GONDWANA 15

North meets South

# ABSTRACTS BOOK

14-18 July 2014, Madrid (Spain)

# GONDWANA 15

***North meets South***

Madrid (Spain)

14-18 July, 2014

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**IGCP Projects 574, 591, 596, 597 & 628 (IUGS-UNESCO)**

# PAST GONDWANA MEETINGS

**Gondwana 1**; 1967
Mar del Plata, Argentina

**Gondwana 2**; 1970
Cape Town & Johannesburg, South Africa

**Gondwana 3**; 1973
Canberra, Australia

**Gondwana 4**; 1977
Calcultta, India

**Gondwana 5**; 1980
Wellinton, New Zealand

**Gondwana 6**; 1985
Ohio, USA

**Gondwana 7**; 1988
São Paulo, Brazil

**Gondwana 8**; 1991
Hobart, Tasmania

**Gondwana 9**; 1994
Hyderabad, India

**Gondwana 10**; 1998
Cape Town, South Africa

**Gondwana 11**; 2002
Christchurch, New Zealand

**Gondwana 12**; 2005
Mendoza, Argentina

**Gondwana 13**; 2008
Dali, China

**Gondwana 14**; 2011
Búzios, Brazil

**Gondwana 15; 2014**
**Madrid, Spain**

## SESSIONS

1) **Gondwana assembly: Neoproterozoic to Cambrian**

2) **Margins of Gondwana**
   a. **The Proto-Andean margin**
   b. **The northern margin and the peri Gondwanan terranes**
   c. **The accretion to Laurussia: the Varsican Orogeny**
   d. **The southern margin**
   e. **The Gondwana orogeny (*cancelled*)**

3) **Processes in Gondwana away from the margins (*cancelled*)**

4) **Gondwana break-up and dispersal: sedimentary record, magmatism and geodynamics**

5) **Ore deposits and Gondwana evolution**

6) **Record of paleo-climatic events in Gondwana (*cancelled*)**

7) **Gondwana biota**

8) **Paleomagnetic constraints on the Gondwana paleo-geographical evolution (*cancelled*)**

9) **Gondwana to Asia (*reduced*)**

# FOREWORD

This Gondwana Symposium takes place for the first time in Europe. It is the 15th of a series of symposia that started 47 years ago in Mar del Plata (Argentina) and which have persisted to date every three years. The symposia were formerly run under the auspices of the IUGS and have been overseen by the Gondwana Committee, currently chaired by Dr. Renata Schmitt of Universidad Federal do Rio de Janeiro. Nowadays the Gondwana Symposium has consolidated the efforts of geoscientists involved in one or more of the many issues involved in the formation, evolution and dispersal of this supercontinent. The topics are relevant to scientists from many different areas and countries. On this occasion the number of attendants is close to 180 which is quite impressive if we consider the many difficulties that geoscientists in general and those interested in basic science in particular are now experiencing. The past few years have been -and still are- times of economic crisis- which for Spain has meant severe cuts in research budgets for all disciplines. Also the timing of the conference in July has discouraged many from attending because it falls within the busiest part of the year at universities and research centres in the southern hemisphere – and it has to be admitted that summer in Madrid is quite hot.

The syponsium will be held at the Superior Technical School of Mines. This institution was first founded in 1777 in Almadén, as an Academy of Mines next to this well-known and world-class Hg-mining district. This was only ten years after the first Academy of Mines was created in Freiberg (Saxony). It is a historical academy and we must gratefully acknowledge the authorities of the school, who were enthusiastic to house the symposium; in particular, the Director, Dr. J.L. Parra and Professor Dr. R. Castroviejo have helped with planning and organization.

We also acknowledge the help of several institutions and people, starting with the Spanish Geological Society (Dr. M. Aurell), the Spanish Geological Survey-IGME (Dr. J. Civis), and its splendid Museum whose director (Dr. Isabel Rábano) has assisted us on many different issues with much skill. Dr. M. Santosh of IAGR has contributed with his sponsoring and advice. The Universidad Complutense has provided logistic help for the intra-conference field trips, and IGEO (UCM-CSIC Institute of Geosciences) has contributed financial support. At a personal level, Dr. A. Díez-Herrero from IGME has been an enthusiastic collaborator through the long process that started three years ago with the earlier idea that the city of Segovia could be the congress venue. Remarkably engineer Ignacio Gutierrez Perez also from Segovia was the website designer and the webmaster in charge of sending massive mailings to all those that we could reunite within a single mailing list built up from previous symposia lists. All those referred to at the start of this abstracts book have collaborated to different degrees and we acknowledge the effort. We are particularly indebted to Sonia Sánchez who was in charge of the registration and the treasury, and to the other two editors of the book, Bob Pankhurst and Pedro Castiñeiras. Carmen Galindo helped to set up the programme.

Gondwana is a concept that is not so central a part of the northern hemisphere cultural heritage as it is for the southern one. Gondwana is truly alive in countries like Australia, South Africa or Southern South America. However the concept is becoming more significant for geologists in Europe, North America or Northern Asia. This symposium will be a modest contribution to enlarge this knowledge and a contribution to tie links between northern and southern cultures of Gondwana.

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# Abstract index

# ABSTRACTS

*The abstracts in this volume have been edited, and the editors take responsibility for any errors or confusion that may have been introduced*

# Precambrian isotopic sources of the Anti-Atlas, Morocco

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The isotopic data stored in detrital and magmatic zircons are crucial for assessing magma sources, terrane correlation, paleogeography and plate reconstructions. In many cases the comparison of the zircon age and isotope signature of a terrane of unknown provenance with the signature of possible sources, generally old cratonic areas, can resolve questions of origin and paleoposition. Obviously, a precise knowledge of the zircon characteristics of these old areas is essential for reliable comparisons.

One of the major sources of sediments of the peri-Gondwanan terranes and of the European Variscan Belt is the West African craton. The northern boundary of this craton is the Pan-African Anti-Atlas belt, which is therefore an ideal place to better constrain the zircon isotopic features of sediments sourced from it. With that aim, we obtained LA-ICM-MS U-Pb and Hf isotopic data of more than 600 zircons separated from six samples of siliciclastic sedimentary rocks from the main Neoproterozoic stratigraphic units of the Anti-Atlas belt, from the Sirwa and Zenaga inliers.

The data suggest that the north part of the West African craton formed during three cycles of juvenile crust formation, with variable amount of reworking of older crust. The youngest group of zircons, with a main population clustering around 610 Ma, has a predominantly juvenile character and evidence of moderate mixing with Paleoproterozoic crust, suggesting that the igneous and metamorphic rocks in which the zircons originally crystallized were formed in an ensialic magmatic arc environment. A group of zircons with ages in the range 1.79–2.3 Ga corresponds to the major crust forming event in the West African craton: the Eburnian-Birimian orogeny. The isotopic data indicate that the provenance area should represent a crustal domain that separated from a mantle reservoir at ~2050–2300 Ma, and further evolved with a time-integrated $^{176}Lu/^{177}Hf$ of ~0.013, characteristic of continental crust. The evolution of the Eburnian orogeny is apparently dominated by new crust formation in a magmatic arc environment. The Lower Paleoproterozoic and Neoarchean evolution (2.3–2.75 Ga) involves a group of detrital zircon ages that has not been identified up to now in the igneous or metamorphic rocks of the north West African craton basement. Their Hf isotopic signature points to reworking of juvenile crust mixed with moderate amounts of Archean crust. The significance of these ages is uncertain: they could represent a tectonothermal event not discovered yet in the Reguibat Shield or the zircons can be far-travelled from an unknown source.

# Tracing the geodymamic evolution of the North Gondwana margin using detrital-zircon geochronology of Pliocene–Pleistocene sand from SW Iberia

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Pliocene–Pleistocene sand of the Alvalade basin was sampled from the sea-cliffs of SW Iberia close to Cape Sines for a provenance study using LA-ICPMS U-Pb dating of detrital zircons. The results are used to compare age distributions and to trace potential source areas based on existing knowledge of zircon-forming events in the pre-Cenozoic basement of SW Iberia. The 492 U-Pb ages obtained span a wide interval ranging from Cretaceous to Archean, with predominance of Paleozoic (31–71%; mainly Carboniferous), Neoproterozoic (19–20%; mainly Cryogenian–Ediacaran) and Cretaceous (21–39%). Two important features were noted: i) Carboniferous ages younger than ~ 315 Ma infrequent or absent in SW Iberia, and ii) Cretaceous ages are interpreted to indicate a Sines massif provenance. The data obtained confirm previous studies that indicate a sediment source in the Paleozoic basement of SW Iberia (Ossa-Morena and South Portuguese zones) but also suggest a more complex history of drainage than previously documented, involving other sources located to the north. The detrital zircons age populations also enable recognition of previously undocumented sources of Pliocene–Pleistocene sands and decipher their paleotectonic meaning: i) Neoproterozoic to Early Paleozoic meta-sedimentary and meta-igneous rocks of the Ossa-Morena and Central-Iberian zones formed in North Gondwana during the Cadomian orogeny and opening of the Rheic Ocean, and ii) Devonian to Carboniferous sedimentary and igneous rocks of the Ossa-Morena, Central Iberian, and South Portuguese zones formed when Gondwana and Laurussia collided (Variscan orogeny).

# Provenance of the Variscan Upper Allochthon (Cabo Ortegal complex, NW Iberian Massif)

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The NW Iberian Massif shows very good exposures and complete sections of the Variscan orogeny of Western Europe. Located above ophiolitic units which outline the Variscan suture, the Upper Allochthon (Upper Units) of the NW Iberian allochthonous complexes is composed of Early–Middle Cambrian magmatic arc related rocks, with siliciclastic and pelitic sedimentary series connected with basin development in this arc context. This Upper Allochthon can be followed in the same structural position along the Variscan belt, from the Iberian to the Bohemian Massifs. This study focusses on the provenance of the Cariño gneiss formation, a gneissic metasiliciclastic unit located in the uppermost structural position of the allochthonous Cabo Ortegal complex. U-Pb and Lu-Hf zircon (LA-ICPMS) and Sm-Nd whole rock analyses have been performed to document the provenance of this unit and so constrain the paleogeographic evolution of the Upper Allochthon.

U-Pb geochronology of 6 samples indicates a Middle Cambrian maximum depositional age, with the following zircon age populations: Paleozoic–Neoproterozoic 36 %, Mesoproterozoic 3.6 %, Paleoproterozoic 46.8 % and Archean 13.6 %. Lu-Hf isotope analyses of these zircons typify Pan-African (Cadomian), Eburnean and Archean orogenic pulses in their respective source areas. Pan-African and Eburnean events entailed abundant input of juvenile material involving broad mixing with older crustal sources. Mesoproterozoic activity is scarce and scattered and so unlikely to represent a major crust generation pulse in the source area of the siliciclastic unit. Sm-Nd whole-rock analyses on 10 samples providean average depleted mantle model age of 1.73 Ga.

This information is compatible with provenance from a source area with Archean crust that registered an important Eburnean orogenic cycle followed by a Pan-African–Cadomian event. Nd TDM ages suggest almost direct derivation from these sources. These data are interpreted as indicative of West Africa craton provenance. The siliciclastic series from which the Cariño gneisses were derived were probably deposited in a back-arc type basin where detritus were mostly sourced from the stable continental area instead of the magmatic arc. Pre-existing U-Pb and Sm-Nd data from another Upper Allochthon unit from NW Iberia (Órdenes complex) points to strong isotopic heterogeneity within this terrane, which is indicative of source area variability. This observation is interpreted to reflect either a temporal evolution of the arc or the possibility that the terrane represented by the Upper Units is composed of more than one domain of the arc-related system.

# Magmatic activity in SE Brazil and SW Africa and the control on continent break-up

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Inland magmatic activity in West Gondwana is a major factor controlling the rifting process that produced the South Atlantic Ocean. Tholeiitic magmatism is distributed throughout a wide area in South America (Brazil, Paraguay, Uruguay and Argentina), Antarctica and Africa (South Africa, Lesotho, Botswana, Namibia and Angola), where the large igneous provinces (LIPs) of Paraná–Etendeka and Karoo, and several dyke swarms and magmatic centres developed. These magmatic events range widely in time, from Late Triassic (Rhaetian) to Early Cretaceous (Late Aptian–Early Albian).
Geochronological ages, from both onshore and offshore basins, range ~ 178-104 Ma. The most frequent are distributed between ~133 and 127 Ma, representing the Paraná–Etendeka magmatic event. The second important cluster, ~ 182–178 Ma, is concentrated in the southernmost South Atlantic, corresponding to the Karoo magmatic event. Two more age clusters are discernible at ~ 151–147 Ma and 107–104 Ma.
The Late Jurassic NNW-trending Vitória-Colatina (VCDS) and Resende (RDS) dyke swarms developed with a subhorizontal $\sigma 3$ tensor of approximately N070, defining an E–W extension. Early Cretaceous Serra Geral–Etendeka volcanism was asymmetrical in distribution, covering a much wider region in South America. Plate reconstruction suggests the presence of either a mantle thermal anomaly or a hot spot during the final rifting episode that led to the break-up of the continental margins in the Aptian, concomitant with the massive outpouring of the lava flows that formed the seaward-dipping reflector wedges observed in the Pelotas–Namibia conjugate margins.
The Early Cretaceous Serra do Mar (SMDS), Ponta Grossa (PGDS) and Florianópolis (FDS) dyke swarms define a triple junction with sub-horizontal $\sigma 3$ of approximately N100. The increasing presence of more abundant and younger dykes offshore indicates progressive lithospheric thinning from about 135 Ma up to the final break-up and the beginning of organized mid-ocean ridge spreading at around 115–105 Ma, as suggested by the reduced number of radiometric ages younger than 115 Ma. Magmatism in the proto-continental margin between SE Brazil and West Africa ceased at around 105 Ma, after the extension focus had shifted to the oceanic spreading centre and the evaporite basin was replaced by a shallow-water carbonate platform associated with the Early Albian marine incursions.
Although magmatism played an important role in the locus of the South Atlantic Rift, it cannot be dissociated from other factors such as the regional stress field, due to asthenosphere–lithosphere interaction, and anisotropies in basement architecture. We suggest that the initial attempt to rupture Gondwana occurred in the Late Jurassic by an extensional $\sigma 3$ stress along an E-W direction, which resulted in N-S extensional fractures (RDS and, partially, VCDS and FDS). The next attempt occurred in the Early Cretaceous, when the appropriate orientation of the Ribeira–Araçuaí belts and the intrusions of the VCDS, SMDS, PGDS and FDS facilitated sinistral oblique rifting along the Rio de Janeiro–Benguela margin.

# Extension and subsequent inversion tectonics in the Ratones section: the boundary between the Central and Western Argentine Precordillera

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The Argentine Precordillera is a fold-and-thrust belt involving Paleozoic, Mesozoic and Cenozoic sediments (Bracaccini, 1946). Regarding the Early Paleozoic facies, the Precordillera is an exotic terrane to Gondwana, probably derived from Laurentia and accreted to the Gondwanan margin in Middle Ordovician times (Thomas and Astini, 2003). The Precordillera has classically been divided into Western, Central and Eastern domains based on stratigraphic and structural features (Ramos et al., 1986). A carbonate platform of Cambrian to Middle Ordovician age extended over the Central and Eastern Precordillera (Bordonaro, 1980), whereas ocean floor facies occurred in the westernmost Precordillera. In the transition between the platform and the oceanic facies there is a block-in-matrix unit interpreted as slope facies (Banchig et al., 1990) related to the ancient continental margin. This stratigraphic unit was usually included in the Western Precordillera domain and the boundary with the Central Precordillera is represented by a thrust surface carrying the slope facies onto well-organized stratigraphic units of the Central Precordillera (Ragona et al., 1995). New data obtained in the Los Ratones area (Rio San Juan section), through paleontological, stratigraphic and structural studies, show that the boundary between these two domains is a complex structure that results from superposition of several deformational stages. The first structures to be developed were syn-sedimentary normal faults sealed by the Devonian Punta Negra Formation. These faults were truncated by two generations of thrusts. The older thrust was a low angle fault carrying the slope facies onto the Central Precordillera. This thrust can be ascribed to the so-called Chanic deformation, because it is covered by unconformable Carboniferous deposits. The younger thrust is a high-angle fault breaching and folding previous thrusts in an out-of-sequence way, giving rise to the duplication of the Central and Western Precordillera stratigraphy, in the same manner that stratigraphic units are repeated by initial thrusts. This duplication re-ordered the initial paleogeographic pattern, producing an apparent paleogeographic inversion in the geological map.



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# Fold reactivation in the Argentine Precordillera

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The Argentine Precordillera is a fold-and-thrust belt involving Paleozoic, Mesozoic and Cenozoic sedimentary rocks (Bracaccini, 1946). Although its present relief developed during Andean deformation, its structure results from superposition of several orogenic events (Ramos, 1988), which are recorded by successive angular unconformities. The Precordillera is an exotic terrane to Gondwana, and the earliest orogenic event resulted from its accretion to the Gondwanan margin in Middle Ordovician times (Thomas and Astini, 2003). Several later angular unconformities were developed in Carboniferous, Permian–Triassic and Cenozoic successions as a result of subsequent orogenic events. In this study we present new data on the structural relationships between different unconformable sequences in the Precordillera. When two angular unconformable sequences are deformed, as a result of a new orogenic event, previous structures underlying the unconformity usually become reactivated, particularly if the shortening direction for the initial and subsequent deformation events is similar, as occurs in the Argentine Precordillera. In this way, pre-unconformity folds are tightened and the unconformable beds have to adapt to the reactivation of those previous folds: the unconformity surface is distorted to a new position and modification of the initial unconformity angle depends on the folding mechanisms in the underlying layers (Alonso, 1989). Thus, when two adjacent beds or multi-layers are deformed by different folding mechanisms, the modification of the unconformity angle will be different for each bed or multi-layer, and cover folds develop overlying homoclinal sequences. Moreover, during fold amplification, the unconformable beds adapt to changes in length of the unconformity surface, which is shortened or elongated as a result of simple shear. As a consequence, the unconformity surface usually becomes a surface of décollement, with detached folds, imbricate thrusts or extensional faults branching from the unconformity. Examples of the structural relationships described above commonly occur between unconformable sequences of different ages in the Argentine Precordillera. Other records of fold reactivation in the Precordillera are flexural slip faults truncating overlying unconformity surfaces.

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Thomas, W.A., Astini, R.A., 2003. Ordovician accretion of the Argentine Precordillera terrane to Gondwana: a review. Journal of South American Earth Sciences 16, 67–79.

# The Cambrian anti-clockwise rotation of Gondwana and its palaeo-biogeographic implications

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Although palaeomagnetism is currently viewed as a primary tool for palaeogeographic research, palaeoclimatic and biogeographic data are key contributors. The existence of du Toit's Gondwana as a supercontinent from Early Palaeozoic through Early Mesozoic times was originally sustained by a variety of geological, palaeontological and palaeomagnetic data. But the latitudinal motion of its margins and possible amalgamation of marginal terranes are still matters of interesting models and interpretations. One example of these discussions is controlled by the scarcity of Cambrian palaeomagnetic data, which has fuelled recent discussions on biogeography and palaeoclimatology (Álvaro et al., 2013; Zamora et al., 2013 and references therein).

During Early Palaeozoic times, West Gondwana was represented by South America, Arabia, Africa, the Mediterranean region and West Antarctica. East Gondwana would then contain Iran, Afghanistan, central Asia, the Himalayan region, Thailand, Vietnam, China, Australia, New Zealand and East Antarctica. Gondwana suffered a Cambrian anti-clockwise rotation, as a result of which West Gondwana recorded a pole-ward drift that affected both sedimentological (migration of climate-controlled sediments and facies, such as evaporites, reef carbonates and arid paleosols) and biodiversity patterns (parallel migration of biodiversity peaks on trilobites and echinoderms).

Palaeomagnetic and palaeogeographic results from East Gondwana (mainly Australia, New Zealand and East Antarctica) also suggest that Gondwana rotated anti-clockwise around an axis near northern Victoria Land, Antarctica, stopping at the end of the Cambrian. In East Gondwana, this change in sense of plate rotation coincides with the termination of the Ross-Delamerian Orogeny along the Transantarctic Mountains and southeastern Australia. A similar migration of biodiversity patterns has been recently documented in trilobites following generalized warming of East Gondwana.

Multidisciplinary studies focused on the Cambrian anti-clockwise rotation of Gondwana, with margins crossing low-mid-high latitudes (so warm, temperate and cold waters), offer a key opportunity to check the interplay of biogeographic, palaeogeographic and biodiversity disciplines to construct a framework of interactive biotic (including climate) and abiotic factors in the early evolution of Gondwanaland.

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# Reconstructing subduction polarity through the geochemistry of mafic rocks of a Cambrian magmatic arc in the Gondwana margin, Órdenes complex, NW Iberian Massif

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Allochthonous complexes in the NW Iberian Massif include three main terranes, of which two (Basal and Upper units) have continental affinity and Gondwanan origin; they are separated by a third terrane consisting of an ophiolite with its protoliths commonly dated at ~ 395 Ma. The interpretation of the Upper Units as a section of a peri-Gondwanan magmatic arc, active at least between Middle Cambrian and Early Ordovician times, is based on various features of the magmatism, deformation, metamorphism and metasedimentary series (Díaz García et al., 2010; Andonaegui et al., 2012). The main plutonic bodies intruding the Upper Units metasediments are the Monte Castelo gabbronorites and the Corredoiras orthogneisses (which include minor meta-gabbronorite bodies), both dated at ~500 Ma. Geochemical differences between these bodies allow determination of the polarity of subduction, which is important in refining paleogeographic reconstructions.

The most significant characteristic is the Sm-Nd and Sr geochemistry. Monte Castelo gabbronorites have high $^{143}Nd/^{144}Nd$ ratios (0.5143119–0.513019, $\varepsilon Nd_i$ values +5.4 to +7.8) whereas initial $^{87}Sr/^{86}Sr$ ratios are low (0.702562–0.703174). In contrast the Corredoiras gabbronorites have low $^{143}Nd/^{144}Nd$ (0.512575–0.512436, $\varepsilon Nd_i$ values -0.7 to +1.8) and higher initial $^{87}Sr/^{86}Sr$ (0.705082–0.706684). In the εNd vs. age diagram Monte Castelo samples have compositions consistent with magma derivation from a depleted mantle reservoir and consequently these are juvenile rocks not influenced by old recycled crust. On the other hand, Corredoiras meta-gabbronorites have much lower $\varepsilon Nd_i$ values and older model ages ranging between 1165 and 1291Ma, which clearly suggests significant participation of an old continental crust component in the genesis of the parent magmas.

The geochemical features of Monte Castelo meta-gabbronorites (trace element and isotopic ratios) indicate a tholeiitic affinity. The origin of this large mafic body was probably related to the first stages of development of an island arc, or else it was located close to the trench of an evolved volcanic arc where the influence of any pre-arc continental crust was negligible. Meanwhile the geochemistry of Corredoiras metagabbronorites indicates a calc-alkaline affinity, with isotopic sources proving a significant contribution of a crustal component. This geochemistry can only be linked to the setting of a mature volcanic arc built up over a well-developed crustal section and thus in a relatively distant position from the trench.

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# Structural of the Sibumasu-Indochina collision, central Thailand: a section through the Khao Khwang fold-and-thrust belt

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Mainland SE Asia includes a number of continental fragments and volcanic arcs, separated by oceanic suture zones, which accreted to the growing Asian continent in the Triassic Indosinian orogeny. The evolution of this orogeny has always been quite controversial. The principal terranes that form the core of SE Asia comprise the North China, the Yangtze block, the Cathaysian block, the Indochina block, the Sibumasu block and the Sukhothai terrane. The Khao Khwang fold-and-thrust belt lies close to the boundary between the Indo-China block and the Sukhothai arc in central Thailand, near the town of Saraburi. Here, the fold-and-thrust belt presents a series of E–W and ESE–WNW orientated thrusts and associated fold hinges, apparently contradicting the commonly held interpretation that the terranes were accreted in a broadly E–W sense along N–S striking collisional zones. Field mapping in the Khao Khwang fold-and-thrust belt reveals that shortening started during the Late Permian and continued until Late Triassic. We conclude that the fold-and-thrust belt formed by forward (northward) propagating deformation in the Triassic and affects only cover strata, which were displaced mainly along weak horizons of incompetent shale within the Khao Khad Formation and were transported by numerous in-sequence thrusts. The in-sequence thrusts of thin-skinned deformation demonstrates that deformation itself migrated from S–SSE to N–NNW along a zone as wide as the fold-and-thrust belt itself, with lateral facies variations. The Khao Khwang has been interpreted as a thin-skinned fold-and-thrust belt developed on a detachment at a depth of between 0.7 and 1.5 kilometres. The Khao Khwang fold-and-thrust belt represents a significant kink in the collision between Sibumasu and Indochina that may be due to either the original geometry of the Indochina margin, or to a poorly recognised ocean strand that split Indochina into two.

# Unravelling the Mozambique Ocean conundrum using a triumvirate of zircon isotopic proxies on the Ambatolampy Group, Central Madagascar

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Madagascar occupies an important location within the East African orogen, which involves a collection of Neoproterozoic microcontinents and arc terranes lodged between older cratonic units during the final assembly of the supercontinent Gondwana. The Malagasy basement preserves a record of the style and timing of amalgamation of Neoproterozoic India with the Congo/Tanzania/Bangweulu block during the final closure of the Mozambique Ocean. Central Madagascar is comprised of a number of Precambrian units. The oldest blocks, the Antongil and Masora cratons, consist of Mesoarchaean ortho- and paragneiss cores in addition to Neoarchaean granitic and metasedimentary rocks. The largest unit, the Antananarivo block, underlies the central highlands and consists of Neoarchaean granite interlayered with voluminous Cryogenian to Cambrian granite, syenite, and gabbro, the majority having subduction-zone geochemical characteristics. Overlying the Antananarivo block are Proterozoic metasedimentary packages (Ambatolampy, Manampotsy, Vondrozo and Itremo-Ikalamavony groups). The Ambatolampy, Vondrozo and Manampotsy groups are major siliciclastic metasedimentary successions characterised by a pelite-quartzite association. The Itremo-Ikalamavony suite consists of probable Palaeoproterozoic greenschist- to amphibolite-facies metasedimentary rocks and is intruded by Cryogenian granitoids and gabbro.

Previously, the Ambatolampy Group was interpreted as a Neoproterozoic sequence with a maximum depositional age of ~1056–650 Ma. A minimum depositional age of ~560 Ma was constrained by metamorphic zircon ages and by intrusive relationships with the Ediacaran Ambalavao suite. New U-Pb zircon data (SHRIMP) for the Ambatolampy Group shows age populations of ~3000 Ma, ~2800–2700 Ma, ~2500 Ma, ~2200–2100 Ma and ~1800 Ma. We did not find the rare Mesoproterozoic zircons reported (but incompletely published) by others. Hence, we tentatively suggest that the Ambatolampy Group may be older than previously thought since the youngest concordant detrital zircon age is ~1800 Ma, similar to the Itremo-Ikalamavony suite. Metamorphic zircons and rims indicate a minimum depositional age of ~540 Ma. We also present complementary $\delta^{18}O$ (SHRIMP SI), and Hf (MC-LA-ICP-MS) isotopic data for Ambatolampy Group detrital zircons, thus providing new constraints on the age, geochemistry and provenance of the metasedimentary rocks. We compare these data with analogous metasedimentary sequences elsewhere in the East African orogen and discuss their tectonic implications.

# The Variscan belt: a two stage collision at the birth of Pangea

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It is broadly accepted that the assembly of Pangea occurred in Carboniferous and Early Permian times, after a long stage of continental convergence that ended with the closure of the Rheic Ocean and the collision of Gondwana with Laurussia. This collision resulted in the formation of the Variscan-Appalachian-Alleghanian orogen, which extends from Europe to eastern North America and contains key information for reconstructing the amalgamation history of the supercontinent. In the Variscan belt, the early tectonothermal events are preserved in a complex suture zone that can be traced from the Iberian Peninsula to the Bohemian Massif. In the NW Iberian Massif, the Variscan suture contains a stack of terranes including two allochthonous units with continental affinity and Gondwanan provenance (Upper and Basal Units), separated by an ophiolite belt where the most common units show protoliths ages of ~395 Ma. The same terranes appear along the belt in Central and Eastern Europe, showing almost identical lithologies, chronology and tectonothermal evolution.

In the Upper Units, ~10000–12000 m of terrigenous sediments intruded by large massifs of Cambrian (~ 500 Ma) I-type calc-alkaline granitoids and tholeiitic gabbros are considered to represent a section of a Neoproterozoic–Cambrian magmatic arc on the Gondwana margin. They record a first high/ultra-high P metamorphism at ~ 410–390 Ma. The Basal Units consist of a thick sequence of Ediacaran–Early Ordovician terrigenous metasedimentary rocks intruded by Cambrian to Ordovician granitoids (calc-alkaline to peralkaline) and minor mafic igneous rocks. They were affected by a second high-P, low-to-intermediate T, metamorphic event at ~370 Ma. True MORB ophiolites derived from typical oceanic lithosphere are unknown in the Variscan suture: the mafic–ultramafic sequences preserved in NW Iberia have island-arc tholeiitic composition and are interpreted as generated in supra-subduction settings. Recent Lu-Hf zircon data obtained from the Early Devonian ophiolites reveal an interaction between old continental crust and the gabbroic magmas, which consequently might not represent open oceanic domains. Due to their buoyant nature, many Devonian ophiolites escaped early Variscan subduction, so they are the most common ophiolites preserved in the Variscan suture across Europe. They were accreted beneath the Upper Units during Variscan convergence at ~ 391–377 Ma.

The tectonothermal evolution of the terranes with continental affinity records two consecutive events of deep subduction affecting the most external margin of Gondwana, both developed in a context of dextral convergence with Laurussia. The two high-P events alternated with the opening of a rather ephemeral oceanic basin, probably pull-apart, in Early Devonian times. This short-lived oceanic domain is suggested as the setting for the protoliths of the most common ophiolites involved in the Variscan suture. Current ideas for the assembly of Pangea advocate a single collision event between Gondwana and Laurussia in Carboniferous times. However, the new evidence from the allochthonous terranes of the Variscan belt suggests a more complex scenario for the supercontinent assembly, with interaction between the colliding continental margins starting earlier and lasting longer than previously considered.

# Palaeozoic stability in sediment transportation paths along the western Gondwana margin – implications from detrital zircon U-Pb ages

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We investigated the Palaeozoic detrital zircon record of the present-day south-central Andes (N Chile and NW Argentina) in order to reveal variations in transport paths through time. Zircon grains from 17 beds of very fine to fine sandstone of Cambrian to Permian age were analysed. The detritus was deposited under shallow-marine, turbiditic, and/or fluvial conditions. Cathodoluminescence images of the grains reveal a dominance of zircon of magmatic origin, little abrasion and mostly only one growth phase. We detected little variation in the age spectra despite the facies differences. Main age clusters for all time periods, except for Cambrian and Silurian units, are at 630 to 440 Ma, representing the Brasiliano, Pampean and Famatinian orogenies. A smaller group is Rodinia-related ("Grenvillian") at 1.3-0.9 Ga. The ages can be explained by main local transport from the Ordovician Famatinian magmatic arc. Additional transport was local or from the south - from the area of the Puna and south to the Sierras Pampeanas, where crystalline rocks of Rodinian, Brasiliano, and Pampean ages are present. The Cambrian and Silurian sedimentary rocks are dominated by Brasiliano (ca. 0.6 Ga) and Transamazonian age zircon (2.2–1.9 Ga). Pampean and Famatinian ages are less common. During these time periods the studied depositional basins were fed by local or southern material (Brasiliano ages) carried in a longer transport system that emanated from the Río de la Plata craton (Transamazonian ages) in the east. Hence, we infer transport from the adjacent N-S directed Famatinian arc throughout the Palaeozoic era. The eastern transport during Cambrian and Silurian times can be explained by the position of the studied depositional basins in relation to the Ordovician magmatic arc, which acted as an effective erosional barrier long after it became inactive and prevented detritus from the Gondwana interior reaching the marginal basins. During Cambrian time transport from the continent itself was not yet hampered. The studied Silurian units crop out on the eastern fringe of the extinct arc and so could receive input from the interior of Gondwana. The zircon suite does not record the Ordovician and Devonian accretions of the Cuyania-Precordillera and Chilenia terranes, which collided with West Gondwana (west of the Sierras Pampeanas) in the south. Furthermore, Ordovician and Devonian–Carboniferous glaciations in west Gondwana, with probable glacial and glaciofluvial transport from the continent interior, were not marked in the zircon record. As such the transport system remained stable for ~ 300 Ma with main transport from the nearby arc. Hence, palaeogeographic reconstructions based on provenance data do not necessarily reflect geological composition in the interior of the continent. Furthermore, detrital zircon ages do not necessarily reflect tectonic changes and may represent a much smaller part of the continent than expected.

# Tectonic evolution of the Dom Feliciano belt and its role during Central Gondwana formation

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Few records of the Neoproterozoic Adamastor Ocean that existed between the major cratons of SW Africa and southeastern South America can be found on either side of the Atlantic Ocean, where a diachronous history of at least 300 Ma can be characterized. Its closure led to the establishment of the major supracrustal belts of Central Gondwana. The events that led to the opening of the Adamastor Ocean began in the Tonian, around 950–850 Ma, with the fragmentation of pre-existing continental masses. Between 780 and 640 Ma rifting, deposition of siliciclastic successions and intrusion of various granitoids occurred. The completion of the volcano-sedimentary paleobasins related to Adamastor seems to have been achieved by ~ 600 Ma.

In the Dom Feliciano belt the consumption of the Adamastor Ocean can be characterized by the development of a long granitoid belt with magmatic-arc signatures (Florianópolis, Pelotas, and Aiguá batholiths). Despite the large area occupied by these granitoids, most of the U-Pb zircon ages are between 640 and 595 Ma, with the vast majority in the narrow interval of 610 to 600 Ma. On the African side there is no evidence of corresponding Neoproterozoic magmatic arcs, with the exception of the westernmost domain of the Kaoko Belt (granitic rocks of the Skeleton Coast) whose ages and geochemical characteristics suggest an affinity to the Florianópolis-Pelotas-Aiguá magmatic arc. In all these arcs the isotopic and geochemical signatures and negative εNd values indicate the involvement of continental crust in their generation.

The supracrustal rocks of the Dom Feliciano belt exhibit a low to medium metamorphic overprint controlled by temperature variations. Ages of volcanic rocks intercalated in the metasedimentary piles and intrusive post-tectonic granitoids constrain the main collisional phase of Dom Feliciano belt between 640 and 600 Ma.

In concordance with what is observed on the South American side, the Neoproterozoic belts of southwestern Africa present the same structural and temporal evolution. Detrital zircon ages of around 550 Ma indicate that deposition of western units of the Saldania, Gariep and Kaoko belts took place after the collisional phase observed in the belts of SE Brazil. Thus, it is suggested that in the SW African belts there are metamorphic units that reflect Ediacaran/Early Cambrian basin fills not associated with the Adamastor Ocean, as this ocean had already closed at that time. It is proposed that these younger units were deposited in an epicontinental sea developed at the eastern border of the Florianópolis-Pelotas–Aiguá magmatic arc, spatially superimposed on older basin fills, making it difficult to distinguish between the metamorphic products of these two episodes.

The detrital zircon age signature typical of the Kalahari Craton (0.9–1.2 Ga) is also a striking feature in the metasedimentary cover of the Florianópolis-Pelotas-Aiguá batholiths. This provides further evidence of a genetic relationship with the Neoproterozoic supracrustal belts in southwest Africa and of juxtaposition of the various segments of the Dom Feliciano belt and its African counterparts only during the closure of the Adamastor Ocean.

# Anisotropy and fabric development in felsic granulites of the HP-HT upper allochthon, Órdenes complex, NW Iberia

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Quantitative fabric analyses of mylonitic felsic granulites from the Sobrado unit (upper allochthon, Órdenes complex) have performed with HIPPO, a TimeOfFlight neutron diffractometer at the LUJAN center, Los Alamos National Laboratory (Gómez Barreiro and Martínez Catalán, 2012). Shape analyses of selected phases were performed with X–ray computed microtomography at ELETTRA (SYRMEP beamline). The Sobrado unit represents an excellent example of laminated mid/lower crust. The unit is a tectonic stack of highly deformed slices of metabasites, paragneisses and ultramafic rocks, with metamorphism ranging from amphibolite facies at the top to eclogites facies at the bottom. Contrasted rheological behaviour suggests that felsic lithologies accommodated most of the flow during the exhumation. We explore the crystallographic preferred orientation or texture to constraint the deformation mechanisms and determine their contribution to the elastic anisotropy of the aggregate. Microstructure and texture evolution suggests that deformation evolved from granulite to amphibolite facies along a N–S flow, driven by dislocation creep partially assisted by grain boundary sliding and diffusion. The kinematic and mechanical implications are discussed in terms of the regional geology.

Gómez-Barreiro, J. Martínez Catalán, J.R., 2012. The Bazar shear zone (NW Spain): Microstructural and Time-of-Flight neutron diffraction analysis. Journal of the Virtual Explorer, Electronic Edition, volume 41, paper 5, doi:10.3809/jvirtex.2011.00296

# New peri-Gondwanan records of the Hirnantia Fauna in the latest Ordovician of Spain

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The Hirnantia Fauna represents a widespread assemblage of opportunistic species of brachiopods and trilobites with almost global distribution that developed at the time of the latest Ordovician Extinction Event. This was caused by the drastic climate change of the Hirnantian glaciation on the Gondwana continent. In Ordovician polar and subpolar paleolatitudes, the Hirnantia Fauna is of extremely low diversity (the "Bani province" assemblage of present-day North Africa and Ibero-Armorica), but diversity increases in slightly more temperate paleolatitudes beyond the circumpolar region (the "Kosov province" assemblage of Bohemia, Sardinia, Carnic Alps and Pontides), and it reaches a maximum in the tropical and subtropical paleolatitudes (the "Edgewood province" assemblage of Laurentia, Baltica or southern China).

In the Iberian Massif of Portugal and Spain, the Hirnantia Fauna is represented by two occurrences of brachiopods in the Central Iberian Zone and by one in the Cantabrian Zone, plus two single records of a typical Hirnantian trilobite from glaciomarine sediments in the Iberian Cordillera and the Ossa-Morena Zone. All these assemblages, poorly studied so far except the one documented from the Criadero Quartzite of Almadén (Villas et al., 1999), belong to the "Bani province" based on the occurrence of the brachiopods *Hirnantia sagittifera* (M'Coy), *Plectotyrella crassicosta chauveli* (Havlícek), *Arenorthis* sp. and the trilobite *Mucronaspis* cf. *mucronata* (Brongniart).

Recent field studies in the Cantabrian Zone of NW Spain resulted in the discovery of a new locality with the Hirnantia Fauna near Argovejo (León province) with a surprising high-diversity assemblage of rhynchonelliform brachiopods belonging to 11 genera (a.o. *Hirnantia*, *Hindella*, *Eostropheodonta*, *Arenorthis*, *Plectothyrella*, *Dalmanella*, *Cliftonia* and *Leptaena*), occurring in association with diverse trilobites (*Mucronaspis*, *Flexicalymene*, plus minute odontopleurids, lichids and homalonotids), bryozoans, gastropods, pelmatozoans, poriferans, machaeridians and escolecodonts. This assemblage can be ascribed to the "Kosov province" type (except for *Arenorthis*) and occurs within an area where Hirnantian tunnel valleys coeval with the Gondwanan glaciation and a "atypical" (Bani province) Hirnantia Fauna have been found (Gutiérrez-Marco et al., 2010).

The co-occurrence of Bani and Kosov faunas in the same palaeogeographic location reopens the question of whether temperature or paleolatitude was limiting factor for the geographical distribution of the Hirnantia Fauna, or alternatively, if other environmental factors such as substrate or depth, also played a significant role.

Apart from this important occurrence of a diverse Hirnantia Fauna in subpolar Gondwanan latitudes, we report a new locality with *Plectothyrella crassicosta chauveli* and *Eostropheodonta* sp. from the Los Puertos Quartzite of the Iberian Cordillera. Also we add to the known occurrences of the "atypical" Hirnantia Fauna from the Cantabrian Zone with the first record of *Eostropheodonta* sp. in the Luna Quartzite of Valdeteja locality; and in the Central-Iberian Zone with the first identification of *Kinnella kielanae* (Temple) among the assemblage of the Criadero Quartzite from Almadén.

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North meets South

# Tectonic control and mass transfer during serpentinisation of mantel sequence of Bou Azzer middle Neoproterozoic ophiolite (Central Anti-Atlas, Morocco)

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The Bou Azzer inler of the Anti-Atlas in Morocco represents a geological window into Proterozoic basement surrounded by a discordantly overlying infra-Cambrian to Paleozoic cover sequence. The serpentinization at Bou Azzer occured in two phases. Pseudomorphic oceanic serpentinisation, represented by the isotropic serpophite preserving the primary form of olivine crystals, affected the entire series homogeneously, often with fibro-struck needles antigorite. Brucite is fairly common, observed as inclusions in the serpentine. Secondly, tectonic continental serpentinisation occurred during subduction and obduction of the ophiolite, producing lizardite and chrysotile (Wafik, 2001).
We focused our work on field investigation by geological and numerical mapping in many cross-sections and sampling of the Mechoui, Ambed, Inguijem and Ait Ahmane massifs. Our laboratory investigation was based on petrographic, metallographic and geochemical studies.
We observed that the serpentinization of ultramafic formations of the Bou Azzer ophiolites related to different level of deformation. Serpentinization is more developed and complex in more deformed areas, where sinestral faults and shear zones, mainly oriented N110-N130 are observed (sometimes N20°E to N60°E). The lineation is mainly oriented N 65–N70. The main paragenesis in the shear zones and faults is lizardite and chrysotile and asbestos with minor antigorite and chromitite and magnetite. Late hydrothermal alteration has transformed serpentinite to chloritic facies with asbestos in thin veinlets and banded textures representing the metasomatic fronts. Some veins and dykes are fully transformed into giobertite and magnesite, as in the case of the Ambed and Ait Ahmane massifs.
In contact with gabbroid and granitoid dykes, the serpentines are transformed. The intrusive rocks also exhibit evidence of metasomatic transformations contacts with serpentinite. In areas of high hydrothermal alteration, the serpentines are transformed into listwenites.
A whole-rock geochemical study of Bou Azzer serpentinites was carried out by ICP-MS. Greisens's mass balance calculation, using Zr, Ti and Y as immobile elements, has been applied to assess water/rock transfer reactions. The results indicate very high mobility of most oxides and metallic elements. Some oxides and elements (e.g., $SiO_2$, $Al_2O_3$, $Fe_2O_3$, MgO, MnO and Sr) are enriched from the less serpentinized core to the fractured and faulted periphery, whereas others ($Na_2O$, $P_2O_5$, $K_2O$ and CaO) are leached. Transition metals are also leached from very deformed serpentinite. This is evidence that serpentinite is the source of Bou Azzer nickel and cobalt arsenides, which were deposited in contacts between serpentinite and intrusive massifs. The combination of tectonics and serpentinisation controlled the mobility and leaching of Ni and Co that are in substitution with Fe in primary the ultramafic minerals olivine and pyroxene.

# Compression–extension tectonics in the evolution of granulites of the Indian peninsula: implication for Rodinia–Gondwana supercontinent assembly

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Granulite terranes of the Indian peninsula have served as an important proxy in reconstruction of supercontinent assemblies. The South Delhi terrane has been extended into the East African orogen and Southern Granulite terrane has been correlated with Madagascar in East Gondwana assembly. Here we highlight the compression and extension tectonics that were important in the evolution of the Indian granulites, and which could provide important criteria for reconstructions.

Granulites occur as an exhumed terrain surrounded by low-grade rocks of the South Delhi terrane in the Delhi–Aravalli mobile belt of NW India. The contact is marked by marginal faults, cataclasites and pseudotachylites. In the early stage of evolution, pelitic granulite, calc granulite, basic granulite and several phases of Ambaji granites underwent compressional tectonics marked by multiple stages of buckle folds. The peak granulite facies metamorphism was syn-tectonic with F1 folding; F2 folding which is coaxial with F1 was accompanied by syn- to post-kinematic brittle–ductile thrusting. Mylonites show a quartz-ductile–feldspar-brittle condition, suggesting shearing P-T conditions of 15 km and 500–550°C. Hence it has been argued that the granulites were exhumed by thrusting from such great depth to as little as 5 km, where brittle deformation led to formation of pseudotachylites and cataclasites. F3 folds produced domal outcrops and caused plunge reversal of the earlier folds. In late stage deformation, extensional faults were developed with associated normal slip, block rotation and roll-over structures. The extension led to crustal thinning so that the granulites were exposed in due course through erosion. SHRIMP U-Pb zircon dating yielded ages of 1200–900 Ma for sedimentation, 860 Ma for F1 folding-granulite facies metamorphism, 800 Ma for F2 folding and thrusting and 750 Ma for late stage granite emplacement. Monazite dating of the granulite and mylonites show the extensional faults to be 699–647 Ma. Thus the South Delhi terrane belongs to the Neoproterozoic era, between Rodinia break-up and Gondwana assembly.

Part of the Southern Granulite terrane lying between the Salem–Attur and Palghat Cauvery shear zones here named the Salem–Namakkal subterrane is Paleoproterozoic. Mafic granulites, charnockites, granite gneisses, granites and BIF are the main rock types, which show coaxial folding (F1 and F2) in a compressional setting. SHRIMP dating shows the peak granulite facies metamorphism to be 2.5 Ga old. However, the granulites were retrograded during low-angle thrusting towards the NNE, which exhumed the rocks to the upper crust. Cataclasites and pseudotachylites were produced subsequently. Based on EPMA dating of monazite, the thrusting is constrained to between 1140±27 Ma and 814.3±16 Ma. Late stage extension gave rise to extensional faults, block rotation, detachment and roll-over structures. Hence thrusting and extension is interpreted to be syn-tectonic with that in the South Delhi terrane. Thus both granulite terranes underwent compression and extension tectonics in their evolution, with exhumation between Rodinia and Gondwanaland orogenies.

# Age, geochemistry and tectonic significance of the Western Ethiopian Shield

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The U-Pb and Hf isotopic analysis of zircons is used to define the maximum depositional age and provenance of the protoliths to metasedimentary units, as well as constraining the age of igneous intrusions located within the Western Ethiopian Shield. Collectively, the data provide provenance and geochemical information as to whether or not the protoliths formed as Neoproterozoic volcanic arcs, created as a result of subduction and the closure of the Mozambique Ocean during the amalgamation of Gondwana.

Western Ethiopia is made up of a range of supracrustal and plutonic rocks. The Precambrian exposures of the Western Ethiopian Shield are positioned within the juvenile Neoproterozoic crust of the Arabian–Nubian Shield and the older, predominately gneissic Mozambique Belt. Detrital zircons, obtained from a meta-sandstone, yielded provenance age peaks at ~2499 Ma, ~1855 Ma and 1100–800 Ma and a maximum depositional age of 838 ± 13 Ma. Hf isotopes from the same zircons demonstrated that both the oldest and youngest populations have broadly juvenile Hf isotopic values, although ~1820 Ma zircons show significantly evolved Hf isotopic values.

SHRIMP U-Pb ages for two granites and two magmatitic tonalitic gneisses in the Nekempt–Ghimbi region of the Western Ethiopian Shield indicate magmatic crystallisation ages. Data suggest two pulses of magmatism at 850–840 and 780–760 Ma. These samples yield positive εNdt (3.9–4.8) and εHft (2.2–9.6) values, indicating that the magmas were generated from relatively juvenile Neoproterozoic mantle sources with minimal involvement of the pre-Neoproterozoic continental crust. Further west, the post-tectonic Ganji granite yielded a $Pb^{206}/U^{238}$ age of 573 ± 7 Ma, approximately 50 Ma younger than previously interpreted. It has formerly been classified as a monzogranite (Kebede and Koeberl 2003), and shows chemical and mineralogical characteristics of within-plate granites, generated and emplaced in an extensional tectonic environment. The Ganji Granite is undeformed and provides an age constraint for the final deformation in the area. It yielded whole εNdt values of 3.74 and εHft values of 6.8–8.0, demonstrating a juvenile origin.

Radiogenic isotopic analysis of volcanic and volcaniclastic successions of the Western Ethiopian Shield revealed positive εNd values signifying relatively juvenile sources. The geochemical signature of these volcanic and volcaniclastic samples were assessed using rare earth element spider-plots. The transitional character of the dolerite and volcaniclastic rocks having partly enriched MORB-like geochemical signatures fits best with continental back-arc or rifted arc palaeotectonic settings.

Collectively, the data support an interpretation that the Neoproterozoic terrane was, in part, formed as the result of the closure of a Neoproterozoic ocean (Mozambique Ocean) and the formation of an arc. However, it wasn't an intra-oceanic arc as sediments clearly show sources that are consistent with derivation from cratonic Africa.

# Margin-oblique spreading in the Permian Dun Mountain Ophiolite, Bryneira Range, New Zealand: a window into the dynamics of the austral Gondwana margin

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The Dun Mountain Ophiolite lies along the boundary between the inboard arc and arc-related basins (to the west) and the outboard accretionary complexes of the active Permian–Mesozoic Gondwana margin. The ophiolite can be traced for over 400 km in the sub-vertical eastern limb of a regional-scale syncline and forms the basement to the Permian and Triassic sediments of the Maitai terrane. The make-up of the ophiolite varies considerably along strike and we describe part of the central section in the Bryneira Range. The section is divided by a sub-vertical fault into a mantle section and a crustal section about 4 km thick. The dike zone is complex and the strongly discordant sheets can be divided by composition, chilled margin development and cross-cutting relationships into two major phases and up to four sub-phases. Attempts have been made to unfold the dike swarm using successive paleo-horizontals represented by the bedding of Permian limestone, the bedding of underlying sedimentary breccias, and the flattening plane of the pillow lavas. Application of these successive rotations produces interpretable patterns for only the younger dikes and suggests they were intruded into older rocks undergoing brittle extension and rotation similar to that seen in the currently extending Bransfield Strait, Antarctica. This comparison also suggests that the faulted contact between the crustal and mantle sections was originally a sub-horizontal detachment with truncation of the crustal section. The younger dikes suggest extension highly oblique to the strike of the Dun Mountain Ophiolite and to the accepted Gondwana margin. The protracted structural development is consistent with geochemical evidence for multi-stage magma generation.

A wide late Paleozoic to Mesozoic magmatic arc developed in eastern Australia and Marie Byrd Land (Antarctica), but the correlative belt in New Zealand is narrow and incomplete, a situation attributed to tectonic erosion. The unusual character of the Dun Mountain Ophiolite may record obliquely orientated stress field(s) in the supra-subduction wedge and magmatic arc.

# The Brasiliano collage in South America

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The Brasiliano collage contains a history of assembly of several descendants of the break-up of Rodinia, from early Cryogenian to Cambrian times. The continental fragments concerned are of various dimensions – small, intermediate and large, the latter representing the main subsequent cratonic domains. Oceans, oceanic branches, gulfs, aulacogens and even rift systems separated the fragmented blocks before and during their assembly. Four main structural provinces are recognized in the Brasiliano collage: Tocantins (central and central northern part of the continent), Borborema (northeast), Mantiqueira (southeast and south) and Pampean (southwest, in Argentina).

Break-up events and dispersal occurred at various times throughout the Neoproterozoic, but with a significant concentration in the early Cryogenian (850–740 Ma). Initial plate interaction events, including accretion (island arc, magmatic arcs) and collision (high-grade regional metamorphism) also occurred in the early Cryogenian (800–750Ma), in part coeval with taphrogenic processes occurring elsewhere.

The most important phase of orogeny took place in late Cryogenian–early Ediacaran times (660–620/610Ma). Accretionary and subsequent metamorphic events (~630-600Ma) are recorded in most of the structural provinces.

A third phase of orogeny occurred in Mid-Ediacaran times (~ 590–560Ma), with clear records in most provinces. Structures formed during this episode resulted in both zones of interaction with the previous orogenic domains and the final closure of remnant oceans and other marine basins that previously separated the Rodinian fragments. Thus, the general outlines of West Gondwana were drawn by the end of this orogenic event (in Mid-Ediacaran times).

A last, minor orogenic phase occurred in Cambrian times, exclusively in the eastern central part of the Mantiqueira province (the Búzios orogeny, Rio de Janeiro) and in the Pampean province of Argentina. This last orogenic event might have extended to the southwesternmost part of the Tocantins province in Brazil (along the Paraguay belt), but this needs further investigation. These localized phases of orogeny ("Búzios" and "Pampean") were in some ways exceptional at that time: they were coeval with the then predominant late and post-tectonic processes (foreland tectonics, molasses, anorogenic volcanism and plutonism, extrusion, etc.,) of the two previous orogenic phases.

The structural trends developed by the mosaic-like branching systems of Brasiliano orogens were very important during the evolution of Phanerozoic sedimentary basins, with remarkable records of tectonic heritage in all of them.

# The unification of Gondwana: from sapphires to diamonds at the dawn of the Phanerozoic—For the times they are a-changin'

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Diamonds are forever only in advertising. In the crustal record of metamorphism, UHP rocks first appear in the Zambezi (late Cryogenian) and Gourma (Ediacaran) belts in south and west Africa, and diamonds appear first in the Cambrian (Kokchetav–North Tianshan belt). Once established, UHP metamorphism became the characteristic feature of Phanerozoic orogenesis in Eurasia. By contrast, 40% of known corundum (sapphire/ruby) deposits are associated with Ediacaran–Cambrian granulite facies and UHT metamorphism in central East Gondwana (eastern Africa, Madagascar, southern India and Sri Lanka). Why? One-sided subduction creates asymmetry in the thermal structure of convergent margins, with lower $dT/dP$ in the subduction zone and higher $dT/dP$ in the orogenic hinterland. During collisional orogenesis these distinct thermal environments are imprinted in the rock record as contrasting types of metamorphism, distinguished by different apparent thermal gradients. Proterozoic orogens present eclogite–HP granulite metamorphism, with gradients of 350–750°C/GPa, and granulite–UHT metamorphism, with gradients of 750–1500°C/GPa. By contrast, in addition to eclogite–HP granulite metamorphism, Phanerozoic orogens manifest UHP metamorphism with strikingly lower gradients of 150–350°C/GPa, but UHT metamorphism virtually disappears from the rock record after the Cambrian. This is the beginning of the modern plate tectonics regime. For contemporary conditions, geodynamic modelling of collisional orogenesis shows that slab break-off occurs at depths > 300 km in all experiments: strong lower crust results in coupled collision with UHP metamorphism, whereas weak lower crust results in decoupled collision with eclogite–HP granulite metamorphism. Increasing the ambient mantle temperature by 80–100°C leads to shallow slab break-off (< to << 200 km) and unconventional modes of collision, *viz* a truncated hot collision regime (strong lower crust) and a two-sided hot collision regime (weak lower crust). Inverting these data, as ambient mantle temperature declined to < 100°C warmer than the present day the change to deeper slab break-off generated a colder environment, as recorded by the appearance of UHP metamorphism, and enabled stronger crust–mantle coupling that allowed subduction of continental rocks to mantle depths. Thus, the appearance of UHP metamorphism was a consequence of secular decrease in ambient mantle temperature. By contrast, the granulite facies and UHT metamorphism of central East Gondwana represents the exhumed deep crust of a large, moderately thick orogenic plateau that formed by Ediacaran collision and hinterland thickening. Radiogenic heating generated peak metamorphic temperatures in the Cambrian. It may be no coincidence that this area could have been located over the African LLSVP at the end of the Ediacaran or that the Zambezi, Gourma and Kokchetav–North Tianshan belts had a subduction polarity broadly towards the core of East Gondwana. The Neoproterozoic–Phanerozoic geological record preserves geochemical indices that show the influence of geodynamics on climate during this critical transition in Earth history. Finally, the Neoproterozoic to Cambrian period also witnessed a change in style of continental break-up and aggregation. During the Phanerozoic, internally generated ocean basins were opened and closed asymmetrically by rifting of ribbon terranes from the northern margin of Gondwana and their accretion to Laurentia, Baltica and Siberia forming the Caledonides, Variscides and Altaides–Tethysides, respectively.

# The palaeogeographic position of the Ossa-Morena Zone during the Cambro-Ordovician

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The paleoposition of the Iberian massif zones prior to amalgamation continues to be a subject of considerable debate. Bea et al. (2010) proposed a new Cambro-Ordovician position for the Central Iberian Zone (CIZ), north of the Sarahan metacraton. The Cantabrian Zone (CZ) and Galicia Tra-Os-Montes Zone (GTMZ) basal units were apparently also in a similar position at that time (Díez-Fernández et al., 2010; Pastor-Galán et al., 2013). Here we consider the position of the Ossa-Morena Zone (OMZ) in relation to the birth of the Rheic Ocean and subsequent amalgamation of Iberia. For this we present new zircon U-Pb SHRIMP ages for an OMZ A-type Cambrian leucogranite and a Serie Negra metasediment. These are combined with a database of Proterozoic–Paleozoic Nd isotope data and zircon ages from the OMZ, CIZ and North Africa.

Neoproterozoic to Cambrian OMZ sedimentary rocks, e.g. Serie Negra sample, have a Nd model age of 1.8 Ga, as does the OMZ Cambro-Ordovician crust-derived magmatism. This is older than the 1.5 Ga model age of CIZ Neoproterozoic metasedimentary rocks and Ordovician orthogneisses. Along the northern Gondwana margin the most westerly Anti-Atlas, West African craton, has a Nd model age of around 1.1 Ga; the easterly Sahara metacraton 1.5 Ga and the central Tuareg Shield 1.8 Ga.

The OMZ detrital zircons have Ediacaran, Cryogenian, Paleoproterozic and Archean ages but show a Mesoproterozoic gap with an absence of a 1.0 Ga cluster. The CIZ detrital zircon ages have a similar distribution to the OMZ but also include a 1.0 Ga cluster and so correlate well with the Sahara metacraton (Bea et al., 2010). The Anti-Altas detrital zircon age patterns show some similarities with the OMZ but with a 1.0 Ga cluster and different Paleoproterozic age distributions. Comparison of the OMZ with the Tuareg Shield reveals that the patterns match almost perfectly: a bimodal distribution with Ediacaran, Cryogenian, abundant Paleoproterozic and Archean ages and no 1.0 Ga cluster. In terms of Nd model and detrital zircon ages, the OMZ shows greatest affinity with the Tuareg Shield north Gondwana terrane. Our new Tuareg Shield associated paleogeographic position for the OMZ fits well with other published work in which the Iberian Massif zones were located along the north Gondwana passive margin fringe but further east (present-day coordinates) than previously thought.

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# A rifted volcanic margin, Red Sea type branch model for the Ossa-Morena Zone during the Cambro-Ordovician

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The Ossa-Morena Zone (OMZ) preserves evidence of a complex tectono-magmatic evolution, including late Neoproterozoic Cadomian orogenesis (~ 650–550 Ma), Cambro-Ordovician rifting (~ 540–450 Ma), and Variscan orogenesis (~390–305 Ma). These episodes are recorded in OMZ magmatic events. Between the Cadomian and Variscan orogenies, terranes rifted off northern Gondwana as the Rheic Ocean opened. In the context of this magmatic evolution, we combine new geochemical data for an A-type granite from the OMZ with a database of published OMZ geochemical data.

The period from 540 to 520 Ma marked a transition from collision, as recorded in the Cadomian continental magmatic arc, to rifting. The main Early Cambrian magmatism (~ 530–525 Ma) comprises peraluminous to metaluminous granites produced during initiation of extension. This is evidenced by abundant A2-type magmatism, formed either at convergent margins or by crustal contamination of A1-type 'OIB-like' magmas. Coincident with this was the generation of crust-contaminated, E-MORB-like basic magmas, now conserved in the Badajoz–Cordoba shear zone. In the main OMZ rift stage (~ 520–500 Ma) mafic magmatism progressed from E-MORB (~ 517–512 Ma) to OIB, and alkaline to tholeiitic (~512–505 Ma). Associated, coeval, felsic S-type and A-type magmatism was also prevalent. Both A1- and A2-type granitoids were generated at this time. Further spreading at ~ 490–470 Ma, resulted in generation of N- and T-MORB mafic rocks. In the late Cambrian–early Ordovician basalts, coincidence of Nd model and crystallization ages indicates new crust formation related to asthenospheric upwelling and proto-ocean basin development. Coeval felsic magmatism was peraluminous and alkaline.

The above pattern of magmatism is temporally and compositionally consistent with a rifted volcanic margin, such as the Ethiopia Rift-Red Sea margin (Pearce, 2008). There, the progression is from E-MORB tholeiitic to OIB-like alkaline and finally N-MORB with a declining crustal input over a period of some 30 Ma. The Ordovician magmatic expression is weaker in the more easterly Central Iberian Zone (Bea et al., 2007) and Galicia Tras-os-Montes Zone (Montero et al., 2009; Díez-Fernandez et al., 2012) than in the OMZ. This is consistent with an eastward-propagating rift which was, we suggest, a 'Gondwana-ward' Rheic Ocean branch, which was apparently preserved in the Badajoz–Cordoba sinistral transpressive shear zone during the Ordovician–Devonian juxtaposition of the OMZ and the CIZ.

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# Early Carboniferous intra-orogenic extension-related 'calc-alkaline' magmatism in the Ossa-Morena Zone, SW Iberia

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The Iberian Peninsula preserves the westernmost segment of the Late Paleozoic Variscan orogeny, a result of collision between Laurentia and Gondwana (Matte, 2001). Early Carboniferous calc-alkaline plutonic rocks crop out in the south of the Ossa-Morena Zone (OMZ), a northern Gondwana continental block. Throughout Pangea formation in Europe, volumetrically minor, but common, mafic–intermediate 'calc-alkaline' stocks intruded coeval granitoid plutons (Pitcher et al., 1993). Here a link is made between Early Carboniferous extension-related emplacement of ultramafic and mafic sills into the mid-crust, the IBERSEIS Reflective Body (IRB) (Simancas et al., 2003), and Variscan magmatism in the Olivenza-Monesterio antiform of the OMZ. Tectonomagmatic and geochronological evidence indicate that active subduction ceased prior to the latest Devonian–earliest Carboniferous (Azor et al., 2008). Recent studies suggest that the tectonomagmatic regime at that time was one of continental collision, so that calc-alkaline magmatism would have occurred after juxtaposition of the OMZ and the South Portuguese Zone. Numerous plutons were emplaced in the Olivenza-Monesterio antiform, including Bazana, Brovales, Valencia del Ventoso, Burgillos del Cerro and Santa Olalla. This ~ 350–320 Ma, Carboniferous magmatism comprises ultramafic to felsic, alkaline, metaluminous calc-alkaline and peraluminous plutons (Casquet and Galindo, 2004 and reference therein). The calc-alkaline character of the magmatism is apparently a result of interaction between mantle-derived alkaline mafic and crust-derived peraluminous felsic magmas. Intra-orogenic extension (Pereira et al., 2009), the ~ 350–320 Ma magmatism, and IRB formation were contemporaneous. Other, comparable, extensional events have been described related to Pangea formation in adjacent terranes in northern Gondwana and Avalonia–Laurentia. Orogenic mafic magmatism may provoke or result from crustal melting apparently depending on the timing of the process controlling mantle melting.

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# The Stenian to Tonian passive margin Lajeado Group and Apiaí gabbro of Southeastern Brazil: Paranapanema continent break-up and Brasiliano ocean formation

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The Lajeado Group in the Ribeira Belt, Southeastern Brazil, corresponds to an open-sea carbonate platform, and comprises seven overlapping siliciclastic and carbonatic formations, intruded in its upper portion by the Apiaí gabbro. These rocks have a Neoproterozoic tectono-metamorphic overprint related to arc magmatism and the Brasiliano collisional orogeny. Geochronological constraints are given by new U–Pb SHRIMP and LA-ICP-MS data for Lajeado Group detrital zircons and for magmatic zircons from the Apiaí gabbro. The analyses of detrital zircon grains from the Lajeado Group show the importance of Palaeoproterozoic source areas (2200–1800 Ma) with some Archean and Mesoproterozoic (1500–1200 Ma) contributions. Ten zircons from a sample of the Apiaí gabbro give indistinguishable concordant ages, with a weighted mean $^{206}Pb/^{238}U$ age of 877±8 Ma, interpreted as the time of magmatic emplacement. Two sites at edges of a single grain showed younger ages (about 600 Ma) with lower Th/U, and are interpreted as indicating a metamorphic and /or hydrothermal event. The youngest 1400–1200 Ma detrital zircons in the Lajeado Group constrain its maximum age of deposition, whereas the 877±8 Ma age for magmatic zircons in the Apiaí gabbro give a minimum age. The Apiaí gabbro has a similar age to other basic intrusive rocks in the Lajeado and Itaiacoca groups and represents tholeiitic MORB-like magmatism that we relate to the initial break-up of the Paranapanema continent and the formation of the Brasiliano oceans. Although most of the Precambrian carbonate platforms in the West Gondwana show Cryogenian to Ediacaran ages, the results presented here stress that the Lajeado Group in the southern Ribeira belt must have been deposited earlier, in the Tonian–Stenian. The findings presented here give new constraints and insight into the evolution of the Brasiliano ocean basins of West Gondwana between the break-up of Palaeoproterozoic continental crust and their closure at the end of the Neoproterozoic.

# Large-bodied carcharodontosaurid and abelisaurid (Theropoda, Dinosauria) dominance and extinction during the Cretaceous period in Gondwana landmasses

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One of the greatest controversies concerning the presence of predator dinosaurs in the Cretaceous period refers to the evolution and extinction of the large theropods of Gondwana (Abelisauridae, Carcharodontosauridae and Spinosauridae). Some areas in the Southern Hemisphere where these theropods have been dated demonstrate the extinction of the Carcharodontosauridae and Spinosauridae, the decline of the Megaraptoridae (*Megaraptor*, *Aerosteon*, *Orkoraptor*), and the presence of Abelisauroidea until the latest Late Cretaceous. It is possible to identify a similar record in South America and North Africa, with the domination and extinction of Carcharodontosauridae and Giganotosaurini (*Giganotosaurus carolini* Coria and Salgado, *Mapusaurus roseae* Coria and Currie and *Tyrannotitan chubutensis* Novas et al.; *sensu* Ortega et al. 2010, Novas et al., 2013) prior to the latest Cenomanian. However the large-bodied giganotosaurini *M. roseae* has been reported from the Turonian Huincul Formation in North Patagonia, confirming co-existence with the derived abelisaurid Carnotaurini (*Ilokelesia aguadagrandensis* Coria and Salgado and *Skorpiovenator bustingorryi* Canale et al.,) that come from the same geological unit. Abelisaurid records are distributed from Cenomanian until Early Maastrichtian, whereas the Carnotaurini were abundant during the Campanian and Maastrichtian in the Gondwana landmasses. The stratigraphic range of the Gigantosaurini and the stem group of the Abelisauridae shows that these dinosaurs were found only in the Cenomanian and Turonian of Africa and South America. This suggests that the dominance of the stem Abelisauridae and crown Carcharodontosauridae of Gondwana changed during the Cenomanian. In the same way this occurred with the Rebbachisauridae that became extinct at the same stage in Africa, South America and Europe.

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# Friderich von Huene's research on Late Cretaceous Central Brazil early last century

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Baron Friderich von Heune (1875-1969) was a vertebrate palaeontologist and geologist during the Second World War. As a researcher, he paid close attention to the smallest details of vertebrate palaeontology, yet he was a man of wide vision, capable of deep scientific insight and geological perspective. He may also be considered a cosmopolitan palaeontologist who undertook the exploration *of Gondwanan* dinosaurs, by himself but keeping important contacts with German and South American researchers. Von Huene was also a respected member of German academic bodies (e.g., *Universität Tübingen) and of Presbyterian circles. During his life he established contact with important Brazilian researchers, such as* Euzébio de Paula Oliveira, director of the 'Serviço Geológico e Mineralógico do Brasil' – SGMB (Brazilian Geological and Mineralogical Survey), and with his German colleague Hermann von Ihering, expert on invertebrates and director of the 'Museu do Ipiranga' – MI (Ipiranga Museum, in São Paulo), who made easy von Huene's stay in Rio de Janeiro and São Paulo in 1928. Von Huene described important specimens of reptiles, which were housed at the SGMB and at the MI and were collected in Minas Gerais state (from the town of Monte Alegre de Minas) and in the state of São Paulo (from Barretos, Colinas and Guaiucaia). Amongst those fossils, there was a meso-eucrocodylian holotype *Brasileosaurus pachecoi* from Guaiucaia, and crocodilian and carnivorous dinosaur teeth from Barretos and Colinas, and also a large femur of a sauropod herbivorous dinosaur from Monte Alegre de Minas. From the scientific and historical point of view, the significance of these descriptions is in their link to the well-known reptiles of similar age from Argentina, India and Madagascar, where von Huene carried out prolific palaeontological works, and opened up important areas to future work for many important palaeontologists (*e.g.* Llewellyn Ivor Price, Richard Estes) in Central Brazil. Presbyterian German colleagues of von Huene, who lived in Brazil, facilitated his travels across the states of Parana and Rio Grande do Sul, starting in the first decades of the last century. In a second step von Huene's trajectory and his important work with reptilian remains from the Late Cretaceous of Central Brazil will be studied considering the context of the early years of the last century in Brazil.

# Late Neoproterozoic magmatism in the metasedimentary Ediacaran series of the Eastern Pyrenees: new ages and isotope geochemistry

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Geochronological U-Pb (LA-ICP-MS) data from metavolcanic felsic rocks of the Canigó and Cap de Creus massifs in the Eastern Pyrenees provide evidence of an Ediacaran magmatic event lasting 30 Ma in NE Iberia. The data constrain the age of the Late Neoproterozoic succession in the Cap de Creus massif, where depositional ages range from 577±3 Ma (near the base) to 558±3 Ma (near the top), and in the Canigó massif, 575±4 Ma to 568±6 Ma (all from the middle of the succession, which could thus be older at the base). Geochemical and isotopic data indicates that the rocks were formed in a back-arc environment and record a fragment of a long-lived subduction-related magmatic arc (620 to 520 Ma) in the active northern Gondwana margin. The homogeneity shown by all these crustal fragments along this margin suggests that differentiation between the Pyrenean basement and the Iberian Massif arose later, probably during its transition from an active to a passive margin in Cambro-Ordovician times.

# The relationship between pre- and syn-Pampean orogeny metasedimentary rocks in the Eastern Sierras Pampeanas

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Two series of pre-to syn-Pampean orogeny metasedimentary rocks can be distinguished in the Sierras Pampeanas on the basis of U-Pb SHRIMP detrital zircon ages. On one hand the Ancaján series consists of meta-siliciclastic rocks (metapsammites and metapelites) and marbles. These have a Grenville Zr age pattern (1.0–1.3Ga) with contributions from the trans-Laurentian granite province (~ 1.3–1.5 Ga) (Rapela et al., 2014; this symposium). They are stratigraphically associated with Ediacaran marbles (540–630 Ma) in both Western and the Eastern Sierras Pampeanas. New U-Pb SHRIMP detrital zircon age data further show that the Ancaján series has a previously unknown extension into the Sierras de Cordoba. The second series crops out only in the Eastern Sierras Pampeanas and corresponds to the well-known Puncoviscana Formation, a thick siliciclastic succession that was deposited before and during the Pampean orogeny (530–570 Ma): it contains major detrital zircon age peaks at 960–1100 Ma (Grenvillian) and 570–680 Ma, and lacks grains derived from the nearby Rio de la Plata craton (2.02–2.26 Ga). This formation crops out over a large area in northern Argentina (Cordillera Oriental and Sierras Subandinas).

The sedimentary precursors of these two series were deposited on opposite margins of an open sea (the Puncoviscana–Saldania–Clymene ocean), which separated large continental masses – Laurentia-–MARA on the west and Kalahari+RPC on the east, which collided obliquely with each other during the Pampean–Saldanian orogeny between ~ 540 and 520 Ma (Casquet et al., 2012). No evidence of significant Pampean overprint is recognized in the Western Sierras Pampeanas, but the easternmost part of the Ancaján series (Sierras de Córdoba) was underwent syn-metamorphic folding and ductile shearing between 530 and 520 Ma. The marbles and meta-siliciclastic rocks of the Ancaján series were affected by major shear zones (e.g., Martino, 2003), suggesting that the latter constitute the boundary between the Ancaján series and the Puncoviscana Formation. A dismembered mafic–ultramafic igneous complex is also located within these shear zones (Bonalumi and Gigena, 1987); this has been interpreted as an ophiolitic complex embracing tracts with oceanic-ridge and probably back-arc chemistry that were tectonically emplaced into a suture (e.g., Ramos et al., 2000). The age of the complex remains poorly constrained.

The evidence provided here that the Ancajan series is also present in the Sierras de Cordoba further strengthens the idea that the Pampean suture occurs there.

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# The continental assembly of SW Gondwana (Ediacaran to Cambrian): a synthesis

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SW Gondwana resulted from complex interplay between continental amalgamation and dispersal between ~ 650 and 490 Ma. The main cratons involved were Laurentia, Amazonia–MARA (Proterozoic Maz–Arequipa–Rio Apa, Casquet et al., 2012), Kalahari, Rio de la Plata (RPC), Congo and East Antarctica (Mawson block). Several collisional orogenic belts resulted, notably the East Africa–Antarctica, Brasiliano–Panafrican, Pampean–Saldania, and Ross–Delamerian orogens.

East-Antarctica broke away from the western margin of Laurentia in Rodinia. After a long drift and counter-clockwise rotation (Dalziel, 2013) it collided with Congo and Kalahari to produce the southern part of the left-lateral transpressional East Africa–Antarctica orogen between 580 and 550 Ma, completing the amalgamation of East Gondwana. The Trans-Antarctic margin became an active one in the Ediacaran and subduction of the Pacific Ocean lithosphere occurred throughout the Paleozoic, forming a tract of the Terra Australis orogen. NW–SE directed compression in Late Cryogenian and Early Ediacaran times promoted closure of the Adamastor Ocean, resulting in the left-lateral transpressional Brasiliano–Pan African orogeny between 650 and 570 Ma.

The Pampean orogenic belt to the west of the RPC resulted from right-lateral collision between Laurentia and its eastern extension MARA on the one hand and Kalahari–RPC on the other. Ocean opening started at ~ 630 Ma and subduction and further collision took place between 540 and 520 Ma, coeval with the northward drift of Laurentia (~ 540 Ma) away from MARA and the consequent formation of the proto-Andean margin of Gondwana. The margins of the intervening Puncoviscana ocean were covered by Laurentia-derived siliciclastic sediments and carbonates on the MARA side between 630 and ~ 540 Ma (Rapela et al, 2014; this symposium), and by the marine siliciclastic Puncoviscana Formation on the other. The latter formation, deposited between a 570 and ~530 Ma, received input from large alluvial fans descending from juvenile Mesoproterozoic and Neproterozoic sources (new Hf isotope evidence) largely located in the southern East Africa–Antarctica orogen. The Pampean orogen extended into the Saldania–Gariep orogen of southern South Africa (545–520 Ma) and was apparently discordant to the earlier Brasiliano–Pan African orogen. In late-Early to late Cambrian times the Pampean–Saldania realm evolved into a passive margin with siliciclastic platform sedimentation. The Pampean-Saldania realm was separated from the active Trans-Antarctic margin of East Antarctica by an inferred transform fault in Ediacaran to Cambrian times. Regional NW–SW shortening in the Ediacaran became N–S directed in the Cambrian, suggesting a major plate reorganization at this time.

Casquet, C., Rapela, C.W., Pankhurst, R.J., Baldo, E.G., Galindo, C., Fanning, C.M., Dahlquist, J.A., Saavedra, J., 2012. A history of Proterozoic terranes in southern South America: From Rodinia to Gondwana. Geoscience Frontiers, 3(2), 137-145.

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# Supercontinents and implications for continental growth

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The supercontinent cycle is intimately tied to the secular evolution of the Earth sytem and has exerted fundamental control on the rock record since at least the end of the Archean. The continental crust is the archive of Earth history and its record of rock units and events is heterogenous with distinctive peaks and troughs of ages for igneous crystallization, metamorphism, continental margins and mineralization. We argue that this largely reflects the different preservation potential of rocks generated in different tectonic settings, rather than fundamental pulses of activity, and the peaks of ages are linked to the timing of supercontinent assembly. In contrast there are other signals, such as the Sr isotope ratios of seawater, mantle temperatures, and redox conditions on the Earth, where the records are regarded as primary because they are insensitive to the numbers of samples of different ages that have been analysed. Understanding the controls on primary and secondary signals and their link to the supercontinent cycle provides new insights into Earth processes. Between 1.7 and 0.75 Ga, overlapping with the Nuna and Rodinia supercontinent cycles, the tempo of Earth processes was characterized by environmental, evolutionary and lithospheric stability contrasting with the dramatic changes in preceding and succeeding eras. The period is marked by a paucity of passive margins, an absence of a significant Sr anomaly in the seawater record, eHf(t) in detrital zircon genrally close to zero, a lack of orogenic gold and volcanic-hosted massive sulfide deposits, and an absence of glacial deposits and iron formations. In contrast, anorthosites and kindred bodies are well developed and major pulses of Mo and Cu mineralization, including the world's largest examples of these deposits, are features of this period. These trends are attributed to the combined effects of lithospheric behaviour related to secular cooling of the mantle and a relatively stable continental assemblage between assembly of Nuna (by 1.7 Ga) and the break-up of its closely related successor, Rodinia (~ 0.75 Ga).

Comparsion of the geological record associated with the Rodinia and Gondwana supercontinent cycles reveals markedly different seawater Sr and zircon Hf isotopic signatures. Rodinia-related (Grenville/Sveconorwegian/Sunsas) orogens display significantly less enriched crustal signatures than Gondwana-related (Pan-African) orogens. Seawater Sr isotope ratios also exhibit a more pronounced crustal signal during the span of the Gondwana supercontinent than at the time of Rodinia. In our preferred model the isotopic signatures of Rodinia-suturing orogens reflect the closure of ocean basins with dual subduction zones verging in opposite directions, analogous to the modern Pacific basin. Conversely, the assembly of Gondwana was accomplished primarily via several single-sided subduction zones that resulted in greater reworking of ancient basement lithologies within the collisional suture(s). The proposed geodynamic models of the assembly of Rodinia and Gondwana provide a connection between the geodynamic configuration of supercontinent assembly and its resulting isotopic signature.

# The Neoproterozoic Riacho do Pontal fold belt, northeast Brazil: a record of a complete plate tectonic cycle at the heart of West Gondwana

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The Borborema Province of northeast Brazil occupies a strategic position in the central portion of West Gondwana, linking three of its major cratons: São Francisco–Congo, Amazon and West Africa. In the southern Borborema province, the Riacho do Pontal fold belt can be subdivided into three tectono-stratigraphic domains, from north to south: the internal (orogenic core), central (ophiolitic) and external (thrust-and-fold belt) zones. The internal zone contains important Tonian-age (1000–960 Ma) augen gneiss intrusions (Afeição suite), which might represent a continuation of the Cariris Velhos orogen further northeast. The central zone is characterized by by metabasalts and deep-sea exhalative and metasedimentary rocks of the Monte Orebe complex. Sm-Nd whole rock data suggest extrusion of the metabasalt protoliths at around 820 Ma. Initial $\varepsilon Nd_t$ of +4.4 indicates a depleted mantle source, which together with T-MORB geochemistry, suggests that the meta-basalts represent obducted remnants of Neoproterozoic oceanic crust. The external zone is characterized by the Casa Nova nappe system, which is composed of two units, from the bottom up: the Barra Bonita Formation, representing a platform sequence which is part of the northern São Francisco paleocontinent passive margin, and the Mandacaru Formation, which is a turbiditic, syn-orogenic unit, deposited in an active margin basin at around 630 Ma ago with sources to the north. Compressive deformation ($D_1$-$D_2$-$D_3$) led to the development of a south-verging nappe system during the Neoproterozoic (~630–575 Ma), followed by strike-slip deformation ($D_4$) during the late stages of the Brasiliano orogeny; extensive syn- to post- collisional granitic magmatism is contemporaneous. We propose a model for the geodynamic evolution of the Riacho do Pontal fold belt and adjacent areas that begins with a triple junction rift system at ~ 960–820 Ma, evolving to a passive margin and culminating in the development of oceanic crust around 820–630 Ma. Onset of subduction at ~630-620 Ma caused the inversion of basins, obduction of oceanic crust slices, and sedimentation of the Mandacaru Formation. Continental collision occurred at ~620–575 Ma, with stacking of the Casa Nova nappes upon the São Francisco craton, crustal thickening, deformation, metamorphism, and melt generation. This was followed by lateral escape tectonics at ~ 575–530 Ma that generated the E–W trending dextral Pernambuco shear zone, which truncates the northern part of the fold belt, along with extensive post-tectonic alkaline magmatism. Thus, the Riacho do Pontal fold belt represents a complete plate tectonic cycle, involving the collision of the São Francisco craton with the Pernambuco–Alagoas block further north. This interpretation challenges current views that the Borborema province acted as a coherent block from Paleoproterozoic times (part of the Atlantica supercontinent), suggesting instead a dynamic setting where multiple plates interacted during the Proterozoic.

# Intra-crustal recycling and crustal-mantle interactions in North Gondwana revealed by oxygen isotopic composition of Neoproterozoic to Ordovician zircons from SW Iberia rocks

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In situ O-isotope compositions of detrital, inherited and melt-precipitated zircons with Neoproterozoic to Ordovician ages are presented to assess the crustal evolution of the North Gondwana margin. Different groups of pre-Mesozoic rocks from SW Iberia were targeted: i) Ediacaran paragneisses and meta-greywakes of the Ossa-Morena Zone – the Serie Negra Group deposited at ~ 560 Ma in a Cadomian magmatic arc setting (Pereira et al., 2008); ii) Early to Middle Cambrian orthogneisses and volcaniclastic rocks of the Ossa-Morena Zone – Evora Massif igneous complexes related to ensialic rifting at ~ 530–500 Ma (Pereira et al., 2008, Chichorro et al., 2008); iii) Late Cambrian to Early Ordovician volcaniclastic rocks and granites of the Ossa-Morena–Central Iberian transition zone – the Urra Formation and Portalegre granite formed at ~ 495– 488 Ma in a extensional setting (Solá et al., 2008); iv) Carboniferous granitoids (Nisa and Arraiolos granites) containing inherited zircons with Cambrian to Ordovician ages (Solá, this volume).

A compilation the results for the period ~ 3.4 Ga to ~ 450 Ma reveals that: **a)** Archean zircons show little variation in $\delta^{18}O$, with most values lying between 4.7 and 7.5‰, (average 6.2‰) comparable with usual $\delta^{18}O$ of zircons from Archean elsewhere (e.g., Valley et al., 2005); **b)** the range of $\delta^{18}O$ in Paleoproterozoic grains increases between 2.1 and 1.8 Ga with $\delta^{18}O$ >7.5‰, indicating increasing supracrustal recycling, but at ~ 1.8 Ga the $\delta^{18}O$ has mantle-like values (<5.1‰), documenting a crustal growth episode at this time; **c)** rare Mesoproterozoic grains have mildly evolved $\delta^{18}O$ values in the range 5.6–7.1‰); **d)** Tonian grains have low $\delta^{18}O$ values (4.2–5.6‰) typical of mantle-derived juvenile magmas but also higher values of 9.9‰ suggesting intra-crustal recycling; **e)** Cryogenian–Ordovician zircons show more variable and higher $\delta^{18}O$ values (~4 to >10‰), indicating great diversity and mixing of sources through intra-crustal recycling and crust–mantle interactions; **f)** some $\delta^{18}O$ values near to or below mantle composition (5.3 ± 0.3‰) were recorded at ~ 590 Ma (Ediacaran) suggesting input of mantle material into the crust; **g)** a decrease in variance of $\delta^{18}O$ occurs from 575 Ma to the Ediacaran/Cambrian boundary, suggesting a relative decrease in the magmatic contribution of surface-derived material; **h)** in Cambrian times, the average $\delta^{18}O$ is higher in the 536–520Ma interval (7.0‰) than in the 520–488 interval (6.2‰), which can be taken as a signal of gradual opening of the system to mantle-derived, mafic, rift-related igneous complexes; **i)** higher values of $\delta^{18}O$ (>7.5 ‰) recorded at ~ 623–574 Ma and 490–470Ma mark periods of pronounced increase in crustal recycling.

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# Permian amalgamation of peri-Gondwanan terranes in the Ogcheon belt, Korea

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The Korean Peninsula, situated at the margin of the Eurasian continent, consists primarily of Precambrian basements and Phanerozoic fold-thrust belts (Ogcheon and Imjingang belts). The NE-trending Ogcheon belt is further subdivided into the autochthonous, fossiliferous Taebaeksan basin (TB) and the allochthonous, non-fossiliferous Ogcheon metamorphic belt (OMB). These two provinces show a marked contrast in lithostratigraphy and degree of metamorphism. Their tectonic evolution and correlation with the North China craton (NCC) or South China craton (SCC) are of prime importance for deciphering the break-up of the East Gondwanan supercontinent and the assembly of Pangea. However, large uncertainties still remain in the tectonic affinities of supracrustal and basement rocks in the Korean Peninsula. Consequently their correlations with tectonic provinces in China and Japan are poorly constrained. Here we first review some of our new and previous sensitive high-resolution ion microprobe (SHRIMP) data on zircon from the OMB and then discuss the implications of these results with regard to the formation of the Pangean supercontinent.

The OMB is recently interpreted as a poly-deformed accretionary complex developing along the southern margin of the Gyeonggi massif (Cho et al., 2013). SHRIMP U-Pb ages of detrital zircons from the OMB range from Archean to Late Paleozoic, and their contrasting age populations attest to the tectonic juxtaposition of various lithotectonic units. Age distribution patterns of detrital zircons permit us to define four lithotectonic slices of metasedimentary terranes. These imbricate thrust slices were deposited episodically from Neoproterozoic (~750 Ma) to Carboniferous–Permian times, and were probably amalgamated at ~270–260 Ma. Cho et al. (2013) suggested that these tectonic slivers resulted from the Paleozoic accretion of allochthons derived from both NCC- and SCC-like crustal materials. This suggestion is corroborated by our new SHRIMP zircon data from both OMB and TB. The overall distribution pattern of detrital zircon ages in the OMB is similar to that derived from peri-Gondwanan terranes. On the other hand, detrital zircon age spectra from the Paleozoic strata in the TB are characterized by the presence of two populations at ~1.87 Ga and 2.5 Ga. This pattern is consistent with that found in the cover rock sequences of the NCC but differs markedly from that reported from the SCC-like OMB unit or the SCC. It is thus likely that the Ogcheon belt is a tectonic collage consisting of autochthonous TB with the NCC affinity and allochthonous OMB of the peri-Gondwanan (either NCC- or SCC-like) affinity. Tectonic juxtaposition among various tectonic terranes occurred first in the Middle to Late Permian Ogcheon orogeny, and subsequently in the Middle to Late Triassic Songrim orogeny. Hence, we suggest that the Pangean supercontinent was still growing at the Permian in the eastern part of Asia.

Cho, M., Cheong, W., Ernst, W.G., Yi, K., Kim, J., 2013. SHRIMP U–Pb ages of detrital zircons in metasedimentary rocks of the central Ogcheon fold-thrust belt, Korea: Evidence for tectonic assembly of Paleozoic sedimentary protoliths. Journal of Asian Earth Sciences 63, 234–249.

# Protoliths of the Trivandrum Block, southern India: field observations and ion probe data

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There is a longstanding debate about the origin of the rocks of the Trivandrum Block (TB), which is centered on two issues: first, whether the protoliths of the metasedimentary rocks were of African or Indian affinity; and, second, whether the leptynites represent sedimentary protoliths or leucogranites prior to granulite facies metamorphism. Recently, Kröner and colleagues (pers. com.) have proposed that the leptynites (grt-bi gneisses) were intrusive into the metapelitic rocks (khondalites), suggesting that the latter were deposited prior to *c*. 2.0 Ga (the U-Pb SHRIMP zircon age of the leptynites). In stark contrast, others have argued that the protoliths of the metasedimentary rocks were deposited during the Neoproterozoic in the Mozambique Ocean on the margin of Africa, prior to the collision of East Africa and Southern India. In this interpretation, the metasedimentary rocks have an African provenance. However, the timing of deposition was not well constrained – post-dating *c*. 2.0 Ga but pre-dating Ediacaran–Cambrian metamorphism.

We examined the field relationships between the dominant lithologies in ~50 quarries in the TB. This field study has been supplemented with SHRIMP zircon and monazite geochronology and REE analyses of these minerals and associated garnet to determine protolith ages and timing of TB metamorphism. The contact relationships between leptynite and khondalite are equivocal and a direct intrusive relationship is not seen. In all places where the relationship was observed, leptynite and khondalite are separated by a grt-bearing leucogranite that was most likely generated by partial melting of the bordering rock units; an unmodified contact relationship was not observed anywhere. Furthermore, the fabric defined by the peak metamorphic assemblage (grt-sill-crd) in the khodalites is cut by the grt-leucogranite. Thus, the timing of the high-temperature metamorphism is a key observation that must be incorporated into any interpretation. Our SHRIMP data, integrated with the REE profiles from zircon and garnet from both khondalites and grt-leucogranites, unequivocally demonstrate that the age of metamorphism and the crystallisation of the discordant grt-bearing leucogranites occurred at 580–530 Ma. More problematic is any determination of the age of the zircon cores from the leptynites. We observe large analytical uncertainties on the $^{207}Pb/^{206}Pb$ ages, reflecting spikes in the analytical traces of the unknowns that are not seen in the standards. This spikiness and the resultant decoupling of the $^{207}Pb$ and $^{206}Pb$ signal in individual zircon analyses means that no reliable, high-precision age determinations on zircon cores could be determined. This effect is seen across multiple sample localities in the TB and is consistent with independent studies of zircon from the TB as well as from other granulite terranes. Based on the morphology and apparent ages, it is not clear that these zircons form a single population, rather they could represent a spectrum of inherited grains from a broadly Palaeoproterozoic source. Thus the absolute age of the protoliths of the TB granulites remains unconstrained – they are younger than the most concordant Paleoproterozoic ages (*c*. 2 Ga) and older than the onset of high-grade metamorphism at 580 Ma.

# The Palaeozoic geography of Gondwana

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Gondwana became united in the Pan-African and related orogenies just before the start of the Cambrian and remained an independent superterrane, the largest on the planet, until its union with Laurussia to form Pangea in the Carboniferous (Torsvik and Cocks, 2013). Although Gondwana also extended well to the north of the Equator until the Devonian, it was located over the South Pole for its entire existence, which is why the short end-Ordovician (Hirnantian) and much longer Carboniferous and early Permian glaciations are reflected so well in Gondwanan sediments of those ages. However, it is only relatively recently that a reliable palaeomagnetic Apparent Wander Path has been constructed for Gondwana over the whole Palaeozoic. The marine benthic faunas in the shelf seas surrounding Gondwana varied in their provinciality, but they all depended on the palaeolatitudes at which they lived, with the Mediterranean Fauna in the Ordovician (and in particular the distinctive large lingulide brachiopods found in the Grès Armoricain quartzite facies in southern Europe and North Africa), and the Malvinokaffric Fauna of South America in the Siluro-Devonian particularly affected by the high latitudes in which they lived. However, the continent was so large that a cline may be seen along both its eastern and western margins; for example, in the early Ordovician there was a cline between the high-latitude Mediterranean Fauna and the quite different tropical faunas found in Australia and neighbouring Gondwanan sectors which straddled the equator.

The continent was largely land for most of the Palaeozoic, but marine incursions were many and various around its margins, some, such as the Larapintine Sea in Australia, even stretching across the superterrane to separate land masses. There were also many large lakes in places at different geological times. Many smaller continents were either united or rifted away from Gondwana during the Palaeozoic: one such was Avalonia, which left the Amazonian sector of Gondwana as the Rheic Ocean opened during the earliest Ordovician; other leavers included Florida and the Armorican terranes as the Palaeotethys Ocean opened in the Early Devonian, and a number of Asian terranes, such as as Sibumasu and the Tibetan terranes, as the Neotethys opened in the Early Permian, although by the latter time Gondwana was the major sector of Pangea. There was a very extensive subduction zone fringing South America, Africa, Antarctica and eastern Australia, which was active during most of the Palaeozoic, beside which numerous island arcs formed, many of which accreted to enlarge the continent. On the opposite side of the continent, most of north-east Africa and Central Asia was situated on a passive margin for much of the era.

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# Detrital zircon and muscovite provenance constraints on the evolution of the Cuddapah Basin, India

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The Cuddapah Basin is one of the largest Indian cratonic basins, covering 46,000 km$^2$, and <10 km deep. Very little has been known about the ages of the sedimentary rocks within the basin, the provenance of the sediments and, particularly, the change of provenance through time. Because of this, basin evolution models lack the essential constraints and the significance of this basin for the tectonic evolution of Proterozoic India is therefore unknown. The detrital zircon ages were obtained as follows, up-sequence:
**Gulcheru Fm** (conglomerates and arenites), the basal formation of the Cuddapah Supergroup, overlying Neoarchaean granitoids of the East Dharwar craton: ~3.4, ~2.5, and ~2.0 Ga. Gradationally overlain by - **Vempalle Fm** (shales with desiccation cracks and halite pseudomorphs passing up into stromatolitic carbonates): unimodal age population at ~2.5 Ga. **Pulivendla Fm**: ~2.6 and ~1.9 Ga. This is overlain by the argillaceous Tadpatri Fm. The boundary with the overlying Gandikota Fm is controversial (conformable or unconformable). **Gandikota Fm**: ~2.6, 1.8–1.6, and ~1.2 Ga. The **Nallamalai Group** is tectonically isolated to the east from the rest of the Cuddapah sequence by a major N-S thrust. Detrital zircons yield ages of ~3–1.6 Ga with maxima at ~2.7, ~2.5, and ~1.8 Ga. The maximum deposition age is 1669 ± 31 Ma. **Srisailam Fm**: ~2.6–2.5 Ga at the base, but arenites at the top of the formation yield younger zircons dated at ~2.3 and 1.8 Ga. Detrital muscovites from this horizon yielded $^{40}Ar$-$^{39}Ar$ total fusion ages of ~1770 Ma. The **Kurnool Group** unconformably overlies the Cuddapah Supergroup. The basal **Banaganapalle Fm** yields detrital zircon ages of 3.4, 3.0, and 2.6 Ga. A stratigraphically higher quartz arenite –the **Panium Fm**– yields ~2.6 Ga zircons, with the youngest concordant zircon dated at ~2.0 Ga.
Gulcheru and Vempalle Fm zircons older than ~2.6 Ga yield Palaeoarchaean $T_{DM}$Hf ages, whereas those of ~2.5 Ga age from these formations, and from the Gandikota Fm, have Neoarchaean $T_{DM}$Hf ages and εHft values ranging from mildly negative (<-5) to close to depleted mantle values. Mesoproterozoic zircons from the Gandikota Fm yield positive εHft values. Hf isotopes from the Kurnool Group show a similar pattern to those seen in the Cuddapah Supergroup samples, suggesting that they either had the same sources or were recycled from the underlying formations. Nallamalai Group zircons yield $T_{DM}$Hf ages of ~2.4–3.4 Ga, which is similar to those from the Srisailam Fm, where ~2.5 Ga zircons yield much more evolved εHft values (>-15) than those from the Cuddapah Supergroup and Kurnool Group (lowest εHft of -5 for ~2.5 Ga grains).
We interpret the data to reflect an evolving rift-passive margin succession (Gulcheru, Vempalle, Pulivendla, Tadpatri Fms), sourced from the Dharwar craton, buried by westward prograding deposits of the late Palaeoproterozoic Krishna orogen (Nallamalai Group and Srisailam Fm). We suggest that the Gandikota Fm represents a lateral equivalent of the Kurnool Group, which appears to be largely derived by reworking Cuddapah Supergroup rocks, possibly due to tectonic movements related to the distal Eastern Ghats orogen.

# Bringing Asia into Gondwana - the Betsimisaraka suture of Madagascar:the site of final closure of the Mozambique Ocean or the figment of an overactive imagination?

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Asian (and Australasian) Gondwana forms the eastern part of the supercontinent whose collision with African and South American Gondwana along the East African Orogen is one of the major continent sutures in Gondwana. Ideas on the evolution of the East African orogen and the nature and timing of this event are tied up with an understanding of the subduction and consumption of the Mozambique Ocean, which separated Neoproterozoic India from the Congo craton.

The Betsimisaraka Suture in Madagascar was proposed by Collins and Windley (2002) and Collins (2006) as the site of final closure of the Mozambique Ocean in the latest Ediacaran/Cambrian—about 80–100 Ma after amalgamation of Azania (a continent consisting of central Madagascar, parts of the Horn of Africa, and central Yemen) with Africa and cessation of much of the deformation and metamorphism in the Arabian-Nubian Shield and Mozambique Belt. The idea of the Betsimisaraka Suture has been challenged recently (Tucker et al., 2011; Tucker et al., in press) by the suggestion that the geology of this part of Gondwana is more consistent with a Greater Dharwar continent. In this presentation we will outline the arguments for and against the existence of the Betsimisaraka Suture and place it in the broader context of the geology of central Gondwana from Arabia to Southern India. We compare in detail the Betsimisraka suture with supposed correlatives in Arabia (Cox et al., 2012) and Southern India (Plavsa et al., 2014) and examine a number of suggested tests for the existence of the suture. We conclude that although uncertainty exists, the weight of evidence points to the existence of the Betsimisaraka Suture as an oceanic suture that closed in the latest Ediacaran–Cambrian, separating African-derived terranes from Neoproterozoic India.

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# Evolution of Phanerozoic Europe from an Hf isotope perspective: implications for supercontinental and Wilson cycles

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Combined U-Pb-Hf isotope studies of zircon provide new insights into the evolution of large-scale, long-term orogenic systems. Recently, the distinct inverted U-shape of some Hf evolutionary arrays has been interpreted as the ocean-closure phase of a Wilson cycle. Here, we evaluate the veracity of Hf isotopes in zircons to recognize Wilson cycles from a prototype area, Phanerozoic Europe. Surprisingly, the inverted U-shaped array extends from 600 Ma to present-day, not at the 150–200 Ma time-scales expected for successive Wilson cycles associated with evolution of the putative Rheic, Paleo-Tethys and Neo-Tethyan oceans. Comparison with circum-Pacific Hf isotopic arrays indicates that the entire peri-Gondwanan margin was part of a retreating accretionary orogen at least until 450 Ma, resulting in the formation of a vast, extended, peri-Gondwanan ribbon. The Hf data require that the Avalonian and Amorican terranes (Iberia, Armorica, France Central and Bohemian massifs) all separated from Gondwana over this 150 Ma period, initially during formation of the Neoproterozoic Cadomian back-arc. If the Rheic Ocean is defined by the ophiolites that separate Avalonian from Armorican terranes, it was also part of this protracted back-arc opening process. Combined with ophiolite geochemistry and other geological constraints, the subsequent semi-continuous reworking of the peri-Gondwanan ribbon reflects repeated back-arc opening–closing events from the Devonian to the present-day, including during the Variscan orogeny. Most inferred Paleo- and Neo-Tethyan ophiolites are remnants of these back-arcs. Only in the Cenozoic does a strongly negative εHf spike develop in the Mediterranean region, indicating subduction and melting of Gondwanan cratonic lithosphere for the first time since the Neoproterozoic. We therefore consider that the main suture between peri-Gondwana and Gondwana closely mimics the present-day southern margin of continental Europe.

Because the inverted U-shaped European Hf array records a longer-term, 600 Ma cycle, rather than 100–200 Ma of Wilson cycles, it appears more likely that such U-shaped arrays record the closure phase of supercontinental cycles. The age of supercontinental initiation phase of the cycle is more difficult to constrain. We suggest that it is represented by the εHf model age of the oldest reworked crust on the ribbon. This is a well-defined crustal evolution line coinciding with Lu/Hf ratio of 0.017 and εHf $T_{DM}$ age of ~1.8 Ga, slightly less than the dominant 2.0 Ga (Eburnian) age of the West African craton. We consider this source is mafic crust underplated beneath the passive margin during Atlantic-style ocean opening. The ensuing >1 Ga gap between 1.8 and 0.6 Ga is the duration of the intervening ocean. Thus, classical Atlantic-style Wilson cycles are probably part of the supercontinental cycle, rather than the short-lived back-arc basin opening and ribbon-transfer process associated with migration of terranes from Gondwana to Baltica that ultimately produced Phanerozoic Europe.

# New geochronological data and evolution of the Late Paleozoic formations in the western Andean Precordillera, San Juan, Argentina

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Late Palaeozoic formations in the western Precordillera (km 114 of the N-20 road) were revisited (Colombo *et al.,* in press). The lower member of the Del Ratón Fm overlies the Devonian basement with marked angular unconformity (D1) and is interpreted as a fjord deposit. It consists of conglomerates with igneous clasts, in which Gallastegui *et al.* (in press) obtained an early Carboniferous (late Tournaisian) U-Pb zircon age of 348±2 Ma. The upper member covers another smooth unconformity (D2), and is interpreted as the deposit of an alluvial fan system which evolved into a coastal fan delta. A sharp rise in relative sea-level resulted in the deep-sea fan Carboniferous deposits of the El Planchón Fm at the end of Chanic orogeny. During the rest of the Carboniferous, these successions were incorporated into the proto-Precordillera high, a remnant of the Chanic cordillera, and a new (D3) angular unconformity is recorded between Carboniferous and Permian deposits. The early Permian (Asselian) Del Salto Fm, which accumulated after the collapse of the proto-Precordillera (Gondwanan orogeny), is essentially composed of sandstone and shale interpreted as coastal and shallow marine deposits. A new tectonic event is recorded at the top of the Del Salto Fm (D4 unconformity), and the coarse-grained alluvial deposits of the Quebrada del Alumbre Fm accumulated during the early Permian according to a new U-Pb zircon age of 293±5 Ma (data) from a pyroclastic fall deposit. Subsequently, a new expansive coastal system (Escombrera Fm) was deposited over a smooth unconformity (D5). Barredo *et al.* (2012) published a middle Permian U-Pb zircon age of 267±7 Ma from an andesite located within this unit. The Quebrada de la Arena Fm rests on another smooth unconformity (D6). This unit consists of siliciclastic deposits accumulated in continental environments (playa-lake, high-sinuosity and braided fluvial systems, and alluvial fans). In the lower part of the Quebrada de la Arena Fm, a new middle Triassic (Ladinian) age of 238±2 Ma (U-Pb zircon) is obtained from a pyroclastic fall deposit. Thus, the D6 unconformity records the limit between the Permian and the Triassic deposits. The Rincón Blanco Group ("sensu lato"), which lies on an angular unconformity (D7), was deposited during the Middle–Late Triassic and displays another angular unconformity (D8) in its lower part.

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# Geochronology of the southernmost part of the East African orogen, in western Mozambique, and its implications for the final amalgamation of Gondwana

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The southernmost part of the East African orogen (EAO) is adjacent to the northeastern corner of the Kalahari craton. In the cratonic area, 2.5–3.3 Ga TTG-type granitoids and gneisses are found, as well as the eastern termination of the Mutare-Odzi-Manica greenstone belt. This cratonic basement is overlain by the Umkondo volcanic-sedimentary sequence, cut by 1100 Ma dolerites. Detrital zircons of about 2000 Ma confirm the Mesoproterozoic age of this unit. Supracrustal rocks also include the Rushinga Group, with felsic metavolcanic rocks dated at 795 Ma (Hargrove et al., 2003), representing an early Neoproterozoic passive margin. To the east, entering the Mozambique Belt of the EAO, both sequences exhibit progressive regional metamorphism from greenschist to granulite facies.

The high-grade paragneisses, granulites and migmatites, characteristic of the Mozambique Belt, occur in close association with the pre-existing Mesoproterozoic granitic rocks of the Barue complex, dated at ca. 1050–1100 Ma. Metamorphic P-T conditions were estimated as 4–6 kb and 700–800°C. Detrital zircons of some paragneisses yielded Neoproterozoic maximum ages of deposition of 700–900 Ma. Moreover, many metamorphic overgrowths on zircon grains yielded Cambrian ages close to 500 Ma (Chaúque, 2012). Finally, K-Ar cooling ages below 500 Ma are widespread over the entire belt, and also across the eastern border of the Kalahari craton.

The metamorphic rocks are arranged into the Chimoio, Macossa and Mungari tectonic units, formed in a series of continental collisions and exhumed at different crustal levels. They are juxtaposed to the Kalahari craton by means of westward-thrust frontal nappes, representing the principal suture of the Mozambique Belt in the Manica region. The *Macossa-Chimoio Nappe*, in the south, is separated from a northern *Mungari Nappe* by a thrust zone with NW-trending tectonic transport. This could correspond to the prolongation of a long-lived tectonic boundary, the Lurio Belt of northeastern Mozambique, which formed during Neoproterozoic to Ediacaran continental collision between 600 and 550 Ma. It was later reactivated in the Cambrian, around 510 Ma, as a large and complex mega-shear zone (Ueda et al., 2012). The Pan-African tectonic units within the Lurio Belt, and especially those of the Nampula block (Macey et al., 2011), include Mesoproterozoic (ca. 1100 Ma) orthogneisses whose geological history closely corresponds to that of the studied region.

In conclusion, as indicated by Chaúque (2012), the final suturing of the Mozambique Belt at its southernmost part is Cambrian in age. This shows that the amalgamation of Gondwana was diachronous along the EAO, starting earlier in the north and finishing later in the south, coeval with the Kuunga orogeny of Australia and Antarctica.

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*North meets South*

# *Syringoalcyon*: a coral-alcyonarian association from the Palaeotethys

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The genus *Syringoalcyon* was named in 1945. Its taxonomic assignment as well as its ecologic implications have been a matter of discussion for a long time. Detailed morphological, microstructural, nanostructural, geochemical and crystallographic analyses allow a closer approach to characterization of *Syringoalcyon*. Samples from several locations and ages (Canada to Morocco; Silurian to Carboniferous) have been studied by means of optical petrography using thin and ultrathin sections, scanning electron microscopy, atomic force microscopy, electron microprobe analysis and computer-integrated-polarization. The coral wall and the "epithecal scales" show conspicuous characteristics:

*Size*: scales are larger than any other element known in Palaeozoic corals.

*Microstructure continuity*: the coral wall is characterized by a continuous frame composed of skeletal elements (lamellae and fibres), which behave as a continuous structure. Microcrystalline elements change gradually between the different morphologies, adapting their c-axes progressively. However the step from lamellae to scales is abrupt.

*Nanostructure*: nanostructural elements of the scales have different shapes and sizes, whereas the nanocrystalline elements of the Syrigoporicae keep the same form and size.

*Mineralogy*: The coral wall is low-Mg calcite except for some altered crystals located just in the wall edges. On the other hand, the scales were originally high-Mg calcite. Some diagenetic alterations have been observed in the skeletal elements but it is clear that these alterations did not completely obliterate the structural and crystallographic properties, and some original regions and their biogenic properties have been preserved.

This body of data implies that *Syringoalcyon* is a commensalistic or mutualistic association between *Syringopora* and an epibiont. The analyses and the shape and distribution of the scales also suggest that the epibiont was an Alcyonarian that attached to the syringoporoid, probably for protection and proximity to sources of nutrients.

Literature references to epithecal scales in the Silurian seem to relate to a similar association of coral and Alcyonarian, but the size and shape of scales clearly differ from the Carboniferous ones. All the reliable Carboniferous records of the association are from the Upper Mississippian of Palaeotethys, mainly in the northern border of Gondwana (Morocco and SW Spain).

# LA-ICP-MS U-Pb and Lu-Hf Ages in zircon of the Sana granite, Rio de Janeiro, Brazil: implications for West Gondwana amalgamation

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The Sana granite and its satellite bodies crop out in the region around the cities of Casemiro de Abreu and Nova Friburgo, northwest of Rio de Janeiro. Isotopic, compositional, structural and mineralogical characteristics of the granite can be related to late magmatism and may be characterized as S-type. Associated shear zones in the basement with preferential N–S to NE–SW and ENE–WSW orientations suggest extensional tectonic activity during emplacement of these bodies.
For this work 29 representative samples of the main Sana granitic unit and its satellites were processed, of which 27 samples were analysed for geochemistry, 5 for U–Pb zircon dating and 4 for Lu-Hf in zircon using LA-ICP-MS in the Multilab laboratory, University of the State of Rio De Janeiro. The rocks are classified as granite to syenite, sub-alkaline to slightly alkaline, with marginally peraluminous and shoshonitic character, which suggests a crustal contribution in these rocks. The monzogranites to syenites show leucocratic, grey to white, fine-to-medium grain size and isotropic texture. The granodioritic and granitic rocks are fine-to-coarse grained, with isotropic textures.
Generally the Sana granite and its satellites have similar geochemical signatures, but the main body is enriched in $K_2O$ and $Na_2O$ whereas the satellites are enriched in $P_2O_5$, $TiO_2$ and Y. A decrease in the HFS transition elements, alkaline-earth and lanthanides is observed in Harker diagrams. In tectonic discrimination diagrams the Sana granites are variously classified as intra-plate, volcanic arc and syn-collisional. Light REE are enriched, with negative Eu anomalies: depleted heavy REE and variable La/Yb ratios suggest a strong magmatic fractionation process during the formations of these rocks.
Isotopic U–Pb LA-ICPMS data yielded crystallization ages of 483–504 Ma for the main intrusion and satellites, compatible with ages in the literature (488–492 Ma). Lu-Hf data for main intrusion yielded $T_{DM}$ values between 1.72 and 1.50 Ga and εHf values between -19 and -12; satellites rocks yielded $T_{DM}$ values between 1.59 and 1.37 Ga and εHf values between -13 and -7, indicating more crustal contamination in the main intrusion. These results show that the Sana granite has similar isotopic signatures to granites generated in a crustal environment and represents an important magmatic event in the Ribeira orogen, probably related to the collision of the Costeiro and Cabo Frio terranes during West Gondwana amalgamation.

# Unravelling the cordilleran magmatic arc of the central segment of the Ribeira belt: implications for West Gondwana amalgamation

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The Ribeira belt of SE Brazil is located in a strategic and central part of West Gondwana; in recent years at least three new Neoproterozoic magmatic arcs were described within it. The eastern arcs are located in the oriental part of the belt and display geochemical and geochronological signatures corresponding to a primitive tectonic setting, evolving from intra-oceanic to cordilleran environment with time. On the other hand, the innermost (western) magmatic arcs in the belt, the Serra da Bolívia complex, point to a cordilleran setting with a significant contribution from the Paleoproterozoic basement. This cordilleran arc may be correlated with the Socorro and Galiléia/Rio Doce magmatic arcs, located respectively at the southern tip of the Ribeira belt and in the Araçuaí belt.

Our data confirm the occurrence of similar arc-related rocks in the segment between the previously described arcs, also intruding Paleoproterozoic basement rocks. Magmatic-arc related rocks are represented by orthogneisses and meta-basic rocks, with varied compositions ranging from gabbro to granite. A group of quartz-poor rocks is represented by monzogabbros, monzonites, monzodiorites and few syenogabbros. Geochemical data suggest that the orthogneisses belong to three calc-alkaline magmatic series: one is a medium-K series, a second one is a high-K series, and the third one has a transitional characteristic signature between shoshonitic and very high K calc-alkaline series. The normalized REE patterns and other discrimination diagrams indicate magmatic arc affinity. U–Pb LA-ICPMS data yielded crystallization ages of ~ 620–585 Ma, with a metamorphic overprint at ~ 580–570 Ma. The rocks of medium-K series are slightly older than the rocks of the high-K series.

The new data point to the lateral continuity of a large cordilleran magmatic arc, extending from the Araçuaí belt to the southern tip of the Ribeira belt, and the first terrane that collided with the São Francisco paleocontinent during West Gondwana amalgamation.

# Upper Mississippian biostratigraphic correlation of the northern margin of Gondwana, Sahara platform

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Geological knowledge of the Sahara platform, an epeiric platform in the northern passive margin of Gondwana extending from Mauritania to Libya, mostly results from mapping projects during the 1950's and 1960's by a few pioneers and some Ph.D. research projects. The vast content of this information, later compiled by Wagner et al. (1985), included the detailed Carboniferous biostratigraphy and correlation within northern Africa, although in some basins or particular formations the correlations could be considered indirect, unsupported by biostratigraphic or chronostratigraphic markers. Some more recent studies, from the late 1990's, led to revisions for some localities and fossil groups (mostly ammonoids and foraminifers), allowing a better calibration of the Mississippian biostratigraphic scales for the different fossil groups, as well as improved chronostratigraphy.

A new biostratigraphic correlation is proposed for the late Viséan to basal Bashkirian basins south of the Atlas Transform Fault, i.e., Tindouf (Morocco–Algeria), Tafilalt (Morroco), Béchar (Algeria), Reggan (Algeria) and Ahnet (Algeria). The most reliable marker was previously taken as the Mid Carboniferous boundary, mostly studied in the Béchar basin and based on the conodont *Declinognathodus noduliferus*; in other basins the location of this Mid Carboniferous boundary was based on indirect correlation. However, foraminifers of the Béchar basin suggest the late arrival of this conodont, so that the boundary might be situated in older beds, an idea supported by similar data in the Moroccan basins. A recent study on conodonts from the Ahnet–Reggan basins suggests a more questionable scenario, with an earlier occurrence of *D. noduliferus*, and re-location of the boundary to very low levels compared to traditional correlation. It also suggests a hiatus and erosional gap in the Ahnet–Reggan basins involving the entire upper Viseán and Serpukhovian strata. Such tectonics have been not previously been described for the region, and considering the more or less stable context for the platform during the late Mississippian this scenario with emerging horsts seems controversial.

Correlation of the Viséan/Serpukhovian boundary can be sustained through a more extensive database of foraminifers, using traditional studies as well as recent analyses. In addition, it is noteworthy that some ammonoid data have been overlooked in past literature, although these can be also used as reliable markers. We conclude that the Viséan/Serpukhovian boundary should be re-located at lower levels, as supported by biostratigraphic data in each basin.

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# The geological setting of Carboniferous magmatism in the proto-Andean margin of Gondwana, Sierra Pampeanas, Argentina

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Our petrogenetic understanding of the Carboniferous granites of the Sierras Pampeanas has improved in recent years, but their geodynamic setting is still not well constrained. Domeier and Torsvik (2014) affirm that there is no documented and unambiguous evidence of an active margin in the proto-Andean margin of Gondwana before the late Carboniferous (~ 320 Ma). Recently, Willner et al. (2011) postulated Middle–Late Devonian collision of a hypothetical microplate (*Chilenia*) and the subsequent emplacement of Early Carboniferous (~ 340 Ma) post-collisional granites in the Cordillera Frontal, although granites with such post-collisional signature remain unproven. However, recent studies in the Eastern Sierras Pampeanas (*e.g.*, Alasino et al. 2012, Dahlquist et al. 2010, 2013) have shown that the Early Carboniferous granites are typical of metaluminous A-type magmatism (intraplate) with participation of both juvenile material and continental crust in the source. Work in course shows that peraluminous A-type granites were also emplaced in the same geodynamic setting (*e.g.*, La Costa pluton, Alasino et al., 2012, 360 ± 3 Ma unpublished). Conversely, recently studied Early Carboniferous granites in the Western Sierras Pampeanas and Cordillera Frontal (ranging from 341 ± 2 to 321 ± 2 Ma, unpublished) show juvenile calc-alkaline characteristics (*e.g.*, Alasino et al. 2012 and unpublished data). Our new geochemical and geochronological data support the presence of a magmatic arc from the Early Carboniferous, located in the western margin of Gondwana (i.e., present-day Cordillera Frontal and Western Sierras Pampeanas) with the synchronous development of A-type magmatism in the foreland region (now the Eastern Sierras Pampeanas). Any geodynamic setting for Carboniferous time must include the presence of both a magmatic arc and intraplate magmatism. A simple collision during the Middle–Late Devonian with subsequent cessation of magmatism during the Early Carboniferous is irreconcilable with our data.

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# Tectono-sedimentary characteristics of the break-up of Pangea in the Iberian Basin

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At the end of the Carboniferous, most of the continental masses were grouped together into Pangea, the most recent of Earth's supercontinents. The Iberian plate was located in a central position between the northern and southern continents of Laurrusia and Gondwana, in the Variscan orogenic mountain belt, which was formed as result of the collision of these continents. This supercontinent, as other previous ones of similar characteristics, was very unstable and broke-up rapidly. The main stages of this process are well known but include some tecto-sedimentary characteristics poorly described previously. We present a case study in the south-east of the Iberian Basin (eastern Spain) showing some of these features.

Collision related to the Variscan orogeny was completed by Late Carboniferous times. The thicker continental crust resulting from overall convergence was isostatically unstable and its roots collapsed, causing increased heat flow, isostatic rebound and an extensional regime at the surface after rapid uplift. These circumstances appeared in central Iberia by Early Permian times. Old lineaments were reactivated as strike-slip or normal faults, and small (< 10 km long), isolated continental basins with half-graben geometry were created along a NW–SE trend in Central Spain that heralded the future Iberian Basin. The initial evolution of these basins was conditioned by the configuration of the Ibero-Armorican and Central Iberian arcs at the end of the Carboniferous.

The general tectono-sedimentary characteristics of the break-up of Pangea observed in the Iberian Basin show the following characteristics: 1) very reduced phases of sedimentary record accumulated between long periods of hiatuses, 2) an Early Permian initial phase of late Variscan strike-slip fault reactivations characterized by rapid subsidence, with breccia accumulation and local calc-alkaline type volcanism, 3) a short Middle–Late Permian phase of sudden lateral extension of continental sedimentation related to a decrease in topographic relief, with geographically restricted volcanism of alkaline affinity, 4) a late Early Triassic continental sedimentary phase of sedimentation representing the connection between the branches of the previous rifting systems. This phase of reactivated subsidence and sedimentation in some of these connected rift branches allowed faunal migration over thousands km all along the European plate. Finally, 5) there was a first rapid Middle Triassic marine transgression following corridors between the still elevated areas.

# Cryogenian crustal dynamics of NW-India: the pre-Gondwana India–Madagascar linkage

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Neoproterozoic geological history of the north-western Indian terrane and its role in the Rodinia to Gondwana transition continues to be debated as, in contrast to other key areas, the records of this geodynamically important time span are masked by the vast expanse of the 770–750 Ma volcanic and plutonic rocks of the Malani Igneous Suite (MIS). The MIS covers >50,000 km$^2$ in NW India with possible counterparts in southern Pakistan.

On account of the generally undeformed and unmetamorphosed nature of MIS rocks, NW India has been regarded as having remained a tectonically stable terrane following the Delhi orogeny during the (~1 Ga) collision of Marwar and Aravalli Bundelkhand cratons. However, there are indications of a tectonically active NE–SW trending corridor along the eastern margin of the MIS, parallel to the general trend of the Delhi Fold Belt and characterized by shear zones, anatexis and synkinematic emplacement of granitoids. This deformation, previously referred to as the "Sirohi orogeny", is prominent in the Sirohi region (southwestern Rajasthan State), where our studies indicate an early Cryogenian imprint, seen in three different tectonomagmatic zones. These zones are referred to from E to W as the South Delhi high-grade metamorphic terrane, Sirohi anatectic terrane and Sirohi fold-and-thrust terrane. Two tectono-magmatic events could be discriminated: older (870–820 Ma) and younger (770–750 Ma), the latter corresponding to MIS activity. A similar bimodal age grouping is also recorded for Neoproterozoic units in central and northern Madagascar and along a number of major shear zones in South India. Linkage of these regions would imply the presence of an early Cryogenian tectonic belt several thousand kilometres long. Madagascar was intimately involved in the tectonic events leading to the formation of Gondwana and recorded in the long time span of Pan-African tectonothermal events. In contrast, records of a Pan-African imprint are generally scarce in NW India, except in some areas (Mt. Abu: 509 ± 2 Ma, 514 ± 2 Ma, Ashwal et al., 2013; Sindreth: 550 to 490 Ma, Sen et al., 2013). These ages post-date the East African orogeny, the main phase of continent–continent collision between East and West Gondwana, but fall in the same age bracket as constrained for the final stages of Gondwana assembly during the Kuungan orogeny. The early Cryogenian mobile belts could have served as pathways for heat convection that triggered this local late Pan-African resetting in NW India.

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# Tectonic setting of the North Gondwana margin during the Early Ordovician: a comparison of the Ollo de Sapo and Famatina magmatic events

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Understanding the processes that resulted in the construction of Pangea requires that we understand the paleogeography and tectonics of the Gondwana and Laurussian continents. The northern (Iberio-Variscan) margin of Gondwana is commonly interpreted as a passive margin throughout the Paleozoic. Subduction of oceanic lithosphere continuous with continental Gondwana is inferred to have resulted in descent of the Gondwana passive margin beneath Laurussia during collision. However, the South American portion of the Gondwana margin, along strike to the west, is commonly modelled as a convergent margin throughout much of the Paleozoic. The presence of along-strike divergent and convergent margins requires their separation by a major transform boundary. Here we test this interpretation using lower Paleozoic magmatic suites from the Ibero-Varisca (the Ollo de Sapo suite) and South America (the Famatina suite).

We compiled available geochronological data to determine if the suites were coeval, and hence provided a snapshot of the Gondwana margin from a single time slice, and also geochemical data to test if the magmatic suites reflected contrasting convergent and divergent tectonic settings. Geochronological data limit Ollo de Sapo magmatism to 495–474Ma, whereas the Famatina magmatic suite was active from 483 to 463Ma. Major element data indicate that both magmatic suites are calc-alkaline to alkali-calcic, which is characteristic of a subduction zone setting. Furthermore, trace element and REE data show magmatic signatures which are indistinguishable and typical of a convergent margin setting.

Interpretation of Ollo de Sapo magmatism as rift-related is based on the high volumes of inherited zircon, supposedly coeval passive margin sedimentation, and the lack of any deformation or metamorphism that could be related to convergent margin processes. However, the zircon inheritance is not diagnostic of a rift-setting and can be interpreted as providing support for melting in response to upwelling of hot wet mantle against the crust in a convergent setting. Two aspects of the 'passive margin sequence' are inconsistent with the interpretation of the Ollo de Sapo as being 'rift-related': 1) passive margin sedimentation began in the Lower Cambrian – hence there was ~30 Ma of passive margin deposition prior to the onset of Ollo de Sapo magmatism, and 2) stratigraphically, Ollo de Sapo magmatism is coincident with either deposition of the Volcano-Sedimentary Unit, an immature tuffaceous unit that is difficult to explain in a mature passive margin setting, or with a major unconformity (the Sardic unconformity) marking a significant hiatus in passive margin sedimentation. Finally, the suggestion that there was a lack of deformation is inconsistent with the angular nature of the Sardic unconformity.

A simpler model of the Gondwana margin in the Early to Middle Ordovician is that it consisted of a single convergent margin. Subduction beneath Gondwana explains the Ollo de Sapo and Famatina suites as along-strike components of a single magmatic arc. Such an interpretation has significant implications for the tectonic assembly of Pangea.

# The Ibero-Armorican arc: indentation *versus* self-subduction

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In the Iberian Variscides it is possible to distinguish major arcuate structures; although highly studied, their characterization and genesis are still a matter of controversy. The main Ibero-Armorican Arc (IAA) is essentially defined by a NW–SE trend in the Iberian branch and an E–W trend in the Brittany branch; however, in northern Spain it is rotated 180º, sometimes known as the Cantabrian Arc (CA). The relationship between these arcs is debatable, being considered either as a single arc generated in one tectonic event, or the result of polyphase bending process. According to the last assumption, there is a later arcuate structure (CA), overlapping a previous major one (IAA). Whatever the proposed models, they must explain the presence of a sinistral transpression regime in Iberia and a dextral one in Armorican branch, and the temporal deformation range of Devonian to Upper Carboniferous (Dias and Ribeiro, 1995).

Another arcuate structure in continuity with the IAA, the Central Iberian Arc (CIA) was recently proposed (e.g., Martínez Catalán et al., 2014; Shaw et al., 2014) mainly based on magnetic anomalies, the geometry of major folds and Ordovician paleocurrents. However, this definition didn't take into account the described deformation events in the southern sectors of the Portuguese Central Iberian zone.

Considering the models proposed for the genesis of Iberian Variscan arcs, they could be ascribed to two major processes: oceanic lithosphere self-subduction and the indentation of a Gondwana promontory. The first argues that self-subduction of Paleotethys oceanic lithosphere induces whole-lithosphere buckling around vertical axes and thus the major Variscan arcuate pattern – according to this model, a previous linear chain was bent in a late and very fast stage (about 10 Ma). Although this model could be applicable to the CA, its extrapolation to the IAA does not explain either the transpressive deformation regimes that prevail in large sectors (dextral in Armorica and sinistral in Iberia), or the Devonian age of part of the Variscan deformation.

If a polyphase indentation model is considered it becomes possible to explain the observed situations: mainly the presence of important transcurrent kinematics in both branches of the IAA, and the progressive deformation from Devonian to Carboniferous times (with an earlier IAA genesis and a latter arcuate structure that is represented by the CA). We do not consider that the CA could be supported by the described Variscan structures.

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# Absolute age constraints on the Upper Parautochthon sedimentary sequence of the Morais allochthonous complex (Iberian Variscan belt, NE Portugal) based on new magmatic zircon U-Pb data

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The Morais allochthonous complex (MAC) is the easternmost far-travelled tectono-metamorphic unit of the Galicia-Trás-os-Montes Zone (GTMZ) in NW Iberia. It is surrounded by a tectonically underlying allochthonous unit known as Parautochthon (or Schistose Domain), which is subdivided into Upper and Lower on the basis of structural and stratigraphic characteristics. Intense and pervasive polyphase Variscan deformation erased most of the fossil record in the Upper Parautochthon (UP) and only a few Silurian graptolites were found in its higher section. Recent field work at the eastern rim of the MAC differentiated three volcanic events in the UP, all displaying tuffaceous facies intercalated in the sedimentary sequence. U-Pb zircon ages were determined for these volcanic rocks to constrain the time span in which these sediments were deposited. The lowermost volcanic episode, known as Mora Volcanics, consists of a bimodal suite of N-MORB tholeiitic basic rocks and calc-alkaline intermediate to acid volcanic rocks which yielded an age of 494±2 Ma age (Furongian, late Cambrian). The intermediate unit, traditionally known as the Saldanha Gneiss, consists of rhyolitic lavas and tuffs of calc-alkaline affinity which gave an age of 485±3 Ma (close to the Cambrian–Ordovician boundary). Both volcanic events are associated with a homogeneous detrital sequence of slate, greywacke, quartz-wacke and quartzite known as the Mora-Saldanha volcano-sedimentary complex. Higher in the sequence, a laterally continuous unit of white quartzites (Algoso Formation) constitutes the only reliable marker bed in the region, defining major folds of several Variscan phases. Above this unit and below the black Silurian facies topping the UP, volcanic rocks are more abundant, yielding different chemical signatures: sub-alkaline basalts (N-MORB and OIB) and rhyolites (WPG), and a peraluminous alkaline rock of trachytic composition. These volcanic rocks are enclosed in a sedimentary unit of black and purple slates with minor jasper bodies named the Peso Formation. The obtained ages range from 460±5 Ma to 450±7 Ma (Middle–Late Ordovician).
This group of ages (Furongian to Silurian) make it possible to correlate the UP sedimentary material and depositional environment with those of the autochthonous Central Iberian Zone (CIZ) and, consequently, to confirm a Gondwanan affinity. The Algoso Formation can be considered as equivalent to the Armorican quarzites widespread in the CIZ. The abundance of volcanic rocks in the UP in relation to the nearby autochthonous sequence (CIZ), suggests that it was formed in a more external shelf position along the northern Gondwana margin, thus suffering more intense extensional deformation and associated volcanism during the Early Palaeozoic.

# Large Upper Cambrian rhyolite olistoliths locked in the Early Carboniferous Variscan syn-orogenic melange of the parautochthonous realm of the NW Iberian Massif

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The Central Iberian Zone (CIZ) occupies a inner position in the Iberian Variscan massif and its north-west half is close to the limit of the Galicia-Trás-os-Montes Zone (GTMZ). In this deeply eroded part of the chain, the Variscan syn-orogenic deposits were only preserved in late Variscan NW–SE synclines. One of these structures, the Alcañices synform, is east of the Bragança complex and north of the Morais complex, the two easternmost far-travelled allochthonous units of the NW Iberia. At the core of the Alcañices synform a set of structurally stacked slices contain Variscan syn-orogenic sediments of Late Devonian to early-Carboniferous ages, as shown by detrital zircon and palynomorph studies.

However, some of the olistoliths found in the structurally upper unit of the synform (Rábano Formation) yielded Silurian graptolites and Lower Devonian conodonts and crinoids. Earlier, these fossils led to an age assignation for the complete lithostratigraphic unit that supported the creation of a parautochthonous domain. This was thought to comprise a somewhat different and thicker Silurian–Devonian sequence than the one identified in the Autochthon (CIZ). This view justified the early Silurian age attribution of a large acid volcanic body found in this area – the Nuez Volcanics, which consists of massive meta-rhyolites and acid meta-tuffs and has normal sedimentary boundaries with the main detrital sequence. A new U-Pb zircon age study of the Nuez Volcanics provides a magmatic age of 497.3±1.7Ma (late Cambrian). A detailed field revision shows that the Nuez Volcanics are indeed a ~ 3 km long olistolith locked inside an olistostromic sequence, thus reinforcing the earlier proposal of a sedimentary melange for the Rábano Formation.

The provenance of this huge olistolith is not straightforward, but there are some possibilities in nearby units. Identical rocks with similar ages are found in the active margin side (GTMZ): the Lagoa gneiss (494±3 Ma), which belongs to the uppermost allochthonous unit of the Morais complex; the rhyolitic tuffs of the Pombais unit, which is the lowermost ophiolitic slice in this complex; the Macedo de Cavaleiros unit which lies immediately below, and where acid volcanic rocks are also reported (in these two last cases the rock ages have not been yet constrained); and the lower rhyolitic lavas and tuffs found in the Upper Parautochthon to the east of the Morais complex, dated at 494±2 Ma. Similar ages are also found in the passive margin (CIZ) "Ollo de Sapo" magmatic rocks, with big exposures towards the N and S of the Alcañices syncline, displaying ages ranging from 495 to 470 Ma.

The presence of quartzite and lidite blocks in this melange points to a sedimentary provenance from the Autochthon and/or Upper Parautochthon. However, some problems arise from the presence of the Devonian limestone olistoliths (which usually bear conodonts and crinoids) whose source has not been found in this region's allochthonous and autochthonous realms. Thus multiple sources for the synorogenic sediments of the Rábano Formation from both active and passive margins are still a plausible option.

# Peralkaline and alkaline magmatism of the Ossa-Morena Zone, SW Iberia: age, sources and implications for the Paleozoic evolution of Gondwanan lithosphere

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The Ossa-Morena Zone in SW Iberia represents a section of the northern margin of West Gondwana that retains a record of rifting that led to opening of the Rheic Ocean in the early Paleozoic. We present U-Pb zircon data from three alkaline to peralkaline syenites intruding Neoproterozoic and Cambrian strata that give crystallization ages ranging between the Upper Cambrian (Furongian) and Early Ordovician (Floian). Lu/Hf isotopic data from the zircons give positive initial εHf values that approach model values for the depleted mantle at the time of crystallization, thus suggesting a significant mantle-derived component and limited mixing/assimilation with crust-derived melts. Alkaline/peralkaline magmatic suites of similar age and chemical composition intruded other sections of the northern margin of West Gondwana. This type of magmatism is traceable along the boundaries of the continental blocks constituting Iberia, which are also characterized by the presence of metamorphic belts with high-pressure rocks formed during the accretion and subsequent collision of peri-Gondwanan domains against Laurussia. Our U-Pb and Lu-Hf datasets indicate that during the Cambrian–Ordovician transition, lithospheric extension reached a stage of narrow intra-continental rifting where deeply-sourced magmas, probably coming from the lower crust and/or the upper mantle, intruded continental upper crust across various sections of the previously stretched crust. We propose that multiple necking of the Gondwana lithosphere led to compartmentalization of extensional activity (multi-block model), favouring the onset of early Paleozoic peralkaline and alkaline magmas. The structure of this broad area of thinned lithosphere underlain by fertile mantle, eventually consisted of several continental micro-blocks. The boundaries of the micro-blocks were zones of inherited crustal weakness that were subsequently reactivated during the Late Paleozoic as major accretionary faults related to the amalgamation of Pangaea during the Variscan orogeny.

# The corystosperm ovulate organ *Fanerotheca* Frenguelli from South Brazil: a first record and its paleogeographical and paleo-ecological meaning

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The southernmost areas of Brazil is known for its remarkable fossiliferous Triassic horizons (Passo das Tropas Member, Santa Maria Formation,) and a "*Dicroidium* Flora", despite the rarity of preserved forked-fronds in earlier records (Guerra-Sommer & Klepzig, 2000). New exposures have revealed an abundant and diversified assemblage, containing exceptionally well-preserved remains including reproductive structures. Here we describe one of those structures and some isolated seeds, which represent the first record of *Fanerotheca* Frenguelli in this flora. This genus was created to include cupulate megasporophylls related to the Umkomasiaceae, until now exclusively found in the Upper Triassic levels of Gondwana in South Africa, Australia and Argentina. In Argentina, the known fossil record is represented by *F. exstans* Frenguelli (or *F. extans*) from the Potrerillos Formation, the same species being described from the basal part of the Upper Triassic of Australia and South Africa, and by *F. dichotoma* Frenguelli, from the Cacheuta Formation (Frenguelli, 1944). In South Africa, four distinct species were found in the Carnian Molteno beds (*F. papilioformis, F. waldeckiformis, F. cruciformis* and *F. elandiformis,* Anderson & Anderson, 2003). The South Brazilian small "flower" exhibits four highlighted appendages (with oval shaped lobes), a leathery appearance and a short and robust stalk. Each lobe is about 5 mm long and 4 mm wide, with a 2 mm wide peduncle (3 mm long). The seed is comparatively larger, bilaterally symmetrical, dorsoventrally flattened (8 mm long/4 mm wide) and winged – characters that approximates it to the South African species *F. papilioformis* Anderson & Anderson. The occurrence of *Fanerotheca* in Brazil substantiates the significance of the Santa Maria Formation as the depository of a rich and diversified Triassic flora and fills an important gap between the African and Argentine record of the *Dicroidium* flora in the Southern Hemisphere. The association of Brazilian forms with a lacustrine succession in a dominantly fluvial deposit also confirms growth near water bodies, in a regional context of hot and seasonal climate.

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# First record of *Hamshawvia* Anderson & Anderson and *Stachiopitys* Schenk in the Triassic if Rio Grande do Sul, South Brazil

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The Triassic levels containing *Dicroidium* and other Corystospermales in South Brazil are also rich in leaves and reproductive structures of Ginkgophyta, representing 17% of the studied paleocommunity. Leaves of *Taeniopteris* and Equisetales are also common, the latter indicating near-water growth of the original flora. In the lacustrine succession, new and well-preserved forms have been found in recent years. Laminated shales, lenticular in geometry, represent a restricted part in the dominantly fluvial deposits, comprising trough and planar cross-bedded sandstones and intra-formational conglomerates assigned to the Passo das Tropas Member, the basal unit of the Santa Maria Formation. In association with diversified leaves of *Baiera* and *Sphenobaiera,* at least three isolated and distinct forms of *Hamshawvia* (ovulate structure) and one of *Stachiopitys* (male fructification) were identified. One of the *Hamshawvia* type specimens exhibits a near relationship with *H. longipedunculata* Anderson & Anderson (Anderson & Anderson, 2003) by its elongated, slender, once-forked axis, bearing a pair of fleshy and round megasporophylls. The other forms are still uncertain in their specific affinities. *Stachiopitys* is represented by numerous pendant microsporangia disposed in rosettes around an axis (not preserved), and suggests affinity both with *S. mazarinus* Anderson & Anderson and *S. lacrisporangia* Anderson & Anderson from the Molteno beds. The *Hamshawia* and *Stachiopitys* fossil record encompasses the Ladinian (Nymboida Coal Measures, Australia), the Carnian of South Africa (Molteno Formation) and the Ladinian–Carnian of Argentina (Potrerillos and Cacheuta formations, Kogogian et al., 1993, Barredo et al., 2012). The presence of reproductive and vegetative organs (even without organic connections), associated with leaves of *Sphenobaiera shenkii* sensu Anderson & Anderson and *Baiera* spp. links these deposits to other Gondwanaland occurrences, especially those from South Africa, and extends the fossil record of the Ginkgophyta in Brazil.

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# The provenance of exotic Ordovician and Devonian sedimentary rock units in the Lindener Mark (SE Rhenish Massif, Central European Variscides, Germany) – a combined U-Pb and Hf isotope study of detrital zircons

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Within the Rhenohercynian zone of the Central European Variscides, the southeastern Rhenish Massif exhibits Ordovician and Lower Devonian greywackes and sandstones in the Kellerwald area, the Lahn-Dill area, and in the Lindener Mark. Their origins and correlations between them are not clear. They contain, in the Devonian, some so-called Hercynian or Bohemian faunas of northern Gondwana biogeographic affinity which are exotic to the surrounding Rhenohercynian realm. Possible similarities between Early Devonian greywackes from the southern Kellerwald (and the Lahn-Dill area – "Erbsloch greywacke") and Early Devonian greywacke lenses within the *Dalmanites* sandstone from the Lindener Mark are also still under discussion.

We present a data set of U-Pb LA-SF ICP-MS ages of 604 detrital zircon grains from five investigated greywacke and sandstone samples. In addition, 155 analyses of Lu-Hf isotopes have been performed. U-Pb zircon ages, εHf ratios, and model ages point to an exotic provenance of the investigated sedimentary rock units, proving that the source area of these rocks was outside of the Rhenohercynian zone. Potential source areas are in the southern Armorican (Cadomian) part of the Variscan orogen, such as the Saxo-Thuringian and Moldanubian zones. The exotic sedimentary rock units of the Lindener Mark and the Lower Devonian Erbsloch greywacke were deposited at the southern margin of the Rheic Ocean, and were thrust northwestwards as nappe complexes over the southern Rhenohercynian zone during the collision of Laurussia and Gondwana caused by the closure of the Rheic Ocean and the Rhenohercynian back-arc basin.

# Cadomian evolution at the NW edge of Gondwana: the South Iberian island arc and related areas.

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The Ossa-Morena Zone (OMZ) of the Iberian Massif developed as an island arc at the northwestern edge of Gondwana during Ediacaran and Cambrian times in a position nearly parallel to the current East coast of Morocco and Tunisia. This Zone, which later would become one of the major components of the Iberian micro-plate, was originally generated rotated 180º from current coordinates. The integration of available petrological, geochronological, geochemical and structural data, coupled with recent data compiled in the Geological Map of Extremadura (Palacios et al. 2013) allow us to reconstruct its evolution during Cadomian times as follows:

The subduction process started at ~ 600 Ma and was directed southwards, with the trench located far from the Gondwana continental margin and probably shortly after the sedimentation of distal slope deposits represented by the Montemolín succession (the lower unit of the Serie Negra Formation). The former trench, and thus its location, is covered by the Carboniferous sucessions of the South Portuguese Zone. The initial angle of the subducting slab was low and the igneous front would have been 300 to 400 km from the trench as indicated by typical calc-alkaline intrusive and volcanic rocks that crop out along northern areas of the OMZ in the Obejo-Valsequillo–Puebla de la Reina domain (Mérida, Palomas, Oliva de Mérida, Valle de la Serena, Valsequillo, Escribano). Close to the trench, in the fore-arc region, E-MORB and N-MORB type basalts were erupted and appear interbedded in the Serie Negra in central and southern areas of the OMZ (Badajoz–Córdoba, Monesterio, etc.). An increase in the dip angle of the subducting slab could have promoted the deformation and metamorphism event dated at ~ 555 Ma in several areas.

A progressive increase in the subduction angle caused migration of the plutono-volcanic front towards the trench and the emplacement of granitoids dated at ~ 550–540 Ma (Ahillones, Mosquil, Monte Agudo, etc.). Calc-alkaline volcanic products (andesites s.l.) of this stage form the so-called Malcocinado Formation. Related serpentinite massifs (e.g. Calzadilla de los Barros) are interpreted as sub-oceanic mantle fragments. In connection with this process there was also thickening of the volcanic arc and subsequent development of anatectic cores dated at ~ 530 Ma (Mina Afortunada, Monesterio, etc.).

A final increase in the angle of the subduction was responsible for the onset of rifting limited to the south by the Hornachos fault. This stage included the eruption of rhyolitic tuffs dated at ~ 514 Ma (Bodonal–Cala porphyroids, Jabugo vulcanites, etc.), the emplacement of albitic granites dated at ~ 510 Ma and widespread volcanic, subvolcanic and plutonic rocks dated at ~ 500 Ma along the OMZ (Castillo, Barcarrota, etc.). The effusion of high volumes of hydrothermally altered basaltic rocks (spilites) of Middle–Late? Cambrian age (Zafra, Ribera de Huelva, Umbría-Pipeta, La Corte, etc.) might represent a late stage of this evolution.

Finally, the cessation of subduction brought about the establishment of a Variscan passive margin.

# The pre-Variscan basement of the southern Central Iberian Zone: a back-arc marginal Cadomian basin. Implications for the paleogeographic reconstruction of the northern edge of Gondwana

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The southern Central-Iberian Zone (sCIZ) contains the fill deposits of a Cadomian back-arc basin developed during Ediacaran–Lower Cambrian times, with the volcanic arc being represented by the Ossa-Morena Zone (OMZ) of the Iberian Massif. These two areas of the proto-Iberian plate have been rotated 180º from their original position. The lowest unit of the sCIZ, the Domo Extremeño Group, crops out extensively in the southern sectors and is progressively covered towards the north by the Ibor Group and olistostromic units. These are described from base to top:

The **Domo Extremeño Group** comprises the *Guadiana Formation* of decimetric to metric alternating turbiditic lutites and greywackes; the *Botija Formation*, a monotonous succession of dark lutites with millimetric parallel laminations and lenticular beds of cross-laminated sandstones; the *Monroy Formation* of alternating decimetric beds of greywackes and lutites with localized micro-conglomerate intercalations; the *Orellana Formation*, a turbititic sequence including abundant thick beds of conglomerates with exotic rounded clasts of quartz-rich sandstone, black quartzite and igneous rocks (rhyolites and rhyodacites) supported in a pelitic or silty groundmass. The conglomerates represent deposits of channelized zones related to the denudation of OMZ Precambrian rocks. At the top is the *Cíjara Formation*, an alternation of phosphate-bearing greywackes, quartz-rich sandstones and black lutites. It includes locally unorganized micro-conglomerates with phosphate clast beds that laterally change to olistostromes, interpreted as representing variation from platform to turbitic sedimentary environments.

The **Ibor Group** contains the *Castañar Formation*, arkosic sandstones interbedded within a monotonous succession of grey lutites with Vendotaenidae and meander-shaped ichnofossils similar to those founded in the Cíjara Formation, and the *Valdecañas Formation*, a thinly bedded sequence of lutite and greywacke that includes sandstone and limestone beds rich in Cloudina (Upper Ediacaran, ~ 548–542 Ma).

The **Olistostromic units and the trilobitic Cambrian.** From the Montehermoso-Garvín fault (Hurdes-Valdelacasa Sector) to the north appears a band of olistostromes that includes the El Membrillar and Fuentes olistostromes, overlain by the homogeneous black lutites of the Pusa and Villanueva Formations.

Thus the pre-Variscan stratigraphic succession represents the progressive filling of a back-arc basin where the provenance of the deepest materials attest to a volcanic arc located to the south. Northwards, the basal units are covered by younger deposits that define a prograde evolution. The main conglomeratic level (Orellana Formation) attests to the emergence above the sea level of the northern edge of the volcanic arc, a process concomitant with a generalized pre-Variscan deformation event across the area. The lowermost units of the Domo Extremeño Group register a Cadomian structural pattern with oblique-to-perpendicular folding relative to Variscan structures. The upper units of the Ibor Group and the Cambrian rest discordantly on the basement in the south, while towards the north they are concordant and exhibit structures parallel to those of the Variscan orogeny. The olistostrome units were deposited at the base of the continental slope of a platform developed in a back-arc basin, itself separated from the northern platform of Gondwana by a deep trough.

# The Cu-Au mineralization in Jbel Haimer (Jebilet central-Hercynian, Morocco)

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Vein deposits are an important class of gitologically known types in the central Jebilet metallic province. The Jbel Haïmer deposit in the volcano-sedimentary Sarhlef series is of copper-gold veins generally oriented NNE, usually mineralized on malachite. The host rocks are spotted schistose and schisto-sandy formations, specifically a hydraulic breccia oriented N20°E with a strong dip (70°) towards the east. The vein-breccia is related to sinestral or dextral ductile planes of deformation striking N40°E and contains blocks of schist. Ore bodies are veins and lenses.
The mineralization is an assemblage of pyrite-pyrrhotite-chalcopyrite-covelline-magnetite hematite with gold, accompagnied by, quartz, chlorite, calcite and dolomite. Associated hydrothermal alteration is characterized by biotitization, silicification, sericitization, chloritisation, tourmalinization and carbonation. It shows mineralogical zoning towards the granitic intrusions, which lead us to suggest a synchronous or superimposed mineralization to peri-granitic phyllic and potassic alteration. According to metallic paragenesis, the Jbel Haïmer Au-Cu deposit can be classed as of epithermal to mesothermal type.

# The Ferrar Large Igneous Province: new high precision U-Pb geochronology from the Transantarctic Mountains and Tasmania, and its implications

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The Ferrar Large Igneous Province (FLIP) is related to the separation of West Gondwana (Africa–South America) from East Gondwana (Antarctica, Australasia, India). The FLIP extends along the length of the Transantarctic Mountains from the Weddell Sea region (Theron Mountains) to North Victoria Land (NVL), and into Tasmania, New Zealand and southeastern Australia, a total distance of 4000 km. Ferrar intrusive and extrusive rocks are characterized by initial isotope ratios (Sr, Nd, Pb) and trace element abundances and patterns indicative of crustal involvement in their genesis and evolution, even in the most mafic compositions (MgO = 9%). Beyond this, Ferrar rocks can be separated into two chemical types. The first, designated the MFCT, comprises the bulk of the Ferrar and the majority of all analyzed rocks, and has a range of geochemical characteristics ($Sr_i$ ~0.709-0.712; MgO ~9-3%; Zr ~60-175 ppm) that can be related by fractional crystallization accompanied by ~5% crustal assimilation. The remaining 1% (by volume), designated the SPCT, has a very distinct, evolved, and restricted composition ($Sr_i$ ~0.7095; MgO ~2.3%; Zr ~230 ppm), which lies off the chemical trends of the MFCT. The SPCT, occurring as the youngest Ferrar lava flows in the Transantarctic Mountains and as minor sills in the Theron Mountains, extends over a distance of 3000 km. The unique geochemical characteristics (initial isotope ratios and trace element patterns and abundances) of the SPCT in particular and the MFCT in general over such a broad area has been interpreted as evidence that these magmas were generated from a magmatic center in the proto-Weddell Sea region and subsequently transported over long distances in the lower crust, probably through dikes.

New high-precision U-Pb zircon dating on 20 FLIP samples, from the Dufek intrusion to the Red Hills Dolerite of Tasmania, indicate a short duration of magmatism (≤0.5 Ma) in the range 183–182 Ma. At the temporal resolution afforded by our data, there are no systematic spatial or geochemical relationships among the samples analyzed. These results show that emplacement of the Ferrar magmas was approximately contemporaneous with those of the Karoo, although comparable temporal precision is not available for the latter. Together, these two LIPs form the Gondwana Large Igneous Province. We interpret the short emplacement duration of Ferrar magmas to indicate rapid magma transport, within a developing rift system, from a center in the proto-Weddell Sea region to SE Australasia. Within the uncertainties of the dating, the Gondwana Large Igneous Province pre-dates and/or overlaps the onset of the Toarcian Oceanic Anoxic Event (183–182 Ma) and therefore, as has been previously proposed, could have been a significant factor in triggering global environmental change.

# The Gondwana Plate Margin in the Antarctic Peninsula sector: implications from zircon geochronology of Permian strata in the Ellsworth Mountains and two isolated Upper Paleozoic outcrops in eastern Ellsworth Land

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The Ellsworth Mountains, Antarctica, remain an enigma in the geology of the proto-Pacific margin of Gondwana. Zircon U-Pb geochronology and provenance studies have been conducted on rocks from the Ellsworth Mountains and eastern Ellsworth Land. Detrital zircons from a sandstone low in the Permian Polarstar Formation (54.3 m in the measured section at Mt Weems), Ellsworth Mountains, are dominated by a peak at ~270 Ma. Those from sandstone higher up-section (210.5 m) have a dominant grouping at ~260 Ma. Both sandstone samples have prominent euhedral igneous zircon grains. Tuffaceous rocks from higher in the same section (at 274.5 m and 420.4 m) have late Permian ages of ~257 Ma and ~263 Ma, respectively, for elongate, euhedral igneous zircon. These results constrain the maximum ages of deposition of the lower and middle members of the Polarstar Formation. The sandstone data suggest that the lowermost member of the Polarstar Formation is a condensed section and the tuff data indicate a latest Permian age for the uppermost *Glossopteris*-bearing member. In eastern Ellsworth Land, detrital zircons from a sandstone in the thin sequence (2–28 m) of *Glossopteris*-bearing Erehwon beds yield three prominent age peaks: two late Permian groups (~264 and ~271 Ma) and one Carboniferous (~325 Ma). Detrital zircons from the quartzose sandstone strata at Fitzgerald Bluffs have a characteristic Gondwana margin provenance signature with abundant late Neoproterozoic to Cambrian grains, and very minor (in this case) Grenville-age grains.
The predominance of interpreted volcanic or subvolcanic zircon in both the Polarstar tuffaceous rocks and sandstones can be linked to the Permian arc along the Gondwana active plate margin for which there is a sparse record of plutonism. These results can also be compared with the record of tuff beds in the Karoo of South Africa. The Permian age peaks for the Erehwon sandstone are comparable with the Polarstar results and with detrital zircons from the Buckley Formation, Victoria Group, in the central Transantarctic Mountains. The Carboniferous peak can be linked to rare plutons of that age in Marie Byrd Land, and also compared with detrital zircons from a Triassic sandstone from the Victoria Group. The quartzose sandstones from Fitzgerald Bluffs are lithologically similar to Devonian beds in the Ellsworth Mountains, the Transantarctic Mountains and the southern Karoo; their detrital zircon spectra are also similar. The location of Erehwon Nunatak and Fitzgerald Bluffs within the trend of the late Paleozoic plate margin magmatic arc is anomalous. Results for these outcrops suggest they are part(s) of a small continental block that is another fragment of the pre-break up Gondwana margin, and separate from the Ellsworth-Whitmore Mountains block. Comparison between the Permian successions suggest that the Polarstar Formation depositional basin was separate and distinct from the Karoo/Falklands basin. The Ellsworth-Whitmore block was not adjacent to the Falkland Islands in a reconstructed Gondwana margin, but located farther along strike, away from Africa and towards the Coats Land/Pensacola Mountains region.

# The Chanic structure of the San Rafael block (S Mendoza, Argentina): evidence of the Chilenia-Cuyania collision

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Rocks of the Palaeozoic basement of the San Rafael block (southern extension of the Andean Precordillera) can be grouped into two sets separated by an angular unconformity: i) the pre-Carboniferous rocks (Cambrian to Devonian) and ii) the Carboniferous series, represented by the El Imperial Formation.

The main outcrop of the pre-Carboniferous rocks, assigned to Silurian by Sepulveda *et al.* (2007), is located between Los Reyunos Dam and the RN-40 road. The eastern part of this outcrop is formed by an alternation of white, coarse-grained sandstones and slates, which dip steeply to the SW and show graded bedding, indicating a facing-up position. The Gondwanan east-directed Los Reyunos thrust constitutes the eastern limit of these rocks and carried them over the El Imperial Formation. They show structures linked to two superimposed deformation events, developed under low-grade metamorphic conditions. During the first episode, a regional slaty cleavage developed in association with west-vergent folds. The second one is represented by centimetric to metric east-vergent folds with a well-developed associated crenulation cleavage. These structures are not present in the El Imperial Formation, and we deduce that they are related to the Chanic orogeny (Middle Devonian-early Carboniferous). Pre-Carboniferous rocks with similar lithological and deformational characteristics have been described to the north and west, in the Plata (Heredia *et al.*, 2012) and Carrizalito ranges (García-Sansegundo *et al.*, 2013) of the Frontal Cordillera, where the western branch of the Chanic orogen (Chilenia terrane) is present.

The non-metamorphic pre-Carboniferous rocks that outcrop east of the Los Reyunos dam, show similar characteristics to those of the same age in the Precordillera (Cingolani *et al.*, 2003; Manassero *et al.*, 2009) which belong to the Cuyania terrane. In view of these data, the Los Reyunos Thrust could represent a Gondwanan (Permian) reactivation of a previous Chanic one. This main Chanic thrust must be responsible for the emplacement of the western branch of the Chanic orogen (Chilenia terrane) over its eastern branch (Cuyania terrane) during the collision between these two terranes.

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# Alpine reactivation of the North Gondwana margin: insights from analogue modelling of late Variscan structures in Iberia

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The present-day topography of Iberia has been related to geodynamic processes involving lithospheric-scale deformation. However, little attention has been paid to the role of previous crustal or lithospheric-scale structures involved in the recently observed large-scale topographic patterns. Whereas the analysis of brittle structures has often been focused on the formation of Mesozoic sedimentary basins and their subsequent response to tectonic inversion, their contribution to mountain building has been underestimated. During the Paleozoic, Iberia formed part of the northern passive margin of Gondwana from the Ordovician–Late Devonian until the closure of the Rheic Ocean and the amalgamation of Pangea. The development of the Ibero-Armorican arc (~310–305 Ma) was followed by the onset of Pangea break-up, with crustal-scale faulting and the accumulation of Permo-Triassic sediments in intracontinental basins. The contribution of these major late- and post-Variscan structures on the Alpine evolution of intraplate relief remains controversial. Consequently, in order to investigate the role of these inherited structures on the final topographic configuration during N–S Pyrenean compression, we have carried out a series of lithospheric-scale analogue experiments complemented by surface velocity field analysis. The evaluation of the modelling results indicates that strain was concentrated along pre-existent crustal structures, producing crustal thickening and controlling the wavelength of lithosphere deformation. Three well differentiated domains were identified according to the putative initial fault trends, which controlled differences on reactivation timing, velocity vector rotations and variations in displacement rates along these structures. The velocity vector field calculated on the surface of the models shows several pulses of fault reactivation occurring on those structures orientated favourably with the N–S alpine stress field. Differences on fault-slip were also observed depending upon the pre-existent fault trends. Our results may explain the short displacements observed during reactivation of some of these probable orocline-bending structures in Iberia during the Cenozoic; unveiled structures may have absorbed most Alpine shortening. Therefore, large-scale lithospheric processes that took place in Iberia during the greater part of the Tertiary are not the only reason for the present-day reliefs; the importance of previous crustal structures on the final topographic configuration must be also recognised. Our experiments shed light on the stress transmission mechanisms that governed intra-plate deformation in Iberia during Alpine shortening, highlighting the influence of the inherited Variscan Gondwana margin structures on present-day topography.

# Whence come detrital zircons in Siluro-Devonian rocks from Iberia?

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Seven Silurian and Devonian samples from the Cantabrian and Central Iberian zones of the Variscan belt have been investigated for paleogeographic purposes using detrital zircon U-Pb ages. A total of 764 analyses were performed. All samples contain four main age populations in variable relative proportions: Ediacaran–Cryogenian (ca. 0.55–0.8 Ga), Tonian–Stenian (0.85–1.2 Ga), Paleoproterozoic (ca. 1.8–2.2 Ga) and Archean (ca. 2.5–3.3 Ga). The two first groups constitute ca. 60–80% of the total population in all samples. In addition, 5 samples contain very minor Paleozoic (Cambrian) zircons and 6 samples contain minor but significant zircons of Middle and Early Mesoproterozoic age (Ectasian–Calymmian). These data, used in conjunction with detrital zircon U-Pb data of underlying Ordovician and Ediacaran strata constrain the evolution of the northern margin of west Gondwana, highlighting the transition from an arc environment (Cadomian-Avalonian arc orogeny) to a stable platform following the opening of the Rheic Ocean and the drift of Avalonian terranes. Variations in detrital zircon populations in Middle–Late Devonian times reflect the onset of Variscan convergence between Laurussia and Gondwana. The abundance (up to ca. 50%) of zircons of Tonian–Stenian age in Devonian sedimentary rocks, that could not have been recycled from the underlying strata, may be interpreted in different ways:
a) the existence of a large Tonian–Stenian arc terrane exposed in the NE African realm (in or around the Arabian-Nubian shield) that was progressively exhumed throughout the Paleozoic,
b) the participation from Ordovician times onwards of a more easterly alongshore provenance of Tonian–Stenian zircons. In this scenario, the South China block could have furnished Tonian–Stenian zircons to the Ordovician and Siluro-Devonian basins of Iberia,
c) increase in the relative proportion of Tonian–Stenian zircons with respect to the Ediacaran–Cryogenian population (arc-derived zircons) due to the drift of the Avalonian-Cadomian ribbon continent following the opening of the Rheic Ocean.

# Detrital zircon geochronology of Cambrian–Carboniferous sandstones of the Cuyania (greater Precordillera) terrane of western Argentina and Neoproterozoic sandstones of the Rio de la Plata craton in Uruguay

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The Cuyania (greater Precordillera) terrane of western Argentina is considered by many to have rifted from the Ouachita embayment of Laurentia in the Early Cambrian, drifted as a microcontinent across the Iapetus Ocean, and docked with the proto-Andean margin of Gondwana in the Middle to Late Ordovician. Varied stratigraphic, paleobiogeographic, geochemical, structural, and paleomagnetic evidence has been cited in support, but it is equivocal (Finney, 2007). Detrital zircon geochronology from 26 samples of Cambrian to Carboniferous sandstones from Cuyania and 1 sample of Neoproterozoic sandstone from the Rio de la Plata craton provide an interesting record of the geotectonic and paleogeographic history of Cuyania. Cambrian sandstones have near uni-modal Mesoproterozoic age populations that include 600–500 Ma and 1600–1500 Ma grains suggestive of a West Gondwana source, and they lack the distinctive Grenvillian peak (1.1–0.9 Ga) that would indicate its rifting from the Outachia embayment of Laurentia. Zircon age populations from Upper Ordovician sandstones have 1600–900 Ma age populations, as well as 700–500 Ma age populations that are consistent with a source in the Pampean orogen. Yet the lack of Early–Middle Ordovician age grains suggests that Cuyania was not outboard of the Famatina magmatic arc at that time as proposed by the Laurentian model. Age populations of Silurian and Devonian sandstones are similar. The Lower Devonian Talacasto Formation has a small population of 500–400 Ma grains that may indicate a Famatinian source, yet they are lacking in the Middle Devonian Punta Negra Formation. Several Carboniferous–Permian sandstones have distinctive 500–400 Ma populations indicative of a source from the Famatinian magmatic arc, suggesting that Cuyania did not arrive at its present location until after the Devonian. A detrital zircon sample from the Neoproterozoic Piedras de Afilar Formation, deposited on the Río de la Plata craton in Uruguay, has a characteristic Transamazonian age population (2100–1700 Ma), but also has a Mesoproterozoic population virtually identical to that of the samples from Cuyania. Together, these samples are consistent with an origin of Cuyania on the southern margin of West Gondwana, its rifting from that position in the Middle to Late Ordovician, its subsequent migration along the margin of Gondwana during the Late Ordovician–Devonian, and its arrival at its present position in the Carboniferous.



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# Making ends meet: subglacial correlations and the role of Antarctica in Gondwana assembly

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Gondwana formed by amalgamation of multiple continental fragments along multiple suture zones at 700–500 Ma, but there is little consensus on the number, size or shape of these fragments, or the locations and orientations of the sutures that lie between them. This is particularly apparent in Antarctica, where correlation of metamorphic basement rocks and structures is limited by poor outcrop, deep erosion levels, sparse isotopic age data, and a likelihood that younger metamorphic events have reactivated older structures (Fitzsimons 2000; Boger 2011; Harley *et al.* 2013). Grenville-age (~ 1.0 Ga) and Pan-African (~ 0.5 Ga) metamorphism have been identified at several locations around the perimeter of East Antarctica, with both events often recorded in the same rocks. Indeed, all exposed Grenville-age belts in Antarctica have local evidence for Pan-African reworking, while all Pan-African belts contain local Grenville-age relics. These same ages are also recorded in sedimentary detritus and glacial erratics at the edge of the ice sheet, and are taken as evidence for both these events in the continental interior. Prominent boundaries in geophysical data presumably reflect the passage of these 1.0 and/or 0.5 Ga orogens under the ice, but they cannot be traced to exposed structures of unambiguous age.

In recent years, these relationships have been used to infer one or more Pan-African sutures crossing Antarctica, but there is no conclusive evidence that 0.5 Ga events were associated with ocean closure at a plate margin. Alternatively, the same structures could be interpreted as 1.0 Ga sutures reactivated at 0.5 Ga, and the sporadic nature of outcrop in Antarctica makes it difficult to rule out this possibility. Thus while future geophysical campaigns in Antarctica will continue to establish the spatial geometry of sub-glacial orogenic belts, their temporal evolution will be less easy to constrain from Antarctic outcrops that rarely expose major tectonic boundaries. The best evidence for the regional significance of 1.0 and 0.5 Ga orogenesis is likely to come from formerly adjacent regions of Gondwana, where outcrop is more varied and extensive, and these areas are also more likely to expose older rock units that can provide high-quality palaeomagnetic poles to constrain the former separation of continental rocks juxtaposed by 1.0 and 0.5 Ga tectonism.

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# Geochemistry of the Ediacaran–Early Cambrian transition in Central Iberia: tectonic setting and isotope sources

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The geochemistry and Sm-Nd isotope signatures of thick sedimentary series showing a complete Ediacaran–Early Cambrian stratigraphic transition, widely exposed in large Variscan anticlines in the southern part of the Central Iberian Zone (Iberian Massif), have been investigated in order to constrain the tectonic setting of this transition. Two different stratigraphic units appear below the Ordovician series: the Early Cambrian Pusa Shales Formation rests unconformably on fine-grained greywackes of the Late Ediacaran Lower Alcudian Formation. Twelve samples of formation were taken in the Valdelacasa and Central Extremadura anticlines, respectively.
The chemical classification of these shales and greywackes is in good agreement with their characteristic compositional groups. Minor compositional variation of Si, Ti, Al, Fe, Mg and K in shales, which have concentrations close to those of PAAS (Post-Archean Australian Shale), argue against important chemical alteration by post-depositional processes. The relatively high $SiO_2/Al_2O_3$ and low $K_2O/Na_2O$ ratios in greywacke samples reflect a predominance of immature sediments, with little evidence of weathering. Both types of samples show little variation in REE content, with fractionation patterns very similar to PAAS, characterized by moderate LREE-enrichment compared to almost-flat HREE patterns. All samples show a slight Eu anomaly. Th/Sc, La/Sc, and Ti/Zr values for shales suggest mixing sources, but Ti/Zr and Zr/Sc values from the greywackes seem to indicate a predominance of felsic sources, confirmed by the low abundances of Cr and Ni.
Trace elements contents in the greywackes indicate deposition of turbidites in a sedimentary basin associated with an active margin (volcanic arc). However, the compositions of the shales are more compatible with a tectonic setting related to passive margins, with Sr, P, and Ti negative anomalies as the most important indicators for such context. $\varepsilon Nd_{565}$ values for the Ediacaran greywackes range between -3.0 and -1.4, while $\varepsilon Nd_{530}$ in the Cambrian shales ranges from -5.2 to -4.0. TDM ages calculated for both series are Mesoproterozoic ranging 1256–1334 Ma in greywackes and 1444–1657 Ma in shales. According to these data, the Ediacaran–Early Cambrian transition in Central Iberia depicts an evolving tectonic setting in the Gondwanan margin, from active to passive. The Nd model ages are compatible with dominance of a cratonic source, probably the West Africa craton. Younger TDM ages in the Ediacaran greywackes of the Lower Alcudian Formation are compatible with mixed isotopic sources involving juvenile material derived from the volcanic arc. However, the mostly stable context that petained during Cambrian times favoured the presence of continental isotopic sources, in agreement with the older TDM ages from the Pusa Shale Formation.

# Formation and accretion of a Neoproterozoic island arc to the West African Craton during Pan-African orogeny

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The Adrar Souttouf Massif represents the northern part of the Mauritanide belt and is located in the southern regions of the Moroccan Sahara. The central areas of this massif consist of the Dayet Lawda and Sebkha Matallah units and are mainly composed of (ultra-) mafic rocks. Their geochemical composition suggests oceanic crust and island arc settings. Ten of 18 samples taken from these rocks yielded 531 zircon grains that were analysed with respect to their morphology, U-Th-Pb and Lu-Hf isotopic composition. In addition, 155 apatite grains were separated from six of the samples and analysed for their U-Th-Pb contents. Most of the zircons are well rounded crystals, and CL images reveal bright overgrowth or leaching zones on most, indicating metamorphic overprint. Only 89 zircon grains could be defined with respect to their morphotypes, which are mostly related to high temperatures during crystal growth. All samples but one yielded two significant zircon age populations: ~ 605 Ma and ~ 634 Ma, with further inherited grains occurring more frequently up to ~740 Ma and very scarcely to ~1190 Ma. Our Lu-Hf data suggest a major contribution of juvenile magmas directly derived from mantle sources for six samples, while the remainder are interpreted as reflecting crustal mixing of Archaean to Mesoproterozoic precursors with juvenile Neoproterozoic components. According to these data, an island arc in assumed at the periphery of the West African craton near time of the Cryogenian–Ediacaran boundary, which underwent metamorphism during accretion and partial obduction onto the basement rocks at about 605 Ma. Obtained apatite ages support the ~ 605 Ma event, while a Variscan overprint could be demonstrated for one sample. The one sample that does not show any of the Neoproterozoic zircon age peaks is characterised by a significantly different zircon age distribution (1.88–3.22 Ga). Furthermore, two apatite age populations were distinguished at 731 Ma and 1533 Ma. The latter age at least has to be regarded as exotic for the West African craton and challenges its supposed post-1700 Ma stability. This case study exemplifies the great potential of the widely occurring metamorphosed mafic and ultramafic rocks along the western margin of the West African craton for palaeogeographic and geodynamic reconstructions of this region during the Late Neoproterozoic.

# The Variscan subduction record: fabric development of Malpica-Tui unit eclogites, NW Iberia

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Quantitative texture analyses of eclogites from the Malpica-Tui unit (basal allochthon, NW Spain) have been performed with HIPPO, a TimeOfFlight neutron diffractometer at Los Alamos National Laboratory (Gómez Barreiro and Martínez Catalán, 2012). Preferred orientations of omphacite and garnet are presented in order to evaluate the kinematic meaning of the linear fabric. Shape analyses of selected phases were performed with X–ray computed microtomography at ELETTRA (SYRMEP beamline) to correlate grain fabric and texture for the first time in eclogites. Kinematic and mechanical implications for the Variscan subduction system are discussed.

Gómez-Barreiro, J. Martínez Catalán, J.R., 2012. The Bazar shear zone (NW Spain): Microstructural and Time-of-Flight neutron diffraction analysis. Journal of the Virtual Explorer, Electronic Edition, volume 41, paper 5, doi:10.3809/jvirtex.2011.00296

# Collision-related magmatism from Northern Gondwana: petrology, geochemistry and P-T modelling of Variscan deformed granites from Galicia, NW Spain

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Late Devonian-Carboniferous collision between northern Gondwana, peri-gondwana terranes and Laurussia generated the Variscan orogenic belt whose remains outcrop extensively in the northern Iberian Peninsula. This orogeny produced important peraluminous granitic magmas coeval with deformation processes: foliated two mica granites (~310-320 Ma) are widespread in northern Spain and Portugal and are the target of this work. The deformation of these granites was produced during its magmatic stage and also after its solidification. Our study site, in the Cies and Ons islands (western coast of Galicia), has excellent outcrops of typical two mica granites composed of quartz, feldspars (Ca-Na-K), muscovite (Ms), and biotite (Bt) ± tourmaline (Tur). There are some modal variations among these phases and in some outcrops new minerals appear: granites with Bt ≥ Ms (and with Bt < Ms), with Ms + Tur, granites with Bt + Ms ± Sill, with Ms + garnet (Grt) ± Bt, or with Tur + Grt. The geochemistry of all these granites shows a limited range of variation. Comparison with experimental melts indicates genesis by partial melting of metapelites in agreement with the peraluminous, S-type, chemistry. P-T modelling was performed to investigate the conditions of ascent and emplacement in the upper crust and also to explore the effects of the deformation/metamorphism that affected these rocks. Thermocalc and Perple_x software codes were used to construct phase equilibrium diagrams for specific bulk-rock compositions (FRX) with $H_2O$ contents taken as 6 mol. % and $O_2$ = 0.1 mol. %. The P-T pseudosections generated show wide Bt-Ms-Ilm (ilmenite) - (liquid/$H_2O$) multivariant fields, agreeing well the observed mineralogy. Isopleth modal contours for Ms and Bt indicates pressures above 4 kbar for the emplacement and solidification of granites whith Ms > Bt, and slightly lower pressures for granites with Ms ≈ Bt. Further subsolidus cooling would promote a decrease of Bt and a slight modal increase of Ms. When less amount of $H_2O$ was considered some of the models for these granite systems predict additional mineral phases such as Sill/Grt/Crd (P-T pseudosections with $H_2O$ = 2 mol. %). This result could explain the development of Ms+Bt ± Sill and/or Ms+Grt (±Bt) granites that occur frequently associated with two mica granites. Tectonic deformation during crystallization and/or afterwards, could facilitate this partial $H_2O$ expulsion leading to such different mineral assemblages. The modal content of biotite is predicted to slightly decrease during supra and subsolidus cooling and some its components (Mg-Fe-Ti-K) could be loss from the system, aided by deformation $H_2O$-squeezing, generating more leucocratic rock compositions. These results and interpretation are in agreement with the trend of Mg-Fe-Ti-K vs. deformation intensity observed for these rocks: as deformation increases and mineral foliation become more intense, the bulk rock Mg-Fe-Ti-K ± Al ± V decreases. This indicates that part of the mineralogy and chemistry of syntectonic two mica granites could be explained by slight differences in emplacement pressures, water contents and tectonic deformation ± $H_2O$ expulsion from these systems.

# Neoproterozoic to Cambrian granitoids of northern Mozambique and Dronning Maud Land, Antarctica: timing, genesis and tectonic implications for Gondwana amalgamation

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Granites with ages ~570 Ma to ~490 Ma are seen in the Namuno and Nampula terranes of northern Mozambique and Malawi as well as in Dronning Maud Land, Antarctica. Their compositions vary from andalusite-bearing peraluminous to metaluminous types. The latter include "syenitic" charnockites, dominantly in central Dronning Maud Land. In northern Mozambique, western and eastern Dronning Maud Land (Sor Rondane) charnockites are rare but they are common in Central Dronning Maud Land. In western Dronning Maud Land, granites are seen in Sverdrupfjella, but not in Kirwanveggan to the south and are thus distributed from just north of the Lurio belt to southern Sverdrupfjella.
No significant major or trace element differences are seen between the charnockitic and non-charnockitic types from southern Africa and Antarctica. Most intrusions have A2 type compositions (after Eby, 1992) typical of melts of thickened crust in continental collisions or areas of extension and Cordilleran compositions (after Frost et al., 2001). The mineralogical differences are interpreted as the result of T and $pH_2O$ differences resulting in subsolvus granites and hypersolvus charnockitic "syenites", rather than differences in bulk chemistry. The granites are late-to-syn kinematic to post-tectonic. In eastern and western Dronning Maud Land they form shallowly inclined sheets, locally conjugate, consistent with compressional emplacement. In Sor Rondane the granites are clearly syn-kinematic to the ~500Ma transpressional Main Shear Zone. Radiogenic isotope data from Mozambique and Antarctica and inherited zircons indicate partial melting of Mesoproterozoic basement and, locally, Archaean Kalahari-craton basement in western Dronning Maud Land. No juvenile isotopic contributions consistent with a juvenile extensional setting are recognised. Granitoids with ages between ~490 Ma and ~525 Ma, mostly seen south of the transpressional Lurio belt of northern Mozambique but not south of Sverdrupfjella, Antarctica, are inferred to result from anatexis in the footwall of a mega-nappe emplaced southwestwards from northern Mozambique over much of Dronning Maud Land during Gondwana amalgamation. Their younger age is consistent with heating in such a setting. Granitoids with ages >~550 Ma, dominantly seen north of the Lurio belt and in central and eastern Dronning Maud Land, are interpreted as related to decompression-driven partial melting in the hanging wall of the mega-nappe structure, possibly assisted by fluid ingress from the footwall.

# The intriguing geometry of the Central Iberian Arc

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The Variscan belt in Iberia appears as an "S"-shaped coupled orocline. The northern one, the Cantabrian orocline, is kinematically constrained as a secondary orocline and thought to be a thick-skinned feature. However, the geometry, kinematics and mechanism of formation of the southern one, the Central Iberian orocline (CIO), are still unclear. Several geometries have been proposed for the orocline, most of them suggesting that the Morais allochthonous complex (NE Portugal) occupies its core.
We combined paleomagnetic directions with structural analysis to constrain the geometry and kinematics of the CIO. We measured paleomagnetic directions in granites of the Tormes gneiss dome and limestones from the Tamames syncline. The sampling locations are situated at different locations around the hypothesized hinge of the orocline. These directions give a constraint on the amount of rotation and the location of the hinge, if rotations are present. We also made a detailed structural study of some outcrops in the hypothesized hinge of the orocline, to the SE of the Morais complex. During the structural analysis we determined three main phases of deformation, the metamorphic degree and the possible kinematics. The three phases formed a fold interference pattern and different generations of foliations.
We used the combined results to determine whether the Morais complex is indeed in the axial zone of the CIO or is part of one of its flanks, Preliminary results of the paleomagnetic measurements indicate directions ranging from ENE to SSE. The structural analysis indicates coaxial deformation between D1 and D3 in the section. We will discuss the implications of these results for the geometry and kinematics of the CIO.

# Repeated reactivation of an old suture zone: the post-Pan African evolution of the Central Anti-Atlas, Morocco

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After the fragmentation of Rodinia, a passive margin developed during the Tonian and Cryogenian in the northern West African craton. An arc–continent collision took place (Pan-African orogeny) during the Cryogenian and Ediacaran and a suture zone formed around what has been called the Anti-Atlas Major Fault (AAMF). During the late Ediacaran, alluvial sediments, lacustrine limestones and volcanic rocks (mainly rhyolites) were deposited in basins bounded by faults with a dominant dip-slip normal motion (XIIIs unit in the classical literature). The most important of these faults was the AAMF, which is currently exposed for about 200 km with a mean WNW–ESE trend. The other recognized faults –mostly located in the northern, hanging-wall of the AAMF– are kilometric-scale and have a wide range of orientations (NW–SE, NE–SW, E–W and N–S), producing basins with a width of 5 to 10 km bounded by faults of any of the previous orientations. As a result, the fill of these basins varies in thickness (up to 700 m), being much reduced or even absent in the uplifted blocks.

In the Adoudounian (latest Ediacaran) and the Paleozoic, a widespread, mostly marine, succession covered a wide region of the continent. In the Central Anti-Atlas, only the Adoudounian and Cambrian strata are preserved (up to 1300 m). The AAMF should have behaved as a normal fault during the sedimentation of younger Paleozoic units (normal slip is still preserved locally), as can be deduced by comparing the present height of the Adoudounian and Cambrian strata between the northern (downthrown) block and the southern (uplifted) one, considering that no significant thickness variations are observed between these two fault blocks.

The studied region was located in the foreland of the Variscan orogeny, but it experienced contractional deformation, mainly around the AAMF, which was reactivated with a S-vergent reverse motion, although locally the previous Paleozoic normal slip was not totally recovered. Several of the kilometric-scale faults bounding the late Ediacaran basins in the hanging-wall of the AAMF were synchronously inverted as reverse faults. As these faults have different orientations and were active simultaneously, they caused the development of sinusoidal fold traces and three-limb synclines in the Paleozoic cover.

It has not been documented whether the Anti-Atlas was ever completely covered by Mesozoic or Paleogene sediments. A peneplain developed over the Proterozoic and Paleozoic rocks, which were covered by pre-Cenomanian continental and Cenomanian marine rocks to the north and south of the Anti-Atlas. The Central Anti-Atlas is located in the foreland of the Cenozoic contractional Atlas System. Gentle WSW–ENE and N–S trending folds of 60–100 km wavelength reactivated Variscan structures, being the major contributors to the present topography of the Anti-Atlas which extends over 1500 m in many areas and over 2000 m in several places. The AAMF was again reactivated as a reverse fault, its hanging-wall being uplifted by as much as 500 m. Several of the previously described kilometric-scale faults were also reactivated as reverse faults, undergoing displacements of tens of metres. The youngest deformation post-dated Pliocene sedimentary and volcanic rocks.

# Gondwana to Pangea dynamics in Western Europe: roll-back vs. ridge subduction, or both?

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Understanding the causes of the opening and closure of oceanic tracts is a major ongoing endeavour in contemporary Earth Science. Ancient oceans are an important part of this process because they preserve a record of the different processes involved and so shed light on the causes of ocean opening and widening, and the subsequent dynamic flip towards convergence and closure. One of the best candidates for unravelling the causes involved in the birth and demise of oceans may be the Rheic Ocean. This is one of the world's most studied ancient oceans because its closure is one of the main factors in the construction of Pangea. Nevertheless, the myriad of different interpretations of its origin and evolution advocated by different working groups make it difficult to conceptualise the causes of its opening and its dynamic flip from oceanic growth to closure. Most recent interpretations rely on the effects of subduction roll-back for the creation and subsequent evolution of this ocean, but other explanations can also be found. In particular, subduction of the mid-ocean ridge during closure of the Iapetus Ocean, the precursor of the Rheic Ocean, or during that of the Rheic Ocean, is seldom mentioned but may be a crucial factor in their evolution.

We present an alternative interpretation for the evolution of the Rheic Ocean from its opening along the northern margin of Gondwana in the Late Cambrian–Early Ordovician and the coeval onset of Iapetus Ocean closure, to the change in its dynamic regime, the opening of subsidiary peripheral oceanic basins, and its final closure. This interpretation is based on the effects of ridge subduction and the consequent coupling between the subduction zone(s) and the passive margins on the opposite side of the Rheic Ocean. This approach better explains some of the enigmas of the Rheic Ocean, such as the absence of magmatic arc related rocks in those areas where subduction zones are placed in many of the existing models proposed by different working groups.

# Raman spectroscopy and temperature estimation of serpentinization in the Beni Bousera mantle peridotites (Internal Rif, Morocco)

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The Beni Bousera massif belongs to the Sebtide units in the internal Rif (Morocco). It is mainly composed of mantle peridotites surrounded by crustal metamorphic rocks (kinzigites, micaschists, schists). Intensity of ductile deformation in the peridotites allows recognition of, from bottom to top: 1) coarse-grained porphyroclastic to granular spinel peridotites including spinel pyroxenites layers, 2) spinel porphyroclastic peridotites with layers of garnet pyroxenites, 3) garnet and spinel mylonites. The deformation gradient and associated recrystallization is related to a normal shear zone between the mantle peridotites and the kinzigites. This shear zone resulted in the exhumation of the deep units and development of a main $S_2$ foliation and LP-HT metamorphism during the Oligocene–Early Miocene times (Negro et al, 2006; Afiri et al., 2011).

Serpentinization is superimposed on the ductile deformation. Following exhumation, fluid circulation induced serpentinization of the peridotites, where it is concentrated at the top, along the mylonitized zone, and decreases towards the bottom of the massif. It is manifested by the development of serpentine along faults, fractures, foliation and olivine cracks. Pyroxene is still intact; this differential serpentinization reflects a low silica activity.

Temperatures of serpentinization have been estimated by applying the Raman spectrometry geothermometer based on the $R_2$ ratio obtained from the Raman spectroscopy (Beyssac et al., 2002). This ratio has a linear correlation with the maximum temperature ($Tmax = -445R_2 + 641$). The temperatures estimated for serpentinization in the Beni Bousera peridotites are high, in the range between 500 °C and 600°C. At such temperatures olivine coexists with Mg-rich serpentine (antigorite) in subduction zones (Evans, 2010). However, the dominant serpentine in the Beni Bousera peridotites is lizardite, with minor amounts of chrysotile in veins and fractures. The occurrence of lizardite instead of antigorite can be related to substitution of Si by Al, which increases the stability conditions of lizardite in HT-LP metamorphic conditions (Caruso et Chernosky, 1979).

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# Cadomian accretionary and mélange-forming processes in the Teplá–Barrandian unit, Bohemian Massif

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The Teplá–Barrandian unit (TBU) of Central Europe's Bohemian Massif exposes perhaps the best preserved fragment of an accretionary wedge (part of the Blovice accretionary complex; BAC) in the Avalonian–Cadomian belt, which developed along the northern active margin of Gondwana during Late Neoproterozoic times. The BAC extends from a ~620–560 Ma volcanic arc (the Jílové belt) in the SE to a large ~540 Ma composite meta-ophiolite in the NW (Mariánské Lázně complex; MLC). The accretionary wedge consists of six fault-bounded linear belts, with three coherent domains of arc-derived and multiply-recycled deep-marine siliciclastic rocks (belts I–III) alternating with belts of ocean-floor bearing (ophiolitic) mélanges (belts 1–3). We interpret these six belts as recording a combination of frontal or slightly oblique trench sediment accretion (belts I–III) interrupted by pulses of mélange formation (belts 1–3). These mélanges could have formed by the successive arrival into the subduction zone of three linear volcanic elevations (remnants of an outboard back-arc basin), triggering extensive gravitational sliding into the trench due to increased wedge taper above the elevations. These gravitational processes resulted in the formation of olistostromes, which were then accreted. The volcanic elevation fragments were subsequently emplaced into the olistostromes by underplating at greater depths.

The Cadomian orogeny in the BAC was terminated at ~550–540 Ma by slab break-off and associated metamorphism, and by final attachment of the most outboard oceanic crust (MLC). While the mélange-forming processes were still active till at least 527 Ma, the inboard, southeastern segment of the TBU was elevated above sea level, rapidly eroded, and was already in an extensional regime resulting in an overall horst-and-graben basement architecture. Erosion is exemplified by the >2500 m thick early Cambrian continental, molasse-type siliciclastic succession of the Příbram–Jince basin. Parts of the BAC are overlain unconformably by middle Cambrian marine successions and Cambro–Ordovician subaerial volcanic rocks, which constrain the pre-middle Cambrian (Cadomian) age for the juxtaposition of belts along their boundary faults.

Consequently, it is difficult or even impossible to apply basic stratigraphic principles to restoring the original stratigraphic and temporal relationships between lithotectonic units in the BAC. Existing strictly non-tectonic stratigraphic schemes are redefined to reflect the complex structure of the BAC.

# Kinematic Analysis and paleostress reconstructions of Neoproterozoic to Neogene fractures in Al-Jamoum area, Saudi Arabia: tectonic implications for Western Arabia

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Progressive convergence of eastern and western Gondwana, predominantly during the late Cryogenian–Ediacaran (650–542 Ma), produced successive ductile, brittle–ductile and brittle deformations in the Arabian-Nubian Shield and the entire East African Orogen. In Tertiary and more recent times the earlier formed structures in the Arabian-Nubian Shield significantly influenced Red Sea rifting, as indicated by rift-related extensional features (listric normal faults, tilted fault blocks, half grabens... etc.) that overprint the Neoproterozoic fabrics and are expressed in the overlying lithologies. Understanding such prolonged kinematic history is, therefore, highly significant in deciphering the tectonic evolution of the Arabian-Nubian Shield. The current work presents paleostress reconstructions obtained from fault-slip data of outcrops ranging in age from Neoproterozoic to Neogene in Jeddah tectonic terrane, western Arabian Shield. The fault-slip data include fault planes, slickenlines and sense of movement. Stress inversion of fault-slip data was carried out using the Right-Dieder method, followed by rotational optimization using the TENSOR program. Results demonstrate a succession of four paleostress tensor stages (groups or regimes). The first tectonic stage is characterized by pure extension stress regime with N–S horizontal extension ($S_{hmin}$). It created normal and oblique-slip (dextral-normal) faulting. The second one is pure compression with E–W horizontal compression ($S_{Hmax}$) creating thrust faults. The third stage is pure compression with N-S horizontal compression ($S_{Hmax}$) producing thrust faults and strike-slip fault. These stages related to Gondwana assembly and are compatible with Pan-African tectonics. The last tectonic stage is characterized by radial extension with poorly defined horizontal direction of extension.

# Post-Accretionary structures in the Ediacaran Ablah Group volcanosedimentary sequence, Asir Terrane, Saudi Arabia

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The Asir tectonic terrane in the Arabian-Nubian Shield extends to the northern border of Yemen. It is separated from Jeddah terrane to the north by the NE/NNE Ad-Damm dextral transpressional shear zone (ADSZ) and from Afif terrane to the east by the NW/NNW Ruwah sinistral transpressional shear zone (RSZ). The unique setting of these terranes (Asir, Jeddah and Afif) involves two collision stages: an early collision between the Asir and Jeddah terranes along the ADSZ, and a later collision between the Asir and Afif terranes along the RSZ. The early collision stage is related to the terrane accretion during the early East African Orogeny. The second collision stage was geographically concurrent with a later collision between East and West Gondwana that led to the closure of the Pacific-sized Mozambique Ocean. The Asir tectonic terrane itself is structurally complicated compared to the other amalgamated Arabian-Nubian Shield tectonic terranes. It belongs, according to recent publications, among the oldest terranes that were formed during the early growth (accretion) phase and internally partitioned by inter-arc sutures. It comprises a collage of structural belts that are connected along N-, NNE- and NNW-orientated shear zones and fault zones. The Ablah Group is structurally-controlled by the Farwah shear zone located along the contact between the Al Lith-Bidah and Shwas-Tayyah structural belts. The Ablah Group is akin to the mixed terrestrial and shallow-marine Ediacaran post-amalgamation depositional basins in the Arabian-Nubian Shield. It shows complex post-accretionary transpressive structural fabrics, represented by composite thrusting, thrust duplexes and thrust-related folding, as well as heterogeneous transcurrent shearing and shear zone related folding. These post-accretionary structures were formed in a transpressive tectonic setting, confirmed by both E–W (to ENE–WSW) horizontal shortening (and vertical lengthening in the shear plane) and N-S (to NNE-SSW, and NNW-SSE) trending shearing.

# Gold endowment in the Hamisana shear system, northern Red Sea Hills, Egypt

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Gold-bearing quartz veins within, and associated with, anastomosing shear zones splaying off the N-trending Hamisana Zone are a common feature in the northern Red Sea Hills. Structural elements including close and tight isoclinal folds, S-C fabrics, stretched/ribboned quartz fabrics, and steeply-dipping shears everywhere and in the orebodies attest to gold deposition concurrent with a long-lasting transpressional regime. The steep faults with opposite sense of shear on either flank of the Hamisana Zone have probably been fluid conduits and seals for a regional gold mineralizing event. The strong structural control of the mineralization, extensive carbonatization and the lack of magmatic activity superimposed on the host rocks argue for metamorphic dewatering of greenstone country rocks as a likely fluid source.
Comprehensive geological mapping and structural analysis of the high strain zones reveal that dilation loci are more likely where the axial shearing foliation is disrupted and deflected eastwards or westwards by coherent (non-deformed) blocks. A clear geological and structural investigation would significantly aid very promising exploration plans for gold along extensive shear zones in this region, as prerequisite for a successful geochemical prospection.

# *Kutchithyris ageri* – a new species, terebratulida from the Oxfordian of northern Sinai, Egypt

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Brachiopoda from the Jurassic rocks of Gebel Umm Mafruth, northern Sinai have not described before. Several brachiopoda fauna were collected from Oxfordian marly limestone, among them small- to medium-sized terebratulid specimens homeomorphous to Zeilleriid forms. However, the internal features of a new proposed species show differences from the genus *Zeilleria*, such as the absence of characteristic dental lamellae, disconjunct deltidial plates protuding horizontally, a broad and shallow cardinal process, and strong hinge teeth inserted into deep socket floor with remarkable denticulum. Teeth are massive, with outer and inner socket ridges well distinct and a confined deep socket floor; outer hinge plates are long slightly curved anteriorly, with a long crural process, shallow median euseptoidum and two weakly distinct lateral euseptoidum. The external and internal characteristics show differences from those described by Feldman (1991 and 2001) from Gebel El-Maghara and Southern Israel, and from those described by Cooper (1989) from Saudi Arabia. They are different also from *Kutchithyris sinaensis* described by Hegab (1992) from Gebel El-Maghara in northern Sinai,Egypt.

# Competing tectonic processes along the western margin of dispersing Pangea: geochronological, geochemical and Sm-Nd isotopic data of Late Triassic–Middle Jurassic rocks from the Ayú Complex in southern Mexico

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Subduction-related processes along the northwestern margin of Gondwana (Middle America) have accompanied the assembly of Pangea since the Devonian through to its final amalgamation in the late Paleozoic. Although evidence of Triassic arc activity in Middle America is scarce, continental magmatic arc activity was re-established in the Late Triassic/Early Jurassic when Pangea began to break apart and reached its peak in the Middle Jurassic when rifting progressed into drifting of the Maya block. The break-up of Pangea thus was accompanied by two competing processes: the opening of the Gulf of Mexico and subduction of the paleo-Pacific at the western margin of Pangea. Dispersal encompassed significant drift associated with N-S transcurrent faulting, leading to a reconfiguration of the Middle American terranes for which various paleogeographic models are still being debated.

Polydeformed, metamorphosed rocks of the Triassic–Jurassic Ayú complex in southern Mexico span the time of the break-up of Pangea and offer the opportunity to study post-collisional, subduction-related processes along the periphery of the dispersing supercontinent. The Ayú complex consists of metasedimentary rocks and amphibolites that were migmatized and intruded by granitoids in the Middle Jurassic. LA-ICP-MS U/Pb zircon and $^{40}Ar/^{39}Ar$ data, as well as trace element and Sm-Nd isotope geochemistry of the studied rock assemblage indicate an active continental Mexican margin including arc magmatism and back-arc formation.

Back-arc rifting was extensive, culminating in the tapping of new mantle, and may have been facilitated by extension in the Mexican hinterland associated with the rifting of the Gulf of Mexico. Following the rapid under-thrusting of the Ayú complex, renewed extension led to decompression melting and final exhumation.

Middle Jurassic transcurrent faulting and syn-tectonic magmatism associated with continental margin tectonics is observed in other localities of southern Mexico and northern South America, suggesting that supercontinent dispersal had a significant influence on tectonic processes along the periphery of Pangea.

# Tracking the Neoproterozoic–Permian tectonic evolution of Avalonia in the Canadian Appalachians: a combined U-Pb-Hf detrital zircon study

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One way in which supercontinents are commonly built is the transfer of ribbon terranes from one continental block to another, via classic or modified Wilson cycles. We investigate whether combined U-Pb-Hf zircon analyses are sensitive enough to provide additional insights into the timing and nature of this transfer process.

Avalonia is a micro-continental ribbon with a complex tectonic history. Following inception as a juvenile arc in a peri-Rodinian ocean, proto-Avalonia was accreted to the Gondwanan margin in the late Neoproterozoic. A major phase of continental arc-magmatism ensued, followed by rifting and separation of Avalonia from Gondwana during the earliest Ordovician. It ultimately collided with Baltica in the late Ordovician, closing the Tornquist Ocean, prior to collision with Laurentia in the Silurian during the final closure of Iapetus. We present a comprehensive U-Pb-Hf detrital zircon data set that covers the late Proterozoic–Paleozoic history of Avalonia.

The Gamble Brook Fm is the oldest sedimentary unit in the Canadian Appalachians. It yields entirely Mesoproterozoic–Paleoproterozoic detrital zircon populations. In contrast, most Late Neoproterozoic–Cambrian sediments (James River, Livingston Cove and Keppoch formations) clearly preserve the isotopic record of peri-Gondwanan arc magmatism in Avalonia (750–600 Ma), and feature scant Mesoproterozoic grains. Early Late Cambrian sediments (Malignant Cove and Black John Formations) preserve similar detrital zircon spectra to the older sequences, but the early Ordovician Redmans Formation (Avalonian Newfoundland) yields a similar Cryogenian–Ediacaran population to the Neoproterozoic-Cambrian sedimentary rocks. Deposition of the Upper Ordovician Beechill Cove Fm coincides with the apparent arrival of Avalonia to Baltica. These strata yield Late Cambrian–Ordovician zircons, as well as early Neoproterozoic and Eburnian populations not previously associated with Baltica. Devonian–Permian rocks record a steady incursion of Silurian–Carboniferous grains, as well as varying populations of Mesoproterozoic and Paleoproterozoic grains. No Archean grains are recorded after the mid-Devonian.

The Avalonian earliest crustal record in the Gamble Brook Fm. indicates that generation and reworking of juvenile crust (εHf= 0 to +10) was an important process in the Mesoproterozoic source terranes, whereas Neoproterozoic strata deposited coevally with the main phase of arc-magmatism record the generation of predominantly juvenile material (εHf= +13 to -5). Although post-orogenic Cambrian strata preserve a similar juvenile ~ 750–600 Ma population, they also incorporate a minor percentage of quite evolved Ediacaran grains (εHf=+15 to -15), and following apparent accretion with Baltica, Silurian strata contain isotopically evolved Ediacaran–mid Cambrian zircon grains (εHf= +5 to -22), indicating derivation from a non-Avalonian Neoproterozoic arc.

Silurian–Carboniferous zircon grains only appear in the detrital record following accretion to Laurentia, and record a steady transition towards more juvenile compositions. The shift began at ~500 Ma and indicates a rapidly diminishing continental input typical of circum-Pacific arc magmatism. This suggests that Avalonia remained on the upper plate throughout its drift history, consistent with models requiring back-arc spreading mechanisms to generate transfer of ribbon terranes from one continent to another.

# Neoproterozoic magmatism and metamorphism at the northern margin of Gondwana: Ossa Morena/Central Iberian zone boundary (Central Portugal)

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In the westernmost part of Europe, a major Neoproterozoic suture has been recognized at the Ossa Morena/Central Iberian zone boundary and the existence of a Cadomian basement has been documented in the geological literature. However, the lack of geochronological data for the basement, particularly in Portuguese areas, limited understanding of the timing of igneous and metamorphic events along the northern edge of Gondwana. We present new geochronological and isotopic data (U-Pb, ID-TIMS method; Sm-Nd) that define a sequence of geological events important to the understanding of the assembly of Gondwana. The study area is located in near Abrantes Central Portugal, at the Ossa Morena/Central Iberian Zone boundary. The rock sequence comprises three lithostratigraphic units from base to top: the Série Negra unit, the Sardoal complex and the Mouriscas complex. The Série Negra is a volcano-sedimentary succession, deformed and metamorphosed under low to medium-grade conditions. It comprises metavolcanic rocks, volcaniclastic rocks, metagreywacke, phyllite, schist with interbedded black chert, greenschist and amphibolite and rhyodacite intrusions. The protoliths of the amphibolite were generated by island arc magmatism. This event can be related to back-arc spreading documented in other areas of the Cadomian basement. The Sardoal complex consists of deformed metamorphic rocks of igneous origin (quartzo-feldspathic schist, orthogneiss, migmatite and amphibolite) and minor rhyodacite intrusions of Carboniferous age (~ 308 Ma). The geochronological results indicate a major felsic igneous event between ~ 692 and 548 Ma that generated protoliths of subalkaline and peraluminous character on an active continental margin. Strong negative $\varepsilon Nd_t$ isotopic signatures (-5.2 to -8.1) and old $T_{DM}$ model ages (1.53 to 1.69 Ga) are consistent with old crustal sources, which have been observed in other Cadomian-type terranes. This event can be correlated with the arc-related magmatism in Cadomia. Paleoproterozoic and Neoarchean inherited zircons (1.7–2.8 Ga) suggest a West African craton provenance, in agreement with Late Neoproterozoic reconstructions that place the Ossa Morena adjacent to the West African craton. Amphibolites interbedded in the Sardoal complex are older than ~ 539 Ma and were generated in a Precambrian island arc. The Mouriscas complex is a deformed and metamorphosed igneous mafic complex that includes amphibolites with an igneous crystallization age of ~ 544 Ma and metatexite, diatexite, protomylonite trondhjemite and garnet amphibolite. Isotopic data indicate sub-continental lithospheric sources and crustal contamination by old crustal rocks ($T_{DM}$=1.51 to 1.81) in intra-plate and active continental margin settings. This magmatic event represents the final phase of Cadomian arc magmatism in the area. A major metamorphic event is recorded in the Sardoal complex amphibolite by metamorphic zircon and titanite and in the orthogneisses by metamorphic monazite (~ 540 Ma). It represents accretion of the peri-Gondwanan terrain (Ossa Morena) to the Iberian autochthonous passive margin. The collisional event caused partial melting of orthogneiss, with formation of migmatite and metamorphism at amphibolite facies conditions, close to the transition to granulite facies (P=7-8 kb, T=640-660ºC).

# The four Neoproterozic glaciations of southern Namibia and their detrital zircon record: a mirror of four crustal growth events during two supercontinent cycles

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The transition from supercontinent Rodinia to the formation of Gondwana took place in the Neoproterozoic. The western margin of the Kalahari craton in southern Namibia underwent rifting at ~ 750 Ma, caused by the break-up of Rodinia, followed by drift events and ongoing sedimentation throughout the Cryogenian (at least from 750 to 630 Ma). These sediments comprise at least three different layers of glacio-marine diamictites (Kaigas 750–720 Ma, Sturtian ~ 716 Ma and Marinoan ~ 635 Ma). The Ediacaran is characterised by collision during the assembly of Gondwana and includes a fourth glacial layer (post-Gaskiers Vingerbreek glaciation at ~ 547 Ma). We present more than 1050 zircon grain U-Pb analyses of different diamictite horizons from southern Namibia and discuss their correlations. For all samples related to the Kaigas, Sturtian and Marinoan glacial events, the youngest obtained zircon ages were at ~ 1.0 Ga, making differentiation by the maximum age of sedimentation impossible. But correlation is still possible using the complete detrital zircon U-Pb age patterns, with a significant change in the relative abundance of concordant Paleoproterozoic to Mesoproterozoic zircons (P/M). This ratio seems to be a good tool to distinguish the Cryogenian diamictites (Marinoan < 0.4, Sturtian 0.4–10, Kaigas > 10). Although all the observed ages can be explained by derivation from local material, none correspond to the Cryogenian rifting events in southern Namibia. Therefore the source area can not be local and more probably is located in the east of the studied areas. The constancy of the main U-Pb ages suggests a constant sediment supply direction throughout the Cryogenian. The same age populations occurring in the Ediacaran Kliphoek Member indicate the same sediment transport direction from the east, but with an increased proportion of zircon grains > 2.2 Ga. This marks a transition to the unconformably overlying Vingerbreek diamictite horizons, which show a significant change in the age spectra: probably due to mixed input from the east (Kalahari craton) and from the west (Gariep belt). The Hf isotope record shows that the only juvenile material input in our samples occurred in the Mesoproterozoic during the Namaqua Natal orogeny. Four Archean-Proterozoic crustal growth events are recognized in the western part of the Kalahari craton: ~ 3.42–2.8 Ga, ~ 2.8–2.27 Ga, ~ 2.27–1.7 Ga and ~ 1.0–1.6 Ga.

# Mineralogical and geochemical characteristics of a carbonate-hosted Cu, Pb, Zn, (Ag, Au) ore deposit at Amensif (Western High Atlas, Morocco)

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The Cu, Pb, Zn, Ag-Au deposit of Amensif is located on the northern flank of the western High Atlas. This deposit is hosted in Lower Cambrian carbonate bars and is structurally controlled by NE–SW to E–W trending fault structures, and is spatially associated with the Permian (273 Ma) Azegour granite. Ore reserves are around 0.5 Mt and grades are 3.21% Zn, 0.58% Pb, 0.86% Cu with 83.31 ppm Ag and 0.41 ppm Au. Sulphide mineralizations occur as local replacement of dolomitized and silicified carbonate bars. Ore mineralization at Amensif is dominantly composed of chalcopyrite, sphalerite, galena, pyrite, and arsenopyrite. Gold and silver are closely associated with tetrahedrite-tennantite and arsenopyrite. Gangue minerals include predominantly chlorite, epidote, tremolite, calcite, dolomite, quartz, sericite, minor andradite and vesuvianite We have recognized three major hydrothermal transformations that affected the carbonate bars: intense silicification and dolomitization, skarnification, and propylitization. These hydrothermal alterations were accompanied by important replacement textures of sulphide minerals. Pb isotope compositions of galena sampled from two regions in the western High Atlas (Amensif and Tighardine) show a wide range in $^{206}Pb/^{204}Pb$ (18.053–18.324), $^{207}Pb/^{204}Pb$ (15.534–15.577), and $^{208}Pb/^{204}Pb$ (37.780–37.986) and extend from relatively unradiogenic massive sulphides to those with radiogenic and internally inhomogeneous isotopic composition. The Pb isotope signature suggests that Pb-Cu-Zn minerals were generated during the remobilization of Pb from the older reservoir in the Cambro-Ordovician volcano-sedimentary units. Combined field, lithological, structural, mineralogical and geochemical data for the Cambrian carbonate-hosted mineralization of the Amensif deposit is compatible with it being a polymetallic carbonate replacement deposit.

# East Antarctica in Gondwana: the significance of eastern Dronning Maud Land for the assembly of Gondwana's heart

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East Antarctica formed by amalgamation of a number of cratons along distinct Ediacaran mobile belts, including the ~ 600–500 Ma East African-Antarctic orogen (EAAO) and the Kuunga orogen that apparently converge in Dronning Maud Land (DML). In central DML, the major Forster Magnetic Anomaly separates rocks with Grenville-age protolith ages of ~ 1130–1000 Ma to the west, from rocks with Early Neoproterozic protolith ages ~ 1000–930 Ma to the east. The Forster Magnetic Anomaly is therefore interpreted as a suture. New field-work during two recent international expeditions, *Geodynamic Evolution of East Antarctica* (GEA) I + II, and the first geoscientific results reveal a complex tectonic architecture between Sør Rondane and central DML. East of the Forster anomaly, the magnetic anomaly pattern changes significantly and typical Maud-type crust is no longer present. GEA II targeted a range of nunataks between Sør Rondane and central DML that had never been visited previously (from Blåklettane and Bergekongen in the east to Urna and Sørsteinen in the west). These nunataks are dominated by medium- to high-grade metasedimentary and metavolcanic rocks of possibly Neoproterozoic age, including abundant marble and graphite schists. Sør Rondane in eastern DML, is dominated by two distinct blocks separated by the dextral Main Shear Zone. The northwestern block appears as part of the EAAO or the Kuunga orogen, where new SHRIMP zircon data from metamorphic rims provide ages of ~ 560 Ma. The southeastern block is made up of a TTG terrane, which provides 12 new zircon crystallistation ages ranging from 1000 to 930 Ma. The TTG terrane has predominantly oceanic affinities and the wide range of ages might indicate long-lasting accretionary tectonics. The TTG terrane shows in part a limited tectonic overprint and could be the southeastern foreland of the EAAO or the Kuunga orogen. Close to the contact of the two blocks, grey geisses and augen-gneisses gave zircon crystallization ages of ~ 750 Ma, ages which were previously unknown from the EAAO. The Forster anomaly therefore separates distinctly different parts of the EAAO: a) a reworked, mainly Grenville-age crust to the west (the overprinted margin of the Kalahari craton) and b) a part of the orogen dominated by Neoproterozoic accretionary tectonics to the east. This difference is also reflected in the geochemistry of voluminous late-tectonic granitoids across the belt.

# From Rodinia to Gondwana with the 'SAMBA' model

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In a model published a few years ago, Johansson (2009) proposed that Baltica, Amazonia and West Africa formed a single coherent landmass from at least 1800 Ma to 800 Ma, and perhaps until 600 Ma, with the (present-day) northwest side of Amazonia attached to the southwest side of Baltica (along the Transeuropean suture zone), and the west coast of West Africa attached to the southern (Black Sea–Caspian Sea) margin of Baltica. In this configuration, the 'SAMBA' (South America–Baltica) model, the geology of the three now dispersed cratons forms a coherent pattern, with Archean nuclei surrounded by early Palaeoproterozoic (2.0–2.2 Ga) orogenic belts in the 'east', and successively younger orogenic belts that can be followed from Baltica to Amazonia in the 'west'. As parts of the Columbia supercontinent, SE Laurentia, SW Baltica and SW Amazonia formed a curved active margin facing an open ocean from 1900 Ma to 1250 Ma. After that, Baltica, together with Amazonia and West Africa, rotated at least 75° clockwise relative to Laurentia and collided with its present-day southeast margin, as part of the process leading to the formation of Rodinia.

In this model, Baltica plus the Proto-Andean margin of South America would form the conjugate margin of Laurentia's Grenville margin, as proposed by Dalziel (1997). With the Kalahari craton close to SW Laurentia (Loewy et al., 2011), followed by the Congo and Tanzania cratons of Africa and the Sao Fransisco and Rio de la Plata cratons of South America, all these cratons would be part of Rodinia, but would still be separated from Amazonia by a wide Brasiliano ocean embayment. East Antarctica, Australia and India are placed west of Laurentia in a SWEAT configuration (Moores, 1991), and northern Siberia attached to northern Laurentia, following either Condie and Rosen (1994) or Rainbird et al. (1998). By rotating the African and eastern South American cratons ~90° counterclockwise around a pole located close to the Laurentia–Kalahari junction, and East Antarctica, Australia and India ~120° counterclockwise around a pole located inside the Kalahari craton, all relative to a fixed Laurentia, these cratons move from a Rodinia to a Gondwana configuration. These rotations open up the Proto-Pacific ocean, close the Brasiliano ocean, and both open and close the intervening Adamastor and Mozambque oceans, creating the various Brasiliano and Pan-African fold belts in the ensuing collisions. The maximum plate velocity, ~ 7.5 cm/year (15,000 km in 200 Ma), will occur along the outer periphery of this rotation, thereby explaining the formation of large amounts of juvenile Neoproterozoic continental crust within the oceanic Arabian–Nubian sector of the Pan-African orogen.

The model outlined above is a somewhat refined version of the Li et al. (2008) model of Rodinia and the original model of Hoffman (1991) for the transition from Rodinia to Gondwana, and was recently published by Johansson (2014).

NB for details of references please see Johansson, Å., 2014. From Rodinia to Gondwana with the 'SAMBA' model – A distant view from Baltica towards Amazonia and beyond. Precambrian Research 244, 226-235.

*North meets South*

# Palaeofloristics of the Kamthi Formation (Late Permian/ Early Triassic), India: a review

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Indian Lower Gondwana sequence comprises the Talchir (Asselian), Karharbari (Sakamarian), Barakar (Artinskian- Kungurian), Barren Measures (Guadalupian) and Raniganj (Lopingian) formations, which are well exposed in Damodar basin, West Bengal. However, the post-Barakar sequence is marked by the coal-absent Kamthi Formation in the Wardha, Godavari (south-eastern India) and Mahanadi (eastern India) basins, the Bijori Formation in the Satpura basin (central India) and the Pachhwara Formation in the Rajmahal basin (eastern India). The Kamthi, Bijori and Pachhwara formations are traditionally correlated with the Raniganj Formation. The name "Kamthi" was first coined by Blanford (1868) after 'Kamptee', a military station near Nagpur, Maharashtra, in the Wardha basin. The Kamthi Formation is characterized by red and grey argillaceous sandstones and conglomerates with interstratified red shales. The status of the Kamthi Formation has been controversial. Some workers have divided it into Lower and Upper members on the basis of lithology, mineralogy and palynology, the Lower Member being equivalent to the Panchet Formation (Early Triassic) and the Upper Member to the Supra-Panchet/ Mahadeva Formation (Late Triassic). Other workers have divided the Kamthi Formation on the basis of flora. According to these workers the megafossils of the Lower Kamthi Formation include the orders Filicales, Lycopodiales, Equisetales, Sphenophyllales and Glossopteridales, representative of typical Glossopteris flora and indicating a late Permian age, while the Upper Kamthi Formation shows the presence of the elements of Dicroidium flora and indicates an Early Triassic age. Some workers consider the Kamthi, Bijori and Pacchwara formations younger than the Raniganj Formation on the basis of the lack of coal seams. Plant fossils from the Kamthi Formation of the Ib-River and Talcher coalfields, Mahanadi basin, belong to orders Lycopodiales (*Cyclodendron*), Equisetales (*Schizoneura, Raniganjia* and *Bengalia*), Sphenophyllales (*Trizygia* and *Benlightfootia*), Filicales (*Neomariopteris* and *Dichotomopteris*), Cordaitales (*Noeggerathiopsis, Cordaites, Euryphyllum* and *Kawizophyllum*), Cycadales (*Macrotaeniopteris*), Ginkgoales (*Ginkgoites*), Coniferales (*Buriadia*) and Glossopteridales (*Glossopteris, Surangephyllum, Gangamopteris, Palaeovittaria, Ottokaria, Senotheca, Scutum* and *Vertebraria*). In the Wardha basin, plant fossils recorded from the Kamthi Formation of the Kamptee and Wardha Valley coalfields comprise the order Equisetales, Filicales, Glossopteridales and Cordaitales. From Godavari Graben, scarce plant fossils belonging to the order Equisetales, Glossopteridales and Cordaitales are recorded from Manuguru and Nagpur areas and the Chintalpudi sub-basin. The Glossopteridales dominate the assemblage. The flora from Kamthi Formation of the Wardha and Godavari basins represents a typical Glossopteris floral assemblage and indicates a Late Permian (Lopingian) age.

The rich and diversified floral assemblage of the Kamthi Formation indicates that climatic conditions during this period were suitable for luxuriant plant growth, i.e., warm and humid. The red-bed facies of the ferruginous sandstones indicates seasonal variability of dry spells, which could be one of the reasons for the non-formation of coal during this time.

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# Ediacaran–Middle Paleozoic oceanic voyage of Avalonia from Baltica via Gondwana to Laurentia: paleomagnetic, faunal and geological constraints

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Current Ediacaran–Cambrian, paleogeographic reconstructions place Avalonia, Carolinia and Ganderia (Greater Avalonia) at high paleolatitudes off northwestern Gondwana (NW Africa and/or Amazonia), and locate NW Gondwana at either high or low paleolatitudes. All of these reconstructions are incompatible with 550 Ma Avalonian paleomagnetic data, which indicates a paleolatitide of 20–30ºS for Greater Avalonia and orientation with the present-day southeast margin on the northwest side. Ediacaran, Cambrian and Early Ordovician fauna in Avalonia are mainly endemic, which suggests that Greater Avalonia was an island microcontinent. Except for the degree of Ediacaran deformation, the Neoproterozoic geological records of mildly deformed Greater Avalonia and the intensely deformed Bolshezemel block in the Timanian orogen extending into eastern Baltica, raise the possibility that they were originally along strike from one another, passing from an island microcontinent to an arc–continent collisional zone, respectively. Such a location and orientation is consistent with: (i) Ediacaran (580–550 Ma) ridge–trench collision leading to transform motion along the back-arc basin; (ii) the reversed, ocean-to-continent polarity of the Ediacaran cratonic island arc recorded in Greater Avalonia; (iii) derivation of 1–2 Ga and 760–590 Ma detrital zircons in Greater Avalonia from Baltica and the Bolshezemel block (NE Timandies); and (iv) the similarity of 840–1760 Ma $T_{DM}$ Hf model ages of pre Uralian-Timanian detrital zircons and Nd model ages from Greater Avalonia. During the Cambrian, Greater Avalonia rotated 150º anticlockwise, ending up off northwestern Gondwana by the beginning of the Ordovician, after which it migrated orthogonally across Iapetus to amalgamate with eastern Laurentia by the Late Ordovician–Early Silurian.

# SHRIMP U–Pb ages of zircon from metasedimentary rocks and a granitic dyke in the Wilson terrane, Northern Victoria Land, Antarctica

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The U–Pb isotopic compositions of zircon from three metasedimentary rocks and a granitic dyke in the Wilson terrane, Northern Victoria Land, were measured using a SHRIMP-II ion microprobe as a preliminary constraint on their depositional and metamorphic ages. The Wilson terrane, together with the Bowers and Robertson Bay terranes to the northeast, is located at the Pacific end of the Transantarctic Mountains. This terrane is primarily composed of Precambrian–Early Paleozoic medium- to high-grade quartzo-feldspathic schists, gneisses, and migmatites as well as Cambro-Ordovician intrusive rocks. The first sample 121214-05 was collected from quartzite layers alternating with biotite schists near Mt. Levick in the Deep Freeze Range, situated along the middle of the Wilson terrane. The sample yielded 50–200 μm long zircon crystals showing variable internal zonation. Eighty-five spots were analyzed from 81 detrital zircon crystals, and their U–Pb age distribution is characterized by major populations at ~600 Ma, ~1.1 Ga, and 2.2–2.5 Ga with a prominent absence of middle Neoproterozoic (700–900 Ma) and middle to late Mesoproterozoic (1.2–1.7 Ga) zircons. The median age of youngest group is 587 Ma, probably representing the maximum depositional age of the quartzite layers. Banded-gneiss samples 121214-01 and 121217-03A consisting of biotite, K-feldspar, plagioclase and quartz with or without pyroxene were collected from near the Capsize Glacier in the Deep Freeze Range and Mt. Murchison at the northeastern margin of the Wilson terrane, respectively. Their U–Pb age distributions of zircon are similar to those of sample 121214-05 except for conspicuous early Cambrian populations in sample 121217-03A. The weighted mean $^{206}Pb/^{238}U$ age of the early Cambrian fraction of zircon is 534 ± 11 Ma ($t\sigma$). This can be interpreted either as the timing of metamorphism in the banded gneiss or as an input of young syn-orogenic sediments progressively towards the northeastern margin. The last sample 121217-03B was collected from a granitic dyke intruding the banded gneiss, sample 121217-03A of this study. Zircon crystals in the sample are euhedral and up to 400 μm in length, mostly with concentric zonation and apparently inherited cores. The weighted mean $^{206}Pb/^{238}U$ age of outer rims is 483 ± 5 Ma ($t\sigma$), probably representing the timing of late- to post-orogenic magmatism. In summary, our preliminary geochronological data may reflect: (1) a series of geological processes involving the late Neoproterozoic sedimentation, early Cambrian metamorphism, and late- to post-orogenic magmatism in the Wilson terrane; or (2) stratigraphic successions younging towards the northeast, metamorphosed possibly between 534 Ma and 483 Ma.

# Non-steady state history of Paleozoic to Mesozoic continental arc magmatism in southern Mexico

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Southern Mexico, located in a marginal position with respect to Pangea during amalgamation and dispersal of the supercontinent, has been influenced by subduction-related processes since the Devonian. A compilation of igneous rock U-Pb crystallization ages and detrital zircon ages suggests that magmatic arc activity in southern Mexico in the period between 400 and 80 Ma fluctuated in a non-steady state manner. Continental arc magmatism was initiated in the Devonian and did not entirely shut off throughout this time interval. Three pulses of intense magmatic activity can be identified: Carboniferous to Permian (310–230 Ma), Jurassic (200–160 Ma), and Cretaceous (150–120 Ma). The respective arc phases are of unequal duration and are separated (i) in time, by periods of low magmatic activity characterized by a low abundance of igneous zircons, as well as (ii) in space, shifting from an outboard to a more inboard, and back to an outboard position. Geological evidence from the Acatlán and Ayú complexes in southern Mexico indicate that the deformational style and the composition of subduction-related igneous rocks in southern Mexico also vary episodically and seem to be strongly correlated with the temporal record of arc activity. In terms of deformation, the Carboniferous to Permian arc phase is (i) preceded by Middle to Late Devonian shortening, associated with subduction erosion of the forearc and HP-metamorphism, and (ii) accompanied by extension, as evidenced by the exhumation of HP-rocks and local back-arc formation during the Carboniferous, as well as transtensional tectonics in the Early Permian. Similarly, local shortening, uplift, and cooling during the Late Triassic, recorded by $^{40}Ar/^{39}Ar$ ages in the Acatlán complex, leads up to the Jurassic arc phase, whereas extensional tectonics, manifested by back-arc rifting (Arteaga basin), characterize the deformation during the Jurassic flare-up event. Geochemically, at the onset of the Carboniferous–Permian and Jurassic arc phases, respectively, Sm/Yb ratios of igneous rocks increase, which indicates the formation of crustal arc roots, and (initial) $\varepsilon Nd_i$ spread out to lower values, indicating an associated higher degree of crustal melt production. During extensional phases, a juvenile, depleted-mantle source with $\varepsilon Nd_i$ of +2 to +7, depleted mantle model ages ($T_{DM}$) < 0.8 Ga and elevated Nb/La and Nb/Zr, is episodically tapped. These observations suggest a cyclic evolution of the southern Mexican continental arc system and a strong link between crustal development and magmatic arc activity.

*North meets South*

# Euler pole migration during the formation of Pangea: the three-stage collision of the Gondwana plate with Laurussia

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The formation of Pangea resulted in closure of the Proto-Tethys and Rheic oceans and orogenic belts spanning from America to Europe and to Asia. The prolonged plate convergence between Gondwana and Laurussia was accompanied by the concomitant opening of Paleo-Tethys and Neo-Tethys in the Devonian and Permian, respectively. Thus, large scale plate convergence between Gondwana and Laurussia was characterized by repeated localized phases of continental break-up.

Here we present Euler pole solutions of the plate motion of Gondwana relative to fixed Laurussia between 430 and 250Ma using large scale deformation patterns of middle to late Paleozoic orogens. Our model explains the temporal and spatial distribution of collisional events. Furthermore, the temporal migration of the rotational axis for the relative plate motion between Gondwana and Laurussia caused the formation of spreading centres due to geometrical constraints on the sphere.

Our proposed three-stage model is as follows:

Stage one (Late Silurian–Early Devonian): initial collision of the Amorican spur of the Gondwana plate is coeval with orogenies along the Proto-Tethys suture and ongoing subduction of the Rheic Ocean east and west of the evolving Variscides, respectively.

Stage two (Devonian–Late Carboniferous): ongoing subduction of the Rheic Ocean west of the Variscan orogen caused the westward migration of the Euler pole, which initiates the opening of Paleo-Tethys in the east.

Stage three (Permian): after the termination of the Variscan orogeny in Central Europe at ~ 300 Ma the continued shift of the Euler pole resulted in the terminal convergence between Gondwana and Laurussia along the Mauritanides–Alleghanides–Ouachita–Marathon belt. Again, the coeval formation of the Central European extensional province and the opening of Neo-Tethys is a geometrical consequence of the migration of the Euler pole.

We demonstrate that during the formation of a supercontinent, the process of Euler pole migration explains both the continued plate convergence along some sections of the plate boundary and coeval divergence (and opening of new oceans) in other regions of the same plate.

# Spatial-temporal distribution of the Early Permian Tarim large igneous province and interaction between mantle plume and lithospheric mantle

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Early Permian basalts in the Tarim basin of northwestern China covered more than 250,000 $km^2$ and constitute a large igneous province (Tarim LIP). We studied the spatial–temporal distribution and conducted systematic analyses of geochemistry and Sr-Nd-Pb-Hf isotopic components of the igneous rock units from the outcropping sections and drill holes in the Tarim basin (Li et al., 2011, 2012). The sequence of magmatism in the central and western parts of the Tarim basin are basaltic lava in the Kupukuziman and Kaipaizileike formations (290–285 Ma), followed by layered mafic-ultramafic rock, mica-olivine pyroxenite breccia pipe, diabase and ultramafic dyke, quartz syenite, quartz syenite porphyry and bimodal dykes (284–274 Ma). In general, the basaltic lavas have low Mg# and Zr/Nb, have high Ti, are enriched in LILE, LREE and Nb with Nb-Ta anomalies, and have high $(^{87}Sr/^{86}Sr)_i$ and low εNd(*t*), indicating that the basalts were probably derived from an OIB-like mantle reservoir with minimal crustal contamination. Geochemically, three distinct types of basalt with specific distributions are recognized in the Tarim LIP. Group 1(a, b) basalts and Group 2 basalts are genetically linked to their spatial distribution, Group-1a basalts covering a large part of the Tarim LIP and probably corresponding to the Kaipaizileike Formation. Group 1b basalts are limited to the Sishichang section, belonging to the Kupukuziman Formation of the Yingan section and He drill hole basalts. Group 2 basalts are located in the Tabei uplift; they have a specific spatial distribution and distinct geochemistry, perhaps due to distinct evolved magmatic and emplacement processes during the rise of the mantle plume and interaction with lithospheric mantle in the Tarim basin. The Tarim basalts, with an OIB-like source, yet with distinct input from an enriched continental lithosphere mantle, resemble basalts of the Permian Emeishan and Siberian LIPs, suggesting a plume origin. We suggest that plume melts penetrated into the Tarim continental lithospheric mantle, producing a coherently depleting trend in Sr-Nd-Hf isotopic compositions from the earlier erupted Group 1b, 1a and 2 basalts to the later mafic-ultramafic intrusive rocks. This implies a rising mantle plume beneath the Tarim block, with subsequent lithospheric interaction and continuous injection of depleted mantle components into the evolved magma source to produce the various igneous rock units of the Tarim LIP. This study was funded by National Basic Research Program of China (2011CB808902 and 2007CB411303).

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# Magmatism and tectonic evolution of Southeastern China: constraints from zircon U-Pb geochronology, geochemistry and Sr-Nd-Hf isotopes of Late Mesozoic granitoids

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Late Jurassic and Early Cretaceous felsic magmatic rocks (180–85 Ma) are widely distributed in South China, intruding the Precambrian crystalline basement and Paleozoic strata. Zircon U-Pb dating, geochemical characteristics and Sr-Nd-Hf isotopes of these granitoids were studied systematically. Our results (Li et al., 2013) reveal three distinct episodes according to spatial-temporal distribution and chemical characteristics. The first episode granitoids (~ 175–160 Ma) are mainly granitic porphyry with an adakitic signature, formed in a compressional setting. The second episode granitoids (~160–145 Ma) are mainly granodiorites with a transitional tectonic setting signature. The third episode granitoids (~130–123 Ma) are mainly aluminous A-type granites related to continental extensional and thinning. The three magmatic phases represent a continuous tectonic transition from compression to continental extension. All these rocks show Y/Nb ratios >1.2, high initial $^{87}Sr/^{86}Sr$ ratios and low εNd($t$), and are depleted in Nb, Ti and Sr, indicating a crustal origin with subduction zone signatures. However, they have varied εHf values, suggesting different magma sources. We argue that the granitoid bodies from Southeastern China might have been derived from the Mesoproterozoic metamorphic basement rocks through partial melting induced by mantle-derived magma in a regional geological environment controlled by the subduction and collisional process of the Western Pacific plate with the Eurasian plate, and multi-plate convergence during the Mesozoic. A regional geological comparison indicates that the geochemical features of the A-type granites in the Eastern Qinzhou-Hangzhou tectonic belt are comparable with the Lower Yangtze A-type granites, but are distinct from the Late Cretaceous A-type granites (105–85 Ma) distributed along the southeastern coastal area of South China. We correlate the formation of the first and secondary episodes granitoids (175–145 Ma) to inland compression associated with the subduction and collision of the paleo-Pacific plate. In contrast, the A-type granites (130–123 Ma) resulted from lithospheric thinning and continent extension accompanied by slab roll-back of the paleo-Pacific plate following the subduction-collision event.

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# What drives the formation of mantle plumes and superplumes?

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Mantle plumes and superplumes (broad lower mantle seismic low-velocity zones, or mantle superswells, that can drive "secondary" mantle plumes above them) are widely believed to be features caused by thermal anomalies or thermal instabilities around the core–mantle boundary that are independent of the plate tectonic system, and are relatively stable with respect to the Earth's core and the rotation axis. It is also believed by some that the antipodal superplumes in the present-day lower mantle could have been a stable feature since Earth's early history. However, geodynamic modelling suggests that slab subduction into the lower mantle could promote the formation of plumes. Here we argue for a case that the formation of both antipodal superplumes (along with secondary plumes above them) and some isolated plumes in the lower mantle are linked to slab subduction. It is widely accepted that the positions of the present-day antipodal Pacific and African superplumes align with the position of the supercontinent Pangea before it broke up. The current global large igneous province (LIP) record also indicates that global plume intensity intensified soon after Pangea assembly and peaked during its break-up, thus permitting spatial and temporal linkages between the Pangea supercontinent and antipodal superplumes. A similar supercontinent–supercontinent coupling has been documented for the time of the Late Precambrian supercontinent Rodinia, and the sub-Rodinia superplume appears to have travelled together with the supercontinent from higher latitude to the paleo-equator through a true polar-wander event. Supercontinent history before 1 Ga is yet unclear, but the global plume intensity appears to show a cyclic nature similar to that during the post-1 Ga time. It has thus been proposed that circum-supercontinent subduction of cold slabs to the lower mantle may have caused the formation of antipodal domes of hot and dense lower mantle, or superplumes, that were aligned with the positions of the respective supercontinents. Preliminary geodynamic modelling has demonstrated the feasibility of such a mechanism. A similar mechanism could also cause the formation of lone plumes away from the superplumes, such as the late Cenozoic Hainan plume. Both primitive Pb-Nd-Os isotopic and seismic tomographic data indicate that the Hainan plume originated from the lower mantle, and seismic tomography also shows the presence of subducted cold slabs surrounding it. We thus suggest that circular descending cold slabs might be the main mechanism that drives the formation of both superplumes and lone plumes in the lower mantle.

# The Givetian (Middle Devonian) conodont succession from the Spanish Pyrenees: a reference standard for Gondwana and beyond

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The International Subcommission on Devonian Stratigraphy has agreed on subdividing the Givetian Stage into three substages (Lower, Middle and Upper) based on globally applied conodont biostratigraphy. This zonal arrangement has been established on the sequential occurrence of parts of the biostratigraphical units in different sections, mainly from Gondwana, Laurentia and Baltica, and their subsequent correlations. Until now no single region has been thought to show sufficient detail to serve as a standard reference. However, thorough study of four selected sections in the southern part of the Spanish Pyrenees has provided one of the best continuous conodont sequences in the world; it contains all the index taxa for identifying the Givetian limits and all the zonal subdivisions. Consequently, this area is crucial for testing the intended threefold subdivision of the Givetian Stage and for accurate intrazonal correlations.
The sequence starts with the entry of *Polygnathus hemiansatus*, the index of the Givetian lower boundary and of the *hemiansatus* Zone. It is followed by the entry of *P. timorensis,* the index of the *timorensis* Zone. These two zones are the basic subdivisions of the Lower Givetian. The lower boundary of the next zone, the *rhenanus/varcus* Zone, coincides with the lower boundary of the Middle Givetian. Both indexes, *P. rhenanus* and *P. varcus*, have been identified in the Pyrenees. The next index *P. ansatus* follows above the previous conodont sequence. The upper part of the Middle Givetian is represented by strata assigned to the *semialternans/latifossatus* Zone; both indexes have been identified in the Pyrenean sections, so that the Middle Givetian threefold subdivision is recognised in the Pyrenees and its conodont record permits further characterization and accurate global correlations. The lower boundary of the Upper Givetian coincides with the lower limit of the *hermanni* Zone, which is defined by the entry of *Schmidtognathus hermanni.* The sequential entry of *P. cristatus* above this serves to subdivide this zone into two parts. The base of the next zone, *disparilis* Zone is defined by the entry of *Klapperina disparilis* and is further subdivided into lower and upper by the entry of *P. dengleri*. The uppermost zone, the *norrisi* Zone, defined by the entry of *Skeletognathus norrisi* is identified in all Pyrenean sections and facilitates global discussions on the problematic Givetian/Frasnian transition and its different zonal approaches.
In brief, the Spanish Pyrenees is a unique region where all the standard Givetian subdivisions can be thoroughly studied in a complete sequence, and thus constitutes a global reference for Givetian studies.

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# Cadomian orogenic processes - evidence from U-Pb ages and the εHf notation of detrital and magmatic zircon

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The Cadomian orogen in the NE Bohemian and northern Armorican massifs shows a distinct orogenic zoning from recent NW to SE consisting of (i) an outboard continental crustal unit comprising Neoproterozoic rocks associated with ~ 2.0 Ga old Icartian basement, (ii) a magmatic arc and back-arc basin, (iii) a foreland or retro-arc basin, respectively, and (iv) the passive margin of the back-arc basin. New U-Pb data for detrital zircon in Neoproterozoic to Fortunian siliciclastics from the Schwarzburg antiform in the Saxo-Thuringian Zone (NE Bohemian Massif) identify the West African craton as the hinterland for the Cadomian orogen, demonstrated by zircon age populations in the ranges 1.8–2.2, 2.5–2.7, 3.0–3.1, and 3.4–3.5 Ga. The dominant zircon population (~50–70% in each sample) is derived from Cadomian magmatic arc activity in the interval 570–750 Ma respectively (Linnemann et al., 2014). The magmatic activity of the Cadomian arc became extinct at ~ 570 Ma. Closure of the back-arc basin by arc-continent collision occurred between ~ 570 and 542 Ma with the formation of a foreland (retro-arc) basin. A short-lived remnant basin existed between ~542 and 540 Ma. Granitoid plutonism at 539 to 540 Ma documents the final pulse of the Cadomian orogeny. Hf isotopes, calculated $\varepsilon Hf_i$ values, and $T_{DM}$ model ages from detrital and magmatic zircon show, that during the ~180 Ma long Cadomian magmatic arc activity juvenile arc magmas became contaminated by the recycling of Eburnian and Archaean crust. Mixture with continental crust is always present. The inferred geotectonic setting is a continental magmatic arc during the Neoproterozoic, developed on stretched Archaean and Palaeoproterozoic (Eburnian) crust. In the case of West African crustal evolution it can be demonstrated that in most cases a 2.5 to 3.4 Ga old basement was recycled during Eburnian orogenic processes (~ 1.8–2.2 Ga). Archaean 2.5–2.9 Ga old magmas recycled a 3.0 to 3.4 Ga old crust. Zircons with an age of 3.0–3.1 and 3.4 Ga are derived from juvenile magmas. Two zircons aged at 2779±22 and 3542±28 Ma imply recycling of pre-existing Eo-Archean to Hadean crust, with $T_{DM}$Hf model ages of 3.98 and 4.29 Ga.

Linnemann, U., Gerdes, A., Hofmann, M., Marko, L. 2014. The Cadomian Orogen: Neoproterozoic to Early Cambrian crustal growth and orogenic zoning along the periphery of the West African Craton—Constraints from U–Pb zircon ages and Hf isotopes (Schwarzburg Antiform, Germany). Precambrian Research 244, 236-278.

# The dispersal of the Gondwana supercontinent mirrored by U-Pb ages of detrital zircon – a view from the circum-Atlantic and Mediterranean orogens

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Early destruction of the Gondwana supercontinent started in Cambrian time by the dispersal of various terranes and micro-continents at its northern periphery. Rift, drift and amalgamation of peri-Gondwanan terranes is the result of opening and closure of the Iapetus, Rheic, and Palaeo-/Neo-Tethys oceans before final destruction by the opening of the Atlantic Ocean and related processes. Rift, rip-up, drift, and amalgamation of Gondwana-derived terranes in pre-Atlantic time is dominated by subduction-related processes such as slab-pull, ridge-subduction, arc–continent and continent–continent collision. Pre-Pangean dispersal is caused by an interaction of slab-pull and superplume formation. Dispersed terranes yield a fingerprint of their origin characterised by the U-Pb ages of detrital zircon in clastic sediments and by inherited zircon in magmatic rocks. Based on that it is possible to establish zircon provinces along the Gondwanan margin, which are the ultimate tool to trace terranes from their recent position in circum-Atlantic and Mediterranean orogens back to their origin.

# Sediment sources and basin analysis of the Central West Gondwana basin complex

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Pioneering stratigraphic correlations by Keidel, du Toit, and Cahen in the first half of the 20th century highlighted significant similarities between Gondwana sequences in south-central Africa and eastern South America. Based on new stratigraphic basin analysis of the Congo–Kalahari, Paraná and Cape–Karoo basins, sediment provenance (U-Pb detrital zircons) and thermochronology (e.g., AFT and (U-Th)/He data on basement terrains), we revisit these early correlations and test the interconnectivity of these basins in the framework of a large (mega-) Central West Gondwana basin (CWGB).
Following Pan African–Brasiliano amalgamation of Gondwana (530–650 Ma), the earliest Paleozoic (Cambrian?) continental red-bed sediments (<540 Ma), derived from the north, were deposited regionally across the Central African and Kalahari shields. Zircons from these sequences have a predominant 950–1100 Ma age population, most likely sourced from the Oubanguides–Central Sahara–Sergipano belts that extend from north-central Africa to northeastern Brazil. Thereafter, Early Paleozoic (Ordovician–Devonian) subsidence first occurred along the southwestern margin of Gondwana, linking the Paraná and Cape basins. Equivalent age sequences are absent in the Congo Basin, indicating a prolonged hiatus and erosion during the Early Paleozoic. This is consistent with the onset of accelerated exhumation of the Tanzanian craton in east-central Africa (~ 7±2 km of unroofing between 460 and 220 Ma). By contrast, succeeding Carboniferous–Permian and Triassic successions are similar across the entire CWGB, albeit derived from different sources, including glacial and deglaciation sequences overlain by recurring terrestrial and arid red-bed sediments. This regional cycle of subsidence during the Late Paleozoic–Early Mesozoic can possibly be linked to long wavelength flexure of the Gondwana continental lithosphere related to the Mauritanian–Variscan and Cape–Ventana orogens along the north-western and southern margins of Gondwana at ~ 300 Ma and 250 Ma, respectively. Thereafter, Jurassic–Cretaceous sedimentation across the CWGB culminated in widespread deposition of aeolian dune sandstones (again red-beds), derived dominantly though northerly paleo-winds blowing from Tethys southward across the supercontinent, episodically interrupted by eruptions from Large Igneous Provinces during the initial phases of Gondwana break-up (at 200 Ma, 183 Ma, and 132 Ma). In addition, a number of tiny zircons in the Congo Basin, dated at 190 Ma and 240–290 Ma, are interpreted as sourced from the proto-Andes (e.g., the Choiyoi and Chon Aike provinces), with comparable zircon ages in air-fall tuffs throughout the CWGB (including the Paraná, Kalahari and Karoo basins), which must have been transported by northeasterly flowing, high-altitude wind systems. The shared sedimentation and climatic history of all these basins was finally disrupted following the Early Cretaceous opening of the South Atlantic and the Kalahari epeirogeny (with ~ 2–7 km of exhumation across the Kalahari plateau of south-central Africa between 120 Ma and 80 Ma), after which the Congo Basin records only intermittent phases of lacustrine and fluvial deposition.

We present these inter-continental correlations with the aim of improving our understanding of the geodynamic evolution of central Gondwana, and we plan to expand this analysis with further fieldwork in Tanzania, Madagascar and India.

# P–T–t constraints and geodynamic implications from blueschists and eclogites of the north Gondwanan margin in Iberia (Malpica–Tui complex, Galicia)

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The Malpica–Tui complex (MTC) in the NW Iberian Massif consists of rocks of Gondwanan affinity. It preserves evidence of late Devonian high-pressure (HP) metamorphism varying from eclogite (P~ 26 kbar and T~ 650 °C) to blueschist facies conditions (19–22 kbar and 460–560 °C). Thermodynamic modelling on the HP rocks reveals a P-T path characterised by a sub-isothermal decompression to ~10 kbar, at 480°C in the blueschist-facies rocks and 650 °C in the eclogites, followed by cooling to ~5 kbar at 380°C and 500 °C, respectively. New $^{40}Ar/^{39}Ar$ data corroborate a minimum age of ~ 370 Ma for the subduction-related HP metamorphism. Subsequent decompression to pressures of about 10 kbar started at ~ 360 Ma and was contemporaneous with thrust-and-fold nappe tectonics and intrusion of early Variscan granodiorites dated at ~ 350–340 Ma. Final exhumation due to the late orogenic gravitational collapse of the orogenic pile, associated with the main detachment system, has been constrained from ~ 340-335 Ma to 320±5 Ma, which is the age of the syntectonic leucogranites constrained by U-Pb (López-Moro *et al.*, this volume), emplaced in the autochthon of the MTC.

Peak P–T conditions correspond to an approximate depth of 70–80 km and a geothermal gradient of 6–7°C $km^{-1}$, attributable to a cold subduction zone. Age differences between the HP event and the beginning of the post-nappe tectonics indicate that the exhumation of the MTC lasted about 15–20 Ma. The nearly isothermal decompression from ~ 26 to 10 kbar provides a vertical component exhumation rate of about 2–2.5 mm/year from ~ 80 to 30 km depth. The last stages of exhumation from 8 to 5 kbar occurred within a period of about 10–15 Ma (from 350 to 340–335 Ma) and from ~ 480–380°C, indicating a cooling rate of 7°C $Ma^{-1}$ (or a geothermal gradient of 10°C $km^{-1}$). These rates suggest that exhumation took place in two stages: (1) a fast, almost isothermal one, followed by a (2) slower episode with substantial cooling once the rocks reached the upper crust.

# An allochthonous sheet over the Iberian Central System? P–T constraints in the Barrovian orogenic section of Somosierra through pseudosection modelling

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The Somosierra region is located in the eastern Iberian Central System (ICS) and displays an almost complete section of upper and middle crustal rocks representing one of the most internal domains of the Variscan orogen in the Iberian Massif. This region constitutes a landmark for the study of Barrovian metamorphism, and has been the subject of numerous studies over time (e.g. Macaya *et al.*, 1991; Escuder Viruete *et al.*, 1998; Rubio Pascual *et al.*, 2013).
Previous P–T–t paths determined in this region indicate a complex succession of processes during Variscan thickening and exhumation. Classical thermobarometric techniques applied to pelitic assemblages in the garnet, staurolite, sillimanite and sillimanite+Kfs zones show medium-pressure clockwise paths characteristic of mid-crustal levels in collisional orogens (Rubio Pascual *et al.*, 2013). Peak pressure conditions reached during $D_1$ (P~7 kbar; T~500 ºC) are 4–5 kbar higher than those deduced from the thickness of the existing lithostratigraphic series (~6 km). Given that metamorphism was 12–15 km larger than expected for this section. A recently published model explains the overburden by overthrusting of a large allochthonous sheet that might be subsequently thermally weakened and gravitationally extended, and thus was not preserved in the ICS (Rubio Pascual *et al.*, 2013). However, this allochthonous sheet would be preserved towards the northwest of the Iberian Massif, in the so called Galicia-Trás-os-Montes Zone. This domain is formed by a succession of allochthonous units with Gondwanan affinity whose thickness reaches 20 km and is widely represented across the European Variscan belt (Martínez Catalán, 1990).
The thickness and the real existence of this inferred large allochthonous sheet above the ICS is highly sensitive to the accuracy of the thermobarometry. Conventional thermobarometry may provide reasonable results but requires important simplifications and has several limitations. To further refine peak pressure constraints, a detailed study of the metamorphic evolution of representative samples of key mineral zones has been carried out using a pseudosection approach. These new data could help understanding of the Variscan metamorphic evolution in the Somosierra region, as well as refining the proposed geodynamic models.

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# The magmatic response to the Variscan Belt collapse in Iberia. U-Pb LA -ICP-MS ages of syn-kinematic granitoids in the CIZ (Tormes Dome, western Iberia)

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One of the main events linked to orogenic collapse in collisional belts is the generation of crustal melts that cool to form leucogranites, whose crystallisation ages are best constrained by U-Pb dating of magmatic zircon. However, a common problem in dating these rocks is the abundance of xenocrystic zircon inherited from the source rocks or assimilated from the country rocks. Benefits of U-Pb LA-ICP-MS dating include the capability of measuring isotopic ratios in a large number of zircons and, therefore, to be able to obtain precise and concordant ages for the often minor population of magmatic zircons or magmatic domains in polygenetic zircons in order to obtain the crystallisation age of the leucogranites. Additionally, analyses of inherited cores will simultaneously provide constraints on the nature of the crustal protolith from which the leucogranites were derived.

The Tormes Dome in Western Iberia is one of the main outcrops where extension-related crust-derived granitoids are well exposed. Sixty zircons from five different samples of syn-kinematic granitoids were dated. Magmatic ages, from the youngest populations found in each sample range between 318 and 325 Ma, which are in accordance with the ages of other similar syn-kinematic granitoids in western Iberia and provide a tight constraint on the age of the extensional collapse of the orogen. In addition to the magmatic ages, all samples provided a wealth of inherited zircons whose concordant ages cluster into several populations: i) ~ 345 Ma, 2) ~ 395 Ma, 3) ~ 500 Ma, 4) ~ 550-800 Ma, and 5) older minor populations of zircon grains clustering at ~ 1000 and 2000 Ma. All the obtained ages coincide with earlier events in which zircons could be produced and/or age groups found in detrital zircons in the country rocks.

Dating of a large number of zircons in syn-kinematic crust-derived granitoids provides information on the timing of the extensional collapse of collisional orogens and opens a window into the zircon-forming events that could have occurred previously in the same region, as well as into the nature of the rocks that acted as source rocks and partially melted during the extension.

# Detrital zircons from the pre-Silurian rocks of the Pyrenees: geochronological constraints and provenance

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We have carried out for the first time a detrital zircon study in the eastern Pyrenees (Andorra). The four samples selected are from the vicinity of the Upper Ordovician La Rabassa unconformity. Three were sampled just below it, and correspond to quartzites interbedded in the uppermost part of the Jujols Group, a rather monotonous, 1500 m thick, succession composed of a rhythmic alternation of sandstone, siltstone and argillite. The other sample was taken just above the La Rabassa unconformity, from the Bar Quartzite Fm., located in the uppermost part of the Upper Ordovician succession.
A total of 540 laser ablation ICP-MS U-Pb analyses were made, of which 101 were discarded because of their discordance.
The maximum depositional age for the Jujols Group samples based on the youngest detrital zircon population is 478±5 Ma, whereas for the Bar Quartzite Fm. It is 443±6 Ma (Late Ordovician–Early Silurian). All the samples show very similar U-Pb age patterns. The main age populations correspond to Cambro-Ordovician (480–510 Ma), Ediacaran (550–750 Ma), Tonian–Stenian (850–1100 Ma), Paleoproterozoic (1.9–2.1 Ga) and Neoarchean (2.45–2.65 Ga). The absence of a Middle Ordovician age population suggests a lack of sedimentation at this time and confirms the presence of an unconformity at the base of the Upper Ordovician succession, already evidenced by structural, stratigraphic and cartographic criteria. The similar age pattern on both sides of the intra-Ordovician discordance implies that there is no change in the source area of these two series.
The obtained age patterns have also been compared with those from other peri-Gondwanan terrains, such as Sardinia and NW Iberia. Similarity to the Sardinian age distribution suggests that they could share the same source area and were paleogeographically related in Ordovician times, i.e., facing the Arabian-Nubian Shield.

# Structural and geodynamic constraints of Late Ordovician volcanism of the Catalan Pyrenees

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The pre-Variscan basement of the Pyrenees includes evidence of many magmatic episodes represented by different types of granitoids and volcanic rocks, which indicates the complex Palaeozoic geodynamic history of this peri-Gondwana terrane. One of the most significant magmatic episodes is that of Late Ordovician (Caradocian) age, which is represented by several granitic and granodioritic bodies, and volcanic rocks mostly of pyroclastic nature. In the Catalan Pyrenees this magmatism is well represented in the Ribes de Freser and Nuria area, where orthogneisses from the Nuria massif and the Ribes granophyre, both with a similar age of 457 Ma (Martinez et al., 2011), seem to form a calc-alkaline plutonic suite comprising rocks formed at both deeper and shallower levels. The presence of numerous pyroclastic deposits and lavas interbedded with Caradocian sediments, intruded by and immediately above the Ribes granophyre, suggests that this intrusive episode also generated significant volcanism (Martí et al., 1986). The area also hosts an important volume of rhyolitic ignimbrites and andesitic lavas strongly affected by Alpine tectonics and commonly showing tectonised contacts at the base and top of the sequences. These volcanic rocks were previously attributed to the Late Carboniferous late-Variscan volcanism extensively represented in the Pyrenees (Robert, 1980; Martí, 1991). However, new laser-ablation U-Pb zircon geochronology from these rocks has yielded a Late Ordovician age (~455 Ma), similar to that of the plutonic rocks of the same area, thus suggesting a probable genetic relation between them. A palinspastic reconstruction of the Alpine and Variscan tectonic units that affect this area allows us to infer the geometry, facies distribution, original position, and thickness of these volcanic rocks previously attributed to the late-Variscan volcanism, and reveals how they are spatially (and stratigraphically) associated with the previously identified Late Ordovician volcanic rocks. In the light of these new data we speculate on the significance of volcanism to the evolution of Late Ordovician terrains of the Catalan Pyrenees and on the structural and geodynamics constraints of this magmatic episode.

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# Variscan deformation of the Malaguide complex (Betic Cordillera, SW Spain): stratigraphic and structural constraints

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The Malaguide Paleozoic shows strong tectonic deformation and mild metamorphic recrystallization that are absent from the unconformable Mesozoic–Cenozoic cover. There are also marked depositional contrasts between the Paleozoic deep marine successions and overlying sediments that start with Triassic continental red beds. Thus Malaguide rocks were affected by pre-Alpine deformation. Metamorphism of the Malaguide Paleozoic increases downwards and the rocks gradually become similar to those of pre-Mesozoic successions of the tectonically underlying Alpujarride complex. The latter shows a pre-Alpine tectonometamorphic evolution marked by development of two superimposed foliations. However, the pre-Alpine structures in the Malaguide complex, their kinematics, timing and relationships with the tectono-metamorphic evolution at deeper structural levels are still poorly understood. This contribution aims to partially fill this gap, from observations in outcrops close to Malaga and Ardales.

The Malaguide Paleozoic succession shows two parts locally bound by a (not always recognizable) cartographic unconformity between Viséan and older pelagites and turbidites and post-Viséan Culm-like clastic rocks. Pre-Culm deposits form deep marine successions deposited in proximal and distal areas of a Paleotethyan margin. Deposition in proximal areas located towards the NW (in present day coordinates) was dominated by fine-grained clastics and conodont-bearing condensed limestones allowing accurate dating of Ordovician–Devonian beds. Distal areas towards the SE were dominated by undated deep marine turbidites (sometimes calcareous) and pelites belonging to the pre-Carboniferous Morales and Santi Petri formations. The basin became deepest and homogeneous during deposition of Tournaisian–Visean cherts and conodont limestones (Falcoña Fm.).

Pre-Culm deposits record intense contractional deformation, which generated markedly asymmetric, SE-vergent folds ($F_{1v}$). It produced buckling of bedding $S_o$ (as it entered the contractional field of the incremental strain ellipsoid during progressive rotational deformation) and heterogeneous simple shear with shear surfaces lying oblique to originally flat-lying $S_o$ and characterised by top-to-the-SE reverse motion. In the pelites this deformation is associated with the development of a foliation (slaty cleavage $S_{1v}$), roughly axial planar or forming divergent fans with respect to hosting $F_{1v}$ folds, together with a mineral/stretching lineation ($L_{1v}$). Top-to-the-east simple shear is also recorded in stretched conglomerates (S–C tectonites, shear bands, shear fibres on slickenside surfaces). Refolding of early structures ($F_{1v}$, $S_{1v}$, $L_{1v}$) most probably occurred within the framework of the same progressive deformation, as suggested by a general coaxiality of fold structures, producing second phase folds ($F_{2v}$) and a new cleavage ($S_{2v}$, which locally becomes the main foliation), on which a mostly W-plunging lineation ($L_{2v}$) developed. Reverse shear zones also occur in the form of post-Viséan E-vergent Variscan thrusts (Ardales) between proximal (hanging wall) and distal (footwall) continental margin successions.

The Culm-like coarse- to fine-grained deep marine clastics (Almogía Fm., Serpukhovian-Bashkirian) are covered by Late Carboniferous olistostromes (Marbella Fm., post-Bashkirian). These strata are affected by at least one shortening event, locally recorded by the development of a foliation that appears to correspond to $S_{2v}$ of the pre-Culm deposits. Subsequent late Variscan extension was dominated by roughly E–W stretching.

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# Timing of deformation and anatectic events in high-grade metamorphic Alpujarride rocks (Internal Domain of the Betic orogen, Southern Spain)

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In the Upper Alpujarride Torrox Unit granitic meta-pegmatite dykes (leucogneisses) bearing andalusite crosscut the main foliation of the enclosing muscovitic schists and gneisses. The main foliation is named $S_2$ because there is a previous relict foliation $S_1$ in the schists. $S_2$ was accompanied by post-kinematic andalusite porphyroblasts, which were later deformed along an $S_3$ foliation frequently parallel to $S_2$, and associated with the syn-kinematic growth of fine-grained kyanite and fibrolite after andalusite (Sánchez-Navas et al., 2012). The meta-pegmatitic dykes are also affected by the $S_3$ foliation, defined by fibrolite after andalusite.
U-Pb SHRIMP zircon dating from one representative leucogranitic meta-pegmatite dyke gave pre-Variscan ages in crystal cores and late-Variscan ages in dark cathodoluminiscence rims rich in U (around 4000 ppm). Some rim analyses provided Mesozoic–Paleogene and Early Miocene ages. When plotted in the Wetherill concordia diagram, the data spread within an interval comprised between Alpine and Pan-African ages; by extrapolating the discordia we obtained two intercepts with Concordia at 292±21 Ma and ~ 22 Ma. The upper intersection represents a magmatic event that partially reset U-Pb ages at the end of the Variscan orogeny, and corresponds to Variscan magmatism and high-grade metamorphism in the crustal envelope of the Betic–Rifian peridotite massifs (Montel et al., 2000; Rossetti et al., 2010). Marked U-enrichment in zircon rims occurred during this Variscan event. The pegmatitic melts have very low REE and Zr contents, and positive Eu anomalies that suggest melting of gneissic protoliths containing K-feldspar and plagioclase. The lower intersection age of ~ 22 Ma represents a later episode of Pb-loss during the Alpine high temperature metamorphism. Miocene mineral ages were also obtained in Torrox by Zeck et al. (1989), and discordant U-Pb zircon dates within the age interval defined by the Alpine and Variscan orogenies by other authors in the Torrox and equivalent units (Rossetti et al., 2010). These new data clearly evidence the poly-orogenic tectono-metamorphic history of the pre-Mesozoic Alpujarride rocks.

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# The geodynamics of northern Gondwana: evidence from Paleozoic volcanic-sedimentary evolution of the Calabria-Peloritani terrane, southern Italy

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In the Calabria–Peloritani terrane two mildly metamorphosed Paleozoic successions have been investigated, combining recent lithostratigraphic and conodont biostratigraphic data with SHRIMP zircon data. They belong to the Longi-Taormina Unit (LTU: Peloritani Mountains, NE Sicily) and the Stilo Unit (Serre Massif, Calabria).

The lower part of both successions is formed of siliciclastic beds that host two volcanic horizons: a lower one of felsic, high-K calc-alkaline, supra-subduction porphyroids, and a higher one of alkaline basalts. Under the microscope a well-defined metamorphic foliation and recrystallization texture are observed in the basic rocks (metabasite) and the felsic porphyroids (meta-rhyolite) of the LTU. Zircon SHRIMP U-Pb dating of the porphyroids of the LTU gave an early Silurian age for the calc-alkaline volcanic event, which is inferred to be the age of the siliciclastic beds, although their base could be as old as Late Ordovician. Zircon grains obtained from metabasites of the LTU are pre-magmatic and constrain the alkaline volcanism as post mid-Cambrian. They also record an early Carboniferous metamorphic event affecting the succession. The alkaline basaltic volcanism is stratigraphically constrained as Silurian, since the metabasites are regionally interposed between the lower Silurian porphyroids at the base of the succession and conodont-bearing nodular limestones recently dated as upper Silurian (Ludlow) to Devonian at the top of the LTU succession (Rodríguez-Cañero et al., 2013; Somma et al., 2013). In the Stilo Unit conodont-bearing Devonian beds also lie above equivalent metabasites and metapelites (Navas-Parejo et al., 2009). The Paleozoic successions of both units end with lower Carboniferous lydites topped by Carboniferous Culm-like siliciclastic deposits.

The calc-alkaline volcanic rocks were formed during southward subduction of Prototethys under Northern Gondwana and represent early Silurian intra-arc or back-arc volcanism. This was followed by extensional collapse of the volcanic arc, which produced Silurian alkaline basaltic volcanism, associated with deep marine clastic to carbonate sedimentation during the Silurian-Devonian. Sedimentation occurred at greater depth in the LTU than in the Stilo Unit. The volcanic–sedimentary evolution records the initial stage of formation of a continental paleo-margin at the western end of Paleotethys. Rifting was arrested in precisely the areas where the studied successions were deposited. During the early Carboniferous the region evolved to a convergent margin with subduction of the previously thinned continental lithosphere under Gondwana and associated Visean metamorphism.

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# The intra-Alcudian (Cadomian) angular unconformity in Central Iberia: constraints from U-Pb detrital zircon ages

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New U-Pb SHRIMP ages of detrital zircons from the successions of the Schist-Graywacke complex (Central Iberian Zone, Iberian Massif, western European Variscan Belt) contribute to reconstructing the geodynamic evolution of Iberia during the Cadomian orogeny. These successions consist of Neoproterozoic–Lower Cambrian, low-grade, thick monotonous alternations of shale and wacke with minor intercalations of other lithologies, mainly conglomerates. They are poorly dated since their fossil content is restricted to a few remains of vague Ediacaran to Cambrian microfauna and ichnofossils. Sedimentation took place in flysch basins contemporaneous with Ediacaran arc magmatism (the Cadomian arc of north Gondwana).

In the eastern part of the complex, an angular unconformity (the 'intra-Alcudian' unconformity) separates the Lower Alcudian succession below from the Upper Alcudian strata and overlying Pusa Group above (Ortega and González Lodeiro, 1986). Samples were taken from just below and above the unconformable surface at two selected locations in the Alcudia area (Palero, 1993). The extracted detrital zircons provided 208 concordant (>95%) U-Pb analyses. The youngest zircon ages (i.e. maximum depositional age) in the Lower Alcudian are ~580–575 Ma, while those in the Upper Alcudian are ~555–550 Ma: the significant time-gap supports the existence of an intra-Alcudian sedimentary hiatus rather than a continuous sedimentary episode. Together with the angular unconformity, this suggests an intra-Alcudian tectonic event, instead of synsedimentary slump-related strata truncations. The tectonic event resulted in moderate folding (without related foliation/metamorphism), so that the Lower Alcudian strata became vertical, emerged and were partially eroded prior to deposition of the Upper Alcudian. Combined with other geological data, the most probable depositional ages are 580–560 Ma for the Lower Alcudian (before the late-Cadomian folding event) and 550–540 Ma for the Upper Alcudian (preceding the overlying Pusian Group and Lower Cambrian sandstones and limestones). Variable late Cadomian tectonothermal events elsewhere in Iberia also fit into the interval 560–550 Ma.

Comparison of the new zircon age spectra with possible source areas verifies recent studies pointing to the Cadomian foreland of northern Gondwana affected by the Pan-African orogeny: the West African craton and/or the Saharan metacraton. Furthermore, ongoing Cadomian arc-related magmatism in Iberia (granitoids and syn-sedimentary volcanic rocks, 605–545 Ma) could represent a more local zircon source. The end of the Cadomian activity is marked by a transient stage (an ephemeral Lower Cambrian platform), which preceded the widespread Cambro–Ordovician rifting of north Gondwana.

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Palero, F.J., 1993. Tectónica pre-hercínica de las series infraordovícicas del anticlinal de Alcudia y la discordancia intraprecámbrica en su parte oriental (sector meridional de la Zona Centroibérica). Boletín Geológico y Minero 104, 227–242.

# Good dates, bad ages – Archean zircon inheritance in Cambrian schist and pegmatite from northeast Madagascar

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Madagascar lies within a wide region of metamorphism in Gondwana reconstructions, widely attributed to collision of the Congo and Dharwar cratons at the close of the Neoproterozoic. More controversial is the location of oceanic sutures in this collision zone, and in particular whether the Antananarivo block of central Madagascar and Antongil craton of northeast Madagascar were separated by an ocean basin in the Neoproterozoic or had been together since the Archean. These alternative models stem from a disputed age for metamorphism in the Ambodiriana Formation, a kyanite-biotite schist unit along the northeast edge of the possible suture. Collins *et al.* (2003) argued that 3500–3000, 2700–2500 and 850–700 Ma zircon in the Ambodiriana Formation was all detrital, with peak metamorphism being recorded by a zircon rim dated at *c.* 520 Ma. Conversely, Schofield *et al.* (2010) and Tucker *et al.* (2011) argued that 2700–2500 Ma zircon from granitic leucosome in these rocks dated peak metamorphism, while only the 3500–3000 Ma zircon was truly inherited and 850–700 and 600–500 Ma zircons grew in later metamorphic or hydrothermal events of limited significance.

To clarify these ages we undertook a SHRIMP U–Pb monazite study of the Ambodiriana Formation. Monazite separates from one sample yielded a single population dated at 517 ± 9 Ma while *in situ* analyses of grains in five other samples, including monazite enclosed by kyanite and staurolite, gave a date of 521 ± 4 Ma. These data, supported by LA-ICPMS $^{207}Pb/^{206}Pb$ ages of 540 ± 21 Ma for xenotime grains, confirm a Cambrian age for peak metamorphism in the Ambodiriana Formation. We interpret the 3500-700 Ma zircon in leucosome dated by Schofield *et al.* (2010) and Tucker *et al.* (2011) as detrital grains inherited from host metapelite, and consider a high level of zircon inheritance in such granitoids to be unsurprising given their origin from low-temperature anatexis. Our results are consistent with a Late Neoproterozoic suture in northeastern Madagascar, and show that reliance on zircon crystallisation dates can lead to events being missed or misinterpreted if the rocks contain polygenetic inheritance.

Collins, A.S., Kroener, A., Fitzsimons, I.C.W., Razakamanana, T. 2003. Detrital footprint of the Mozambique ocean: U-Pb SHRIMP and Pb evaporation zircon geochronology of metasedimentary gneisses in eastern Madagascar. Tectonophysics 375, 77–99.

Schofield, D.I., Thomas, R.J., Goodenough, K.M., De Waele, B., Pitfield, P.E.J., Key, R.M., Bauer, W., Walsh, G.J., Lidke, D.J., Ralison, A.V., Rabarimanana, M., Rafahatelo, J.M., Randriamanamjara, T. 2010. Geological evolution of the Antongil Craton, NE Madagascar. Precambrian Research 182, 187–203.

Tucker, R.D., Roig, J.-Y., Delor, C., Amelin, Y., Goncalves, P., Rabarimanana, M.H., Ralison, A.V., Belcher, R.W. 2011. Neoproterozoic extension in the Greater Dharwar Craton: a reevaluation of the "Betsimisaraka suture" in Madagascar. Canadian Journal of Earth Sciences 48, 389–417.

# The tectonic significance of multi-isotopic provenance proxies on latest Ediacaran–Cambrian orogenesis in Central South America (Northern Paraguay orogen, Brazil)

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The timing of orogenesis and the tectonic significance of deformation in the northern Paraguay Belt, west Brazil, is the focus of considerable controversy regarding the timing of amalgamation of Gondwanan South America. The view of many is that collision between the Neoproterozoic São Francisco/Congo continent and Amazonia occurred at ~640–620 Ma, based on the timing of terrane amalgamation in the Brasília Belt (see Cordani et al., 2013). Others have noted that the palaeomagnetic record and geology of the Paraguay-Araguaia orogen, which lies between the Brasília Belt and Amazonia, is consistent with late Ediacaran closure of an oceanic margin (McGee et al., 2014a; McGee et al., 2014b; Trindade et al., 2006). In this presentation we highlight changes in age and isotopic provenance in the foreland to the northern Paraguay orogen. We use stratigraphically controlled $^{40}Ar/^{39}Ar$ data from detrital muscovites, and U-Pb and Hf isotopic data from detrital zircons from strata that are pre-orogenic, syn-orogenic, and ranging through to post-orogenic. The data demonstrate the influx of a non-Amazonian material, which we interpret as indicating the collision of an exotic block with Amazonia during the late Ediacaran closure of the Clymene Ocean as western Gondwana amalgamated during final Gondwana assembly.

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McGee, B., Collins, A.S., Trindade, R.I.F., Jourdan, F., 2014b. Tracking glaciation, orogenic exhumation and foreland basin evolution: Sedimentology and $^{40}Ar/^{39}Ar$ detrital muscovite provenance in the Paraguay Belt, Brazil. Sedimentology in press.

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# Geodynamic evolution of Ossa-Morena Zone in a SW Iberian context during the Variscan cycle

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Ossa-Morena Zone (OMZ) is crucial to understanding the geodynamic evolution of the Variscan cycle in SW Iberia. We review previous data, from Early to Late Paleozoic.

The early Cambrian (conglomeratic and felsic metavolcanic units) lies unconformably upon Neoproterozoic formations and shows a carbonate sequence with bimodal volcanic rocks, accompanied by intrusion of plutonic bodies (535–520 Ma). This could be interpreted as result of rifting process (Sánchez-García *et al.,* 2010). The middle Cambrian is marked by a significant crustal stretching episode: siliciclastic sedimentation is accompanied by bimodal volcanism, with transitional alkaline geochemical features, symptomatic of an intra-plate environment. The Cambrian–Ordovician transition is marked by the absence of sedimentation and/or an erosional episode. This period is concomitant with large plutonic intrusions (~ 510–485 Ma). This is related to opening of the Rheic Ocean: geochemical (N- and T-MORB signatures) and geochronological data support the existence of anorogenic oceanic magmatic activity during this period (~ 485–480 Ma). From the Mid Ordovician until the end of Silurian, magmatic features are related to passive margin evolution and tectonic stability.

Rheic Ocean subduction begins in SW Iberia in the early Devonian(Emsian or earlier). Four major tectono-metamorphic episodes (TM) are identified:

$TM_1$ – the first episode, related to northward subduction, as evidenced by the geochemical signatures of volcanic rocks: proximal tholeiitic to distal calc-alkaline (Odivelas) and shoshonitic (Veiros–Vale Maceira). The age of this orogenic magmatism is in accord with that of a high pressure metamorphic event (eclogitic facies) in the south-west border of the OMZ (≈370 Ma; Araújo *et al.*, 2013).

$TM_2$ –is characterized by transtensional kinematics and the exhumation of the high pressure rocks (≈360 Ma; Araújo *et al.,* 2013). It resulted from locked subduction and subsequent slab break-off, leading to asthenospheric upwelling and crustal melting recorded in the first pulses of the Beja igneous complex and Iberian pyrite belt volcanism (360–345 Ma).

$TM_3$ – is characterized by the presence of first order sub-vertical folds (*e.g.* Estremoz anticline). Metamorphism is low-grade, although it can be high-grade in the Évora–Beja–Aracena massif. This indicates a high thermal flux in the southern border of the OMZ, in accordance with the presence of 340–320 Ma plutonic bodies.

$TM_4$ – the last episode, during post-collisional crustal thickening, led to the formation of NNE–SSW sinistral shear zones, accompanied by the last magmatic intrusions in the OMZ (300–270 Ma).

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Sánchez-García, T., Bellido, F., Pereira, M.F., Chichorro, M., Quesada, C., Pin, C., Silva, J.B., 2010. Rift related volcanism predating the birth of the Rheic Ocean (Ossa-Morena Zone, SW Iberia). Gondwana Research 17, 392–407.

# New data on Lower Ordovician graptolites from Colombia and their correlation around the Gondwanan margin of South America

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Lower Ordovician graptolites from South America are mostly known from the Central Andean Basin, where a nearly complete biozonation covering most of the Tremadocian and Floian stages has been established for Argentina and Bolivia. North of this basin, a single record of the Tremadocian graptolite *Rhabdinopora flabelliformis* (Eichwald) was recognized from a deep borehole in Los Llanos (plains) of Colombia, west of the Guyana Shield. From the same country a number of occurrences of poorly preserved "Arenig" graptolites have been listed from the Central Cordillera (La Cristalina Formation), the Eastern Cordillera (La Uribe and Venado Fms.), the Serranía de La Macarena and the boreholes Negritos-1 and Trinidad-1 from eastern Llanos. However, many of these occurrences have not been published in detail and the cited graptolites display a wide chronostratigraphic range from the Floian to the lower Darriwilian stages (= Arenig s.l.), and thus could be of either Dapingian or early Darriwilian age (Middle Ordovician).

Undisputable Floian graptolites from the northern Andean domain in Colombia are recorded here from the Venado Formation northeast of Baraya, possibly not far from the "La Uribe trail" section mentioned by Trumpy (1943) and later authors. The first Ordovician graptolite collected from this formation was identified as "cf. *Didymograptus murchisoni* (Beck)" by Villarroel et al. (1997, fig. 3), but based on their illustration it looks more like a Floian species such as *Acrograptus filiformis* (Tullberg). A more recent find is reported by Moreno-Sánchez et al. (2008), who identified several specimens of *Phyllograptus* sp. in association with an unidentified graptolite (a stipe of dichograptoid) from typical outcrops of the green shales belonging to the Venado Formation and the Vereda El Totumo of the Río Venado. Further collection at the same locality bears nicely preserved specimens of *Baltograptus kurcki* (Törnquist), *Phyllograptus* cf. *ilicifolius* (Hall) and *Expansograptus* cf. *extensus* (Hall). This assemblage can be adscribed to the late Floian *Baltograptus minutus* Biozone.

Two other localities with Colombian graptolites have been examined from the Serranía de La Macarena area, where Trumpy (1943) reported the occurrence of Arenig graptolites studied by Turner (1960). Our new localities are in green shales of the Zanza Formation near the type section (the Río Zanza, a tributary of the Río Güéjar). There we have collected *Acrograptus filiformis* (Tullberg) and abundant deflexed graptolites (presently under study) of the *Baltograptus varicosus* (Wang) and *B. turgidus* (Lee) groups, indicative of the Floian *Baltograptus jacksoni* to *Baltograptus minutus* biozones and their equivalents in Argentina and Bolivia.

Fom a paleogeographic perspective, the new records of Lower Ordovician graptolites from Colombia deserve special interest. First, because they can be easily correlated with similar Floian assemblages described from the Central Andean Basin in Argentina and Bolivia, so far completely unknown in the northern Andean-west Guyana Domain. Second, because they constitute the first "intermediate" peri-Gondwanan occurrence of some robust deflexed baltograptids, originally defined from SW China but also reported from Argentina, Bolivia and southern Britain.

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# Reconstructing Pangea: testing the Southern Appalachian-West African connection with detrital zircon ages

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For over 50 years reconstructions of the supercontinent Pangea have, to a first order, involved closure of the Atlantic Ocean along primary fracture (transform) zones. In southeastern North America, this approach has led to correlation of the Suwannee succession (~2 km of lower Paleozoic clastic sedimentary rocks) of the Suwannee terrane with the Bove basin (West Africa). Although the Suwannee terrane is completely buried by post-rift sedimentary rocks, it has been imaged seismically and penetrated by numerous petroleum exploration wells. Data obtained reveal four important aspects of the succession: 1) it is undeformed and unmetamorphosed, 2) it contains Gondwanan fossils, 3) detrital zircons yield a Gondwanan distribution of ages, and 4) it is intruded by Alleghanian-age plutons (Heatherington et al., 2010). Furthermore, the succession appears to rest on undeformed Neoproterozoic basement, in contrast to the adjacent, strongly deformed Uchee terrane (Steltenpohl et al., 2008). The proximity of the undeformed-unmetamorphosed Suwannee terrane (and enclosed sedimentary succession) to the purported Alleghanian suture (Suwannee suture) has always represented a significant conundrum in terms of terrane emplacement within models that call for sequential ocean closures immediately preceding assembly of Pangea.

The U-Pb age spectra of detrital zircons from the Suwannee succession show a clearly non-Laurentian signature with well-defined concentrations of ages corresponding to the Pan-African/Trans-Brasiliano and the Birimian/Trans-Amazonian orogenic events (Mueller et al., 2014). Significantly, Grenville-age Mesoproterozoic zircons, which dominate lower Paleozoic and younger strata in Laurentia north of the Suwannee suture, are notably lacking in the Suwannee samples. In contrast, U-Pb ages of detrital zircons from a range of Paleozoic sedimentary rocks within the Bove basin (Villeneuve, 2005) indicate more diverse provenance. For example, two samples from the Nicola-Koba Group and one from the Guemeta Fm. (Pita Group) have strong concentrations of Pan-African ages and the first two also have concentrations of Birimian/Trans-Amazonian ages, similar to Suwannee terrane samples. Three other samples from the Bove basin, however, have strong concentrations of ages in the range 1200–1300 Ma and lesser concentrations of older zircons (e.g., Birimian/Trans-Amazonian). Overall, the variations among detrital-zircon populations in samples from the Bove basin suggest changes through time in provenance and sediment dispersal patterns, which were only partially captured in the Suwannee succession. Although not definitive, these data are permissive of a pre-Pangean Suwannee–Bove connection.

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Mueller, P., Heatherington, A., Foster, D., Thomas, W., Wooden, J., 2014. The Suwannee suture: Significance for Gondwana-Laurentia terrane transfer and formation of Pangea. Gondwana Research 26, 365-373.Steltenpohl, M., Mueller, P., Heatherington, A., Hanley, T., 2008. Gondwanan/Peri-Gondwanan origin for the Uchee terrane, Alabama and West Georgia: Carolina zone or Suwannee terrane (?) and its suture with Grenvillian basement of the Pine Mountain window. Geosphere 2, 131-144.

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# An eastern Mediterranean analogue for the Late Paleozoic evolution of the Pangaean suture zone in SW Iberia

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It has long been recognized that the Late Paleozoic evolution of SW Iberia preserves a record of terrane accretion, collision and suturing between Laurussia (South Portuguese Zone) and Gondwana (Ossa Morena Zone), which is one of the key events in the development of the Variscan orogen and the amalgamation of Pangea. The suture zone (Pulo do Lobo Zone) is classically considered to be an accretionary complex and is characterized by an assemblage of greenschist facies, poly-deformed and imbricated meta-sedimentary rocks, mélanges, and mafic complexes. However recent work has shown some of the metasedimentary rocks and mélange were probably not derived from either the upper or the lower plates. Mafic complexes in the mélange have NMORB compositions with highly depleted Sm-Nd isotopic signatures, and geochronological data imply that their protoliths probably formed between ~ 350 and 340 Ma. Geochronological data also imply that components of the mafic mélange contain very little ancient continental detritus. The Pulo do Lobo Zone was also intruded by ~ 360–310 Ma composite plutons and related dykes ranging from gabbro to granite in composition. The oldest phases of these intrusions are syn- to late-tectonic with respect to the deformation. Taken together these recent observations suggest that much of the tectonic evolution of the Pulo do Lobo suture zone post-dates the onset of collisional tectonics elsewhere in the Variscan orogen, and is broadly analogous to the complex Cenozoic tectonic evolution of the eastern Mediterranean oceanic tracts that relate to the ongoing collision between the African, Eurasian and Arabian plates.

# Transatlantic correlation of the Meguma terrane

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The peri-Gondwanan Meguma terrane of southern Nova Scotia, Canada, is the only major lithotectonic element of the northern Appalachian orogen that has no clear correlatives elsewhere in the Appalachians and lacks firm linkages to the Caledonide and Variscan orogens of western and southern Europe. This is in marked contrast with its immediate peri-Gondwanan neighbour, Avalonia, which shows similarities to portions of Carolinia in the southern Appalachians and has been traced from the Rhenohercynian Zone of southern Britain eastward around the Bohemian Massif to the South Carpathians and western Pontides.

At issue with transatlantic correlation of the Meguma terrane is the tendency in Europe to assign all peri-Gondwanan terranes (like Meguma) lying north of the Rheic suture to Avalonia, characterized by relatively juvenile basement and detrital zircon ages that include Mesoproterozoic populations, and all those to the south of the suture to Cadomia, characterized by a more evolved basement and detrital zircons with ages that match Paleoproterozoic and older sources in the West African craton.

The unexposed basement of Avalonia and the Meguma terrane are thought to be isotopically similar, but the sedimentary cover in the Meguma terrane contains scarce Mesoproterozoic zircons and is dominated instead by Paleoproterozoic and older populations like those of Cadomia. Because of this relationship, felsic magmas produced by crustal melting in the Meguma terrane (e.g., the ~370 Ma South Mountain batholith) are isotopically more juvenile ($\varepsilon$Nd = -5 to -1, $T_{DM}$ = 1.3 Ga) than the rocks they intrude ($\varepsilon$Nd -12 to -7, $T_{DM}$ = 1.7 Ga). Since this relationship can be identified isotopically, it provides a potential means of identifying areas in Europe that may be correlative with the Meguma terrane. For example, the same distinctive relationship is recognized between the Sierra Norte batholith (~330 Ma; $\varepsilon$Nd = +1 to -3, $T_{DM}$ = 0.9–1.2 Ga) and its Late Devonian host rocks ($\varepsilon$Nd = −5 to −11) in southern Spain, where it has been used to suggest the possible extension of the Meguma terrane into the South Portuguese Zone. Available data for the Cornubian batholith of SW England (~270–290 Ma; $\varepsilon$Nd = -5 to -7, $T_{DM}$ = 1.3–1.8 Ga) and the Devonian metasediments it intrudes ($\varepsilon$Nd = −8 to −11) suggests that this may also be true of that part of the SW England (Rhenohercynian Zone) with which the South Portuguese Zone is traditionally correlated.

# The supercontinent cycle

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The supercontinent cycle, by which Earth history is seen as having been punctuated by the episodic assembly and break-up of supercontinents, has influenced the rock record more than any other geological phenomenon, and its recognition is arguably the most important advance in Earth Science since plate tectonics. It documents fundamental aspects of the planet's interior dynamics and has charted the course of Earth's tectonic, climatic and biogeochemical evolution for billions of years. But whereas the widespread realization of the importance of supercontinents in Earth history is relatively recent, the concept of a supercontinent cycle is not new, and episodicity in tectonic processes was recognized long before plate tectonics provided a potential explanation for its occurrence. With interest in the supercontinent cycle surging, it is instructive to recall the historical context from which the concept developed. To provide this perspective, we trace the development of ideas concerning long-term episodicity in tectonic processes from early views on episodic orogeny and continental crust formation, through the first realization that such episodicity was the manifestation of the cyclic assembly and break-up of supercontinents, to the growth of interest in supercontinent reconstructions. We then examine some of the key contributions of the ensuing decade and the rapidly expanding developments of the past ten years.

# Mississippian conodonts from Caborca, northwestern Sonora, Mexico

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Fossiliferous Paleozoic rocks in Sonora, northwestern Mexico, have been recognized since the first decade of the last century. Recent publications report the presence of diverse fossil groups of this age, some of which yield important biostratigraphic information, such as conodonts, fusulinids, foraminifers, corals or brachiopods. This information, together with lithostratigraphy and tectono-sedimentary studies, indicates a NW to SE progression from shallow- to deep-water environments. However, very few detailed studies discuss fossil associations or their paleoecological implications. In this contribution, we present the first results from a study in progress, which focuses on the paleogeographic evolution of Carboniferous and Permian rocks in Sonora. These results confirm the presence of Mississippian beds from conodonts recovered from outcrops in the Caborca region. In northwestern Sonora, Mississippian rocks have been grouped in two units: the Represo Formation (Kinderhookian-Osagean, *i.e.* Tournaisian) and the Venada Formation (upper Meramecian, *i.e.* middle Visean), also informally called El Represo Limestone (lower Mississippian) and La Venada Limestone (upper Mississippian) by Poole et al. (2012). The identified conodont fauna contains *Gnathodus pseudosemiglaber* (Thompson and Fellows) and *Gnathodus semiglaber* Bischoff, which points to an early Visean age (*anchoralis-praebilineatus* zones). This confirms a Mississippian age for the section although the Venada Fm. may be slightly older than previously considered by Cooper and Arellano (1946), Brunner (1975) and Poole et al. (2012). In addition, the presence of the *Gnathodus* genus suggests an open marine (below wave base) paleoenvironment (Krumhardt et al. 1996). The importance of understanding these rocks lies in the position they had along the southern margin of Laurentia during the late Paleozoic. In the latest Paleozoic, during the Alleghanian-Variscan orogeny, western Gondwana was accreted to this continental margin. Regional biostratigraphic studies will help to understand possible timing and paleogeographic affinities of the late Paleozoic faunas and strata of Sonora. Further work on these successions is needed to improve knowledge of their geological evolution and discern their role in the closure of the Rheic Ocean and the final assemblage of the Pangaea supercontinent.

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# Western Paleotethys palaeogeographic evolution: new insights from the intra-Alpine terranes of the Betic Cordillera (southern Spain)

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Recent studies of the Alpine Paleozoic massifs of SW Europe have rarely tried to fit the geological history of these pre-Alpine basements to any of the different models proposed for the evolution of the mid-to-late Paleozoic oceans. Most of these models overlook the role of Paleotethys opening, which resulted in the complete detachment of a ribbon continent from Northern Gondwana. This ribbon continent would include the different segments of the Paleozoic terrains of the Western Mediterranean Alpine orogen (WMAO) within the so-called intra-Alpine (Hunian or Galatian) terranes These models, however, rarely consider the recent advances in stratigraphy of the different segments of the WMAO. This is the aim of this study, with reference to the outcrops of the Malaguide complex close to the Internal-External zone boundary of the Betic Cordillera, where recent studies allowed its subdivision in three Alpine tectonic units: from bottom to top (and from S to N), these are: Epimetamorphic Malaguide Unit (EMU), Lower Malaguide Unit (LMU), and Upper Malaguide Unit (UMU).

The EMU and the LMU include the thickest and most widespread Malaguide pre-Carboniferous formations, consisting of pre-Devonian(?) slates and shales alternating with meta-sandstones and meta-conglomerates (Morales Fm) followed by Devonian(?) fine-grained limestones and calcareous greywackes known as *Calizas alabeadas* (Santi Petri Fm). These facies formed in a basin depositional context. In contrast, the pre-Carboniferous UMU succession is characterized by pelites, including thin and laterally discontinuous beds of Silurian–Devonian conodont-bearing limestones that were deposited in high-bottom areas with condensed carbonate sedimentation in open marine, moderately deep and hemipelagic environments close to the deepest areas of a distal continental margin. Hence, the lateral facies evolution from the UMU to the EMU–LMU corresponds to a proximal to distal margin zonation from NW to SE (in present-day coordinates).

Lower Carboniferous formations are more or less equivalent in all Malaguide units, being composed of very thin Tournasian radiolarites (lydites) followed upwards by Visean conodont-bearing limestones (Falcoña Fm), in turn overlain by very thick, locally unconformable and coarse-grained turbiditic siliciclastic Culm facies (Almogía Fm). This facies evolution indicates a sharp depositional change during Serpukhovian time, related to palaeogeographic and geodynamic revolution in the basin, evolving from a mature divergent to a convergent continental margin related to the Variscan orogeny.

The Malaguide realm constitutes the westernmost transect in the continental margin of a ribbon continent in the western end of Paleotethys, which seems to have not been completely detached from Gondwana, since no traces of ophiolites have been found in Malaguide or in equivalent Paleozoic successions of the WMAO. The maximum opening of Paleotethys in these realms occurred during the early Carboniferous as testified by the deposition of the Tournaisian lydites. In these regions, closure of Paleotethys started in mid-Carboniferous time, as demonstrated by the Culm facies deposition. This evolution fits well with that known for other intra-Alpine terranes derived from the North Gondwanan ribbon continent.

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# Stratigraphic update of the Paleozoic succession of the Peloritani Mountains, north-eastern Sicily, southern Italy

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Lithostratigraphic analyses on the mildly metamorphosed Paleozoic succession of the Longi-Taormina Unit (Peloritani Mountains, north-eastern Sicily) have been integrated with conodont biostratigraphic data, providing new constraints on the stratigraphy of the Calabria-Peloritani terrane of southern Italy.

The studied succession consists, from base to top, of the following formations:

- *Castelmola Formation* of siliciclastic deposits including calc-alkaline volcanites (porphyroids), determined as early Silurian by U-Pb SHRIMP dating of zircon (see Martín-Algarra et al., this symposium);
- *Lower Pizzo Leo Formation* (Silurian) composed of siliciclastic deposits with alkaline volcanic rocks (metabasites) and lenses of nodular limestone in the upper part;
- *Upper Pizzo Leo Formation* (upper Silurian–Lower Devonian) formed by calc-schists, metamarls, and meta-limestones with minor metapelites.

The oldest and youngest conodont associations are found within the carbonates of the Upper Pizzo Leo Formation and point to late Silurian and Early Devonian ages, respectively. The oldest, obtained from nodular limestones, belong to the Ludlow (*ploeckensis - siluricus* zones; Rodríguez-Cañero et al., 2013). The youngest fauna, found in calc-schists, belong to the Emsian *(kitabicus*, *excavatus*, and *nothoperbonus-inversus* zones; Somma et al., 2013). The existence of younger Devonian beds reported in previous studies could not be confirmed.

The stratigraphic succession of the Longi-Taormina Unit ends with lower Carboniferous (?) lydites topped by Carboniferous ?Culm-like siliciclastic rocks.

From the environmental point of view, a sharp transition from siliciclastic to carbonate facies occurred during the late Silurian, within a general upwards-deepening trend from the Ordovician(?)–Silurian to the early Carboniferous.

The studied Paleozoic succession, being analogous to others better known in Calabria (Stilo Unit), SW Sardinia, the Carnic Alps, the Betic-Rif cordillera, and eastern Pyrenees, presumably formed near the western end of Paleotethys and in its northern margin.

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# New stratigraphic data on the Late Devonian of the Serre Massif (eastern Calabria, southern Italy) in the frame of the western Paleotethys

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The Paleozoic stratigraphic framework of the intra-Alpine terrains exposed in the Calabria-Peloritani arc (southern Italy) has been successfully reinforced by new biostratigraphic and lithostratigraphic data from the Longi-Taormina Unit of the Peloritani Mountains (north-eastern Sicily) and the Stilo Unit of the Serre Massif (eastern Calabria). In the latter, the oldest conodont associations from nodular limestones of the fiumara Assi indicate an Early Devonian age (Navas-Parejo et al., 2009a), whereas the youngest conodont associations limestones found in the Vina bridge indicate a Famennian (Late Devonian) age (Navas-Parejo et al., 2009b).

In this contribution, we confirm the Famennian stratigraphy of the Stilo Unit with new conodont biostratigraphic data from a 13m thick stratigraphic section never previously studied in the San Giovanni area, to the NE of Bivongi. Eleven samples taken from the meta-carbonates of the San Giovanni section yielded Famennian conodonts of the *crepida*, *rhomboidea,* and *marginifera* zones. The San Giovanni Famennian deposits consist of thin-bedded reddish limestones with nodular structure that were probably deposited in a high-bottom (pelagic swell) area. In the neighbouring Vina bridge section, SW of the San Giovanni area, coeval sediments were deposited in slightly deeper environments, being characterized by greyish, pelagic, thin- to medium-bedded limestones. The outer position within the continental margin and the slightly deeper depositional setting inferred for the Vina bridge section is reinforced by evidence of the Upper Kellwasser anoxic event (Navas-Parejo et al., 2009b). Thus, lateral facies changes can be inferred in the Stilo Unit during the Late Devonian.

The studied Devonian facies can be interpreted in the frame of a changing hemipelagic to pelagic sedimentary basin within a faulted continental margin, with deposition of nodular limestones in a high-bottom area and of alternating pelagic limestones and pelites with local black shales in a deeper area. From the regional point of view, the Devonian beds of the Stilo Unit resemble those of the Peloritani Mountains (Longi-Taormina Unit), SW Sardinia (Mason Porcus Fm), the Carnic Alps, the Gibraltar arc (Malaguide-Ghomaride Units), and the eastern Pyrenees. This testifies to a common palaeogeographic origin for most of these domains, mostly interpreted as related to the rifting and later drifting of North Gondwanan fragments, leading to the opening of the Paleotethys Ocean.

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# Late Paleozoic marine faunal succession in the Itararé Group, Paraná Basin, Brazil: towards an integrated brachiopod and bivalve biocorrelation scheme

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During the Late Paleozoic, the Paraná Basin was a huge intracratonic basin mainly filled by continental, marine and fluvial deposits. In this context, the basal portion of the Carboniferous–Permian sequence corresponds to the Itararé Group. This records one of the most continuous and thickest glacio-marine successions in South American Gondwana, including glacial diamictites, sandstones and shales. The succession is capped by coal-bearing sandstones of the Sakmarian–Artinskian Rio Bonito Formation. Marine invertebrates are rare and sparsely distributed in the Itararé succession. However, in the eastern border of the basin, at least nine marine assemblages were recorded in the Mafra and Rio do Sul (=Taciba) formations. Ongoing taxonomic analyses indicate that 10 brachiopod and 19 bivalve species can be recognized. Low diverse, linguliform-dominated brachiopod assemblages are recorded in the mid portion of the Mafra Formation (late Carboniferous) and in the basal portion of the Rio do Sul Formation (Lontras shale, Carboniferous–Permian boundary), and are associated with marine intercalations generated by transgressive events. At the top of the Rio do Sul/Taciba Formation, above the last diamictite beds, at least seven bivalve-dominated assemblages were recorded. The unique exception is the Butiá assemblage, Mafra county, Santa Catarina state, which is dominated by productid brachiopods. The older fauna, the *Heteropecten paranaensis-Pleurophorella* sp. assemblage, is recorded in sandstones deposited in shallow water conditions. This is stratigraphically succeeded by the following assemblages: *Praeundolomya* cf. *subelongata-H. paranaensis*; *Exochorhynchus itararensis-Cosmomya* (*Paleocosmomya*) *baitaquensis-H. paranaensis* (plus *Tomiopsis* cf. *harringtoni* and *Streptorhynchus*? sp.); *Atomodesma* (*Aphanaia*) *orbirugata-H. paranaensis* (plus *Sulciplica*? sp.); and *Myonia argentinensis-H. paranaensis* assemblages, which were found in siltstones deposited in shelf conditions. The youngest fauna is represented by the *Phestia* aff. *sabattiniae-Palaeoneilo* sp. (plus *Chonetes*? *rionegrensis*, *Crurithyris roxoi*, *Langella*? *imbituvensis* and *Orbiculoidea guaraunensis*) assemblage and is recorded in massive or well-laminated shales, deposited under anoxic to dysaerobic offshore conditions. Within the studied assemblages key bivalve species for biocorrelations are: *A.* (*Aphanaia*) *orbirugata*, *H. paranaensis* and *M. argentinensis*, which indicate correlations with the *Eurydesma* Fauna of the Bonete Formation, Sauce Grande–Colorado basin, Argentina. The probable occurrences of *Tomiopsis* cf. *harringtoni* in the *E. itararensis-C.* (*Paleocosmomya*) *baitaquensis-H. paranaensis* assemblage would also support this correlation. The presence of the productid brachiopod *Lyonia* and pectinid bivalves (=*Heteropecten*) in the Butiá assemblage, Taciba Formation, is also noteworthy, suggesting a possible late Asselian–early Sakmarian age, and biocorrelation with Gondwanan deposits of the Carnarvon and Perth basins, Western Australia. In summary, the taxonomic composition of the faunal succession of the Itararé Group, mainly of the Rio do Sul/Taciba Formation, suggests the presence of endemic species in association with marine, cosmopolitan and Gondwanan brachiopod and bivalve species. This offers valuable clues to better constrain these faunas to the late Asselian–early Sakmarian lapse, linking them to faunas of eastern Argentina and, to a lesser extent, Western Australia.

# Connecting West Gondwana orogens in southeastern Brazil: the Rio Doce arc revisited

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Magmatic arcs can help to correlate Precambrian orogenic belts. Araçuaí and Ribeira are neighbouring orogenic sectors of the Neoproterozoic Mantiqueira Province in southeastern Brazil, with important geological targets for understanding West Gondwana assembly. Among them, we focus on batholiths and metavolcano-sedimentary successions from the central to southern Araçuaí and northern Ribeira sectors, constituting the Rio Doce magmatic arc and including the G1 plutonic supersuite and the metavolcano-sedimentary Rio Doce Group. Lithochemical, isotopic (Nd and Sr) and U-Pb geochronological data from G1 plutons and Rio Doce volcanic rocks characterize a medium- to high-K calc-alkaline magmatic arc, generated on an active continental margin from ~ 630 Ma to ~ 580 Ma. Two samples of dacitic to rhyolitic metapyroclastic rocks from the lower Rio Doce Group (Palmital do Sul Formation) yielded zircon U-Pb ages of 595 ± 13 Ma and 584 ± 5 Ma. A magmatic crystallization age of 585 ± 4 Ma was obtained from a dacitic metavolcaniclastic rock of the middle Rio Doce Group (Tumiritinga Formation). U-Pb ages of detrital zircon grains from a metapelite of the Palmital do Sul Formation suggest a maximum depositional age of 665 ± 25 Ma, indicating provenance from sources located in the Cryogenian Rio Negro magmatic arc and/or the South Bahia alkaline province. The detrital zircon age spectra for metasandstones from the São Tomé and João Pinto formations (upper Rio Doce Group) record maximum depositional ages of 594 ± 3 M and 619 ± 19 Ma, respectively, indicating a significant contribution from sources located in the Rio Doce arc. Tonalitic to granodioritic gneisses from Baixo Guandu, Muriaé and Conceição da Boa Vista batholiths (G1 supersuite) yielded zircon U-Pb ages of magmatic crystallization at 621 ± 5 Ma, 620 ± 3 Ma and 586 ± 7 Ma, respectively. These ages are similar to those obtained from other arc batholiths (e.g., Galiléia, São Vítor) in the Araçuaí orogen, composing a dataset of forty U-Pb ages, including data from the Serra da Bolívia complex located in northern Ribeira orogen. In fact, the southern tip of the Conceição da Boa Vista batholith is spatially connected to the Serra da Bolívia complex, representing the southern segment of the Rio Doce magmatic arc. Therefore, this arc is an important connection between the Araçuaí and Ribeira orogens. The Rio Doce arc also represents an active continental margin developed during the plate convergence process that culminated in the amalgamation of this Mantiqueira Province sector with its counterpart in southwestern Africa, the West Congo and Kaoko belts after ~ 580 Ma. U-Pb ages from S-type granites in the arc region and zircon metamorphic overgrowths in arc-related rocks suggest an onset of the collisional event around 580–575 Ma, representing an outstanding time marker for West Gondwana assembly in this region.

# Geochronology of orthogneiss in the Jebba–Bode Saadu area, southwestern Nigeria and implications for the Paleoproterozoic evolution of this part of West Gondwana

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The Jebba–Bode Saadu area of southwestern Nigeria is underlain by metasedimentary and meta-igneous rocks, including migmatitic orthogneisses which have been intruded by largely undeformed granitic rocks of probable Pan-African age (~ 600 Ma). The metamorphic rocks have been subjected to several phases of both ductile and brittle deformation.
LA-ICP-MS in-situ U-Pb dating of zircons on four suites of orthogneisses outcropping in the area have yielded upper Concordia intercept Paleoproterozoic ages of 2207±20 Ma, 2236±29 Ma, 2228±32 Ma and 2179±28 Ma. These are interpreted as the times of crystallization of these rocks. The gneisses bear the imprints of several deformation events in the form of foliations, folds and shear zones. The geochronological data enable constraints to be placed on the timing of the development of some of these structures, with the S1 fabric and their tight-to-isoclinal folds being of Eburnean age while the ductile shears and the close open folds are of Pan-African age.
These orthogneisses may be correlated with widely abundant Paleoproterozoic granitic magmatism now represented by many orthogneisses and documented in other parts of southwestern Nigeria, the West African craton, the central Tuareg Shield in western Africa, the Borborema Province, the Gurupi Belt, Sao Luis craton and Sao Francisco craton in Brazil. This supports their recognition as integral part of the Western Gondwana in Paleoproterozoic times.

# Ediacaran–Cambrian paleogeography and geodynamic setting of the Central Iberian Zone: constraints from coupled U–Pb–Hf isotopes of detrital zircons

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The combination of U–Pb geochronology and Hf isotopes in detrital zircons represents a valuable tool in the characterization of sediment sources and accordingly helps in paleographic reconstructions. This analytical methodology has been applied to seven Neoproterozoic to Lower Cambrian metasediments from the northern and southern domains of the Central Iberian Zone, which represent part of the Cadomian basement in the Iberian Massif. The southern domain samples (belonging to the so-called Schist–Greywacke complex) yield Ediacaran maximum depositional ages (582–550 Ma), whereas northern samples range from 588 Ma in the Talavera area to 536 Ma in the Guadarrama sector. The zircon U–Pb age distribution provides similar broad age ranges in all cases: abundant Late Cryogenian–Ediacaran zircons (540–700 Ma), and less abundant ages in the following ranges: 700–850 Ma, 880–1100 Ma, 1900–2250 Ma and 2400–2800 Ma. However, southern Central Iberian Zone samples display important juvenile input at ca. 1000–1075 Ma, 800 Ma and in the range 700–570 Ma, which contrasts with the mostly recycled nature of zircons from the northern part of the zone. The Ediacaran juvenile signature probably derived from the nearby Cadomian arc, as sedimentation probably occurred in a back-arc setting. The presence of recycled zircons in the same time period might imply mixing with an old (Archaean) component. However, the Early Cryogenian and Stenian juvenile peaks are more characteristic of basement rocks from NE Africa, which might have also provided the coeval recycled zircons. These data suggest that the Central Iberian Zone was situated near the Saharan metacraton and the Arabian–Nubian Shield during Late Ediacaran (since the West African craton does not show ages in the range of 800–1700 Ma). On the other hand, data from the younger Guadarrama sediments of the northern Central Iberian Zone seem to indicate important geodynamic modifications in northern Gondwana at the Ediacaran–Cambrian boundary. They show predominantly evolved components (Eburnean and Neoarchaean) and the juvenile inputs are reduced to a minimum, contrary to data from the southern zone metasediments. These differences can be interpreted as resulting from transition from a back-arc scenario to development of new basins after the arc collided with the main continent. With subduction being replaced by transform tectonics, the arc signature would decline and an increasing influence of hinterland regions would appear as a dominant mature component. This scenario might have quickly evolved towards a new convergent stage that would have permitted, after burial and later partial melting, the formation of a paired I- and S-type granitic magmatic belt of Late Cambrian–Early Ordovician age (500 to 478 Ma) intruding both metasedimentary realms. This is suggestive of an extensional post-collisional evolution in a complex continental margin, active from Ediacaran to Cambrian times.

# LA-ICP-MS U-Pb zircon ages and geochemical-isotopic highlights of Mongaguá granitic rocks, Coastal Terrane, Southeastern Brazil

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The Mongaguá domain (MD) represents the Coastal Terrane in the State of São Paulo, characterized by gneisses and migmates of Itariri complex and Areado and Ribeirão do Óleo granitic associations. The Itariri complex (IC) comprises the oldest rocks of the MD, being composed of tonalitic-to-syenogranitic orthogneiss and granodiorite to monzogranite. LA-ICP-MS zircon analysis of the biotite tonalite orthogneiss yielded U-Pb ages around 745 Ma, with 790 Ma cores. These rocks represent the basement of the MD, with a peraluminous medium- to high-K calc-alkaline signature. Zircon crystals exhibit both nuclei and rims with oscillatory zoning representing successive zircon growths in a magmatic environment with the younger values indicating the age of the rock. The crustal influence is characterized by εNd of about -10 and initial $^{87}Sr/^{86}Sr$ of 0.720, unlike those of any other granite in the area.

In the coastal area, between the cities of Mongaguá and Itanhaém, orthogneiss and migmatites of the IC with monzogranitic to syenogranitic composition occurs. These rocks are transitional from meta- to per-aluminous and have high-K to shoshonitic signatures. U-Pb (TIMS) ages range between 612 and 618 Ma. $T_{DM}$Nd ages are around 1.8 Ga, with εNd of about -7 and initial $^{87}Sr/^{86}Sr$ of 0.708 indicating a crustal contribution to their origin. Additionally, the syn-collisional peraluminous biotite monzogranites with high-K calc-alkaline signature yield LA-ICP-MS U-Pb zircon ages of 603 Ma. Zircon inheritance of 2.2, 1.8, 1.2 and 1.1 Ga is found. $T_{DM}$Nd ages of 2.25 Ga, εNd of about -14 and initial $^{87}Sr/^{86}Sr$ of 0.718 characterize these granites.

The igneous overgrowths on zircons in granitic rocks of the Itariri complex suggest that these rocks crystallized in more than one magmatic pulse. Despite the 2.2 and 1.1 Ga zircon inheritance found in the IC granitoids, rocks with these ages are not observed in Mogaguá domain. Whole-rock Sr and Nd isotopic data and the presence of zircons with inherited cores confirm the various crustal contributions in the genesis of the igneous rocks of the Itariri complex.

The intrusive rocks in the Itariri complex is represented by the Areado and Ribeirão do Óleo granites that comprise a calc-alkaline, high-K metaluminous to peraluminous magmatism. The Areado granite has Paleoproterozoic zircon inheritance and a crystallization age of 576±12 Ma. The 561±8 Ma Ribeirão de Óleo granite, distinct from the others in the area, shows Paleoproterozoic (2.2 Ga) and Neoproterozoic (690 and 611 Ma) zircon cores. Initial $^{87}Sr/^{86}Sr$ is 0.715 in the Areado granite and around 0.708 in the Ribeirão do Óleo granite. The Nd isotopic data indicate for both granites gives $T_{DM}$ of 1.7 Ga and εNd of about -10.

As is typical of other studies in southeastern Brazil, the Itariri, Areado and Ribeirão do Óleo granites have geochemical characteristics which point to the involvement of different crustal sources during the generation of the magmas.

# To be or not to be Armorican: the Paleozoic Iberian question

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The Cantabrian Zone of NW Iberia preserves a voluminous, almost continuous, sedimentary sequence that ranges in age from Ediacaran to Early Permian. Its tectonic setting is controversial and recent hypotheses include (i) passive margin deposition along the northern margin of Gondwana, (ii) an active continental margin, (iii) the margin of a drifting ribbon continent and (iv) a combination of the three aforementioned possibilities.

One of the main disputes in the evolution of Rheic Ocean is the paleoposition of NW Iberia and other terranes involved in the Variscan orogeny during Silurian and Devonian times. On the basis of paleomagnetic data, some authors interpret NW Iberia during the Late Silurian as part of a drifting ribbon continent generally called Armorica. In this scenario, the drift of Armorica from Gondwana is responsible for the opening of the Paleotethys Ocean and its collision against Laurentia for the closure of the Rheic Ocean and the onset of Variscan orogenesis. Other authors, however, place Iberia along the northern Gondwana passive margin throughout the Paleozoic, and most of these models consider that subduction of Rheic Ocean lithosphere, which began in the Early Devonian, was directed northwards, i.e., away from the Gondwanan margin.

Geochemical and geochonological data from Ediacaran to Early Permian detrital rocks in the Cantabrian Zone allow a comprehensive analysis of changing tectonic scenarios and provenance through time. Collectively, these data indicate that this portion of Iberia was an active margin during the Ediacaran that evolved to become part of the passive margin of Gondwana at least from Ordovician to Late Devonian times. Changes in geochemistry, zircon age distribution and Sm/Nd isotopes during the Carboniferous are attributed to the far-field effects of the onset of the collision between Gondwana and Laurussia, and related processes such as recycling of older sedimentary sequences. Geochemical and geochronological data largely supports an autochthonous Gondwana margin situation for NW Iberia.

# And the Variscan orogen buckled

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The Western European Variscan shows a lithospheric-scale "S"-shaped map pattern and has been interpreted as two coupled oroclines; a northern Cantabrian orocline and southern Central Iberian orocline. The northern Cantabrian orocline shows a striking 180°curvature that is concave towards the east. The orocline model for this relies on a wealth of paleomagnetic and structural data, and implies that an early longitudinal orogen generated by East–West shortening was subsequently buckled about a vertical axis of rotation during North–South shortening (in present coordinates). Timing constraints limit the Cantabrian orocline formation to a period of ~ 10 Ma in the uppermost Carboniferous–Early Permian. Formation of the Cantabrian orocline was synchronous with (1) an important, widespread thermal event that included emplacement of granitoid intrusions from the hinterland to the east into the foreland basin, (2) significant changes in the isotopic signatures of mantle-derived igneous rocks, (3) extensive mineralization, including emplacement of high-grade epithermal gold deposits, (4) rapid thermal maturation of syn-orogenic coal sequences, and (5) pervasive remagnetization. Robust geological and geophysical data are currently lacking for a comprehensive model of formation of the Central Iberian orocline and its link with the Cantabrian orocline, although tentatively they are connected in space and time.
Our interpretation links these observations with orocline formation, through a tectonic model in which thick-skinned lithospheric-scale oroclinal buckling triggered lithospheric thickening and subsequent foundering of a lithospheric root. Lithospheric delamination resulted in mantle replacement by young, hot asthenosphere. A major change in the orientation of the stress field (~ 90º) at the onset of the oroclinal development is required to produce the buckling of the previously linear Variscan orogen. What caused this dramatic stress field flip is still unknown, but because the Variscan orogen is inferred to record the continental collision responsible for the formation of Pangea, it was probably a global scale process.

# New Structural and Paleomagnetic constraints on the Western Variscan oroclines

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The Western European Variscan belt shows two coupled oroclines arranged in an "S"-shaped pattern consisting of northern (Cantabrian) and southern (Central Iberian) arcs. Paleomagnetic and structural constraints provide evidence that the northern arc was developed during the Late Pennsylvanian after the closure of the Rheic Ocean and the formation and collapse of a more or less linear orogen; it is therefore considered to be post-orogenic. On the other hand, neither the geometry nor the kinematics of the Central Iberian orocline, situated in the central part of the Iberian Peninsula, are properly known. Different authors have considered that both these oroclines developed approximately synchronously, as a response to different lithospheric-scale scenarios, as proposed for coupled oroclines found elsewhere. In order to provide new constraints on the geometry and kinematic evolution of the Iberian Variscan oroclines our results show new insights into: 1) structural and paleomagnetic evidence constraining the extension and geometry of the Cantabrian orocline to the north of the Rheic suture, in the Avalonian terranes (Munster Basin. Ireland) and beyond the Variscan front; 2) paleomagnetic constraints from sedimentary and igneous rocks of the Central Iberian orocline and their relationship with the paleomagnetic data previously collected in the Cantabrian orocline; and 3) the significance and relevance of lithospheric-scale orocline formation during the latest stages of amalgamation of Pangea.

# West Gondwana assembly: a view from southeastern Brazil

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Rock records from ocean opening and closure, like ophiolites and magmatic arcs, and of collisional to post-collisional magmatic events can provide important timing markers to solve palaeocontinent dispersal and assembly puzzles. The Araçuaí-Ribeira orogenic system (AROS), extending from southern Bahia to northern Paraná states in southeastern Brazil, includes rock records of all evolutionary stages expected from plate margin orogens, and presents a quite complete time record to figure out West Gondwaland assembly along that region and its counterpart in Africa (the West Congo and Kaoko belts). The youngest ophiolite slivers formed in AROS from ~ 660 Ma to ~ 595 Ma, and are found in places hundreds of kilometres apart from each other (e.g., Ribeirão da Folha, São José da Safira, Santo Antônio do Grama, Pirapora do Bom Jesus, Piên). These ophiolite complexes have been related to the Neoproterozoic Adamastor Ocean. Pre-collisional, calc-alkaline magmatic arcs (e.g., Rio Doce, Serra da Bolívia, Socorro, Cunhaporanga, Três Córregos) mostly developed from ~ 630 Ma to ~ 585 Ma, connecting AROS segments over almost 1500 km. This suggests that subduction of the northern Adamastor Ocean lasted at least until ~ 585 Ma. Ocean closure seems to have involved exotic terranes (e.g., Rio Negro island arc, Curitiba microplate) in the AROS segment to the south of latitude 21°S; to the north of this, an Adamastor ridge branch ended within an inland-sea basin (the Araçuaí–West Congo gulf) surrounded by the Congo–São Francisco palaeocontinent. The collisional climax, marked by the generation of a huge amount of S-type granites, took place from ~ 575 Ma to ~ 550 Ma along the AROS high-grade core. Late collisional (~ 550–520 Ma) thrust-related features occur in the northern AROS sector (associated with suture-related low-angle shear zones), and in the Búzios region (related to closure of a back-arc basin). Lateral escape tectonics along NE-trending, dextral, strike-slip shear zones, superimposed on preceding thrust fabrics, is a striking feature found from the central to southern AROS segments. A myriad of post-collisional plutons and mafic dykes intruded the AROS high-grade core from ~ 520 Ma to ~ 480 Ma, post-dating the collision-related regional foliation, as well as lateral escape shear zones. In this geotectonic scenario, the amalgamation of AROS together with the West Congo and Kaoko belts might be related to the regional collision climax (~ 575–550 Ma), which is a solid time marker for the assembly of this West Gondwana sector. As assembly of West Gondwana was coming to an end elsewhere, intraplate processes, including the latest closure of orogenic basins, terminal collision episodes, lateral escape shear zones and post-collisional plutonic activity, took place from ~550 Ma to ~ 480 Ma in the Araçuaí–Ribeira orogenic system.

# Unravelling the juvenile Tonian arc of the Ribeira belt, SE Brazil: implications for West Gondwana amalgamation

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The identification of magmatic arcs and related basins, ophiolite sutures and high-pressure metamorphic rocks, together with paleomagnetic data, are key points to better understand the paleogeography prior to Gondwana amalgamation during Neoproterozoic to Cambrian times. Most of the belts that made up the western side of the Gondwana collage are deeply eroded and study of the exposed magmatic arcs brackets the vergence and duration of the subduction process that took place before final amalgamation of the supercontinent.

The Oriental terrane of the Ribeira belt, SE Brazil, encompasses Neoproterozoic magmatic arcs that collided with the São Francisco craton around 620 to 580 Ma (Machado et al., 1996; Tupinambá & Heilbron, 2002; Heilbron & Machado, 2003; Tupinambá et al., 2012, Heilbron et al., 2013). Geochonological data for the development of the magmatic arcs (Rio Negro and Serra da Bolívia) fall in the ~ 790–595 Ma interval. Nd and Sr data point to intra-oceanic to cordilleran settings.

In this work we present new data for a third magmatic arc association (the Serra da Prata arc), located to the east of the other in the Ribeira belt. Arc-related rocks are represented by foliated diorites, tonalites and granodiorites, intruded by leucogneisses. U-Pb data yielded ages between ~ 860 Ma and 635 Ma. Nd and Sr isotopic data point to a primitive and probably intra-oceanic setting, with TDM model ages between 1.3 and 0.9 Ga, εNd values of +5 to -1 and $Sr^{87}/Sr^{86}$ initial ratios of 0.7033– 0.7041.

La-ICPMS U-Pb data indicate that the development of this Tonian–Cryogenian magmatic arc started earlier than the Rio Negro Negro and Serra da Bolívia arcs.

In the scenario of West Gondwana, three other coeval magmatic arc episodes are known: the Mara Rosa arc in the Brasília belt (~ 860 to 630 Ma) and the São Gabriel arc (~ 840 to 690 Ma) are located on the western side of the São Francisco and Rio de la Plata cratons, respectively, and the several magmatic arcs of the Arabian-Nubian Shield (~ 870 to 690 Ma) on the African side. The juvenile character is also a common feature in these associations, indicating intra-oceanic tectonic settings. The combination of these older Tonian magmatic arcs with the previously reported Cryogenean to Ediacaran magmatic arcs of the Gondwana Neoproterozoic belts suggests more than 250 Ma of subduction all around the older cratonic blocks that made up Western Gondwana.

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# Figueira de Castelo Rodrigo-Lumbrales anatectic complex (Central Iberian Zone): new geothermobarometric data

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In the Central Iberian Zone (Iberian Massif) there is a significant change in the Variscan $D_1$ trend from the dominant NW–SE to E–W (Marofa and Ahigal de los Aceiteros synclines). This change is due to the 65 to 100 km sinistral movement of the Juzbado–Penalva do Castelo shear zone (JPCSZ), a composite structure where several shear bands formed as a result of progressive deformation (Pereira et al., 2013). Despite some uncertainties, the JPCSZ has been considered to have been active during the Variscan $D_3$, syn- to-post regional metamorphic peak (Villar *et al.,* 2000). The JPCSZ was responsible for the exhumation of the Figueira de Castelo Rodrigo–Lumbrales anatectic complex, resulting in its juxtaposition to low-grade (350–450 ºC) metasediments. The complex is essentially composed of metatexites, diatexites and two-mica anatectic granites. We present new geothermobarometric data in order to better constrain the regional metamorphic climax, as well as the evolution of this first-order Variscan tectonic feature.

Mineral analyses were conducted on a JEOL JXA-8200 electron microprobe and P-T estimates were obtained using THERMOCALC software (Holland and Powell, 1998), version 3.33. Due to lack of garnet in the migmatites, peak metamorphism calculations were made using interlayered calc-silicate rocks with a mineral assemblage of plagioclase + biotite + amphibole + clinopyroxene + garnet ± titanite ± apatite ± zircon ± oxides. These minerals are chemically unzoned, displaying flat rim-core-rim chemical profiles. The garnet is grossular-rich ($X_{Alm}$ = 0.51; $X_{Py}$ = 0.05; $X_{Gr}$ = 0.31; $X_{Spss}$ = 0.13), whereas clinopyroxene is essentially hedenbergitic ($X_{En}$ = 0.25; $X_{Fs}$ = 0.28; $X_{Wo}$ = 0.47). Peak paragenesis is also composed of plagioclase ($X_{An}$ = 0.95) and ferrohornblende. P-T estimates using garnet-pyroxene-amphibole-plagioclase equilibrium reactions establish the metamorphic peak at 725±50 ºC and 5.4±1 kbar.

These new results are compatible with a geothermal gradient of 36 $ºC·km^{-1}$, slightly higher than that prevailing in typical Barrovian-type conditions, implying relatively shallow depths for crustal anatexis during Variscan orogenic events. These new results provide an explanation for the absence of garnet in the anatectic pelites, whereas the absence of mineral zoning in the peak parageneses suggests fast exhumation of the Figueira de Castelo Rodrigo–Lumbrakes complex induced by the JPCSZ. If the low-grade rocks were formed under the same geothermal gradient, the vertical exhumation of migmatitic rocks from their level of generation to the final juxtaposition with greenschist facies rocks is estimated to be over 12 km.

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# Sedimentary record of the amalgamation and break-up of Pangaea: U-Pb detrital zircon geochronology and provenance of Carboniferous–Triassic siliciclastic rocks, SW Iberia

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In SW Iberia there is a basal unconformity where Triassic sandstones overlie previously deformed Carboniferous turbidites. This important stratigraphic boundary records the transition from the final stages of Pangaea's amalgamation to the initial stages of break-up. U-Pb dating of detrital zircon from Carboniferous greywackes of the South Portuguese Zone and Triassic sandstones of the Algarve and Alentejo basins was carried out to conduct a study of sedimentary provenance. The radiometric ages obtained by LA-ICP-MS show that most of the samples have common age spectra which are typical of North Gondwana sources: Archean and Paleoproterozoic ages characteristic of the West African craton, Neoproterozoic ages associated with Cadomian and Pan-African orogenies, and Cambrian ages related to the intra-continental rifting of North Gondwana. The only exception is a Visean immature greywacke that was probably derived from Devonian magmatic arcs related to the Variscan orogeny. Very rare pre-Devonian zircons indicate faint contributions from recycled sediments. In contrast the Serpukhovian to Moscovian greywackes are derived from felsic mature source rocks and include Proterozoic and Paleozoic detrital zircons suggesting recycling of an old basement. They also include Ordovician and Silurian detrital zircons, the ages of which have no correspondence in North Gondwana, and thus indicate an external source (Laurussia?). U-Pb ages younger than Ordovician are significant in the Triassic sandstone of the Alentejo basin and resemble the zircon populations of the Serpukhovian to Moscovian greywackes from the South Portuguese Zone. U-Pb ages younger than Neoproterozoic are poorly represented in the zircon population of the Triassic sandstone from the Algarve basin, which rests unconformably upon Moscovian turbidites, pointing to Upper Devonian quartzites of the South Portuguese Zone as probable sources, since they are dominated by Precambrian detrital zircons. These differences occurring in the Triassic basins suggest that detrital zircon populations could be derived from two independent sources and paleo-drainage systems due to complex crustal-block extension architecture.

# New U-Pb zircon dating of Late Neoproterozoic magmatism in Western Meseta (Morocco)

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We present new U-Pb zircon ages from magmatic rocks of the Western Meseta, part of the Moroccan Variscan belt. The Neoproterozoic–Cambrian stratigraphy in the region of Goäida (Aguelmous massif, SE of Moroccan Central Massif) consists of limestones with conglomeratic and felsic volcaniclastic levels, pelites and mafic volcanic rocks assigned to the Cambrian which unconformably overlie rhyolites, andesites and rhyodacites and felsic tuffs associated with the Aguelmous granite of probable Neoproterozoic age. The Neoproterozoic–Cambrian stratigraphy of the region of Sidi Ali is roughly similar and also includes a volcanic-sedimentary complex with limestones, arkoses rhyolites and conglomerates. These conglomerates contain pebbles of granite and rhyolite, whose source may be the Neoproterozoic basement. In order to constrain the age of the Precambrian felsic magmatism we sampled and dated zircons (LA-ICPMS) from the Goäida granite and a pebble of granite included in the conglomeratic levels of the volcanic-sedimentary complex at Sidi Ali dome (central Rehamna massif). In the Goäida granite, zircon ages are Ediacaran ranging between ~ 610 Ma and ~ 540 Ma, with a discordia upper intercept age of 598±32 Ma (MSWD=0.04) that could be interpreted as the age of intrusion. However, if we consider only the two youngest ages we obtain a Concordia age of 590±3 Ma (MSWD= 0.34). In the Sidi Ali pebble sample the majority of zircon ages are Cryogenian–Ediacaran in the range ~ 640–600 Ma, with the youngest yielding a Concordia age of 609±2 Ma (MSWD=0.04), indicating the intrusion age of the granite from which the pebble derived. These results support the existence of Cadomian/Pan-African magmatism in the Western Meseta of Morocco, characterized by the intrusion of granites at ~ 609 Ma and ~ 590 Ma. This result is important for studies of sedimentary provenance and to improve paleogeographic reconstructions of the northern margin of Gondwana during the Neoproterozoic.

# New insights into the tectonic evolution of the Southwestern Iberian Shear Zone

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New structural and radiometric data have improved our knowledge of the timing of deformation and the geometric framework of the southwestern Iberian Shear Zone. This Variscan collisional boundary, located in the Iberian Massif between the Ossa-Morena Zone (OMZ) and the South Portuguese Zone (SPZ), is characterized by a complex evolution dominated by transpressive left-lateral kinematics. The tectonic evolution we propose can be summarized as follows:

1) Emplacement of high-pressure and thin ophiolitic allochthonous units onto the southern border of the OMZ. These units attest to the closure of the Rheic Ocean and the subduction of the OMZ continental margin. The kinematic interpretation of early stretching lineations indicates that the convergence was oblique left-lateral.

2) A transtensional event temporarily interrupted the convergence and admitted a very narrow aisle of early Carboniferous oceanic-like crust, represented by the Beja-Acebuches Amphibolite (BAA), previously interpreted as the Rheic Ocean suture. Abundant c. 340 Ma mafic and acid magmatism was intruded/extruded on both sides of the oceanic strip.

3) Oblique convergence was resumed immediately after transtension, first causing obduction of the oceanic-like unit and north-verging folding observed in the metasedimentary Pulo do Lobo unit in the southern border of the suture. Subsequently, a south-vergent large-scale fold was developed affecting the BAA, with coeval left-lateral granulite-amphibolite facies shearing. In the eastern sector of the suture, only the southern (inverted) limb of this overturned fold crops out. However, in the western sector new mapping of the high-grade tectonic fabric developed in the BAA, shows the complete folding pattern, not previously recognized.

4) Shear deformation in amphibolite to greenschist facies gave way to a WNW-ESE low-pitch stretching lineation concentrated on the southern limb of the BAA fold. It constituted a complex ductile 2–3 km-thick left-lateral shear band that evolved and cooled southwards to low-temperature greenschists in the northern border of the Pulo do Lobo unit. Radiometric dating of acid volcanic rocks affected by the low-grade shear zone has set an older limit of 337 Ma for this shearing.

5) Finally, oblique convergence propagated southwards across the SPZ in late Carboniferous time, though lateral displacements decreased rapidly in favour of shortening. Brittle left-lateral faults partially broke and displaced the previous syn-metamorphic shear zone during the latest deformation.

To sum up, the transpressive OMZ/SPZ boundary shows strain partitioning, with left-lateral displacements concentrated in high-to-low temperature shear zones, and moderately oblique convergence affecting a broad zone of the SPZ foreland. A prior transtensional magmatic stage had a disrupting effect on the OMZ/SPZ boundary. This complex tectonic evolution has strongly obliterated the original features of the Rheic suture in Southern Iberia.

# New data on Taphrosphyini (Pleurodira, Bothremydidae) from the Paleogene of Mali: the study of the shells

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One of the most diverse groups of Pleurodira is the extinct clade Bothremydidae (Pelomedusoides). It was composed of forms inhabiting both freshwater and littoral environments (Lapparent de Broin and Werner, 1998). The northern half of Africa has been identified as an area of bothremydid diversification in the Late Cretaceous and Paleogene, with many taxa recorded in near-shore marine deposits (Lapparent de Broin, 2000; Gaffney et al., 2007). The Paleogene record of this group from Mali is very relevant. In fact, two new representatives, *Azabbaremys moragjonesi* and *Acleistochelys maliensis*, both corresponding to new genera and species, have recently been described there (see Gaffney et al. 2001, 2007). Furthermore, the presence of *Nigeremys gigantea*, or a possible closely-related form, has been notified (Gaffney et al., 2006), and *Taphrosphys* sp. has been recognized there (Lapparent de Broin and Werner, 1998; Lapparent de Broin, 2000). All these taxa of side-necked turtles correspond to large coastal bothremidids, belonging to Taphrosphyini (sensu Gaffney et al., 2006).

*Azabbaremys* is only known by its holotype, a complete skull lacking lower jaws. *Acleistochelys* is also exclusively known by its holotype, which gives good cranial information but few and uninformative associated shell fragments. The material assigned by Gaffney et al. (2006) to *Nigeneremys* corresponds to a single specimen, consisting of the articulated right and left premaxillae and maxillae, and a partial quadrate. The material attributable to *Taphrosphys* sp. has not been described, but it includes isolated plates. Thus currently available information on the shells of Bothremydidae from the Paleogene record of Mali is extremely limited.

Abundant and well-preserved shell material of Bothremydidae from the Paleogene of Mali is presented here. These hitherto unpublished specimens were found in expeditions in the early 1980s, and deposited in the Natural History Museum (London). The holotype of *Azabbaremys* was also found as a result of these surveys. The specimens analyzed here not only correspond to isolated plates and articulated fragments of shells, but also to nearly complete plastra and shells. This study sheds new light on the anatomy of the members of Taphrosphyini that lived during the Paleogene in Africa.

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# Finding the supposedly lost holotype and only known specimen of the podocnemidid *Stereogenys libyca*, a turtle from the early Oligocene of Egypt

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The shell-based species *Stereogenys libyca* (Pleurodira, Podocnemididae) was described by Andrews (1903) from one specimen collected during his 1902 expedition to the Fayum Depression (Egypt). It comes from early Oligocene levels. That nearly complete shell is the only specimen so far robustly attributed to this taxon. Andrews (1903) described it and published a figure consisting of three drawings: much of the dorsal and ventral views, and the right lateral view. He reproduced the same figure in another paper in 1906, but no photograph of this specimen was ever published. Discussions by other authors, in subsequent papers, are based on the data provided in the two mentioned works. Recently, Gaffney et al. (2011) conducted a detailed review and update of knowledge of Podocnemididae. They indicated that the current whereabouts of the holotype of *Stereogenys libyca* was unknown, not having been identified in the Cairo Geological Museum (Egypt), where it should have been held from the 1960s. Therefore, Gaffney et al. (2011) figured and discussed *Stereogenys libyca* solely of the basis of the works of Andrews (1903, 1906).
The holotype of *Stereogenys libyca* has now been located. It is presented here, being recognized as one of the best preserved shells from the Fayum Depression. Its study allows me to assess the validity of the interpretation of the morphology of the plates and scutes proposed by Andrews. Furthermore, the anatomy of the visceral region, both of the carapace and of the plastron, can be analyzed. Other skeletal elements, such as the pelvis, are studied here for the first time. The new study of this specimen, performed over 110 years after its original description, greatly improves knowledge of this taxon. Because of holotype was not available to them, Gaffney et al. (2011) could not confirm the validity of *Stereogenys libyca* or recognize it as a junior synonym of *Stereogenys cromeri* (another taxon of the Fayum Depression, defined by Andrews in 1901). Its recovery, together with those of several partial shells attributable to *Stereogenys* also from the Fayum Depression, should allow me to test whether there are separate species, or to recognize them as included in the range of variation of a single taxon.

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# An update on the diachronous migration to Europe of several Gondwanan lineages of pleurodiran turtles

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Extant turtles belong to two lineages: Pleurodira and Cryptodira. Pleurodira are principally characterized by sutured contacts between pelvis and shell, and the acquisition of horizontal neck retraction. They principally developed in Gondwana, while Cryptodira spread through Laurasia (Lapparent de Broin, 2000). Pleurodira are now restricted to relatively warm regions, with a more limited geographical distribution than Cryptodira. They now basically live in freshwater environments, usually of intertropical areas, in continents that formed part of Gondwana: Africa, South America and Oceania. The relative position of the landmasses, and variations in global temperatures, resulted in changes in their distributions. Pelomedusoides are Gondwanan pleurodires, known from the Early Cretaceous. Their most abundant and diverse representatives are Bothremydidae and Podocnemididae, both recognized in the European record.

The fauna of freshwater turtles from the Early Cretaceous of Europe was mainly composed by Laurasiatic Cryptodira. However, Pleurodira experienced a significant development in the Late Cretaceous, with the introduction of marine taxa adapted to freshwater environments (Pérez-García, 2012). At least some of these Gondwanan pleurodires belong to Bothremydini (sensu Gaffney et al., 2006), a clade of Bothremydidae that probably reached Europe before the Santonian.

A single specimen of Pelomedusoides has been identified in the Paleocene of Europe: the French *Taphrosphys ambiguus* (see Broin, 1977). It belongs to another clade of Bothremydidae: Taphrosphyini. It was found in a marine environment. Paleocene sites with continental fauna are rare and always exhibit Laurasiatic taxa.

The greatest European diversity of Pelomedusoides is recorded in the Eocene. More than a dozen species of Podocnemididae are identified, all corresponding to the African clade Erymnochelyinae.

The European post-Eocene record of Pleurodira is extremely limited. Only two specimens have been cited. "*Chrysemys*" *montolivensis*, from the Oligocene of France, was initially attributed to Cryptodira. Broin (1977) reassigned it to Pelomedusoides, pointing to its possible affinity with Bothremydidae in subsequent papers. The other is the holotype of *Nostimochelone lampra*, from the Early Miocene of Greece. The limited available information does not allow a precise determination.

The European record represents several diachronic migrations of African pleurodires to Europe. The transformation of several lineages from originally continental forms to littoral taxa facilitated the dispersion. Some of these migrations were very successful. A review of the taxa involved, and the study of abundant unpublished material (including several new taxa), allow us to improve knowledge of the systematics and paleobiogeography of these forms.

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Lapparent de Broin, F. de, 2000. African chelonians from the Jurassic to the present: phases of development and preliminary catalogue of the fossil record. Palaeontologia Africana 36, 43–82.

Pérez-García, A., 2012. Las tortugas mesozoicas de la península Ibérica. Ph.D. thesis, Universidad Complutense de Madrid.

# On the debatable generic assignment of the African "*Podocnemis*" *fajumensis* and the endemism of *Neochelys*

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Pelomedusoides is a clade of turtles that originated in Gondwana. It experienced a major radiation during the Early Cretaceous, resulting in several groups, such as the abundant and diverse Podocnemididae (Lapparent de Broin, 2000a). Podocnemididae is currently represented by the South American *Podocnemis* and *Peltocephalus dumerilianus*, and the African *Erymnochelys madagascariensis*.

The African record of Podocnemididae is relatively abundant, with sites in several countries, corresponding to different stages of its geological history. The Fayum Depression, in Egypt, is the area where the greatest diversity has been recorded in both the Eocene and Oligocene (Lapparent de Broin, 2000b). From the early Oligocene here, Andrews (1903) defined *Podocnemis fajumensis* from the anterior region of a plastron. Other partial and relatively complete shells were recognized in subsequent papers, including those of its junior synonym "*Podocnemis blanckenhorni*" (e.g. Reinach, 1903; Andrews, 1906).

The attribution of "*P.*" *fajumensis* to *Podocnemis* cannot be supported. Lapparent de Broin (2000b) recognized it as belonging to an undescribed genus, related to *Erymnochelys* (aff. *Erymnochelys fajumensis*). Gaffney et al. (2011) identified, for the first time, the presence of skulls associated with shells of "*P.*" *fajumensis*. They admitted that its shell is very similar to that of *Erymnochelys*, showing differences with the European Eocene *Neochelys*. *Neochelys* is an abundant and diverse taxon. However, only a deformed skull, corresponding to the French *N. arenarum*, had been thoroughly figured as attributed to this genus. Gaffney et al. (2011) considered the skull of "*P.*" *fajumensis* as hardly distinguishable from that of *N. arenarum*, proposing the new combination *Neochelys fajumensis*.

The analysis of the so far published material of *Neochelys*, and the study of abundant new cranial and postcranial specimens, allow us to review the anatomy of each of the known species, and to propose a new generic diagnosis. As a result, *Neochelys* is recognized as exclusively distributed in the Eocene of Europe. Numerous differences in both the cranial and postcranial skeleton are identified between *Neochelys* and "*Podocnemis*" *fajumensis*. Therefore, this African species cannot be attributed to *Neochelys*, being identified as a possible member of the *Erymnochelys* group.

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# Did the Messinian salinity crisis allow the migration of large tortoises from Africa to Europe?

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Fossil testudinids are known in Europe since the Eocene. As well as relatively small taxa (usually < 30 cm in length), the European record includes several taxa of medium and large size. The largest size is achieved by several Neogene taxa, mainly early Miocene and Pliocene. The description of new specimens and a review of the previously published ones have allowed us to gain a better understanding of the morphology of the European large testudinids and to recognize that all these large taxa are part of a monophyletic lineage. However, we have identified a new European species, coming from levels near the Miocene–Pliocene limit that cannot be assigned to that lineage. This new taxon shares several characteristics with the extant African *Centrochelys sulcata*. The African lineage of *Centrochelys* has been recognized from pre-Messinian levels (Lapparent de Broin et al., 1999; Gmira et al., 2013).
The Messinian salinity crisis is one of the most important events in the history of the circum-Mediterranean area, causing major changes in the paleogeography and affecting the faunal assemblages in latest Miocene times, for example enabling the migration of representatives of the African fauna into Europe. The interaction between Europe and Africa has been demonstrated based on large and small mammal species, but so far there has been no evidence regarding the chelonian assemblages. The hypothesis proposing this new European tortoise as an African immigrant is evaluated here.

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# Geochronological vs. paleontological dating of the Estremoz Marbles (Ossa Morena Zone, Portugal) – new data and reappraisal

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The "Volcanic-Sedimentary Complex of Estremoz" (VSCE, up to 240 m thick), located in the Portuguese part of the Ossa-Morena Zone, constitutes one of the most distinctive units in the Paleozoic basement of SW Iberia. Thick-bedded intercalations of recrystallized limestone (70–100 m) in the Estremoz anticline support an important extractive industry, the most famous of which are the Portuguese fine-to-medium grained white marbles. However, the stratigraphy and age of the complex are poorly understood due to its intense tectonization and metamorphism, and to the scarcity of valuable biostratigraphic data. The Estremoz marbles were first considered as lower Cambrian (1966–1980's), then ?Ordovician (1984–1994) and finally as Silurian–Devonian (1994–2010), owing to the discovery of some crinoid remains and rare conodonts in recrystallized limestone in the Estremoz and Ferrarias anticlines (Piçarra & Le Menn, 1994; Piçarra & Sarmiento, 2006).
The biochronological data were recently challenged: Pereira et al. (2012) expressed doubts over correlation between the Estremoz and Ferrarias antiforms, whereas Araújo et al. (2013) suggested that paleontological samples were possibly contaminated with younger exotic conodonts, re-sedimented in cryptic limestone infillings. Pereira et al. (2012) obtained a geochronological age of ~ 499 Ma (Furongian) for a single rhyolite body that they consider as interbedded in the upper part of the Estremoz marbles. On the basis of a single sample of 10 zircon grains from a locality west of Estremoz, they applied this age to the entire Volcanic-Sedimentary complex. The same "rhyolite" (a strongly foliated felsic meta-volcanic rock) was previously described and mapped by Coelho & Gonçalves (1970) and Mata & Munhá (1985). It is definitely not interbedded with the Estremoz marbles but occurs as a lenticular body, 6 km long, restricted to the SW flank of the Estremoz anticline, separating the typical marbles of the VSCE from Silurian shales, and always displaying tectonized contacts. Coelho & Gonçalves (1970) even consider it as post-Silurian. As there is no record of undisputed Furongian sedimentary or volcanic rocks anywhere in the Ossa-Morena Zone, it is possible that the zircons studied by Pereira et al. (2012) may represent relicts of reworked crystal grains inherited by a younger pyroclastic rock, which is now a completely recrystallized metamorphic rock of a gneissic aspect.
In the present work we demonstrate the occurrence of fossils of free-living tentaculitoids, probably Early Devonian in age, from the lower marble beds of the VSCE. The single fossil locality lies immediately east of the town of Bencatel, and is consistent with the occurrences of post-Cambrian pelmatozoan columnals along the SW flank of the Estremoz anticline, as well as of holomeric crinoid ossicles and post-Ordovician conodonts recorded from the southeast prolongation of the same beds in the Ferrarias anticline. The new paleontological and biochronological data suggest a maximal Early Devonian age for the VSCE, in contrast with the geochronological data provided by pre-Variscan metavolcanic rocks that do not belong to this complex and are probably much younger than late Cambrian.

# New paleomagnetic data from the Late Paleozoic New England orogen (Eastern Australia) and a developed kinematic model of its evolution

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The New England orogen is the youngest segment of the eastern Australian Tasmanides. It was developed as an accretionary orogen during the late Paleozoic to early Mesozoic Gondwanide orogeny (310–230 Ma) that extended along the Pacific margin of the Gondwana supercontinent. The orogen exhibits a doubly vergent oroclinal structure with southern (Manning orocline) and northern (Texas–Coffs Harbour orocline) segments displaying S- and Z-shaped sets of oroclines, respectively. These opposite vergences led to contrasting models of formation. Cawood et al. (2011) proposed an animated model for the paleomagnetically permissive evolution of the orogen. However this model is not unique due to the limited number of reliable paleomagnetic data. In particular, the northern Texas–Coffs
Harbour orocline has been strongly under-represented paleomagnetically. Additionally, the previously published results of paleomagnetic studies in the North Tamworth terrane involved rocks which are ~ 20 Ma younger than the paleomagnetically studied rocks from the southern (Manning) orocline. Recently we collected oriented paleomagnetic samples from the Visean Caroda Formation of the North Tamworth block, from the previously unstudied Emu Creek block located at the eastern flank of the Texas orocline, and from Late Carboniferous to Early Permian rocks in the Manning orocline. Our new paleomagnetic results from the North Tamworth block are comparable in age with previously published Visean data from the Manning orocline. The comparison of these results suggests that the North Tamworth terrane was rotated 90° anticlockwise between 330 and 260 Ma. The new data from the Emu Creek block support the previous model of the movement of the Texas block (Cawood et al., 2011). Here we present the revised animated model of the evolution of the New England orogen.

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# History and evolution of Gondwana: a geological perspective from its northern periphery

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The concept of Gondwana has played a major role in establishing the foundations of our current understanding of the Earth's evolution, with very profound impact on cultural and scientific issues. Despite not being originally a part of the "*Land of the Gonds*", the relatively small piece of land that forms the Iberian Peninsula contains a protracted geological record spanning a large part of the evolution of Gondwana as the southern hemisphere supercontinent. The terranes making up the Iberian Peninsula always occupied peripheral positions at or near the northern margin of the supercontinent, from the amalgamation stage in Neoproterozoic–early Cambrian times until the opening of the Thetis ocean in the Lower Jurassic. The study of such terranes, their mutual boundaries and the processes involved in their formation and juxtaposition may contribute to better understanding the evolution of the supercontinent. The following sequence of "Gondwanan" events is recognized in Iberia:

1) Evidence of the amalgamation stage is beautifully exposed in the Iberian Massif, the westernmost extent of the peripheral Cadomian orogen. It shows the juxtaposition of a Neoproterozoic terrane, recently correlated with northeast African units, with a peripheral arc terrane (Ossa-Morena zone) adjacent to the West African craton.

2) A subsequent rifting stage was recorded during the Cambrian and culminated in opening of the Rheic ocean and drifting away of a peri-Gondwanan fragment in the Lower Ordovician (presumably Avalonia and correlatives).

3) The evolution during Ordovician–Devonian times was characterized by stable platform sedimentation onto the northern passive margin of Gondwana.

4) This regime persisted until the onset of the Variscan orogeny that lasted in Iberia from the mid-Devonian until the Early Permian, and culminated in the suturing of Gondwana and Laurussia to form Pangea. The Variscan orogeny in Iberia records the collision between a promontory in the former, as a result of which an outstanding structural difference between the northern (normal convergence) and southern (left-lateral transpression) Iberian Massif was established.

5) The post-Pangea evolution preserves the record of the onset of the breakup of Gondwana, evidenced in Iberia by a Late Permian–Triassic rift event that culminated in opening the Thetis ocean in the Lower Jurassic. After that, Iberia and most of the Gondwanan units in southern and central Europe remained in Laurasia, whereas the rest of Gondwana drifted apart, subsequently being subjected to further break-up and dispersal.

6) Finally, some Gondwanan units returned to Iberia during the Alpine orogeny, being currently exposed in the Internal Betics (Alborán Domain).

# Early Paleozoic construction of southwest Gondwana: evidence from detrital zircons in the Sierras Pampeanas

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Basement exposures in the Sierras Pampeanas at 26º–33ºS give a unique opportunity to compare paleo-sediment sources along a significant stretch of the Andean foreland. To this end we have studied a large number of widespread samples using U-Pb SHRIMP age determination of detrital zircons, coupled with identically-located Hf and O determinations. The study includes comparison with neighbouring sectors in NW Argentina and Patagonia, and inferred sources in Eastern Laurentia, Southern Africa and East Antarctica.

The detrital zircon age patterns of metasedimentary rocks from the Western Sierras Pampeanas (WSP) indicate predominant derivation from the adjacent 1330–1030 Ma Mesoproterozoic complexes, with the same lithologies and time span as the Grenville province in Eastern Laurentia. More specifically, an important secondary detrital peak at ~ 1.4 Ga shows the same juvenile Hf isotope signature (εHft from +11.2 to +5.3) as the Southern Rhyolite Province of the southeast USA, which lies along the western margin of the Grenville province. Terranes with Laurentian affinities are also found in the Puna and Arequipa to the north, and probably to the south in the North Patagonian Massif. Thus a large, ribbon-like collage of drifted Laurentia-derived terranes (MARA) is inferred to have been welded to SW Gondwana during the Early Cambrian Pampean orogeny.

The MARA terrane collage collided obliquely with the Eastern Sierras Pampeanas (ESP), the latter consisting of a 540–530 Ma continental volcanic arc and its Neoproterozoic to Early Cambrian metasedimentary envelope. The detrital zircon patterns of ESP high-grade metasedimentary rocks deposited before the Pampean orogeny are identical to those of the low-grade tract of the Puncoviscana Formation of NW Argentina. The main pattern of the "Puncoviscan series" is strongly bimodal, with peaks at ~ 570–670 and ~ 1000 Ma and a minor Late Paleoproterozoic peak (1860–1900 Ma). There are no obvious nearby sources for the main peaks, which are probably derived from SW Gondwana sources such as the East Africa–Antarctic orogen and/or the Dom Feliciano belt.

Although volumetrically very scarce compared with the "Puncoviscan series", distinct detrital zircon age patterns have been reported from both the ESP and NW Argentina. For example, our sample from the Ancaján series, which is tectonically interleaved with the "Puncoviscan series" near the eastern slope of Sierra de Ancasti, has several characteristics in common with the metasedimentary rocks and Neoproterozoic cover of the WSP. This includes important Early Mesoproterozoic components (1200–1500 Ma), significant Late Paleoproterozoic peaks (~ 1800–1900 Ma), and the absence or very minor presence of Late Neoproterozoic peaks. This important observation strongly suggests that the Laurentian platform sediments of MARA were tectonically involved with SW Gondwana sediments during the Early Cambrian Pampean collision. The accretion of MARA shaped the outer edge of SW Gondwana, becoming the basement for future Andean episodes.

# A brief history of the oceans that split Gondwana

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The growth of the oceans that now separate the continents of Gondwana has been worked out, step-by-step from first principles, from the record of fracture zones in ocean-floor topography, time-calibrated against marine magnetic anomalies, where available. The principles set out by Reeves and de Wit (2000) have been followed more precisely. Within the Indian Ocean, the oceanic crust separating India from Antarctica has a simpler and better-defined record than that separating India from Africa. The latter is complicated by the interposition of Madagascar, the Seychelles, the Mascarene fragments and several ridge jumps. New certainty in the relative position of Africa and Antarctica from conjugate M-series magnetic anomalies 153 to 125 Ma (Kimmeridgian to Aptian) (König and Jokat, 2010) then allows more robust examination of the relative movements of Madagascar and India within the system in this period through closure of the Africa-Antarctica-India plate circuit. The tight starting position of the Precambrian fragments of Gondwana is essentially that published by Reeves et al. (2004) with minor refinements. The oceans as shown on CGMW Geological Map of the World (Bouysse, 2010), colour-coded according to age, have been used to demonstrate the model in a computer animation for the period from the start of the Jurassic to the present day. Areas of ocean 'of uncertain age' have been clarified as a result of the systematic modelling. The role of mantle plumes in initiating changes in otherwise stable regimes of relentless ocean growth is evident. A small number of key events, starting at 183 Ma (Toarcian) with the impact of the Bouvet/Karoo plume in Mozambique, followed by that of the Kerguelen and Tristan plumes (135 Ma, Hauterivian) and the Marion plume (88 Ma, Coniacian) punctuate processes of ocean growth driven principally by ridge push. The animation of the result, more refined than any published previously, is freely available for download on the website www.reeves.nl/gondwana.

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# An appeal for a map of Precambrian Gondwana with input from regional geophysical programmes in Africa and elsewhere

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Central Gondwana existed as a stable continental landmass for more than 300 Ma from its consolidation in early Cambrian times until disruption started in earnest in early Jurassic times; it's originally continuous Precambrian terrane is now dispersed into at least six present-day continents. Much of Africa's share of Gondwana's Precambrian geology is obscured by either Phanerozoic cover formations or weathering products of the Precambrian basement that frustrate exploration for mineral resources largely hosted by these older rocks. The situation is similar in South America, India and Australia. Antarctica's Precambrian is mostly obscured by the ice-cap but has been investigated geophysically.

In a bid to stimulate exploration for mineral resources, most countries in Africa have employed airborne geophysical surveys – principally aeromagnetic and gamma-ray spectrometer surveys – to reconnoitre the hidden Precambrian geology in the past 50-60 years. The objective has been to map the regional geology so that commercial exploration investments may be better-focussed on areas that hold the greatest promise for exploitable minerals. The World Bank and the European Union have supported many of these activities financially with funding from the global tax-payer at a level of hundreds of millions of dollars. Interpretation of national surveys has produced many profound insights into hidden geology and structure at scales of 1:1 000 000 or better.

Field mapping in recent decades, supported by the widespread application of modern dating techniques, has produced valuable contributions to understanding the sometimes far-flung outcrops of Precambrian rocks in Africa. The scientific literature often shows attempts at correlating distant Precambrian terranes and relating them to a pattern of cratons and mobile belts that has become reasonably well-known in southern Africa, for example.

This talk is an appeal to integrate these two streams of information – modern geological field mapping and geochronology on the one hand with geophysical mapping and interpretation on the other – at a scale of, say, 1:10 million across all Africa. In this way, the non-specialist could see a defensible picture of Africa's Precambrian terranes (where there is consensus) and specialists could have an informed discussion. Postulated geological or tectonic discontinuities and terrane boundaries that are at variance with clearly-defined geophysical trends and boundaries could be re-evaluated. Gravity anomaly data from earth-orbiting satellites (e.g. GOCE) also now has the potential to contribute useful constraints at such a scale, even though ground gravity data collection has been neglected over most of Africa. The African Precambrian map could then be correlated with similar information in a more advanced state for South America, India and Australia as a valuable contribution to the up-coming second edition of the Geological Map of Gondwana (IGCP 628).

# Preliminary age data from Mount Creswell, central Prince Charles Mountains, East Antarctica: evidence for terrane assembly at 900 Ma and not 500 Ma

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The Prince Charles Mountains of East Antarctica are divided into three terranes: the Beaver terrane in the north with dominant magmatism and metamorphism at 1000–900 Ma, the Ruker terrane in the south with major periods of magmatism and metamorphism at ~ 3100 and 2700 Ma, and the Lambert terrane sandwiched between them with dominant magmatism and metamorphism at ~ 2400 and 2100 Ma. Detailed studies have focused on the Mawson Escarpment at the eastern edge of the mountains, where the Lambert terrane records metamorphism at 1000–900 Ma indicating a link with the Beaver terrane by this time (Corvino *et al.,* 2008), and the boundary between the Ruker and Lambert terranes is a high-strain zone recording metamorphism at deformation at ~500 Ma. This has been interpreted as a Cambrian suture inferred to extend east–west across Antarctica (Boger *et al.,* 2001).

Few age constraints are available further west, but we have undertaken a SHRIMP U–Pb study of the Mount Creswell region, some 100–150 km west of the Mawson Escarpment. Two samples of garnet-biotite-quartz gneiss contain oscillatory-zoned detrital zircon grains with identical age populations at ~ 3100, 2700, 2500, 2300, and 2100 Ma. These ages correlate closely with basement rocks in the Ruker and Lambert terranes, suggesting the protolith was eroded from these terranes sometime after they had amalgamated. Garnet amphibolite interleaved with the felsic gneiss yields a single population of un-zoned, low-uranium zircon grains with a Concordia age of 957 ± 18 Ma. This is interpreted as the age of amphibolite metamorphism in the Mount Creswell region, indicating that these rocks are part of the Beaver terrane. Our preliminary data suggest that the Ruker, Lambert and Beaver terranes amalgamated before peak metamorphism at 1000–900 Ma in the Beaver terrane, challenging the widely held view that there is a Cambrian suture in the Prince Charles Mountains and consistent with arguments that the Prince Charles Mountains might have assembled at ~1.0 Ga (Phillips *et al.,* 2009; Mikhalsky *et al.,* 2010).

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# Coral assemblages in the Viséan and Serpukhovian from Southern Spain and North Africa: paleogeographic implications

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The southern region of western Palaeotethys (Iberian Peninsula and North Africa) is important for understanding relationships between the Palaeotethys and Rheic oceans and between Laurasia and Gondwana during the Carboniferous. Rugose and tabulate corals are common in Upper Mississippian (Viséan and Serpukhovian) rocks from this area, and their distribution gives important information on geographic barriers and sea connections that existed at that time.

Four basin areas can be distinguished in Southwestern Palaeotethys: Ossa-Morena Zone, Betic Cordillera, Central Moroccan Meseta and Sahara. Two main basins in the Ossa-Morena Zone have a Late Mississippian marine record: Los Santos de Maimona and Guadiato. The record from Betic Cordillera is indirect because it is contained in boulders of the olistostromic Marbella Formation. Two areas from the Moroccan Meseta show excellent record of fossil corals: Adarouch and Khenifra, respectively in the northern and southern regions of the Azrou-Khenifra Basin. The Sahara region shows a complex system of partly interconnected basins: we distinguish the Tindouf, Tafilalt, Bechar and Reggan-Ahnet basins but two other important basins (Illizi and Taoudenni) have poorly-known coral assemblages and will be only partly considered here. A separate basin in northeast Morocco (Jerada) is also included in our analysis.

Many rugose and tabulate genera show a wide geographical distribution during the Mississippian. *Axophyllum*, *Caninia*, *Clisiophyllum*, *Cyathaxonia*, *Dibunophyllum*, *Lithostrotion*, *Michelinia*, *Multithecopora*, *Palaeosmilia*, *Siphonodendron* and *Syringopora* occur throughout Palaeotethys and their absence in any area implies either quite specific environmental conditions or some kind of geographic isolation. However, most coral genera show irregular distributions, and their presence or absence gives valuable information on the geographic relationships between different areas (e.g., *Actinocyathus*, *Amygdalophyllum*, *Arachnolasma*, *Auloclisia*, *Corwenia*, *Diphyphyllum*, *Gangamophyllum*, *Lonsdaleia*, etc.).

In spite of the proximity between the Los Santos de Maimona and Guadiato areas, they show important differences that imply some kind of barrier between them. Los Santos de Maimona has a quite impoverished assemblage (in terms of diversity) that marks a degree of isolation, whereas the Guadiato area shows a strong relationship to the northern Moroccan basins. As expected, Adarouch and Khenifra show a high degree of proximity. Comparing the Saharian basins, Tindouf and Bechar show conspicuous differences, probably due to a barrier represented by the Ougarta High and/or ecologic differences. The Reggane-Ahnet basins have assemblages intermediate between those of Bechar and Tindouf and could represent a connection between them.

# Palaeogeographic features of the Malaguide complex (Betic Cordillera, Southern Spain) during the Frasnian/Famennian crisis from evidence obtained in redepositional and condensed stratigraphic horizons

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The Malaguide complex includes the highest Alpine thrust nappes of the Betic Internal Domain and bears a Palaeozoic succession including pre-Hirnantian to Upper Carboniferous formations. In beds underlying Tournaisian radiolarites (Falcoña Formation) the Frasnian–Famennian crisis is evidenced by stratigraphic discontinuity surfaces associated with conodont biofacies shifts (Marbella: Herbig, 1985; Almogía: Rodríguez-Cañero, 1993) and by redepositional horizons of pebbly mudstones overlying thin-bedded mixed calcareous-siliciclastic turbidites similar to the Santi Petri Formation, Falcoña (Rodríguez-Cañero & Martín-Algarra, 2014).

At Almogía, a stratigraphic gap in the Frasnian *linguiformis* Zone is associated with a decimetric limestone bed with Fe-rich crusts and nodules, followed by a drastic faunal change in the Famennian Lower *triangularis* Zone (Rodríguez-Cañero, 1993). At Arroyo de la Cruz (Marbella), a similar gap includes the *linguiformis* and Lower *triangularis* zones (Herbig, 1985). At Falcoña, the redepositional horizons of pebbly mudstones contain abundant shallow marine to hemipelagic limestone clasts, which yielded Frasnian conodonts (from *falsiovalis* to *rhenana* zones) belonging to six biofacies: i) mesotaxid-polygnathid, ii) palmatolepid-polygnathid, iii) polygnathid-icriodid, iv) ancyrodellid-polygnathid, v) polygnathid and vi) mixed biofacies. The clasts show ten microfacies: i) coral boundstones, ii) coral rudstones, iii) microbial bindstones encrusting corals, iv) fenestral clotted wackestones, v) fenestral mudstones, vi) coarse-grained grainstones, vii) fine-grained grainstones-packstones, viii) fine- to medium-grained, greyish packstones, ix) brownish-orangish and slightly terrigenous packstones-wackestones, and x) orangish-reddish mudstones-wackestones, sometimes slumped.

The limestone clasts of the Falcoña pebbly mudstone allow redefinition of the latest Devonian palaeogeography of the Malaguide realm as a part of the northern continental margin of Paleotethys within its westernmost embayment. Their features indicate that, before basin drowning allowed generalised deposition of Tournaisian radiolarites, there was great environmental diversity, from reef-related shallow marine to open marine, sometimes condensed, deep pelagic carbonate environments, and finally to carbonatic turbiditic environments probably located towards the SE (present-day coordinates).

Redepositional horizons and stratigraphic gaps are not uncommon in Devonian beds close to the F/F boundary events in the Alpine–Mediterranean region. In the Malaguide realm, they were related to tectonic instability that produced the collapse of a Late Frasnian carbonate platform immediately before platform drowning and Early Carboniferous deepening. This was probably induced by seismic shocks and/or sea level falls, storms or tsunamis that occurred globally during the Lower *triangularis* Zone.

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# From extension to contraction in the Anayet Stephano-Permian basin, central Pyrenees

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Stephanian and Permian times correspond to the transition between the Variscan orogeny and the beginning of Pangea break-up. In the Pyrenees, this extensional event generated rapidly subsiding intracontinental basins with pull-apart geometry, scattered mainly along the southern border of the Axial Zone with E–W elongation. The Anayet basin is located in the western part of the Axial Zone, between the Aragón and Tena valleys. It is WNW-trending and has an elongated geometry (10 x 3 km). The predominance of breccias, conglomerates and red sandstones supports the continental origin of the sediments. The sedimentary succession begins with plant-bearing limestones of Stephanian age that rest discordantly over Devonian to Carboniferous limestones, sandstones and slates and constitute the first post-Variscan deposits in the area.

Detailed cartography of the area shows increasingly older rocks to the northwest of the basin. A mean slope of around 3.5% to the west is deduced for the floor of the basin. These data point to a depocentre located to the west and also suggest a N10°E fault splitting of the basin. The contact between the Permian and the Devonian–Carboniferous rocks is mainly unconformable, but near the Río Aragón it corresponds to a normal fault that was reactivated as a high-angle reverse fault during the positive inversion tectonics induced by the Alpine orogeny.

Subsequently, the Alpine orogeny led to the formation of south-vergent chevron folds and a ubiquitous cleavage in the Anayet basin. These folds have wavelengths of ~ 400 m and N115°E-trending subhorizontal fold axes. The axial plane cleavage is E-trending and dips 40° to 60° to the north. Moreover, normal faults with three main orientations crop out: N10°E, N50°E and N330°E.

The Anayet basin has three interbedded Permian volcanic episodes showing a transition from calcalkaline to alkaline chemistry. These volcanic episodes coeval with the opening of the Anayet basin evidences the instability of the lithosphere during the extensional regime. These conditions prevailed at least until 259 Ma, the youngest reported age for the Permian magmatism in the Pyrenees (Rodríguez-Méndez et al., 2014).

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# Precambrian and Phanerozoic microbialites in Brazilian Gondwana

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We are completing an atlas financed by Petrobras (*Rede Petrobras de Sedimentologia e Estratigrafia*) documenting the morphological variety and stratigraphic context of Brazilian microbialites - predominantly stromatolites and oncolites – ranging in age from Paleoproterozoic to the present. Many occurrences of stromatolites provide relevant insights for elucidating paleoenvironmental, paleoclimatic and paleogeographic aspects of West Gondwana prior to, during and following its amalgamation. Among the oldest Brazilian microbialites are closely spaced, columnar stromatolites in bioherms of the 2.1 Ga-old Fecho do Funil Formation (Paleoproterozoic), which post-date thick, intensely mined banded iron-formation of the Quadrilátero Ferrífero in Minas Gerais. Latest Mesoproterozoic to early Neoproterozoic stromatolites (Vazante and Paranoá groups) are scattered along the Brasília fold belt in central Brazil but may be coeval with similar successions in southeast Brazil (Itaiacoca Group) and on the Congo and West African cratons. Typical of this period are unbranched, conically-laminated columnar stromatolites (*Conophyton)* that formed in the deeper photic zone of carbonate ramps and platforms. Most Brazilian occurrences of *Conophyton* exhibit upward shallowing, as indicated by the appearance of branching (= *Jacutophyton*) and changes in laminar form from conical to more gently convex. More proximal settings are indicated by hummocky cross-stratified beds of coated grains (including oncoids and microphytolites) or by extensive stratiform stromatolites. Changes in stromatolite morphology, sediments and sedimentary structures in continuous successions may reflect cyclic variations in sea level at local and possibly global scales. In the Neoproterozoic, Brazilian microbialites either comprise largely monotypical vertical successions (Bambuí Group and Capiru Formation) or exhibit lateral and vertical variation within bioherms (Salitre Formation). Following the Neoproterozoic, great areas of Brazil were subject to denudation or located at very high southern latitudes – conditions clearly unfavourable for the development and preservation of microbialites. Microbialites reappear, however, within mixed carbonate-siliciclastic depositional environments of the intracratonic Paraná and Parnaíba basins in the Permian following Gondwana glaciation, as epeiric seas regressed and desertification of West Gondwana began. Restricted conditions are represented by elongate stromatolites of metric dimensions and containing remains of aquatic mesosaurid reptiles along the northeast margin of the Paraná basin (Passa Dois Group) and in areas of Namibia bathed by the same epicontinental sea. Much smaller stromatolites, however, are more common in the Brazilian Permian, often as complex small bioherms and biostromes. “Microstromatolites” encrusting bivalve shells and intraclasts are locally common in the Paraná basin and represent recurrent opportunistic colonization of available hard substrates in stressful settings. As the Southern Atlantic Ocean began to open, microbialites, now cropping out in northeastern Brazil, developed in Cretaceous hypersaline continental waters. Thickly laminated, pseudocolumnar, often bizarre stromatolites in the Codó Formation may correlate with at least partly microbial carbonates containing vast hydrocarbon reserves in the “Pre-Salt” beds of southeastern Brazil.

# Magmatic tin–tungsten deposits within the Acadian–Variscan–Alleghanian orogen: from the Gondwana source to the mineralisation

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The more than 3000 km long belts of the Acadian, Variscan, and Alleghanian orogens of Europe and Atlantic Northern America host a wide range of different granite-bound tin and/or tungsten deposits and lithium-caesium-tantalum (LCT) type pegmatites. The distribution of these deposits is heterogeneous along these belts and seems to be primarily controlled by (i) the occurrence of enriched source rocks, (ii) the volume of these source rocks, and (iii) the mobilization of these source rocks, i.e., the distribution of appropriate heat sources. Additional enrichment during magmatic fractionation and fluid-mediated metal redistribution at the emplacement-level – although of great importance on the scale of individual deposits – are only of secondary importance on the large scale, i.e., the regional distribution within the orogenic belts.

The intense Cambrian chemical weathering of sedimentary debris, which was dominantly derived from the Cadomian magmatic arc, on stable Gondwana resulted in a distinct enrichment of Sn and W, but also Li, K, and Rb, and a strong depletion of Na, Ca, and Sr. Break-up of Gondwana eventually resulted in the erosion and redistribution of these intensely weathered sediments to basins and graben structures at the margins of the continent, where they reach thicknesses of several thousand meters. During later tectonic events, these lithologies sometimes further stacked, creating locally large volumes of Sn–W-enriched source rocks. Both, sedimentary and tectonic accumulation seem to be necessary requirements for the subsequent development of major Sn–W districts.

Within the Acadian, Variscan, and Alleghanian orogenic belts, melting of source rocks occurred in four different settings: (i) above subduction zones; (ii) in orogenically thickened crust by internal heating; (iii) in orogenically thickened crust by advective heat input from exhumed ultra-high–temperature (UHT) metamorphic units; and (iv) post-orogenic crustal extension with mantle upwelling. Melting due to internal heating will generate minimum-temperature melts and may not result in the efficient mobilization of Sn and W, but may generate melts that have the potential to develop into LCT-type rocks. In contrast, the other three settings are characterized by advective heat transport (mantle-derived melts, tectonic emplacement of UHT-rocks), where melting may occur at higher temperatures, resulting in efficient transfer of Sn and W from the enriched source rocks into the melt. The uncoupling of source enrichment, source accumulation, and source melting not only accounts for the heterogeneous distribution of Sn–W granites and LCT pegmatites within an orogenic belt, but also explains (i) the diachronous occurrence of tin granites and LCT pegmatites along the Acadian, Variscan, and Alleghanian orogens, (ii) the occurrence of Sn-deposits and LCT pegmatites on both sides of the Rheic suture, and (iii) the contrasting tectonic setting of Sn-deposits within this belt.

# Gondwana break-up and the formation of world class coastal diamond and heavy mineral placer deposits along the West Coast of Southern Africa

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The West Coast of Africa is the host to several Cenozoic placer deposits of diamonds and heavy minerals that formed along the seaboard after Gondwana break-up and opening of the Atlantic Ocean during the early- to mid-Cretaceous. The economically most significant of these deposits occur towards the south and include the gem quality alluvial and marine diamond placers of South Africa and Namibia and heavy mineral deposits which mainly occur in South Africa. The diamond resources have been effectively depleted after more than 100 years of active mining producing several million carats of gem quality stones. The heavy mineral industry, however, started producing in the late 1980's and has developed into a major contributor of zircon, ilmenite and rutile to the global market with operating mines at Namakwa Sands and Tormin.
The geomorphological evolution of the West Coast started with the break-up of Gondwana. The resulting trailing margin of the African plate is characterized by orthogonal and coast-parallel rifts and half grabens that produced a 1000 m.a.m.s.l. escarpment and narrow coastal plain with an irregular coastline. Active erosion associated with rapid continental uplift and a tropical climate during the late Cretaceous exploited the structural grain and is shown by deeply incised paleochannels orientated parallel and at right angles to the coast. These channels are filled with immature kaolinized sediments, including diamonds and were derived from the escarpment and early Cretaceous Bushmanland Plateau. A prolonged period of erosion is marked by a 100 Ma hiatus and was followed by the deposition of a sequence of siliciclastic marine and aeolian sediments in response to sea-level changes and coastal tectonism during the late Cenozoic. Heavy mineral and diamond concentrations are both associated with marine terraces and adjacent dune fields host vast quantities of heavy minerals. Spatial distribution of economically viable concentrations, however, is a function of coastal morphology (J-bays) and strong onshore winds that dispersed and winnowed the sediments along aeolian corridors.
Provenance studies using mineral chemistry and zircon U-Pb geochronology showed that most of the heavy mineral suite was derived from the proximal Mesoproterozoic gneissic basement rocks and siliciclastic Paleozoic Table Mountain Group as well as syenite intrusions related to early Gondwana break-up magmatism. Diamonds in the paleochannels were initially transported by and sourced from Carboniferous Dwyka Group diamictites and subsequently concentrated during peneplanation of the Bushmanland Plateau. Marine terrace hosted diamonds have been derived from both pre- and late-Cretaceous kimberlites.

# Orogen-parallel thickening in NW and central Iberia: foreland shortening coupled to an extension channel in a mid-European Variscan plateau?

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The Variscan orogen formed a > 3500 km long, 1000 km wide chain, with two opposing fold-and-thrust belts and central "hot" zones characterized by orogen-parallel, syn-collisional extension in western Europe and by gravity overturns and vertical extrusion in east-central Europe. Its main four geodynamic elements are similar to those of PURC models developed to explain the tectonics of doubly vergent orogens (a southern Pro-wedge, Uplifted central hot regions, northern Retro-wedge and Channel of thermally weakened and extended orogenic infrastructure).

The Variscan tectono-thermal structure of the NW and central Iberian Massif suggests an important orogen-parallel or slightly oblique component of thickening during the Early Carboniferous, prior to its thermal weakening and gravitational collapse in the Middle Carboniferous. According to PURC mechanics, the oblique emplacement of a 12–20 km thick allochthonous-parautochthonous terrane on the Iberian foreland could be related to the lateral extension of an orogenic plateau that grew in the complex process of indentation between Gondwana and Laurussia.

The closure of oceanic domains occurred in (at least) two stages: Early–Mid Devonian and Late Devonian–Early Carboniferous, with HP metamorphic records at 410–390 and 380–360 Ma, respectively, recognized all along the chain. The last closure progressed from the west (Iberia in present coordinates), where northward continental subduction occurred in the Late Devonian, to the east (Bohemia), where southward or bilateral subduction lasted until the Early Carboniferous. A wide south-vergent collisional pro-wedge developed by the exhumation and emplacement of the allochthonous subduction complex above the autochthonous lower plate (more internal zones of the extended and thin continental margin of Gondwana) from SW Iberia to at least the French Massif Central.

After consumption of oceanic crust beneath the Andean-type Bohemian margin of Gondwana, a north-vergent collisional retro-wedge progressed from east to west, developing sinistral/thrust shear zones such as those in the Bohemian Massif, North Armorican domain and the Ossa Morena and South Portuguese zones. Continued underplating and crustal duplication beneath Bohemia in the Early Carboniferous produced uplift of deep crustal rocks, westward tilting along the Gondwana margin and subsequent large-scale, orogen-parallel, slide-down, extension towards the west of the older, thermally weakened, plateau rear of the southern wedge. Westward extension was nearly orthogonally constrained between renewed deformation in the southern wedge front and the back-stop effect of the younger northern wedge, not yet thermally weakened. Slide-down flow in the plateau extension channel was coupled to (accommodated by) foreland shortening through spreading of the allochthonous terrane on the NW and central Iberian autochthon.

# The first Paleozoic record of the trace fossil *Rotundusichnium* (Middle Ordovician of Portugal): paleoenvironment and behavioural pattern of the trace maker

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The ichnogenus *Rotundusichnium* (type, *Helminthoida zumayensis*) is a ?concentric to tightly spiral trace widely recognized from Late Cretaceous to Paleogene in turbidites and hemipelagic marlstones of Europe and South America. It represents a subhorizontal burrow with active infill, generated by a shallow mud burrower in deep-sea environments under poor oxygenation conditions, with high organic matter input and low sedimentation rate. The tight, regular pattern of this trace suggests that it was produced by a systematic deposit-feeder.

We report here the exceptional discovery of a giant representative of *Rotundusichnium* from the Middle Ordovician of Portugal, which represents the oldest geological record for this ichnogenus. The Paleozoic form is defined by almost concentric burrows, with a large elliptical outline (major axis up to 130 cm long), five times the size of the largest specimens of the circular to moderately elliptical *R. zumayensis* (= *R. magnum*). The trace has an internal concentric division produced by endichnial ribbons inclined to the centre of the structure, yet apparently smooth burrow walls.

The Portuguese material occurs sparsely towards the middle part of the Valongo Formation in the Arouca region (50 km SE of Oporto). Specimens were collected from large surfaces of roofing slate in the Valerio quarry of Canelas, which also includes an outstanding middle Darriwilian *Konzentrat-Lagerstätte* (Gutiérrez-Marco et al., 2009). Here, the sediments indicate, in ascending order and with episodic fluctuations, a general trend from anoxic to normal shelf oxygenation, within a relatively shallow water clastic environment indicated by a typical shelly fauna (*Neseuretus* biofacies). Towards the middle part of the unit, temporary dysoxic beds with the large grazing traces of *Rotundusichnium* and giant opportunistic trilobites closely follow others with typical shallow water trilobites (*Neseuretus*). These special local conditions were regarded as the result of a stratified-water basin within the inner shelf produced by extensional basement tectonics, periodic stagnation being implicated in the formation of the *Lagerstätte* (Gutiérrez-Marco et al., 2009).

Post-Paleozoic records of *Rotundusichnium* were restricted to bathyal/abyssal environments under oxygen-depleted conditions. The trace was originally assigned to an agile opportunistic shallow colonizer of newly deposited turbiditic layers, but Frey and Seilacher (1980) interpreted *R. zumayensis* as a spiral echinoid burrow (*Scolicia*) which produce “cannibalistic” coils, incompatible with simple sediment feeding and representing a kind of bacterial farming. The Ordovician record of *Rotundusichnium*, long before the first occurrence of the heart urchin (spatangoid) burrowers, is commonly associated with remains of orthocone nautiloids, which are often preserved below each structure. This strongly suggests that, after burial, the imploded fragmocones favoured microbial growth around them, and these were systematically harvested in tight centrifugal coils by the opportunistic trace maker of *Rotundusichnium*. Similarly flattened nautiloids in younger and normally oxygenated beds within the same sequence are encircled by mineral coloured halos but lack evidence of burrows.

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# Neoproterozoic U-Pb and Lu-Hf ages of granitic rocks of the Ribeira belt: insights into collisional magmatism in the Pedra Dourada (Minas Gerais) and Porciúncula (Rio de Janeiro) region

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The NE–SW Mantiqueira Province, 3,000 km long, is related to the evolution of West Gondwana and extends from Bahia State in Brazil to Uruguay. The province comprises three segments: south, central, and north, respectively including the Dom Feliciano and San Gabriel, Ribeira and Araçuaí Neoproterozoic orogenic belts. The crustal evolution of this province resulted from the convergence of the São Francisco-Congo, Angola, Rio de la Plata and minor micro-continents, as well as magmatic arcs.

The studied Pedra Dourada and Porciúncula region is in the northern segment of the Mantiqueira Province, in the connection between the Ribeira and Araçuaí belts. The region encompasses granites and high-grade metamorphic rocks, divided into three basic units: orthogranulites of the Paleoproterozoic basement, Neoproterozoic supracrustal units and magmatic suites related to various evolutionary stages of the orogen. The Paleoproterozoic basement is represented by the Juiz de Fora complex, orthogranulites varying from enderbite to charnockite in composition, with minor gabbroic rocks. The supracrustal unit, interpreted as a distal portion of the Andrelândia Group, comprises psammitic to pelitic paragneiss locally interlayered with quartzite, cal-silicate, Mn-rich rocks and amphibolite. Granitic rocks are represented by the Leopoldina (Salvaterra) suite with charnockites charno-enderbites, the Pangarito suite with (garnet) leucogranites, and porphyritic and hornblende bearing granites. One body of the arc-related Galilea suite was mapped to the west of the target area.

New U-Pb LA-ICP-MS zircon data for the region were obtained at Multilab-UERJ. Basement rocks yielded upper intercepts, interpreted as magmatic crystallization ages, of 2118±17 (MSWD=1.5, n=16), 2157±23 (MSWD=0.76, n=20), 2156±25 (MSWD=3.3, n=21), 2176±17 (MSWD=1.4, n=10) and 2117±66 (MSWD=0.39, n=15), consistent with previously reported ages for the Juiz de Fora complex. Lu-Hf results from Paleoproterozoic zircons indicate εHf from 1 to -3 and $T_{DM}$ from 2.6 to 2.4 Ga. These results suggest a mantle source for these magmatic rocks. The Brasiliano overprint is marked by lower intercepts in the basement rocks (interpreted as metamorphism), as well as in granite and charnockite rocks, of between 615±28 and 590±16 Ma. A younger granitic body rendered an age of 565±12 (MSWD=0.53, n=7). Lu-Hf results indicate a crustal source of these granites; they may have been generated by crustal melting of Paleoproterozoic protoliths, as indicated by εHf values from -22 to -31 and $T_{DM}$ from 2.3 to 2.0 Ga. This exemplifies the geological complexity story of the Pedra Dourada and Porciúncula region.

# U-Pb and Lu-Hf zircon study of the Paleoproterozoic Região dos Lagos complex, Rio de Janeiro, Brazil: implications for West Gondwana evolution

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The studied region is located in Rio de Janeiro State and is part of the Ribeira Belt, in central Mantiqueira Province. The rocks of this region were affected by the Brasiliano/Pan-African orogeny, from Neoproterozoic to the early Paleozoic times. The basement is comprised of Paleoproterozoic rocks, Mesoproterozoic and Neoproterozoic sedimentary and volcano-sedimentary rocks, Neoproterozoic intrusive granitic rocks. These rocks are interpreted as associations of magmatic arcs, sedimentary sequences of passive margins and late kinematic granites, respectively. The central segment of the Ribeira Belt can be divided into Oriental, Occidental, Costeiro, and Cabo Frio terranes. The study area is located in the Cabo Frio terrane, where the basement is represented by the Região dos Lagos Complex.

The Região dos Lagos complex includes granitic (biotite-microcline-plagioclase gneiss), and tonalitic (biotite-orthoclase-plagioclase gneiss) intrusive rocks. Supracrustal rocks include sillimanite-garnet gneiss with partial melt levels (Palmital unit), and garnet-gneiss (Cassorotiba unit). Syn-tectonic intrusive bodies are observed as: (i) porphyritic biotite gneiss with garnet, microcline and plagioclase phenocrysts (Maricá unit); (ii) biotite gneiss with biotite aggregations (Tinguí unit); and (iii) post-tectonic granites (Caju unit).

U-Pb and Lu-Hf zircon studies of the Região dos Lagos Complex were carried out in order to identify the ages of crystallization and crustal residence of this complex and to define magmatic-metamorphic events in the Ribeira Belt. The method used includes preparation of zircon samples for MEV imaging and dating by the U-Pb and Lu-Hf methods using LA-ICP-MS. The Lu-Hf analyses were performed after U-Pb, analysing the same area of the zircon grain. The U-Pb ages obtained were: sample CRL-12, 1957 ± 15 Ma (13 points, MSWD = 0.20); sample CRL-08, 1975 ± 13 Ma (15 points, MSWD=0.36); and sample CRL-09, 1981 ± 8 Ma (13 points, MSWD = 0.34). Sample CRL-12 gave εHf values between -19 and -12 and values between 2.4 and 2.59 Ga. The corresponding εHf and $T_{DM}$ values for CRL-08 were -11 to -4 and 2.5 to 2.6 Ga, respectively and, for CRL- 09, -32 to -15 and 2.43 to 2.48 Ga.

These results suggest that the Região dos Lagos complex crystallized between 1990 Ma and 1950 Ma, and formed from crustal protoliths whose mantle extraction ages are between 2.4 and 2.6 Ga. Thus these rocks were generated in a magmatic arc with significant crustal contamination and represent an important magmatic event in the Ribeira Belt basement formed prior to Gondwana amalgamation.

# Age and correlation of the Loma del Aire Unit, Ossa-Morena Zone, SW Iberia

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The Loma del Aire Unit is one of many fault-bounded structural units making up the Ossa-Morena Zone (OMZ) of the Variscan Iberian Massif. Its correlation, age and interpretation have been controversial owing to a lack of fossils. The exposed record is composed of two laterally related successions: a metasedimentary siliciclastic succession and a complex succession made of marbles and volcanic tuffs and lavas (Loma del Aire Formation). Deformation is highly penetrative and polyphase. Metamorphic grade is low or very low. Some authors have considered this unit to be Precambrian and correlative with the arc-related volcano-sedimentary Malcocinado Fm., widespread across the OMZ. Others have interpreted these rocks as the oldest exposed in the OMZ on the basis of ~ 623 Ma old concordant zircon in the volcanic rocks. Yet others have preferred a correlation of the Loma del Aire carbonates with the Lower Cambrian Detrital-Carbonate Fm. of the OMZ, and of the volcanic rocks with the Bodonal Porphyroid and related granitoids ascribed to an Early rift-related igneous event.

Our study focuses on the volcanic and volcano-sedimentary rocks. Within the former, massive porphyritic types predominate, with plagioclase phenocrysts embedded in a fine-grained matrix made of plagioclase, quartz, phyllosilicates and locally idiomorphic magnetite crystals. Volcano-sedimentary rocks are mainly tuffs and tuffites showing textural and compositional banding; coarse-grained beds are quartzo-feldspathic, whereas the finer-grained beds are richer in phyllosilicate matrix. Breccias are also abundant (autobreccia, brecciated tuffs and hyaloclastites).

Major and trace element compositions of the rocks of this unit overlap with those of the Malcocinado Fm. and those of the Early Cambrian rift-related igneous event. They are silica-oversaturated ($SiO_2$= 63.8–82.9%), peraluminous and Na-rich (average $K_2O/Na_2O$ = 0.81). Most show a distinctive evolved tholeiitic affinity in the AFM diagram, and plot in the VAG+syn-collisional field of the Nb-Y tectonic discrimination diagram. LREE are moderately enriched relative to HREE, with little fractionation of HREE, and a small or absent negative Eu anomaly (average Eu/Eu* = 0.79). These REE patterns overlap with the range shown by the arc-related Malcocinado Fm. and Early Cambrian rift-related group. LREE fractionation in the Loma del Aire Fm. ($La_N/Sm_N$= 3.01) is similar to that of the early rift-related rocks ($La_N/Sm_N$= 3.31) and higher than that of the Malcocinado Fm ($La_N/Sm_N$= 2.54). εNd values vary between approximately -4 and +4, suggesting contribution of magmas from both mantle and crustal sources; one sample (the one dated at 505+/-2 Ma) has a εNd value of +0.6, and we interpret it as belonging to the later, Middle Cambrian–Lower Ordovician, main rift-related event.

New TIMS U-Pb zircon dating of massive auto-brecciated lava has yielded an age of 526±2 Ma. A sill intercalated in the metasedimentary succession has yielded a nearly concordant age of 505+/-2 Ma (Middle Cambrian). These two ages fall within the ranges of the early and the main rift-related events, respectively, suggesting correlation of the Loma del Aire Fm. with the Cambrian–Ordovician rift-related succession of the OMZ rather than with the Neoproterozoic subduction-related Malcocinado Formation.

# U-Pb geochronological evidence for Ediacaran arc-related magmatism in the Ossa-Morena Zone (SW Iberia)

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Neoproterozoic rocks of the Ossa-Morena Zone (OMZ, Iberian Massif) include abundant meta-igneous lithotypes that either constitute an integral part of the so-called "Serie Negra" ("black series") or are geometrically related to it. The meta-igneous rocks and associated meta-sedimentary deposits were related to arc settings during the Avalonian–Cadomian peripheral orogeny, as also recorded in originally neighbouring regions of NE America, Gondwanan Europe and North Africa. After a rifting event, this active margin was involved in the amalgamation of Pangea during the Variscan orogeny.

Metabasite geochemical data (Sánchez Lorda et al., 2013) show that these rocks exhibit N-MORB, E-MORB and volcanic-arc signatures similar to those found in young active island arcs. The geochemical data also reveal a compositional trend congruent with a single, N-dipping (in present day geographical coordinates), subduction surface located to the south of the current Ossa-Morena Zone but well-established ages for the crystallization of syn-orogenic Cadomian intrusives are scarce. The protoliths of mafic to intermediate, arc-related, calc-alkaline meta-igneous rocks of the Mérida-Montoro massif along the northern OMZ were dated at ~ 575 Ma by U-Pb methods (Bandrés et al., 2004). Their tectonic contacts with metamorphic rocks of the "Serie Negra", however, preclude a definitive assignment to this formation.

In order to better constrain their paleotectonic setting and elucidate their age relationships, zircons from metabasite units within the Serie Negra and correlatable formations have been dated by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) methods. The results obtained are as follows:

-Metabasites with E-MORB affinities, probably derived from basaltic units from a fore-arc environment and represented by medium-grained to coarse-grained amphibolites of the El Cuartel unit (Mina Afortunada gneiss dome in the northern OMZ) yield ages of 575±10 and 585±9 Ma, respectively.

-Metabasites akin to calc-alkaline basalts in composition, probably derived from subvolcanic or deeper intrusive rocks and represented by medium-grained amphibolites from La Cardenchosa, within the Badajoz–Córdoba blastomylonitic band, yield ages of 580±14 Ma.

-Metabasites similar to N-MORB type basalts, represented by fine-grained amphibolite layers enclosed by the Serie Negra in the Almadén de la Plata Massif (southern OMZ), yield ages of 495±7 Ma.

These results show that metabasite layers enclosed by the Serie Negra represent different products of a protracted igneous activity. Metabasites from El Cuartel and La Cardenchosa are related to arc settings during the Cadomian orogeny. Metabasites from the Almadén de la Plata massif represent rift-related rocks deformed during Variscan times and are equivalent to other basic rocks related to the Cambrian rifting (e.g., 'spilites' of Rivera de Huelva and La Corte).

Bandrés et al., 2004. The northern Ossa-Morena Cadomian batholith (Iberian Massif): magmatic arc origin an early evolution. Int J Earth Sci (Geol Rundsch) 93, 860-885.
Sánchez Lorda et al., 2013. Geochemistry and paleotectonic setting of Ediacaran metabasites from the Ossa-Morena Zone (SW Iberia). Int J Earth Sci (Geol Rundsch) DOI 10.1007/s00531-013-0937-x

# Detailed isotope geochemistry of the Cambrian Vila de Cruces ophiolite: dual magmatic source of a complex oceanic terrane

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The Vila de Cruces ophiolite is one of the mafic units involved in the Variscan suture of NW Iberia (the allochthonous complexes of Galicia). It is located in the S–SE of the Órdenes complex, stacked above basal units with crustal affinity and below the Devonian Careón ophiolite (Díaz García et al., 1999). It consists of several tectonic slices piled up to 4000 m, mainly of mylonitic greenschist with some intercalations of phyllite and scarce metagabbroic and orthogneissic bodies. The mafic lithologies have chemical compositions compatible with island arc tholeiites and the tonalitic orthogneisses have volcanic arc signatures, both supporting a supra-subduction origin for this ophiolite (Sánchez Martínez, 2009). Arenas et al. (2007) attempted to date the orthogneiss by ID-TIMS multi-grain U-Pb zircon analysis: 17 grains grouped into 4 fractions gave a concordia age of 500 Ma. Subsequently Sánchez Martinez (2009) obtained U-Pb zircon ages of ~1170 Ma from two samples of metagabbro by LA-ICP-MS. A more detailed study was clearly required and is reported here.

Ten samples of the predominant greenschist lithology failed to yield sufficient zircons, but some were separated from one sample of metagabbro and three of orthogneiss: all the ages obtained by LA-ICP-MS were consistently ~ 500 Ma, with no inherited zircon grains, suggesting Cambrian crystallization of both gneiss lithologies. Initial εHf values of the Cambrian zircons are consistently positive and very similar to those of Cambrian depleted mantle, indicating juvenile magmatic sources. Whole-rock Sm-Nd data for most of the greenschists and metagabbros show growth lines sub-parallel to that of depleted mantle evolution so that their TDM ages are very variable, although initial εNd is always positive. The orthogneisses have growth lines with negative slope and initial εNd similar to the values of the Cambrian depleted mantle, in agreement with the εHf data. Only one greenschist sample is characterized by a negative initial εNd, giving a TDM of ~1150 Ma. Thus the combined isotope data the Cambrian magmatism that generated the protoliths of both mafic and acid rocks was juvenile and mantle-derived. The presence of a few 1.15 Ga zircons and comparable Nd TDM ages indicate participation of an old crustal component, probably Mesoproterozoic. Mesoproterozoic zircon grains have been also reported from other ophiolites in NW Spain, e.g., the Devonian (~ 395 Ma) Purrido ophiolite, for which 1160 Ma zircons were attributed to a xenolithic/inherited origin (Sánchez Martínez et al., 2011). This feature may suggest a similar setting for both Cambrian and Devonian ophiolites, representing two events of basin development affecting the wide Gondwanan shelf.

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# Pangea break-up recorded by U-Pb ages of detrital zircons: the Permo-Triassic series of the Iberian Ranges

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The provenance of the Permo-Triassic series of the Talayuelas anticline (Iberian Ranges) has been studied using U-Pb geochronology (LA-ICP-MS) of detrital zircons. These intracontinental siliciclastic series were formed by extensive sandy braided fluvial systems associated with ephemeral-lake deposits and aeolian sediments, with paleocurrents suggesting constant NW-SE transport directions. The detrital zircons of six samples spanning the Upper Permian (Lopingian) to the Middle Triassic (Anisian) succession were studied, performing age calculations, concordia diagrams and binned frequency histograms.
Upper Permian reddish sandstones from the Upper Alcotas Formation (Lopingian) contain a dominant Variscan zircon population (290–360 Ma), which indicates source areas located in the axial zone of the Variscan belt, in the core of the Ibero-Armorican arc. However, in the Lower Triassic sandstones of the Cañizar Formation (Olenekian) the Variscan zircon population is almost completely replaced by Cadomian zircons (520–750 Ma), also with important Avalonian (390–520 Ma), Mesoproterozoic (900–1750 Ma), Eburnian (1.78–2.35 Ga) and Archaean (>2.4 Ga) zircon populations. This detrital zircon content now suggests source areas located more to the northwest, in the Avalonian microcontinent, although a limited supply from the southern part of Laurentia cannot be ruled out. Finally, in the Middle Triassic (Anisian) provenance returned to the Variscan axial zone, as the Variscan zircon population again becomes highly dominant.
The changes detected in the source areas of the Permo-Triassic series are related to the development and propagation of the Iberian rift, one of the large extensional structures which determined the generation of the sedimentary basins and finally caused the break-up of Pangea. The methodology followed in this paper is very useful to understand the generation and evolution of these intra-continental basins, and also the relationships between the different rift systems generated in the North Atlantic realm during Permo-Triassic times.

## The new Gondwana Geological Map – first draft

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We present here the first draft based on the results of *"The Gondwana Map Project– the geological map and the tectonic evolution of Gondwana" (IGCP-628)*, which aims to update the 1988 Gondwana Geological Map of Maarten de Wit. The most recent geological data from all the Gondwana continental pieces were compiled in the scale of 1:5,000,000 in a GIS database. These were then compiled in one big map with a common legend. In the proposed legend, the colours indicate the age of formation of each geological unit, according to the IUGS geological time scale. The patterns within the polygons refer to the nature of the rocks (classification and chemistry). Only the major continental fragments were rotated and fitted in this first draft. Other continental Gondwana-derived fragments are also being updated (European, North American, Asia terranes), but are not shown in this draft. Configuration of the large plates followed the methodology of *GPlates,* both rotation and fit were taken at 150 Ma. The polyconic projection was chosen in ArcGis, because the other tested projections generated a lot of deformation on the original files. In this Gondwana 15 Symposium, the draft is presented in order for it to be evaluated and criticized by the scientific community. Structures are not yet represented and will constitute an important layer on the map, since interpreted major sutures will be shown. In some continental fragments, tectonic reactivation is shown by the colour of the patterns. For example, all lithological units that underwent pre-Neoproterozoic tectonic events are displayed with a black pattern. Using these criteria, the major pre-Gondwana cratons can be recognized more easily. One of the main aims is to trace better the continent-ocean boundary (COB) along the actual continental margins. In the present work, the location of the COB identified by previous studies was based on several different datasets and the criteria applied to define this boundary relies, in general, on the identification of the first crust with oceanic affinities. The prolongation of onshore geology in continental margins to offshore platforms will improve the fit between the present continents in order to restore the Gondwana paleocontinent. Another ongoing action is to reconstitute the paleogeology of Gondwana. For the South American map, we tested the elimination of the post-Cretaceous layers, to produce a paleogeological map and evaluate the possibility of inferring the geology in the white areas. This project started in 2011 from a cooperation between UFRJ and PETROBRAS, and in 2013 was approved as IGCP-628 (UNESCO-IUGS-project), continuing until 2017. The leaders of IGCP-628 are: Renata Schmitt (UFRJ, Brasil), Maarten De Wit (Nelson Mandela Metropolitan University, South Africa), Edison Milani (PETROBRAS, Brazil), Umberto Cordani (USP, Brasil), Alan Collins (University of Adelaide, Australia), Colin Reeves (Earthworks, The Netherlands), and Phillipe Rossi (CCGM - CGMW, France).

# North Gondwana, South Gondwana, Armorica, Avalonia, Perunica ...... and other debatable terms

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Palaeogeographers, geographers and structural geologists use different well-defined terms to designate continental and tectonic units, whereas biogeographers, palaeobiogeographers and palaeontologists use a wide range of subjective terminologies to describe biogeographical and palaeobiogeographical units. The absence of clear definitions and of rules or guidelines for palaeobiogeographical nomenclature has resulted in frequent misunderstandings and general confusion, in particular when applied to ancient time periods, such as the Palaeozoic.

In recent decades various research studies have focused on the reconstruction of Palaeozoic Europe, reflecting the complex geodynamic history related to the formation of the supercontinent Pangaea. It has been demonstrated that Palaeozoic Europe comprises a series of tectonostratigraphical units, or 'terranes', located between the remnants of three major palaeocontinents: Gondwana, Laurentia and Baltica. Some of these 'terranes' have been referred to as 'micro-continents', a typical (palaeo-)geographical term, and as 'microplates', a typical plate-tectonic term, giving rise to misunderstandings and a continuing scientific debate. This confusion is based primarily on an inconsistent use of different palaeogeographical terms by specialists from different scientific disciplines. Whereas large palaeocontinents such as Baltica and Siberia have been named as terranes by some workers, several peri-Gondwanan 'terranes' have been attributed to microcontinents or microplates, without conclusive reasoning.

We here critically review the terminology used not only for North and South (etc.) Gondwana, but also for three European peri-Gondwanan palaeogeographical entities: 'Avalonia', 'Armorica' and 'Perunica'. The review indicates that only Avalonia should be considered as a separate (micro-)continent on a separate (micro-)plate. Armorica has many different definitions and is commonly considered to be composed of several terranes. It is, however, not at all evident if Armorica was a separate (micro-)continent and/or an independent (micro-)plate. For Perunica, defined originally as a separate microplate, current evidence demonstrates that it can probably be considered only as a palaeobiogeographical province.

After a revision of palaeogeographical and palaeobiogeographical terminology used in Palaeozoic geology and palaeontology we make a number of proposals for future use of terms to avoid confusion and misunderstandings.

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# Flexural accommodation of oroclinal buckling: A structural study of the Cantabrian Orocline, NW Iberian Massif

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Though oroclines are common features of the world's orogenic belts, the mechanisms that drive oroclinal formation, and the manner in which these lithospheric-scale vertical-axis folds of orogens are accommodated at different structural levels, are poorly understood. An s-shaped pair of isoclinal coupled oroclines characterizes the Variscan orogen of the Iberian Massif. Structural continuity between the northerly Cantabrian and the southerly Central Iberian oroclines suggest that they formed contemporaneously and in the same fashion. Exposures of the Ediacaran Narcea Slates within the so-called Narcea Antiform trace a 150 km long arcuate belt around the 180-degree Cantabrian orocline. The Narcea Slates of the western flank of the Narcea Antiform are characterized by a penetrative steep to vertical cleavage (S1) and subparallel 2 km-wide reverse shear zones with a penetrative fabric (S2). These fabrics are affected by asymmetric meso- to outcrop-scale vertical-axis folds with a dominant vergence toward the oroclinal hinge; i.e., fold sense is dominantly dextral in the southern limb of the Cantabrian orocline and dominantly sinistral in its northern limb. Vertical-axis folds affecting the Narcea Slates are of the appropriate scale and geometry to be parasitic structures developed in response to flexural shear within the limbs of the Cantabrian orocline and are therefore consistent with and argue for a model of formation of the Iberian coupled oroclines by buckling in response to a principle compressive stress orientated at a high angle to initial orogenic trend.

# Impact of the Mesozoic Karoo-Maud plume and east–west Gondwana break-up on evolution of the East Antarctica igneous province

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Deep plumes play a prominent role, if not the main one, in the formation and rifting of the continental landmass. Gondwana was affected by several. The Central Atlantic plume was active about 200 Ma ago within the western part of West Gondwana and led to the separation of North America from Africa and opening of the central Atlantic Ocean about 160 Ma ago. The Karoo–Maud plume operated in the interior of the paleocontinent 180–170 Ma ago and resulted in Africa separation from Antarctica and opening of the Southern Ocean. The Parana–Etendeka plume was active during break-up 130 Ma ago and initiated separation of South America and Africa and formation of the South Atlantic Ocean. In all cases, continental structure and composition could have played a significant role in the type of magmatism manifested on the continents and in the early stages of oceanic rifting. Plume impact within Antarctica expanded towards the south and east, leading to the formation of extended igneous provinces along Transantarctic Mountains and along the east coast (Queen Maud Land province and Schirmacher Oasis). Moreover, this plume activity might have been reactivated, about 40 Ma after its first cessation, as the Kerguelen plume within the newly-formed Indian Ocean. The head of the Karoo–Maud plume migrated beneath the lithosphere, producing basaltic in the Lambert Glacier fracture region of Antarctica, in eastern India and SW Australia, on the Naturaliste Plateau and the Bruce Bank about 130 Ma ago.

Upwelling plume melts had both depleted asthenospheric characteristics and enriched lithospheric signatures. Nd, Sr, Pb isotope and lithophile element compositions of the alkaline ultrabasic rocks from Jetty Oasis and the Gaussberg volcano (Antarctica) represent the final stage of evolution of the Kerguelen-plume from Cretaceous to Quaternary times. Geochemical patterns of the early enriched basalts from oceanic rises in the eastern Indian Ocean connected to the Kerguelen-plume (Kerguelen Plateau, Ninety East Ridge and Afanasy Nikitin Rise), as well as alkaline ultrabasic magmas of the Jetty Oasis reflect close affinity of the enriched melt sources.

The East Antarctica igneous province magmatism and the later Kerguelen plume-related magmatism show many common geochemical features which may be due to the involvement of Gondwana lithosphere fragments in the melting sources. However, Karoo–Maud plume-related magmatism is marked by relatively restricted variation of Pb isotope ratios compared to the Kerguelen-related magmatism, and is probably determined by crust thinning and perhaps more rapid melt percolation, whereas in the latter case plume spreading and eastward migration involved more intensive interaction of the plume with the lithosphere. Thus Kerguelen-related magmas become more enriched, with the least radiogenic Pb isotope signatures indicating an old crust component, and with the most radiogenic lead component ($^{208}Pb/^{204}Pb \sim 40.0$ and $^{207}Pb/^{204}Pb \sim 15.7$) in the most enriched lavas confined to the apical parts of the plume.

# Gondwana: paleomagnetism, paleogeography and plumes

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Gondwana is reviewed from the unification of its several cratons in the Late Neoproterozoic, through its combination with Laurussia in the Carboniferous to form Pangea and up to its progressive fragmentation in the Mesozoic. Despite its enormous size, we only identify 124 reliable paleomagnetic poles between Gondwana assembly at 550 Ma and the Jurassic separation of West and East Gondwana at around 170 Ma; 38% are detrital sedimentary poles that we have corrected for inclination shallowing ($f$=0.6) before calculating a common apparent polar wander path for Gondwana. The Late Neoproterozoic and Early Cambrian South Pole (keeping southern Africa fixed) were located in South America (Amazonia), and migrated to NW Africa during the Lower Palaeozoic, followed by SE motion and a distinct Silurian–Devonian cusp. By the Carboniferous, the South Pole was located within East Antarctica.

For much of that time Gondwana was the largest continental unit on Earth, covering almost 100 million km$^2$, and its remnants constitute 64% of all land areas today. New palaeogeographical reconstructions are presented, ranging from the Early Cambrian through to just before the final Pangea break-up at 200 Ma, which show the distributions of land, shallow and deep shelves, oceans, reefs and other features. The South Pole was within Gondwana and the Gondwanan sector of Pangea for nearly all of the Palaeozoic, and thus the deposition of significant glaciogenic rocks in the brief Late Ordovician (Hirnantian) and the much longer Permo-Carboniferous ice ages help in determining where the ice caps lay.

In the lifetime of Gondwana, there are only five large igneous provinces (LIPs) that directly affected Gondwanan continental crust, and three of them assisted the breakup of Pangea and Gondwana. 143 Gondwanan kimberlites have been reported, and the majority and all LIPs have been derived from plumes associated with the African thermochemical reservoir in the lowermost mantle.

# The Sierra de Cachi (Salta, Argentina): evidence of an Ordovician retro-arc in the western margin of Gondwana

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The Sierra de Cachi, a mountain range that extends more than 50 km in a N–S direction along the Calchaqui valley, forms an inlier where Neoproterozoic and Paleozoic rocks of the Andes crop out in a plutono-metamorphic dome surrounded by Mesozoic and Cenozoic sedimentary rocks. This dome consists of: 1) greywacke and slates of the uppermost Neoproterozoic to Early Cambrian Puncoviscana Formation, 2) schists, gneissic rocks and migmatites grouped in the so-called La Paya Formation, and 3) granodiorite and trondhjemite plutons, intruded at different structural levels within the La Paya Formation.

Detailed cartographic and structural data in the Sierra de Cachi show a dominant N–S striking and W-dipping schistosity that post-dates the regional metamorphism. This schistosity is associated with a major $D_2$-folding event and is superimposed on an older extensional foliation preserved in the gneissic domain. After the east-verging folds and development of the main foliation, protracted shortening ended in the local production of narrow mylonitic bands along the reverse limbs of the folds. The extensional deformation is linked to a complex plutono-metamorphic dome with a thermal, high-temperature metamorphism displaying strong telescoping of the isograds. However, the $D_2$-folding led to reverse metamorphism, ranging from very-low grade conditions below to migmatization at upper structural levels. The metamorphism reached partial melting conditions and was coeval with the intrusion of the sheeted granodiorite and trondhjemite plutons. These plutons are concordant with the metamorphic zoning and are also affected by the east-verging folds.

These structural features are consistent with positive inversion tectonics at intermediate crustal levels. The metamorphic–structural evolution points to an extensional event, whereas the younger east-verging folding indicates the superposition of a subsequent compressional stress field. New U-Pb zircon dating by TIMS and SHRIMP methods yields similar ages for the migmatization (480±4 Ma) and the emplacement of granites (472±11 Ma), constraining the extensional event to Early Ordovician times. We also report the finding of gabbro boulders that yield a similar U-Pb SHRIMP zircon age of 478±4 Ma (Hongn et al., in press). From these new data, we propose that the extensional event recognized in this sector of the Calchaqui valley took place in a retro-arc setting associated with the eastward-directed subduction of the western margin of Gondwana in Ordovician times.

Hongn, F.D., Tubía, J.M., Esteban, J.J., Aranguren, A., Vegas, N., Sergeev, S., Larionov, A., Basei, M., in press. The Sierra de Cachi (Salta, NW Argentina): geological evidence about a Famatinian retro-arc at mid crustal levels. Journal of Iberian Geology.

# Lochkovian (Lower Devonian) conodont biotic events in the Spanish Pyrenees and their relevance to establishing a reference time-frame for Gondwana stratigraphy

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Deciphering the geological history of any given time interval and region, and its correlation with both neighbouring and distant areas for building a global picture, depends on a sound chronostratigraphical scheme that can be applied in most areas. For Lochkovian pelagic facies, this scheme is mostly based on the sequential occurrence of conodonts. The record from nine Pyrenean sections allows the establishment of the most detailed array of events that can be used in fine correlations (for some time slices with accuracy of about 100 ka) between Gondwana regions, between Gondwana and Laurentia, and between pelagic and neritic facies. The Lochkovian conodont succession starts in the Pyrenees with the entry of icriodids of the *woschmidti* group, which represents the first radiation of the genus. Two main groups split out from the basic stock, one is represented by *Icriodus transiens* and the other by species of the *angustoides* group. These taxa are mostly represented and developed in neritic facies of the northern peri-Gondwana regions (chiefly belonging to the Mauro-Iberoarmorican region), and their occurrence in pelagic facies represents an extraordinary correlation tie-point between these two major facies. The second Lochkovian innovation event is recorded in the Pyrenees with the entry of the genus Ancyrodelloides; the first taxon, *A. carlsi,* is recorded together with *I. bidentatus.* This is followed by a rapid radiation that produced up to seven successive taxa, most of them of global distribution. Especially important is the sequential occurrence of *A. transitans, A. trigonicus* and *A. kutschery*, which permits tie correlations with key peri-Gondwanan sections in the Alps and Bohemia and also with crucial Laurentian sections of western North America. Slightly later, the innovation and radiation of the genus *Lanea* with four taxa (*L. omoalpha, L. eoeleanorae, L. eleanorae* and *L. telleri*) support and add some details to intra-Gondwana and Gondwana–Laurentia correlations. The rapid innovation, radiation and extinction of the genus *Flajsella* is an extraordinary "clock" within the middle parts of the Lochkovian; it has been recorded both in Gondwana and Laurentia. Another important event is the radiation of the genus *Masaraella* in the upper part of the Lochkovian. *M. pandora beta,* which represents the beginning of this radiation, defines the base of the upper Lochkovian. The upper Lochkovian record in northern peri-Gondwanan regions is scarce, but a radiation within the genus *Pedavis*, which is best represented in the Pyrenean sections, permits fine correlations for this interval.

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# The exceptionally preserved Fezouata Biota from the Early Ordovician of Morocco: an overview of current research

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Since the first discovery some 12 years ago of non-biomineralised fossils in the Tremadocian of the Lower Fezouata Formation north of Zagora, south-eastern Morocco, the Fezouata Biota has become one of the world's most important marine Konservat-Lagerstätten, being the only exceptionally preserved fauna to document the critical Cambro-Ordovician faunal transition. It has revolutionized our understanding of Ordovician marine ecosystems, showing that Burgess Shale-type faunas, long thought to have disappeared after the middle Cambrian, continued to flourish well into the Ordovician while co-occurring with a host of remarkably derived, typical post-Cambrian organisms, many of which had been believed to have appeared much later. These findings indicate that the turnover between the Cambrian and Palaeozoic Evolutionary Faunas was more protracted than hitherto realized, while the presence of several surprisingly advanced forms in the biota suggests that at least in some non-biomineralised groups, the Great Ordovician Biodiversification Event (GOBE) started considerably earlier than thought previously. This supports the idea that, rather than two discrete events, the Cambrian Explosion and the GOBE are in fact different phases within the same large-scale diversity dynamic. With time, an international team was established to study the various aspects of the Fezouata Biota, resulting in an improved understanding of its age and depositional environment. While it was originally believed that exceptionally preserved fossils occurred from the top of the Lower Fezouata Formation throughout the Upper Fezouata Formation, the latest data suggest that the majority of specimens collected so far derives from just two intervals near the top of the Tremadocian Lower Fezouata Formation. The first interval is ~25 m thick and belongs to the *Araneograptus murrayi* biozone, while the second is ~15 m thick and falls within the *Hunnegraptus copiosus* biozone. The fauna is considered to have lived in a relatively shallow off-shore setting, likely just within storm-wave base. Current systematic work focuses on a range of taxa, the most conspicuous of these being a giant filter-feeding anomalocaridid reaching a length in excess of 2 m. The three-dimensionally preserved material of this taxon has afforded several major new insights into anomalocaridid biology, the most striking being the discovery of a second pair of lateral flaps, indicating that the lower flaps are homologous to walking limbs. Other taxa currently under study include stylophorans preserving the digestive system, palaeoscolecid worms, trilobites with preserved limbs, a small liwiid, an aberrant aglaspidid exhibiting only six tergites, and the oldest known horseshoe crab, which displays a remarkably complex ontogeny. In addition to this horseshoe crab, the fauna includes several other chelicerate taxa, indicating that this part of Gondwana was a hotbed of chelicerate diversity during the Early Ordovician.

# Post-collisional Early Ordovician magmatism in the Central Iberian Zone: evidence from zircon Hf isotopes in meta-granitic orthogneisses from the Spanish Central System

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Meta-granitic orthogneisses are abundant in the Central Iberian Zone and stratigraphically occur below Floian (Arenig) quartzites. In the easternmost sector of the Spanish Central System they define a batholith that extends over 4000 km$^2$. These rocks show a prolonged trend of chemical differentiation from meta-granodioritic to leucogranitic composition (60 to 78 wt% $SiO_2$), having much lower CaO and $Na_2O$ contents than typical calc-alkaline granites from continental margins. This felsic magmatism has a highly peraluminous composition that increases with the mafic character of the rock, as in typical S-type granites, common in continental collision environments. The peraluminosity of these S-type meta-granites is markedly higher than that of the later peraluminous Variscan granite series.

The studied orthogneisses yield Early Ordovician U-Pb zircon ages (493 to 497 Ma), overlapping with published data (mostly from 500 to 477 Ma). They intrude metasedimentary sequences recently dated by U-Pb zircon geochronology at about 536 Ma. Inherited zircons are common in the orthogneisses (10 to 75% of the total zircon population) with the highest abundance being recorded in restite-bearing metagranites; most range from Neoproterozoic to Late Mesoproterozoic in age (0.52 to 1.25 Ga) and show marked positive $\varepsilon Hf_t$ values (> +5). These high positive $\varepsilon Hf_t$ values are rare in the metasedimentary host rocks of the orthogneisses in the northern Central Iberian Zone: potential source rocks for this wide range of relatively juvenile input are the metasedimentary rocks of the Schist Greywacke Complex in the southern part of the zone. Proposed linkage between the southern metasediments (as sources) and the studied orthogneisses is reinforced by their similar Sr-Nd isotopic signatures and the highly peraluminous character of the orthogneisses.

The essentially recycled crustal origin of the Early Ordovician magmatism in the Central Iberian Zone suggests a collisional scenario as the most credible setting for this highly peraluminous magmatism. The absence of associated basic rocks and mafic microgranular enclaves is significant. The orthogneisses define a huge linear S-type batholith (with associated minor metavolcanic rocks, the "Ollo de Sapo" Formation) cropping out for over 650 km from central Spain to Galicia. The time lapse of ~35 Ma between sedimentation and granite intrusion is consistent with crustal thickening thermal models and typical of classical continental collision zones (e.g., the Himalaya). This post-collisional stage ultimately evolved towards a passive margin scenario, allowing the deposition of the siliciclastic Ordovician series which covered the previous terranes. Minor late Floian tholeiitic magmatism, which gave rise to scarce and small metabasite outcrops in the Spanish Central System, probably postdates and marks this tectonic change.

# New conodont records from the Los Sombreros Formation, an Ordovician mélange in the Argentine Precordillera

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The Lower Paleozoic slope facies in the Argentine Precordillera, San Juan Province, is well preserved in the Los Sombreros Formation, an olistostromic unit that inter-fingers with a Cambro-Ordovician carbonate platform to the east and has ocean-floor sedimentary rocks including pillow lavas and mafic-ultramafic bodies to the west. It contains blocks as large as hectometre-scale of Lower Cambrian to Lower Ordovician limestones, as well as arkosic sandstones and conglomerates with rounded basement-derived clasts (metamorphic and igneous). Extensional structures related to submarine sliding by gravitational collapse give rise to block-in-matrix formations in isolated places. The variable degree of deformation, the scarcity of the faunas and discontinuity of outcrop impede the temporal depositional constraints. Upper Cambrian, Tremadocian, Floian and Darriwilian conodont faunas were recovered at Ancaucha, del Telégrafo Creek, Los Ratones Creek, Ojo de Agua Creek, El Salto Creek and Los Túneles del Río Jáchal. In order to constrain the age of olistostrome formation, we collected 7 conodont samples (each from 9 kg of digested rock) from a tributary creek close to Río San Juan, between Pachaco and Los Ratones. A carbonate-cemented sandstone provided 10 poorly preserved conodonts with CAI 6 (~360–550ºC) and abundant fractures and recrystallization. The fauna consists of *Tropodus* sp. and *Scolopodus* sp., suggesting a Floian age. The other conodont samples were barren except for a lime-mudstone that yielded over 1100 conodont elements including a mixed species association with *Ansella jemtlandica, Baltoniodus* sp., *Costiconus ethingtoni, Drepanodus arcuatus, Drepanoistodus bellburnensis, D. costatus, D. forceps, J. serpaglii, Microzarkodina* sp., *Paltodus? jemtlandicus, Parapaltodus simplicissimus, Parapanderodus nogamii, Paroistodus horridus, P. originalis, Periodon macrodentatus, Polonodus* sp., *Protopanderodus gradatus, P. rectus, Pseudooneotodus* sp., *Spinodus spinatus, Venoistodus venustus* along with the index species *Oepikodus evae* (late Floian) and *Eoplacognathus pseudoplanus* and *Histiodella kristinae* of late middle Darriwilian age. These specimens exhibit a CAI 3-4 (~110–200ºC) and are frequently fractured and covered with mineral overgrowths. Since reworked conodont elements behave as heavy-mineral grains, different CAI values may reflect variable taphonomic/thermal histories. This phenomenon was previously observed in autochthonous and allochthonous conodont elements from the Los Sombreros Formation at Los Túneles del Río Jáchal, where Darriwilian specimens have CAI 3 and Tremadocian elements CAI 5. The occurrence of reworked conodont elements with high CAI values from rocks associated with younger conodonts preserved with low thermal alteration in Los Sombreros Formation reflects an Ordovician metamorphic event, which would be consistent with collision of the Cuyania Terrane with the proto-Andean margin of Gondwana during the Early–Middle Ordovician.

# Advances in conodont biostratiography of the Santa Victoria Group (Cambro-Ordovician) in its type area, Cordillera Oriental, NW Argentina

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The Cambrian–Lower Ordovician stratigraphic sequences of the Central Andean basin cropping out in the Cordillera Oriental of NW Argentina are characterized by thick siliciclastic open-to-shallow marine platform deposits. These strata (Santa Rosita and the Acoite formations of the Santa Victoria Group) are separated from underlying and overlying stratigraphic units by regional unconformities, as originally defined on the eastern flank of the Cordillera Santa Victoria. In this remote region of Salta Province near the Bolivian border, conodont studies have not been accomplished until recently.

The middle part of the Santa Rosita Formation is superbly exposed along Lizoite Creek, consisting of dark shales and interbedded sandstones and siltstones of greenish gray colour. Lensoid calcareous coquinas sparsely interstratified in the siliciclastic succession bore a rich conodont fauna, including *Acanthodus humachensis*, *Acodus primitivus*, *Decoriconus peselephantis*, *Drepanodus arcuatus*, *Drepanoistodus andinus*, *D. chucaleznensis*, *Filodontus carolinae*, *Kallidontus gondwanicus*, *Paltodus deltifer peracutus*, *Paroistodus numarcuatus*, *Utahconus purmamarcensis* , *U. scandodiformis*, *Variabiloconus variabilis* and *Paltodus d. deltifer,* indicative of homonymous Subzone of the *P. deltifer* Zone (middle Tremadocian).

At the confluence of Lizoite Creek with Chulpíos Creek, the uppermost part of the Santa Rosita Formation is characterized by fine-to-medium amalgamated sandstones with planar stratification up to 2 m thick, and sandstones interbedded with pelites that contain rhabdosomes of *Araneograptus murrayi*, late Tremadocian in age. The sandstone beds frequently include coquinas at their bases, and provid a low diversity fauna of *Acodus apex* and *D. costatus*, which is referable to the *Acodus deltatus – Paroistodus proteus* Zone. Grey shales and sandstones with yellowish weathering from the Acoite Formation conformably overlie the mostly sandy package of the upper Santa Rosita Formation, reaching 1843 m in thickness throughout Chulpíos Creek, where it is unconformably covered by Cretaceous sediments. The lowest productive sample from the Acoite Formation, 60 m above its base, yielded *Acodus apex*, *Drepanodus arcuatus*, *Drepanoistodus andinus*, *D. costatus*, *P. d. deltifer*, *Paltodus d. peracutus* and *Paroistodus* sp. This conodont association verifies the continuity of the *Acodus deltatus – Paroistodus proteus* Zone through the basal strata of the Acoite Formation. Hence, the regional unconformity recognized in the western border of the Cordillera Oriental (*e.g.*, Los Colorados) is apparently biostratigraphically constrained, the Acoite Formation starting in the late Tremadocian. The conodonts *Gothodus* cf. *andinus* and *Trapezognathus? primitivus,* along with graptolites probably referable to the *Hunnegraptus copiosus* Zone, occur about 500 m above the base, suggesting that even in the lower part of the Acoite Formation deposition continued into the upper Tremadocian. The subsequent conodont samples exhibit high abundance and low diversity, consisting of *D. andinus, D. costatus, D. arcuatus, D. reclinatus*, *Gothodus andinus,* and *Trapezognathus? argentinensis.* A similar fauna collected in the Laguna Verde section of the Zenta Range suggests a late Floian age. These records extend the original contemporaneous fauna described by previous authors from the Cieneguillas Formation close to Purmamarca. The described record of key conodont assemblages allows for precise links with Lower Ordovician chronostratigraphic intervals of the South American margin of Gondwana and high latitude paleo-plates, such as Baltica and Avalonia.

# The Cambro-Ordovician Gondwana margin in Europe

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The Palaeozoic Gondwana margin and its interaction with Laurentia–Baltica was strongly related to the history of the Rheic Ocean (Nance et al., 2010, Stampfli et al., 2013). Before this opening, the geodynamics of different sectors of the Gondwana margin must have evolved continuously from Cambrian times, and need to be considered in an early Palaeozoic reconstruction, when Variscan nappe-stacking and late Carboniferous oroclinal bending had not yet transformed older structures.

In the European geodynamic context (Martínez-Catalán et al., 2009, their Fig. 1), "allochthonous domains with ophiolites" appear not only in the allochthonous domains above the Central Iberian basement, but also in the South Armorican zone, the French Massif Central, the Bohemian Massif, the Saxothuringian zone, and comparable Cambrian–Neoproterozoic structural elements in the Alpine domains (von Raumer et al., 2013); Neoproterozoic–Cambrian metabasites from the Ossa Morena Zone are here included in this discussion. Although Neoproterozoic–Cambrian (or proto-Rheic) ocean-derived rock suites may appear anywhere along the Gondwana margin, they could represent pieces of a former continuous magmatic arc along the Gondwana margin, before they were dissipated during the Variscan plate-tectonic processes. All these domains host mafic and ultramafic rock-units preceding the opening of the Rheic Ocean, and are mostly allochthonous. For the early Palaeozoic, Stampfli et al. (2013) envisaged an active margin setting with corresponding back-arc rift basins. Geodynamic evolution from a Neoproterozoic intra-oceanic arc setting to back-arc opening and formation of an Ordovician continental arc is generally supposed. When comparing the different sectors, distinct aspects of a pre-Cambrian to Ordovician evolution could appear.

In an Early Paleozoic reconstruction, the Neoproterozoic–Cambrian ocean-derived rock suites along the Gondwana margin may have constituted the eastern prolongation of a Neoproterozoic suture and a Proterozoic–Cambrian active margin setting, discussed by Murphy et al. (2006) for the former more western domains.

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# The collision of South China with NW India to join Gondwana in the Cambrian: results of foreland basin sedimentology and provenance analyses

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The paleogeographic position of the South China Block during the late Neoproterozoic to early Paleozoic is important for understanding the break-up history of Rodinia and the formation of Gondwanaland. We report here the evolution of an early Paleozoic foreland basin (the Nanhua Basin) in South China, and discuss South China's connection with Gondwana and potential tectonic triggers for both the early Paleozoic Wuyi-Yunkai orogeny and similar-age orogenic events along northern Gondwanan margins. The basin evolved in two major stages according to stratigraphic and sedimentological analysis: (1) during the Cambrian and earliest Ordovician, the basin was in an under-filled stage with marine turbidites and shallow marine clastic deposits, fed by detritus from outboard of the South China Block; (2) from the middle Ordovician to the Silurian, the basin was in an overfilled stage with fluvial-dominated deltaic and alluvial fan clastic deposits, fed by the northwestward advancing Wuyi-Yunkai orogen.

Detrital zircon U-Pb ages and Hf-O isotope analyses of Cambrian sandstones/metasandstones from southwestern South China reveal major age populations at 2500 Ma, 1100–900 Ma, 850–750 Ma and 650–500 Ma, with a predominant group at ~980 Ma. Zircon Hf–O isotopic results suggest three Precambrian episodes of juvenile crustal growth for the source area(s): 3.0 Ga, 2.5 Ga and 1.0 Ga, with major crustal reworking at 580–500 Ma. Source provenance as defined by the zircon U-Pb and Hf analyses is distinctly different from the known tectonomagmatic record of the South China Block, but matches well with that of the Ediacaran to Cambrian clastic sedimentary rocks and granitic intrusions in the NW Indian Himalaya. Overall, these data show a close affinity with the provenance record of Cambro-Ordovician sandstones and tectonomagmatic events in NW India. Together with other evidence, we propose that South China likely collided with NW India during the assembly of Gondwana in Ediacaran–Ordovician times. The collision generated the "Pan-African" orogeny at the northern margin of India as well as the intraplate Wuyi-Yunkai orogeny (>460 Ma to 415 Ma) in South China, and peripheral foreland basins on both the Indian and the South China sides.

# Geochemistry and U-Pb zircon ages of Ielova granitic gneisses (South Carpathians, Romania) – evidence for a *ca.* 500-Ma old A-type magmatic event

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Part of the Alpine orogenic belt, the South Carpathians have basement units representing fragments of Gondwana (Balintoni et al., 2014). Located in south-eastern Romania, the Ielova metamorphic sequence (IMS) is such a basement unit with Cadomian affinities.
Ielova granitic gneisses occur as a NW–SE "belt", transversely cutting the volumetrically-dominant metasedimentary rocks of the IMS. Macroscopically, the granitic gneisses are relatively uniform at the outcrop scale, although some textural differences in foliation can be observed. K-feldspar, quartz and biotite are the main minerals, with sphene, zircon, apatite and opaque minerals as accessory phases. No previous geochemical or geochronological studies on Ielova granitic gneisses are known. For this study, whole-rock geochemistry was determined by XRF and ICPMS at University of Vienna, and Acme Labs Vancouver, while U-Pb ages were obtained on zircons by LA-ICPMS at the National History Museum, London.
The geochemical composition of Ielova granitic gneisses is relatively uniform for both major oxides and trace elements, with a calc-alkaline and slightly peraluminous character. The chemical characteristics, such as high $SiO_2$, $Na_2O + K_2O$, Fe/Mg, Ga/Al, Zr, Nb, Ga, Y and Ce, and low CaO, fit with those of an A-type granite. Regarding the magma source, an $A_2$ character (Eby, 1992) suggests that the magmas were generated from crust that has been through a cycle of subduction or continent–continent collision, being emplaced in extensional settings.
Zircon grains extracted from one gneiss sample are elongated and euhedral, many with bipyramidal terminations and simple oscillatory zoned interiors under CL imaging. From 47 zircon crystals analyzed (1 spot/grain), 35 concordant analyses (90–110%) span 523-487 Ma. A group of 21 apparent ages between 509±8 and 491±11 Ma shows statistical coherence and has a calculated concordia age of 503±2 Ma (95% conf., MSWD=1.8), which can be interpreted as the crystallization age of Ielova granitic gneisses.
Many ~500 Ma-old granitoids with a geochemical signature typical of an extensional tectonic regime have been reported all around Europe, including numerous A-type anorogenic felsic granitoids from the Northern Bohemian Massif, as evidence for the large-scale extension and continental break-up that culminated with opening of the Rheic Ocean at about 485 Ma. Within this framework, the ~500 Ma old, A-type granitic gneisses of the IMS point out a similar extensional event preserved in the South Carpathians.

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# Latest developments from the Emu Bay Shale biota (Cambrian, South Australia), the oldest BST *Lagerstätte* in Eastern Gondwana

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The Emu Bay Shale biota (Cambrian Series 2, Stage 4), on the north coast of Kangaroo Island (South Australia), is the most-diverse Burgess Shale-type assemblage in the Southern Hemisphere and the oldest BST *Lagerstätte* in Eastern Gondwana. The assemblage, with over 50 species, is dominated by the trilobite *Estaingia*, with other trilobites including numerous *Redlichia* (up to 25cm long) and rarer *Balcoracania, Megapharanaspis* and *Holyokia*. The second-most common taxon is the bivalved arthropod *Isoxys* (2 species) along with *Tuzoia* (2 species) (García-Bellido et al., 2009). Other fossils include the nektaspid arthropods *Emucaris* and *Kangacaris* (Paterson et al., 2010), the megacheirans *Oestokerkus* (Edgecombe et al., 2011) and *Tanglangia* (Paterson et al., *in press*), the artiopodans *Squamacula* and *Australimicola* (Paterson et al., 2011), and *Anomalocaris* (2 species, Daley et al., 2013). A spiny lobopodian, reminiscent of *Luolishania* from Chengjiang and Collins' Monster from the Burgess Shale, was recently described (Garcia-Bellido et al., 2013a). The biota includes priapulids, such as the palaeoscolecid *Wronascolex* (2 species, García-Bellido et al., 2013b), vetulicolians, polychaetes, brachiopods, leptomitid sponges, chancelloriids, hyolithids and an assortment of new arthropods, plus several taxa pending revision such as the possible opabiniid *Myoscolex* and possible nectocaridid *Vetustovermis*.

Besides preserving soft parts such as guts, gills, muscles, mid-gut glands and trilobite antennae, the unique preservation of Emu Bay Shale has also revealed sophisticated compound eyes with >3,000 lenses and a bright zone capable of vision in dim light belonging to an as yet unknown arthropod (Lee et al., 2011), and that *Anomalocaris* possessed compound eyes with >16,000 lenses (Paterson et al., 2011).

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