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Rodinia 2017: Supercontinents and Global Dynamics

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Supercontinent Cycles & Global Geodynamics

IUGS UNESCO IGCP Project 648 Supercontinent Cycles & Global Geodynamics

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Bringing together a diverse range of geoscience expertise to harness recent breakthroughs to explore the occurrence and evolution and geodynamic processes of supercontinents.

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Rodinia 2017: Supercontinents and Global Dynamics

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Theme Coordinators

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Dr Jacqui Halpin (University of Tasmania).
Dr Robin Armit (Monash University).
Prof. Peter Betts (Monash University).

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Prof. David Evans (Yale University)
Dr Johanna Salminen (University of Helsinki)

THEME 3: How supercontinents assemble.
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THEME 4: New developments in Paleogeographic reconstructions: Reconstruction software; data mining; and database development.
Prof. Bruce Eglington (University of Saskatchewan).

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Prof. Louis Moresi (University of Melbourne)
Prof. Shije Zhong (University of Colorado)

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10:20:00 AM	Feifei Zhang	Geochemical, Ar-Ar geochronological and Sr-Nd isotopic constraints on the origin of Late Mesozoic volcanic rocks from the West Qinling area in China
10:40:00 AM	Yunpeng Dong	Tectonic evolution of the East Kunlun Orogen, Northern Tibetan Plateau
11:00:00 AM	**Morning tea**	
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11:40:00 AM	Shengsi Sun	Deformation of the Songshugou ophiolite in the Qinling orogen
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3:20:00 PM	**Afternoon tea**	
3:40:00 PM	Shuguang Song	Secular breakup of Rodinia from mantle-plume activity to continental rifts to ocean basin (Northern Tibetan Plateau)
4:00:00 PM	Shihong Zhang	A Combined Geochronological and Paleomagnetic study on ~1220 Ma mafic dykes in the North China Craton and its tectonic implications
4:20:00 PM	**Invited**: Steven Denyszyn	Beyond the Barcode: Geochronological methods responsibly applied to supercontinent reconstructions
4:40:00 PM	Nicolas Flament	Implications of the mobility of the Perm Anomaly for tectonic reconstructions in deep geological time
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10:00:00 AM	Simon Williams	Open-source tools for the study of deep time plate tectonic reconstructions: a GPlates update
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2:20:00 PM	Louis Moresi	The evolving nature of continental dynamics since the Archean
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3:20:00 PM	**Keynote: Bill Collins**	**Billion year, mantle convection cycles through Earth history**
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		Theme coordinators: Dr Jacqueline Halpin, Dr Robin Armit, Prof. Peter Betts
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10:40:00 AM	Jacob Verbaas	A sedimentary overlap assemblage spanning the Gawler Craton and northwestern Laurentia at 1.6 Ga
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11:40:00 AM	Jacob Mulder	Rodinian devil in disguise: Correlation of 1.25—1.15 Ga strata between Tasmania and Grand Canyon, Arizona
12:00:00 PM	Bo Yang	Spatial and Temporal Detrital Zircon U-Pb Provenance of the Hydrocarbon-Bearing Upper Roper Group, Beetaloo Sub-basin, Northern Australia
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4:00:00 PM	Michael Doublier	3D model of the major crustal boundaries of Australia: implications for mineral systems understanding
4:20:00 PM	George Gibson	Late Paleoproterozoic-earliest Mesoproterozoic orogenesis and sediment-hosted Pb-Zn mineralisation in northern Australia: a legacy of supercontinent assembly and plate convergence between Australia
4:40:00 PM	David Huston	Mineral systems of the Paterson Province, Western Australia: diverse metallogeny associated with Rodinia break-up
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10:00:00 AM	Geoffrey Grantham	Insights into the extent of southern Gondwana in Rodinia: Geochronology and Nd and Sr radiogenic isotope data
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11:20:00 AM	Erin Martin	Evaluation of full-plate reconstructions of the Neoproterozoic using Hf isotopes in zircon
11:40:00 AM	Naresh Kochhard	Archean continental crust beneath Mauritus: Implications for the Greater Malani Continent
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1:40:00 PM	Piotr Krzywiec	Rodinia break-up along the SW margin of the East European Craton (SE Poland) – new evidence based on deep seismic and grav-mag data
2:00:00 PM	Bin Wen	Paleomagnetism of early-Neoproterozoic volcanic rocks in SW Tarim and its paleogeographic
2:20:00 PM	Robert Boris	Constraints on the Ediacaran Inertial Interchange True Polar Wander Hypothesis: a New Paleomagnetic Study in Morocco (West African Craton)
2:40:00 PM	**Afternoon Tea**	
3:00:00 PM	Jiu-long Zhou	Ca. 750–720 Ma tectonic transition recorded in the Bemarivo terrane balances the global plate kinematic budget during Rodinia break-up
3:20:00 PM	Qiwei Li	Heterogeneous mantle source modified by subduction beneath the western Yangtze Block, South China: evidence from Neoproterozoic Dengxiangying mafic dikes
3:40:00 PM	Zhibin Lei	LA-ICP-MS U-Pb Dating of Heishitougou Basaltic Zircons: Implications for a More Extensive and Lasting Effect of the Paleo-Asian Ocean Southward Subduction
4:00:00 PM	**Discussion**	
4:20:00 PM	**Presentation and Prizes**	

THEME 1.

Assembly of Australia in supercontinent cycles.

Coordinators: Dr Jacqueline Halpin (University of Tasmania).

Dr Robin Armit (Monash University).

Prof. Peter Betts (Monash University)


Rodinia
2017

Palaeogeography of the South Australian Craton within Nuna

R.Armit[1,*], P.G. Betts[1], B.F. Schaefer[2], L. Ailleres[1], D. Giles[3]

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[2]GEMOC, Department of Earth and Planetary Sciences, Macquarie University, NSW, Australia
[3]School of Natural and Built Environments, University of South Australia, SA, 5000

Integrated geochronology, isotopic and REE geochemical analysis from the northern Gawler Craton were used to test if major boundaries interpreted from geophysical datasets (Baines et al., 2011) truly represent sutures between allochthonous crustal blocks. The northern Gawler Craton appears to be underlain at least in part by Neoarchaean substrate (Reid et al., 2014) that is isotopically similar to basement rocks in southern Gawler Craton and the North Australian Craton. The correlation of Neoarchaean basement in both the southern and northern Gawler Craton (Reid et al., 2014) and lack of systematic isotopic and REE variations suggest that these boundaries separate autochthonous crustal blocks that have been attenuated (and possibly rifted from each other) and re-amalgamated in the Late Palaeoproterozoic to Mesoproterozoic. A modern analogue for this is the SW Pacific in which continental ribbons (e.g. Lord Howe Rise) have been separated from the Australian plate.

The Palaeo-Mesoproterozoic meta-sedimentary and magmatic rocks of the South Australian Craton evolved in a continental far-field back-arc setting that was affected by rapid tectonic mode switches along long-lived convergent margins along the south and east of the Australian continent. The older ca. 1740 Ma meta-sedimentary sequences in the northern Gawler Craton share isotopic and geochemical affinities with rocks in the North and South Australian cratons (Armit et al., 2017) and suggest that they form part of an extensive and contiguous Late Palaeoproterozoic basin system (Fig. 1) that was inverted during the ca. 1730-1690 Ma Kimban-Strangways-Nimrod-Yavapai orogenic system, and subsequently reactivated during the ca. 1650 Ma Ooldean-Liebig event and the ca. 1590-1560 Ma Kararan-Chewings Orogen. This requires the South and North Australian cratons to be co-located in the Late Palaeoproterozoic rather than as separate entities as is proposed in several reconstructions (e.g., Wade et al., 2006; Myers et al., 1996). This suggests that the use of these terms for the two distinct cratonic blocks may only be relevant after the Early Mesoproterozoic, when they have been interpreted to have evolved independently (e.g., Giles et al., 2004; Smits et al., 2014; Aitken et al., 2016).

In the Mount Painter Province, the Early Mesoproterozoic ca. 1595 Ma meta-sedimentary rocks are derived from the Gawler Craton and are poly-deformed between ca. 1590 and ca. 1550 Ma which correlates with events in the northern Gawler and North Australian Craton rather than the southern Gawler Craton and Curnamona Province (Armit et al., 2014). The implication of this is that the north-western Curnamona Province must have been co-located with the Gawler Craton and the North Australian Craton in the Early Mesoproterozoic (Fig. 2).

The rapid switches in the tectonic mode recorded in South Australian Craton in the Late Palaeoproterozoic to Early Mesoproterozoic are linked to small-scale perturbations within long-lived convergent subductions systems along the southern and eastern margin of Australia that most likely reflect the commencement of roll-back of steep subduction zones resulting in extension (e.g. Kararan and Strangways events) in the overriding plate punctuated by episodic phases of shortening.

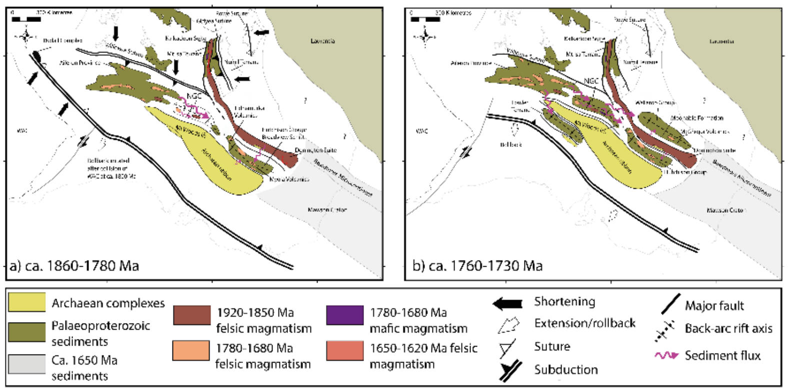

Figure 1: ca. 1860-1730 Ma reconstruction of eastern Proterozoic Australia

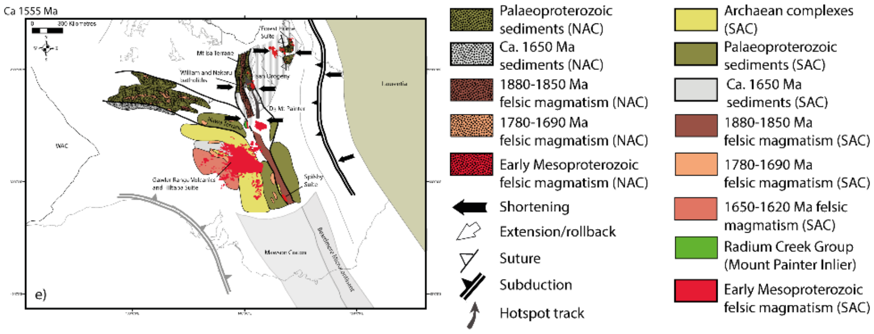

Figure 2: ca. 1555 Ma reconstruction of eastern Proterozoic Australia

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Accretion of Northern Australia during Nuna amalgamation via recycling of ribbon microcontinents

Betts, Peter G[1], Armit, Robin[1], Blaikie, Teagan[1,2], Ailleres, Laurent[1].

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The evolution of the Australia continent is dominated by two periods of rapid accretion associated with supercontinent cycles during the Paleoproterozoic assembly of Nuna and Phanerozoic assembly along the eastern margin of Gondwana. This abstract focusses on the Australian record of Nuna assembly, which occurred between ca 1860 Ma and 1710 Ma. Previous interpretation of the Australian continent have largely been formulated using the North, South, and West Australian Craton (NAC, SAC, WAC) nomenclature that was initially introduced by Myers et al. (1996), which accreted together during the Mesoproterozoic assembly of the supercontinent Rodinia. Several researchers recognised that the SAC shared similar geological histories of the NAC (e.g. Curnamona Province and Mount Isa Inlier), which led several groups to propose alternative architectures of the Australian continent during the Paleoproterozoic (Betts and Giles, 2006; Wade et al. 2006; Gibson et al. 2008; Payne et al. 2009), and whilst providing a context for the evolution of the Australia continent, did not address the Proterozoic assembly of the continent.

A significant investment in the collection of regional seismic transects and potential field data provided unprecedented imaging of major crustal-scale structures and terrane boundaries (Korsch et al. 2012; Korsch and Doublier, 2016). Major suture zone include the: Willowra Suture (Goleby et al. 2006) (southern margin of the Proto-North Australian Craton); Kalinjala Shear Zone (Betts et al. 2016), eastern Gawler Craton; Gidya Suture (Korsch et al. 2012), eastern margin of the Mount Isa Inlier; Rowe Fossil Subduction Zone (Korsch et al. 2012), eastern Proterozoic Australia; and Hall Creek Fault Zone in the eastern Kimberley region. A suture is also identified in seismic and potential field data in the Curnamona Province (Williams et al. 2010). The suture between the WAC and the NAC is less well-defined. Australian Proterozoic suture zones are relatively discontinuous but can be reconstructed into a series of linear belts that resemble elongate continental ribbons that accreted onto the margin of the proto-NAC during the Paleoproterozoic (Betts et al. 2016). Using the geological constraints, the accretion of the ribbons are constrained to have occurred between ca 1860 Ma and ca 1740 Ma.

Accretion along the southern margin of the NAC occurred via south-dipping subduction and involved the collision of the Aileron Province and contiguous parts of the Gawler Craton to the southern proto-NAC. The Willowra Suture and the Kalinjala Shear Zone are correlated. The radiogenic isotope characteristics of the Aileron Province and the Gawler Craton are similar to the Pine Creek region of the NAC. This suggests this ribbon originated from the NAC, was ripped off the craton margin and was re-accreted during Nuna assembly between ca 1860-1840 Ma (Betts et al. 2016). The timing of the accretion of the Kimberly Craton along the northern margin of the Proto-NAC, with interpretations of both west- and east-dipping subduction (*cf*. Lindsay et al. 2016; Betts et al. 2016), both based on potential field modelling. Our preferred interpretation is east-dipping subduction because it explains the continental back arc basin formation in the Tanami Province of the proto-NAC. The Kimberley Craton is interpreted to be allochthonous with respect to the proto-NAC. Previous interpretations suggested that the accretion of the WAC and the NAC must have occurred on the northern margin of the WAC during the ca 1800 Ma Yapungku Orogeny near the Rudall terrane. This interpretation is supported by paleomagnetic constrains, which suggest WAC and NAC amalgamation must pre-date ca 1700 Ma (Li. 2000) as well as correlation of the sediment fill in the Earaheedy Basin and the basins of the NAC after ca 1800-1750 Ma (Allen et al. 2015). However, this interpretation has been called into question with recent results suggesting that medium-pressure metamorphism occurred during the Mesoproterozoic (Collins et al. 2016). Alternatively, the new results possibly suggest multiple cycles of collision between the WAC and NAC, with the final architecture established during the Mesoproterozoic.

Seismic data along the eastern margin of the NAC suggests the presence of two terrane boundaries, the west-dipping Gidyea suture zone (Korsch et al. 2012), which separates the Mount Isa terrane from the buried Numil Seismic Province, and the Rowe Fossil Subduction Zone. In our reconstruction, this suture is correlated with a buried terrane boundary that transects the Curnamona Province (Williams et al., 2010). This boundary is stitched by the ca 1690-1660 Ma Calvert Superbasin and ca 1710 Ma sediments of the Willyama Supergroup, which provide a minimum age for the accretion of the Numil terrane with the proto-North Australian Craton. Our best estimate of the collision of the Numil with the Mount Isa terranes is between ca 1740 Ma and 1710 Ma, which is recorded by basin inversion, the Leichhardt Event in the Mount Isa terrane (Blaikie et al. 2017).

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Australo-Antarctica in Gondwana: A view from the edge

Halpin[1], Jacqueline A., Daczko[2], Nathan, R., Whittaker[1], Joanne M., Fitzsimons[3], Ian C.W.

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[2]*Department of Earth and Planetary Sciences, Macquarie University, Sydney NSW, Australia*
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Plate reconstructions that consider Neoproterozoic (770-750 Ma) paleomagnetic data from India and Australia imply significant (~3000-5000 km) relative displacement between these continents before they reached their unified Gondwana fit by ~540 Ma (Fig. 1; e.g., Li et al., 2013). Therefore, these models require a plate boundary (or boundaries) between Neoproterozoic India and Australia, with or without accreted terranes that may have been in between. The inferred plate boundary must also penetrate East Antarctica, separating the Indo-Antarctic and Australo-Antarctic blocks. However, there is considerable flexibility around the magnitude of displacement, as well as the nature of the motion, depending on: (1) the Euler pole selected using the 95% confidence level ellipses of the paleomagnetic data, and (2) the location and geometry of the plate boundary. These constraints have implications for the width of a pre-Gondwanan ocean basin between Indo-Antarctica and Australo-Antarctica, the timing of collision along the margin, and the tectonic style expected to be recorded in the rocks.

Here we review the various models for the amalgamation of Indo-Antarctica and Australo-Antarctica to form Gondwana, and explore the implications of approaching this problem via integration of geological and geophysical data in a plate reconstruction framework. We focus on the western edge (present day co-ordinates) of the Australo-Antarctic craton, which we define by incorporation of:

(1) a compilation of detrital zircon ages from marine sediments offshore Antarctica, which fingerprint two coastal subglacial basement provinces between 60 and 130°E, one of “Indian” affinity with dominant ca. 980–900 Ma ages (Indo-Antarctica) and one of “Australian” affinity with dominant ca. 1190–1140 and ca. 1560 Ma ages (Australo-Antarctica),

(2) new U-Pb SHRIMP zircon and U-Th-Pb chemical monazite ages for key basement rocks in the Denman Glacier region of Antarctica, which all exhibit an “Australian” affinity (based on above),

(3) geological data from Batavia and Gulden Draak knolls (now lying in the Indian Ocean ~1600 km from Western Australia), which are microcontinents comprising a felsic-intermediate igneous-metamorphic basement complex (Gardner et al., 2015). Together with the Naturaliste Plateau, these microcontinents reconstruct offshore the Denman Glacier region of East Antarctica (Fig. 1 inset), and based on zircon age data from basement dredge samples, we interpret these microcontinents to represent crust of “Australian” affinity.

This approach confines the *location* of the Antarctic coastal intersection of the paleo-plate boundary to between Mirny station (~93°E; with ages characteristic of Indo-Antarctica) and Cape Harrison/Mt Strathcona (~99°E; with ages characteristic of Australo-Antarctica). We suggest a plausible candidate for at least part of this boundary is a prominent geophysical lineament identified at ~94°E near Mirny (Fig. 1 inset; Aitken et al., 2014). We have recently obtained new rock samples from rare outcrops in this region to further test this hypothesis.

To assess the *type* of plate boundary along the margin that intersects the East Antarctic coast we examine the age and Hf-isotope signature of zircon from ~580-530 Ma felsic igneous rocks from the microcontinents, which lay close to (but on the “Australian” side of) this interpreted plate boundary. Primary igneous zircon populations exhibit a narrow range of very low initial Hf isotopic ratios suggesting derivation of melts from very ancient crust (T DM Hf crustal model ages = 3.8–2.9 Ga) with

Very limited juvenile input. We suggest that crustal reworking of Archean (Yilgarn) crust, together with other regional constraints, argues against any significant subduction/magmatic arc along this segment of the Neoproterozoic-Cambrian plate boundary zone.

In summary, when our geological data from the western edge of Australo-Antarctica are integrated with other regional geological constraints and available aerogeophysics in Antarctica, and considered in a plate reconstruction framework, we suggest a dominantly sinistral strike-slip margin related to Gondwana assembly as the most likely tectonic setting in this region. This analysis also allows us to speculate on the geometry and location of this paleo-plate boundary further into the interior of subglacial Antarctica. We suggest the boundary turns west, and links with a subduction margin along the boundary of very thick crust (~60 km) and lithosphere (>200 km) forming the Gamburtsev Subglacial Mountains and East Antarctic Mountain Ranges.

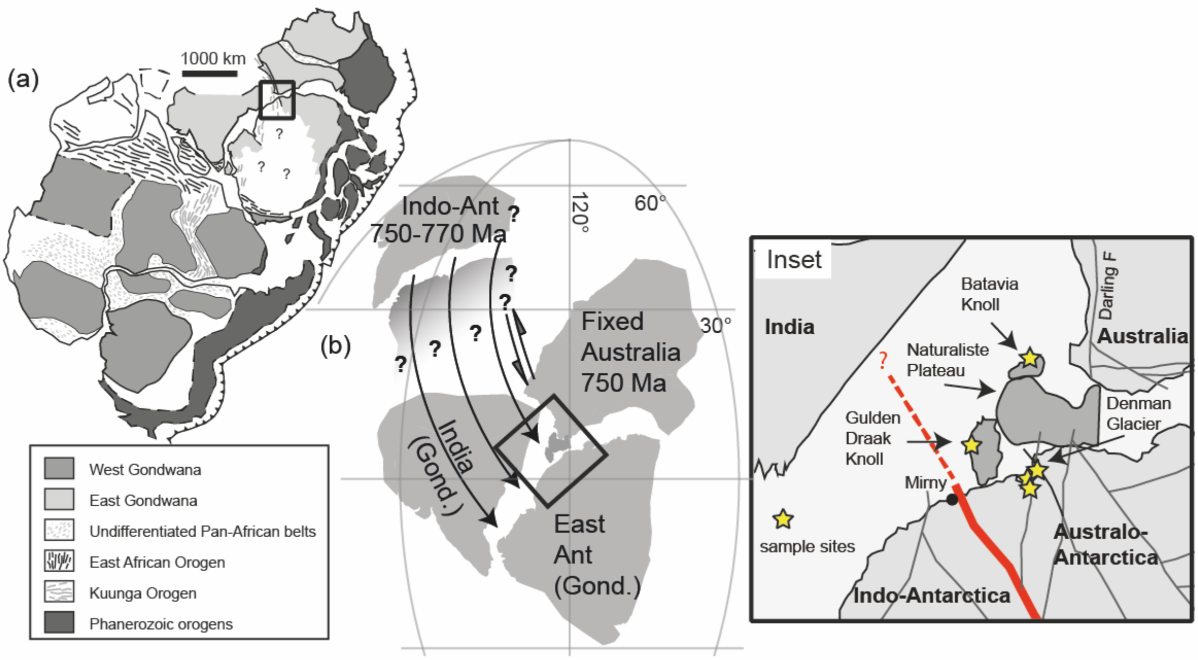

Figure 1. (a) Schematic reconstruction of Gondwana at c. 530 Ma. The focus of this study is within the Kuunga Orogen (area in bold rectangle). (b) Reconstruction showing motion of Indo-Antarctica from 750-770 Ma to accretion into a Gondwanan fit, in a fixed Western Australian 750 Ma reference frame (modified after Gregory et al., 2009). Motion paths (black arrows) indicate a dominantly SE-directed motion of Indo–Antarctica. Inset: plate tectonic reconstruction of Gardner et al. (2015). Yellow stars show locations of geological samples discussed here. Grey lines denote major tectonic lineaments in Australia and Antarctica from Aitken et al. (2014). Lineament identified in red is plausible paleo-plate boundary segment between Indo-Antarctica and Australo-Antarctica.

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Palaeomagnetism of the Boonadgin Dyke Suite, Yilgarn Craton: Implications for the Assembly of the Western Australian Craton and Possible Connection with India

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Mafic dykes are ideal targets for palaeomagnetic study as they are routinely dateable and are generally more likely to preserve the primary remanence. We conducted a palaeomagnetic study on the newly identified ca. 1.9 Ga Boonadgin dyke suite (Stark et al., submitted). Ten dykes revealed high-temperature characteristic remanent magnetization (ChRM), the direction of which is bipolar, either SW shallow downward (4 sites) or NE shallow upward (6 sites). We argue that the ChRMs of the Boonadgin dyke suite is primary based on: (1) a positive baked contact test; (2) a positive reversal test; (3) dissimilarity between the direction of ChRM and published younger palaeomagnetic directions from the region; (4) the fact that the nearby ca. 2.4 Ga Wigiemooltha supersuite preserved primary magnetizations (Smirnov et al., 2013), indicating the absence of pervasive overprint events in the region; and (5) the unblocking temperature is generally between 530 °C and 590 °C, and such a high unblocking temperature makes the ChRM unlikely a thermal overprint.

The closeness of palaeomagnetic pole from the 1.9 ~ 1.8 Ga Frere Formation (Williams et al., 2004) to our new pole suggests that the Yilgarn Craton and the Earaheedy Basin of the Capricorn Orogen were close to each other at ca. 1.89 Ga. This age predates the Capricorn Orogeny and thus favours the two-stage formation model for the Western Australia Craton (WAC): the 2215–2145 Ma Ophthalmian Orogeny first brought the Pilbara Craton and the Glenburgh Terrane together to form the so-called Pilboyne craton, which in turn collided with the Yilgarn craton to form the WAC during the 2005 – 1950 Ma Glenburgh Orogeny (Johnson et al., 2011).

Although the assembly time for Precambrian Australia is still debated, most workers consider it to be ca. 1.8 Ga or younger (Betts et al., 2016; Cawood and Korsch, 2008; Li, 2000; Li and Evans, 2011; Myers et al., 1996). Therefore, our new pole represents the West Australian Craton (WAC). The new Boonadgin dyke pole places WAC close to the paleoequator. Meanwhile, paleopole from the ca. 1.88 Ga Dharwar dykes of South India, supported by a positive baked-contact test (Belica et al., 2014), puts India at a similar paleolatitude. The Dharwar dykes and Boonadgin dykes are identical in age and can be parts of the same radiating dyke swarm. If so, the western margin of the WAC should be reconstructed at the vicinity of eastern margin of South India. We therefore propose that WAC and South India were connected at ca. 1.9 Ga.

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VanDieland in the life and death of Rodinia

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The oldest rocks in the Tasmanian region of VanDieland are found on King Island and in the Rocky Cape Zone in north western Tasmania. The areas have sedimentary rocks containing detrital zircons slightly older than 1400 Ma, with metamorphic monazites of 1290±20 Ma and 1314±23 Ma. While the King Island rocks are probably of deep marine origin and so may have been deposited on oceanic crust, the Rocky Cape rocks are marginal marine and probably sit on an older craton that has a Nd T_{DM} model age of 2000 Ma or slightly younger. Comparison of zircons from the surrounding granites and sedimentary rocks to the southeast of the Rocky Cape Zone suggests that the concealed basement contains an excess of late Palaeoproterozoic (~ 1600 to 1650 Ma) detrital zircons. Another constraint on VanDieland is the presence on the east South Tasman Rise of granites with ages of ~1120 Ma and 1050 Ma and metamorphic ages from ~1015 Ma to ~920 Ma (Berry *et al.* 2008), suggesting a connection to other Grenville-aged sequences..

The earliest Rodinian breakup events seen in Tasmania are ~780 Ma zircon in an altered granite in the Arthur Complex and ~775 Ma zircon in felsic dykes on King Island (Calver *et al.* 2013). As well, meta-turbidites of the Oonah Formation have been intruded by mafic sills with a K-Ar minimum age of ~710 Ma. Both the Oonah Formation and the Rocky Cape Zone can be traced over 800 km north into central Victoria. In Tasmania, both sides of the former are constrained by major fault systems. The eastern side is characterised by Cambrian ophiolites that have been obducted west onto the underlying Oonah Formation. On the western side, the Arthur Complex also contains rift tholeiites and meta-gabbros and was metamorphosed to blueschist facies in the Middle Cambrian Tyennan Orogeny. Elsewhere, extension is mostly seen in the development of the Smithton Basin and equivalents. This Neoproterozoic unit contains at least 3 km thickness of shallow marine dolomite, diamictite and other clastic rocks and mafic volcanic rocks. The last clear rifting event is west of the Rocky Cape Zone and is defined by the presence of a 50 km-wide zone of tholeiitic basalt from which Meffre *et al.* (2004) obtained a Nd-Sm isochron age of 579±16 Ma.

By the end of the Neoproterozoic, VanDieland would appear to have been extended to form several ribbons separated by thinned continental to transitional oceanic crust, similar to those described by Péron-Pinvidic and Manatschal (2010). These ribbons were re-amalgamated in the Tyennan Orogeny.

The timings of the events recorded in VanDieland are shared with the southwestern USA (Whitmeyer & Karlstrom 2007). Crust with Nd-Hf T_{DM} model ages younger than 2000 Ma is present in the Yavapai and Mazatzal provinces, and granite in the latter could also have provided 1600 Ma zircon. The 1400 Ma zircon in VanDieland may have come from the Granite-Rhyolite Province rocks, and various phases of the Grenville Orogeny could have been responsible for the ~1050 Ma and 1120 Ma granites and ~1300 Ma to 920 Ma metamorphism. Aligning the South Tasman Rise with the Grenville Orogen places onshore Tasmania adjacent to the Granite-Rhyolite Province and the Yavapai-Mazatzal region (Moore *et al.* 2015). Breakup events in southwestern USA are also similar to those in VanDieland (Yonkee *et al.* 2014). Like VanDieland, the earliest recorded extension was at ~770 Ma, with final breakup at ~570 Ma.

Another possibility is that VanDieland lay outboard of the central Transantarctic Mountains. In this region, Borg and DePaolo (1994) suggested that the T_{DM} model ages were less than 2000 Ma, granite and sedimentary rocks of similar ages to those in Tasmania have been found containing 1400 Ma zircons (Goodge *et al.* 2008). As well, Grenville-age rocks are known from the Shackleton Range and

Coats Land. The Beardmore Group was also deposited in a rift environment as it contains a ~670 Ma gabbro and associated pillow basalt. Goodge *et al.* (2012) recorded the presence of ~560 Ma Ross Orogeny related granite, suggesting that breakup had ceased and that subduction had commenced by this time.

Since either alternative seems possible, we suggest that a SWEAT-like assemblage, perhaps similar to that suggested by Li *et al.* (2008) or Li *et al.* (2013), would most closely fit the above observations. In this scenario, VanDieland would be placed between East Antarctica and southwestern Laurentia.

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Rodinian devil in disguise: Correlation of 1.25—1.15 Ga strata between Tasmania and Grand Canyon, Arizona

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Paleogeographic reconstructions of Rodinia typically place Australia or East Antarctica adjacent to the southwestern margin of Laurentia. Of critical importance to these reconstructions is a linkage of the 1.30—1.00 Ga Grenville orogen in southern Laurentia to Late Mesoproterozoic orogens in Australia or East Antarctica. The Grenville Orogeny in southern Laurentia was associated with an extensive episode of syn-orogenic sedimentation throughout the continental interior of southwest Laurentia, which is preserved as a series of isolated foreland basin exposures extending from present-day Texas through to New Mexico and Arizona and into California (Fig. 1). Like the hinterland of the Grenville orogen, this syn-orogenic basin system is truncated by the Neoproterozoic rift margin of Laurentia and may extend into the continent(s) to the west of Laurentia within Rodinia. This contribution explores the correlation of syn-orogenic basins in southwest Laurentia and Late Mesoproterozoic strata in Tasmania (southeast Australia). We present new field observations and detrital zircon U-Pb age and Hf isotopic data from the most complete exposures of the Late Mesoproterozoic syn-orogenic basin system of southwest Laurentia represented by the Unkar Group (Grand Canyon, Arizona) and from Late Mesoproterozoic strata comprising the upper Rocky Cape Group in Tasmania. The age and stratigraphy of the Unkar and upper Rocky Cape Groups show striking similarities with both successions comprising a lower package of *ca.* 1.25 Ga dolomite and shale, which is disconformably overlain by an upper succession of *ca.* 1.15 Ga quartz arenite (Fig. 1). We suggest the upper Rocky Cape Group is a correlate of the Unkar Group and represents a remnant of the extensive foreland basin system of the Grenville orogen in southern Laurentia, which supports the interpretation that Tasmania was located along the southwest margin of Laurentia in the Late Mesoproterozoic. Detrital zircon U-Pb age and Hf isotopic data indicate that both the Unkar Group and upper Rocky Cape Group were derived mainly from 1.80—1.40 Ga crust similar in character to basement terranes in southwest Laurentia. The Unkar and upper Rocky Cape Groups also contain abundant *ca.* 1.20 Ga detrital zircons with εHf_i values between +10 and +2, consistent with a Late Mesoproterozoic source in the Grenville orogen of southern Laurentia characterized by a mixture of juvenile material and reworked southwest Laurentian Paleo—Mesoproterozoic basement. However, the *ca.* 1.15 Ga westerly-derived upper parts of the upper Rocky Cape Group also contain *ca.* 1.20 Ga detrital zircons with evolved Hf isotopic compositions (εHf_i = -2 to -6), which are not observed in the Unkar Group dataset. Comparison of the upper Rocky Cape Group detrital zircon dataset with detrital zircon U-Pb-Hf isotopic data compiled from Late Mesoproterozoic orogens in Australia, East Antarctica, and South China indicate that Late Mesoproterozoic crust concealed beneath ice cover in the central Transantarctic Mountains of East Antarctica is the most suitable source for the westerly-derived parts of the upper Rocky Cape Group. A Late Mesoproterozoic position for Tasmania along the southwest margin of Laurentia and an East Antarctic provenance for the upper parts of the upper

Rocky Cape Group support a connection between southwest Laurentia and East Antarctica within Rodinia at *ca.* 1.15 Ga.

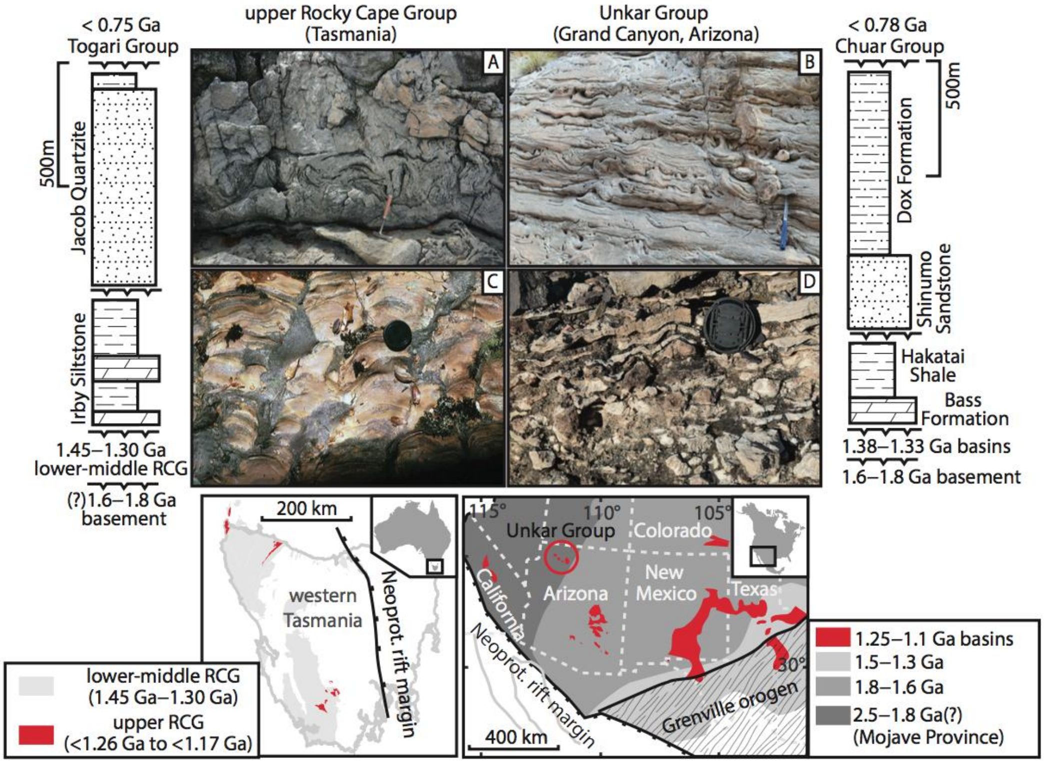

Figure 1: Regional Geology, stratigraphy, and field photographs of Late Mesoproterozoic strata in Tasmania (upper Rocky Cape Group, left) and Grand Canyon (Unkar Group, right). Field photographs A and B show soft sediment deformation folds in quartz arenite of the Jacob Quartz and Shinumo Sandstone respectively, photographs C and D show stromatolitic dolomite from Irby Siltstone and Bass Formation respectively.

Laurentian crust in NE Australia: A critical tie-point during the assembly of the supercontinent Nuna

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Precise supercontinental reconstructions rely on identifying key tie-points between now-dispersed continents. A key tie-point for Rodinia between Australia and North America was initially based on similarities noted in sedimentary successions (Jefferson, 1978). This tie-point between east Australia and west Laurentia has also been proposed for the Proterozoic supercontinent Nuna (Hoffman, 1991), mostly in a Proto-SWEAT (Southwest U.S. - East Antarctica) configuration (Payne et al., 2009; Zhang et al., 2012; Zhao et al., 2002). In this configuration, the Proterozoic Georgetown Inlier of NE Australia is juxtaposed to the Yukon region of NW Canada (Betts et al., 2016; Furlanetto et al., 2016; Pehrsson et al., 2016). Detrital zircon age spectra from sedimentary strata within the Georgetown Inlier show three distinct signals in sedimentary provenance (Neumann and Kositcin, 2011): (1) The lowermost units (Dep age ~1700-1650 Ma) have detrital zircon age spectra that strongly resemble Laurentian magmatic ages; (2) Sediments deposited from ~1650 to 1610 Ma show a unique proximal signature, and (3) sediments deposited post-1550 Ma have zircon age spectra that resembles the Mt. Isa Inlier of NE Australia. Along with new paleocurrent measurements, the detrital zircon age data challenge current models that suggest the Inlier was part of the North Australian Craton before ~1700 Ma (Betts et al., 2016; Gibson et al., 2017). Rather, we suggest it was a continental ribbon rifted from west Laurentia during slab-rollback and development of an east-dipping subduction zone at approximately 1690 Ma. By 1650 Ma the Georgetown Inlier had completely rifted from Laurentia and by 1600 Ma was colliding with Australia. We show that the Georgetown Inlier is an important tie point between west Laurentia and the North Australian Craton during Nuna assembly between 1700 and 1550 Ma. The geological evolution of the inlier indicates Nuna assembly was unlikely completed prior to 1700 Ma as numerous previous studies suggested (Zhang et al., 2012; Zhao et al., 2002); instead, the assembly likely completed ca. 1600–1550 Ma through the accretion of the Laurentia-originated Georgetown Inlier terrane with the NAC, and the closure of an internal subduction system between the inlier and Laurentia.

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Tectonic evolution of NE Australia during the assembly of supercontinent Nuna: a multi-disciplinary reappraisal

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Despite substantial improvements in our understanding of the mid-Proterozoic supercontinent Nuna (or Columbia) over the past decade, the time of its final assembly has been equivocally placed at around 1.8 Ga (Zhao et al., 2002; Zhang et al., 2012; Wang et al., 2016) or, alternatively, shortly after 1.6 Ga (Pisarevsky et al., 2014; Pehrsson et al., 2016). In the latter view, globally widespread 2.1–1.8 Ga orogenic events are regarded as being associated with the amalgamation of the constituent cratons of Nuna. Hence, the 1.9– or 1.7–1.5 Ga continuous geological record in the eastern N-Australian Craton, which is commonly considered to have connected to W Laurentia in the core of Nuna, is critical to understand the evolution of Nuna.

Northeastern Australia is characterised by regional orogenic events during 1.6–1.55 Ga, associated with N–S and E–W shortening, low-P/high-*T* metamorphism, anatexis and S-type magmatism. Diagnostic geological indicators of subduction processes (e.g. high-*P*/low-*T* metamorphic rocks, ophiolites, arc-type calc-alkaline igneous rocks) are missing and terrane boundaries cannot be easily established. Significant burial, along continental collision–like thermal regime, is recorded by early grown garnet in medium-grade metapelite of the Mt. Isa and Georgetown inliers (Cihan et al., 2006; Sayab, 2006; Rubenach et al., 2008). Similar records were also documented further north in the Dargalong, Yambo and Coen inliers (Blewett, 1992; Bultitude et al., 1993; Blewett and Wilford, 1996).

In this study, we apply Lu–Hf garnet geochronology on the sporadically distributed prograde metamorphic assemblages throughout NE Australia, which were not overprinted by subsequent low-*P*/high-*T* metamorphism. This approach shall allow possible spatial–temporal variations of early shortening events in NE Australia to be evaluated and the timing and mode of assembly of the different Proterozoic inliers during the late Paleoproterozoic and early Mesoproterozoic to be established.

This work is a part of a field-based multi-disciplinary project on Proterozoic NE Australia that also includes studies of (i) the structural and petrological evolution of the Georgetown Inlier (see Volante et al., this volume), (ii) the depositional environments and sedimentary provenance (see Nordsvan et al., this volume), and (iii) the thermal history of the NE Australian inliers. The ultimate aim is to improve our understanding of the tectonic evolution of NE Australia and its connections with other continents in Nuna.

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Missing links in understanding the assembly of southern Proterozoic Australia

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The assembly of southern Proterozoic Australia has long been regarded to have resulted from Mesoproterozoic ‘Grenville-age’ continental collision of the West Australian Craton (WAC) and the South Australian Craton (SAC), which is part of the greater Mawson Craton (MC). The Albany–Fraser Orogen, situated along the margin of the WAC in southern Western Australia, was considered to have formed by orogenic processes during this collision, although the region was poorly understood and the positions of suture zones and tectonic models were speculative. The problem was compounded because of the ~200,000 km^2 of unknown basement to the northeast and outboard of the Albany–Fraser Orogen that is buried by the Mesozoic to Cenozoic Bight and Eucla Basins, the surface of which forms the Nullarbor Plain. This hidden crust is informally known as the Eucla basement. Furthermore, to the south of the orogen its rifted counterparts are sparsely exposed in Antarctica. Hence, to test models of continental collision between the WAC and MC required a more robust understanding of the WAC margin itself, and importantly, what lay beyond that margin. Here we present work spanning the last decade that has gone a long way to addressing these issues, and which does not support models of continental collision.

In addition to targeted mapping, sampling and geophysical interpretation GSWA undertook a stratigraphic drilling program to investigate the hidden Eucla basement. In combination with sparse exploration drillcores, this provided a means of effectively mapping below the cover. The lithological, structural, geochemical, isotopic and geochronological results from this work define the connections and differences between the Albany–Fraser Orogen and the various surrounding Proterozoic provinces, and provide vital information for geophysical interpretations. The Albany–Fraser Orogen provides evidence for a protracted history of Archean craton margin (WAC) modification including continental rifting and basin formation from at least 1815 Ma, leading to an ocean-continent transition by c. 1500 Ma (Fig. 1). To the east of the orogen, in the western Coompana Province, calc-alkaline dioritic to granitic gneisses of the Toolgana Supersuite record c. 1700–1600 Ma primitive-arc magmatism. This has been interpreted as part of the same arc system represented by the c. 1610 Ma St Peter Suite of the Nuyts Domain in the Gawler Craton. At c. 1500 Ma, intra-plate rifting of oceanic-arc rocks such as those represented by the Toolgana Supersuite, partial melting of lower mafic crust and the introduction of additional mantle-derived magmas led to emplacement of broadly A-type metagranites and metavolcanic rocks of the Undawidgi Supersuite. These rocks record progressive recycling of the oceanic substrate. Isotopic data from both the Madura and Coompana Provinces indicates formation of oceanic crust at c. 1950 Ma — defined as the Mirning Ocean — potentially reflecting stranded vestiges of an exterior ocean captured into juvenile crust generated between the WAC and SAC.

The suture zone between the Albany–Fraser Orogen (WAC margin) and the Madura Province is recognized geophysically, geochemically, and isotopically as the southeasterly dipping Rodona Shear Zone. This broad shear zone network defines the eastern limit of reworked Archean crust, over which the Arubiddy Ophiolite Complex of the Madura Province was obducted. The ophiolite complex consists of two main components: 1) older, non-subduction related continental margin ophiolitic rocks including metabasalt with E-MORB affinity, and 2) younger, subduction-related rocks including arc metabasalts (Sleeper Camp Formation, Malcolm Metamorphics), tholeiitic mafic-ultramafic intrusive rocks and near-contemporaneous plagiogranites (1415–1389 Ma Haig Cave Supersuite), interpreted as an oceanic-arc system (the Loongana Arc). Oceanward-dipping subduction led to closure of the marginal basin and obduction of this ophiolite complex between 1389 Ma (the age of the youngest-known plagiogranite and estimated timing of deformation) and 1330 Ma (the oldest Recherche Supersuite intrusions, which effectively stitch the suture). This event triggered Stage I of the Albany–Fraser Orogeny, a consequence of which was diachronous, cratonward migration of felsic and mafic magmatism defining the Recherche Supersuite.

Thus, southern Proterozoic Australia preserves evidence of Paleoproterozoic oceanic crust formation, continental rifting and marginal basin formation, and Mesoproterozoic oceanic-arc formation and obduction which led to tectonothermal events within the WAC margin (Stage I of the Albany–Fraser Orogeny). This was followed by a magmatic event of exceptional proportions centred between the continental masses that locked in remnants of recycled oceanic material that had escaped subduction, or were distal to sites of continental accretion or obduction.

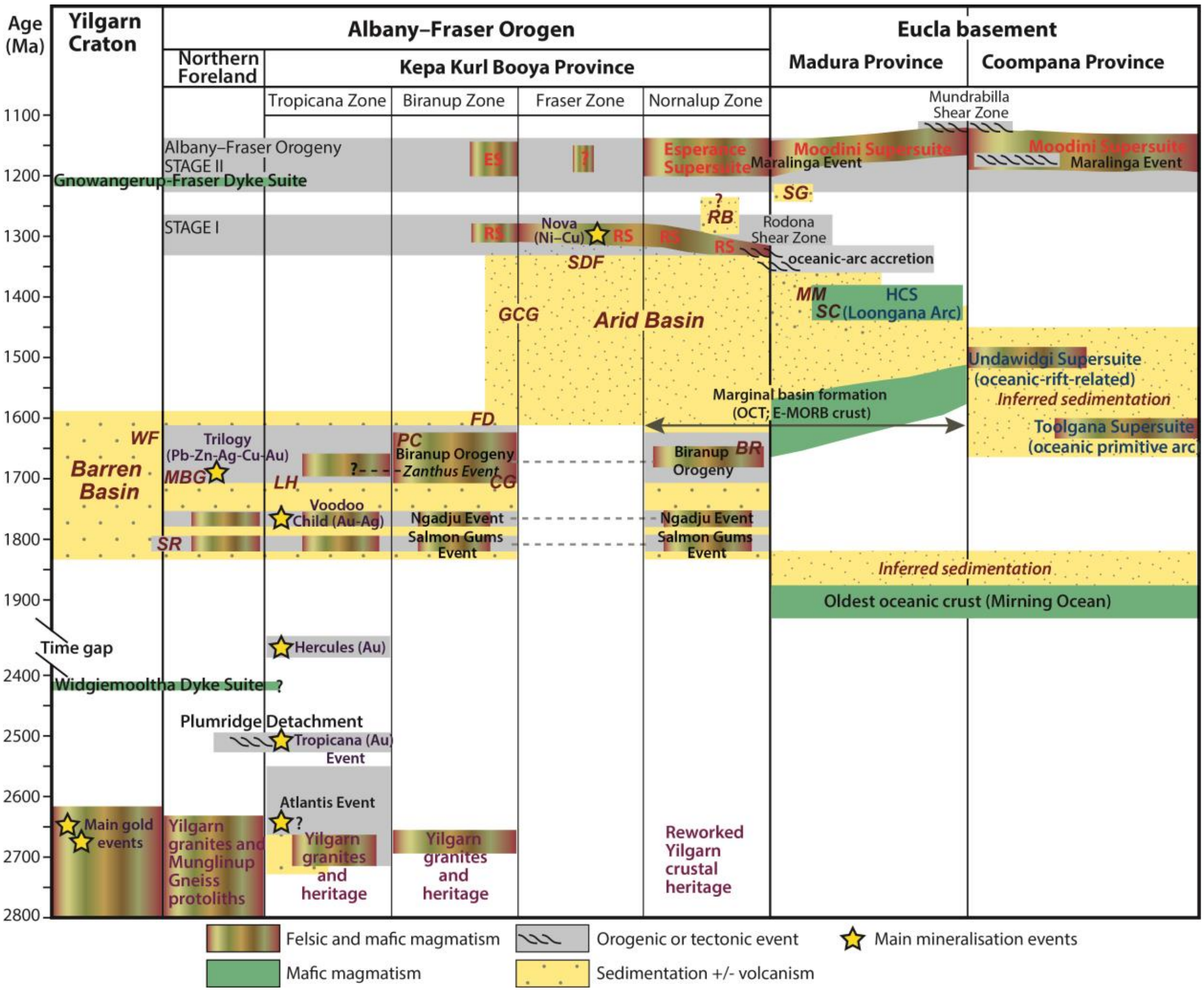

Figure 1. Time-space diagram showing major tectonothermal and mineralising events and tectonic units in the Albany–Fraser Orogen, Madura Province and western Coompana Province. Abbreviations used: BR–Big Red paragneiss; CG–Coramup Gneiss; ES–Esperance Supersuite; LH–Lindsay Hill Formation; FD–Fly Dam Formation; GCG–Gwynne Creek Gneiss; HCS–Haig Cave Supersuite; MBG–Mount Barren Group; MM–Malcolm Metamorphics; OCT–ocean-continent transition; PC–Ponton Creek paragneiss; RB–Ragged Basin; RS–Recherche Supersuite; SDF–Snowys Dam Formation; SC–Sleeper Camp Formation; SG–Salisbury Gneiss; SR–Stirling Range Formation; WF–Woodline Formation (see GSWA Reports 133, 150, Record 2015/10 for further details).

A sedimentary overlap assemblage spanning the Gawler Craton and northwestern Laurentia at 1.6 Ga

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The Wernecke Breccia is a set of hydrothermal breccia zones that occur in northern Yukon, Canada. The brecciation has been dated at 1.599 Ga by U-Pb on metasomatic titanite. The host rock is the Wernecke Supergroup, a sedimentary succession deposited on the Laurentian margin between 1.66 and 1.60 Ga. The breccia clasts are dominated by Wernecke Supergroup lithologies, but also include anomalous clasts that were sourced from other units. The anomalous clasts consist of plutonic, volcanic and sedimentary rock that are locally hundreds of metres in size. The igneous clasts were sourced from Bonnetia, a non-Laurentian volcanic arc terrane that was thrust over the Wernecke Supergroup prior to 1.60 Ga.

The anomalous sedimentary clasts comprise red interbedded mudstone and sandstone, red conglomerate and green mudstone. Textures of these sedimentary clasts include undulatory and contorted boundaries and indicate that these units were soft during Wernecke Breccia formation. The anomalous sedimentary clasts were incorporated into the breccia zones as (partially) unlithified sediments after the hydrothermal systems breached the surface. Detrital zircon extracted from the sedimentary clasts is largely subangular. An age profile obtained by LA-ICPMS and SHRIMP analysis displays a prominent peak at 1.78 to 1.68 Ga, lacks 2.4 – 2.1 Ga ages, and has a minor peak at 2.5 Ga.

The detrital zircon age profile is unlike those from the Wernecke Supergroup. However, it is remarkably similar to age profiles of lithologically similar sedimentary clasts preserved within the ~1.59 Ga Olympic Dam breccias on the Gawler Craton of Australia. Based on this similarity and previous reconstructions that link the Wernecke and Olympic Dam hydrothermal provinces, these clasts infer the former existence of a sedimentary overlap assemblage that was deposited on both the Gawler Craton and northwestern Laurentia. The only known relics of this once-extensive succession are the clasts within the Wernecke and Olympic Dam breccias. Much of the zircon was likely derived from metasediments and intrusions of the Gawler Craton. In order to accommodate subsequent deposition of sediment from northeast Australia onto Laurentia at ca. 1.5 Ga, we propose that Australia moved southwards (current coordinates) along the Laurentia margin from 1.6 – 1.5 Ga.

A multi-scale structural and metamorphic study of the Georgetown Inlier, NE Queensland — Implications for the assembly of the supercontinent Nuna

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Models for the Proterozoic supercontinent Nuna generally feature connections between NE Australia, NW Laurentia and possibly W Siberia (Betts et al., 2015; Furlanetto et al., 2016; Zhang et al., 2012). Palaeoproterozoic sedimentary–volcanic sequences exposed in NE Australian are believed to have deposited in continental back-arc setting with S- and/or W-dipping subduction (Betts et al., 2015; Scott et al., 2000), and underwent metamorphism during regional-scale shortening events ca. 1600 to 1500 Ma (Betts et al., 2006; Foster & Rubenach, 2006). These tectonic events were ascribed to continental collision between NE Australia and NW Laurentia. Available palaeomagnetic data permit such a connection by ca. 1580 Ma (Pisarevsky, et al., 2014). However, the question of how the two continents got connected remains unsolved. The late Palaeoproterozoic–early Mesoproterozoic tectonic history of the NE Australian inliers, and the Georgetown Inlier in particular, is therefore critical for testing the proposed links. The Georgetown Inlier is the largest (200x200 km) and the best exposed among the easternmost NE Australian inliers, and it encompasses the longest geological record (>1700–1540 Ma), which is contemporaneous with Nuna amalgamation. The tectono-metamorphic evolution of the Georgetown Inlier and the role that it played during the assembly of the supercontinent Nuna remain poorly understood.

Does the Georgetown Inlier preserve any records suggesting continental collision? The low-P, high-T metamorphic imprint preserved in the central and eastern parts of the Georgetown Inlier is not characteristic of a crustal thickening event that generally features regional medium T/P gradients. Recent geophysical studies suggested the existence of two concealed Palaeoproterozoic suture zones in NE Australia (the Gidyea and Rowe fossil subduction zones (Korsch et al., 2012); however the entire region lacks any geological feature diagnostic of subduction (e.g. high-P, low-T metamorphic rocks, ophiolitic units, or arc-type calc-alkaline magmatism).

The Georgetown Inlier preserves the W–E crustal section of an early Mesoproterozoic orogen. Undeformed and unmetamorphosed *ca.* 1550 Ma volcanic rocks (Black & Withnall, 1993) in the west lie unconformably on top of low-grade metasedimentary sequences. In the central and eastern domains, plutonic counterparts of the volcanics (S-type intrusive rocks) are exposed among greenschist- to granulite facies metasedimentary and meta-mafic rocks (Black et al., 1979; Boger & Hansen, 2004), with increasing deformation eastwards. Conflicting interpretations amongst previous research (Bain et al., 1985; Bell & Rubenach, 1983; Black et al., 1979; Cihan & Parsons, 2005; Davis, 1995; Withnall & Hutton, 2013) reflect the critical lack of geochronological constraints on the development of successive rock fabrics and thus the timing of tectonic events in the Georgetown Inlier. An in-depth investigation of this region will therefore provide important insight into the processes of deformation and metamorphism at different structural levels of the continental crust.

The main aims of this study are to unravel the tectono-metamorphic evolution of the Georgetown Inlier and to test whether the reconstructed multi-point pressure–temperature–deformation–time (*P–T–d–t*) paths for different sectors of the Georgetown Inlier are indicative of a collisional or accretionary evolution. We will take a multidisciplinary approach of combining multi-scale petro-structural analysis (Gosso et al., 2015), *P–T* estimation (using equilibrium phase diagrams and thermobarometric calibrations), and geochronology (U–Pb in monazite and zircon). The outcomes of this study will include the identification of different tectono-metamorphic domains within the Georgetown Inlier, an evaluation of their structural positions and tectonic evolutions, and, based on comparisons with other terranes in Australia and other continents, a new understanding of the role of NE Australia during Nuna amalgamation.

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Supercontinent Cycles & Global Geodynamics

East Gondwana breakup and microcontinent formation

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The Eastern Indian and Australian Southern Ocean were formed through the breakup of East Gondwana – Australia, India and Antarctica. Today these ocean basins contain numerous submerged features with crustal thickness much greater than normal oceanic crust, including Large Igneous Provinces (LIPs), microcontinents and 'failed' microcontinents still attached to Australia's passive continental margins, e.g. the Naturaliste Plateau and the South Tasman Rise. The features point to a wide range of interacting surface and mantle processes such as mantle plumes, plate tectonic reorganisations, varying seafloor spreading rates and directions, and downwelling slabs.

The interior of Eastern Australia is composed of complicated geology with numerous accreted ‘exotic’ terranes. It is possible that at least some of these terranes were microcontinents rifted from passive continental margins. Microcontinent formation may also have been widespread during the breakup of previous supercontinents such as Rodinia and Nuna, but the fate of such fragments remains poorly know. Similarly, ‘failed’ microcontinents that might have formed during the breakup of earlier supercontinents, Rodinia and Nuna, are little recognized.To explore the record of microcontinent formation through deep time, we first need to document the microcontinents preserved at present-day and understand the mechanisms that create them. Understanding the spectrum of sizes and shape that rifted and ‘failed’ microcontinents can take, and their likely crustal architecture (for example, whether a large volcanic component is typical if plumes are an important ingredient) places bounds on the likely characteristics of ‘exotic’ accreted terranes and ‘failed’ microcontinents attached to the older supercontinents of Rodinia and Nuna.

Microcontinents are isolated pieces of continental crust, that by definition, are formed by a ridge jump – where spreading at a mid-ocean ridge ceases and extension localises within a neighbouring continent. It is well established that the newly forming plate boundary will preferentially rupture continental crust rather than adjacent oceanic crust that is approximately three times stronger (Vink et al., 1984). However, the relative roles of plate tectonic or mantle dynamic forces in driving the ridge jump remain controversial. Particularly enigmatic is the rifting of microcontinents from mature, as compared with juvenile, continental rifted margins. Conceptual models, and in particular those that invoke some influence from mantle plumes, are able to account for many of the key observed features of microcontinents. However, the significance of plumes in microcontinent genesis has been questioned (Péron-Pinvidic and Manatschal, 2010) and observations from the Seychelles (Collier et al., 2008), Jan Mayen (Gaina et al., 2009) and the Perth Abyssal Plain (Whittaker et al., 2016) suggest that changing plate boundary forces may play a dominant role in microcontinent formation.

Numerous microcontinents were created during the breakup of Pangea, with particularly intense formation in the Indian and Australian Southern Ocean. Rifting between India, Australia, and Antarctica generated microcontinents including Elan Bank, Wallaby Plateau, parts of the Kerguelen Plateau, and potentially the Zenith Plateau. Extended continental platforms include the Naturaliste Plateau, Bruce Rise, while further east, breakup of Australia-Antarctica lead to formation of the Adelie Rift Block, and the South Tasman Plateau. In 2011, we discovered two new microcontinents offshore Western Australia: Gulden Draak and Batavia microcontinents (Williams, 2011; Gardner et al., 2015), recovering some 300 kg of basement and rift-related sedimentary and igneous rocks by dredging from the R/V Southern Surveyor.

Both Batavia and Gulden Draak knolls are microcontinents on the western edge of the Perth Abyssal Plain (PAP), composed of continental rocks including felsic granitic rocks, gneisses, schists and sandstones (Gardner et al., 2015; Halpin et al., in review). Gulden Draak Knoll comprises a high-grade basement complex, including pelitic paragneiss (deposited < 1.1 Ga) and mafic orthogneiss (emplaced >600 Ma) intruded by Cambrian granite (~540 Ma) (Gardner et al., 2015). Batavia Knoll felsic granitiod samples suggest protracted magmatism and overprinting during the latest Neoproterozoic–early Cambrian (c. 580–530 Ma). The results from these knolls, coupled with other regional geological constraints, are consistent with magmatic intrusion and subsequent disturbance along a late Neoproterozoic–Cambrian sinistral strike-slip margin related to Gondwana assembly (Halpin et al., in review).

At Gondwana breakup, the Batavia and Gulden Draak microcontinents sat within Greater India, rifting from Australia at ~136 Ma (Gibbons et al., 2012). Around 30 million years later (~101–104 Ma), a reorganisation of plate boundaries saw them separate from India (Whittaker et al., 2016), and jump to the Australian plate. Geophysical and seafloor geological constraints indicate that initiation of the major clockwise tectonic reorganisation in the PAP region occurred at ~105 Ma related to a dramatic change in the direction of India's motion (Matthews et al., 2012), which immediately preceded microcontinent calving at ~101–104 Ma. In contrast, while there is evidence for widespread Kerguelen plume related volcanism between 120–110 Ma across Australia, India, Antarctica and the nascent Indian Ocean, the Batavia and Gulden Draak microcontinents remained part of the Greater India passive margin through this period. Additionally, little volcanism is recorded between 108–101 Ma, coeval with Batavia and Gulden Draak calving. The timing of widespread Kerguelen plume-related volcanism, and the onset of changing Indian-Australian relative plate motions as part of a global '100 Ma reorganisation event', suggest that changing plate tectonic forces pulled the trigger for microcontinent formation (Whittaker et al., 2016). The Kerguelen plume likely played a supporting role by preconditioning the Indian passive margin through thermally weakening.

Our model highlights an import role for long-offset transform faults (in this case the Wallaby-Zenith Fracture Zone) in controlling plate tectonic motions. Transform faults act as long-term stress guides, maintaining steady plate motions for long periods and may play a key role in abrupt changes in plate motions. The initiation of a new pathway for the India–Australia plate boundary not only calved the microcontinents from Greater India, but also destroyed an approximately 1500 km long segment of the India–Australia plate boundary along the WZFZ, removing a large resistance to change in India–Australia relative motion that facilitated the plate reorganisation event centered around 100 Ma.

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Long-travelled sediments from India to Australia in the assembled Gondwana

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Previous studies of the late Neoproterozoic to early Paleozoic sedimentary strata in the Centralian Superbasins of Australia revealed their sedimentary sources from the local Paterson-Petermann orogen and Musgrave Inliers during the Gondwana assembly, based on the prevailing 700-500 Ma and 1.2-1.0 Ga zircon age populations and Hf isotope affinities of these sedimentary rocks with that of the magmatic suppliers in the Petermann orogen and Musgrave Inliers (e.g., Maidment et al., 2007; Martin et al., 2017).

Investigations on the Cambrian strata of the Ord Basin in northern Australia, however, reveal a provenance affinity which is different from the Australian suppliers. The prevailing 980-930 Ma zircon population with dominant positive epsilon Hf values from the Ord basin Cambrian sediments indicates a dominant Indian Himalaya source which features the matching zircon age and Hf signals (e.g., Yao et al., 2014). Furthermore, the northeastern-directed paleocurrents in the Cambrian coastal marine environments of the Ord basin agree with the possibility of the Cambrian detritus travelling along the northeastern Gondwana shoreline from Indian Himalaya to the Australian Ord basin. This work demonstrates that, during the Gondwana assembly, Australian basins not only received local sediments, but also caught detritus travelled for thousand kilometres from Indian Himalaya.

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Supercontinent Cycles & Global Geodynamics

Spatial and Temporal Detrital Zircon U-Pb Provenance of the Hydrocarbon-Bearing Upper Roper Group, Beetaloo Sub-basin, Northern Australia

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The Mesoproterozoic successions of the Beetaloo Sub-basin, northern Australia, comprises a series of shallow to deep water clastic sedimentary rocks that form the depocentre of the Roper Group; the volumetrically largest part of the 1000 km-scale outcropping Wilton Package (Fig.1). Shale formations in the Roper Group form the world's oldest proven gas reserve and are likely to be commercialised in the next few years (Revie, 2015; Close et al., 2017). LA-ICP-MS detrital zircon U–Pb age data presented here illustrate the power of the technique by showing that the Roper Group extends to younger ages than previously recognised. The maximum depositional age of the Bessie Creek Sandstone is constrained at 1386 ± 13 Ma. The Velkerri Formation is now constrained to being deposited between 1345 Ma and 1320 Ma. The maximum depositional age of the Moroak Sandstone is also defined by the youngest near concordant analysis (1298 ± 47 Ma) from the Velkerri Formation. The Kyalla Formation was deposited after 1313 ± 47 Ma. The maximum depositional age of the lower and upper Jamison sandstones are constrained to 1092 ± 16 Ma and 959 ± 18 Ma, respectively.

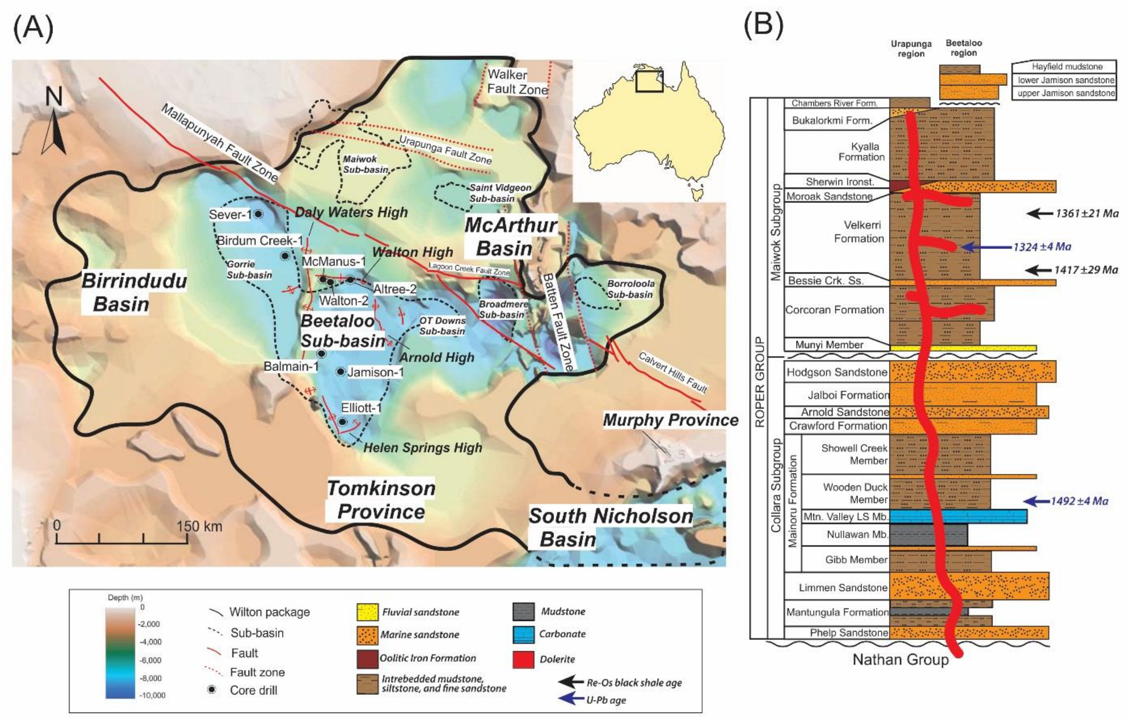

Fig.1 (A) The extent of the Wilton Package based on the Proterozoic SEEBASE^{TM} basement surface, showing the locations of drill hole and major structural highs. The SEEBASE image is from Pryer and Loutit (2005); (B) Stratigraphic columns of the Roper Group modified after Cox (2016).

This large detrital zircon data set illustrates spatial and temporal provenance variations. Coupled multidimensional scaling (MDS) (Vermeesch, 2013) and kernel distribution estimate (KDE) analysis of U-Pb detrital zircon ages indicate that zircons from the Maiwok Subgroup (the upper sub-group of the Roper Group) were derived from Palaeoproterozoic and earliest Mesoproterozoic rocks (age maxima at ca. 1590 Ma, 1740 Ma, 1823 Ma and 2480 Ma). These are consistent with derivation from the surrounding exposed basement. However, detrital zircon age variations up-stratigraphy suggest a systematic temporal change in provenance. The oldest formation analysed (the Bessie Creek Formation) has a major source dated at ca. 1823 Ma. Rocks of this age are common in the northern basement exposures (the Halls Creek, Pine Creek and Arunta regions). One Bessie Creek Formation sample, and samples from the overlying Velkerri Formation, show the derivation from a ca. 1590 Ma source, consistent with rocks exposed in Queensland or possibly from the Musgrave region. The Moroak and the Kyalla Formations show progressively more ca. 1740 Ma detritus which is consistent with sources in the Arunta and western Mount Isa region. We suggest that this variation is recording exposure and denudation of western Queensland rocks at ca. 1400 Ma due to rifting between Laurentia and the Northern Australian Craton. From then, until at least ca. 1280 Ma, the increased ca. 1740 Ma detritus suggests continued uplift in Queensland and possible widening of the source region to include the Eastern Fold Belt of Mount Isa. In addition, the Arunta Province is likely to have been exposed and denuded.

The Jamison sandstone represents a marked change in provenance, with the appearance of ca. 1186 Ma zircons and the near-absence of Palaeoproterozoic detritus. The last provenance shift happened after the amalgamation of the Australian part of the supercontinent Rodinia (Merdith et al. 2017). We suggest that the Jamison sandstone represents a newly-recognised sandstone-rich basin that may have formed a shallow, long wavelength foreland basin to the Musgrave Orogeny (Fig.2).

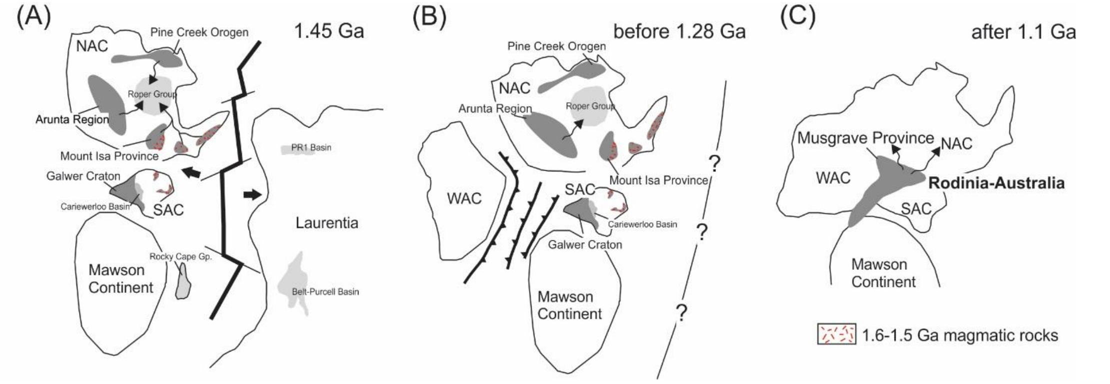

Fig.2 Tectonic scenario sketch showing the deposition history of the Maiwok Sub-group and the Jamison sandstone between 1.45 Ga to ca. 1.0 Ga. (A) the separation of the North Australia Craton and the Laurentia, forming a series of extensional basins on the both sides. (B) The collision of West Australia Craton, North Australia Craton and South Australia Craton, uplifting and exposing the Arunta Block and allowing it to become a source for the sands in the Kyalla Formation. (C) Exhumation of the Musgrave Province after final amalgamation of the Australian part of Rodinia and the Warakurna LIP.

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THEME 2.

New Progress and constraints on Supercontinent reconstructions.

Coordinators:

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Rodinia in Zealandia; some clues from Precambrian zircons

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Although New Zealand and its surrounding submarine plateaux (together ’Zealandia’) have no proven Precambrian rocks, detrital zircons of this age are commonly found in all sedimentary rocks there, from Cambrian to Cretaceous age. These are mainly in two age groups: late Neoproterozoic (550-700 Ma) and late Mesoproterozoic (1000-1200 Ma) although Paleoproterozoic and Archean zircons are quite frequent (up to 3650 Ma). These are features much in common with rocks of similar age in eastern Australia, East and West Antarctica, southern South America and South China. The provenance of the Zealandia Precambrian zircons is usually, and most plausibly, placed within the Australian Precambrian craton, although the relative abundance of the above age groups does not sit well with the age of known sources there. Also very long sediment transport paths (>5000 Ma) have to be postulated at the early margins of Gondwanaland to distribute ‘Rodinia’ zircons from northeast Queensland to West Antarctica and even southern South America. Some alternative possibilities are introduced:

(1) The relative abundance of the above major age groups (especially in the late Neoproterozoic) in early Paleozoic rocks in Zealandia are slightly different from those in eastern Australia. Precambrian zircons in Cretaceous fluviatile sandstones above local Zealandia basement are significantly concentrated (especially late Mesoproterozoic). These two features suggest that a late Mesoproterozoic and/or late Neoproterozoic complexes might now be hidden beneath the Campbell Plateau under southern Zealandia.

(2) Early Paleozoic sedimentary rocks in South China share the same ‘Rodinia’ zircon age patterns as those described above. South China also has both a Neo-Mesoproterozoic, and an Archean core. If South China shares an Ordovician paleolatitude with Australia, and if South China was formerly at its eastern margin, then South China would be immediately north of Zealandia in its early Paleozoic position.

In this way, both Zealandia and South China would be additional possibilities for sources of ‘Rodinia’ zircons around the eastern Gondwanaland margin.

Suturing Madagascar and India – new insights from Lu-Hf data and multi-dimensional scaling of U-Pb detrital zircon data

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It has long been recognised that Madagascar was contiguous with India until the Late Cretaceous, however the timing and nature of the amalgamation of these two regions is still highly contentious as is the location of Madagascar against India in Gondwana. We have collected new detrital zircon U-Pb and Lu-Hf data from the Karwar region of west peninsular India, and compared it with published data from Madagascar and India to constrain the tectonic evolution of these regions. We have additionally obtained Lu-Hf analyses of zircons from central Madagascar and the Antongil-Masora domains of eastern Madagascar.

New U-Pb data from Karwar-region detrital zircons yield two dominant age peaks at c. 2500 Ma and c. 3100 Ma. The c. 3100 Ma population has relatively juvenile εHf values that trend toward an evolved signature at c. 2500 Ma. The c. 2500 Ma population shows a wide range of εHf values reflecting mixing of an evolved source with a juvenile source at that time.

These data and new Lu-Hf data from Madagascar, are compared with a new compilation of over 8000 U-Pb and Lu-Hf analyses from Madagascar and India. We have used multidimensional scaling to assess similarities in these data in a statistically robust way. We propose that the Karwar region of west peninsular India is an extension of the western Dharwar Craton and not part of the Antananarivo Domain as has been suggested in some models.

Based on εHf signatures we also suggest that India (and the Antongil-Masora domains of Madagascar) were palaeogeographically isolated from central Madagascar (the Antananarivo Domain) during the Palaeoproterozoic. This supports a model where central Madagascar and India amalgamated during the Neoproterozoic along the Betsimisaraka Suture.

Paleomagnetism of Paleozoic Era Glacial tillites and Neopropterozoic Era Black Limestone (Ngash Synclinorium), Nothern Ethiopia.

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Glaciogenic sediments of Palaeozoic age and Metasedimets of the Tambien Group of the Arabian Nubian Shield both in Northern Ethiopia have been sampled for palemagnetic investigations. The results from both are respectively presented.

The Glacial sediments; although there was no doubt about the glacial origin of these rocks, there has been a debate as to whether they are correlable with either of the Upper Carboniferous-Early Perminan glacial rocks of southern Africa or of Ordovician glacial rocks in Northern Africa. Twenty core samples from a tilted bed (strike & dip 1300/270SW) of the Edaga Arbi Glacials and thirteen core samples from sub-horizontally bedded Enticho Sandstone from Enticho area were collected during a single field season to determine the age. For both sediments Alternating Field (AF) demagnetization techniques could only demagnetize about 50% of the total intensity of magnetization and thermal demagnetization is proved to be effective. The intensity of magnetization is about 0.08A/m. A viscous remagnetizations (VRM) and one stable component of magnetization were identified. Between a temperature range of 1200C – 3500C the VRM is removed; further heating until a temperature of ~ 6500C resulted in smooth decay in magnetization intensity to about 50%. The rest of the magnetization is efficiently removed by heating to 6900C. The high stability component defines straight-line segment starting 4000C and directed towards the origin revealing the Characteristic Remanent Magnetizations (ChRM). The site mean directions from 11 locations are reversed in polarity with a better grouping in the tilt-corrected coordinate and pass the McFadden fold test. This overall site mean direction is Dec = 143.40, Inc = 58.80 (N = 11, □95 = 9.70) and the corresponding mean pole position is Lat = 26.00, Lon = 249.50 (N = 11, A95 = 13.10). This geomagnetic pole position was later rotated into West Africa coordinates to allow for extensional rifting in the Benue Trough about an Euler pole position, at 19.20N, 352.60E through an angle −6.30 (clockwise) (Lottes & Rowley, 1990). The resulting pole position is located at □s = 246.60E, □s = 31.80S (N = 11, A95 = 13.10), this pole with its 95 per cent confidence circle intersects the 270–310 Ma, segment of the APW path (Besse & Courtillot 2003) for West Africa consistent with ages of between late Carboniferous and early Permian. The result also implies that the Late Carboniferous Dwyka land ice sheet had probably extended more than 1000 km further north to Ethiopia than previously known.

Eighty-one paleomagnetic cores were collected from 10 locations across a black limestone unit within the core of Negash Synclinorium, northern Ethiopia in order to test a proposed Snowball Earth events of Sturtian glaciation (e.g. Miller et al. 2003; Alene et al. 2006) recorded in the diamictite unit of the Tambien Group, which is part of the Arabian Nubian Shield, representing mostly juvenile crust and chiefly low-grade metavolcanic, metasedimentary assemblages. Rock magnetic analyses revealed goethite, pyrrhotite, titano-magnetite, and titano-hematite to be the major magnetic materials. In most cases paleomagnetic directions are defined by a single component of magnetization that defined straight-line trajectories directed towards the origin and considered as the ChRM. When site mean ChRM directions are plotted on stereogram, their distribution is relatively clustered in geographic coordinates and the overall mean direction is Decg = 358.50, Incg = 16.60 (□95 = 3.80, K = 162.8, N = 10). After a structural restoration to the horizontal is made the directions disperse and fail the fold test of both McElhinny's and McFadden's tests and the mean direction for this stratigraphic coordinate is Decs = 353.50, Incs = 8.80 (□95 = 18.90, K = 7.5, N = 10). This is interpreted to result from a later remagnetization of the black limestone and the ChRM is determined to be secondary. Virtual Geomagnetic poles (VGP) in the unrestored position is determined and used to calculate overall mean VGP position resulting long = 235.70E, latg = 84.50N (A95 = 3.00, N = 10). Comparison of this pole with the apparent polar wander path (APWP) curve for Africa of Besse & Courtillot (2003) and with the 2 Ma reference pole of stable Africa (Kidane et al. 2003) is found to be consistent with remagnetizations during the Quaternary period. Hence, the proposed Snowball Earth event could not, unfortunately, be confirmed from paleomagnetism on this rock. Further study needs to be made on different rock types and different locations.

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A structural transect through central Madagascar – constraining the Neoproterozoic tectonic evolution

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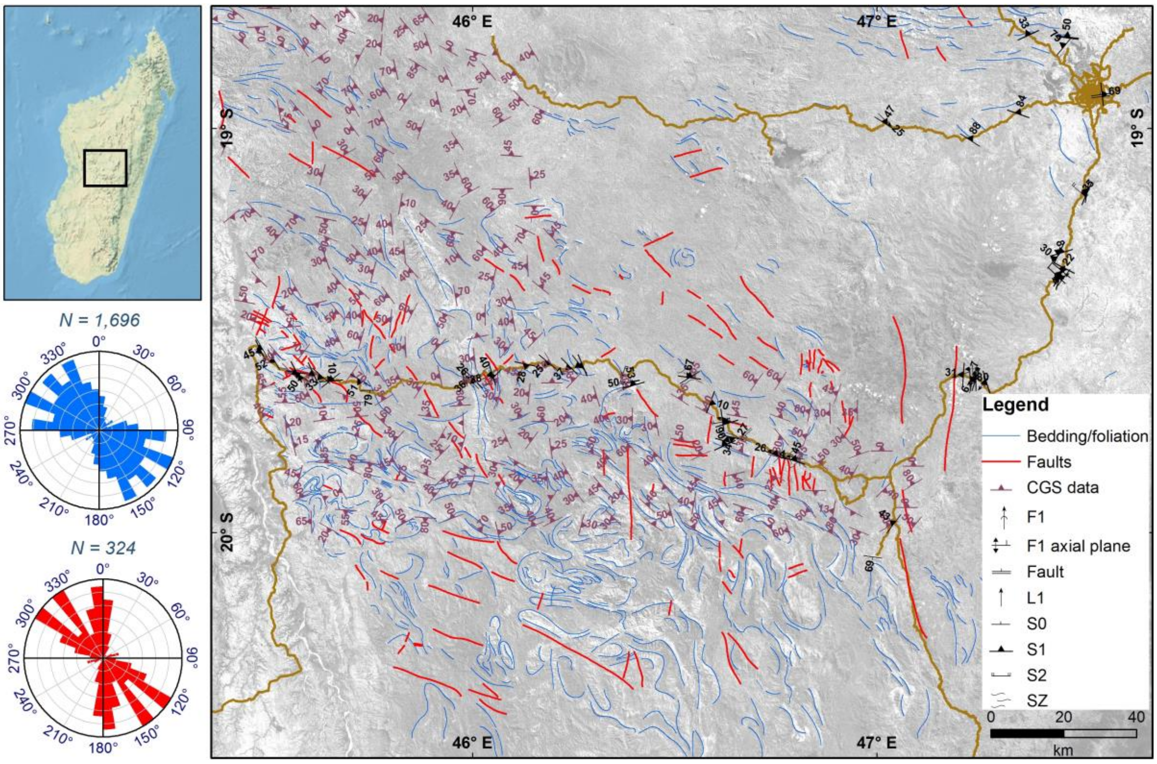
The assembly of central Gondwana occurred along the Neoproterozoic–Cambrian East African Orogen. This formed by at least two orogenies; the c. 650 Ma East African Orogeny and the c. 550–530 Ma Malagasy Orogeny. How these orogenies deformed terranes in central Madagascar has not yet been studied in detail. Understanding the style and extent of deformation throughout central Madagascar will help constrain the tectonic evolution of this region.

We have used satellite imagery and Landsat data to remotely delineate mesoscopic structural features throughout central Madagascar. In addition, we have collected structural measurements of outcrops to ground truth our study and integrated these with published structural data. Undeformed magmatic samples that cross-cut deformation fabrics are used for U-Pb geochronology to provide a lower age constraint for deformation.

The transect extends from Miandrivazo in the west, along an approximately east-west trending road to Antsirabe, and continues northward to the capital, Antananarivo (figure). From satellite imagery and Landsat we have classified structures as either bedding/foliation or faults, and produced rose diagrams for these features weighted by polyline length (figure). In general, rock fabrics and faults trend in a northwest orientation. We present a series of interpreted maps and a model for the deformation sequence of central Madagascar.



Constraints on the Ediacaran Inertial Interchange True Polar Wander Hypothesis: a New Paleomagnetic Study in Morocco (West African Craton)

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The paleogeographic evolution of the Ediacaran (635-542 Ma) is dominated by the dispersion of Rodinia and the assembly of Gondwana. Paleogeographic reconstructions for this epoch are still highly debated due to the low amount of reliable paleomagnetic data. The most documented but also the most problematic database comes from the continent Laurentia which displays fast and large oscillations in its apparent polar wander path (APWP) from high to low latitudes between 615 and 565 Ma. Such oscillations, if interpreted as plate drift, imply extremely high plate velocities which seem inconsistent with plate tectonics. Several hypothesis have been proposed in the literature such as (1) the presence of unreliable paleomagnetic data and/or inaccurate age datings used to propose continental reconstructions, (2) the oscillation between an Earth's magnetic field dominated by an axial and an equatorial dipole (3) recording of an equatorial dipole field as a transitional field between opposite polarity states (4) inertial interchange true polar wander (IITPW) episodes involving the tumbling of the bulk Earth with respect to its spin axis. If one of these latter mechanisms occurred, the rapid and large oscillations observed for Laurentia should be recorded in any other rocks of the same age from other continents.

In this study, we tested these hypotheses by bringing new paleomagnetic data from another continent, the West African craton (WAC). We conducted a paleomagnetic study on late Ediacaran and early Cambrian volcanic deposits and lava flows from the Ouarzazate and Taroudannt groups in the Anti-Atlas, Morocco. Four stable magnetic components have been isolated using thermal demagnetization technique. A first component "A" is most probably a remagnetization acquired during the Hercynian related tectonic phases, and yields a paleomagnetic pole (λ=-29.3° N, φ=56.6° E, A95=4.1°) indistinguishable from the 330-300 Ma segment of the Gondwana APWP. The Cambrian Djebel Boho formation of the Taroudannt group and the Ediacaran Tadoughast and Fajjoud formations of the Ouarzazate group yield two poles of similar directions respectively "B1" (λ=21.9° N, φ=31.0° E, A95=15.6°) and "B2" (λ=27.3° N, φ=27.1° E, A95=14.9°). In the Adrar-n-Takoucht formation (oldest part of the Ouarzazate group), another component is observed, yielding a paleomagnetic pole "C" (λ=-57.6° N, φ=295.6° E, A95=15.7°). The primary nature of these last three components is supported by paleomagnetic tests and we interpret them as magnetizations acquired during or shortly after the deposit of volcaniclastics or emplacement of lava flows. Using these new data, we reappraised the West African Craton (WAC) APWP and found two large paleomagnetic shifts of some 90°, the first one between 615 and 571 Ma and the other one between 571 and 565Ma. Based on stringent selection criteria, we also reappraised the APWP of Laurentia and Baltica. Both APWP display a large loop similar in amplitude and age to our WAC APWP loop (Figure 1.a.). The superimposition of these APWP leads to a paleogeography geologically consistent with the opening of the Iapetus and Tornquist oceans related to the final dislocation of the supercontinent Rodinia (Figure 1.b.). Therefore, data artifacts creating this large oscillation seem unlikely. The polar wander velocities are compatible with two rapid IITPW if large perturbations of the mass distribution inside the mantle occurred. Large continental reorganizations due to the Rodinia dislocation and the accretion of Gondwana during the Ediacaran may have played a major role in the Earth inertial evolution. Consequently, our preferred mechanism to explain our signal goes toward an IITPW process. Nevertheless, more paleomagnetic and radiometric data are still necessary to ascertain the mechanisms involved in this rapid polar change, including continuous records in order to assess the existence of magnetic field perturbations.

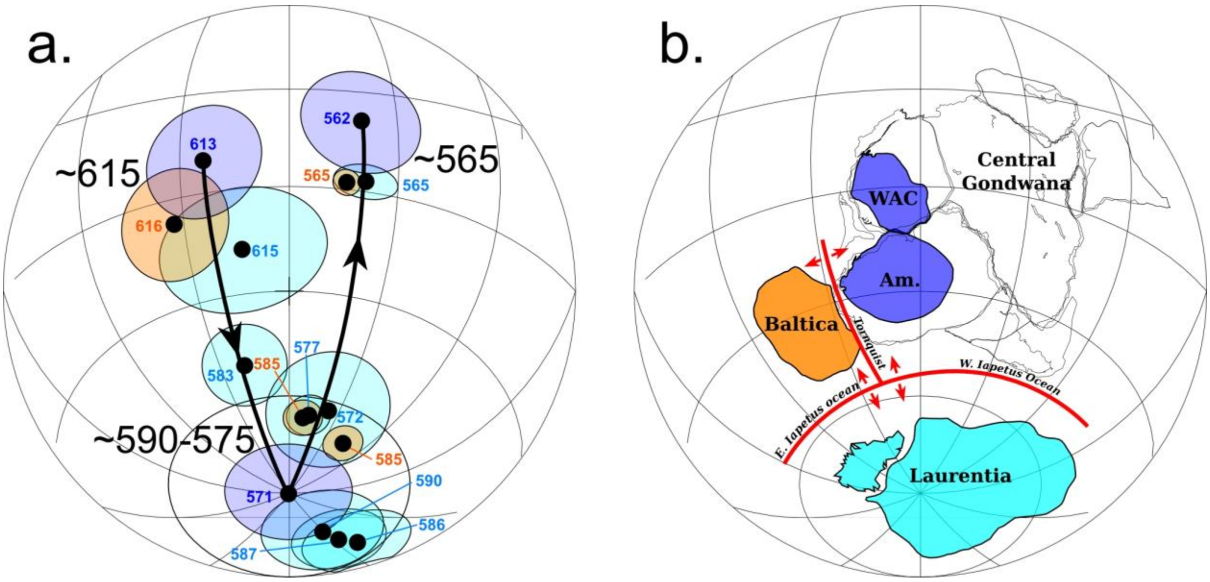

Figure 1: a. Fit of the 575-565 Ma segments of the APWP of WAC, Laurentia and Baltica. The selected poles (mean age in Ma as shown) from each continent are distinguished by the color of the 95% ellipse of confidence: dark blue for WAC, light blue for Laurentia and orange for Baltica. b. Corresponding paleogeography at ~575 Ma. The color of the blocks refers to the color of the poles described in the figure a. Red lines correspond to ridges associated to the opening of the eastern (E.), western (W.) Iapetus oceans and the Tornquist Ocean. Am: Amazonia.

Insights into the extent of southern Gondwana in Rodinia: Geochronology and Nd and Sr radiogenic isotope data.

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Geochronological, geochemical and radiogenic isotope data from two common lithologies in Namibia, Namaqualand, Natal, western Dronning Maud Land (WDML), Antarctica, northern Mozambique and Sri Lanka suggest that they form a virtually continuous geological belt of Mesoproterozoic age with ages ranging between *ca* 1225 to *ca* 1025 Ma. The extent of these rocks in Gondwana is shown in Figure 1.

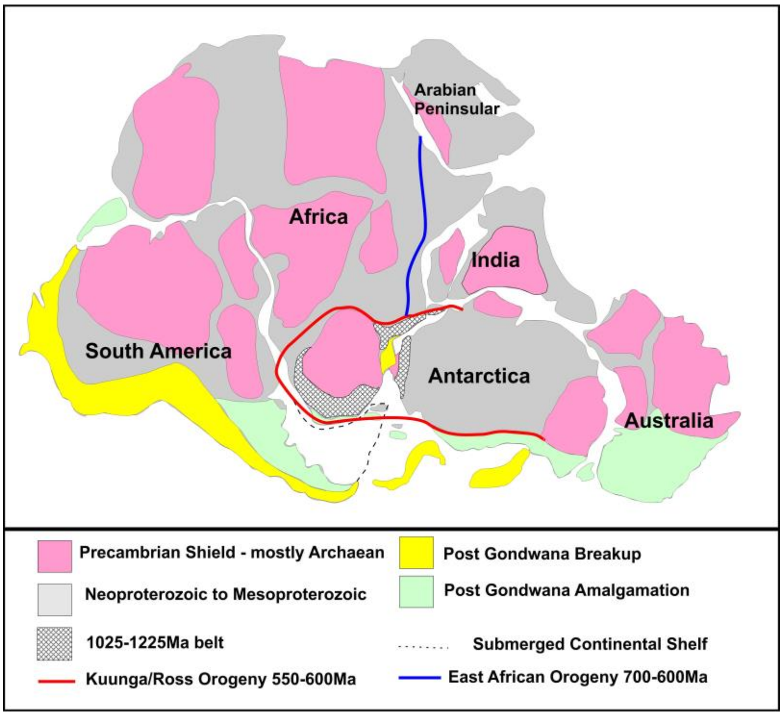

Figure 1. Schematic reconstruction of Gondwana showing the extent of the 1025-1225Ma belt stretching from Namibia, through Namaqualand, Natal, Antarctica, Mozambique to Sri Lanka.

The two common lithologies comprise tonalitic gneisses inferred to be typical of island arc subduction settings and megacrystic granitic rocks with A-type chemistry. The tonalitic gneisses include the Sinclair Group (Namibia), Areachap Group (Namaqualand)[1], Mzumbe Suite (Natal)[2], Kvervelnatten and Jutulrora Gneisses[3] (Western Dronning Maud Land, Antarctica), Chimoio Gneiss[4] (central Mozambique), Mocuba Suite[5] (Nampula Terrane, N. Mozambique) and tonalitic gneisses of the Vijayan Complex[6] (Sri Lanka).These rocks are typically inferred to have been formed in accretionary settings.

The megacrystic granites and orthogneisses include the Keimoes Suite[7] and Spektakel Suite[8] (Namaqualand), the Oribi Gorge Suite[9] (Natal), the Kirwanveggan Orthogneiss[3] (WDML), the Nhansipfe Gneiss[4] (central Mozambique), the Culicui Suite[5] (Nampula Terrane, N. Mozambique) and megacrystic augen gneisses of the Vijayan Complex[6] (Sri Lanka). In almost all these areas, these rocks are locally charnockitic, with textures typical of primary igneous charnockites and in the undeformed state, frequently have rapakivi textures. These rocks are typically inferred to represent late to post-tectonic intrusions.

Within each of these lithology groups, two age ranges are apparent. Age groups within the tonalitic gneiss are *ca* 1220-1280 Ma in Namaqualand and Natal whereas in WDML Antarctica and Mozambique ages are typically ca 1140Ma. The junction between these two groups is inferred to be located in Heimefrontfjella, WDML[10].

Age groups within the megacrystic granitic rocks are *ca* 1070-1090 Ma and *ca* 1025-1050 Ma.The older age group are recognised from Namaqland to Sri Lanka attesting to the contiguity of the belt. Whereas the younger group are only seen in Namaqualand and Natal with the intrusions being located toward the southern margin of the belt.

Available Nd and Sr radiogenic isotope data from these rocks, particularly from those areas adjacent to continental margins, show similarities supporting correlations between continental fragments. No significant differences in the Nd-Sr characteristics between the lithological varieties in the various areas are seen (ie. between tonalitic and granitic rocks). The similarities between crustal blocks include (1) the contact between the Vijayan Complex of Sri Lanka and the Nampula Terrane of northern Mozambique, (2) the contact between the Heimefrontfjella and Kirwanveggan, Antarctica and the Natal Belt, South Africa[11], (3) the contact between the Gjelsvikfjella area, WDML, Antarctica and the Nampula Terrane of N. Mozambique (4) and the contact between the western Maud Belt, WDML, Antarctica and the Barue Complex, central Mozambique[4]. The Nd-Sr data from the first three crustal block contacts defined above, all show relatively juvenile signatures with limited crustal residence time or contributions from older crust. In contrast the fourth crustal block contact between central Mozambique and the western Maud Belt, WDML, indicate significant older crustal involvement, consistent with their close proximity to the eastern margin of the Kalahari Craton, implying probable contributions from Archaean crust at depth.

An implication of these data is that the southern Gondwana crustal fragments comprising the Namaqua-Natal Belt, South Africa, the Maud Belt of WDML, Antarctica, the Barue Complex and Nampula Terrane of northern Mozambique and the Vijayan Complex of Sri Lanka define a broadly continuous *ca* 1025-1225 Ma old unit implying a unitary block at that time; a belt which has not been truncated by the East African Orogeny which affected northern Gondwana.

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Supercontinent Cycles & Global Geodynamics

Archean continental crust beneath Mauritus: Implications for the Greater Malani Supercontinent

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Based on the occurrence of Archean protolith, plume related anorogenic (A-type) bimodal magmatism (750Ma) Vendian shallow water sedimentary sequence of carbonate, phosphorites and evaporites in the Trans – Aravalli block of NW Indian shield South China, Siberia, Mongoloia, Kazakhstan, Tarim in the north and Arabian- Nubian shield. Seychelles- Madagascar, Central Iran, Kochhar (2013a, b; 2016) has proposed that all these micro-continents formed the configuration of the Greater Malani supercontinent (Fig. 1)

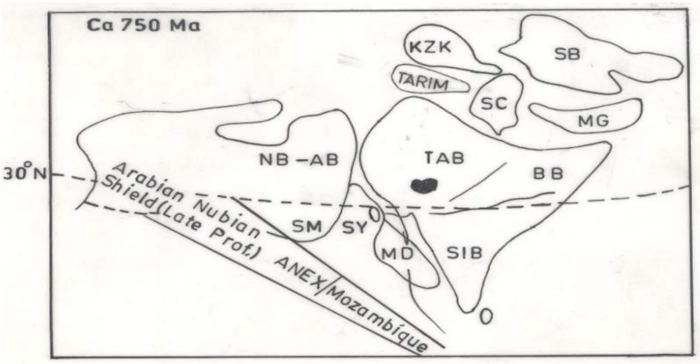

Figure 1. Assembly of the Greater Malani Supercontinent. NB-AB : Nubia Arabia, SM : Somalia, MD : Madagascar,SY : Seychelles, SC : South China, KZK: Kazakhstan, SB: Siberia, MG: Mongolia; TAB : Trans Aravalli Block of the Indian Shield, AD: Aravalli -Delhi Mobile Belt, BB : Bundelkhand Block, SIB : South Indian Block.

Recently Ashwal et. al. (2017) have demonstrated the existence of Archean (2.5 – 3.0 Ga: U/Pb Zircon) continental crust beneath Mauritus, which formed originally part of ancient nucleus of Madagascar Antongil, India (Dharwar) the Maurita continental fragment.

This recent work of Ashwal et. al., (2017) further support the existence of the Greater Malani Supercontinent. However they have overlooked the robust geological and isotopic data of Rajasthan.

1. The Archean crustal protolith has been well documental from BGC, Rajasthan (3.2 Ga), Kazakhstan, (Anrakhai terrain (1789±6Ma, 2.18 ± 0.05 Ma, εNd (t) – 6.4, Mongolia (Ust, Angara complex, εNd (t) +8 to -6), Seychelles and ANS (Archean BGC), Tarim (2.7-2.5 Ga).

2. The Mahe (750 Ma) and Ste Anne (764 Ma) granite of Seychelles have been correlated with 732 Ma old hypersolvus (Siwana) and Subsolvus (Jalor) granite of Malani Igneous suite. These granite have A-type geochemical signatures and owe their origin to the same protolith of Archean crust (BGC of Rajasthan) (Ashwal et al., 2002). The Seychelles and Malani granite have low oxygen isotope ratios – δ^{18} O ‰ SMOW:

Siwana: -0.10 to + 1.8 ‰

Jalore: -4.60 to + 1.2‰

Seychelles: +3 to +4‰.

At 750 Ma Seychelles and Rajasthan (MIS) were only 600 km apart . The evolution of the TAB crust (Jalor and Siwana ring complexes of MIS) with positive Nd (T) values is very much similar to the evolution of ANS and CAOB terrains.

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Rodinia break-up along the SW margin of the East European Craton (SE Poland) – new evidence based on deep seismic and grav-mag data

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Baltica was one of continents formed as a result of Rodinia break-up 750-550 Ma. It was separated from Amazonia along the Tornquist Ocean (Johansson 2014), the opening of which was preceded by Ediacaran extension in a network of continental rifts. Some of these rifts were subsequently aborted whereas the NW-SE oriented Tornquist rift (present-day coordinates) gave rise to splitting of Rodinia. The results of 1D subsidence analysis at the fossil passive margin of Baltica in Poland and Scandinavia provided insight in the timing and kinematics of continental rifting that led to break-up of Baltica (Poprawa, 2006). Rifting was associated with (1) the Ediacaran syn–rift subsidence accompanied by deposition of continental coarse-grained sediments and emplacement of continental basalts, and (2) transition from syn-rift to post-rift phase in the latest Ediacaran to earliest Early Cambrian concomitant with deposition of continental conglomerates and arkoses, laterally passing into mudstones (Poprawa, 2006; Pacześna, 2010). The proposed scenario of Baltica break-up assumed the existence of a triple junction and two linked rift arms: the Orsha Volhyn Aulacogen, a failed rift branch that ceased activity by the Ediacaran-Cambrian transition, and the Peri-Tornquist Zone that gave rise to the development of the Tornquist Ocean in the Cambrian.

The extensional scenario of the break-up of Rodinia along the SW margin of the Baltica proposed by Poprawa et al. (1999) was based on mainly indirect evidences, i.e., the character of tectonic subsidence curves, evolution of syn-rift and post-rift depocentres in time, as well as geochemistry and geochronology of the syn-rift volcanics (Poprawa, 2006). The results of 1D subsidence analysis have been recently reinforced by the high-quality deep seismic reflection data of the PolandSPAN® survey (Fig. 1) calibrated by deep wells.

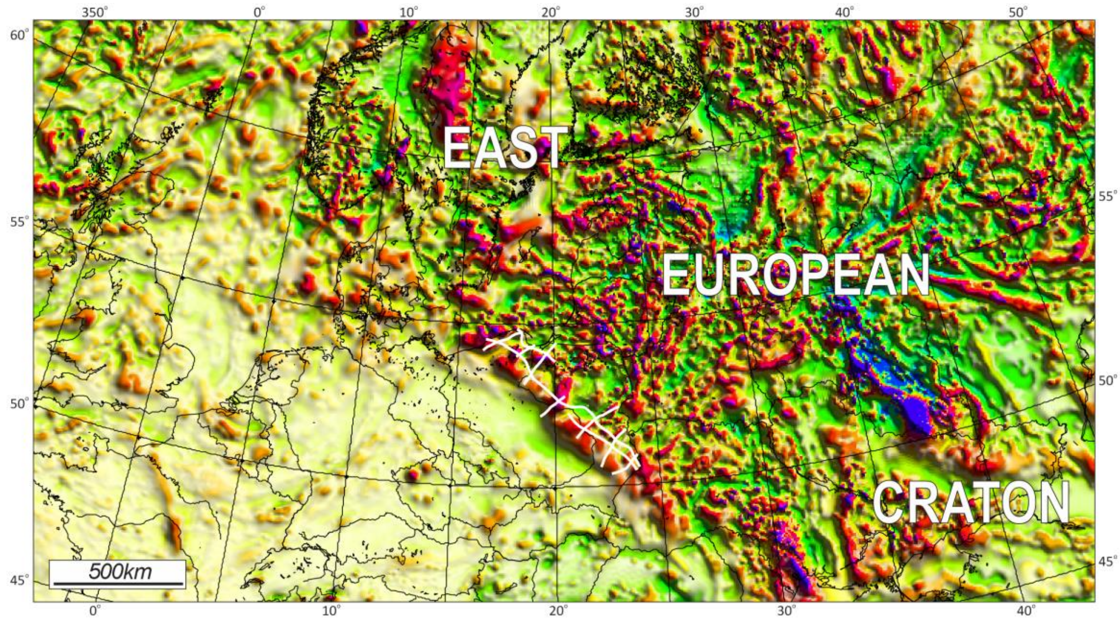

Figure 1. Magnetic map of central Europe depicting the East European Craton and its SW edge located in Poland and Ukraine. White lines: deep seismic reflection profiles of the PolandSPAN® survey

Integration of data from several deep wells with the high-resolution regional seismic profiles allowed mapping of the Neoproterozoic continental to shallow marine syn-rift clastic sedimentary succession. In some segments of the study area, deeply buried (10-15 km) well-preserved extensional features (tectonic half-grabens), filled with the presumably Neoproterozoic syn-rift volcano-sedimentary succession, were identified (Fig. 2). The graben developed in the Palaeoproterozoic crystalline basement. The age of the graben fill is directly constrained only for its uppermost part. Crustal-scale major faults might have acted as the pathways for the Ediacaran up-section lava migration. To the NW of the analysed area, in the SW part of the Baltic Sea, deep seismic constraints led to similar conclusions as for presence of the Neoproterozoic extensional grabens (Lassen et al., 2001).

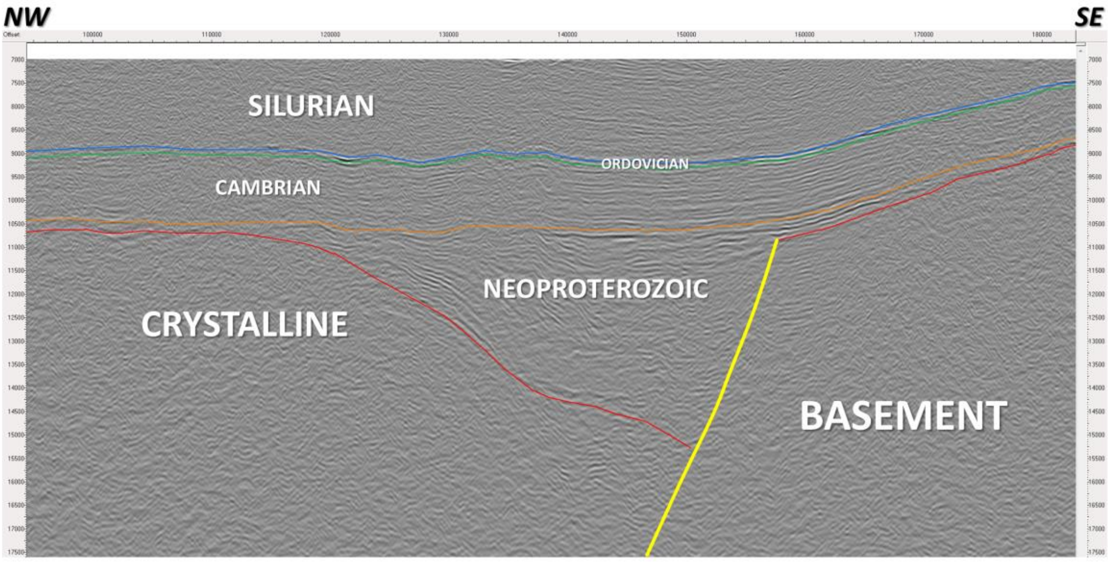

Figure 2. Seismic example of a deeply buried extensional half-graben developed within the SW edge of the East European Craton and filled by the Neoproterozoic volcano-sedimentary succession

The results of depth-to-basement study based on integration of seismic and potential field data show the distribution of local ENE-WSW elongated Neoproterozoic depocentres on the SW slope of the East European Craton. Furthermore, they document the rapid south-eastwards thickness increase of the Neoproterozoic-earliest Cambrian succession towards the NW-SE oriented craton margin. This documents extensive crustal thinning occurring in the Peri-Tornquist Zone prior to the break-up of Rodinia and formation of the Tornquist Ocean.

ION Geophysical is thanked for providing seismic data of the PolandSPAN® deep seismic survey.

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LA-ICP-MS U-Pb Dating of Heishitougou Basaltic Zircons: Implications for a More Extensive and Lasting Effect of the Paleo-Asian Ocean Southward Subduction

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The closure of the Paleo-Asian Ocean left remarkable landmarks, (e.g. the Central Asian Orogenic Belt), when the eastern Euro-Aaian continent formed during the Late Paleozoic. Southward, the oceanic slab subducted beneath the North China Craton (NCC), which completed its crustal growth and stabilization forming a rigid plate ~ 2.9 to 1.8 Billion years ago. The NCC was thought to have kept being stable until the Late Mesozoic. But the basalt sample we collect in the Heishitougou, which is located in the northern Ordos Basin in the western NCC, suggests another story based on the results of LA-ICP-MS U-Pb zircon dating.

The U-Pb dating results indicate an average age of 231.3 ± 2.4 Ma (Fig. 1). The age is far too old compared with other basalts, which are mostly much younger than 200 Ma in the NCC. On the other hand, the age is younger than other igneous rocks, which are mostly older than 250Ma within the Central Asian Orogenic Belt. Besides, it is rather rare to find igneous rocks within the Ordos Block, since the block remained quite stable even during the destruction of the NCC in the Late Mesozoic.

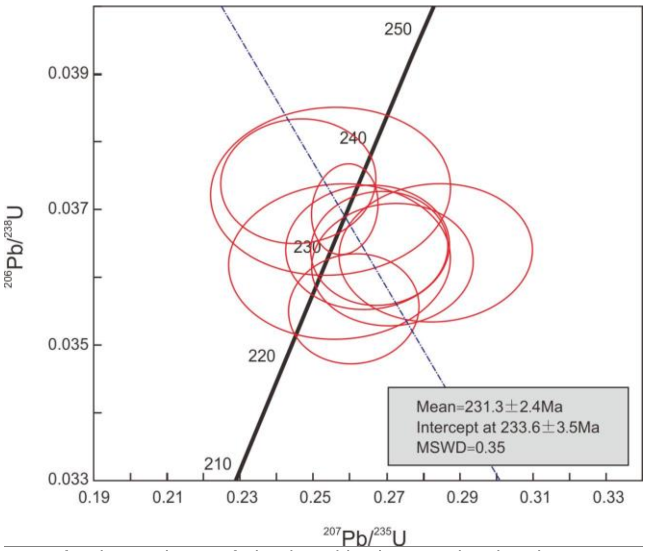

Figure 1. U-Pb concordia diagram for the analyses of nine basaltic zircons, showing the mean age is 231.3 ± 2.4 Ma with the interception at 233.6 ± 3.5 Ma (MSWD=0.35).

Such results may bring new thoughts to the tectonic evolution in the northern Ordos Block, and extend both temporal and spatial effects that the southward Paleo-Asian Ocean subduction posed on the NCC during its closure.

Heterogeneous mantle source modified by subduction beneath the western Yangtze Block, South China: evidence from Neoproterozoic Dengxiangying mafic dikes

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Neoproterozoic mafic dikes have been widely distributed in the Precambrian cratons. They were previously considered as the part of a giant plume-derived radiating dike swarm related to the breakup of Rodinia supercontinent (Park et al., 1995). South China plays a significant role in the evolution of Rodinia during the Neoproterozoic. Although various geological models of arc, mantle-plume and plate-rift have been proposed to interpret the formation of Neoproterozoic igneous rocks in the Yangtze Block, their petrogenesis and tectonic setting are still controversial (Li et al., 1999; Zhou et al., 2002; Zheng et al., 2007). Numerous ~800 Ma mafic dikes intruded the Mesoproterozoic Dengxiangying Group in the western Yangtze Block. They provide an ideal opportunity to examine the petrogenesis, nature of the mantle source and tectonic evolution. These dikes consist of fine-medium grained diabases and have sub-alkaline geochemical compositions with variable SiO_2 from 42.80 to 57.20 wt.%, MgO from 5.16 to 13.15 wt.% and total alkali from 0.05 to 4.41 wt.%. They show LREE-enriched chondrite-normalized REE patterns with negative Eu anomalies ($(La/Yb)_N$ = 1.18-5.36, Eu/Eu* = 0.67-1.09), as well as enrichment of Pb and depletion of Nb, Ta, Sr in the primitive mantle-normalized trace element patterns. They have obviously lower $(Dy/Yb)_N$ ratios (0.91-1.24) than the mantle plume-related mafic rocks (Mayborn and Lesher, 2004). Rocks from the mafic dikes show variable initial $^{87}Sr/^{86}Sr$ ratios (0.652431 to 0.730039) and εNd values (-2.5 to +2.6) and relatively consistent Pb isotopic ratios ($^{206}Pb/^{204}Pb$ = 17.53-17.88, $^{207}Pb/^{204}Pb$ = 15.60-15.63, $^{208}Pb/^{204}Pb$ = 37.66-38.38). These geochemical features suggest the mafic dikes have been derived from the metasomatic mantle source modified by sediment-derived fluid, with insignificant fractional crystallization and crustal contamination. Partial melting modeling reveals their parental magmas were generated by 5-20% melting of spinel lherzolite. The Dengxiangying mafic dikes were probably formed by the back-arc extension behind the Panxi-Hannan arc system (Zhou et al., 2002). Combined with the geochemistry and Sr-Nd-Pb isotopes of the mafic-ultramafic intrusions from the western margins of the Yangtze Block, we suggest a heterogeneous lithospheric mantle modified by subduction during the Neoproterozoic. This conclusion supports a marginal position for the South China in the Rodinia supercontinent.

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Geochronology and geochemistry of the mafic dykes in the Helanshan complex: implications for the Mesozoic tectonics

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The abundant mafic dykes in the northern Helanshan are keys to understand the magmatic evolution of the tectonic belt. They are mainly of diabase consisting of plagioclase (45–60%), pyroxene (25–35%) and minor Fe-Ti oxides. LA-ICP-MS U–Pb dating on the zircons from representative dyke yields an age of 206±1.9 Ma, which represents the crystallization age of the dyke. The diabases are composed of high $Fe_2O_3^T$ content (11.88–17.55%) but low contents of SiO_2 (45.65–50.95%) and MgO (3.31–5.50%) with low Mg# of 33–44. They are characterized by enrichment of light rare earth element (LREEs) and large ion lithophile elements (LILEs) (e.g., Rb, Ba and Pb), and slight depletion of high field strength elements (HFSEs) (e.g., Nb, Ta, Hf and Ti). The geochemistry suggests that the magma has undergone extensive crystallization fractionation of olivine, pyroxene but minor crustal contamination during magama evolution. They were derived from low degree (about 1-5%) parting melting of an enriched garnet+spinel lherzolite source. In combination with regional geology, the mafic dykes in the northern Helanshan are interpreted to have formed in an intracontinental extensional setting in the Late Triassic time.

Evaluation of full-plate reconstructions of the Neoproterozoic using Hf isotopes in zircon

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It has long been argued that plate motion is fundamentally linked to mantle convection, with various numerical models attempting to recreate plate motions by simulating mantle convective conditions. Recent work has addressed the interactions between mantle convection and plate dynamics, specifically the coupling of superplumes and supercontinents. This work presented a two-stage mantle convection model with: (1) degree-1 mantle convection with a single superplume and an antipodal downwelling zone leading to continent amalgamation, and; (2) degree-2 mantle convection, with two antipodal superplumes separated by a downwelling expressed as a subduction girdle (Li and Zhong, 2009). The subduction girdle of the degree-2 condition is comparable to the modern circum-Pacific system (flanked by the African and Pacific superplumes), which has arguabely existed for the entire Phanerozoic. Reconstructions for the Neoproterozoic, however, are debated. Current plate reconstructions rely on palaeomagnetic data, which indicate where and when plates moved, but not how the plates interacted with one another during orogenic cycles. Thus, an understanding of Neoproterozoic orogens is required to evaluate the Rodinia-Gondwana supercontinent cycle. Hf isotope analysis of magmatic zircon differentiates between accretionary orogens, formed at subduction girdles external to a supercontinent, and collisional orogens internal to a supercontinent (Collins et al., 2011). Importantly, adjacent sedimentary basins provide a more complete record of the duration of magmatism. The Hf evolutionary array from these basins can be directly compared to the magmatic record to fully ascertain the location and timing of convergence of individual plates, from initial subduction to terminal collision of continents.

To test plate reconstructions, U-Pb-Hf data from global Neoproterozoic magmatic rocks were used to reconstruct internal and external orogens during the Rodinia-Gondwana transition. This clarifies the location of plates where palaeomagnetic data is lacking. Most importantly, the data reveals that a subduction girdle did not establish around Rodinia at ~900 Ma as many authors have suggested. Rather, a disconnected system of magmatic arcs progressively encircled Rodinia and circum-supercontinent subduction did not stabilize until 580-550 Ma, during the final stages of Gondwana amalgamation. The global Hf isotope array also suggests that mantle convection patterns for the Neoproterozoic were dominated by the degree-1 condition, which does not require a peripheral subduction girdle around Rodinia. Thus, the Neoproterozoic orogenic and global Hf isotope record suggests that an entirely different mantle circulation pattern to that which characterizes the Phanerozoic era.

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Project 648
IUGS UNESCO
Supercontinent Cycles & Global Geodynamics

New data from the northern Uchur-Maya region (eastern Siberia) seem to confirm the Siberia-Laurentia coherence during the Late Mesoproterozoic-Early Neoproterozoic.

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Even though the idea of Siberia-Laurentia connection within the Rodinia supercontinent is generally accepted in geological-geophysical community. However, there is not so much evidence supporting it.

Probably, one of the most firm arguments for this hypothesis comes from the similarity of Late-Mesoproterozoic – Early Neoproterozoic segments of Siberian and Laurentian APWP's (e.g. Pavlov et al., 2002; Pisarevky and Natapov, 2003 et al.). The paleomagnetic poles which constitute corresponding part of the Siberian APWP are relatively well established and more or less well dated. Nevertheless, the number of these poles and duration of relevant time period seems not to be sufficient to affirm with certainty that observed APWP's similarity is not coincidental. Thus there is a clear need to extend the Siberian APWP further both back and forward in time.

The available Siberian Late Mesoproterozoic – Early Neoproterozoic paleomagnetic poles have been obtained mainly from Meso-Neoproterozoic rocks of the southern part of the Uchur-Maya region, for (from bottom to top) the Malgina Formation, Zipanda Formation, Neruen Formation (Kumakha, Milkon and Nelkan sub- formations), Ignikan Formation and Judoma sills. The late Mesoproterozoic Totta Formation (age estimated to be between 1100 and 1050 Ma) which underlies the Malgina Formation also has been studied, however grey and dark siltstone and fine grained sandstone of this formation shows no presence (with one exception: see Pavlov, 1994) of the primary magnetization.

At the same time in the northern sections of the Uchur-Maya region this formation is composed mainly by red siltstone and sandstone, promising, a priori, for paleomagnetic studies. During last couple of years we have carried out paleomagnetic studies of the Meso-Neoproterozoic section exposed along the valley of the Belaya (Khanda) river (northern Uchur-Maya) region. Main target of our study were redbeds of the Totta Fm. Preliminary paleomagnetic pole which we have obtained from these redbeds is located at ~ Plat= 10.2°; Plong =80.2° (K=17.9; A95 = 4.2°). This pole position is in a good agreement (after corresponding rotation, see, for eample, Pavlov et al., 2002) with APWP of the Laurentia for ~1100-1050 Ma.

Whereas southern Uchur-Maya region belongs to the stable part of the Siberian platform, its northern part is considered to be thrust-folded disturbed margin. Thus the possibility of vertical axis rotation of the tectonic blocks there can't be excluded. To estimate the scale of possible post Mesoproterozoic vertical axis rotations we have also studied the rocks of the Malgina Formation, exposed here, to compare their paleomagnetic record with this one obtained from earlier studied southern sections. The uppermost part of the Malgina Formation from the valley of the Belaya (Khanda) river valley yields the pole, whose location (Plat= 24.3°; Plong =52.4°; K=29.7; A95 = 4.6°) is very similar to this one, which comes from southern regions. Therefore there is no evidence for vertical axis rotation of the Belaya river section with respect to the Siberian platform and the Totta pole can be used for construction of the Siberian APWP. Simultaneously we have studied several Neoproterozoic dolerite sills exposed along the valley of the Allakh-Jun River (also northern Uchur-Maya region). These sills are nearly coeval to these ones studied by us earlier in the southern part of the Uchur-Maya region. New data from Allakh-Jun sills allow checking of the reliability of the poles obtained earlier and they better constrain the Neoproterozoic part of the Siberian APWP.

In conclusion, new data seem further confirm the reality of the Siberia-Laurentia connection in Meso-Neoproterozoic.


Rodinia
2017

New Progress and Constraints on Supercontinent Reconstructions

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The popular concept of supercontinent cycles suggests the existence of one Phanerozoic and at least two Precambrian supercontinents, referred to as Pangea (± Gondwana?), Neoproterozoic Rodinia and Mesoproterozoic Nuna (or Columbia). A number of various paleogeographic reconstructions of these supercontinents and some kinematic models of their assembly and breakup have been published in recent years (e.g. Domeier and Torsvik, 2014; Matthews et al., 2016; Li et al., 2008; Pisarevsky et al., 2014; Merdith et al, in press). There are also several hypotheses about pre-Mesoproterozoic supercontinents – Kenorland, Superia etc. (Pesonen et al., 2003; Bleeker, 2003).

A sufficient amount of new paleomagnetic, geological and geochronological data require modifications of previous reconstructions, among them are: (i) paleomagnetic and geochronological data from Paleo- and Mesoproterozoic and Early Neoproterozoic rocks in Baltica, North China, Sao Francisco, Amazonia, Australia, Siberia, Laurentia; (ii) discoveries of Large Igneous Provinces with ages between 2000 and 900 Ma in Siberia, North China, Sao Francisco and Congo; (iii) geological and geochronological data from Europe and South America, which do not support the popular SAMBA model of long-lived connection between Baltica and Amazonia in late Paleoproterozoic and Mesoproterozoic; (iv) geological data from Laurentia and new ideas about pre-Mesoproterozoic supercontinent (Pehrsson et al., 2013). These and other data suggest modifications are required for the configurations of Precambrian supercontinents.

Unfortunately there is no consensus about the definition of a supercontinent. For example, is Gondwana a supercontinent? Depending on the answer, various estimations of the longevity of supercontinent cycle(s) arise. Moreover, there is a general disagreement about supercontinents' tenure. In my view, the best definition of the supercontinent's tenure is "the time from a final assembly (i.e. when the latest large piece of continental crust collided to a previously assembled entity) and an initial breakup (i.e. when the first large piece of continental crust broke away from the rest)" (Fig. 1a). Fig. 1b illustrates a variety of different approaches to this definition.

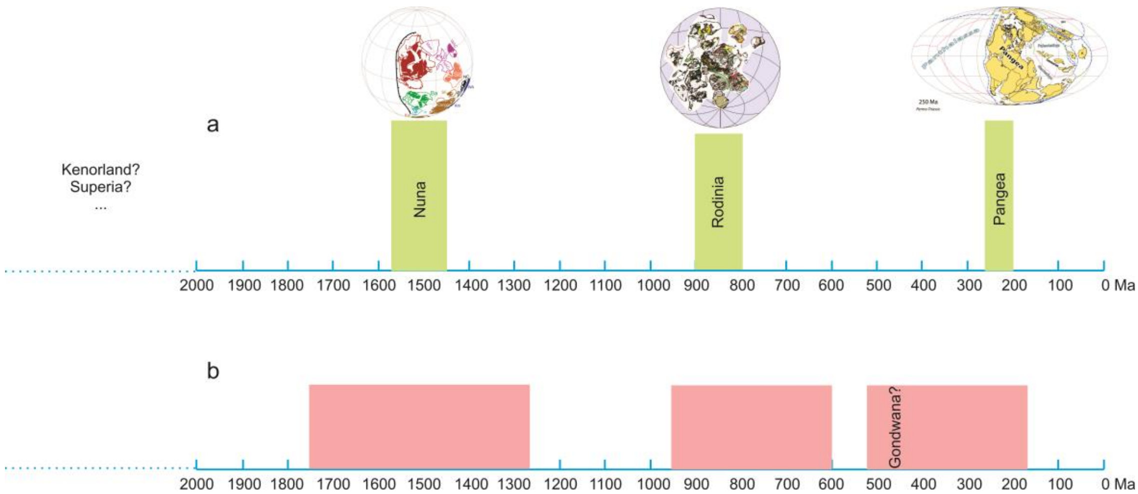

Figure 1. Variety of definitions of the supercontinent cycles; (a) a conservative approach, reconstructions: Nuna – modified from Pisarevsky et al. (2014), Rodinia – after Li et al., 2008; Pangea – after Domeier and Torsvik, 2014; (b) other approaches.

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Expanding the core of Nuna supercontinent - Paleogeography of the Congo/São Francisco craton at 1.5 Ga

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The existence of the Paleoproterozoic supercontinent Nuna (a.k.a. Columbia, Hudsonland) has been proposed by many researchers (e.g. Hoffman, 1991). The main geological argument supporting the assembly of Nuna is the presence of 2.1-1.8 Ga orogens in the majority of continents. Many proposed Nuna configuration models differ from each other. However, there is a consensus that Baltica and Laurentia form the core of the Nuna in the geologically and paleomagnetically viable North Europe North America (NENA; Gower et al., 1990) connection between ca. 1.75 and ca. 1.27 Ga (Salminen and Pesonen, 2007; Evans and Pisarevsky, 2008), but different configurations have also been presented (e.g., Johansson, 2009). Based on Mesoproterozoic passive margins surrounding Siberia and similar geology between Siberia and Western Greenland from 1.9 Ga onward it was recently proposed that Siberia forms the Nuna core together with Baltica and Laurentia in tight fit between East Siberia and Western Greenland (e.g., Evans and Mitchell, 2011; Evans et al., 2016). This tight fit is supported by 1.8 - 1.38 Ga paleomagnetic data from Siberia, Baltica and Laurentia, but an alternative view has also been presented by Pisarevsky et al. (2008). Adding cratons around the core of Nuna has been a major initiative among paleogeographers in recent years that has led to the paleogeographical model of Nuna to take shape.

Congo/São Francisco (C/SF) craton has been lacking reliable paleomagnetic data for the supercontinent Nuna interval (ca. 1600-1300 Ma) until recent. Salminen et al. (2016) obtained a new, high-quality paleomagnetic pole for C/SF craton from 1506.7 ± 6.9 Ma (Silveira et al., 2013) mafic dykes from Curaçá regions in Brazil. This pole reconstructs C/SF craton to mid-latitudes and allows us to reconstruct the extended core of the supercontinent Nuna at 1.5 Ga. Based on coeval 1.5 Ga and 1.38 Ga magmatism in Baltica, Siberia and C/SF, we favour the position where Southwest Congo is reconstructed against present South-Southeast (S-SE) Baltica (Figure 1). We explore two alternative 1.5 Ga reconstructions of Nuna's core. In both of them Baltica and Laurentia are shown in the well-defined NENA (Northern Europe North America) fit, together with Siberia in a tight fit to northern Laurentia, but the positions of Amazonia and C/SF vary. In reconstruction option A, more traditional fit of Amazonia with Baltica is shown, slightly differing from the geologically based SAMBA (South AMerica Baltica; Johansson, 2009) model to accommodate paleomagnetic data. In this option, however, West Africa must be extricated from SAMBA because C/SF has taken its place. Amazonia's and Baltica's 1.78 Ga and ca. 1.4 Ga paleopoles support this fit. For reconstruction option B, C/SF is in tight fit with Baltica, but Amazonia is shifted requiring an unconventional dynamic reconstruction of south Amazonia to West Baltica.

Option B conforms better to our new 1.5 Ga paleomagnetic data for C/SF. We have plotted the 1.38 Ga pole from Kunene anorthosite complex in Figure 1 (Kac), and it is not similar to 1.38 Ga poles from other cratons either option, but due to that pole's low quality we cannot exclude the continuation of either fit at 1.38 Ga. Both of the C/SF juxtapositions with Baltica are incompatible with paleomagnetic data from those cratons at 920 Ma, indicating their separation during late Mesoproterozoic time. However, we are currently unable to test the duration of either configuration option more precisely.

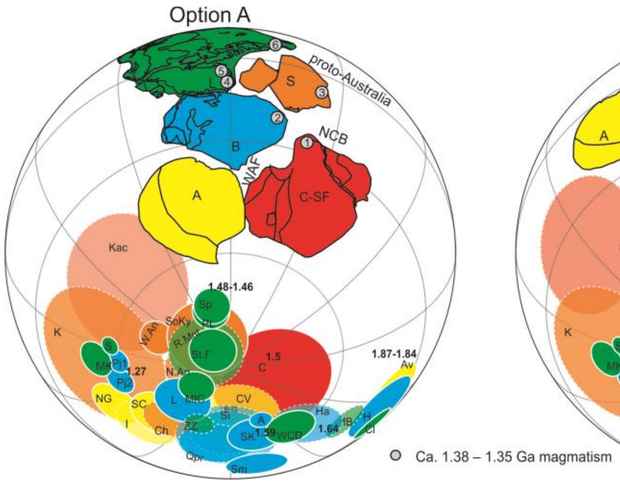

Figure 1**.** Plausible reconstructions on the extended core of Nuna at 1500 Ma including Baltica (B, blue); Laurentia (L, green); Siberia (S, orange); Congo/São Francisco (C/SF, red); and Amazonia (A, yellow). Poles, listed in (Salminen et al., 2016; 2017), are color-coded according to craton, shaded according to reliability (darker with solid outline = key pole), and rotated to the reconstructions presented. Used Euler rotations in Salminen et al. (2016). Grid lines are 30° and absolute palaolongitude is arbitrary. Ca. 1.38 – 1.35 Ga magmatism; 1 Kunene anorthosite complex; 2 Mashak volcanics; 3 Chieress dyke; 4 Midsommerso sills and Zig Zag volcanics; 5 Victoria Land dykes; and 6 Hart River sill. WAF West Africa; NCB North China Block. Bold numbers are ages in Ga. Figure modified from Salminen et al. (2016, 2017).

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Paleomagnetism of early-Neoproterozoic volcanic rocks in SW Tarim and its paleogeographic implications

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The supercontinent Rodinia has been linked to many essential conditions of broader Earth system evolution across the most late-Mesoproterozoic to Neoproterozoic Era, yet debate remains on the connection between Australia-East Antarctica and Laurentia near the center. A synthesis (Li et al., 2008. Precambrian Res 160, 179-210) and subsequent reconstructions emphasized the need of a "missing link" between Australia and Laurentia. Our recent study positioned Tarim in that role either by itself or together with South China (Wen et al., 2017. Earth Planet. Sci. Lett 458, 92-106), but lack of early Neoproterozoic paleomagnetic data demand further tests of that model. Here we present new paleomagnetic data from ca. 890-880 Ma volcanic rocks of southwest Tarim. Excluding secondary directions, a coherent stable, NE-up characteristic remanent magnetization (ChRM) is obtained from 11sites. As of now, there are no field tests available, but further sampling is being planned. The preliminary paleopole is distinct from all published younger poles from Tarim; this fact, plus low anisotropy and original magnetic fabrics revealed by the magnetic anisotropy susceptibility (AMS) data, suggest its robustness. This new result and mid-Neoproterozoic paleopoles published recently from Tarim, coincide with coeval poles from Australia, Laurentia and Baltica, when Tarim is rotated into a "missing-link" configuration (81.9°N, -10.5°E, 124.5° to Laurentia) similar to that proposed by Wen et al. (2017), and constitute a long-lived connection for the nucleus of Rodinia.

Ca. 750–720 Ma tectonic transition recorded in the Bemarivo terrane balances the global plate kinematic budget during Rodinia break-up

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Break-up of Rodinia between ~750 and 720 Ma (Li et al., 2008, 2013) requires the establishment of contemporaneous convergent plate boundary around the supercontinental periphery to balance the lithospheric construction and destruction within a constant radius Earth (Cawood et al., 2005). Igneous rocks of mid-Neoproterozoic age now exposed in Central Madagascar, the Seychelles and NW India have been widely believed to represent the Andean-type magmatic arc above an elongate paleo-subduction zone along Rodinia's western margin, which could consume the Mozambique oceanic lithosphere and thus serve as a potential site to preserve the global plate kinematic budget during Rodinia break-up (Fig. 1; e.g., Ashwal et al., 2002; Bybee et al., 2010; Handke et al., 1999; Torsvik et al., 2001a,b; Tucker et al., 2001). However, as revealed by previous high-precision U–Pb geochronology, all the magmatic components of this proposed Andean-type arc were instead generated during the period of ~870–750 Ma prior to Rodinia break-up, making such an interpretation inapplicable. Furthermore, their petrology, chemical composition, isotopic signatures, as well as metallogenic associations are also incompatible with an Andean-type arc origin. So, was there any convergent plate boundary built when the Australia-East Antarctica (or South China) rifted away from the western margin of Laurentia?

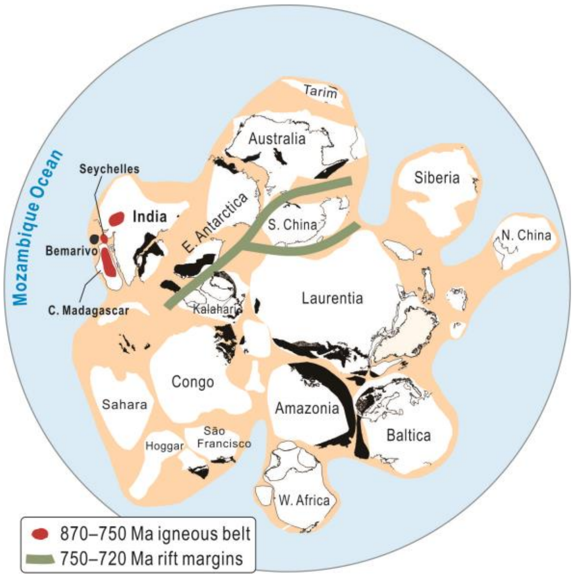

Figure 1. Reconstruction of the supercontinent Rodinia after Li et al. (2008), showing locations of the 750–720 Ma rift margins and the 870–750 Ma igneous belt with an inferred Andean-type arc origin. Note that the position of the Bemarivo terrane in Rodinia is constrained by geological correlations with no paleomagnetic data available, and only shown for the purpose of illustration.

The Bemarivo terrane is a tectonic building-block accreted to the northern margin of cratonic Central Madagascar in earliest Cambrian time. Dominantly exposed are the Neoproterozoic intrusive suites and volcano-sedimentary sequences, including the Antsirabe Nord Suite (ANS), the Manambato Suite (MS), and the Daraina-Milanoa Group (DMG) (Thomas et al., 2009; Tucker et al., 2014). New in-situ zircon U–Pb, Hf and O isotope data, together with published information, demonstrate that (1) the Neoproterozoic igneous rocks in the Bemarivo terrane have a bimodal age distribution, i.e., ~760–750 Ma for the ANS and ~720–700 Ma for the DMG and MS. (2) A Paleoproterozoic basement is probably present beneath the Bemarivo terrane, lying outboard of Central Madagascar and facing the Mozambique Ocean in Rodinia time. Most importantly (3), a switch of tectonic setting from intra-plate ANS to supra-subduction DMG and MS is indicated by several distinctive geochemical signatures and geological features.

We suggest that this tectonic transition between around 750 and 720 Ma recorded by the Bemarivo terrane was a plate kinematic response to the break-up of Rodinia. The Bemarivo terrane may represent a fragment of a larger continental terrane once outboard of Rodinia's western margin to witness the destruction of Mozambique oceanic lithosphere, and can possibly be traced to both East Africa and NW India.

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THEME 3.

How supercontinents assemble.

Coordinator:

Prof. Ricardo Trindade (Universidade de São Paulo).

Lithospheric Evolution and the supercontinent cycle

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The lithosphere is the long term archive of Earth's history. Its formation and evolution are driven by thermal energy from the planet's interior and modulated by solar radiation which regulates the temperature at its surface. The evolving thermal budget of the Earth has resulted in a multistage history of the lithosphere. This is recorded in progressive changes in its composition, its differentiation into, and changing proportions of, continental and oceanic variants, changing thicknesses, and patterns of interaction with underlying asthenospheric mantle and overlying hydrosphere, atmosphere and biosphere. On this basis, we envisage 5 main stages in the evolution of the Earth and its lithosphere: 1) Initial accretion and differentiation of the core/mantle system within the first few 10's of millions of years with a surface magma ocean, on an anoxic prebiotic Earth; 2) Generation of crust prior to 3.0 Ga, in a pre-plate tectonic regime associated with the evolution of early life and large fluctuations in atmospheric chemistry; 3) Early plate tectonics involving hot, presumably shallow subduction over the period from 3.0-1.7 Ga, associated with changes in the composition of new crust from mafic to intermediate and an increase in crustal thickness and recycling, along with massive changes in the biosphere, ocean and atmospheric chemistry, and global climate, including the initial rise in atmospheric oxygen and global glaciations; 4) Earth's Middle Age from 1.7-0.75 Ga, characterized by lithospheric, environmental, and evolutionary stability, and the evolution of early eukaryotes; 5) Initiation of modern cold subduction at ~0.75 Ga, associated with a second rise in atmospheric oxygen, extensive global glaciations, and the radiation of animal life. Supercontinents have operated during the last three stages and their assembly and dispersal require horizontal motion of the lithosphere through plate tectonics. Volume of continental lithosphere, reflecting the tectonochemical interplay of processes of generation and recycling, increased until Earth's Middle Age and they may have been decreasing for the last ~1 Ga.

A Full-Plate Global Reconstruction of the Neoproterozoic: An Essential Step in Quantifying Ancient Geodynamics

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Neoproterozoic tectonic geography was dominated by the formation of the supercontinent Rodinia, its break-up and the subsequent amalgamation of Gondwana (Merdith et al. 2017). The Neoproterozoic was a tumultuous time of Earth's history, with large climatic variations, the emergence of complex life and a series of continent-building orogenies of a scale not repeated until the Cenozoic. Here we synthesise available geological and palaeomagnetic data and build the first full-plate, topological model of the Neoproterozoic that maps the evolution of the tectonic plate configurations during this time. Topological models trace evolving plate boundaries and facilitate the evaluation of "plate tectonic rules" such as subduction zone migration through time when building plate models.

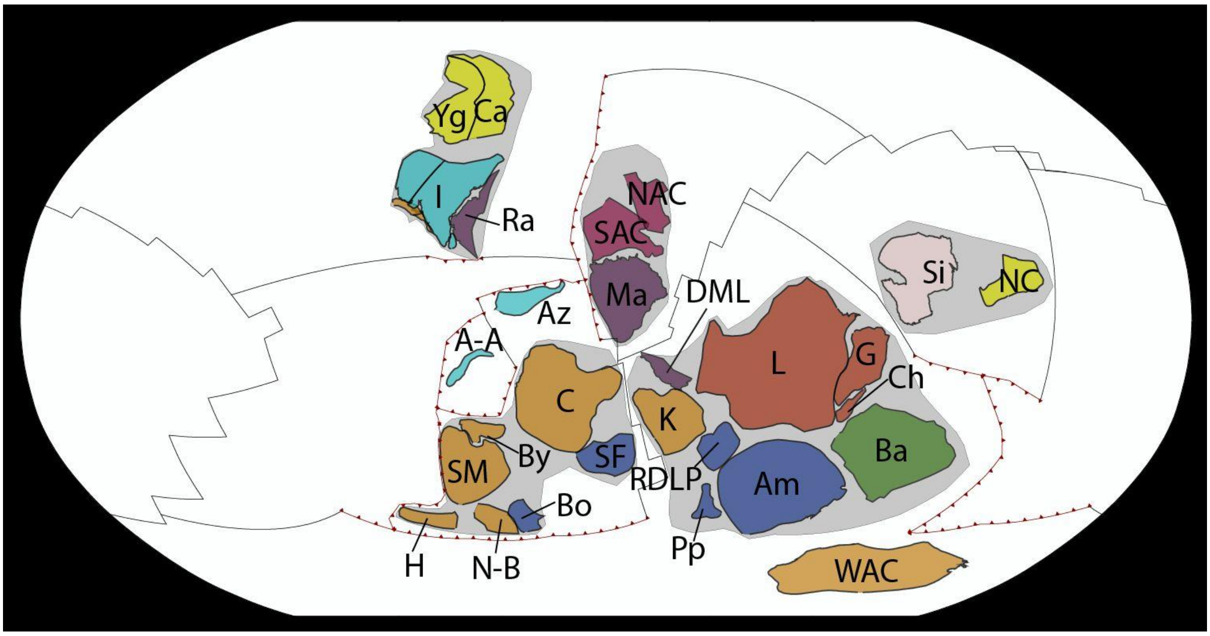

Figure 1 (above): Tectonic geography at 750 Ma. A-A, Afif-Abas Terrane; Am, Amazonia; Az, Azania; Ba, Baltica; Bo, Borborema; By, Bayuda; Ca, Cathaysia (South China); C, Congo; Ch, Chortis; G, Greenland; H, Hoggar; I, India; K, Kalahari; L, Laurentia; Ma, Mawson; NAC, North Australian Craton; N-B, Nigeria-Benin; NC, North China; Pp, Paranapanema; Ra, Rayner (Antarctica); RDLP, Rio de la Plata; SAC, South Australian Craton; SF, São Francisco; Si, Siberia; SM, Sahara Metacraton; WAC, West African Craton. Shaded grey area is inferred extent of Rodinia and is meant as a guide only. The longitude is arbitrary and unconstrained, and used here as a relative reference. Cratonic crust is coloured by present day geography: North America, red; South America, dark blue; Baltica, green; Siberia, grey; India and the Middle East, light blue; China, yellow; Africa, orange; Australia, crimson,; Antarctica, purple

There are a rich history of subduction zone proxies preserved in the Neoproterozoic geological record, providing good evidence for the existence of continental and intra-oceanic subduction zones through time. These are preserved either as volcanic arc protoliths accreted in continent-continent, or continent-arc, collisions, or as the detritus of these volcanic arcs preserved in successor basins. Despite this, we find that the model presented here only predicts, on average, ~90% of the total length of subduction active today, suggesting that we have produced a conservative model and are likely underestimating the amount of subduction, either due to a simplification of tectonically complex areas, or because of the absence of preservation in the geological record (e.g. ocean-ocean convergence).

Furthermore, the reconstruction of plate boundary geometries provides constraints for global-scale earth system parameters, such as the role of volcanism or ridge production on the planet's icehouse climatic excursion during the Cryogenian. Besides modelling plate boundaries, our model presents some notable departures from previous Rodinia models. We omit India and South China from Rodinia completely, due to long-lived subduction preserved on margins of India and conflicting palaeomagnetic data for the Cryogenian, such that these two cratons act as 'lonely wanderers' for much of the Neoproterozoic. We also introduce a Tonian-Cryogenian aged rotation of the Congo-São Francisco Craton relative to Rodinia to better fit palaeomagnetic data and account for thick passive margin sediments along its southern margin during the Tonian. The *GPlates* files of the model are released to the public and it is our expectation that this model can act as a foundation for future model refinements, the testing of alternative models, as well as providing constraints for both geodynamic and palaeoclimate models.

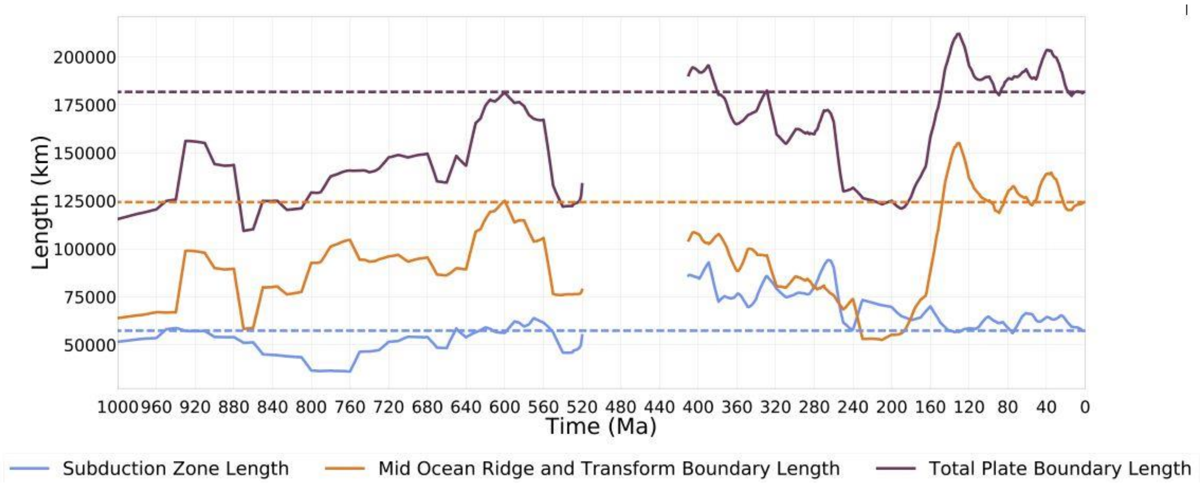

Figure 2 (above): Length of plate boundaries, extracted at 1 Myr intervals and calculated as 10 Myr rolling average. The present-day length of plate boundaries are plotted as straight dashed lines. Boundary lengths are from the model presented here and the model from Matthews et al. (2016), which is a compilation of the Domeier and Torsvik (2014) and Müller et al. (2016) models.

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Tectonic evolution of the East Kunlun Orogen, Northern Tibetan Plateau

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The Kunlun Orogen can be divided into East Kunlun Orogenic Belt (E-KOB) and the West Kunlun Orogenic Belt (W-KOB) by the Altyn Tagh fault. The EKOB, which constitutes the western segment of the Central China Orogenic System, is considered to be formed by the collision between the Qaidam Block and Qiangtang or Bayanhar Terrane due to closure of the Kunlun Ocean (brunch of the Paleo-Tethyan Ocean. Based on a huge amount of newly published high quality data, this contribution provides an overview of the composition, nature and ages of the principal tectonic elements including ophiolitic mélanges and related volcanic rocks, intrusive plutons and sedimentary covers in the E-KOB. According to the multiple lines of evidence from different tectonic units, we proposed herewith a Paleozoic-Triassic subduction and accretionary tectonic model interpreting the spatial and temporal tectonics and evolutionary process, as well as the polarity of the plate subduction, accretion and collision of the E-KOB. Three major ophiolitic mélange zones have been identified in the E-KOB, which are the Qimantag-Xiangride ophiolitic mélange zone (QXM), the Aqikekulehu-Kunzhong ophiolitic mélange zone (AKM) and the Muztag-Buqingshan-Anemaqen ophiolitic mélange zone (MBAM), from north to south. According to these ophiolitic mélange zones, the E-KOB is divided predominantly into the Northern Qimantag belt, Central Kunlun belt, South Kunlun belt and Bayanhar Terrane. Based on the systemic evidence of geology, geochemistry and geochronology, the South Kunlun belt is indicated as a Paleozoic to Triassic fore-arc and accretionary complex related to the northward subduction of the Kunlun Ocean from Ordovician to Triassic. The AKM, MABM and the South Kunlun belt constitute a wide accretionary complex which represents the Kunlun Suture zone of the major Paleo-Tethyan Ocean, while the QXM marks the suture of the Qimantag back-arc basin. The Central Kunlun belt represents a long-lived island-arc terrane which was split out of the Qaidam Block due to the spreading of the Qimantag back-arc basin during ca. 485 - 425 Ma. Taken into all the geological, geochemical and geochronological lines of evidence together, it is suggested that the E-KOB has been involved into a trench / arc / back-arc basin tectonic system, and evolved into a long-lived tectonic process of northward-subduction and accretion along the Kunlun Suture during Paleozoic and Triassic times.

Project 648
IUGS UNESCO IGCP
Supercontinent Cycles & Global Geodynamics

Nascent Palaeoproterozoic episodic collisional orogenesis: The Eburnean Orogeny of the West African Craton

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The Palaeoproterozoic Eburnean Orogeny of the West African Craton (WAC) represents the earliest event during a period of worldwide collisional orogenesis between 2.1 and 1.9 Ga. This study presents a multi-disciplinary analysis of the Sefwi greenstone belt in the southeastern portion of the WAC (Fig. 1) in order to better elucidate the enigmatic tectonic settings responsible for amalgamation of the alternating, juvenile granite-greenstone terranes of the WAC.

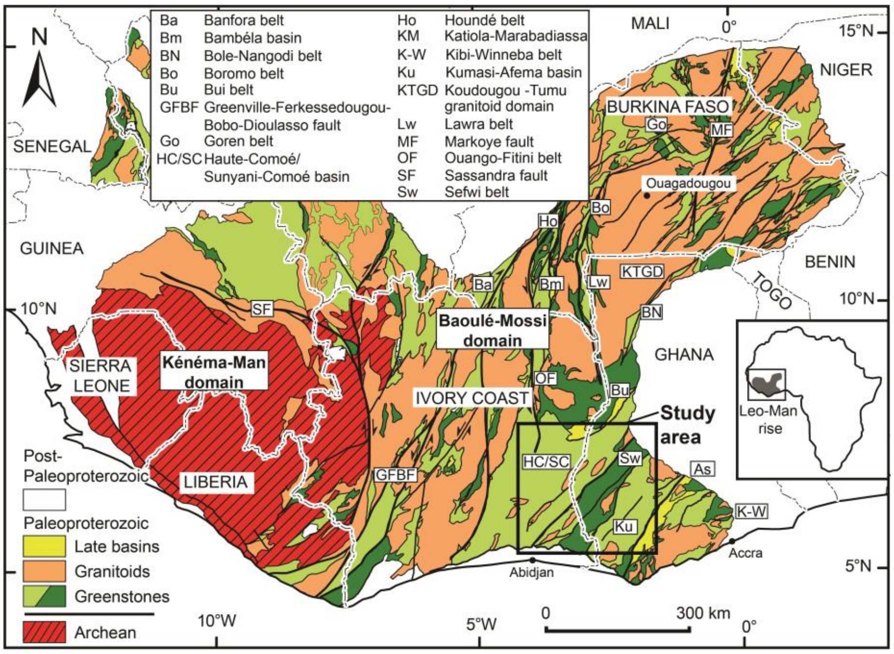

Figure 1. Geological map of the southern portion of the West African Craton (modified after BRGM SIGAfrique, Milési et al., 2004). Greenstone belts in the Palaeoproterozoic Baoulé-Mossi domain are divided into mafic to intermediate volcanic greenstone belts (dark green); volcano-sedimentary, volcaniclastic and intermediate volcanic provinces (light green). Granitoid composition ranges from tonalite-trondhjemite-granodiorite and granite. Late fluvio-deltaic sediments (yellow) unconformably overlie greenstone belts in narrow, fault bounded basins.

Integration of regional geophysical datasets, belt-wide field observations and detailed metamorphic studies reveal initial high-pressure–medium-temperature (HP-MT) metamorphic assemblages and low apparent geothermal gradients and conditions of 10.0–11.5 kbar, 600–650 °C. S1 is a ubiquitous bedding parallel foliation in both high and low grade domains. Combined structural and metamorphic evidence suggest D1 is a crustal thickening event associated with N-S shortening. Subsequent partial melting in high grade domains indicate metamorphism occurred at the amphibolite-granulite facies transition (7.5–9.5 kbar, 650–700 °C) following contemporaneous heating and minor exhumation during thermal relaxation. In-situ U-Pb SHRIMP monazite analysis constrains the timing of peak- to

post-peak metamorphism along clockwise P-T-t paths at ca. 2.07 Ga. High grade metamorphism of this age has not previously been recorded in the southeastern portion of the WAC.

D2 WSW-ENE transtension is characterised by constrictional E-W folds, with coaxial L2 stretching lineations and F2 fold axes, coupled with sinistral displacement along major NE-SW trending shear zones and clockwise retrograde P-T paths to amphibolite facies conditions. Transtension resulted in late-orogenic differential exhumation, tectonically juxtaposed domains of contrasting metamorphic grade along regional-scale NE-SW shear zones and NNE-striking normal faults after 2.07 Ga. Transtension occurred under continued N-S to NW-SE convergence with orogen-parallel extension likely facilitated by rheological weakening of the lower crust due to partial melting and competing boundary and gravitational forces. Dextral reactivation of regional NE-SW shear zones associated with localized retrograde greenschist facies metamorphism suggests a switch in tectonic mode to E-W shortening during D3.

We propose that the structural and metamorphic evolution of the Sefwi greenstone belt related to collisional orogenesis, thus suggesting the greenstone belt demarcates a suture within the craton. This is supported by the significant difference in timing of deformation and metamorphism recorded by high-grade paragneisses and orthogneisses in neighbouring NW Ghana and central Ivory Coast, 30–60 M.y. prior. The combination of cold apparent geothermal gradients and transtension-related exhumation evident in SW Ghana (this study) and gravitational collapse documented in NW Ghana (Block et al., 2016) suggests that the lithosphere was sufficiently cold and strong to accommodate heterogeneous crustal thickening. We suggest the amalgamation of the craton can be characterised by episodic collisional events between small continental blocks during the Eburnean Orogeny, which culminated with the collision of the Archean nucleus and the assembled Palaeoproterozoic blocks at ca. 2030 Ma (Kouamelan et al., 1997). Illustrating increasing metamorphic and structural diversity relative to Archean provinces, the Eburnean Orogeny of the WAC potentially provides crucial evidence for understanding the secular evolution of orogenic processes early in the Palaeoproterozoic, prior to the appearance of hallmark subduction-related petro-tectonic indicators.

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Kinematic Constraints on the transition from ‘West’ Rodinia to East Gondwana

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Earth’s plate tectonic history during the breakup of the supercontinent Pangea is well constrained from the seafloor spreading record, but evolving plate configurations during older supercontinent cycles are much less well understood. Deep time plate reconstructions rely on a rage of observations, such as palaeomagnetic, geochronological and geological data, to constrain both the positions of, and relationships between, cratonic blocks at specific times. The limited variety and amount of data available for Precambrian reconstructions compared to Phanerozoic reconstructions (which can also use fossil data and fracture zones in ocean basins) requires the utilisation of novel approaches to determine reasonable plate motions and configurations. During times when continents are arranged into supercontinents, a small amount of data (palaeomagnetic and geological) can help constrain most cratons, however, times of supercontinent dispersal and assembly are more difficult to constrain, as each craton moves independently. Implicit within restricting cratonic position at (multiple) discrete times is kinematic data that can be extracted and used to help discriminate between competing plate motions and configurations, as well as to help provide some confidence for plate motions between the times that are well constrained (i.e. for supercontinent assembly and dispersal). However, deep-time reconstructions are typically built using absolute motions defined by palaeomagnetic data, and do not consider the kinematics of relative motions between plates, even for occasions where they are thought to be ‘plate-pairs’, either rifting apart leading to the formation of conjugate passive margins separated by a new ocean basin, or brought together by collision and orogenesis. Here, we use open-source software tools (GPlates/pyGPlates) that allow geoscientists to easily access quantitative plate kinematics inherent within alternative reconstructions, such as rates of absolute and relative plate motion. We analyse the Rodinia-Gondwana transition during the Neoproterozoic, investigating the four proposed Australia-Laurentia configurations during Rodinia, and the motion of India colliding with Gondwana. We find that earlier rifting times provide more optimal kinematic results. The AUSWUS and AUSMEX configurations with rifting at 800 Ma are the most kinematically supported configurations for Australia and Laurentia (average rates of 57 and 64 mm/yr respectively), and angular rotation of ~1.4°/Myr, compared to a SWEAT configuration (average spreading rate ~76 mm/yr) and Missing-Link configuration (~90 mm/yr). Later rifting, at 725 Ma necessitates unreasonably high spreading rates of >130 mm/yr for AUSWUS and AUSMEX and ~150 mm/yr for SWEAT and Missing-Link (Figure 1). Recent suggestions that parts of South China may represent a Late Mesoproterozoic-Early Neoproterozoic accretionary zone in addition to the presence of a plume head underneath Rodinia could help alleviate some of these kinematic issues, as the lack of a deep cratonic root could help permit faster motions via decoupling from the underlying mantle. Finally, using motion paths and convergence rates, we create a kinematically reasonable (convergence below 70 mm/yr) tectonic model that is built upon a front-on collision of India into Gondwana, while also incorporating a sinistral strike-slip motion against Australia and East Antarctica. We use this simple tectonic model to refine a global model for the break-up of western Rodinia and the transition to eastern Gondwana.

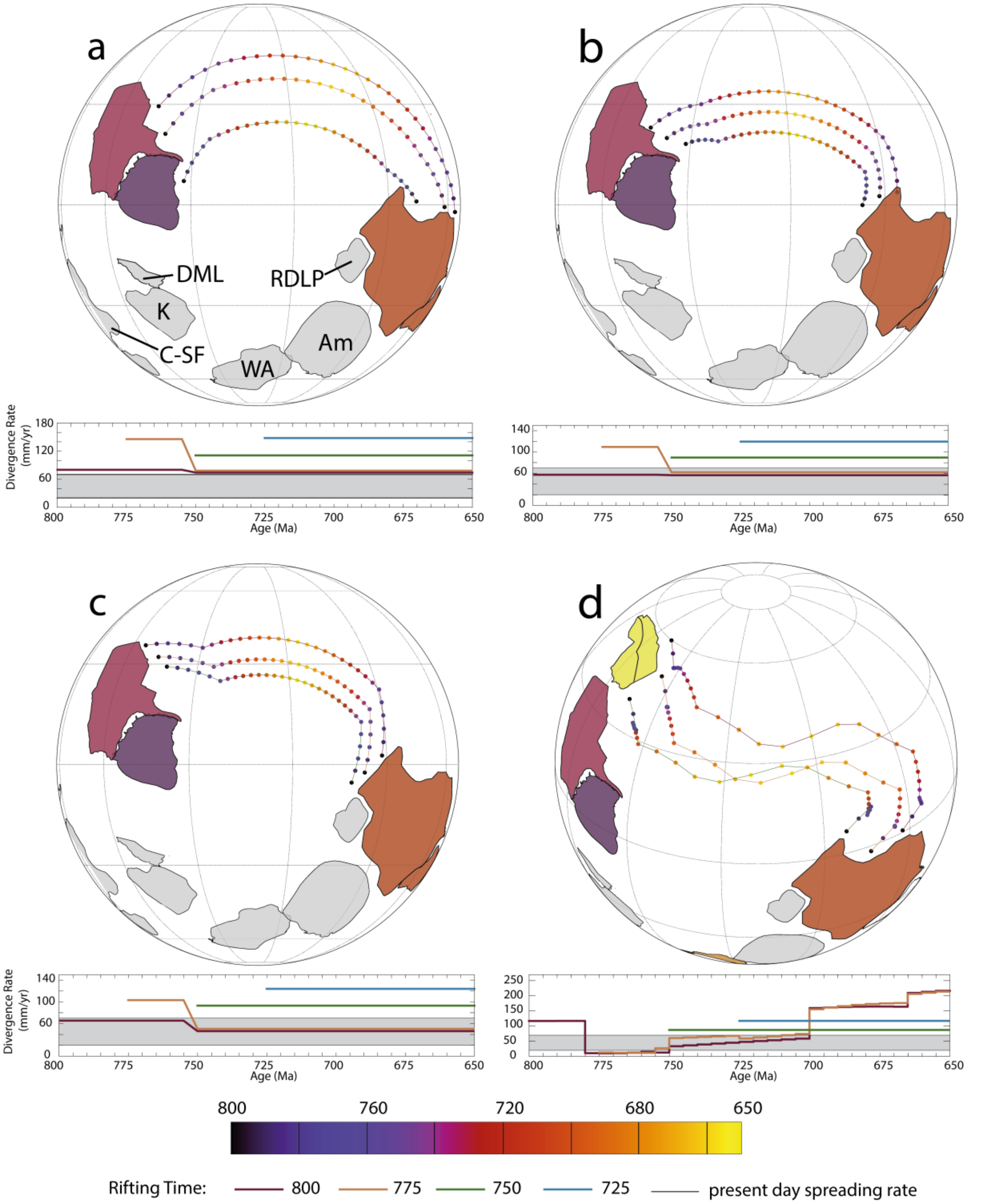

Figure 1. Results from kinematic tests at 800 Ma. (a) SWEAT configuration, (b) AUSWUS configuration, (c) AUSMEX configuration, (d) Missing-Link configuration. Am, Amazonia; C-SF, Congo-Sao Francisco; DML, Dronning Maud Land; K, Kalahari; RDLP, Rio de la Plata; WA, West Africa. Gray shaded area represents the range of typical modern day divergence rates. Flowlines are with rifting at 800 Ma, though they are similar for all rifting times due to the same starting configuration.

Deformation of the Songshugou ophiolite in the Qinling orogen

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The Qinling orogen forms the middle part of the China Central Orogenic Belt. Geochemical data and geochronology of ophiolites, magmatic rocks, as well as sedimentary reconstruction suggest the orogen was constructed by multiple convergent and subsequent collisional event between the North China and South China blocks. However, this model lacks deformation constraints consistent with subduction/collision. The Songshugou ophiolite outcropped to the north of the Shangdan suture zone represents fragments of oceanic crust and upper mantle. Previous works have revealed that the ophiolite was formed at an ocean ridge and then emplaced in the northern Qinling belt. Hence, deformation of the ophiolite would provide constraints for the rifting and subduction processes.

The ophiolite consists chiefly of metamorphosed mafic and ultramafic rocks. The ultramafic rocks contain coarse dunite, dunitic mylonite and harzburgite, with minor diopsidite veins. The mafic rocks are mainly amphibolite, garnet amphibolite and amphibole schist, which are considered to be eclogite facies and retrograde metamorphosed oceanic crust. Amphibole grains in the mafic rocks exhibit a strong shape-preferred orientation parallel to the foliation, which is also parallel to the lithologic contacts between mafic and ultramafic rocks.

Electron backscattered diffraction (EBSD) analyses show strong olivine crystallographic preferred orientations (CPO) in dunite including A-, B-, and C-types formed by (010)[100], (010)[001] and (100)[001] dislocation slip systems, respectively. A-type CPO suggests high temperature plastic deformation in the upper mantle. In comparison, B-type may be restricted to regions with significantly high water content and high differential stress, and C-type may also be formed in wet condition with lower differential stress. Additionally, the dunite evolved into amphibolite facies metamorphism with mineral assemblages of olivine + talc + anthophyllite. Assuming a pressure of 1.5 GPa, which corresponds to equilibration in the spinel stability field, application of the olivine-spinel thermometer (Ballhaus et al., 1991) suggests temperature of 622 ± 22 °C.

Amphibole schists display well-developed amphibole CPO with [100], [010] and [001] axes concentrate parallel to Z-, Y- and X-directions, respectively. The strong CPO of amphiboles could be interpreted as anisotropic growth and passive rigid-body rotation under various different stresses rather than results of dislocation creep. The Hbl + Pl thermometer (Holland and Blundy, 1994) constrains the equilibrium temperature to be 640 ± 34 °C for the amphibolite facies metamorphism.

Zircons in light-color from the amphibolite with Th/U<0.1 and depletion of HREE yield a U-Pb age of 504 ± 10 Ma, representing the metamorphic age of eclogite. In comparison, the zircons in dark-color from amphibolite showing flat HREE patterns and negative abnormal of Eu give a U-Pb age of 489 ± 5.2 Ma, constraining the time of retrograde metamorphism of eclogite.

Together with field investigation and regional geology, our new data propose that the A-type olivine CPO was formed in oceanic upper mantle with the spreading of the Shangdan Ocean before ca. 514 Ma. At ca. 504 Ma, the deep subduction of oceanic lithosphere endured eclogite facies metamorphism and induced B-type olivine CPO. Up to ca. 489 Ma, obduction of the fragments of metamorphosed oceanic lithosphere resulted in the C-type olivine CPO in dunite and amphibole CPO in the retrograded metamorphic eclogite.

Geochronologic constraints on formation and exhumation of the Foping migmatitic gneiss dome, Qinling Orogen, central China

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The Foping dome situated at the narrowest conjunction between the eastern Qinling and the western Qingling, occupies the northeastern Tibet Plateau foreland, and is a key region to understand the post-orogenic tectonic evolution of the Qinling and the Late Cenozoic eastward growth of the Tibet Plateau. This work addresses the exhumation pattern in the poorly understood Foping dome. Multi-method geochronology reveals the thermal history of the gneiss and granitoid rocks from their metamorphism/ emplacement to near-surface conditions. LA-ICP-MS U–Pb zircon dating suggests an identical age of gneiss metamorphism at ca. 215 Ma and granitoid emplacement at 216 Ma, respectively. Both ages confirm the occurrence of Late Triassic magmatism and high temperature metamorphism in the Foping dome. This interval correlates with the Triassic collision between the North China Block and South China Block. Biotite $^{40}Ar/^{39}Ar$ age of ca. 130 Ma, zircon fission-track ages of ca.100 Ma and zircon (U-Th)/He age of ca. 92 Ma record regional rapid cooling in Early Cretaceous with rate of 3^{o}C to 5 ^{o}C/ Myr. This data is interpreted to reflect intracontinental deformation from the Late Jurassic to Early Cretaceous of the Qinling Orogen after the Triassic collision. Apatite fission-track (AFT) and apatite (U–Th)/He (AHe) thermochronology and thermal-history modeling indicate cooling in two stages: (1) rapid cooling at 70–40 Ma with rate of 3.3^{o}C/ Myr is correlated with the Late Cretaceous–Early Cenozoic transtension in Eastern China, which is characterized by series dextral strike-slip fault zones within variably oriented extensional stress fields along the Dabie to Qinling; (2) very slow cooling post-Eocene (after ca.40 Ma), stagnation, which suggests insignificant exhumation, implying that the Foping dome was least effected by the Late Cenozoic exhumation and has not been or was little involved into the eastward growth of the eastern Tibetan Plateau.

Geochemical, Ar-Ar geochronological and Sr-Nd isotopic constraints on the origin of Late Mesozoic volcanic rocks from the West Qinling area in China

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A set of integrated geochemical and geochronological data for basalts from Duofutun and Hongqiang in the West Qinling orogenic belt (China) is carried out to constrain the characteristics of magma source and Late Mesozoic geodynamics of the region. Two basaltic samples from Duofutun have yielded $^{40}Ar/^{39}Ar$ ages of 112.0 ± 0.6 Ma and 111.5 ± 1.4 Ma, respectively.

All the analyzed samples are typical alkaline series volcanic rocks with low SiO_2 (44.98-48.20%), CaO (8.92-12.14%) and high MgO (7.25-12.19%) contents, and Cr and Ni concentrations. They show enrichment in light rare earth element (LREE), strong high field strength element (HFSE, e.g., Nb, Ta) and large ion lithophile element (LILE) enrichment. These geochemical features exhibit OIB-like trace element distribution patterns with insignificant Eu anomalies (1.00-1.10) and low $(^{87}Sr/^{86}Sr)_i$ ratios (0.702769-0.703919) and high $\varepsilon_{Nd}(t)$ values (6.01-10.10). All the samples can be further divided into two groups based on their geochemical results. Group 2 shows higher Al_2O_3 (14.05-16.48 wt.%), lower P_2O_5 (0.41-0.67 wt.%) contents, La/Yb (La/Yb <20) and LREE/HREE ratios relative to Group 1. Given the moderately depleted Sr-Nd isotopes, we infer that the Group 2 originated from deep asthenospheric mantle with delaminated lithospheric signatures. Group 1 are characterized by low Al_2O_3 (12.23-12.66 wt.%) and high TiO_2 (2.69-2.87 wt.%), P_2O_5(0.72-0.81 wt.%) contents, as well as the high La/Yb (La/Yb >20) and LREE/HREE ratios, and derived from the mantle south of Group 2 experiencing the high-pressure fractionation of garnet.

Together with the eruption of the andesitic-dacitic volcanic rocks with age of ~130 Ma, we suggest that petrogenesis of the early Cretaceous volcanic rocks in the West Qinling orogenic belt reflects delamination of thickened lithosphere resulting in asthenospheric upwelling.

THEME 4.

New developments in Paleogeographic reconstructions: Reconstruction software; data mining; and database development.

Coordinator: Prof. Bruce Eglington (University of Saskatchewan).

Achieving improved constraints for crustal evolution: the advantages of multiple, diverse datasets

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Understanding the evolution of the Earth's crust and its associated mineral deposits becomes increasingly difficult further back in time due to variable preservation, fewer constraints and greater uncertainty in all datasets available. Similar issues plague the development of plate reconstruction models to visually represent changing patterns in space and time.

Availability of multiple, diverse, digital datasets facilitates the development of models and understanding of crustal evolution processes by providing spatially constrained comparisons, so highlighting evidence which may be contradictory. Development of a number of structured databases for the IGCP 509 and 648 projects has provided a framework for capture of data that aid the development of improved models since all data can be located quantitatively in both time and space and may be exported in a repeatable, standardised format for processing with a consistent work process. Since most of the database systems are available online with web interfaces, the projects are also able to leverage compilation activity by many individuals.

Combination of geological, palaeomagnetic, geochronological and isotope geochemical data with ore deposit location data for geodynamically sensitive styles of mineralisation provide distinct patterns related to long, linear zones of activity, such as volcanic and accretionary arcs or collision zones, similar to the present-day Pacific ring of fire. Isotope geochemical data, no matter whether Sr, Nd, Pb or Hf indicate the extent of older crustal reworking, so assisting in the delineation of crustal blocks with similar protolith parentage. Several deposit styles, such as volcanogenic massive sulphides, porphyries, clastic Pb-Zn and orogenic gold reflect specific geodynamic settings or are more common at certain stages of crustal accretion, collision or rifting while others may relate to plume-driven igneous activity. In many cases the mineralisation styles either compliment other data or fill the gaps. Regional spatial coherence in metamorphic ages typically reflect collisional processes while closure temperature ages are indicative of later regional uplift and cooling. Detrital zircon and other mineral data provide useful information on the age and source of exposed, erodible, sources or of the reworking of pre-existing sedimentary units. Chemical variations in the detrital minerals, for instance Th/U ratios and rare earth element patterns and ratios in zircons, together with other isotope geochemical signatures may be linked to protolith domains. Combination of these with lithostratigraphic information and palaeocurrent information in allied databases developed for IGCP 509 and 648 provide additional constraints, as does information on the location, azimuth and age of large igneous province features such as dyke swarms. Lithostratigraphic information such as depositional environment for sediments or lithological association and inferred geodynamic setting for igneous and sedimentary units delineate patterns which need to be regionally consistent with associated plate motions. Raster datasets such as gravity, aeromagnetics and radiometrics further assist in the delineation of distinctive crustal blocks.

Since global geochronology for both igneous and metamorphic activity (see below) are consistent with long-term cyclic processes (repeating on ~500 and ~800 Ma periodicities), one can also add geometric constraints associated with the repeated formation and breakup of a series of supercontinents (Pangaea, Rodinia, Nuna, etc) to the process and predict older amalgamations, even though the geochronology record in older times is sparse.

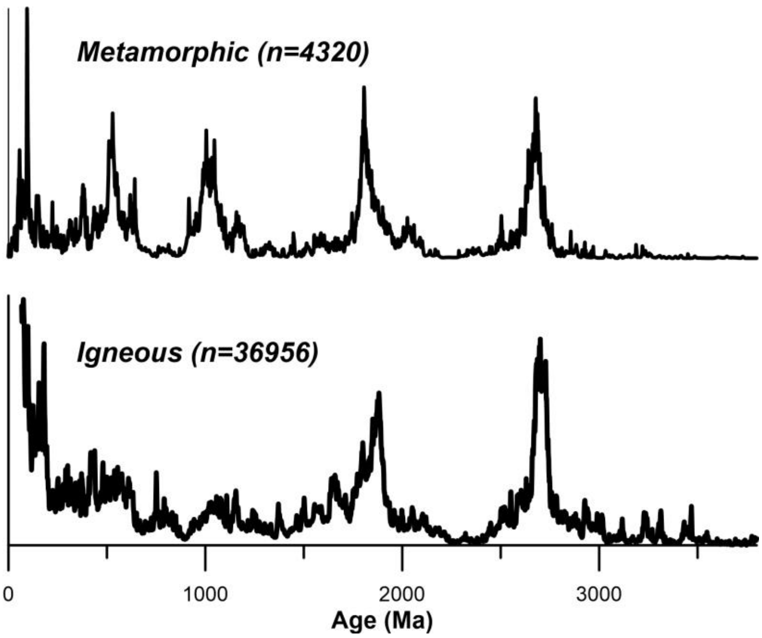

Figure 1. Probability distribution (Gaussian AND) for global igneous and metamorphic ages from the DateView database.

Combination of these multiple lines of evidence, together with other database systems under development (for instance lithogeochemistry), provide major constraints for improved understanding and definition of changes to the amalgamation and rifting of the Earth’s crust and lithosphere through time. Representation of activity in its palaeocontext allows the human brain to detect patterns and thus better understand past processes so as to predict the location of mineralised districts for exploration targeting.

Continuous quantitative model of global paleogeography through 1.8 billion years

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Global paleogeographic changes via plate tectonics have been quantified in continuous models through Phanerozoic time, or the last ca. 540 million years. Previous efforts to constrain Precambrian continental motions have been qualitative in nature (Rogers, 1996; Rogers and Santosh, 2002; Grenholm and Scherstén, 2015), or restricted in their scope: either in time (Li et al., 2008; Li et al., 2013; Pisarevsky et al., 2014; Pehrsson et al., 2016) or in a limited number of cratonic blocks (Pesonen et al., 2003). Here we present a continuous quantitative model, integrating tectonostratigraphic and paleomagnetic data, of comprehensive global paleogeography from present time back to 1.8 billion years ago.

Although many Precambrian paleogeographers restrict their models and discussions to major cratons, about 15-20 in number through the intervals of the Rodinia and Nuna supercontinents, we adopt a different approach that utilizes the entire extant geological record from hundreds of continental terranes defined by potential-field geophysical boundaries and an extensive geochronological/stratigraphic database (Eglington et al., 2009, 2013; Pehrsson et al., 2016). Our terranes are “born” at ages coincident with the earliest robust geochronological records inside their polygonal areas. To define the polygonal boundaries, we draw from both traditional tectonic definitions and magnetic/gravity datasets.

Our Phanerozoic model generally conforms to existing models, honoring seafloor spreading data from the past 200 million years as well as constraints from quality-filtered paleomagnetic databases (e.g., Torsvik et al., 2012). East Asian blocks present a special challenge, even in Mesozoic time, as they are bounded by subduction zones and hence cannot be linked via the global plate circuit. Nonetheless, we follow earlier compilations in restoring most East Asian blocks to the northern margin of Gondwana in Paleozoic time, with various adjustments to honor paleomagnetic data and stratigraphic linkages.

Our pre-Mesozoic model follows the orthoversion concept of Mitchell et al. (2012) to define paleolongitude according to large apparent polar wander (APW) swings interpreted as true polar wander (TPW) episodes around a consistent equatorial axis at 100°E longitude. In so doing, we ascribe the largest-amplitude swings of Gondwana across the southern polar regions to Cambrian-Devonian TPW episodes. Such swings have been shown to coincide with migrating ice centers across the semi-supercontinent (Caputo and Crowell, 1985; Evans, 2003), suggesting that they are not merely artifacts of an unusually behaving geodynamo. An earlier set of inferred TPW rotations, mainly through 1.1-0.9 Ga, is assumed to occur around an equatorial axis at 190°E, also in accordance with a Nuna-Rodinia transition via orthoversion.

The Ediacaran Period remains exceptional in its complexity, and no model is able to honor all paleomagnetic data of apparently high quality with uniformitarian rates of motion. Large, oscillatory APW swings observed in both the Laurentian and Australian records may be extremely rapid forerunners of the Paleozoic TPW events, in which case paleolongitude may be similarly constrained about the 100°E post-Rodinia axis. Alternatively, the rapid APW may instead be explained as an unusual form of geomagnetic paleosecular variation (Halls et al., 2015) or other strange phenomenon of the Ediacaran geodynamo (see Abrajevitch and Van der Voo, 2010). In any case, our model is able to migrate kinematically, albeit awkwardly, from Cambrian time back to the more sure-footed mid-Neoproterozoic Rodinia interval.

Our Rodinia model employs the modified "missing-link" of Tarim craton lying between Australia and Laurentia (Wen et al., 2016), the "right-way-up" model of Baltica (Cawood and Pisarevsky, 2006; Evans, 2009), and the long-lived, tight Siberia connection adjacent to northern Laurentia (Ernst et al., 2016; Evans et al., 2016a). West Africa, Amazonia, Plata, and São Francisco (SF)/Congo are placed in typical positions opposite the Grenville margin of Laurentia, despite lacking high-quality paleomagnetic data other than the new 0.92 Ga pole from SF (Evans et al., 2016b). Kalahari is shown to collide with southern Laurentia after converging from a distant location at 1.11 Ga with the Namaqua-Natal belt at the leading edge of its motion (Swanson-Hysell et al., 2015; Kasbohm et al., 2016).

Our model of Nuna essentially follows that of Pehrsson et al. (2016), modified to accommodate recent 1.5 Ga paleomagnetic data from SF/Congo (Salminen et al., 2016). Although the Pehrsson et al. (2016) analysis extended back to 2.1 Ga, our integrated model stops at 1.8 Ga; new paleomagnetic data from the preceding interval (e.g., Klein et al., 2016; Lubnina et al., 2016; Semami et al., 2016) will require integration into a modified kinematics of that time period. Whether the pre-Nuna era included an earlier Kenorland supercontinent (Gumsley et al., 2017) or merely continent-sized supercratons (Bleeker, 2003) represents a frontier of paleogeographic research.

In our model, Precambrian continental motions are generally consistent in both rate and style to those of the post-Pangea era, after subtracting the effects of TPW that occurred in punctuated episodes as rapid as ~50 cm/yr (but usually much more modest). Aside from Cryogenian panglacial ("Snowball Earth") climate states, the model generates paleolatitudes of paleoclimate indicators that are broadly consistent with those expected from modern Köppen zones.

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Linking plate motions to geodynamic models in deep time – a review of current obstacles and potential solutions

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Coupled plate tectonic–geodynamic models for post-Pangea times have been developed for about 2 decades, and are relatively mature. They have led to a good and generally agreed-upon understanding that the large-scale mantle structure observed today, using seismic tomography, is the consequence of the post-Pangea subduction history, leading to a degree-2 mantle structure of two large upwellings, associated with large low shear velocity provinces (LLSVPs) in areas away from subduction in the last 250-200 million years. Several generations of somewhat differently derived absolute plate motion models all yield subduction zone locations through time that are consistent with this result. Tectonic models with continuously evolving plate boundaries used as surface boundary conditions for these geodynamic models have some particular characteristics. Absolute continental plate speeds are largely limited to less than 10 cm/yr, with rare exceptions, and it has been shown that both the percentage of Proterozoic regions as well as cratonic area as part of any continent impedes plate motions, i.e. large, old continents with substantial lithospheric keels do not move very fast. Equivalently, the migration speed of subduction zones is generally characterised by slow retreat between 0-3 cm/yr, ranging from relatively fast trench retreat of 5cm/yr to slow trench advance of up to 2 cm/yr. Global average continental RMS speeds in these models are below 5 cm/yr in the last 200 Ma, with a mean around 3 cm/yr. The only published plate model with evolving plate boundary topologies that goes back into the Paleozoic to 410 Ma displays very different characteristics. Global continental RMS speeds rise to over 14 cm/yr in the mid-Paleozoic (Devonian) while trench retreat reaches values of over 10 cm/yr and trench advance reaches peaks of ~ 10cm/yr. None of these values are considered geodynamically reasonable, and are far outside the range of values characteristic of the behaviour of continents and plate boundaries for the last 200 million years. The mobility of subduction zones in this reconstruction results in subduction zones crossing over the present-day location of LLSVPs. The "geodynamic unreasonableness" of this model is the consequence of disregarding maximum plate velocities and subduction zone mobility in deriving absolute plate motion and plate boundary histories in this model, making it unsuitable for geodynamic models with imposed plate motions. In addition, if the long-term stability of LLSVPs is used to orient the positions of plates in such models, independently testing the idea of LLSVP stability becomes impossible. Models with imposed plate motions are currently the most practical way to test contrasting models for the long-term evolution of the mantle, and plate-mantle interaction, informed by the geological record. In order to apply these well-established techniques to model the Phanerozoic and beyond, absolute plate models need to be designed that do not depend on assuming LLSVP stability and abide by some "rules of geodynamics" informed by post-Pangea plate tectonics, including limits on subduction zone migration speed, RMS speeds of continents and/or net rotation of the plates. We outline how such models can be constructed and used for studying the long-term evolution of the plate-mantle system.

A Palaeoproterozoic gap in the global geologic record

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The hypothesis of a Palaeoproterozoic tectonic shutdown occurring ca. 2.3-2.2 billion years ago has yet to be definitively tested. Here we present an appraisal of the global geologic and magmatic record that argues for not only a shutdown of continental arc magmatism, but also for a ~50-million-year-long gap in the geologic record. The geologic gap is followed by a flare-up of juvenile magmatism, the intensity of which likely reflects the release of pent up heat energy accumulated heat in the mantle during the shutdown. The post-gap flare-up of juvenile magmatism is distinguished from earlier such events magmatic extraction from the mantle may have yielded the critical crustal area to form Earth's first hemispheric supercontinent, Nuna. Additionally, the rise and fall of atmospheric oxygen, with alternating global glaciation immediately preceded and continued during the shutdown. The subsequent juvenile magmatic flare-up led to the first Palaeoproterozoican oxygen "overshoot" and disruption of the carbon cycle. These events set the stage not only for, and may have been facilitated by the stalling and starting of the rock cycle presented here the transition to a modern realm of plate tectonics and the supercontinent cycle, but also led to the final oxygenation of the atmosphere and equilibration of the carbon cycle.

A computational framework to optimise global absolute plate motion models

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Plate tectonic reconstructions are essential to understand Earth's paleogeography and the configuration and behaviour of continents through time on both global and regional scales. Tectonic reconstructions are relatively well constrained back to ~200 Ma via the seafloor spreading record, but constraining motions for older times represents a significant challenge. Typically, models derived from seafloor spreading histories constrain only the relative motions between plates, representing the "how" of plate motion evolution, which for example could include how fast two plates separated by rifts or a mid-ocean ridge move apart, or how plates converge at subduction zones. This, however, represents only half the information, as these data contain limited information of the absolute location of plates on the Earth's surface, the "where" of plate motion evolution. Due to this limitation, relative plate motion (RPM) models are often coupled with absolute plate motion (APM) models to provide the missing information and insight into the relationship that exists between surface motions and the underlying mantle. Traditionally, APM models are derived from a single 'absolute' constraint including (among others) palaeomagnetic data, hotspot trails, and seismic tomography. APM models derived in this way produce a wide variety of predictions, but are susceptible to biasing the constraining quantity through unintentional over-fitting. Significant issues exist in solving the problem of APM, including data variability and consistency, data and model uncertainty, and the validity of the included assumptions. To address this, we present a numerical approach combining constraints from multiple, diverse sources into a suite of unified geodynamically reasonable models of absolute plate motions from 220 – 0 Ma. Models are constrained using any combination and weighting of hotspot data (for times younger than 80 Ma), net lithospheric rotation minimisation, and optimal trench migration behaviours. The method employs an inverse approach to iteratively optimise the motion path of a given reference plate through time to converge on the solution that most closely conforms to selected constraint parameters. The method also provides a new way to more efficiently and accurately evaluate various kinematic, geological, and geodynamic properties of a given tectonic reconstruction, providing a way forward towards quantifying uncertainties in plate models.

Open-source tools for the study of deep time plate tectonic reconstructions: a GPlates update

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A fundamental consideration for the study Earth through deep time is that the configurations of the continents, tectonic plates, and plate boundaries is continuously changing. Within a diverse range of fields including geodynamics, paleoclimate, and paleobiology, the importance of considering geodata in their reconstructed context is widely recognised. For studies addressing pre-Pangean cycles of supercontinent aggregation and dispersal, uncertainties in plate configurations are significant and the relative sparsity of available data allow for multiple, starkly contrasting models. Computer-based tools for building and visualising these models, and in particular the open-source software GPlates, form the foundation for discussion and iterative improvement of reconstructions. Here, we present an update on developments within GPlates family of plate tectonic tools.

GPlates has become widely known as a paleo-geographic information system for geoscientists to combine a wide variety of geodata and examine them within tectonic reconstructions through time. The most recent version, GPlates 2.0, contains significant updates over previous incarnations. A major new advance is the ability for users to define deformation zones - regions combining extension, compression and shearing that accommodate the relative motion between rigid blocks that follow more traditional concepts of Euler pole rotations. Users can explore how strain rates, stretching/shortening factors and crustal thickness evolve through space and time within deformation regions, and interactively update the kinematics associated with deformation to see how these parameters are influenced by alternative scenarios. Where datasets described by geometries (points, lines or polygons) fall within deformation regions, the deformation can be applied to these geometries. Together, these tools form the basis for building reconstructions that quantitatively describe the cycles of rifting, mountain building, and intra-continental shearing proposed to accompany supercontinent assembly and dispersal.

The availability of powerful tools such as GPlates brings new challenges – we want to learn something about the key associations between reconstructed plate motions and the geological record, but the high-dimensional parameter space is hard for a human being to visually comprehend and quantify these associations. To achieve true spatio-temporal data-mining, new tools are needed. To this end, we have developed a new branch of the GPlates ecosystem - a Python-based tool for geotectonic analysis. In contrast to existing GPlates tools that are built around a graphical user interface (GUI) and interactive visualisation, *pyGPlates* offers a programming interface for the automation of quantitative plate tectonic analysis of arbitrary complexity. The vast array of open-source Python-based tools for data-mining, statistics and machine learning can now be linked to *pyGPlates*, allowing spatial data to be seamlessly analysed in space and geological "deep time", and with the ability to spread large computations across multiple processors. Basic applications include data querying, filtering, and reconstruction (including spatial proximity of reconstructed geometries), and file-format conversions. For the innovative study of plate kinematics, *pyGPlates* has been used to explore the relationships between absolute plate motions, subduction zone kinematics, and mid-ocean ridge migration and orientation through deep time; to investigate the systematics of continental rift velocity evolution during Pangea breakup; and to make connections between kinematics of the Andean subduction zone and ore deposit formation. To support numerical modelling community, *pyGPlates* facilitates the connection between tectonic surface boundary conditions contained within plate tectonic reconstructions (plate boundary configurations and plate velocities) and simulations such as thermo-mechanical models of lithospheric deformation and mantle convection. To support the development of web-based applications that can serve the wider geoscience community, we will demonstrate how *pyGPlates* can be combined with other open-source tools to serve alternative reconstructions together with a diverse array of reconstructed data sets in a self-consistent framework.

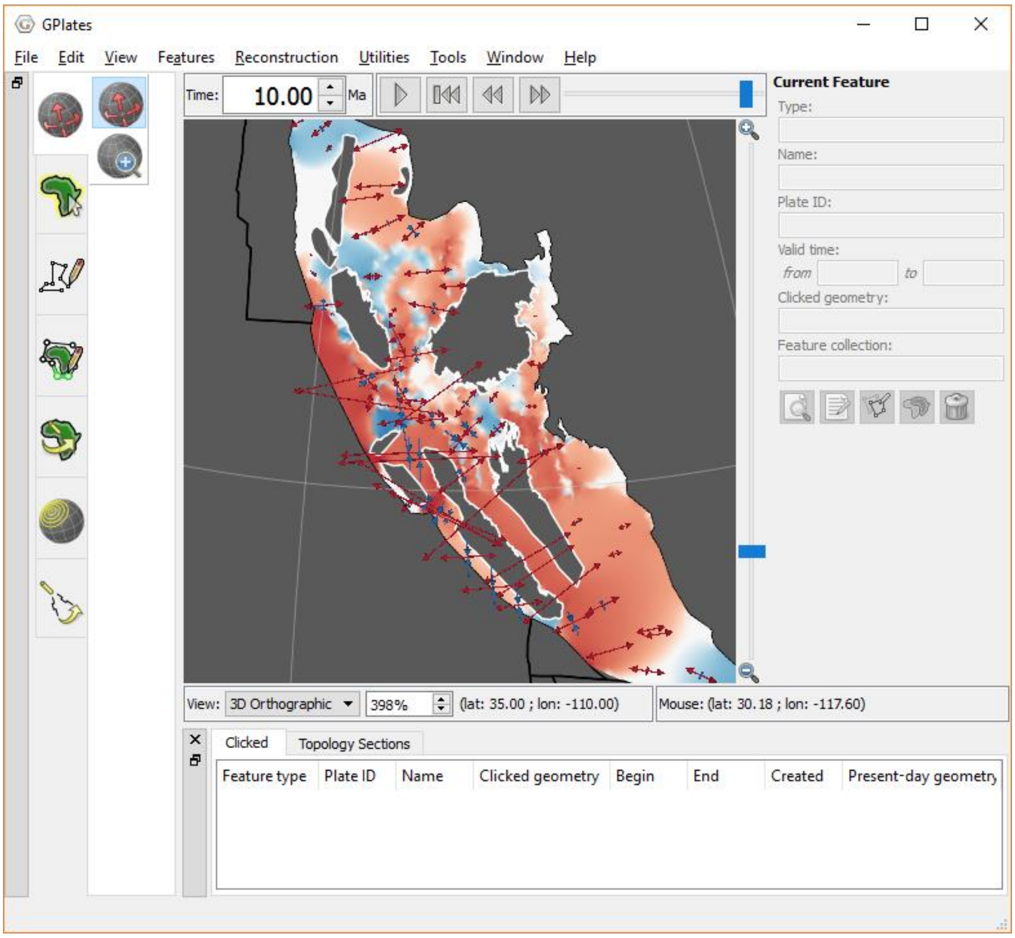

Figure 1: A screenshot of GPlates 2.0, showing interpolated strain rates and evolving strain markers within a deforming region that describes extension in the Basin and Range, western United States.

Finite-Element analysis for ensuring the kinematic pattern of fault-related fold in Wei Bei Area base on Flac 3D

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Based on the 2D seismic data, the geophysical data and the ground geological survey, research on geometrical characteristics of fault-related folds in Weibei area and analysis of kinematic evolution model are conducted through seismic data interpretation technology, balanced cross-section techniques and triangle shear simulation software. Summarizing above research results and utilizing the Finite-Element simulation software (Flac 3D), the faults and strata of original seismic section 08xy-2 were digitized using unique software codes on the condition of the application of Cullen-Moore inner model (mainly setting three layers: the ductile basement strata, the brittle sedimentary strata and the overlaying strata). Thereby, a simple and ideal mathematical model has been established and the deformation process of cross-section 08xy-2 can be easily observed after experienced 20000 steps operating. The final deformation shape of the model indicates a high similarity compared with the real geological body. The simulation results also demonstrate that the fault-related folds in the study area mainly formed at Yanshan epoch and affirm that the most suitable kinetic evolution model for large-scale fault-related folds is a triangle shear model accompanied with basement involvement. Through 2D average stress map and plastic zone distribution map at the X-X axis, the rock formation-failure zones which can predict high-quality reservoirs can be easily identified.

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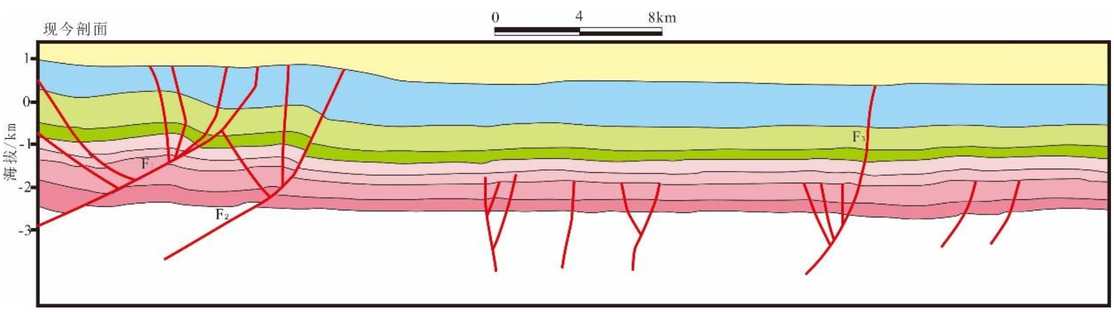

Figure 1 Seismic section interpretation result on 08xy-2

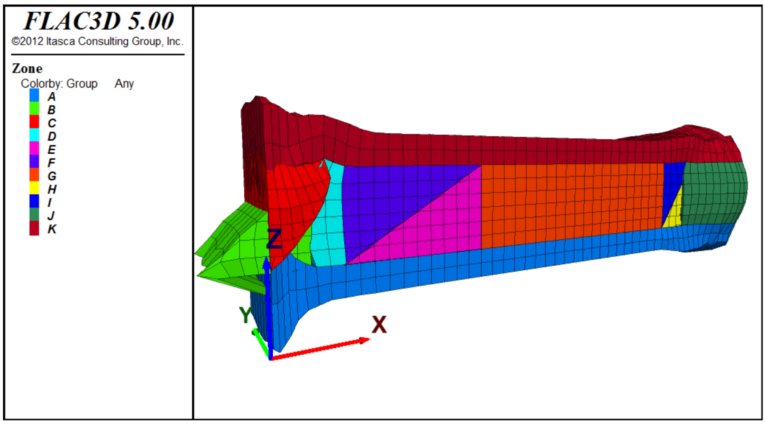

Figure 2 The result of mathematical model after deforming

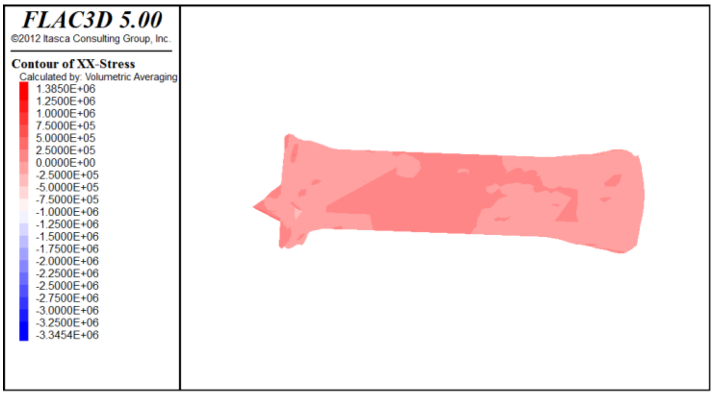

Figure 3 Contour of X-X stress

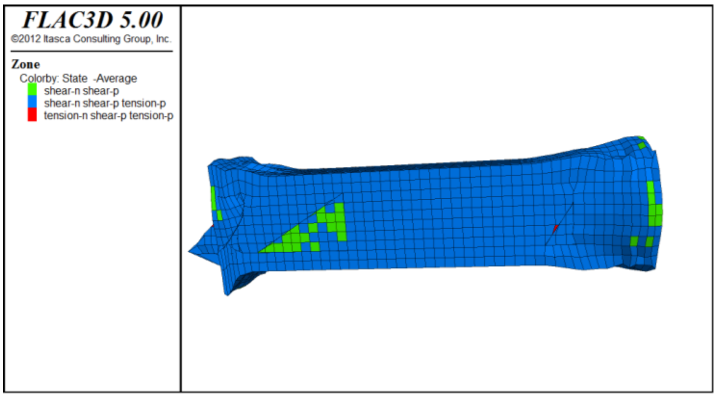

Figure 4 Contour of plastic zone

THEME 5.

Supercontinent cycles and Geodynamics.

Coordinators:
Prof. Zheng Xiang Li (Curtin University)

Prof. Louis Moresi (University of Melbourne)

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Geodynamics of plate motions and long-term Earth evolution

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A systems-level understanding of Earth's evolution requires a dynamically consistent, v. 2.0 kind of model of plate tectonics that integrates the supercontinental cycle and other complexities of thermo-chemical planetary convection including fractionation and volatile exchange. In particular, Paleozoic plate reconstructions should at least be statistically consistent with geodynamic constraints, and Cenozoic tectonics should in principle be firmly guided by force balance and dissipation minimization approaches. Yet, even plate driving forces for the present-day configuration remain debated. Here, I review a range of global and regional modeling efforts that can guide our understanding of likely and unlikely Plate Tectonics 2.0 scenarios. In particular, I highlight a few examples as to how uncertainties in geodynamic models can be reduced in data-rich environments, and where remaining uncertainties arise. I also discuss a number of possible future ways of enhancing the range of geophysical and geological constraints available for such integrative models, and how "fundamental" geodynamic modeling might be combined with models that have regional specificity.

Billion year, mantle convection cycles through Earth history

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Billion year cycles in Earth evolution, operating at approximately twice the temporal scale of the supercontinental cycle, are evident from a global compilation of radiogenic(*) Hf and Sr isotopic data. These cycles show harmonic variations over the last 2.5 billion years from peak mantle inputs (+εHf) at ~1.5 Ga and the present-day (0 Ga), and peak crustal inputs (-εHf) at ~2.0 Ga and 0.55 Ga. We suggest this billion-year cyclicity reflects the alternating presence and absence of a hemispheric subduction girdle, which is presently represented by the circum-Pacific subduction system, and geologically by the Phanerozoic circumPacific accretionary orogens. The girdle's presence is recorded by isotopic shifts to +εHf, reflecting a degree-2 convective mantle structure. Isotopic shifts to -εHf values record the demise of degree-2, and establishment of degree-1 convection, characterised by a single downwelling zone on the planet, and geologically expressed as the pan-Arican orogens of Gondwana. This billion-year alternation has resulted in different types of supercontinent formation; by extroversion during closure of Pacific-type oceans (degree-2) forming Rodinia, and introversion during closure of Tethyan-type oceans (degree 1) forming Nuna and Gondwana/Pangea. Archean cratons were shielded from orogenesis by dominantly accretionary tectonics during degree-2 convection that dominated the Paleoproterozoic and Mesoproterozoic, but were reworked during degree-1 convection in the Neoproterozoic, culminating with the marked excursion to -εHf values at 600-550 Ma as Rodinia was turned inside out. Earth history since 2.5 Ga can be explained by cyclic transitions between degree-1 and -2 mantle convection, which requires harmonic waxing and waning of superswell (plume) activity within the Earth's mantle at billion year duration, relegating the supercontinental cycle to second-order hierarchy.

Does the Earth have a fundamental frequency?

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The ~500 million-year-long supercontinent cycle of episodic assembly and breakup of continental lithosphere is commonly considered the longest period variation to affect mantle convection. Here we demonstrate that multiple records exhibit a ~1 billion-year-long periodicity that would seem to have been active throughout Earth history.

The detrital zircon record is one of the prominent geological archives that displays cyclicity and is typically interpreted as an expression of the supercontinent cycle[1]. Strictly it is a record of felsic magmatism, as it is felsic magmas that commonly saturate in zircon[2]. Consequently, zircons record the combination of both arc magmatism along with orogenic events that result in crustal anatexis and the production of granitic melts. However, the interpretation of the zircon record as solely reflecting the magnitude of felsic magmatism is complicated due to tectonic environments that may lead to preferential preservation, such as during continental amalgamation[3].

Regardless of whether zircons reflect crustal production, preservation or some combination of the two, the detrital zircon record[4] provides a record of episodic crustal processes. However, spectral analysis of this mineralogical expression of crustal processes reveals that the ~500 million-year-long supercontinent cycle is a comparatively recent feature, an older and perhaps more fundamental ~1-billion-year-long cycle is also present (Fig. 1a).

To further investigate cyclicity within the earth system we conducted spectral analysis on other geological records, including a compilation of ~500,000 igneous compositions. Focussing on incompatible elements (Fig. 1b) we again find long wavelength cyclicity on the order of ~1 Gyr and surprisingly no evidence for a ~500 Myr supercontinent cycle.

The Earth's heat engine is dominated by the mantle, in which planetary cooling is achieved mainly through mantle convection. Current research estimates that ~50% of this heat is produced from radioactive decay in Earth's mantle and a further ~50% from primordial sources[5]. We speculate that the ~1 billion-year cycle is due to the boundary conditions in place since planetary differentiation and the initiation of this planetary heat engine. The comparatively recent supercontinent cycle, while affecting mantle convective circulation, seems to have had a relatively minor effect on this heat engine and the cycling of geochemical compositions.

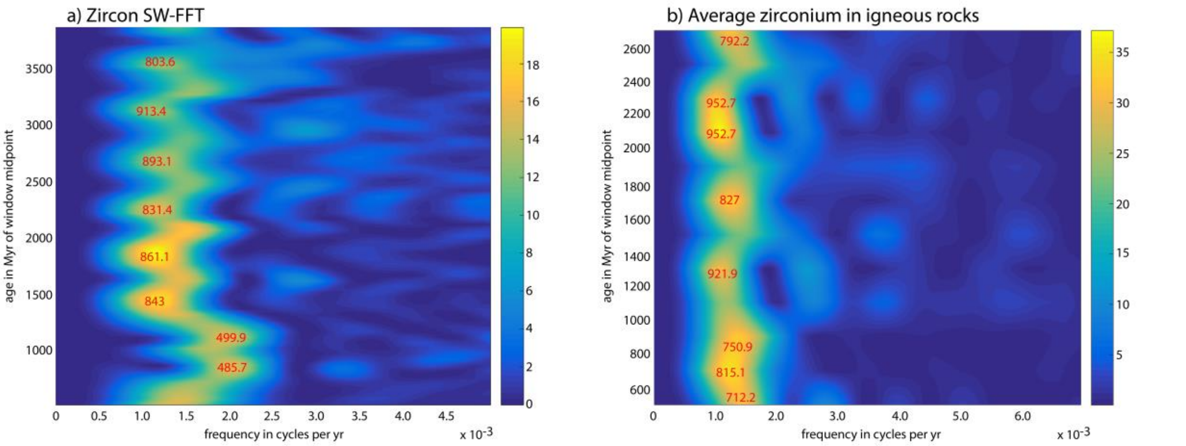

Figure 1. (a) Sliding window fast fourier transform (SW-FFT) of the detrital zircon record[4] revealing both a short (~500 Myr), and long (ave. = 857 Myr) cyclicity. (b) SW-FFT of the average concentration of Zr in igneous rocks which exhibit a single stable long wavelength cyclicity (ave. = 840 Myr).

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A geodynamic model for the Paleoproterozoic Birimian Orogen of the southern West African Craton

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The Birimian Orogen of the West African Craton (WAC) is an extensive accretionary-collisional orogenic system composed primarily of juvenile crust, which formed during an orogenic cycle between ca. 2260-2050 Ma[1]. In the WAC, the Birimian Orogen is exposed mainly in the northern Reguibat and the southern Man-Leo shields, where the Birimian crust is juxtaposed with Archean cratons (fig. 1). This work focuses on the Man-Leo shield, which has been the subject of multiple detailed structural, geochronological and geochemical studies. However, these have in many cases highlighted seemingly contrasting histories between different domains. There is therefore a need to develop an updated regional geodynamic model that can provide a framework for understanding how these domains relate to each other. The purpose of this presentation is to present work in progress on a geodynamic model for the Birimian Orogen in the Man-Leo Shield.

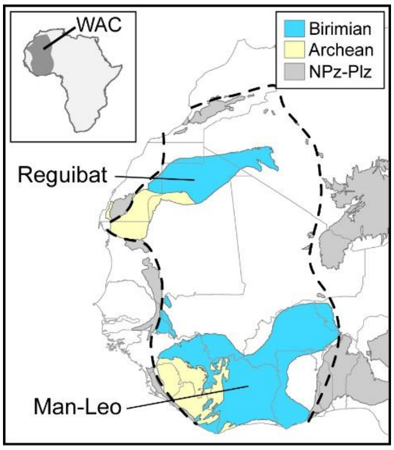

Figure 1.

The Birimian crust in the Man-Leo Shield is comprised of an assortment of volcanic, volcanoclastic, and siliciclastic sequences, multiple suites of intrusives, gneiss-migmatite domains and mafic-ultramafic complexes[1,2,4,5]. These have been variably affected by polycyclic deformation involving folding, shearing and thrusting, and subjected to regional greenschist-amphibolite facies metamorphism. The geodynamic evolution of the Birimian Orogen in the Man-Leo Shield can be broadly divided into an early accretionary phase that transitioned into a regional collisional phase. The accretionary phase lasted between ca. 2260-2150 Ma, during which early generations of volcanic-dominated supracrustal sequences and intrusive suites were formed. This is generally considered to have occurred within volcanic arc systems, although a contribution from oceanic plateaus has also been evoked by some authors. The collisional phase lasted between ca. 2150-2050 Ma and is referred to broadly as the Eburnean Orogeny, which appear to have been diachronous across the shield with tectonic and magmatic activity transitioning from east to west[2]. The orogeny is characterized by crustal shortening through folding and thrusting, strike-slip displacement along faults and shear zones, opening and subsequent closure of volcano-sedimentary and siliciclastic basins, and emplacement of multiple suites of intrusives. This was also a significant period of orogenic gold mineralization within the Birimian Orogen.

The model focuses on the evolution of the Man-Leo Shield during the Eburnean Orogeny and the displacement of crustal units along major shear zones and faults that were active during this time, with the aim to reconstruct their movements and restore their pre-Eburnean positions. A simplified version of the model is shown in figure 2. On a first order, the geodynamic model for the Man-Leo Shield can be divided into a western and an eastern domain that are separated by the dextral NE-SW oriented Grenville-Ferkéssédougou-Bobodialasso (GFB) shear zone[1,2] (fig. 2a). The western domain is characterized by the contact between the Archean craton and the Birimian crust, which is marked by the sinistral Sassandra (Sa) shear zone[3] (fig. 2a). This fault is in turn linked to the north with roughly N-S trending shear zones[2]. The overall geometry and kinematics of the shear zones in the western domain suggests a setting in which the Archean craton acted as an eastwards-directed indenter, leading to northwards expulsion of Birimian crustal blocks[2] (fig. 2a-c). However, the degree of displacement of the Birimian units along shear zones during indentation is poorly constrained, and the positions of the blocks depicted in figure 2 remain an approximation.

The eastern domain is defined by the NE-SW oriented GFB[1], Sefwi-Sunyani-Comoé (SSC)[3] and Bolé Nangodi (BN) dextral shear zones[2,4], which together bound a series of N-S oriented sinistral shear zones[2] (fig. 2a). The overall kinematics indicate that the eastern domain was subjected to west-directed compression against its central section (fig. 2a-c). Transtension within the crust during early collision would have allowed the basins to open, whereas closure and inversion resulted from continued convergence. Although the inferred indenter is not exposed, its location is indicated by the contrasting evolution of the Birimian crust in the SE and NE Man-Leo Shield, respectively. The former is characterized by NE-SW oriented basins, which are proposed here to have opened in response to N-S extension during west-directed compression, and subsequently been rotated into their current position during ongoing convergence (fig. 2a-c). Meanwhile, sinistral displacement along the Markoye (Ma) shear zone[5] and NE-SW dextral displacement along Bole Nangodi[2,4] is compatible with lateral escape of this area to the NE.

Restoring the crustal units defined by the major shear zones suggest a setting in which the Birimian crust now exposed in the Man-Leo Shield formed an elongate assemblage that was squeezed in a relative sense from the west and east (fig. 2c). It is proposed that the paleogeographic environment in

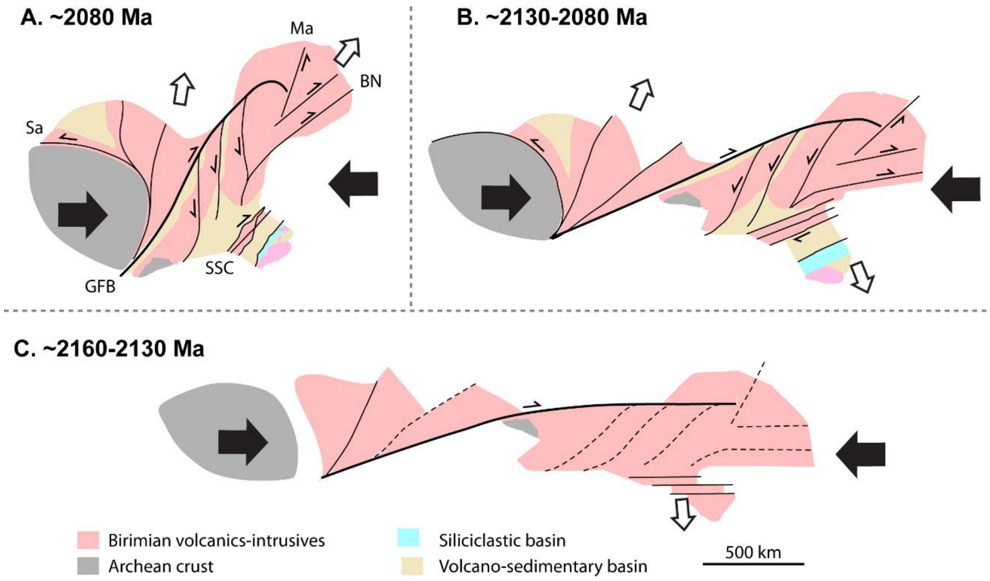

Figure 2.

which this occurred was similar to present day SE Asia and the West Pacific, where the Birimian crust assumed a position comparable to the Philippine Archipelago[6] between mainland Asia and the converging Australian plate and with the GFB shear zone in a similar position to the Philippine fault. Such a setting would be compatible with the formation of the Birmian crust in volcanic arc systems, and also carry the potential for significant input of isotopically juvenile material.

The model represent work in progress and many uncertainties remain, not least concerning the precise timing and extent of displacement along faults and shear zones, as well as the effect of volume change on the Birimian crust during deformation. However, the overall kinematics seem unlikely to change, since they are based on relatively well-constrained structural studies. Ultimately, the model presented here is an attempt to reconcile these first order movements, and provide a framework for more detailed future reconstructions.

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Decoding Earth's rhythm: Modulation of supercontinent cycles by longer superocean cycles

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The supercontinent cycle of episodic assembly and breakup of continental lithosphere is commonly considered the longest period variation to affect mantle convection. However, global zircon Hf isotopic signatures and seawater Sr isotope ratios suggest the existence of a cycle twice the duration of the supercontinent cycle. Here we demonstrate that superoceans surrounding supercontinents survive every second supercontinent cycle since at least 2 Ga, as supported by global paleogeographic history and time variation of passive margin and orogenic records that exhibit two periodic signals at 500-700 and ~1350 million years. We argue that supercontinents assemble alternatingly through dominantly extraversion (destruction of the Panthalassa-type superocean) after a more complete breakup, and dominantly introversion (survival of the superocean) after an incomplete breakup of the previous supercontinent, giving rise to the two harmonic supercycles. Interference of the two supercycles reflects an oscillatory mantle thermal state during supercontinent cycles.

Girdle Earth: The snowball Earth arc magmatism system

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Supercontinents may not all be created equal. Here we suggest a billion-year modulation of the supercontinent cycle where every other configuration resembles a great-circle "girdle" (Superia, Rodinia, etc.) instead of a small-circle "sickle" (Pangaea, Nuna, etc.). The geodynamic and geochemical consequences of the long-term alternation are profound. Due to true polar wander, the tectonic Euler pole of the sickle aligns with the rotational equator, dispersing the continents relatively uniformly in latitude; on the other hand, that of the girdle aligns with the spin axis, dispersing the continents along an equatorial girdle. Furthermore, due to the roughly orthogonal relationship between the equatorial girdle of continents and the meridional girdle of convective downwelling associated with degree-2 mantle flow, an exceptionally extensive, along-strike magmatic arc would have formed outboard of the continents in the form of dominantly ocean arcs instead of continental arcs, which is supported by igneous geochemistry. An increase in tropical continental area in the case of the girdle Earth ocean arc—increasing planetary albedo, reducing CO_2 emissions due to the dominance of ocean arcs, and consuming CO_2 through enhanced chemical weathering, particularly basaltic weathering of volcanic atolls and large igneous provinces emplaced before continental breakup—can account for both the presence of "snowball Earth" conditions during Palaeoproterozoic Superia and Neoproterozoic Rodinia and the absence thereof during Mesoproterozoic Nuna and Phanerozoic Pangaea. Accumulated volcanic CO_2 emissions during glaciation is traditionally invoked to trigger deglaciation; in our girdle model, the magmatic arc naturally evolves due to slab rollback, implying a shift during glaciation from oceanic to continental arc magmatism that can explain both glacial advance and termination, respectively.

Project 648
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Supercontinent Cycles & Global Geodynamics

The evolving nature of continental dynamics since the Archean

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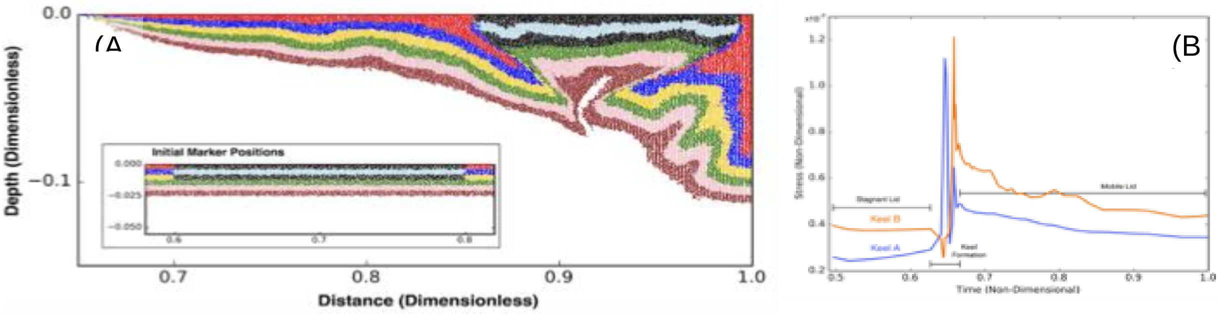
There are some counter-intuitive aspects to the cooling of a terrestrial planet that are particularly influential when it comes to understanding the Earth's global tectonic style over time. The stress that the convecting mantle can exert on the lithosphere is lower when the mantle is hotter because the effective viscosity is lower. As a result, it is expected that young, hot planets will have trouble sustaining plate tectonics and will instead be in a stagnant one-plate state with heat loss dominated by magmatism. A transition to plate tectonics becomes possible as the planet cools and mantle stresses increase. Recent work has demonstrated that a stagnant lid with the right combination of intrusive and extrusive heat-pipe magmatism, is potentially capable of satisfying the thermal and petrological constraints for the early Archean Earth. (e.g. Moore and Webb (2013), Rozel et al, (2017)). These models naturally become unstable with respect to mobile-lid convection models as the level of internal heat production decreases.

This immediately raises an interesting question: *how do we assemble cratonic lithosphere in the low-stress environment of the young Earth that is strong and resistant to tectonic recycling in the older Earth where much higher stresses should be available?*

A possible resolution of this puzzle is to understand whether the transition phase between stagnant lid and a mobile-lid or plate-tectonic style of convection is capable of building or assembling the cratonic lithosphere and not just destroying the stagnant lithosphere. The stresses during the collapse of the thick, stagnant lid can be significantly higher than the convective stresses in either the steady, stagnant lid or the mobile-lid convective regimes (figure frame B).



In the simple models shown in the figure (frame A), the collapsing stagnant lid produces an over-thickened, folded structure from an initially thin layer within the upper part of the stagnant lid that is strong enough to resist subsequent convective stresses. An anomalously strong region arbitrarily embedded within the stagnant lid can survive the lid collapse with very little deformation at the surface but with underthrusting and stacking of the lower crust and the mantle lithosphere.

We discuss these models and compare the deep lithospheric structure with that which occurs when growth is driven by lateral accretion. This builds upon previous studies by Cooper and Miller (2013) and Cooper et al (2016).

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THEME 6.

Supercontinent cycles and mineral systems.

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3D model of the major crustal boundaries of Australia: implications for mineral systems understanding

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For over 35 years, deep reflection seismic profiles have been acquired across Australia (Kennett *et al*., 2016) to better understand the crustal architecture and geodynamic evolution of key geological provinces and basins, and their resource potential. Major crustal-scale breaks have been interpreted in many of the profiles, and are often inferred to represent relict sutures between different crustal blocks. The widespread coverage of reflection seismic profiles has allowed construction of the 'Major Crustal Boundaries of Australia' dataset by using geological (e.g. outcrop geology, drill holes, geochronology, isotopes) and geophysical (e.g. gravity, aeromagnetic, magnetotelluric) data to map the plan form distribution of major crustal boundaries away from the reflection seismic profiles (Korsch and Doublier, 2016).

The continental-scale 3D model of the 'Major Crustal Boundaries of Australia' presented here (Doublier *et al.*, 2016; Fig. 1) is constructed utilising the planform interpretation by Korsch and Doublier (2016), and depths and geometry constraints from past deep reflection seismic profiles. Both the 2D and 3D datasets allow for a better understanding of the evolution and amalgamation of the Australian continent through time, from the Mesoarchean to the Cenozoic. They also provide a powerful reference frame for integrated studies focused on crustal and lithospheric architecture utilising datasets such as isotopic maps (e.g. Sm-Nd; Champion, 2013) and seismic velocity models (e.g. P- and S-wave velocity; Kennett and Salmon, 2012).

From a mineral systems point of view, these first order structures represent major architectural breaks that provide pathways for mineralising fluids and/or melts into the middle and upper crust and, in recent years, the distributions of a range of different types of mineral deposits have been interpreted to be spatially and genetically associated with crustal boundaries (e.g. Huston *et al*., 2016). For example, Goleby *et al*. (2004) showed that orogenic gold deposits are associated with major crust-penetrating structures identified in seismic profiles, Groves *et al*. (2010) proposed that iron-oxide copper-gold deposits are genetically associated with, and localised within a few hundred kilometres of, major crustal boundaries, and Begg *et al*. (2010) suggested a similar relationship between some orthomagmatic Ni-Cu deposits and cratonic margins.

The relevance of this kind of large-scale 3D model for both integrated studies and mineral systems understanding is illustrated by the example of the Archean Yilgarn Craton, where various geophysical, geochemical, geological and geochronological datasets have matured over the last decade to the point that craton-scale investigations are now possible. Integration of these data sets with the 3D crustal boundaries shows that the latter provide additional important constraints for models of the crustal development and the location of mineral deposits within the Yilgarn Craton. For example, while lode gold deposits can be found in wide parts of the Eastern Goldfields, larger deposits show a strong spatial correlation with the major crustal boundaries.

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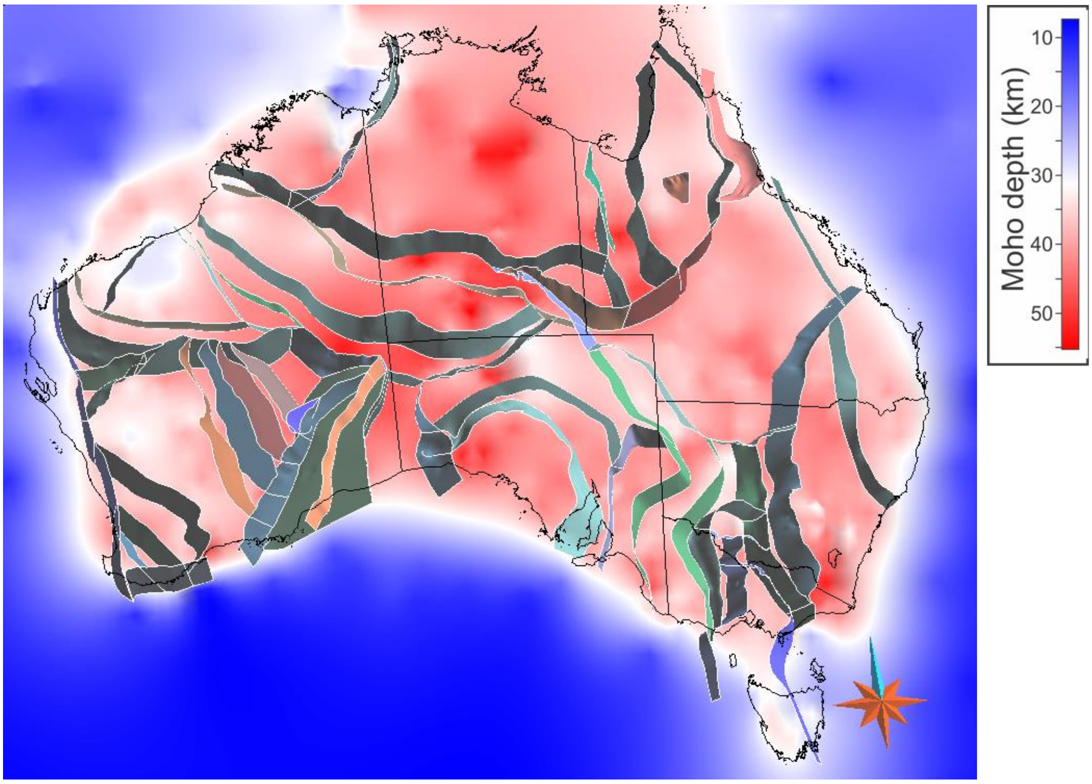

Figure 1. 3D model of the 'Major Crustal Boundaries of Australia' (Doublier et al., 2016) with a vertical exegeration of three. Backgropund colour image shows the Moho depth (Salmon *et al*., 2013).

Late Paleoproterozoic-earliest Mesoproterozoic orogenesis and sediment-hosted Pb-Zn mineralisation in northern Australia: a legacy of supercontinent assembly and plate convergence between Australia and western Laurentia

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Deep seismic reflection imaging combined with geological and paleomagnetic data indicate that the late Paleoproterozoic-earliest Mesoproterozoic sediment-hosted Pb-Zn deposits of northern Australia are not part of a passive margin sequence or sag phase as is commonly assumed but occur towards the top of the Calvert (1730-1640 Ma) and Isa (1640-1575 Ma) superbasins in their respective syn-tectonic, syn-inversion sedimentary fractions. During these stages of basin evolution, extensional faulting all but ceased and the depositional environment bore more resemblance to a foreland basin in which basin fill was controlled by uplift and erosion of an emergent fold and thrust belt driven by far-field stresses or collision at a continental margin distal to the Mount Isa region.

Collision-related basin inversion events are recognized at ca. 1650-1640 and 1615-1575 Ma, broadly coinciding with times of Pb-Zn mineralisation and marking critical stages in the progression towards assembly or reassembly of the Nuna supercontinent. In these two instances, crustal shortening resulted in thrust faulting and reactivation of earlier-formed extensional faults leading to upward expulsion of mineralising fluids at or close to the seafloor while basin inversion and sedimentation were still in progress. The 1620-1575 Ma Isan Orogeny is widely regarded as the most likely trigger for Pb-Zn mineralisation in the 1575 Ma Century deposit and is a temporal equivalent of the Racklan Orogeny in northwest Canada. Both orogenic events were imposed on sedimentary basins younger than 1640 Ma (Isa and Wernecke basins) and both verge landward away from the inferred point of collision. As such they possibly represent mirror images of each other and once formed part of the same doubly divergent fold and thrust belt.

The older pre-1640 Ma inversion event gave rise to major deposits at Mount Isa and Hilton-George-Fisher around 1654 Ma and is a better match for the ≤ 1663 Ma Forward Orogeny, best known from seismic reflection images and whose early stages were similarly accompanied by basin inversion and the deposition of syn-tectonic sediments (Hornby Group; cf. Gun and Loretta supersequences). As in northern Australia, an angular unconformity separates the older, earlier-deformed sedimentary sequence (Hornby Group) from the younger overlying ≤ 1640 Ma basinal sequence (Wernecke Supergroup; Isa Superbasin). This is contrary to most existing models for Pb-Zn ore genesis in northern Australia where fluid flow and mineralisation have been attributed to syn-extensional processes accompanying continental breakup or thermal sag. Instead, mineralisation occurred in a depositional and tectonic environment (foreland basin) not dissimilar to that proposed for carbonate-hosted Mississippi-type Pb-Zn deposits elsewhere in the world, highlighting the importance of basin inversion and orogenesis as drivers of fluid flow and mineralization more generally, if not globally.

Mineral deposits through time: reflections of Earth's tectonic and environmental history

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Although it has been known for several decades that some types of mineral deposits have episodic distributions through time, recent improved constraints on ages of mineralisation have allowed increased resolution of their episodicity (Figure 1). This improved resolution and a better knowledge of Earth's history have greatly improved the understanding of how these distributions are linked to Earth's tectonic and atmosphere/hydrosphere evolution. In this contribution we present up-to-date compilations of the temporal distributions of selected mineral deposits and related these distributions to the tectonic evolution and the oxidation of the atmosphere and hydrosphere.

The distributions of volcanic-hosted massive sulphide (VHMS), orogenic gold and pegmatite deposits, which typically form along convergent margins, at least in geologically young tectonic systems, are closely associated with supercontinent assembly (Figure 1). In the case of Pangea and Nuna, there appear to be peaks in VHMS abundance that can be ascribed to different stages in its assembly.

In contrast, the vast majority of porphyry copper deposits, which also presently form along convergent margins, have ages of less than 100 Ma, although minor deposits are known as far back as the Paleoarchean. The presence of these minor deposits suggest that porphyry copper-style mineralisation is not a young phenomena, but that the observed distribution is strongly influenced by preservation. Porphyry copper deposits typically form at high levels in the crust and, hence, are less likely to be preserved in the geological record.

In some convergent metallogenic provinces there appears to be a progression in the style of mineralisation as orogenic cycles evolve: VHMS deposits form early during arc-back-arc basin formation, followed by orogenic gold deposits during orogenesis, and, in some cases, pegmatite and rare metal deposits (e.g. Sn, W) during post-orogenic extension. This progression can be seen during Superia assembly (Figure 1).

The temporal distribution of other classes of deposits is strongly dependent on the oxidation state of the hydrosphere and atmosphere. This is best expressed by the change in the style of uranium deposits relative to the Great Oxidation Event (GOE). Prior to this event, when the atmosphere and hydrosphere are thought to be been largely anoxic, uranium deposits are exclusively paleoplacer deposits of uraninite, which is stable under anoxic conditions, but highly soluble under oxic conditions. In contrast, hydrothermal uranium deposits, including unconformity related deposits, as shown in Figure 1, but also sandstone-hosted deposits, exclusively formed after the GOE. Other deposit types restricted to after GEO include carbonate-hosted (both Mississippi Valley- and Irish-types) and shale-hosted Zn-Pb deposits, which are thought to have formed from oxidised basinal brines.

For some deposit classes, characteristics of deposits within the class also change with time. For VHMS deposits, the lithological make-up of the host packages, the geochemistry of associated volcanic rocks and the mineralogy of the ores and alteration assemblages change with time. These changes not only provide clues to changes in tectonic processes and environmental conditions over time, but also influence the physical properties and, therefore, the explorability of the deposits.

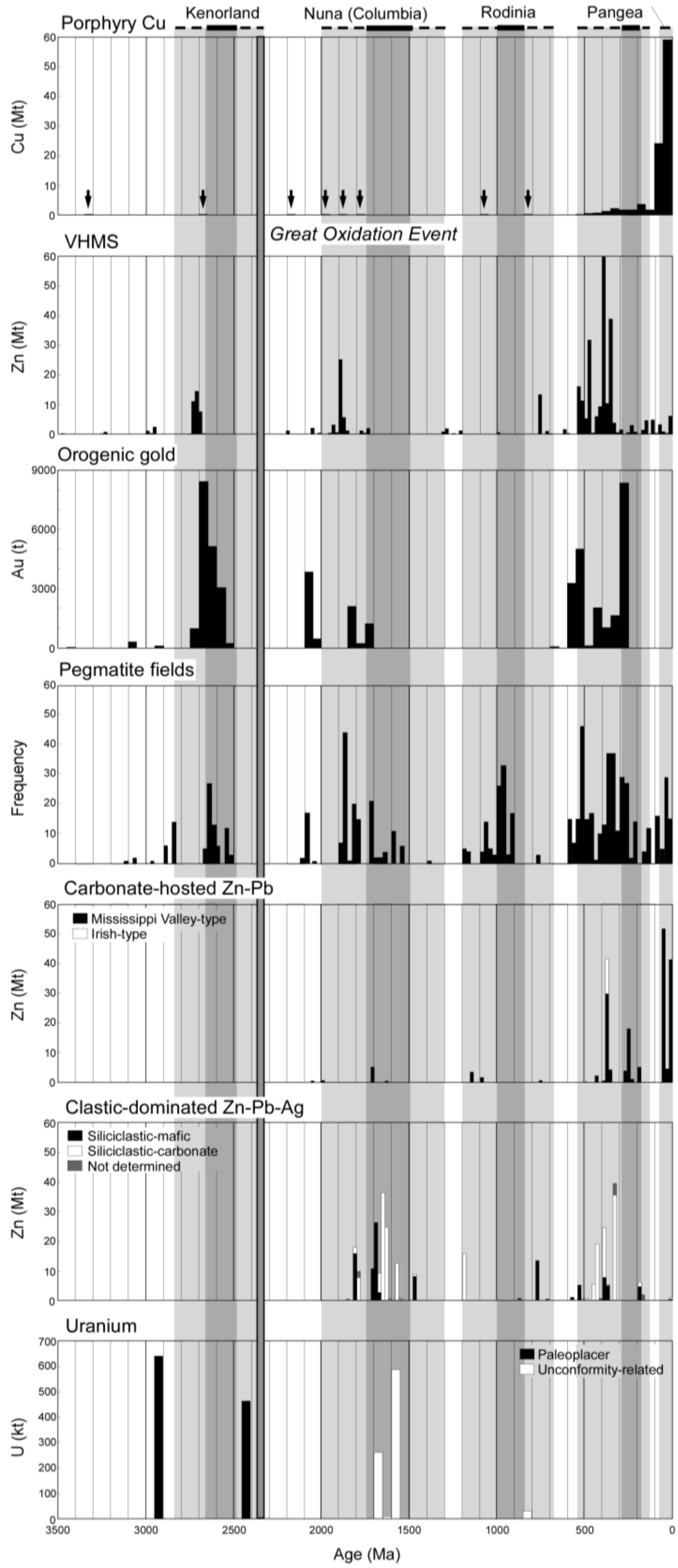

Figure 1. Variations in the abundance of mineral deposit types based on total metal content (except for pegmatite deposits, which are based on total number of fields). The arrows indicate periods with minor porphyry copper deposit formation/preservation.

Mineral systems of the Paterson Province, Western Australia: diverse metallogeny associated with Rodinia break-up

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Following the discovery of the giant Telfer Au-Cu deposit in the late 1970s, exploration in the remote Paterson Province of Western Australia resulted in the discovery of a diverse group of mineral deposit types in the early to mid-1980s, including sediment-hosted Cu (e.g. Nifty and Maroochydore), unconformity-related U (e.g. Kintyre) and carbonate-hosted Zn–Pb (e.g. Warrabarty) deposits. More recent exploration has added intrusion-related W–Cu–Zn (e.g. O'Callaghans) and shale-hosted Zn–Pb (e.g. Millennium) to the list of different deposit types present in the province. This diversity in the style of mineralisation, although not unique, is unusual for metallogenic provinces. Moreover, the age of mineralisation, which all formed in the Neoproterozoic, is also unusual, not only for Australia, but the world in general.

Two major mineralising events are thought to have occurred in the Paterson Province. The first, which is associated with the initial break-up of Rodinia, occurred between ~840 Ma and ~790 Ma, and includes unconformity-related U, sediment-hosted Cu, carbonate-hosted Zn–Pb and, possibly, shale-hosted Zn–Pb deposits. The second event, which occurred between ~650 Ma and ~600 Ma overlapped with granitic magmatism and includes intrusion-related Au–Cu and W–Cu–Zn deposits. The ages of mineralisation, along with age constraints on sedimentation and magmatism, are presented in Figure 1.

The first event, which involved low temperature, oxidised fluids capable of transporting U, Cu, Zn and Pb, is thought to have developed during the latter stages of development of the host Yeneena Basin or during the first inversion of this basin. Oxidised basinal brines moved through the basin and underlying Rudall Complex basement, depositing metals at favourable redox traps, including near the basal unconformity (U), black shale horizons (i.e. Broadhurst Formation: Cu(U), Zn-Pb-Ag) and carbonate units (e.g. Isdell Formation: carbonate-hosted Zn–Pb). This basin-related event is the most significant mineralising event in Australia related to Rodinia break-up. It also suggests that other parts of the Centralian Superbasin, particularly those involving extension and coeval mafic magmatism, may have potential for similar styles of mineralisation.

The second mineralising event is associated with intrusions of magmas associated with the 645–605 Ma O'Callaghans granitic supersuite. This event in detail comprises two periods of mineralisation, at ~650–630 Ma and ~605 Ma. Deposits associated with the earlier period are Au–Cu deposits and include the world-class Telfer deposit and a number of prospects, such as Magnum and Calibre in the Citadel region to the north. Known deposits associated with the later period are restricted to the O'Callaghan W–Cu–Zn skarn. Magmatism between 650 Ma and 600 Ma is unusual for Australia, and the tectonic significance is not clear, taking place during the period between the break-up of Rodinia and the assembly of Gondwana.

Data from the Paterson Province highlight the potential of Neoproterozoic basins around the world for different styles of mineralisation. Although there is significant controversy regarding the age of mineralisation, some sediment-hosted Cu deposits in the Zambian copper belt may overlap the age of the Paterson copper deposits. It may be that the end of the metallogenically "boring billion" may have produced significant mineralisation in a number of provinces throughout the world.

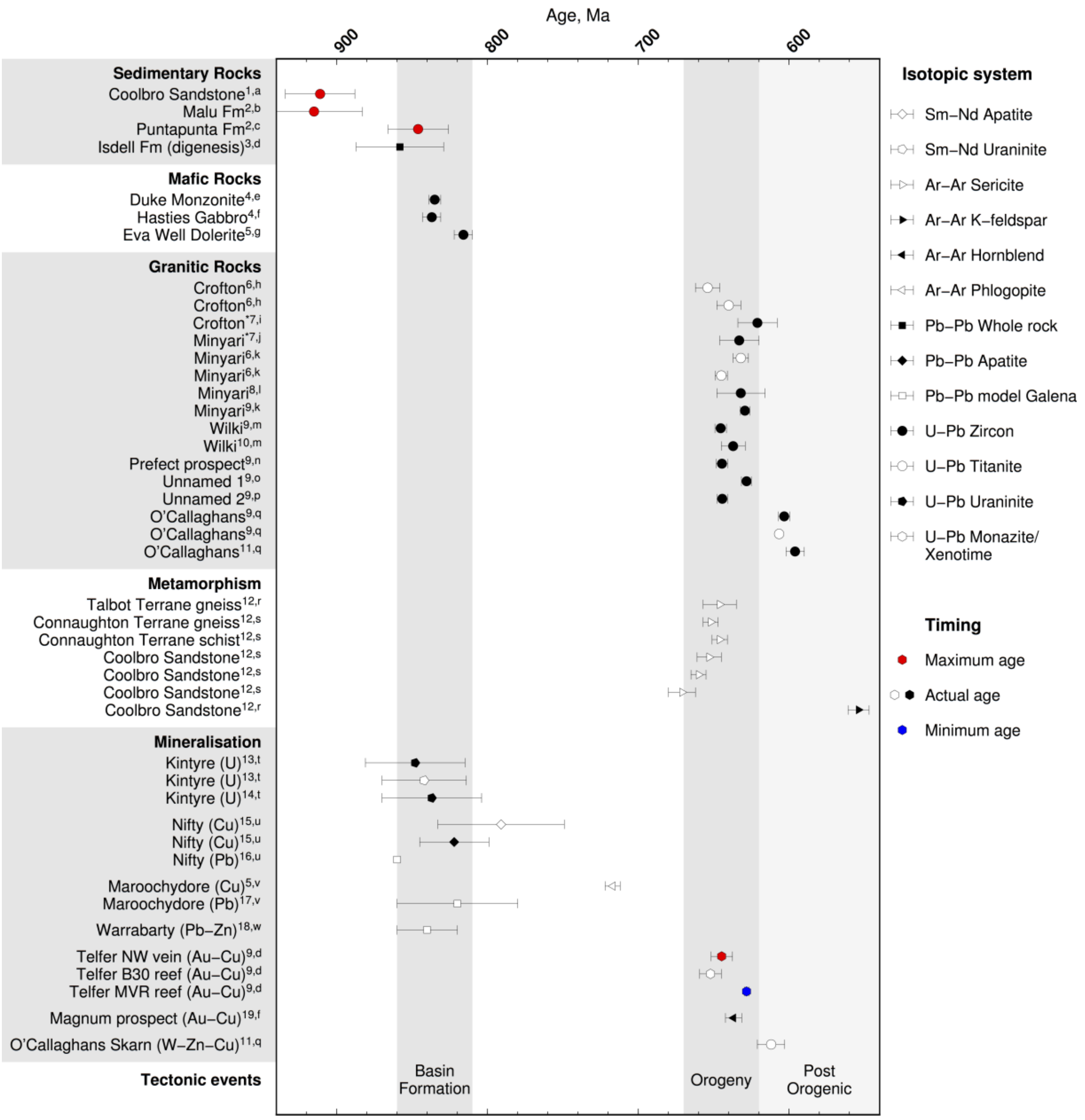

Figure 1. Salient age data for geological events in the Paterson Province (authors can provide full compilation). Symbol colour refers to maximum, actual or minimum age constraints. Asterisk indicates high-U zircons, which have the potential to have been affected by isotopic disturbance.

Gulf of Nuna: Mesoproterozoic hydrocarbon burial during supercontinent breakup

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Similar hydrocarbon-rich, clastic sequences intruded by dolerite sills of similar age in both North Australia and North China cratons[1,2,3] share affinities that suggest similar tectonostratigraphic setting. Alignment of both available palaeomagnetic data and geological piercing points cannot reject the simplest hypothesis that the Velkerrie Formation of the McArthur Basin of Australia and the Xiamaling Formation of a back-arc basin of North China were part of a single, contiguous basin.

At the edge of Palaeoproterozoic-Mesoproterozoic supercontinent Nuna, the "Gulf of Nuna" basin was tectonically similar to the Gulf of Mexico during Pangea rifting. Cyclostratigraphic time scales for both sides of the Gulf of Nuna[4] allow for the correlation of a ~15-Myr-long excursion of elevated organic carbon burial (Fig.1). This work demonstrates the ability to identify and correlate Proterozoic hydrocarbon burial events similar to "oceanic anoxic events" in Phanerozoic time.

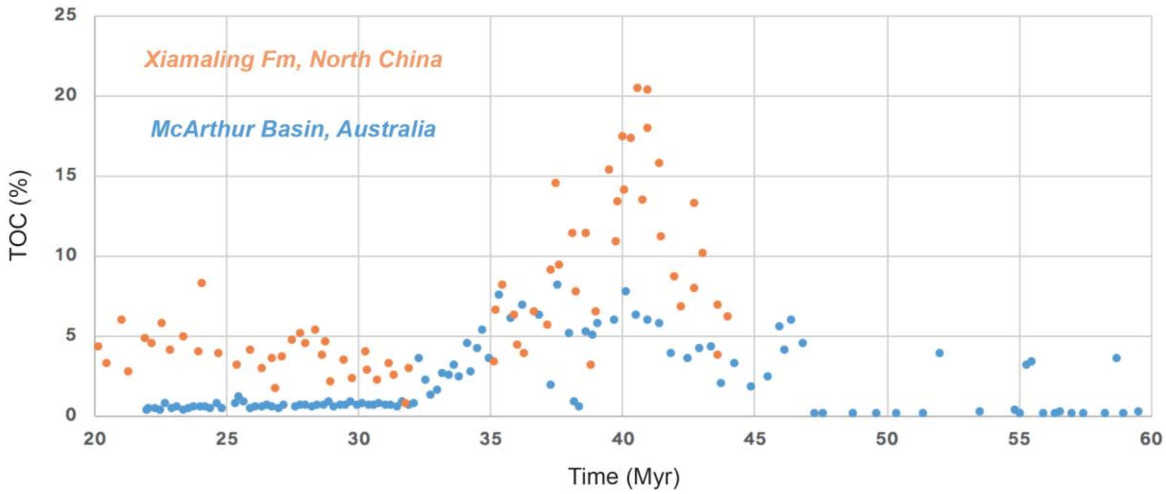

Figure 1. Total organic carbon (TOC) versus duration in Myr for the McArthur Basin, Australia and the Xiamaling Fm, North China based on independent cyclostratigraphy.

[1]ABBOTT, S. *ET AL.* in *1:250000 Geological Map Series Explantory Notes* (Northern Territory Geological Survey, Darwin, 2001).

[2]RAWLINGS, D. J. *ET AL.* in *1:250000 Geological Map Series Explanatory Notes* (Northern Territory Geological Survey, 1997).

[3]ZHANG, S.-H. *ET AL*. 2017. Earth and Planetary Science Letters, 465, 112-125.

[4]ZHANG, S. ET. AL. 2015. PNAS, 112(12), E1406-E1413.

Effect of supercontinent assembly on metal endowment in space and time

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Mineral deposits are formed and preserved through a complex interplay of subsurface and surface processes. The link between their observed episodicity in the rock record and the supercontinent cycle is well established, but this general framework has not, however, been able to explain a lack of deposits associated with some accretionary orogens during specific periods of Earth history, nor the appearance of some deposit types with certain parts of the supercontinent cycle. Utilizing spatial and temporal reconstructions for the Proterozoic, and reviewing spatial and temporal variability of syngenetic, syn-orogenic and late-syn orogenic deposits through to the modern day we show that there are intriguing correlations between styles of orogenesis and the potential for deposit formation and/or preservation.

New models for the transition from assembly of the Paleoproterozoic supercontinent Nuna to Neoproterozoic Rodinia show that that lode gold, volcanic-hosted-massive-sulphide and nickel-copper deposits peak during closure of Nuna's interior ocean but decline during subsequent peripheral orogenesis. This suggests that accretionary style is important to deposit preservation. Following our most recent reconstructions (and bearing in mind this choice influences geometry) Nuna was an introverted supercontinent, assembling on recently rifted interior margins, whereas Rodinia extroverted, assembling on older exterior margins that predated Nuna's breakup, profoundly influencing the character of the bounding orogens and their metallogeny. Introversion with its young, oceanic lithosphere, abundant juvenile pericratonic arcs and minimal subduction erosion allowed rapid obduction, trapping newly formed submarine VMS deposits before they could be consumed and providing a fertile source and appropriate structural environment for lode gold. Extroversion, with its subduction of older, thicker, oceanic lithosphere, accretion of old arc-microcontinent systems and often strong subduction erosion inhibited preservation of VMS and inhibited gold fertility. Amongst the introverted masses orogenic lode gold endowment appears enhanced in smaller, more simply assembled juvenile supercratons or continents (2.7 Ga Superia, 2.1 Ga Birimian) than the early stages of Nuna. It is also enhanced in those orogens that did not subsequently undergo substantial orogenic collapse (e.g. Taconic Euramerica compared to 1.8 Ga Trans-Hudson).

The late assembly, peripheral orogenic phase of supercontinent amalgamation is associated with formation of both intrusion-related and sedimentary-hosted deposit types. Magmatic-hosted gold and rare-earth deposits (e.g. 1.8-1.7Ga Post-Trans-Hudson, 1.3 Ga Gardar) are apparently late-synorogenic to post-orogenic locally but form in overall extensional to back-arc settings temporally linked to active external subduction zones. They are hosted by magmatic belts hundreds of kilometres inboard that spatially mimic the exterior subduction zones but nevertheless transect earlier pre-assembly structural trends.

Late phases of external collision, such as Australia to Laurentia in Nuna during the Isan-Racklan Orogeny, drive a trinity of sedimentary-hosted, contraction-linked deposits that can form up to 1500

km inboard of the supercontinent margin. These deposits, including some of the world's oldest hydrocarbons, carbonate-hosted lead-zinc (1.6 Ga Kamarga, Esker), and unconformity uranium (1.6 Ga and younger Athabasca, McArthur), form in evaporative paleolatitudinal belts in contemporaneous foreland sequences or superimposed on older favourable hosts. In some instances, carbonate-hosted lead-zinc deposits (1.2 Ga Borden basin) form, and are preserved from erosion in, impactogens situated in the far foreland of the assembled supercontinent, but similarly linked stratigraphically and structurally to collisional events in the periphery (1.2 Ga Elzeviran orogeny).

These observations highlight that understanding differing accretionary styles, orogenic phases and paleogeography of supercontinent amalgamation, although challenging, particularly for the Precambrian, can be a powerful predictive tool for mineral exploration targeting. Conversely, examining patterns of regional metallogenesis linked to supercontinent assembly can provide crucial additional pins for reconstruction.

THEME 7.

LIPS, Plumes, and supercontinents.

Coordinator: Prof. Richard Ernst (Carleton Univeristy).

Dr Simon Jowitt (University of Nevada).

The Derim Derim Event of Northern Australia – Geochemical characterisation and impact on hydrocarbon development.

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The Derim Derim Dolerite Suite of magmatic sills (1324 ± 4 Myr[1]) intrude Mesoproterozoic sediments of the Roper Group, McArthur Basin. While intersected by numerous mineral and petroleum wells, no volcanic equivalents have been identified, but these sills have been correlated[1,2] with the Galiwinku Dykes (1325 ± 36 Myr[3]) and with the coeval Yanliao mafic sills of North China[4]. Intruding at multiple stratigraphic levels within the Roper Basin, geochemical characterisation shows that these dolerites are typical continental tholeiites (Fig. 1).

These sills represent the most obvious thermal event to have affected the basin, consequently, they will be an important control on the thermal maturity of organic rich sediments of the Velkerri Formation. Estimates of emplacement temperatures, coupled with thermal modelling and maturity measurements of organic matter reveal that this event has likely affected hydrocarbon development.

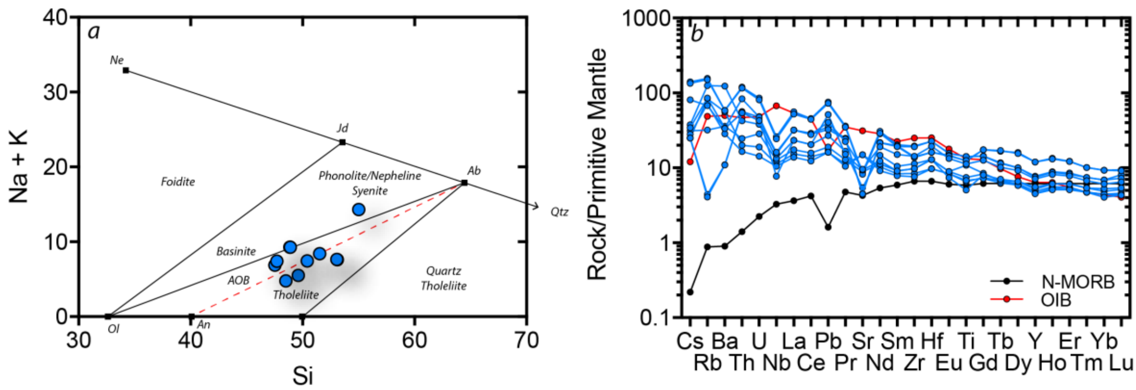

Figure 1. a) Na + K vs. Si - Derim Derim dolerites. b) Trace element spiderplot

[1]ABBOTT, S. *ET AL.* in *1:250000 Geological Map Series Explantory Notes* (Northern Territory Geological Survey, Darwin, 2001).

[2]RAWLINGS, D. J. *ET AL.* in *1:250000 Geological Map Series Explanatory Notes* (Northern Territory Geological Survey, 1997).

[3]WHELAN, J. A. *ET AL.* in *AGES 2016* (Northern Territory Geological Survey, Alice Springs, 2016).

[4]ZHANG, S.-H. *ET AL*. 2017. Earth and Planetary Science Letters, 465, 112-125.

Beyond the Barcode: Geochronological methods responsibly applied to supercontinent reconstructions

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With geological correlation and paleomagnetism, geochronology is one of the principal tools in re-assembling now-distant continents. But there are various "flavours" of geochronology, and different situations require different techniques and applications of these methodologies, each of which has strengths and drawbacks.

Modern absolute dating methods, based on radioactive-decay systematics of elements contained in minerals, generally record the timing of when that mineral cooled below a certain temperature and thus the magmatic age of a rock. This enables the correlation of igneous events in space and time, though subsequent heating or hydrothermal activity can partially or entirely reset that timing. Geochronological studies of detrital minerals can provide a maximum age of deposition of sediments related to rifting or basin development, but hiata in sedimentation and availability of contemporaneous magmatic source rocks can limit the usefulness of such an age in supercontinent reconstructions. Mid- to low-temperature dating methods (Ar-Ar, (U-Th)/He) can identify shared tectonic histories, but are relatively easy to reset. Even when an appropriate isotopic system and mineral are selected, the analytical method (e.g., *in situ* vs. mineral separate) can strongly influence the resulting age data, with implications for the validity of reconstructions.

When using geochronological data in paleogeographic reconstructions, not only are the selected materials and methods used to acquire that data important, but also the interpretation and application of the data. Generally, the most precise and accurate age data are obtained using U-Pb geochronometers (zircon and baddeleyite) and Isotope Dilution – Thermal Ionization Mass Spectrometry (ID-TIMS) analysis. But the meaning of even these data in the context of testing reconstructions is partly dependent upon interpretation. The example of U-Pb ID-TIMS data from baddeleyite from the Southwest Laurentia Large Igneous Province will be used to demonstrate the importance of "apples to apples" comparison of data, with different choices of calculation and presentation leading to different conclusions. Different methods can be combined to generate increasingly robust correlations: Neoproterozoic magmatism in Tasmania, hosted in Mesoproterozoic sedimentary rocks, is linked to a conjugate margin of Laurentia through both magmatic and detrital ages, resulting in a refined Rodinia fit of Tasmania/East Antarctica and Laurentia. The "magmatic barcode" method to identify nearest neighbours by identifying shared magmatic histories requires more than strictly geochronology to create solid reconstructions, as exemplified by ca. 1.89 Ga dyke swarms in the western Australian and eastern Indian cratons in the context of a period of increased global magmatism.

Commonly-used measures of reliability can also be misleading; like most other forms of geochemical data, responsibly presenting and using geochronological data requires an appreciation and understanding of methods, meaning, and interpretation. In the context of supercontinental recontructions, fits will be more robust and constraints will be better applied by looking a little more closely at the age data.

A Combined Geochronological and Paleomagnetic study of the ~1220 Ma mafic dykes in the North China Craton and their tectonic implications

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This study presents new combined geochronological and paleomagnetic data for 10 mafic dykes in the western Liaoning Province and Taihang areas of the North China Craton (NCC). New SIMS zircon dating of three of these dykes and baddeleyite dating of a further one of these dykes yielded weighted mean $^{207}Pb/^{206}Pb$ ages of 1226.9 ± 3.4, 1222.9 ± 6.1, 1215.2 ± 7.7 and 1219.1 ± 4.3 Ma, respectively, suggesting that these dykes were emplaced at ~1220 Ma.

Rock magnetic analyses indicate that the dominant magnetic carriers are single domain (SD) + multiple domain (MD) magnetite or titanomagnetite. All samples underwent step-wise thermal demagnetization and two components were isolated. The low temperature component (LTC) was identified at temperatures generally <300°C. Their directions are around the present day geomagnetic dipole field (PDF) and are thus interpreted to be recent viscous overprints. The high temperature component (HTC) was isolated from all 10 dykes (309 samples) at unblocking temperatures between 540°C and 580°C. The HTCs are directed eastward and down with moderate inclinations and pass a positive backed-contact test that means these components are primary. Any secular variation has also been effectively averaged out by using results derived from the analysis of virtual geomagnetic pole (VGP) scatter. The paleomagnetic poles obtained using the HTC are dissimilar to any younger published poles for the NCC, meaning that we consider these new data to represent a key pole for the NCC at ~1220 Ma.

Our new results place the NCC in a low to moderate paleolatitudinal region at ~1220 Ma. A comparison of the high quality, coeval poles for the NCC, Australia and Laurentia supports the idea that the breakup of Nuna had commenced by ~1220 Ma. In addition, the ~1.33 Ga rifting events evidenced by the presence of bimodal magmatic rocks in the northern NCC may have caused the breakup of the NCC from the northern Australia at this time (Zhang et al., 2017). The relative position of the NCC and Laurentia at ~1220 Ma is also different from their positions in Rodinia (e.g. Fu et al., 2015), with the NCC reaching western Siberia by ~920 Ma.

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Precambrian Mantle Plume Centres and Breakup Margins Identified Using the Large Igneous Province Record

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[3]Earth Dynamics Research Group, ARC Centre of Excellence for Core to Crust Fluid Systems (CCFS), The Institute for Geoscience Research (TIGeR), and Australia-China Joint Research Centre for Tectonics and Earth Resources (ACTER), Department of Applied Geology, WASM, Curtin University, GPO Box U1987, WA 6845, Australia

Large Igneous Provinces (LIPs) represent a powerful tool for locating mantle plume centres and also for identifying the timing of breakup along the margins of crustal blocks (*Ernst and Bleeker, 2010*). This tool is complementary to paleomagnetic studies for reconstructing the configurations and histories of paleocontinents (*Bleeker and Ernst 2006; Ernst et al. 2008; Ernst 2014*). An increasing number of LIPs are recognized to be associated with giant radiating dyke swarms whose convergence points are interpreted as mantle plume centres. Furthermore, plume centres are typically associated with continental breakup (and the formation of new oceans), or in some cases with rifting but failed breakup. The correlation between LIPs/plumes and continental breakups is well demonstrated for the progressive breakup history of the Pangea supercontinent. The breakup history of Precambrian supercontinents is more cryptic since the rift-related sequences are poorly exposed as erosional remnants, but the Proterozoic LIP / radiating dyke swarm record can be used to capture this history. The number and size of recognized Precambrian LIPs (and especially their dyke swarms) has dramatically increased in the past decade particularly because of the industry supported 2010-2016 LIPs and Supercontinent Reconstruction project (*Ernst et al. 2013*). With this improved LIP record we are in a position to provide a more robust identification of plume centres through time along with the interpretation of associated rifting and continental breakup. Below we show some applications of this approach for various crustal blocks.

As a next step of our study, we will systematically integrate this temporal-spatial distribution of LIPs (and their plume centres and interpreted breakup margins) with the paleomagnetic record in order to improve Precambrian supercontinent reconstructions.

Some examples are provided below of Proterozoic plume centres and continental breakup margins identified through the LIP record (in approximate order of decreasing age):

Superior craton (breakup from Karelia-Kola, Wyoming, & Hearne cratons): breakup along the southern -southeastern margin linked to the 2100-2070 Ma Marathon- Fort Frances LIPs; attempted (failed) breakup linked to the 2500-2450 Ma Mistassini and Matachewan LIPs (*Ernst and Bleeker 2010; Kilian et al. 2016*).

Kaapvaal craton: breakup (or attempted breakup) along the southern margin linked to the 2425 Ma Ongeluk LIP (*Gumsley et al. 2017*).

Slave craton: breakup along the eastern margin at 2230-2210 Ma linked to the Malley and MacKay LIP events; breakup (or attempted breakup) along the western margin linked to the 2120-2100 Ma Indin LIP (*Buchan et al. 2010; Ernst and Bleeker 2010*).

Dharwar craton: breakup (or attempted breakup) along the NW margin linked to the 2180 Ma Mahbubnagar-Dandeli LIP (*French and Heaman 2010; Ernst and Srivastava 2008*)
North Atlantic craton: breakup (or attempted breakup) along the western margin (Nain portion) linked to the c. 2040 Ma Kangamiut-MD3 LIP (*Nilsson et al. 2013*).

Karelia-Kola craton: breakup on the W or NW margin linked to the c.1970 Ma Pechenga-Onega LIP.
North China craton & northern Australian craton: breakup linked to the 1320 Ma Yanliao – Galiwinku-Derim Derim LIP (*Zhang et al. 2017*).

Laurentia: breakup on the northern margin (from southern Siberia) linked to the 725-715 Ma Franklin-Irkutsk LIP (Ernst et al. 2016). Breakup on the eastern side (from Baltica) linked to the 615-550 Ma multiple pulses of CIMP (Central Iapetus Magmatic Province) (*Ernst and Bleeker 2010*); breakup on the western margin (from South China, or perhaps Australia) linked to the Gunbarrel LIP (*Li et al. 2008*)

Australian craton: breakup (or attempted breakup) near the northern margin linked to the 510 Ma (Kalkarindji LIP); breakup (or attempted breakup) on western margin linked to the 755 Ma (Mundine Well LIP).

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Implications of the mobility of the Perm Anomaly for tectonic reconstructions in deep geological time

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Earth's lower mantle is characterized by two large-low-shear velocity provinces (LLSVPs, ~15000 km in diameter, ~500-1000 km high) located under Africa and the Pacific Ocean. In addition, a single, much smaller (~1000 km in diameter, ~500 km high) deep mantle structure named the "Perm Anomaly" was recently identified through the analysis of seismic tomography models. This discovery challenges current reconstructions of the evolution of the plate-mantle system that invoke plumes rising from the edges of the two LLSVPs, assumed spatially fixed and non-deforming in time. Here, we present mantle flow models constrained by tectonic reconstructions that reproduce the present-day structure of the lower mantle, and show a Perm-like anomaly. In the dynamic models, spanning 230 Myr, subducting slabs deform an initially uniform basal layer containing 2% of the volume of the mantle. Basal density, convective vigour, mantle viscosity, absolute plate motions, and relative plate motions are varied in a series of model cases. We use cluster analysis to classify equally-spaced points on Earth's surface into two groups with similar variations in present-day temperature between 1000-2800 km depth, for each model case. The procedure reveals a high-temperature cluster and a low-temperature cluster with respect to ambient mantle temperature below ~2400 km depth. The spatial extent of the high-temperature cluster is in first-order agreement with the outlines of the LLSVPs and of the Perm Anomaly revealed by a similar cluster analysis of seven tomography models. Model success is quantified by computing the accuracy (between 0.56 and 0.76) of the temperature clusters in predicting the low-velocity cluster obtained from tomography, and qualified by the occurrence of a separate Perm-like anomaly. The anomaly formed in isolation prior to 150 Ma within a long-lived subduction network ~22,000 km in circumference composed of the Mongol-Okhotsk subduction along Eurasia to the west, northern Tethys subduction to the south, and east Asia subduction to the east, then migrated ~1,500 km westward at an average rate of 1 cm/yr, indicating a greater mobility of deep mantle structures than previously recognized.

The mobility of the Perm-like anomaly implies that lowermost thermochemical structures in the Earth's mantle are not fixed and rigid, and that the exact present-day and location of LLSVPs cannot be used to infer the paleolongitude of tectonic plates carrying Large Igneous Provinces.

Secular breakup of Rodinia from mantle-plume activity to continental rifts to ocean basin (Northern Tibetan Plateau)

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Since the Rodinia supercontinent was conceptualised in the 1990s, its paleocontinental reconstruction, assembly and breakup had attracted much attention (e.g., Li et al., 2008). The Neoproterozoic intraplate magmatism related to Rodinia breakup widely occur in Australia, South China, North American, Tarim, India, and Africa. The geodynamic mechanism of breakup and the supercontinental cycle are also well-studied. We report a discontinuous intraplate magmatism (850-600 Ma) in the Northern Tibet, including 850-820 Ma LIPs in the north margin of the Qaidam Block (Xu et al., 2016), ~760 Ma and 600-585 Ma volcanic-sedimentary rock sequences of rifting basins in Kunlun and Qilian (Xu et al., 2015), which preceeded the ~580 Ma opening of the Qilian Ocean (Iapetus Ocean or Proto-Tethys Ocean).

1. 850-820 Ma LIPs. A ~850-820 Ma LIP was recognised in the Qaidam continental margin. The remnants of this LIP includes the Yingfeng -Aolaoshan doleritic-volcanic rocks, and protoliths of eclogites in the North Qaidam UHPM belt. The Yingfeng dolerite dykes experienced the greenschist facies metamorphism, while the Aolaoshan volcanic sequences underwent the HP granulite metamorphism. Zircon U-Pb analyses (SIMS and LA-ICP-MS) demonstrate that these volcanic rocks formed at 852-823 Ma, the same as the protolith ages of the North Qaidam eclogites (847-828 Ma). Aolaoshan volcanic rocks were metamorphosed at 439 Ma, identical to the ages of the UHP metamorphism (438-420 Ma). These 850-820 Ma mafic rocks have geochemical characteristics of the OIB to enriched-MORB. These geochemical features coupled with their high potential temperature (Tp = 1434-1524°C) suggest these mafic rocks are remnants of the ~850-820 Ma North Qaidam LIP caused the upwelling of a mantle plume, and represents the onset of Rodinia break-up. These Neoproterozoic basaltic rocks preserved in the northern passive margin of the Qaidam block were further destroyed during the continental collision/subduction at 440-420 Ma (Song et al., 2014), to experience low, medium to ultra-high pressure metamorphism.

2. ~760 Ma Volcanic-sedimentary sequence. This volcanic-sedimentary sequence (Wanbaogou Group) is situated in the southern margin of the Qaidam Basin and East Kunlun Orogenic Belt, and consists of thick basalts, volcanic clastic rocks and sedimentary interlayers. Zircon SIMS chronology indicates the Wanbaogou basalts were erupted in 762 Ma. Geochemically, basalts include two groups: (1) high-Ti (HT) alkaline; and (2) low-Ti (LT) tholeiitic basalts. The HT group shows high Ti/Y (502-660), Nb/Y (0.8-1.6) and TiO2 (2.8-5.0%) similar to OIB, and is derived from the relatively low-degree partial melting (10-20%) of garnet peridotite (BSE component). The LT group has low Ti/Y (383-439), Nb/Y (0.3-0.4) and TiO2 (1.8-2.5%) which resemble E-MORB, and is generated by the higher-degree melting (>30%) of the same mantle source. The positive εNd(T) values (1.6-4.2) and enrichment in HFSE (Nb/La = 1.12-1.73; Nb/Th = 12.0-17.6) imply the basalts suffered little lithospheric assimilation. The volcanic-sedimentary sequence and geochemical characteristics suggest that the volcanic-sedimentary sequence was formed in a continental rift environment and is coincident with intraplate magmatism (760-750 Ma) in Australia, India, South China, Tarim and Qilian-Qaidam Blocks. This episode of magmatism is related to the 780 Ma mantle plume/s, which caused the separation of Laurentia from Rodinia and the formation of Proto-Pacific Ocean.

3. 600-580 Ma volcanic-sedimentary sequence. The volcanic-sedimentary sequence (Zhulongguan Group) in the western segment of the North Qilian Orogenic Belt is a sequence of thick (up to 300 m) basaltic lavas, shallow marine dolomitic limestone, mudstones and siltstones. The SIMS ages of zircons show that the volcanic-sedimentary sequence was formed in the latest Neoporterozoic (600–580 Ma). Basalts can be also subdivided into tholeiitic and alkaline series. The former are characterized by the low and varying ε_{Nd}(T) values (-3.1~2.6), negative Nb-Ta anomalies and positive Th-U anomalies (Nb/La = 0.6-1.4 and Nb/Th = 2.5-7.7) , which are analogous to the low-Ti basalts of

LIPs and indicate the contamination of upper crust. The latter display the high and uniform $\varepsilon_{Nd}(T)$ values (4.1~5.3), positive Nb-Ta anomalies (Nb/La = 1.6-2.7 and Nb/Th = 14-25), which are similar to the high-Ti basalts of LIPs and experience no crustal assimilation. The occurrences, rock associations and geochemical features suggest that the Zhulongguan Group was formed in a continental rift setting and exhibited close affinity to the passive continental margin (~600 Ma) in southeastern Australia and northern Tarim. We suggest a link of the Qilian-Qaidam Block with SE Australia (also Tarim and South China). In view of the oldest MORB-type ophiolites (550 Ma) and the initial arc magmatism (520 Ma), the opening of the Paleo-Qilian Ocean (a branch of Proto-Pacific ocean) may be limited at 580-550 Ma. These synchronous within-plate magmatism in Australia, Tarim and Qilian-Qaidam may represent the relatively late stage of a long duration fragmentation of Rodinia.

The Neoproterozoic magmatism in the Qilian-Qaidam block responses to the breakup of Rodinia and eventually results into the opening of the Palaeozoic oceanic basins. The correlation of multi-phase magmatic events (1000-900 Ma, 850-820 Ma, 760 Ma and 600-580 Ma) demonstrate that the Qilian-Qaidam block has close affinities with South China, Australia and Tarim in Neoproterozoic, and is located at the eastern margin of East Gondwanaland. Therefore, we conclude that the breakup of Rodinia is a long-lasting, polyphase and multi-staged process. In the pre-rift stage (850-820 Ma), the upwelling of mantle plume generated the North Qaidam LIP with area of 100,000 km^2, including flood basalts and mafic dykes/sills, layered mafic-ultramafic intrusions, anorogenic granitoids. The syn-rift stage includes two phases of continental rifting (760-750 Ma and 600-580 Ma). The Wanbaogou Group (760 Ma) in East Kunlun indicate the separation between the southern margin of Qilian-Qaidam and South China, and the formation of the Proto-Pacific Ocean. However, the Zhulongguan Group (600-580 Ma) in North Qilian imply the dismemberment between the northern margin of Qilian-Qaidam and Australia, and the formation of the Paleo-Qilian Ocean.

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The ca.1.23 Ga mafic magmatism in the Yan-Liao rift, North China

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The North China Craton (NCC) began to undergo stable deposition after ~1.8 Ga, as evidenced by the development of the Xiong’er and Xu-Huai rifts in the south and the Yan-Liao and Bayan Obo rifts in the northern part of the craton (Peng, 2015a; Fig. 1a). The Yan-Liao rift contains sediments of the Changcheng, Jixian and Qingbaikou systems from bottom to top and represents about one billion years of sedimentation (Fig. 1b). The Xiamaling Formation (Fm) represents the first section of the Qingbaikou System and was deposited before 1.32 Ga, as evidenced by geochronological constraints from bentonites/tuffs and mafic sills within the Fm, (Gao et al.,2007; Zhang et al., 2017; Fig. 1b). Subsequent regional tectonism in the form of the Yuxian movement caused the Xiamaling Fm to be overlapped by the later Changlongshan (Longshan or Luotuoling) and Jingeryu Fms although the depositional ages of these units remain unclear (Zhu et al., 2012; Fig. 1b).

Recent research has identified ca. 1.23 Ga magmatism in the eastern part of the Yan-Liao rift in the form of dykes or stocks (Wang et al., 2015, 2016; Xiang, 2014). Some synchronous mafic intrusions and dykes have also been identified distal from this rift (Pei et al., 2013; Peng, 2015b). U–Pb dating indicating that all of these rocks formed at 1209-1244 Ma. The dykes crop out in various areas and have widths of 10-40 m (Fig. 1a). Wang et al. (2015) divided related samples into alkaline and sub-alkaline series, with the former derived from lower degree partial melting of a depleted region of the asthenospheric mantle with limited involvement of a lithospheric mantle. Wang et al. (2015) also considered that upwelling asthenospheric material triggered the 1.23 Ga breakup of the NCC from the Columbia supercontinent. All dated samples are classified as alkaline basalts within a Zr/TiO_2-Nb/Y diagram. In addition, alkaline series rocks are commonly associated with continental rifting, as exemplified by the East African rift, the Prakasam rift in India and within the Gardar Province in Greenland (Goodenough et al., 2002; Kumar and Rathna, 2008; Winter, 2014). However, identifying alkaline magma sources remain problematic as a result of possible lithospheric superimposition (Kumar and Rathna, 2008). Alkaline rocks in these rift settings usually have high $(La/Yb)_N$ values and OIB-like trace elements patterns, as is the case for the 1.23 Ga samples from the NCC, with $(La/Yb)_N$ values of 5.6-13.7 (normalized to the chondrite composition of Sun and McDonough, 1989). These values record changing degrees of partial melting of the source(s) regions for these magmas or reflect changing depths of melting during rift evolution and progressive extension. Winter (2014) suggested that the progressive development of the East African Rift involved alkaline magmas sourced from deep-seated but ascending asthenospheric material, with grabens developing during rifting.

The magmatic centre may be located within the eastern branch of the Yan-Liao rift, as suggested by the dense accumulation of dykes in this area, although dyke geometry seems to contradict this region being a magmatic centre. Both the 1.23 Ga dykes and the 1.32 Ga sills (Zhang et al., 2017) within this rift plot in the within plate part of a Zr/Y-Zr diagram. However, regional sedimentary contact relationships indicate that magmas are parallel to slightly angular Yuxian unconformity was caused by (potentially Grenvillian) crustal extrusion (Qu et al., 2010; Zhu et al., 2012). The Yuxian movement represents a complex event involving uplift giving way to folding, where the 1.32-1.23 Ga magmatism represents a second phase of the rift-related activity in a similar way to the earlier ~1.7-1.62 Ga magmatism. It also remains unclear whether the NCC breakup from Columbia occurred at 1230 Ma (Meng et al., 2011; Peng, 2015b; Wang et al., 2015; Zhang et al., 2017).

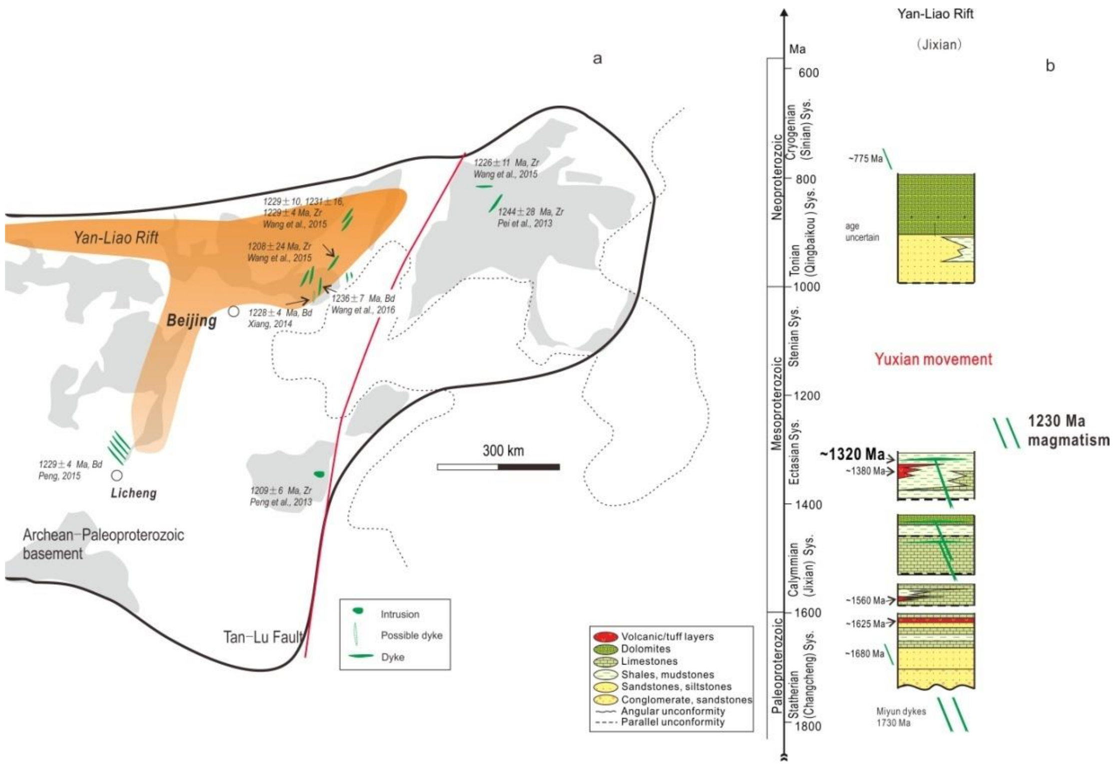

Figure 1. (a) Map showing the distribution of reported and potential ca. 1.23 Ga magmatism within the NCC; adapted from Pei et al. (2013), Peng et al. (2013), Peng (2015b), Wang et al. (2015, 2016), and Xiang (2014).(b) Mesoproterozoic to Neoproterozoic units of the Yan-Liao system and related magmatism (modified after Peng, 2015b and Wang et al., 2016; Zr = Zircon, Bd = Baddeleyite).

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Dyke Swarms Distribution and Remote Sensing Images Characteristics in NE Hami, Xinjiang, China

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Dyke swarms often form in extensional tectonic settings (Hongbo et al., 2012) and have characteristics that can reflect tectonic stress fields during emplacement as well as the characteristics of the magmatic activity at that time. This means that understanding the distribution and development of the dyke swarms can provide insights into the geological evolution of a region (Halls et al., 1982). A large number of dyke swarms are located in the Xinjiang area of NW China, especially the Hami area. The study area is located 35 km northeast of Hami (Fig. 1) on the western edge of Halirk mountain at 93°40'-93°44' E, 42°05'-43°08'N. The spatial distribution and geological significance of the dyke swarms in this area were examined using high resolution remote sensing imagery and field investigations. We used WorldView-2 high-resolution and Landsat ETM+ remote sensing imagery, ASTER GDEM digital elevation data and 1: 200,000 scale geological mapping data to obtain geological information, including dyke swarm orientations, thicknesses, and lengths.

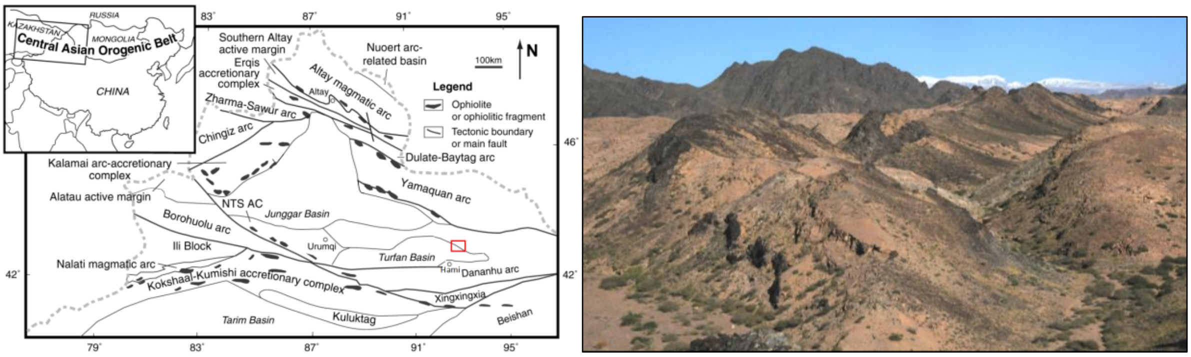

Figure 1. Tectonic map of the northern Xinjiang area of NW China (left; after Xiao et al., 2004) and an image showing the typical distribution of dikes in this area (right).

The spatial distribution of dykes in the study area is complex and the swarms often bifurcate and recombine. Here, we facilitate the analysis and information extraction using the following criteria to define single dykes: The distance between individual dykes is greater than that of the thickness of the two dykes in the area and any bifurcated area is considered to be part of the dyke if the individual dyke is more than ten times thicker than the bifurcated area. These criteria led to the identification of 201 individual dykes within the swarms in the study area.

The dykes in the study area are widespread and appear to be free of folding or faulting. This in turn suggests that the direction of minimum principal stress σ3 during dyke emplacement was perpendicular to the main orientation of the dykes, with Fig. 2 indicating that the majority of these dykes are parallel and trend nearly E-W (85-105° to 265°-285°). In addition, combining the digital elevation model with ASTER GDEM elevation data and Landsat7 ETM + remote sensing data suggests that the area contains dikes with two distinct strike directions.

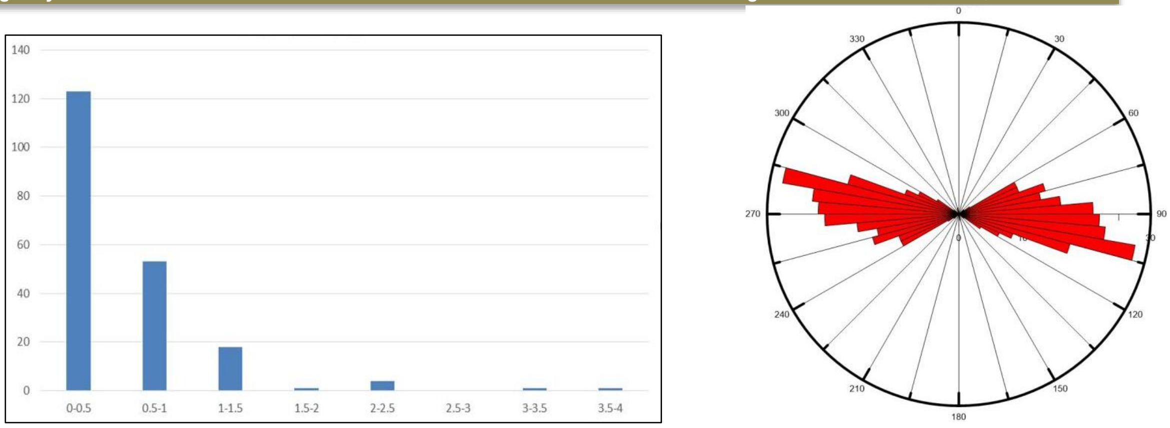

Figure 2. Diagrams showing the lengths (left) and orientation (in a rose diagram; right) of dykes in the Hami area.

The dykes in the Hami area have a distinctly linear distribution, with dyke lengths between 37 m and 3.77 km, yielding an average length is about 0.54 km. The dykes were divided into 20 groups at 0.2 km intervals, yielding cumulative frequencies and associated R^2 values. This indicates that the lengths of dykes within the study area have a power law distribution with an R^2 value of 0.8711 (Fig. 3; Table.1).

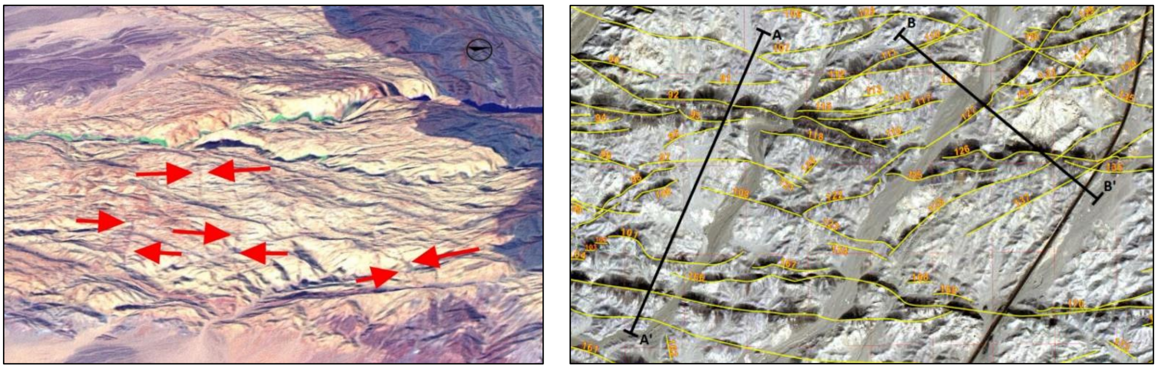

Figure. 3. Remote sensing images showing the location of dykes (left) and the location of the cross-sections A-A' and B-B' referred to in Table 1 (right).

Table 1. Comparison of dykes within cross-sections A-A' and B-B'

	Length in image	Real Length	Total thickness	Crustal extension ratios	
A-A'	135 cm	2.7 km	0.437 km	0.193106496	19.34%
B-B'	150 cm	3 km	0.4072 km	0.157050293	15.71%

High-resolution remote sensing enabled the extraction and identification of the spatial distribution of dykes in the Hami area of Xinjiang, China. This indicates the usefulness of remote sensing information in determining the geometry of individual dykes. This approach identified 201 dykes that dominantly strike east-west (85°-105° to 265°-285°) and have lengths that vary between 37 m and 3.77 km, with an average length of about 0.54 km. The thickness of these dykes varies between 1.2 m and 69.8 m with an average thickness of about 16.7 m. These dykes have a length distribution that is close to a power-law distribution but have thicknesses that follow a normal logarithmic distribution. The data obtained during this study yielded crustal extension ratios of 15.71%-19.34%.

Project 648
Supercontinent Cycles & Global Geodynamics

Paleomagnetism of Paleozoic Era Glacial tillites and Neopropterozoic Era Black Limestone (Ngash Synclinorium), Nothern Ethiopia.

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Glaciogenic sediments of Palaeozoic age and Metasedimets of the Tambien Group of the Arabian Nubian Shield both in Northern Ethiopia have been sampled for palemagnetic investigations. The results from both are respectively presented.

The Glacial sediments; although there was no doubt about the glacial origin of these rocks, there has been a debate as to whether they are correlable with either of the Upper Carboniferous-Early Perminan glacial rocks of southern Africa or of Ordovician glacial rocks in Northern Africa. Twenty core samples from a tilted bed (strike & dip 1300/270SW) of the Edaga Arbi Glacials and thirteen core samples from sub-horizontally bedded Enticho Sandstone from Enticho area were collected during a single field season to determine the age. For both sediments Alternating Field (AF) demagnetization techniques could only demagnetize about 50% of the total intensity of magnetization and thermal demagnetization is proved to be effective. The intensity of magnetization is about 0.08A/m. A viscous remagnetizations (VRM) and one stable component of magnetization were identified. Between a temperature range of 1200C – 3500C the VRM is removed; further heating until a temperature of ~ 6500C resulted in smooth decay in magnetization intensity to about 50%. The rest of the magnetization is efficiently removed by heating to 6900C. The high stability component defines straight-line segment starting 4000C and directed towards the origin revealing the Characteristic Remanent Magnetizations (ChRM). The site mean directions from 11 locations are reversed in polarity with a better grouping in the tilt-corrected coordinate and pass the McFadden fold test. This overall site mean direction is Dec = 143.40, Inc = 58.80 (N = 11, □95 = 9.70) and the corresponding mean pole position is Lat = 26.00, Lon = 249.50 (N = 11, A95 = 13.10). This geomagnetic pole position was later rotated into West Africa coordinates to allow for extensional rifting in the Benue Trough about an Euler pole position, at 19.20N, 352.60E through an angle −6.30 (clockwise) (Lottes & Rowley, 1990). The resulting pole position is located at □s = 246.60E, □s = 31.80S (N = 11, A95 = 13.10), this pole with its 95 per cent confidence circle intersects the 270–310 Ma, segment of the APW path (Besse & Courtillot 2003) for West Africa consistent with ages of between late Carboniferous and early Permian. The result also implies that the Late Carboniferous Dwyka land ice sheet had probably extended more than 1000 km further north to Ethiopia than previously known.

Eighty-one paleomagnetic cores were collected from 10 locations across a black limestone unit within the core of Negash Synclinorium, northern Ethiopia in order to test a proposed Snowball Earth events of Sturtian glaciation (e.g. Miller et al. 2003; Alene et al. 2006) recorded in the diamictite unit of the Tambien Group, which is part of the Arabian Nubian Shield, representing mostly juvenile crust and chiefly low-grade metavolcanic, metasedimentary assemblages. Rock magnetic analyses revealed goethite, pyrrhotite, titano-magnetite, and titano-hematite to be the major magnetic materials. In most cases paleomagnetic directions are defined by a single component of magnetization that defined straight-line trajectories directed towards the origin and considered as the ChRM. When site mean ChRM directions are plotted on stereogram, their distribution is relatively clustered in geographic coordinates and the overall mean direction is Decg = 358.50, Incg = 16.60 (□95 = 3.80, K = 162.8, N = 10). After a structural restoration to the horizontal is made the directions disperse and fail the fold test of both McElhinny's and McFadden's tests and the mean direction for this stratigraphic coordinate is Decs = 353.50, Incs = 8.80 (□95 = 18.90, K = 7.5, N = 10). This is interpreted to result from a later remagnetization of the black limestone and the ChRM is determined to be secondary. Virtual Geomagnetic poles (VGP) in the unrestored position is determined and used to calculate overall mean VGP position resulting long = 235.70E, latg = 84.50N (A95 = 3.00, N = 10). Comparison of this pole with the apparent polar wander path (APWP) curve for Africa of Besse & Courtillot (2003) and with the 2 Ma reference pole of stable Africa (Kidane et al. 2003) is found to be consistent with remagnetizations during the Quaternary period. Hence, the proposed Snowball Earth event could not, unfortunately, be confirmed from paleomagnetism on this rock. Further study needs to be made on different rock types and different locations.

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