Newsletter #2 - 16th April 2020

Amateur Geological Society of the Hunter Valley Inc.

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Editorial

Greetings fellow AGSHV members, families and friends.

Many thanks for your contributions to Newsletters #1 & #2. Keep 'em coming! All are welcome, long scholarly articles, and little snippets (the little snippets are especially useful for filling a half-a-page space. Light relief in the current situation is good. Many thanks **Chris Morton** (p 24).

Hands up all ex-Uni students who've never been on a Sit-In. Hands down, you're in one now!

Once again, I've put in links to several videos. The general criteria here are:- fairly lengthy (more than 1-2 minutes); and accurate. I *won't* say interesting too... because it's not my business to tell you what would interest you. I have also included a link to one of my favourite blogs; *The Landslide Blog,* written by Dave Petley of University of Sheffield in the UK; and this leads into several other blogs hosted by The American Geophysical Union (AGU) in all sorts of Earth Sciences fields, not just geophysics. This should keep you going for a while.

I might do a regular feature (for a while at least). I have two themes in mind. One is a follow-up with extra information about some district visited by AGSHV in the past. On 13th September 2019, the members on Safari 2019 visited Moogerah Dam on Reynolds Creek in S E Queensland. It may not have been clear that Reynolds Creek is an antecedent/superimposed stream that leaves fairly flat country, and flows into a gorge right through a prominent hill. This is rather like Esk Creek near Esk, where we looked at various features during *Safari 2018 – Carnarvon Gorge and Beyond*. (I included this in Newsletter #1.) See p 19.

There is another theme that I could spread over a few issues: various circular or otherwise round structures on the ground. There are three main types: circular mounds about 5-20 m wide and 1-2 m high, elongate round depressions about 5-10 m across and 1 m deep, and circular flat areas about 5-10 m across. In the first instalment (this Newsletter #2) I deal with one type of round depressions. See p 25.

We have some wonderful contributions from members in this issue. **Steve Low** sent me a photo of the Finke River, which cuts through an anticline in the Northern Territory. The circumstances behind the photo are really interesting, so see p 14. I've added a bit of detail about how this geological situation could have happened, and its significance for the geological history of Central Australia.

Winston Pratt is writing a series of articles with a particular theme for our Newsletter – PALEO PERIOD PLANTS of SOUTH-EASTERN AUSTRALIA, illustrated by representative specimens, for each Period from the Silurian/Devonian to the Quaternary. This major undertaking is a work in progress; I won't store these articles up until Winston finishes; I'll include them as they arrive, starting on p 8 of this Newsletter.

Once again, I've included something unusual about the geology or landscape of southern Africa (not necessarily South Africa every time). This counts also as an article on round depressions. See p 25.

There is also some visual and audiovisual content about a long-standing puzzle in Death Valley in California, and how the puzzle was solved, on p 33.

Rick Holden has forwarded a couple of papers on aspects of the Lachlan Orogen. I've included a summary paper presented at the 2019 Australasian Exploration Geoscience Conference. See p 34.

Geological videos

Here's a list of videos I found on-line...

Active Volcanoes in Australia?!
or https://www.youtube.com/watch?v=n6DGDQ4AYJc
(This is from the website http://exploringtheearth.com/, which is one of my new favourites.)

Geoscience: Beneath the Australian Alps
or https://www.youtube.com/watch?v=_S-024Cb5VE

Geoscience: The Stavely Arc – uncovering the geological evolution of western Victoria
or https://www.youtube.com/watch?v=yPf4UAK4k14

Volcano alert! Towards predicting volcanic eruptions - BrisScience - 6 August 2018
or https://www.youtube.com/watch?reload=9&v=R5sztEu6mk0

Siccar Point - the birthplace of modern geology
or https://www.youtube.com/watch?v=JCEDCcHcpYE

Catastrophe - Episode 1 - Birth of the Planet
or https://www.youtube.com/watch?v=TaQg0M1BhW4

Catastrophe - Episode 2 - Snowball Earth
or https://www.youtube.com/watch?v=HV4EirRu6bA

Catastrophe - Episode 3 - Planet of Fire
or https://www.youtube.com/watch?v=00ILddHJlKw

Catastrophe - Episode 4 - Asteroid Impact
or https://www.youtube.com/watch?v=hqt4US72yec

Catastrophe - Episode 5 - Survival Earth
or https://www.youtube.com/watch?v=9ggh2iHIneM

When Antarctica Was Green
or https://www.youtube.com/watch?v=cC4WiBCoVeo

The Power of Volcanoes Pt. 1: Years without Summer | Full Documentary
or https://www.youtube.com/watch?v=D7fR2Z880z8&t=1608s

The Power of Volcanoes Pt. 2: In the Shade of burning Mountains | Full Documentary
or https://www.youtube.com/watch?v=gzJ5oy-DBoA

BBC Men of Rock 1 of 3 Deep Time
or https://www.youtube.com/watch?v=FYfuI2uZLmg

BBC- Men of Rock 2 of 3 Moving Mountains
or https://www.youtube.com/watch?v=w8k5iqCnUnM

BBC Men of Rock 3 of 3 The Big Freeze
or https://www.youtube.com/watch?v=K7Ej2-mFsIQ

Birth of Britain 1 of 3 Hidden Volcanoes
or https://www.youtube.com/watch?v=aBWJZBdWug0

Birth of Britain 2 of 3 Ice Age
or https://www.youtube.com/watch?v=nvk6DUmTuvE

Birth of Britain 3 of 3 Gold Rush
or https://www.youtube.com/watch?v=oQaT6IVIzs0

Australia's Jurassic Park - BrisScience - 22 May 2017
or https://youtu.be/ZkkJgFHkHI0

That Time the Mediterranean Sea Disappeared
or https://www.youtube.com/watch?v=HooZ84rpovQ

Rick Miller has sent in the following, which opens as an on-screen pdf (not a video). (Thanks Rick!)

Emerging geological concepts, and how they are changing Victorian gold and base metals prospectivity
or
http://www.australiaminerals.gov.au/__data/assets/pdf_file/0010/47674/Presentation-New-Developments-in-Victorian-Geology-and-Mineral-Prospectivity-GSV.pdf

Blogs hosted by AGU (American Geophysical Union)

The AGU hosts several blogs in a variety of Earth Science fields, not just Geophysics. One of my favourites is *The Landslide Blog*, posted by Dave Petley of University of Sheffield in the UK:

https://blogs.agu.org/landslideblog/

Petley updates his blog every week or two; there are accounts of recent landslides (with video if available, often local news footage), re-visits to famous historical landslides, and notices of upcoming conferences and reports of recent ones. There is an article for every day or two... we live on an unstable world, Even if you don't care for landslides, hop in anyway, and scroll down three or four screen views. Over on the right side is a panel like the one below. Click on anything that takes your fancy. *This won't work from the Newsletter; the panel below is a screen grab from the web page, not a collection of live links.*


AGU BLOGS

Dan's Wild Wild Science Journal >>

Editors' Vox >>

From The Prow >>

From a Glacier's Perspective >>

GeoEd Trek >>

GeoSpace >>

Georneys >>

Magma Cum Laude >>

Martian Chronicles >>

Mountain Beltway >>

On the Job >>

Terra Central >>

The Bridge: Connecting Science and Policy >>

The Field >>

The Landslide Blog >>

The Plainspoken Scientist >>

The Trembling Earth >>

Third Pod from the Sun >>

Thriving Earth Exchange >>

Water Underground >>

PERIOD PALAEO PLANTS of SOUTH-EASTERN AUSTRALIA

Following will be a series of posts in which fossil vascular plants for each of the Geological Periods from Late Silurian to Quaternary will be presented. These posts will include the Gondwana floras of the Permian Glossopterids and Triassic Dicroidium floras. These Gondwanan floras, so well represented locally, are not well represented in publications which largely originate in the Northern Hemisphere.

While not all members of each flora can be shown, where specimens are available, some representative examples will be.

(Winston Pratt)

PERIOD PALAEO PLANTS of

SOUTH-EASTERN AUSTRALIA

1. THE BARAGWANATHIA FLORA

LATE SILURIAN—EARLY DEVONIAN (c. 425—395 Ma)

Vascular plants are plants with a structure in the stem enabling the plant to stand vertically and to transport water and minerals from the roots upwards to the leaves. These are the dominant land plants. The oldest known vascular plant in the world, *Baragwanathia longifolia,* a lycopod, was discovered at this site (**Photo 1**) on Limestone Road, Yea, Victoria. This photo also shows the small quarry formed during road widening of this crest on a narrow country road. **Photo 2** shows the steeply dipping attitude of the host siltstone sediments on the immediately opposite side of the road. The specimens shown were collected from this site well before it was declared a heritage site. On subsequent visits when photos 1 and 2 were taken not a single specimen was seen.

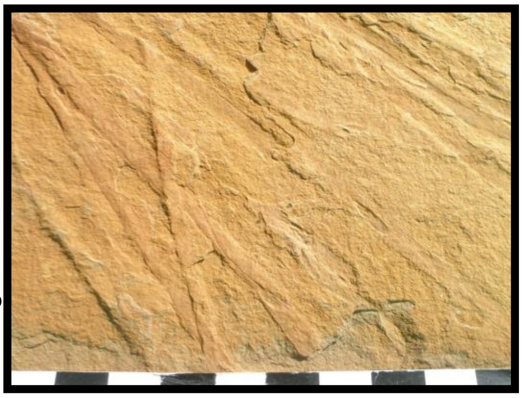
Photo 1

Photo 2

Photo 3 (left) shows the tip of a young frond of ***Baragwanathia longifolia.***

Photo 4

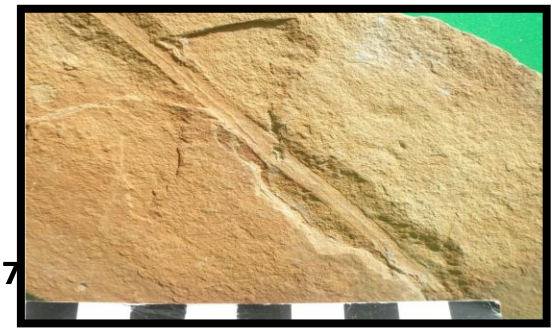
Photo 5



Photos 4 & 5 show fronds of *Baragwanathia longifolia* (5mm wide on specimen, 3mm in 'Greening of Gondwana' by Mary White) which (under the binocular microscope) show in places patches of sporangia at a spacing of about six across the width of the frond.

Photo 6

Photo 7



Photos 6, 7 & 8 show a possible stem of *Baragwanathia longifolia* with a distinct midrib but lacking the leaf scars as in Photo 70 in 'Greening of Gondwana' by Mary White. In Photo 70 the stem is 25mm in width but in the specimen here is only 4 mm in width.

(Winston Pratt)

PERIOD PALAEO PLANTS of

SOUTH-EASTERN AUSTRALIA

2. The GIANT CLUBMOSS (Lycopod—*Leptophloeum*) FLORA

Mid DEVONIAN—Early CARBONIFEROUS (c. 395—330 Ma)

The late Silurian—Early Devonian Baragwanathia Flora had evolved dramatically, producing extra thickening, strengthening and conducting tissues so enabling plants to grow into tall trees. Their spores were then able to be released higher into the air column and so be spread further. As the small inconspicuous leaves fell, the leaf cushions continued to grow with the secondary growth of the branch, and so the pattern of leaf scars expanded. By Mid Devonian times the main groups of higher plants were already delineated. The spore-producing pants were Lycopods (Clubmosses), Articulates (Horsetails) and ferns.

The specimens shown are of *Leptophloeum australe* and were all collected from locations in the Devonian Yarrimee Formation (393—372 Ma) between Purfleet and Tinonee (including the old quarry, now the site of the Taree Council Landfill), Manning Valley, NSW, Australia.

Leptophloeum australe has closely related forms in North American floras

emphasising the cosmopolitan nature of early plants and climate.

(Winston Pratt)

PERIOD PALAEO PLANTS of

SOUTH-EASTERN AUSTRALIA

3. The GIANT CLUBMOSS (Lycopod— *Lepidodendron*) FLORA

Early CARBONIFEROUS - Mid CARBONIFEROUS (c. 350—320 Ma)

By the Late Devonian the Australian land mass had moved by 35° of latitude from its Silurian— Early Devonian position and was heading southwards. The climate was cooling and stressing the Giant Clubmoss Flora which needed a tropical, swampy and high rainfall habitat for survival. The dominant lycopod in South-east Australia at this time was *Lepidodendron*. Other flora included the arborescent horsetail *Calamites.*

Photo 1 shows a plaster cast of a latex mould of a poorly reserved specimen on top of a very large boulder of the Flagstaff Formation, 25 km north of Dungog, NSW. The Flagstaff Formation is a medium grained, thickly bedded, marine lithic sandstone of Early Carboniferous (Visean, c. 335 Ma) age.

Photo 2 shows a photo of *Lepidodendron mansfieldense* taken from 'Australian Fossil Plants' by Mary E White, and in which the bark pattern of elongated lens-shaped leaf bases can be more clearly seen.

Photo 1

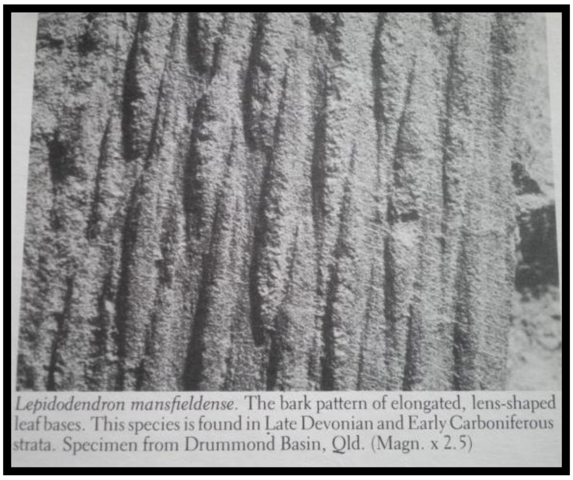

Lepidodendron mansfieldense. The bark pattern of elongated, lens-shaped leaf bases. This species is found in Late Devonian and Early Carboniferous strata. Specimen from Drummond Basin, Qld. (Magn. x 2.5)

Photo 2

(Winston Pratt)

The Finke Gorge, and the "World's Oldest River"

Steve Low sent me a photo that he took in-flight of the marvellous Finke Gorge, about 115 km WSW of Alice Springs:

Finke Gorge from 20,000 ft. View looking NW upstream along the Finke River. Note meanders incised in the rocks of the anticline. Photo – Steve Low, 1971.

He says that *"...our formation of three Mirages was on track that day.*

On the flight to Alice the previous day, my compass was the only one indicating the correct heading, and as I was a very junior pilot and the other two had the same error, they used theirs. We flew in cloud in close formation for 45 minutes before becoming visual over the Simpson Desert, and abeam Alice we were 50 nautical miles north of track.

I shut down at Alice with 13 gallons of fuel that day and had a few beers afterwards in what would replaced by "counseling" these days. At best of times Mirages were a akin to a very high speed Tiger Moth, but these particular aircraft were stripped of much electronic equipment (like radar) for the RAAF golden jubilee airshow in Perth."

The above is a quote from one of Steve's emails. He must have many other stories to tell (or keep to himself).

Here is a vertical view of the area.

Finke River meanders incised in folded rocks, at Finke Gorge, Northern Territory. The river flows from north to south.

This view shows where the Finke Gorge is located, and displays several other examples of incised meanders:

Location of Finke Gorge, towards lower left corner. Note also: other incised meanders upstream and downstream from Finke Gorge; Hugh River's meanders incised in Lawrence Gorge through the Waterhouse Range (centre), and on Hugh River where it cuts through the James Ranges (lower middle). There are many other instances of incised meanders outside this field of view, especially to the west.

The interpreted geological history is quite fascinating but rather roundabout.

Stream meanders form on flat land, in the stream's own alluvial sediment. If the meanders are incised in rugged land (especially on a stream cutting right through rugged tracts), there is a strong argument that the land's ruggedness developed after the stream's meanders formed. So the stream would be older than the age of the ruggedness. This is a stream that is **antecedent** to the surrounding topography.

There is an exception to this scenario: The rugged land can be covered by a later stratigraphic unit, into which the meanders were cut, and eroded down into the rugged basement. In this case the stream postdates the cover and the basement's ruggedness. This scenario requires *all* the postulated cover sequence to vanish *completely* by erosion. This is a stream that is **superimposed** on the underlying rock units.

Putting this together for the Finke Gorge meanders... The folds are assigned to the Alice Springs Orogeny, a protracted deformation and mountain-building episode in Central Australia, stretching from approximately 400 million years ago (Ma) to about 330 Ma. The interpretation is that the Finke was a meandering river, in-place on flat land before the folding commenced; and as the orogeny got under way, the folds (and the ruggedness associated with mountain building) developed too slowly to displace the path of the stream, which continued to erode its gorge in the same place. The river is older than the episode of folding.

This notion suggests that the Finke's course is older than the Alice Springs Orogeny... and has led to touristy claims that "the Finke is the World's Oldest River". In this scenario it is difficult to choose in age between the Finke and any other of the region's rivers that display incised meanders. Likewise in other orogens (including overseas), incised meanders would be older than their deformed host rock, but proving that the Finke River is oldest of all would require an exhaustive search of the World's orogens, to find one older than the Alice Springs Orogeny (or at least the event at Finke Gorge) which displays incised meanders, and then a detailed program to date the orogeny.

Is there any evidence for the alternative scenario... a younger cover into which the river was cut, but which has been largely or completely eroded away? Careful inspection of the appropriate 1:250,000 Geological Sheets doesn't reveal evidence for an extensive covering sequence that has been largely removed by erosion, so some tracts of the Finke's course (and others) very probably are antecedent i. e. older than ~330 Ma (or earlier, perhaps even earlier than ~400 Ma).

Other features in Central Australia consistent with antecedent streams cutting through topographic features include the numerous water-gaps: (Trephina Gorge, Undoolya Gap, Jessie Gap, Emily Gap, Heavitree Gap, Honeymoon Gap, Standley Chasm, Ormiston Gorge, Glen Helen Gorge, and so forth.) The climate is arid, so water rarely flows through them; but they aren't wind-gaps (where a stream no longer flows through a gap because the stream has shifted to a different course).

There is an interesting link here back to Winston's articles, especially the one on the Baragwanathia Flora. The oldest (Late Silurian, ~420 Ma) known vascular land plant genus is *Baragwanathia* (as Winston points out), and the first-ever (unknown) vascular plans were probably not much earlier. It is very likely that the vascular plants were the first ones with sufficient strength to hold the soil together. Before then the land surface was presumably much more prone to erosion than now. There is a view that meanders can form in alluvium only when it is tightly-bound by land plants, and that at earlier times, braided streams were more prominent (in modern times, braided streams are prominent where vegetation is sparse, such as arid and frigid areas).

The start of the Alice Springs Orogeny is quite close to the time of the earliest vascular plants. It is probable that meandering streams could not have formed much earlier than those in the Finke River. "Older" rivers might necessarily have been braided rather than meandering.

The earliest body fossils of land animals were of a millipede-like creature from Shropshire (England), also about ~420 Ma; although trace fossil tracks, possibly of millipedes go back to Late

Ordovician (~450 Ma) of Pennsylvania. Is the advent of dry-land animals related to the development of vascular plants?

The real jewel in this region is Hugh River, where it cuts through the James Range:

Hugh River cuts through James Range. Note four meander cut-offs on Hugh River; two incised near the middle, a larger one incised at bottom centre on the west side of Hugh River, and a more recent smaller one (not incised) opposite the latter. There is another small incised meander cut-off on the stream that flows in from the northwest corner, somewhat short of halfway downstream to the confluence with Hugh River.

(Bill D'Arcy)

Read any Good Books Lately?

The Measure of All Things; The Seven Year Odyssey and Hidden Error that transformed the World – By Ken Alder – 2002; The Free Press (a division of Simon & Schuster) – 422pp.

In June 1792 Jean-Baptiste-Joseph Delambre set out to survey the distance from Paris to Dunkirk; meanwhile fellow astronomer and mathematician Pierre-François-Andre Méchain set out to survey from Paris to Barcelona in Spain. They were embarking on a project sponsored by the French Academy of Sciences to determine the North-South distance between the two towns, which could be extrapolated to find the distance from the North Pole to the Equator along the Meridian through Paris. This distance was to be divided by 10-million to define the new standard of length – the meter.

Unfortunately their expedition coincided with the French Revolution, and they were hampered by many things, especially over-zealous citoyens they encountered who suspected them to be counter-revolutionary Loyalists and spies, or even sorcerers. Their accreditation documents from the Ancien Régime worked against them. ("There *is* no 'Cademy anymore.") Some citoyens even thought that their surveying instruments were weapons. Relations deteriorated so far between Spain and France that Méchain was suspected by the Spanish of being a spy, and was greatly impeded in his work, especially when near the border. His scrupulous pursuit of perfection, and self-doubt further delayed his progress.

The two savants met in Paris in 1795 to "reduce" the survey measurements and document their activities; whereupon Méchain suddenly returned to Mediterranean Spain to extend the southern leg to the Balearic Islands. His progress was even slower now, because he needed to wait for clear weather to make the long-range sightings from mainland Spain to the islands. Unfortunately, while working around marshy terrain on the mainland, it is evident that he was bitten by malaria-bearing mosquitoes, and he died in the coastal town of Castellón de la Plana on 20th September 1804, leaving Delambre to complete the computations, and document the expedition and their measurements.

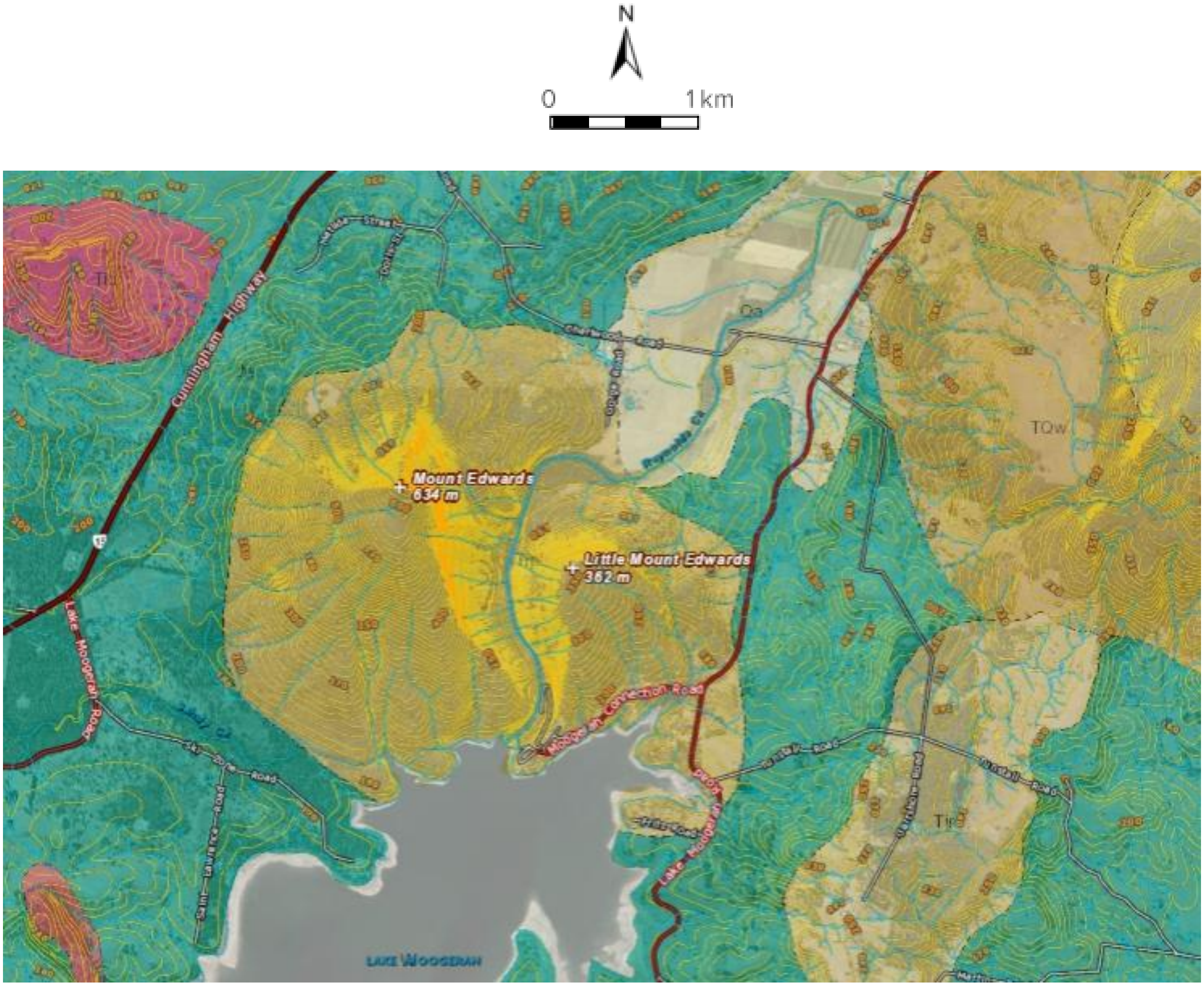
Another Look at Moogerah Dam (shades of Safari 2019).

Members on Geological Safari 2019 visited Moogerah Dam (and several other localities) on September 13th. It may not have been apparent that the stream dammed there flows right through a prominent hill.

Reynolds Creek is dammed at Moogerah Dam. Immediately downstream, the creek is in a gorge through a prominent double hill; Mount Edwards (634 m AHD) to the west, Little Mount Edwards (362 m AHD) to the east. About 2 km downstream from the dam wall, Reynolds Creek breaks out of the gorge onto a broad valley at about 110-100 m AHD). Reynolds Creek enters the reservoir at 155 m AHD (when full).

The hill consists of fine-grained feldspathic volcanic rock (trachyte) which is almost certainly intrusive.

GEOLOGY AROUND MOOGERAH DAM



Green is Walloon Coal Measures (Late Jurassic sedimentary rocks).

Mid-tan in centre is trachyte of Mount Edwards.

Mid-tan in NE corner is Mt French (intrusive rhyolite, a sill). Surrounding this is an apron of rhyolite scree (TQw) shed from cliff-forming sill.

Light-tan in SE is also intrusive rhyolite, probably a sill at lower elevation than Mt French.

Pink in NW & SW corners are intrusions of “Tertiary” dolerite.

Cream in N is alluvium of Reynolds Creek.

Mount Reynolds is a hill because it is more resistant to erosion than the surrounding Walloon Coal Measures (host rocks of the trachyte intrusion).

To the northeast of Moogerah Dam is Mount French, a composite rhyolite body that is believed to be intrusive. The individual rhyolite masses are flat-lying, and the hilltop steps up to the south, culminating at almost 550 m AHD. This suggests a sill that steps upwards to the south. Any previous cover has been eroded away, but would have been Walloon Coal Measures, up to an elevation of more than 550 m AHD. This situation points to a considerable thickness of Coal Measures, now eroded away at the location of Mount Edwards nearby; and probably even enough to once have covered the intrusion. The proto-Reynolds Creek would have flowed across this cover rock, eroding its channel at a level some distance above the body of the intrusion. As the channel floor eroded downwards it encountered the intrusion. The channel walls confined the stream against lateral deflection, and the channel deepened into the more resistant trachytes, forming a gorge. Subsequent regional erosion removed much of the more-easily eroded Walloon Coal measures, leaving the trachyte intrusion as a hill, with a stream cut right through it (off-centre). This scenario is an example of a superimposed stream.

This situation is similar to that at Esk (visited on Safari 2018), where Esk Creek cuts through the Esk Igneous Complex in a gorge, also hundreds of metres deep. See Newsletter #1.

Moogerah Dam: Lake Moogerah on the left (S), Reynolds Creek gorge downstream to the right; Mount Edwards in the background. *(Google Earth Street View)*

View looking downstream (N) along Reynolds Creek gorge. Mount Edwards to the left (W), flank of Little Mount Edwards to the right (E). *(Google Earth Street View)*

View looking SW towards the downstream exit of Reynolds Creek gorge. Mount Edwards to the right (W), Little Mount Edwards to the left (E), Moogerah Dam wall is out of sight, 2 km up the gorge. *(Google Earth Street View).*

(Bill D'Arcy)

Holmes and Watson on AGSHV Safari 1891 – The Peak District

Sherlock Holmes and Dr Watson are camping out on the AGSHV Safari to the Peak District in 1891.

After a good dinner and a bottle of wine they retire for the night and drift off to sleep. A few hours later, Holmes wakes up, and nudges his good friend awake.

> “Watson, look up and tell me what you see.”
>
> “I see thousands and thousands of stars” replies the Doctor.
>
> “And what do you deduce from that?” asks Holmes.

Watson thinks for a while and answers:

> “Well, astronomically-speaking, it tells me that there must be millions and millions of stars in the Universe, and potentially, millions of planets around them.
>
> “Speaking astrologically, I can see that Jupiter is in Pisces near the border of Aries, and Mars is in Capricorn.”
>
> “And horologically, it must be around half-past-eleven, or perhaps a little later, judging by the position of the Plough in relation to the North Star.”
>
> “Also, in a meteorological sense, the visibility of so many stars confirms that the sky has cleared, and we might expect excellent weather for visiting the outcrops tomorrow.”
>
> “In the theological domain, it confirms to me the majestic power of our Maker, who built such an infinite firmament; and also the insignificance of our part in His Creation.”
>
> He pauses, and asks: “But what does it tell *you* Holmes?”
>
> “Watson...” Holmes replies angrily, “...someone has stolen our tent!”

(*Thanks to Julie Lancaster - Editor of* Event Horizon, *newsletter of Southern Astronomical Society. Appearance of the sky, late-August 1891 date, time of night, and geographic location are all mutually consistent.*)

Light Relief during the Corona Virus Sit-In.

(Thanks Chris Morton.)


(Pinched off the Net)


(Cobbled together by Bill D’Arcy)

DOING THE RIGHT THING

Well.... It stops me from touching my face

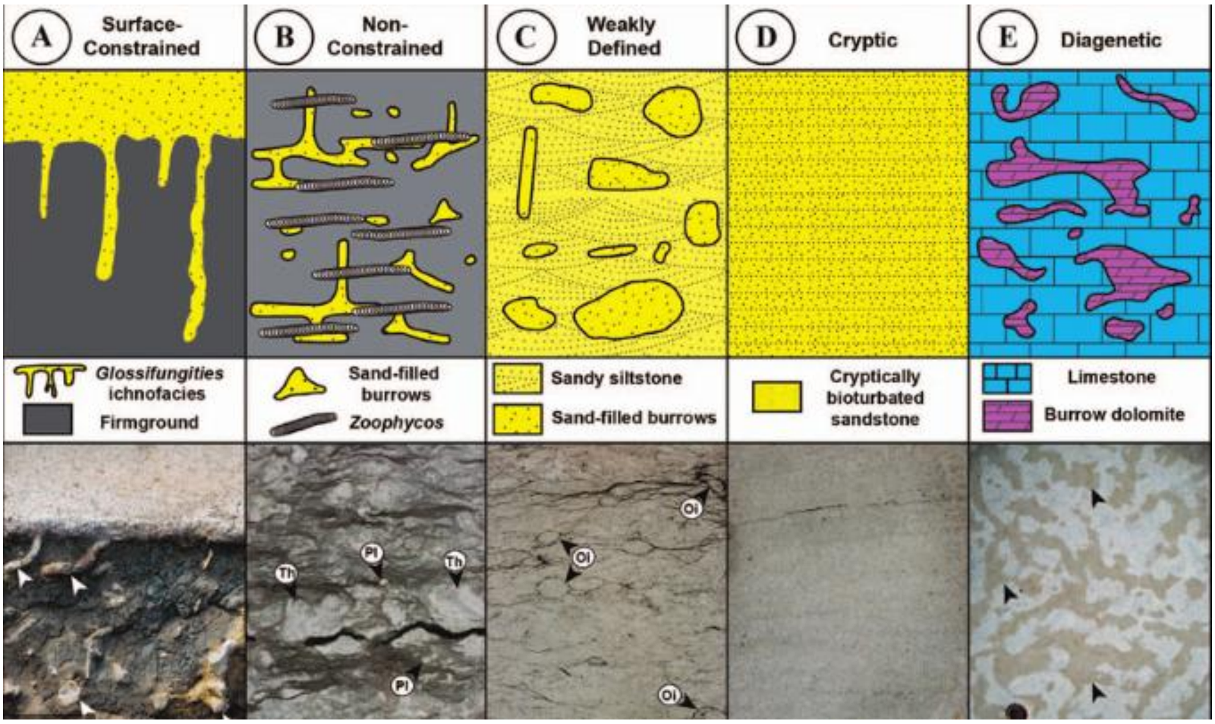
But.... Sneezing into my elbow gets messy

With Bioturbation on our Side – The Battle of Amalinde 1818.

Let's start on familiar ground. Here is a still-shot from a YouTube video; this man is on a tidal flat, pumping up salt-water yabbies for bait:

The "lumpy" surface is caused by the activities of burrowing invertebrates (including salt-water yabbies). Naturally, they disturb the shallow sub-surface sediment too. This is what most people think of as bioturbation in modern day sediment.

When such sediment has been lithified into sedimentary rock, it is often possible to study former bioturbation (the general term for the disturbance) in the vertical plane. The individual burrows etc are examples of "trace fossils" or "ichnofossils":



Earthworms also burrow, and sometimes leave their casts on the surface. This si bioturbation too:

The casts shown here are multi-coloured, showing that the earthworm responsible was moving through different soil horizons. These are the casts of an unidentified (presumably "normal-sized") garden earthworm.

Terrestrial bioturbation by earthworms plays a significant role in agriculture by improving the texture and nutrient content of soil.

In the early 19th Century bioturbation was a crucial factor at a battle in southern African.

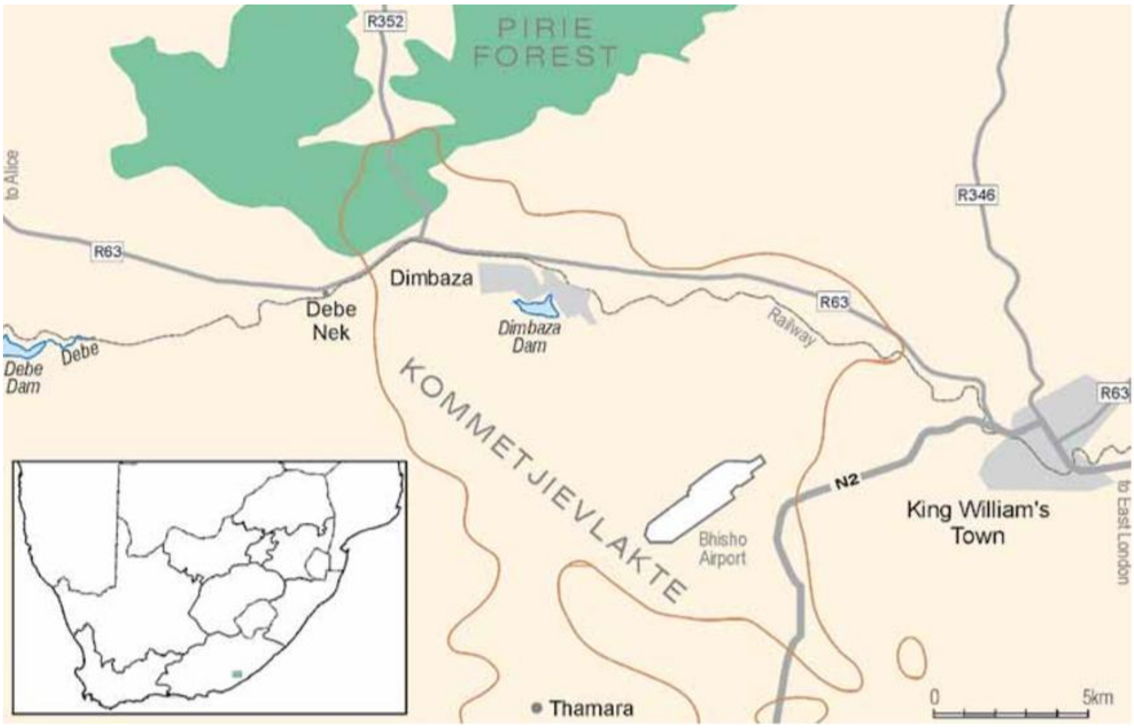
During the late 18th and early 19th Centuries, in what is now the southeast of South Africa, the Xhosa people (amaXhosa) alternated between factional rivalry and civil war. (The most famous umXhosa are the late Nelson Mandela, former President of South Africa; and stand-up comedian Trevor Noah. My own late wife had an umXhosa paternal grandmother.)

I will simplify the history and military affairs a bit, and avoid several difficult-to-pronounce personal names, by saying that young chief Ngqika decided to invade the land of his paternal uncle Ndlambe in October 1818.

Ngqika's father, chief Mlawu, died before the boy was old enough to rule as chief in his own right; so uncle Ndlambe ruled as regent for his nephew. As Ngqika came of age he wanted to claim his birthright as soon as possible, but uncle Ndlambe held on the regency too long; and this was the origin of conflict between the two. After Ngqika became chief, insult was added to injury when

Thuthula, one of uncle Ndlambe' wives, took a fancy to Ngqika, her nephew-by-marriage. Accounts differ on the degree of involvement but it was taboo under Xhosa custom, and would have deepened the personal rift. A political dimension was added when Ngqika met with Lord Charles Somerset, the Governor of neighbouring Cape Colony, in 1817. Under pressure, he ceded a large tract of Xhosa land for settlement by British farmers. As a junior chief, Ngqika had no right to do this, and King Hintsa raised a coalition of Xhosa chiefs' armies including Ndlambe, to punish Ngqika, who used the impending conflict as an opportunity to bring the battle to Ndlambe.

According to legend, the uncle's general (his own son Mdushane, cousin to the invader Ngqika) set up the defence very well. He positioned a small party of warriors out in the open as bait. The invaders, sensing an easy victory, charged at this group, which fled along a carefully-chosen escape route. Their headlong flight was past a tract of land pocked with depressions where the main defending army lay concealed. As the invaders streamed past, the defenders rose from hiding and took their foes in the flank and rear, winning the battle. This was the Battle of Debe Flats, otherwise called the Battle of Amalinde, much celebrated in Xhosa history. ("Amalinde" is derived from an isiXhosa word meaning the bowl of a ladle or spoon, and refers to the depressions in which the defenders hid. "Debe" is derived from another Xhosa word meaning pockmarked. The evocative Afrikaans name for this location is Kommetjievlakt – "small-basins-plain".) The victory shifted the balance of power in the Xhosa nation for decades, until their society collapsed following conflict with European settlers in the mid 19th Century.



Setting of the Battle of Amalinde (1818) in what is now Eastern Cape Province, South Africa. The battle-site is on the eastern outskirts of the modern town Dimbaza.

Looking SW across the Debe Flats towards the modern town of Dimbaza. The battle site was probably in the upper-left. Note the abundant amalinde-depressions in the fore-ground and middle-ground.

The amalinde-depressions here are typically elongate N-S, often 10- to 20-m long, 5- to 10-m wide, and about 1-m deep. They are interwoven with ridges that are said to resemble grave-mounds (but are rather larger, about 3- to 5-m wide); these ridges form an anastomosing network around the depressions. Amalinde-country consists of patches of this ground, typically about the size of a football field, scattered over several square kilometres.

Ground-level view of amalinde-country. The hummocky ground beyond the roadside fence consists of amalinde- (isiXhosa) or kommetjie- (Afrikaans) depressions, ringed by "grave-mound" ridges (somewhat degraded by European-style agricultural and pastoral activities). Looking northeast towards the southwestern outskirts of Zabalaza, 3 km to the west of Dimbaza town, at 32° 49' 26" S, 27° 11' 09" E, 610 m ASL.

View of a typical single amalinde-depression.

Amalinde-country seems to have been best-developed where there is a deep clay-rich soil, and was especially common on the river flats of the smaller streams. The larger rivers don't have broad alluvial plains because they are incised in narrow gorges about 100 m into the general land surface, which is typically 450-650 m above sea level.

Amalinde-country was formerly quite extensive, but has been largely obliterated by urban development, and European-style agricultural and pastoral activity. The city of East London has a suburb called Amalinde, but I don't know whether it was named in honour of the battle, or because of the presence of amalinde-country; urban development would have obscured any amalinde depressions there. The Debe Flats area north of Dimbaza and southeast of Pirie Forest (5 km to the north) is the most prominent surviving tract.

Tract of amalinde-country 3 km west of Dimbaza. The settlement in the northeast corner is part of Zabalaza. The mid-grey blobs are the amalinde or kommetjie depressions; the pale-grey anastomosing network comprises the "grave-mound" ridges between the depressions. The ground-level view of amalinde-country on p 28 is in the upper-left of this vertical view.

This remarkable micro-topography has been created by the giant earthworm *Microchaetus rappi* which some people claim is the largest earthworm in the world. (The other candidate is the giant Gippsland earthworm *Megascolides australis* from Victoria.)

Microchaetis rappi *from South Africa, the "World's Largest Giant Earthworm".*

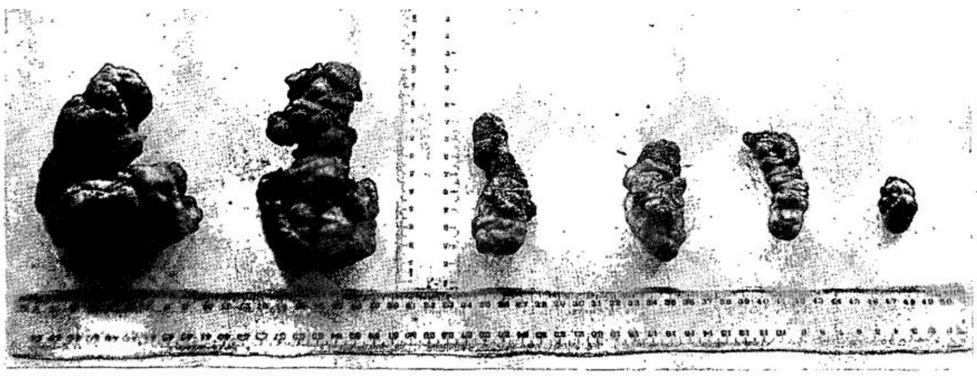
Megascolides australis *from Gippsland, Australia; the* ***other*** *"World's Largest Giant Earthworm".*

When the deep clay-rich soil became waterlogged by heavy rain, the worms got above the raised water-table by ingesting the soil rapidly, and adding the resulting piles of casts to the "grave-mound" ridges (created by their distant ancestors), into which they retreat. The topography is long-lived, so the earthworms' refuge survives from one rainy season to the next, and over many generations of earthworms. Here is bioturbation on a monumental scale.

The *Military History Journal* of The South African Military History Society published an account of the battle in 2006 in Volume 13, No 5: *The Site of the Battle of Amalinde* by F Herbst and D Kopke. The following extract describes the topography of the battlefield through European eyes, uncoloured by Xhosa folklore:

Amalinde
The exact site of the battle of Amalinde remains uncertain. It seems unlikely to have been literally on the Amalinde. The old isiXhosa word, *i-linde* or *umlinde*, means 'grave mound and/or furrow', hence the descriptive name, *Amalinde*, used to describe many of them (Kropf, 1915, p 217). No armed force would willingly choose to fight in veld covered by these features. The Amalinde mounds are up to a metre in height and the hollows between them are inconsistent in depth and size, too large to jump over. There is no level ground anywhere. The mounds are also usually covered by worm casts up to 10cm high with a mass of anything up to 800g. The Amalinde mounds and hollows are formed by the activity of giant earthworms (*Microcheatis*) in the waterlogged conditions occurring there during wet weather. Using their enormous casts, these large worms build up these mounds and retreat into them to avoid becoming soaked. The sodden conditions occur as a result of an impervious underlying rock layer which is also resistant to subaerial erosion (Kopke, 1980, pp 146-55). Men running barefooted over these micro landforms could only do so with the greatest of difficulty, so fighting here would not be by choice. And, yet, the evidence suggests thatthe terrain over which the battle of Amalinde was fought had indeed been chosen in advance. Ndlambe's strategy was that he reputedly stationed his young and inexperienced warriors in the open to serve as bait to draw out his arch-rival, Ngqika. His older and more experienced warriors were hidden and only came into action later after Ngqika's force was scattered and tired after the first encounters with the young warriors (Bokwe, 1914, pp 21-22).

A study by S.A. Materechera, O. T. Mandiringana and K. Nyamapfene, (1998): *Production and physico-chemical properties of surface casts from microchaetid earthworms in central Eastern Cape*; published in *The South African Journal of Plant and Soil* hints at the potential of these earthworms to modify the micro-topography. At a field site near Dimbaza, the production rate of worm casts for a 12-month period was calculated at 192 ± 43 tonnes per hectare (from ten 0.5m x 0.5m sampling spots). Average cast size (n=500 casts) was 6.8 ± 3.4cm high, with an average diameter of 5.6 ± 2.8 cm. The sampling zone was not on a site of amalinde micro-topography.



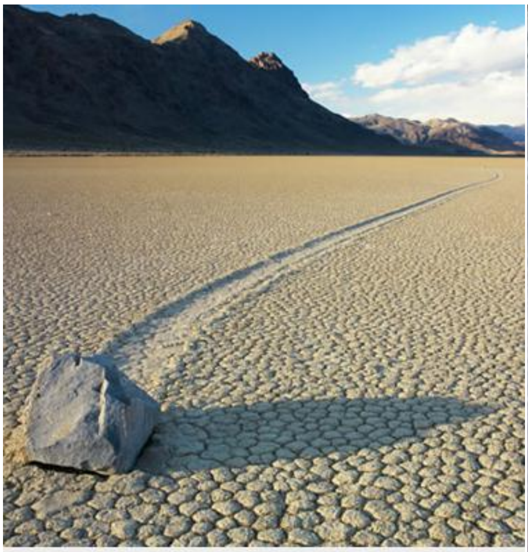
Variation in size of earthworm casts from one of the study sites.

I came across this phenomenon years ago, without recognising it. During a family gathering with my late wife's relatives in East London (South Africa) in December 2005, our son-in-law and I felt a bit "extra", so we escaped to the local bookstore. I bought a book about obscure South African battles other than the Zulu (1879) and Boer Wars (1899-1902). There is chapter in it devoted to the Battle of Amalinde. On a drive a few days later, I took a wrong turn in King William's Town, and came out along the R63 road towards Dimbaza. Before I drove too far, I recognised my mistake and returned to "King". (I wouldn't have recognised amalinde-country those days, even if I had gone as far as the Kommetjievlakte.) Only in 2019, while re-reading my copy of Tim Couzens' Battles of South Africa *did I make a serious effort to find Debe Flats in Google Earth; and then I understood the amalinde-country; and how close to it I was without knowing it.*

(Bill D'Arcy)

The Sliding Rocks of Racetrack Playa

This doesn't need text... the pictures and video are so good.



Rocks of many sizes and shapes leave tracks across Racetrack Playa. Image copyright iStockphoto / David Choo.

Landsat image of Racetrack Playa. It is the flat white area

View all three, in this order:

Geologist's Dream - Riddle of the Moving Stones
or https://www.youtube.com/watch?v=msRvp6R7bUI

How Rocks Move
or https://www.youtube.com/watch?v=uyHcs7B27Zk

The Racetrack Playa's Sliding Rocks
or https://www.youtube.com/watch?v=fGTDMhZgvQE

Here's a fairly short recent summary paper on the Lachlan Orogen, presented in Perth at the Australasian Esploration Geoscience Conference in September 2019. (Many thanks to **Rick Miller.**)

AEGC2019 Data to Discovery

Modelling the Palaeozoic tectonic evolution of the Lachlan Orogen

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SUMMARY

The Lachlan Orogen's mineral wealth is a direct result of tectonic processes that took place in the early Palaeozoic, but the exact nature and timing of events is widely contested. Here, we apply new methods of deforming tectonic reconstruction modelling to the area. The resulting reconstructions enable us to consistently compare alternative, previously-proposed models and test them against new and old data. This approach highlights model self-inconsistencies and incompatibilities with available data. We adopted an approach where the most valid components of individual tectonic reconstructions were combined to produce a new reconstruction model constrained by the most recent data. The new model invokes two concurrent subduction zones from the Early Cambrian to the Late Ordovician. It includes a consistent continent-dipping subduction at the Eastern Gondwanan margin, and an outboard subduction complex, which experiences multiple reversals. These are responsible for an unnamed Cambrian Arc and its obduction in Tasmania, which is part of the microcontinent VanDieland before accretion to Gondwana in the late Cambrian. The Macquarie Arc later develops in the Ordovician over the Cambrian Arc. A single continent-dipping system then resumes following the Benambran Orogeny, when oroclinal folding occurs across south-eastern Australia followed by east-west shortening of the Tabberabberan Orogeny.

Key words: Lachlan Orogen, Orocline, Tectonic Reconstructions, Macquarie Arc, GPlates

INTRODUCTION

The Palaeozoic Lachlan Orogen encompasses much of south-eastern Australia, including much of New South Wales, Victoria, and Tasmania, as well as Northern Victoria Land in Antarctica, parts of South Island New Zealand and the Lord Howe Rise (Figure 1). It is host to numerous economically-important world-class ore deposits (Hough, et al. 2006), however much of the basement rock lies under thick cover sequences, hence vast, potentially mineralised areas remain unexplored. Tectonic modelling aims to provide a means of determining the history of the Lachlan Orogen, and subsequently the characteristics of covered bedrock, which may aid in the increasingly-important endeavour of deep-cover mineral exploration.

Many attempts have been made to reconstruct the tectonic history of the Lachlan Orogen. Many of these published models implement the accretion of the microcontinent "VanDieland". Thought to comprise Proterozoic basement rock, it lies beneath the Melbourne Zone and is connected to the Western Tasmania Terrane (WTT) (Cayley 2011, Pilia, et al. 2015, VandenBerg, et al. 2000).

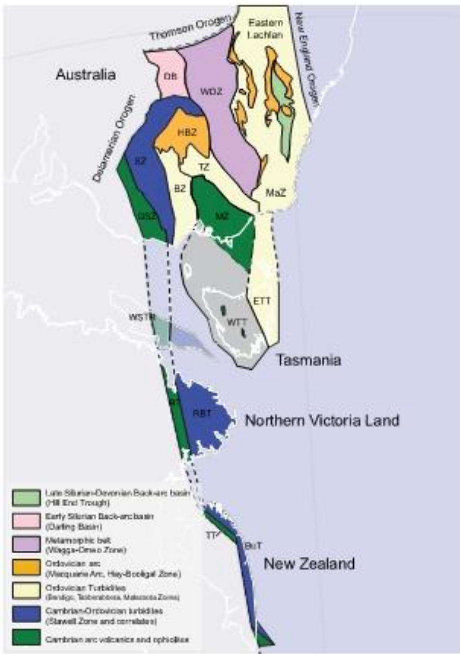

Figure 1. Modern distribution of Lachlan Orogen terranes superimposed on a Middle Palaeozoic tectonic reconstruction. Abbreviations: BT – Bowers Terrane; BuT – Buller Terrane; DB – Darling Basin; ETT – East Tasmania Terrane; GSZ – Grampians-Stavely Zone; MaZ – Mallacoota Zone; MZ – Melbourne Zone; RBT –

Robertson Bay Terrane; SZ – Stawell Zone; TT – Takaka Terrane; TZ – Tabberabbera Zone; WOZ – Wagga-Omeo Zone; WSTR – West South Tasman Rise; WTT – West Tasmania Terrane. Modified from Glen (2013).

The concept of Silurian-Devonian oroclinal folding is gaining increasing traction in modern models, based on structural vergence (Musgrave 2015) and geodynamic modelling (Moresi, et al. 2014). In this paradigm, originally parallel, north-striking accretionary terranes exist on the forearc of a continent-dipping subduction zone at the Gondwanan margin. The accretion of VanDieland causes the subduction zone to become "pinned" in the south, subsequently retreating asymmetrically and wrapping around VanDieland, dragging the forearc crust with it and causing it to fold as an orocline, resulting in the convoluted distribution of structural zones seen today.

One of the outstanding enigmas these models grapple with is the quantity, timing, polarity, and placement of subduction zones throughout the Palaeozoic. Some models opt for singular subduction (e.g. Cayley, et al. 2018), while others invoke multiple concurrent subduction zones that experience polarity reversals and retreats (e.g. Fergusson and Colquhoun 2018).

Further complicating the issue is that many published models do not consider the Lachlan Orogen in its entirety, often focussing on narrow areas in time and space. Moreover, research that has taken a broader perspective often omits the roles of Northern Victoria Land and New Zealand.

This research aims to utilise modern plate reconstruction software (*GPlates*) as a medium to produce intuitive, quantitative models that test current tectonic concepts against empirical data. This approach will facilitate the development of new models that consider the most robust aspects of the literature as well as identify areas of uncertainty.

METHOD

Tectonic reconstructions are commonly presented as two-dimensional paleogeographic maps depicting important geodynamic events at specific points in geological time. To construct a time-continuous animated tectonic reconstruction in GPlates, static tectonic models were selected from the literature that were: (a) easily testable against data and knowledge; (b) exemplars of a particular geodynamic concept; and (c) considered geologically robust. Based on these criteria, a series of published models collectively covering the entire Lachlan Orogen over a period from the Neoproterozoic to the Devonian were considered.

Static time slices from the selected tectonic models were georeferenced and imported into *GPlates* as raster images and digitised into vector features suitable for manipulation. Terranes were digitised as topological network features which, unlike normal polygons, are able to be distorted. This is useful as these features can then be used to calculate strain rates and crustal thickness changes, as well as the original geometries of enclosed structures (Gurnis, et al. 2018). The Lachlan Orogen models produced here were superimposed on a global Phanerozoic *GPlates* model (Wright, et al. 2013) combined with a model of Australian cratonic subdivisions (Collins and Pisarevsky 2005).

Published models were compared where they described similar events, and/or where they overlapped in time and space. Individual models were also assessed against more regional spatio-temporal events and constraints. For example, a given model may describe events which occur during the Cambrian in Tasmania with greater accuracy than others, but these may not be tectonically possible in the context of events occurring in Antarctica and Australia. Modifications were either made to the model in question and/or the spatio-temporal context, or it was rejected.

The models considered in this project were compared and tested against empirical data to assess their feasibility. Datasets directly used and experimented with include regional Australian magnetics and gravity grids, geochronology, structural geology (e.g. shortening estimates) and palaeobiology. These data are readily integrated into *GPlates* where they can be reconstructed according to the motion and deformation of the geology. Once the relative strengths and weaknesses of each model were determined, the most robust components of each model were extracted and iteratively modified into a new workspace to provide a comprehensive model incorporating the entire Paleozoic evolution of the Lachlan Orogen.

RESULTS AND DISCUSSION

Models were digitised and assessed, and a new comprehensive model is herein discussed, summarised by Table 1 and Figures 2a-d and 3. As work progresses and new data become available, this new model will be adjusted accordingly.

In the Neoproterozoic-Early Cambrian, most models consider VanDieland as a rifted microcontinent lying in the Palaeo-Pacific outboard of the Gondwanan margin following the breakup of Gondwana and Laurentia. Subduction to the east developed an unnamed intra-oceanic island arc which was drawn towards Tasmania and Australia, eventually obducting to form ophiolite sequences (Cayley 2011, Glen 2013, Münker and Crawford 2000). An alternative model (e.g. Cayley, et al. 2018) invokes a single continent-dipping subduction zone between VanDieland and Gondwana in the Cambrian, or alternatively at the New Zealand and Antarctica boundaries, synchronous to ocean-dipping subduction at Australia and Tasmania (Münker and Crawford 2000). These models invoke a genetic link between the Mount Read Volcanics and the Stavely Arc. However, while these formations are similar in age and chemistry, they have disparate Pb-isotope signatures indicating that the Stavely Arc formed on the forearc of the Gondwanan margin, whilst the Mount Read Volcanics formed within the outboard VanDieland block (Duncan and Bastrakov 2018). The Cambrian Mount Wright Volcanics at Broken Hill and the Mount Windsor Volcanics in Queensland's Charters Towers Province are here considered as northern extensions of the Stavely Arc (Cayley, et al. 2018). Subduction of the Palaeo-Pacific plate eventually draws VanDieland into a collision with the Gondwanan margin, representing the Ross-Delamerian-Tyennan orogenies (Cayley 2011) (Figure 2a-b).

Potential correlates of the Stavely Arc are inferred south of Victoria in the Western South Tasman Rise (WSTR; Gibson, et al. 2011), in Northern Victoria Land's Bowers Terrane (Finn, et al. 1999), and in New Zealand's Takaka Terrane (Bradshaw 2007, Wombacher and Münker 2000), indicating a belt of forearc volcanics extending across the Gondwanan margin above continent-dipping subduction. Flanking this arc are the Cambrian-Ordovician clastic sedimentary sequences of the Stawell Zone in Australia, the Robertson Bay Terrane in Antarctica (and its alleged correlate in the WSTR), and the

Buller Terrane in New Zealand (Figure 2b). The position occupied by New Zealand during the Palaeozoic is scarcely mentioned. Presuming the aforementioned correlations with the Takaka and Buller Terranes are accurate, our model places Palaeozoic New Zealand on the Gondwanan forearc south of Northern Victoria Land, situated such that the modern west coast is on the outboard side of Gondwana (Münker and Crawford 2000).

In the Ordovician, Cayley (2011) invokes sinistral strike-slip motion on the Gondwanan boundary which carried Northern Vitoria Land and the accreted VanDieland north towards mainland Australia. Synchronous to this was the early development of the Macquarie Arc overlying the former Cambrian Arc basement in the Palaeo-Pacific. While this arc was likely initially striking parallel to the Gondwanan margin, a change in subduction polarity is invoked by Fergusson and Colquhoun (2018) with ensuing rollback and clockwise rotation of the arc, allowing for Gondwana-derived turbidite sequences to surround the Macquarie Arc. A second subduction reversal brought the Placo-Pacific crust back towards Gondwana, culminating in the Benambran Orogeny (Figure 2c-d; Glen, et al. 2007). Palaeomagnetic data from the Macquarie Arc may further develop this aspect of the model.

Following the Benambran Orogeny, the hypothesised orocline described and modelled by Moresi et al. (2014) begins to form. Results of testing for the presence of a Lachlan Orocline are yet to be finalised, but the concept is carried forward here as a means of creating a digital workspace into which new data, such as palaeomagnetism, can be integrated. Orocline development concludes with the Devonian Tabberabberan Orogeny, bringing much of the Lachlan Orogen into its modern configuration (Figure 3). Later work aims to implement palaeomagnetic data currently being collected to test for this orocline (Musgrave 2015). An important question raised in this portion of the models is the role and composition of the Hay-Booligal Zone, which is depicted by Moresi et al. (2014) as a southern extension of the Macquarie Arc transported west by dextral strike-slip motion.

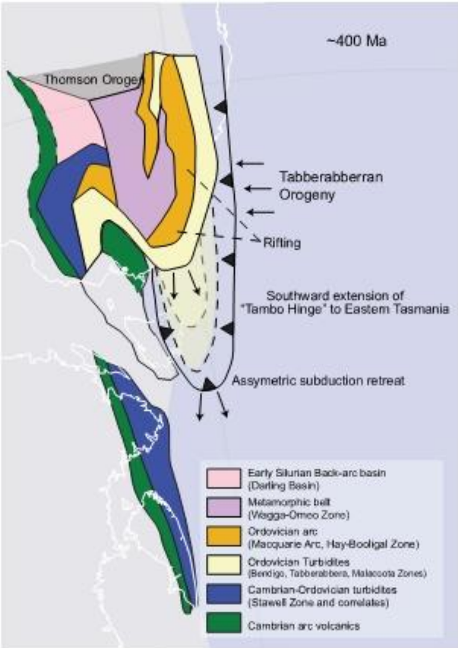

Figure 3. Oroclinal folding of the Lachlan Orogen following the Benambran Orogeny. Final configuration shown in Figure 1.

Table 1. Summarised sequence of geodynamic events and palaeogeography described in the new tectonic model for the Lachlan Orogen

Time	Palaeogeography/event	Relevant literature
Early-Mid Cambrian	Continent-dipping subduction at Gondwanan Margin	Duncan and Bastrakov (2018)
	East-dipping subduction in Palaeo-Pacific, ophiolite obduction	Cayley (2011) Münker and Crawford (2000) Mortensen, et al. (2015)
	VanDieland microcontinent on Palaeo-Pacific plate	Cayley (2011) Fergusson and Colquhoun (2018)
Late Cambrian	Ross-Delamerian-Tyennan Orogeny: accretion of VanDieland	Cayley (2011) Pilia, et al. (2015) Bradshaw (2007)
Early Ordovician	Sinistral strike-slip of Tasmania and NVL	Cayley (2011)
	Formation of Macquarie Arc over Cambrian Arc	Glen, et al. (2012) Crawford, et al. (2007)
Middle Ordovician	Subduction reversal in Palaeopacific, drawing Macquarie Arc towards Gondwana	Fergusson and Colquhoun (2018)
Early Silurian	Benambran Orogeny	Glen, et al. (2007)
Silurian	Lachlan Orocline	Moresi, et al. (2014) Musgrave (2015)
Devonian	Tabberabberan Orogeny	Fergusson (2017)

CONCLUSIONS

The many sources of literature that consider the tectonic evolution of the Lachlan Orogen have resulted in an array of contesting models. With the aid of digital plate reconstruction software, these models were systematically analysed and compared. Components of models that do not adequately reflect geological observations have been identified and rejected, and robust components integrated into a new model. This model will be continually adjusted as new data become available. Our model suggests that Cambrian accretion of the microcontinent VanDieland, lying between two opposing subduction zones in the Palaeo-Pacific outboard of Gondwana and their respective volcanic arcs, is accountable for the Ross-Delamerian-Tyennan orogenies. Development of the Macquarie Arc in the Ordovician overlaps the pre-existing Palaeo-Pacific island arc as two episodes of subduction reversal cause it to alternately rotate about its southern point before accretion in the Benambran Orogeny. Later suturing of VanDieland with mainland Australia in the Early Silurian affords the conditions for oroclinal bending of the originally north-striking terranes of the modern southern Lachlan Orogen such that it assumes its modern configuration following compression in the Tabberabberan Orogeny.

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REFERENCES

Bradshaw, J.D., 2007, The Ross Orogen and Lachlan Fold Belt in Marie Byrd Land, Northern Victoria Land and New Zealand: Implication for the Tectonic Setting of the Lachlan Fold Belt in Antarctica. *Open-File Report*.

Cayley, R., Taylor, D., Sladzien, P., Cairns, C., Duncan, R., Huston, D., Schofield, A., and Lewis, C., 2018, 4.1 Geodynamic Synthesis and Implications for the Geological Evolution of Stavely. in A. Schofield (ed.) *Regional Geology and Mineral Systems of the Stavely Arc, Western Victoria*, Geoscience Australia, 165-84.

Cayley, R.A., 2011, Exotic Crustal Block Accretion to the Eastern Gondwanaland Margin in the Late Cambrian–Tasmania, the Selwyn Block, and Implications for the Cambrian–Silurian Evolution of the Ross, Delamerian, and Lachlan Orogens. *Gondwana Research* **19**, 628-49.

Collins, A.S. and Pisarevsky, S.A., 2005, Amalgamating Eastern Gondwana: The Evolution of the Circum-Indian Orogens. *Earth-Science Reviews* **71**, 229-70.

Crawford, A.J., Glen, R.A., Cooke, D.R., and Percival, I.G., 2007, Geological Evolution and Metallogenesis of the Ordovician Macquarie Arc, Lachlan Orogen, New South Wales. *Australian Journal of Earth Sciences* **54**, 137-41.

Duncan, R. and Bastrakov, E., 2018, 3.2 Isotopic Characteristics of Known Mineral Occurrences in Stavely. in A. Schofield (ed.) *Regional Geology and Mineral Systems of the Stavely Arc, Western Victoria*, Geoscience Australia, 151-59.

Fergusson, C.L., 2017, Mid to Late Paleozoic Shortening Pulses in the Lachlan Orogen, Southeastern Australia: A Review. *Australian Journal of Earth Sciences* **64**, 1-39.

Fergusson, C.L. and Colquhoun, G.P., 2018, Ordovician Macquarie Arc and Turbidite Fan Relationships, Lachlan Orogen, Southeastern Australia: Stratigraphic and Tectonic Problems. *Australian Journal of Earth Sciences*, 1-31.

Finn, C., Moore, D., Damaske, D., and Mackey, T., 1999, Aeromagnetic Legacy of Early Paleozoic Subduction Along the Pacific Margin of Gondwana. *Geology* **27**, 1087-90.

Gibson, G.M., Morse, M.P., Ireland, T.R., and Nayak, G.K., 2011, Arc–Continent Collision and Orogenesis in Western Tasmanides: Insights from Reactivated Basement Structures and Formation of an Ocean–Continent Transform Boundary Off Western Tasmania. *Gondwana Research* **19**, 608-27.

Glen, R.A., 2013, Refining Accretionary Orogen Models for the Tasmanides of Eastern Australia. *Australian Journal of Earth Sciences* **60**, 315-70.

Glen, R.A., Meffre, S., and Scott, R.J., 2007, Benambran Orogeny in the Eastern Lachlan Orogen, Australia. *Australian Journal of Earth Sciences* **54**, 385-415.

Glen, R.A., Quinn, C., and Cooke, D.R., 2012, The Macquarie Arc, Lachlan Orogen, New South Wales: Its Evolution, Tectonic Setting and Mineral Deposits. *Episodes* **35**, 177-86.

Gurnis, M., Yang, T., Cannon, J., Turner, M., Williams, S., Flament, N., and Müller, R.D., 2018, Global Tectonic Reconstructions with Continuously Deforming and Evolving Rigid Plates. *Computers & Geosciences* **116**, 32-41.

Hough, M.A., Bierlein, F.P., and Wilde, A.R., 2006, A Review of the Metallogeny and Tectonics of the Lachlan Orogen. *Mineralium Deposita* **42**, 435-48.

Moresi, L., Betts, P.G., Miller, M.S., and Cayley, R.A., 2014, Dynamics of Continental Accretion. *Nature* **508**, 245-8.

Mortensen, J.K., Gemmell, J.B., McNeill, A.W., and Friedman, R.M., 2015, High-Precision U-Pb Zircon Chronostratigraphy of the Mount Read Volcanic Belt in Western Tasmania, Australia: Implications for Vhms Deposit Formation. *Economic Geology* **110**, 445-68.

Münker, C. and Crawford, A.J., 2000, Cambrian Arc Evolution Along the Se Gondwana Active Margin: A Synthesis from Tasmania-New Zealand-Australia-Antarctica Correlations. *Tectonics* **19**, 415-32.

Musgrave, R.J., 2015, Oroclines in the Tasmanides. *Journal of Structural Geology* **80**, 72-98.

Pilia, S., Rawlinson, N., Cayley, R.A., Bodin, T., Musgrave, R., Reading, A.M., Direen, N.G., and Young, M.K., 2015, Evidence of Micro-Continent Entrainment During Crustal Accretion. *Scientific Reports* **5**, 8218.

VandenBerg, A., Willman, C.E., Maher, S., Simons, B.A., Cayley, R.A., Taylor, D.H., Morand, V.J., Moore, D.H., and Radojkovic, A., 2000, *The Tasman Fold Belt System in Victoria: Geology and Mineralisation of Proterozoic to Carboniferous Rocks*. Geological Survey of Victoria.

Wombacher, F. and Münker, C., 2000, Pb, Nd, and Sr Isotopes and Ree Systematics of Cambrian Sediments from New Zealand: Implications for the Reconstruction of the Early Paleozoic Gondwana Margin Along Australia and Antarctica. *The Journal of Geology* **108**, 663-86.

Wright, N., Zahirovic, S., Müller, R.D., and Seton, M., 2013, Towards Community-Driven Paleogeographic Reconstructions: Integrating Open-Access Paleogeographic and Paleobiology Data with Plate Tectonics. *Biogeosciences* **10**, 1529-41.

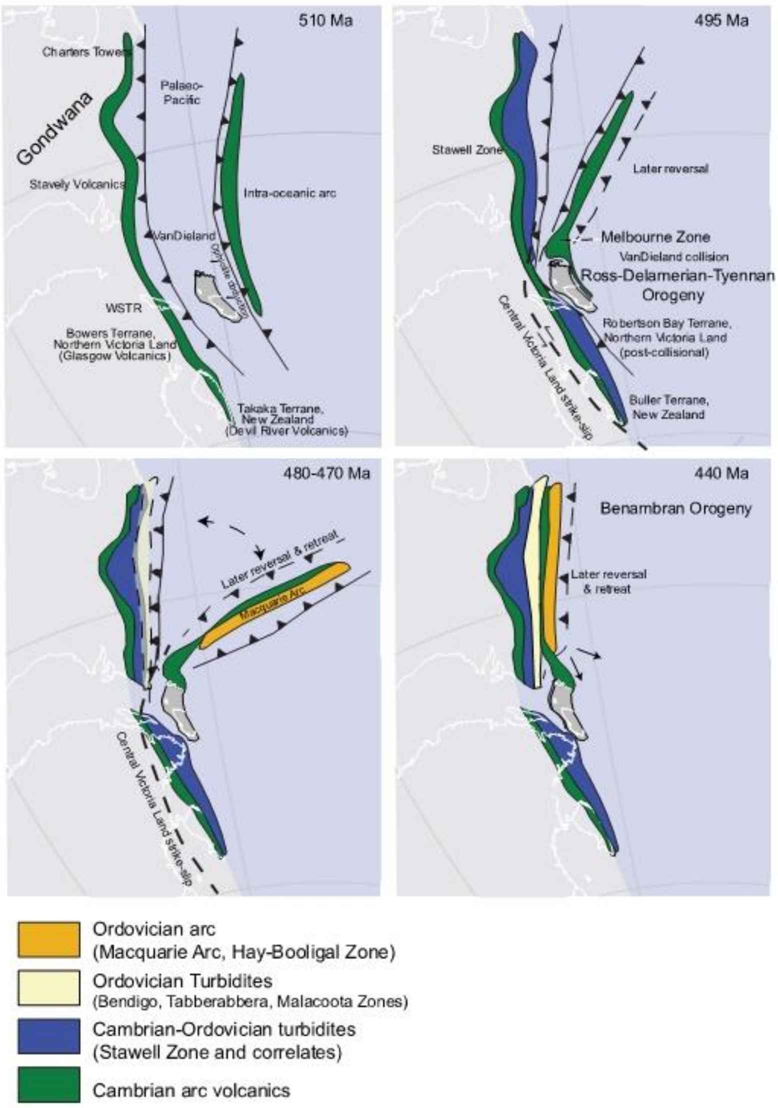

Figure 2. New tectonic model proposed for the Lachlan Orogen in the Early Palaeozoic.