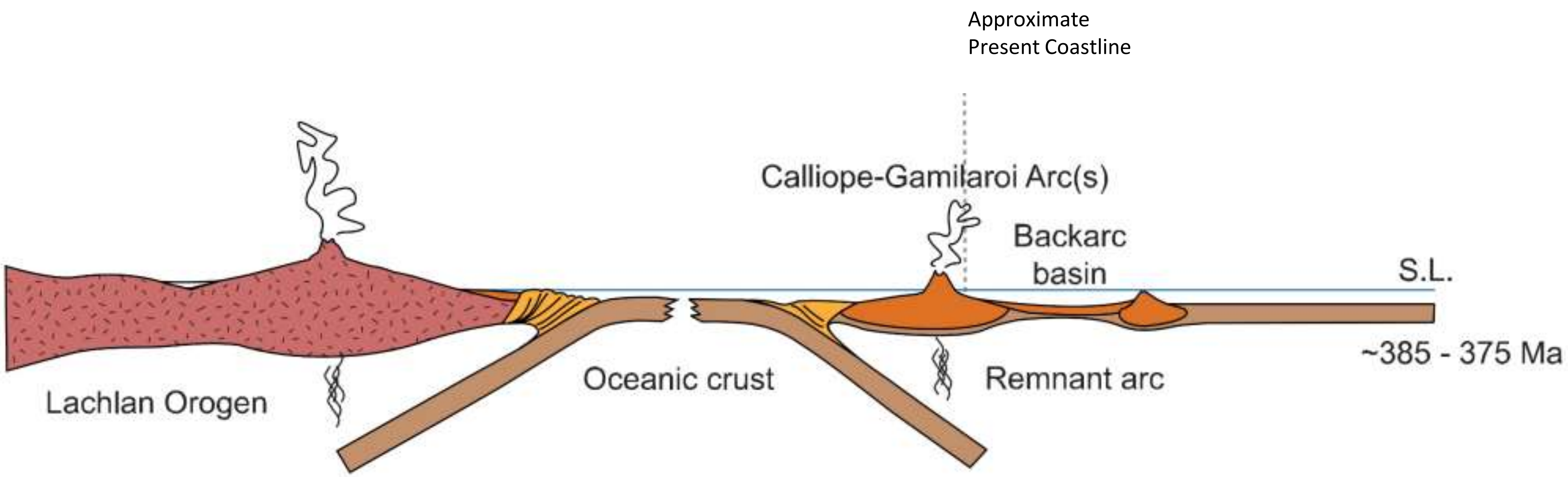
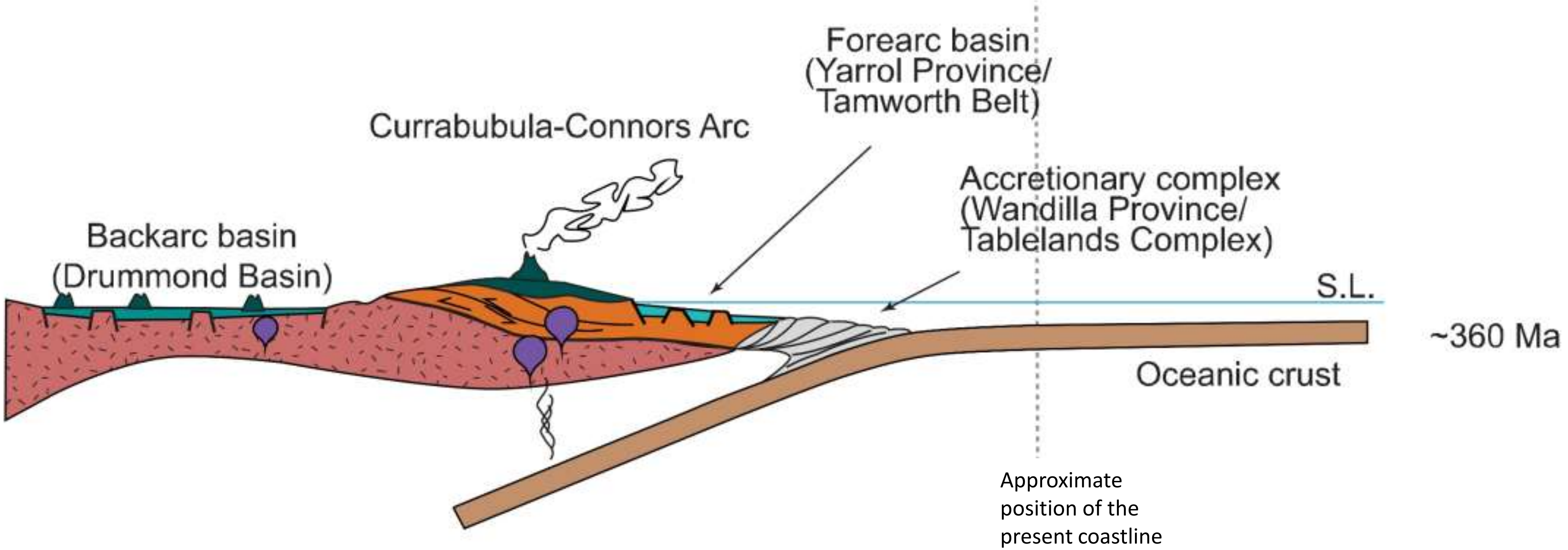
The Geomorphology of the New England Orogen and its impact on the Sydney Basin from the late Carboniferous to the Present

R Miller 2024

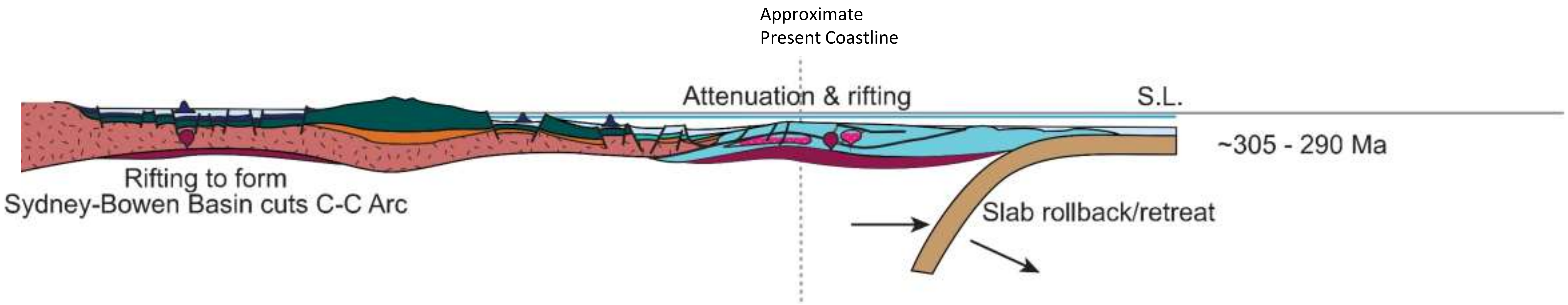


At the end of the Lachlan Orogeny, about 375 Ma in the Devonian, it is thought that two subduction zones existed off the coast of Gondwanaland. The oceanic zone produced an intra oceanic arc termed the Calliope-Gamilaroi Arc.

Cross-section from Tectonic cycles of the New England Orogen: A Review Jessop et al 2019



In the Carboniferous (about 375-305 Ma) this changed to a single, westward dipping subduction zone off the coast of Gondwanaland and it was situated in the area between the present Mid Nth Coast NSW and the Sydney Basin (Ferguson 2019)

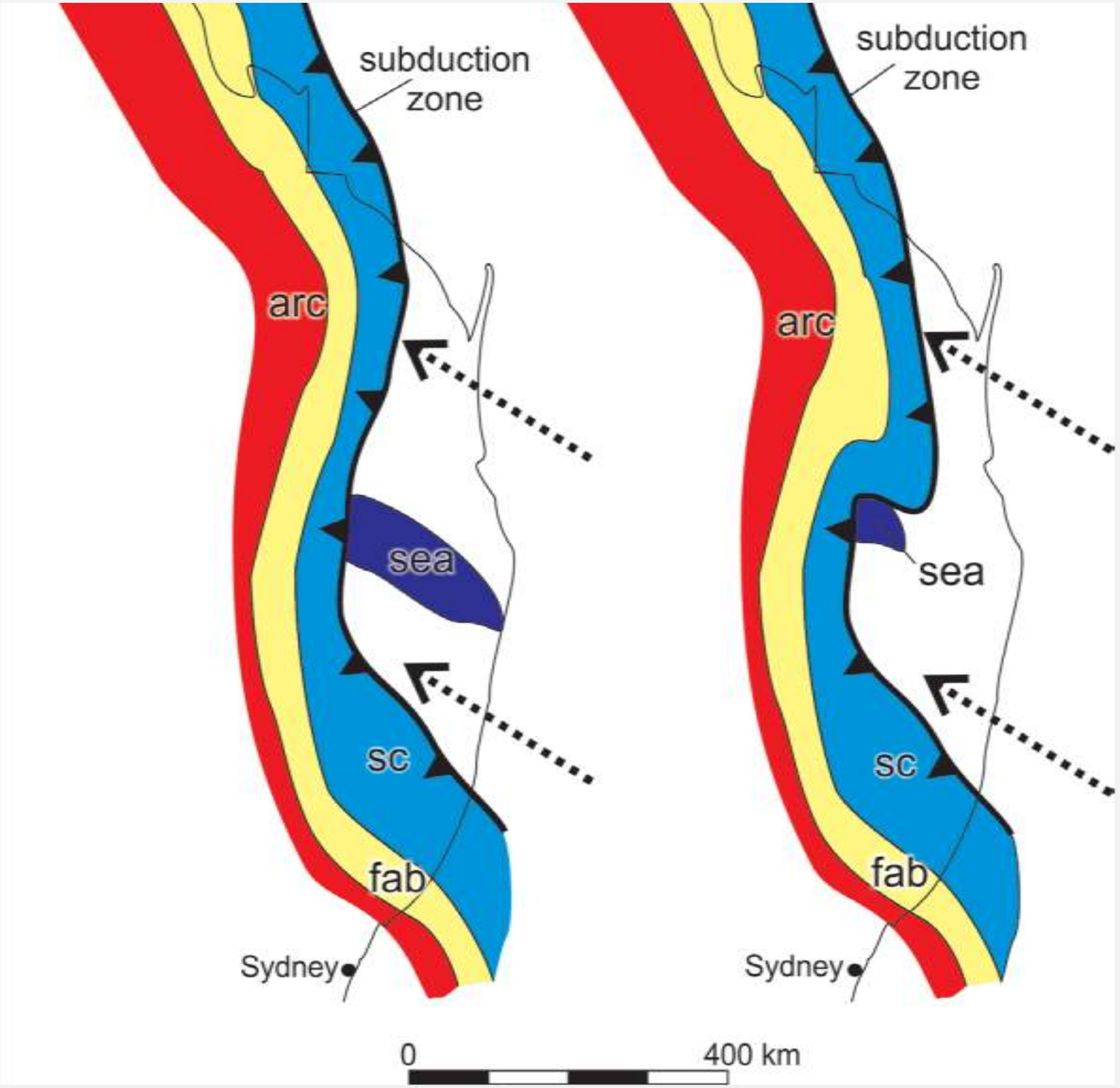


Compression Cycle 1.

The Calliope-Gamilaroi Arc was obducted onto the edge of Gondwanaland.

The Currabubula-Connors Arc was then formed with a forearc basin (The Tamworth Belt) and a back arc basin (The Drummond Basin). The accretionary wedge at the subduction zone now forms much of the Tablelands Complex.

Cross-section from Tectonic cycles of the New England Orogen: A Review Jessop et al 2019

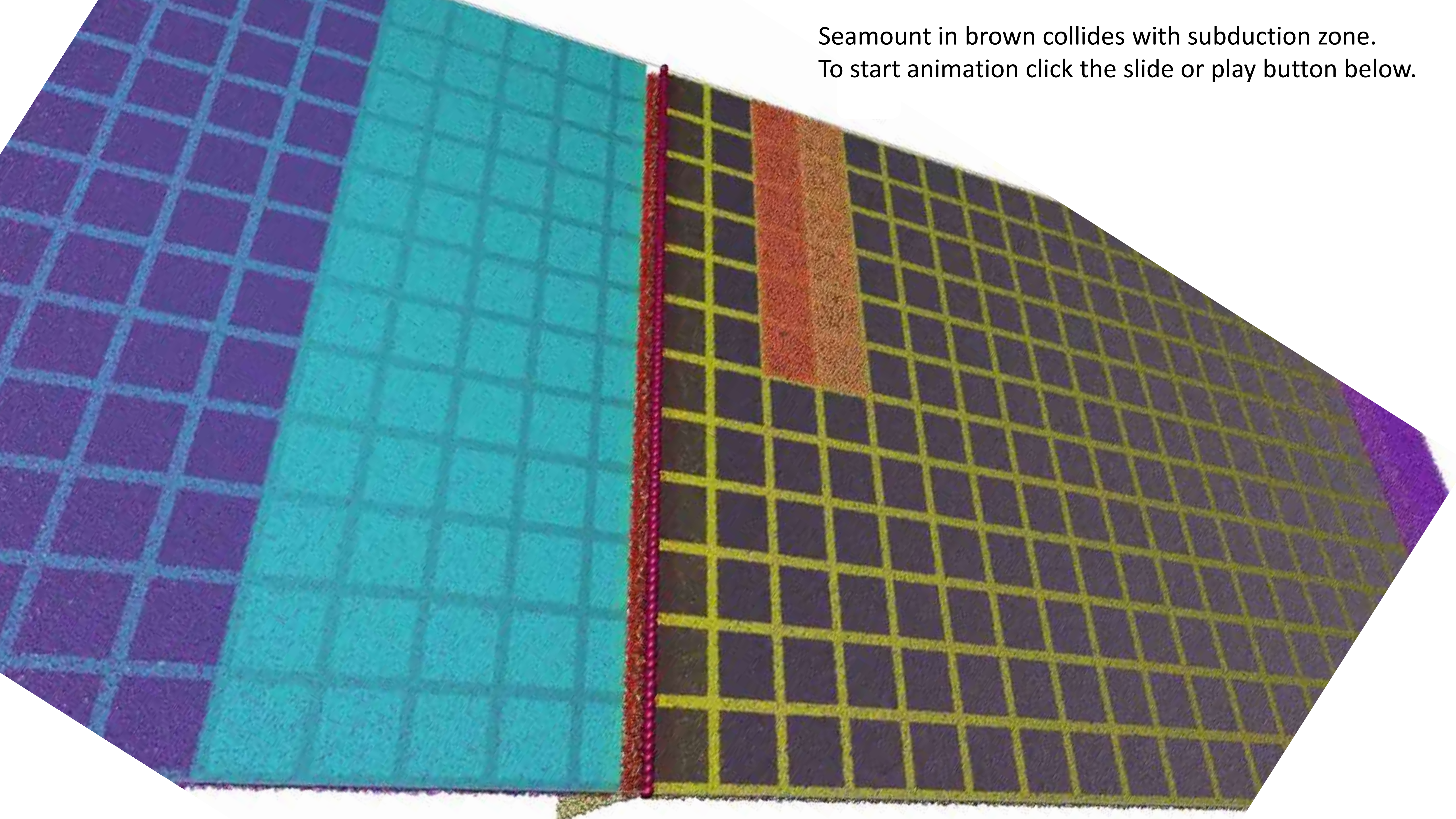


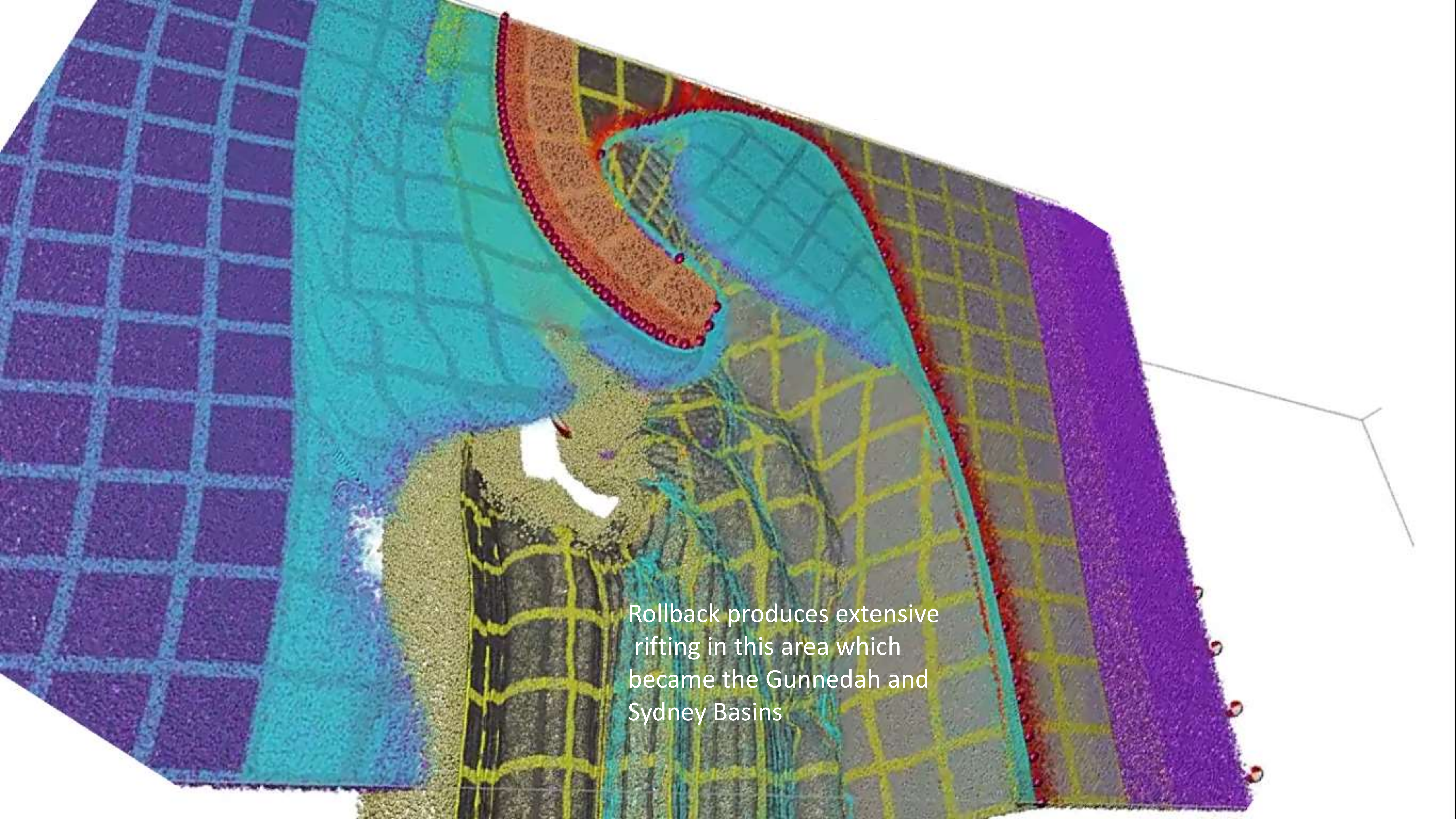
At approximately 330 Ma a seamount on the subducting plate caused the zone to be congested. An Orocline began to form as the subduction zone on either side of the seamount began to rollback/ retreat. Ferguson (2019)

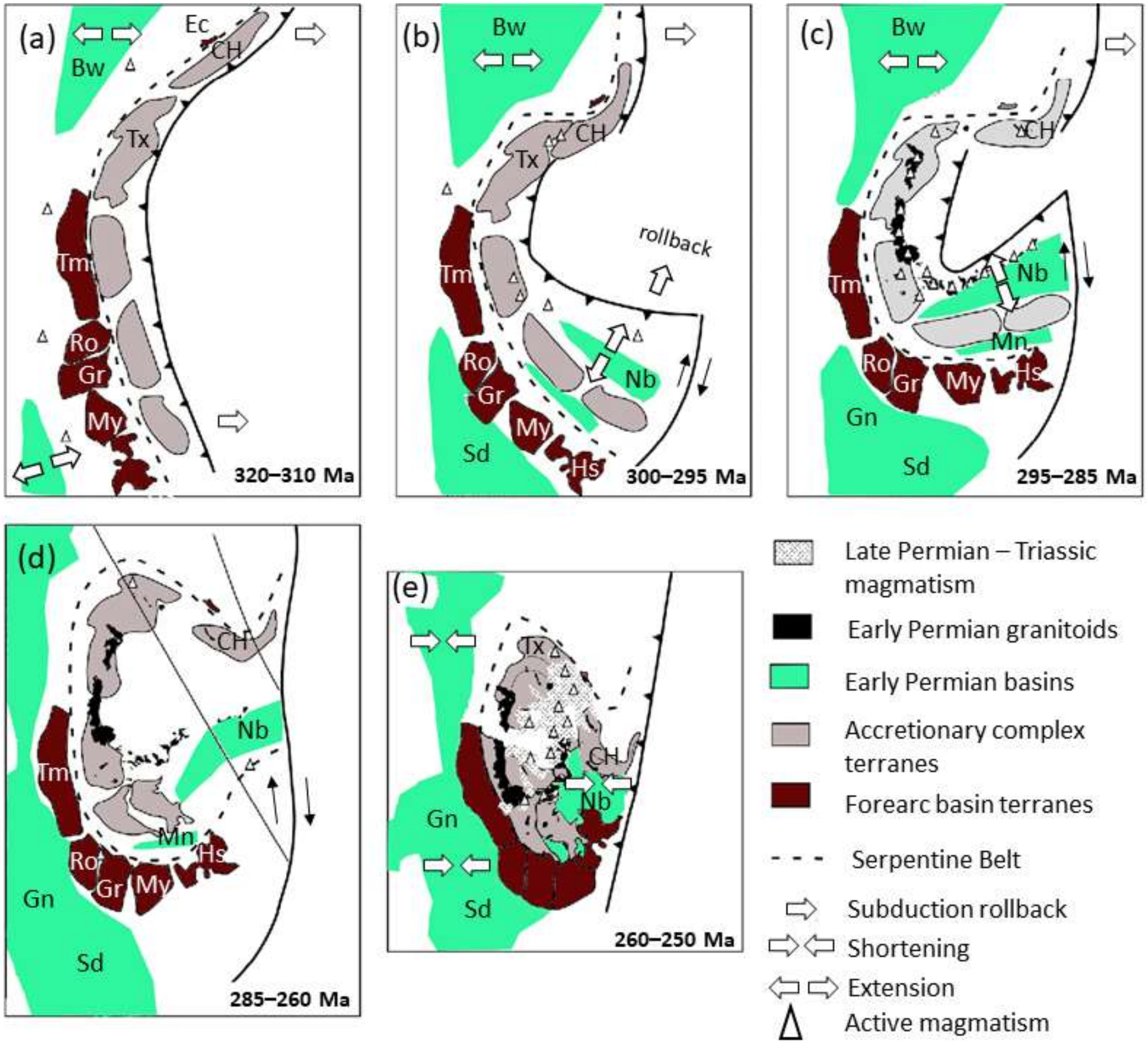
This process is illustrated in the model developed by Louis Moresi and shown in the next slide

https://www.youtube.com/watch?v=cVulRP2tUGM

Seamount in brown collides with subduction zone.
To start animation click the slide or play button below.




Rollback produces extensive
rifting in this area which
became the Gunnedah and
Sydney Basins



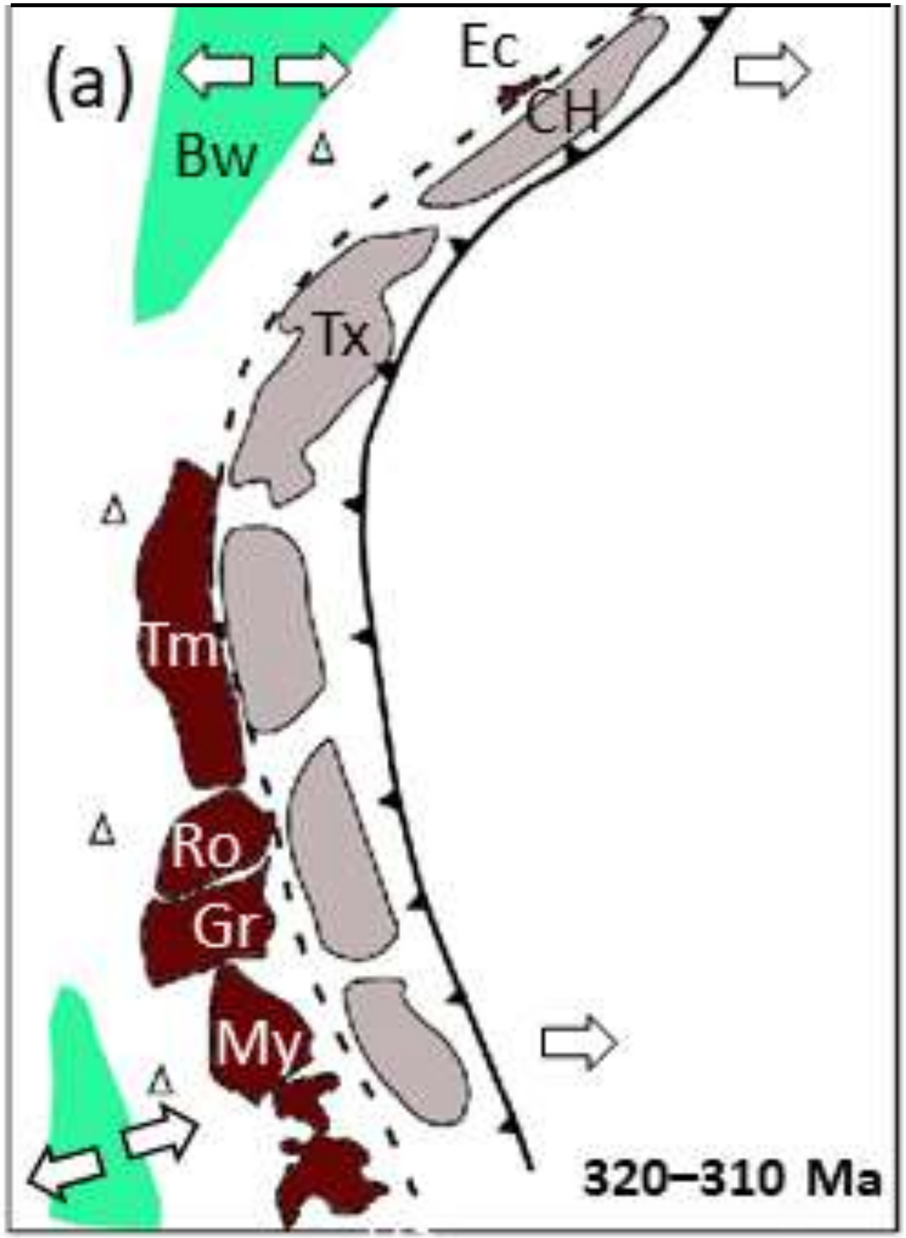
A schematic conceptual model for the development of the New England Oroclines. From Rosenbaum et. al. (2012)

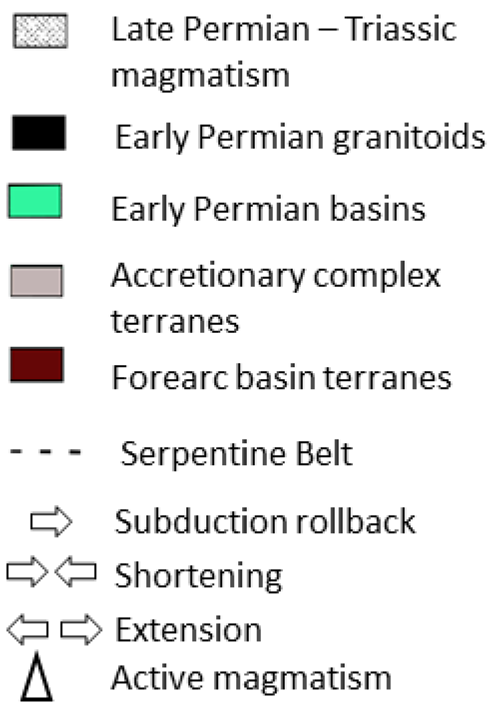
Rollback/extension in the over riding plate produces extensive rifting and the formation of the Sydney/Bowen Basin.

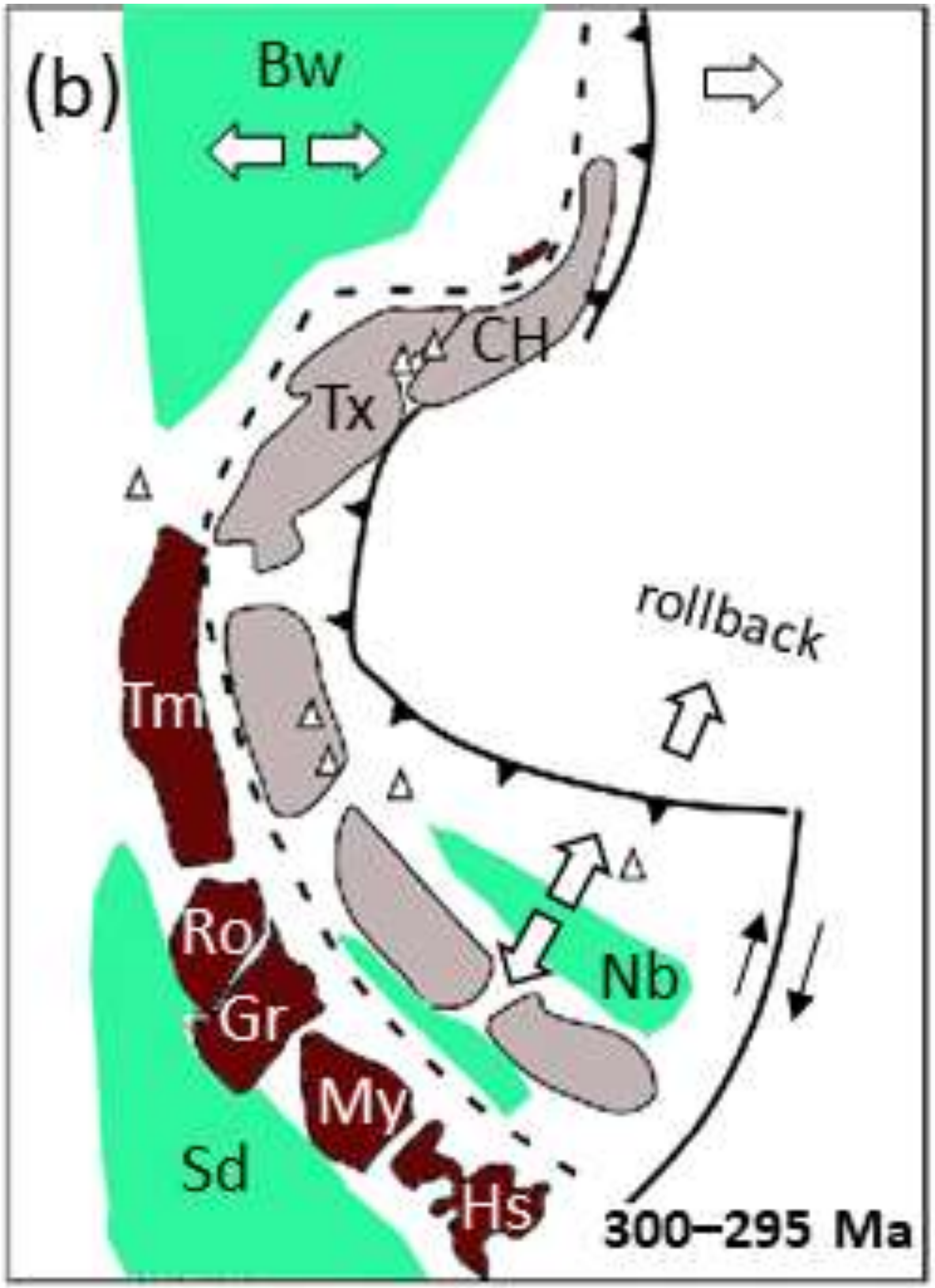
Bw	Bowen Basin
Gn	Gunnedah Basin
Sd	Sydney Basin
Ec	Emu Creek Block
CH	Coffs Harbour Block
Tx	Texas Block
Tm	Tamworth Block
Ro	Rouchel Block
Gr	Gresford Block
My	Myall Block
Hs	Hastings Block
Nb	Nambucca Block
Mn	Manning Block

In the first compressional phase a gently curved Andean-type subduction zone exists; it is west dipping.

Rollback on either side of the congested area begins a period of rifting and this initiates the Bowen and Sydney/ Gunnedah Basins

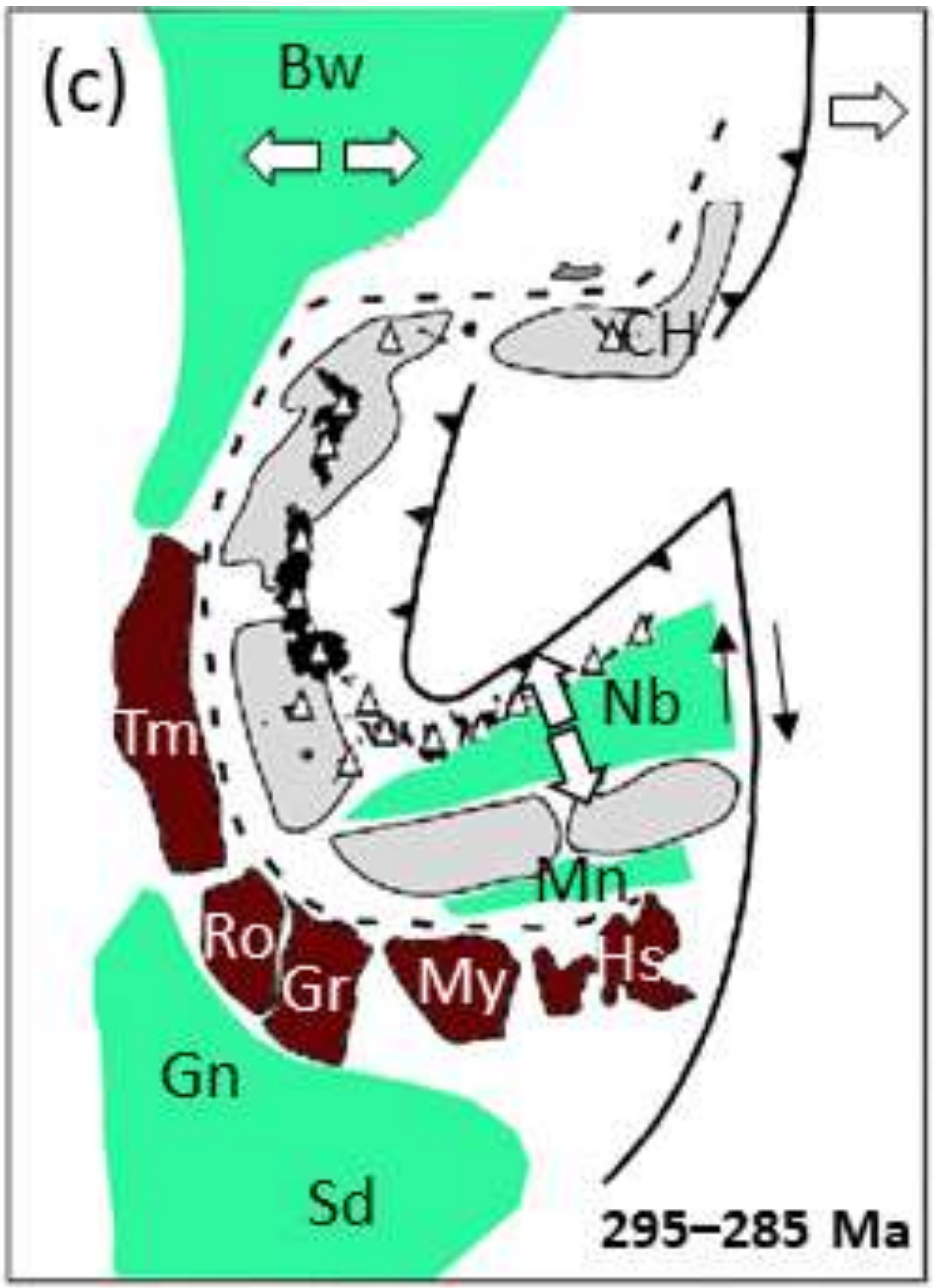






At approximately 305 Ma the congested subduction begins a period of extension and relaxation. Rollback causes slab segmentation in the north and asymmetric backarc extension in the south.

- Late Permian – Triassic magmatism
- Early Permian granitoids
- Early Permian basins
- Accretionary complex terranes
- Forearc basin terranes
- - - - Serpentine Belt
- ⇨ Subduction rollback
- ⇨⇦ Shortening
- ⇦ ⇨ Extension
- Δ Active magmatism



Nearing the culmination of rollback, wholesale crustal extension produces the Manning Orocline and associated Basins.

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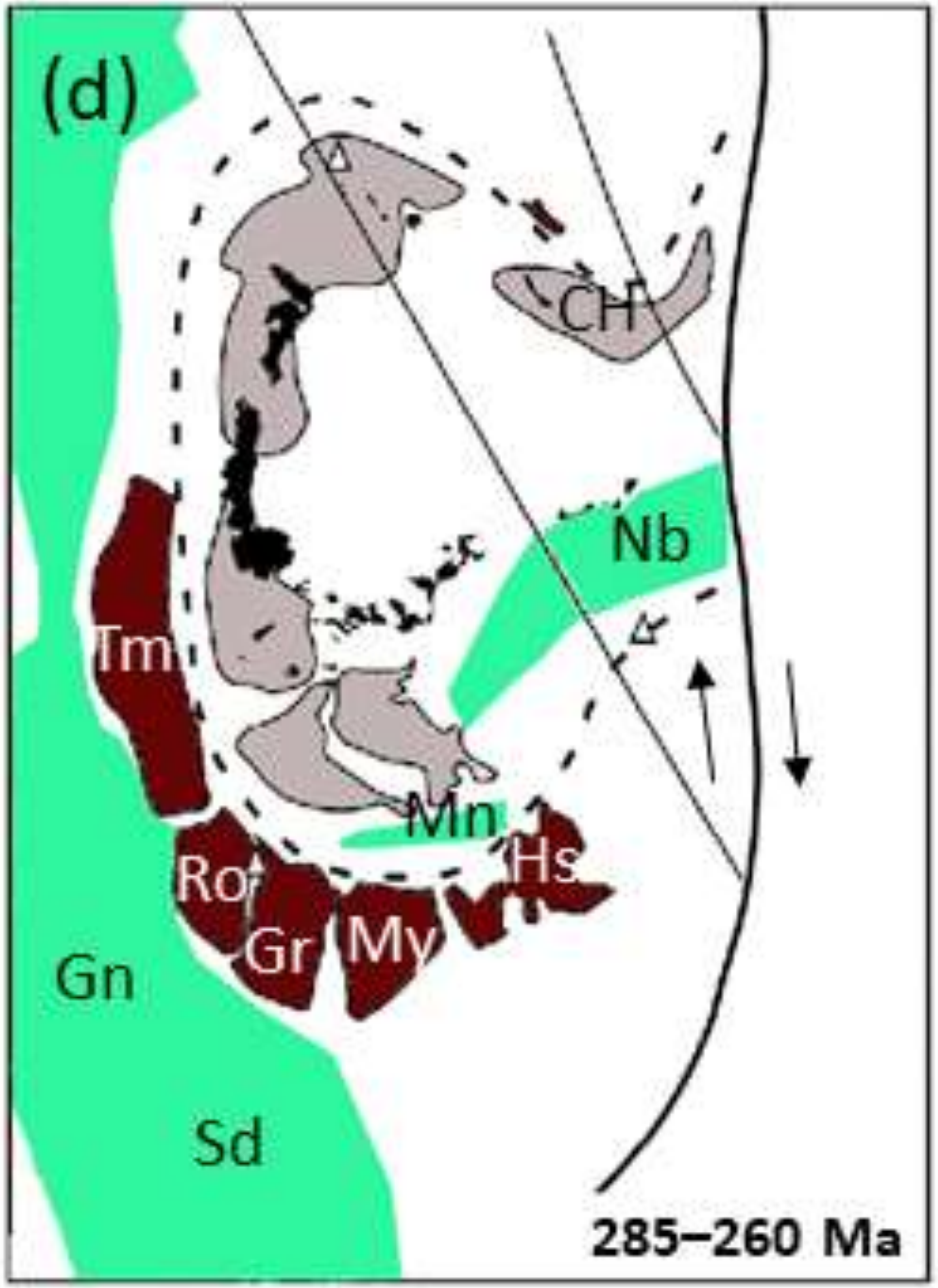
- Extension
- Active magmatism



As the Permian continues plate reorganization results in the establishment of a dextral transform boundary and associated oroclinal bending in the Texas, Coffs Harbour and Nambucca Oroclines.

Extension and relaxation deepens the Sydney Gunnedah Basin and allows magma to intrude into strata distorted in the Oroclines.

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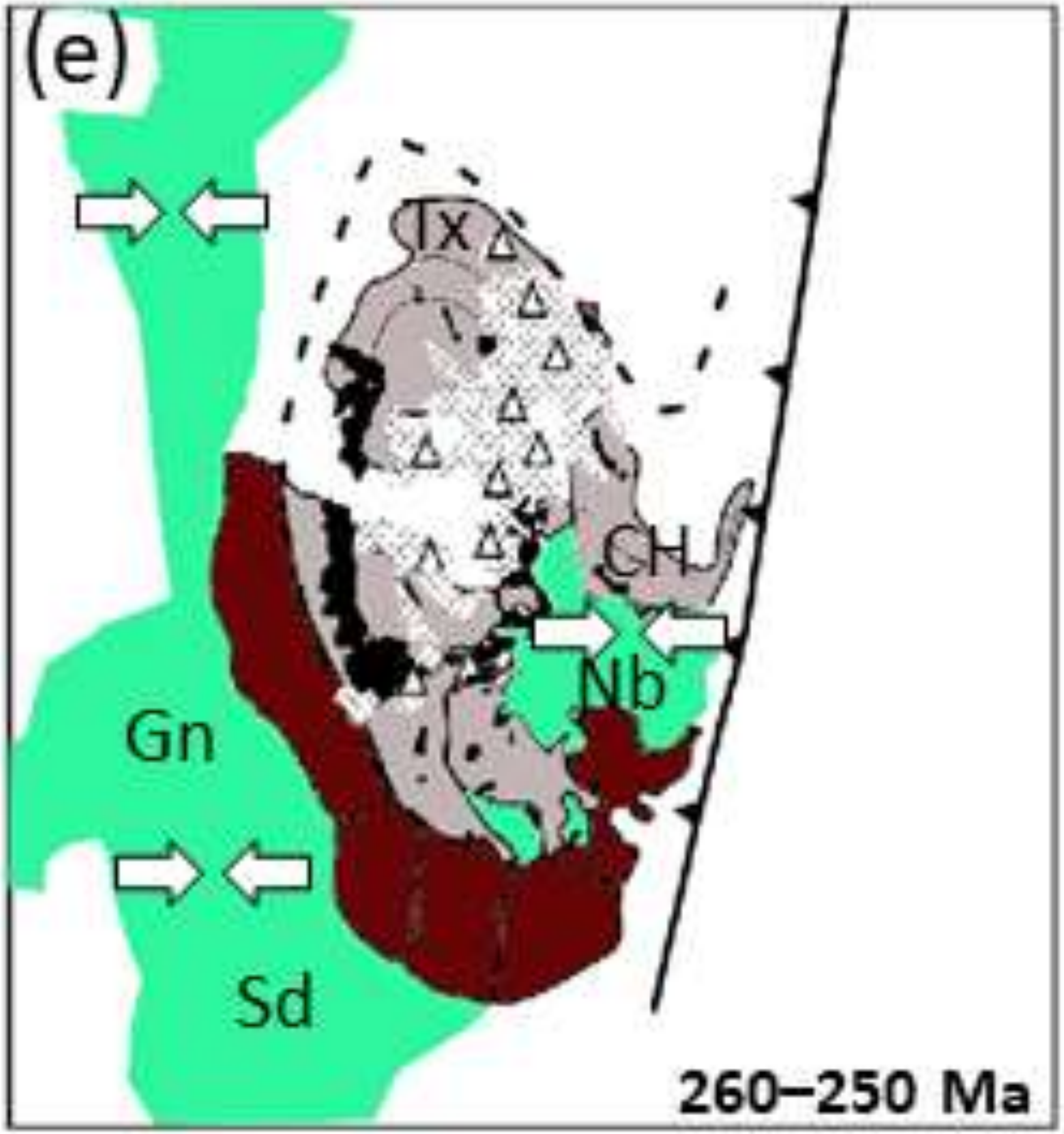
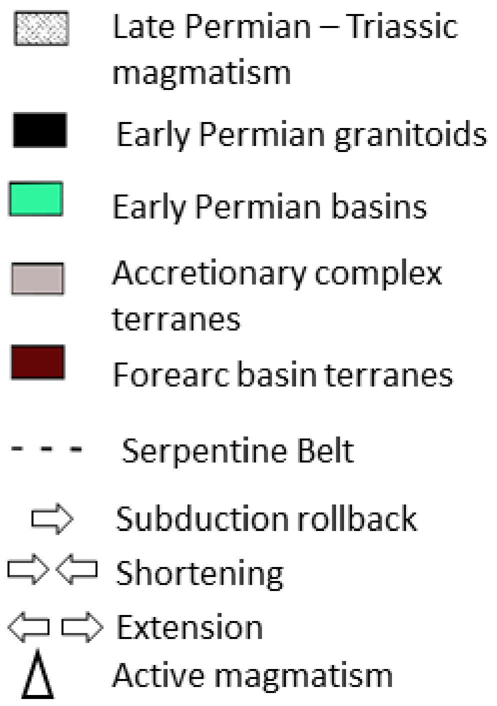
- Active magmatism



Re-establishment of an Andean-type subduction zone in the Late Permian begins a second period of compression and this is accompanied by voluminous calc-alkaline magmatism and crustal shortening.

This is known as the Hunter-Bowen Orogeny



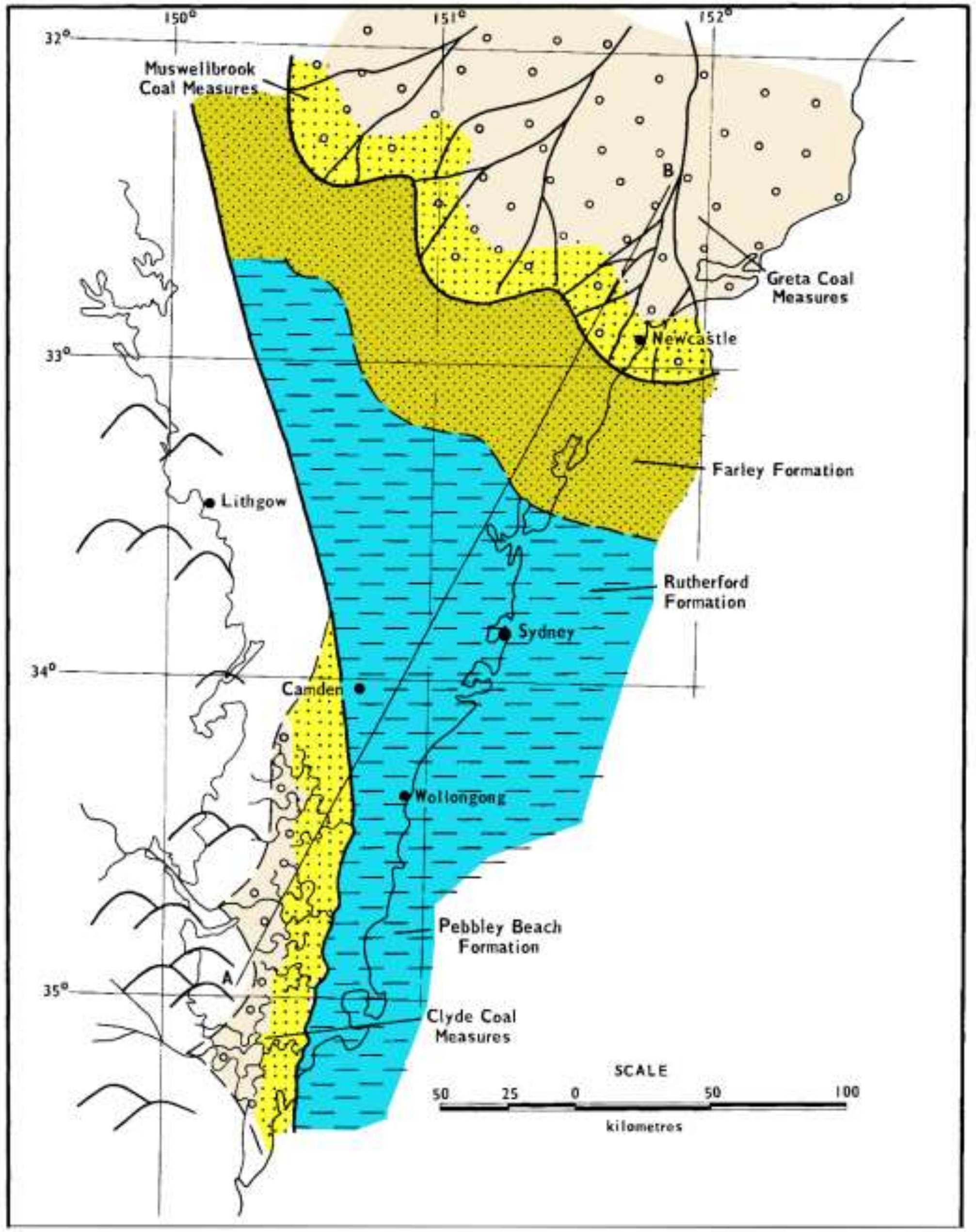
There are three main depositional stages in the development of the Sydney Basin from the Permian (299 Ma) to the end of the Triassic (205 Ma). Each has separate episodes as outlined below.

They are :

1. The Hunter Tectonic Stage
   - Greta
   - Snapper Point
   - Nowra-Muree
2. The Bowen Tectonic Stage
   - Lower Tomago
   - Upper Tomago
   - Newcastle
3. The Hawkesbury Tectonic Stage
   - Narrabeen
   - Hawkesbury
   - Wianamatta

There is evidence for further deposition in the Jurassic but this has almost entirely been eroded away. Debris from these sediments has been found in some of the many diatremes that dot the Basin. This debris (breccia) includes coalified logs thrown in the air, before falling into the hole made by the diatremes explosion.

The following maps/diagrams are based on material from A guide to the Sydney Basin by Chris Herbert and Robin Helby. 1980.



The Hunter Tectonic Stage

The Late Greta Depositional Episode

The newly formed Sydney Basin was largely filled by the sea in the Early Permian (298-273 Ma).

In this first period of rollback and extension the highlands to the North supplied sediment to large braided rivers and these deposited deep layers of conglomerate and sandstone in large alluvial fans, into the Sydney Basin region.

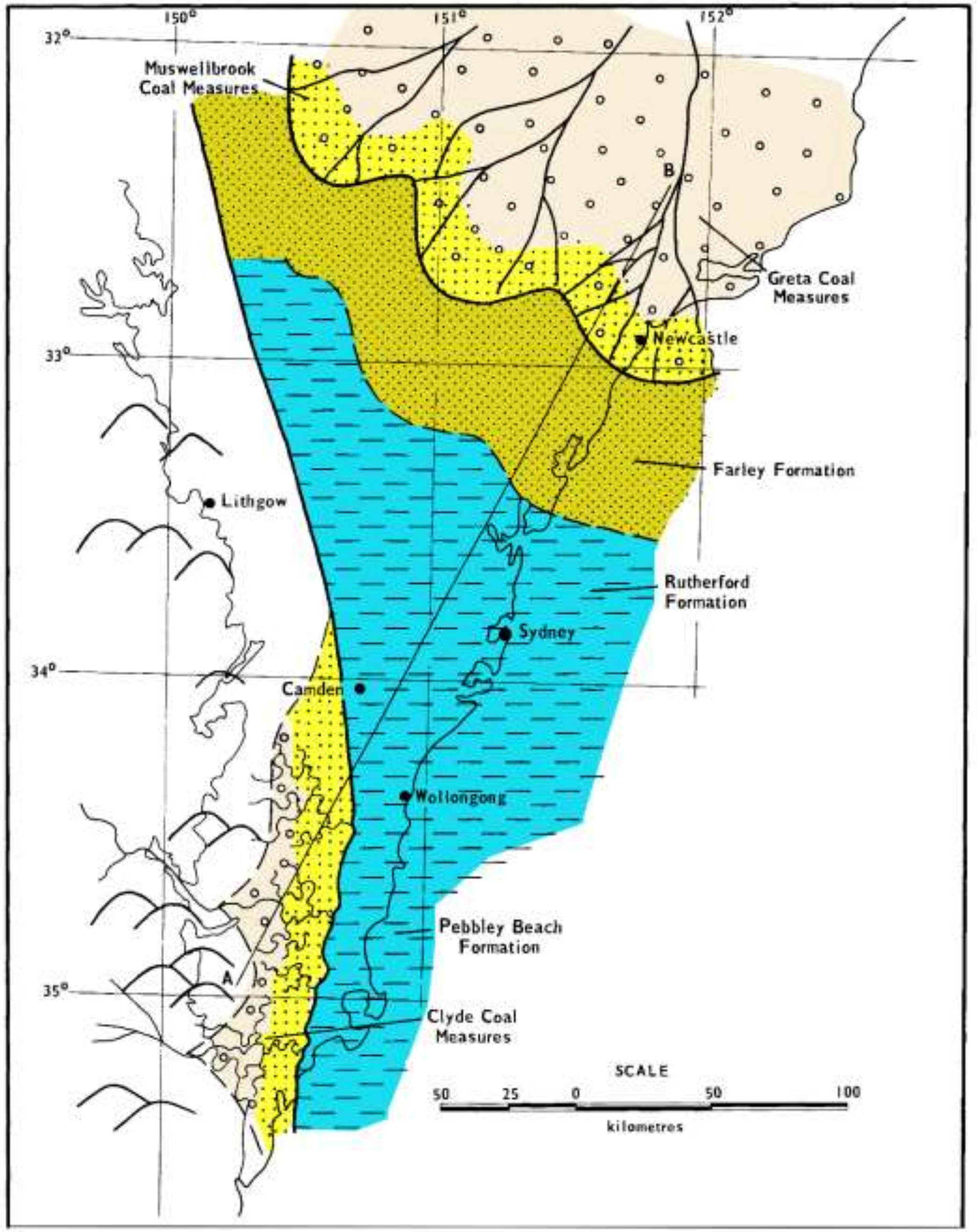
Alluvial, alluvial fan sediments – conglomerate, sandstone, siltstone, claystone, and coal

Alluvial, deltaic, intertidal, swamp – sandstone, siltstone, claystone, coal

Beach, barrier islands, near–shore marine, delta front – sandstone, laminite

Marine, pro-delta, shelf – siltstone

The late Greta Depositional Episode (cont.)

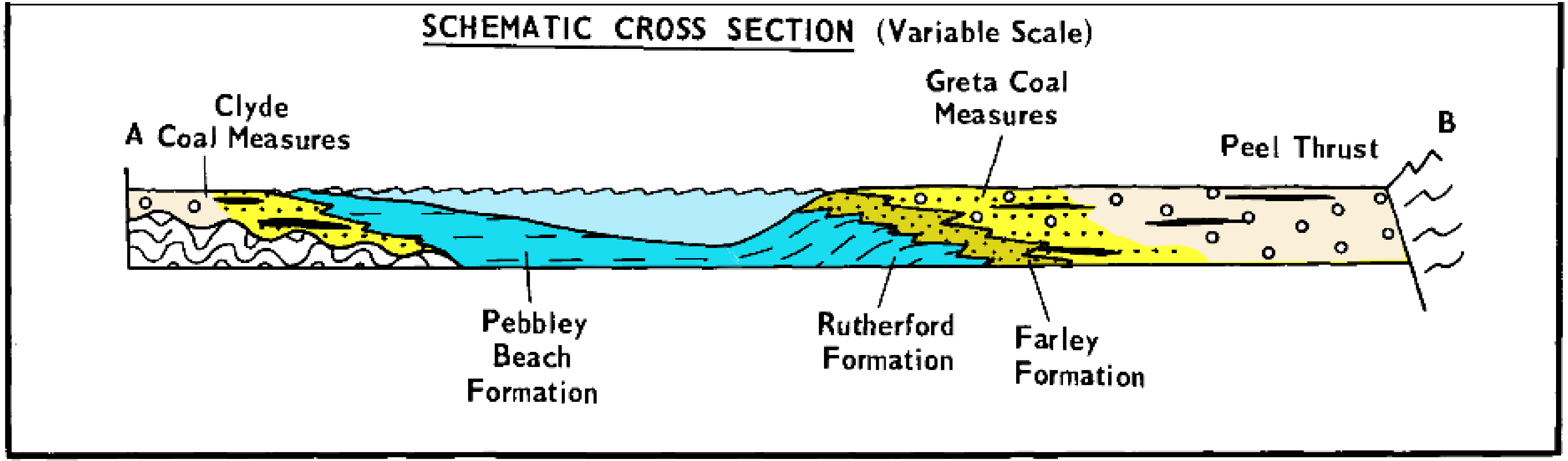


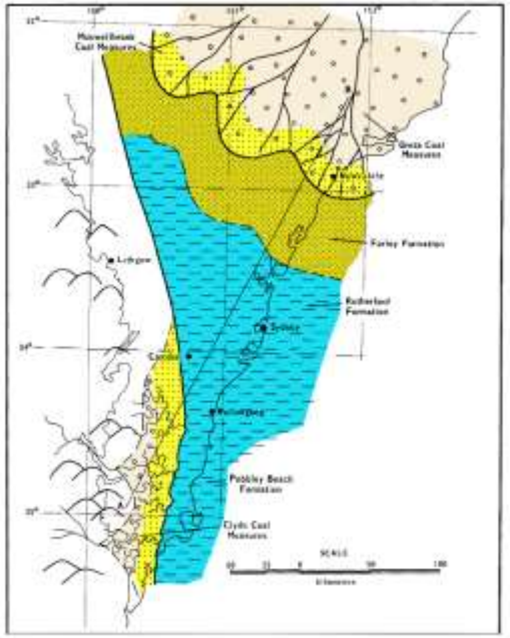
Coal is formed when plant material in swamps accumulates faster than it can decay. When covered by sediments their weight compacts the organic layers, increasing the temperature and pressure and this leads to physical and chemical changes in the plant material.

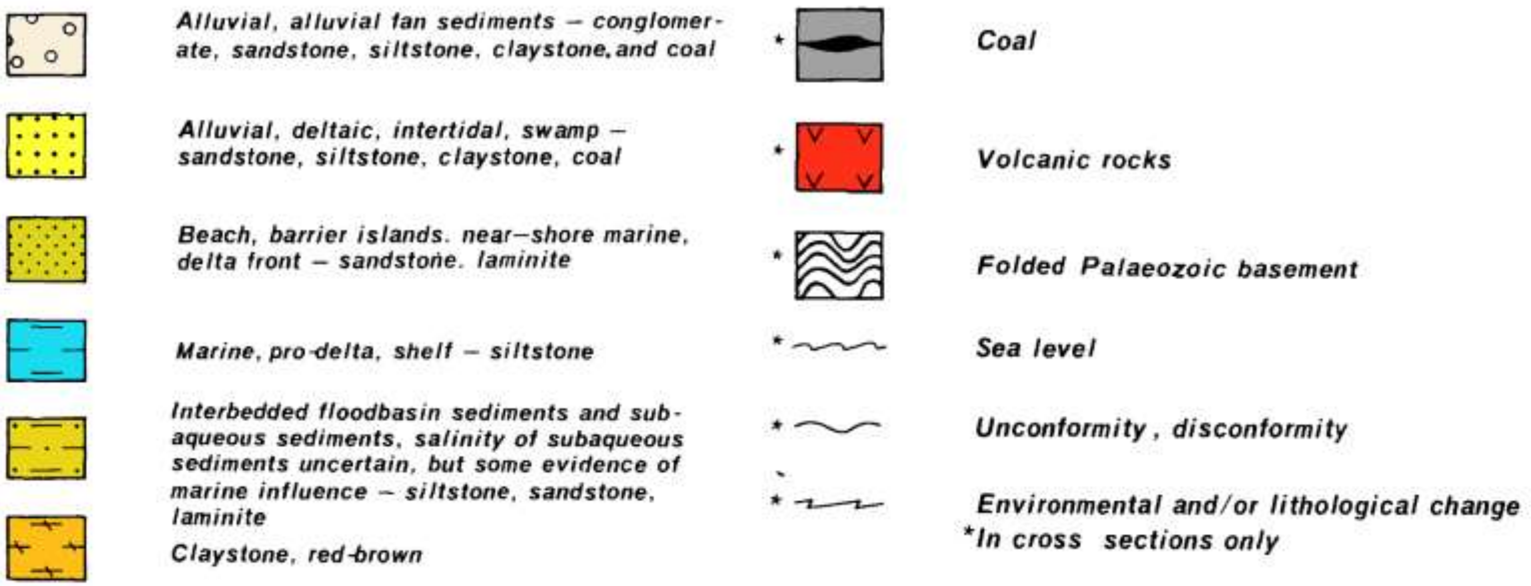
Water, carbon dioxide and methane are produced and some escape. The material becomes progressively enriched in carbon and with increasing time, higher heat and pressure, the plant material first forms into peat, then into brown coal, then sub-bituminous coal, bituminous coal, and lastly anthracite.

The Greta Coal Measures were formed in the riverine swamps and extensive deltas emanating from the NEO around 280-270 Ma.

In the South, swamps associated with the rivers flowing out of the Lachlan Orogen produced a narrow coastal plain and the Clyde Coal Measures.


SCHEMATIC CROSS SECTION (Variable Scale)
A
Clyde Coal Measures
Greta Coal Measures
B
Peel Thrust
Pebbley Beach Formation
Rutherford Formation
Farley Formation


Greta Coal Measures
Farley Formation
Rutherford Formation
Pebbley Beach Formation
Clyde Coal Measures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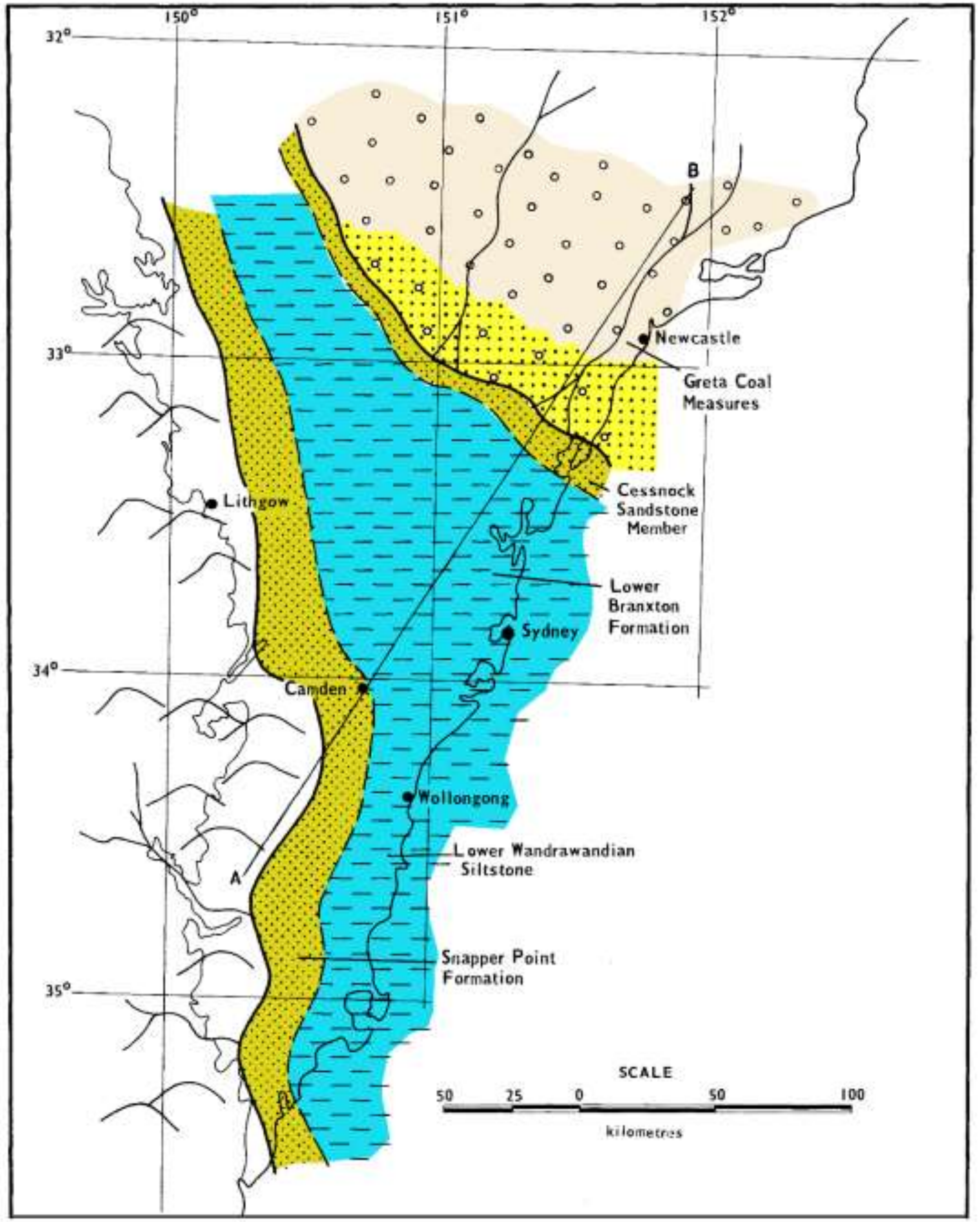
Marine, pro-delta, shelf — siltstone
Interbedded floodbasin sediments and subaqueous sediments, salinity of subaqueous sediments uncertain, but some evidence of marine influence — siltstone, sandstone, laminite
Claystone, red-brown
* Coal
* Volcanic rocks
* Folded Palaeozoic basement
* Sea level
* Unconformity, disconformity
* Environmental and/or lithological change
*In cross sections only



Snapper Point Depositional Episode
Early Permian 298 -273

Continuing extension in the NEO produced basin wide subsidence and caused the sea to drown parts of the Lachlan Fold Belt and the delta areas of the Greta Coal Measures 273-270 Ma

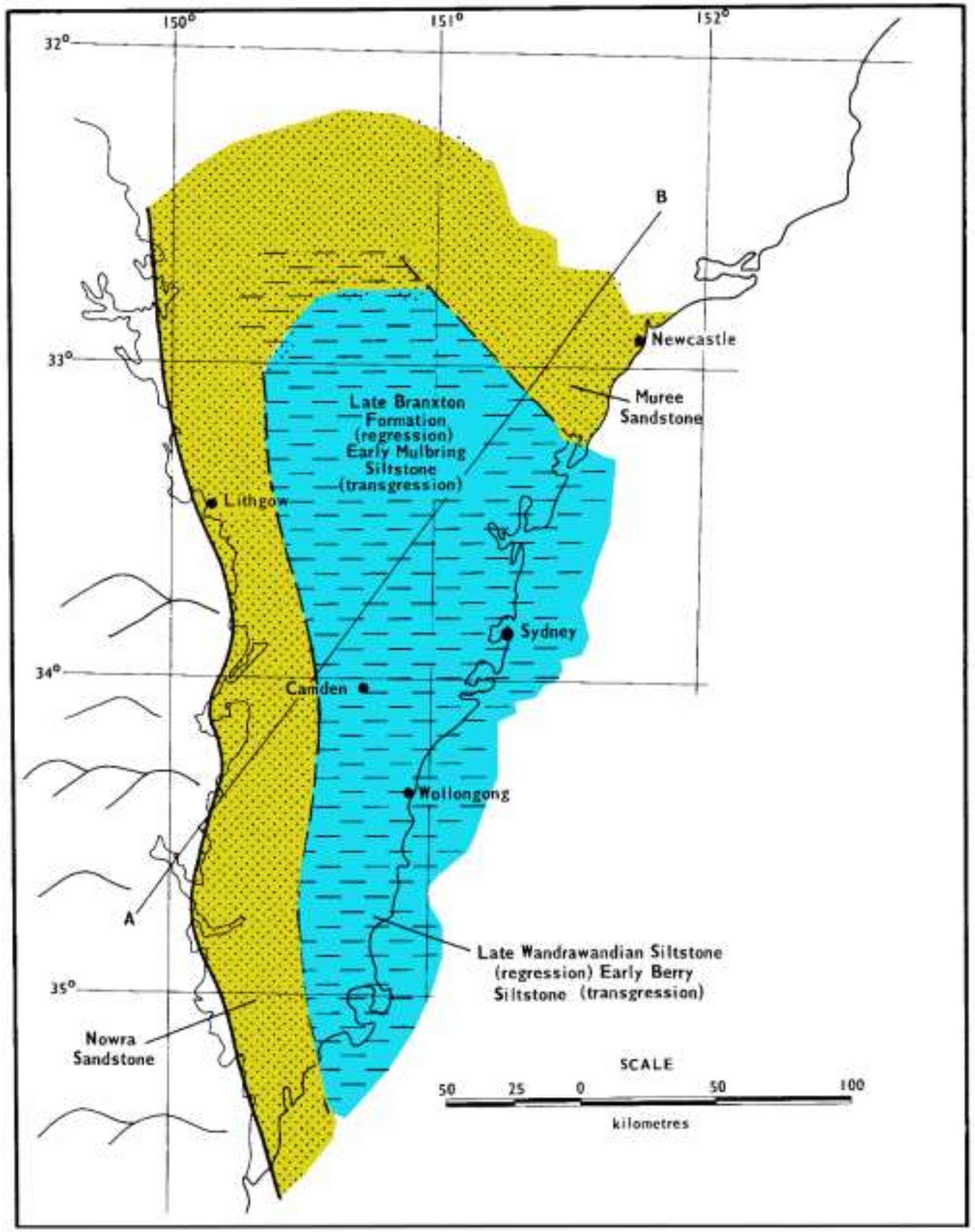
Areas of predominantly sandstone were created from eroding cliffs in the South and in the North probably from reworked off shore sand.

Alluvial, alluvial fan sediments — conglomerate, sandstone, siltstone, claystone, and coal

Alluvial, deltaic, intertidal, swamp — sandstone, siltstone, claystone, coal

Beach, barrier islands. near—shore marine, delta front — sandstone. laminite

Marine, pro-delta, shelf — siltstone

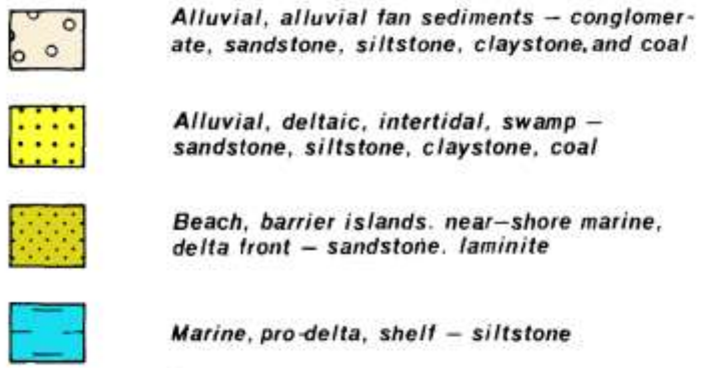


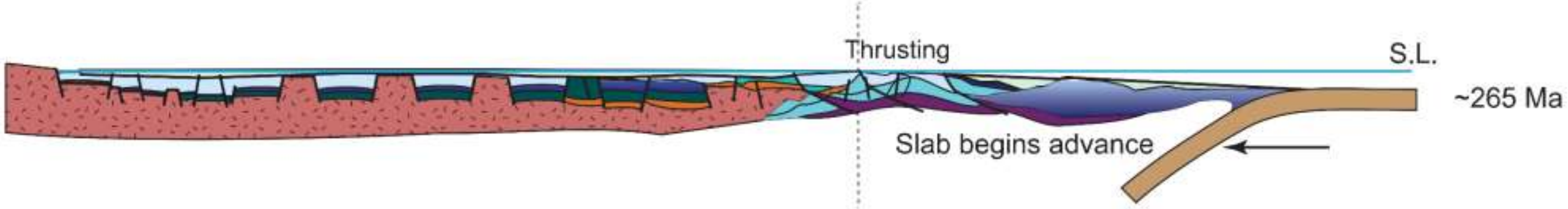
<u>Nowra- Muree Depositional Episode</u>- 268-265 Ma

As rollback in the NEO reached its peak, rivers deposited sand over areas of previous marine silt.

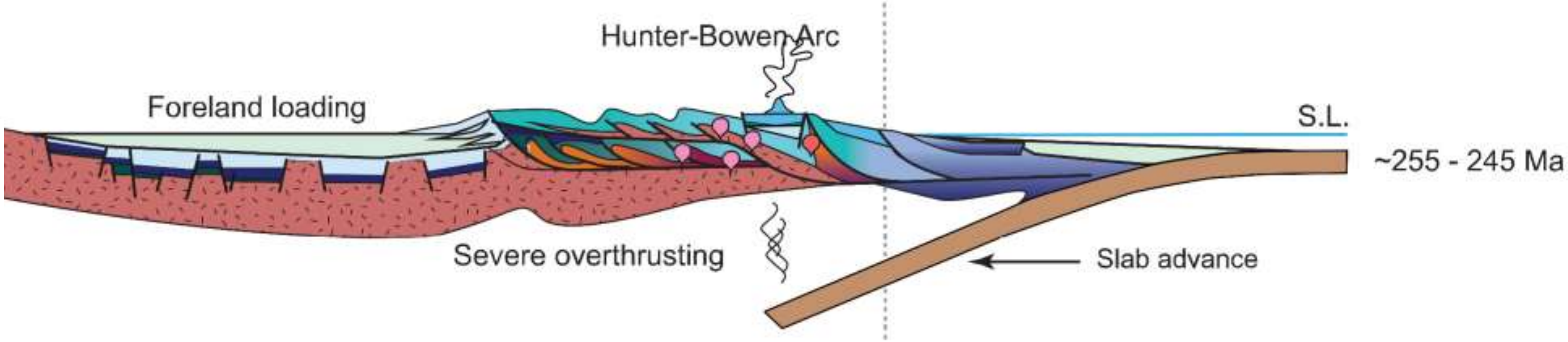
A subsequent rise (transgression) removed much of this.

This concludes the Hunter Tectonic Stage

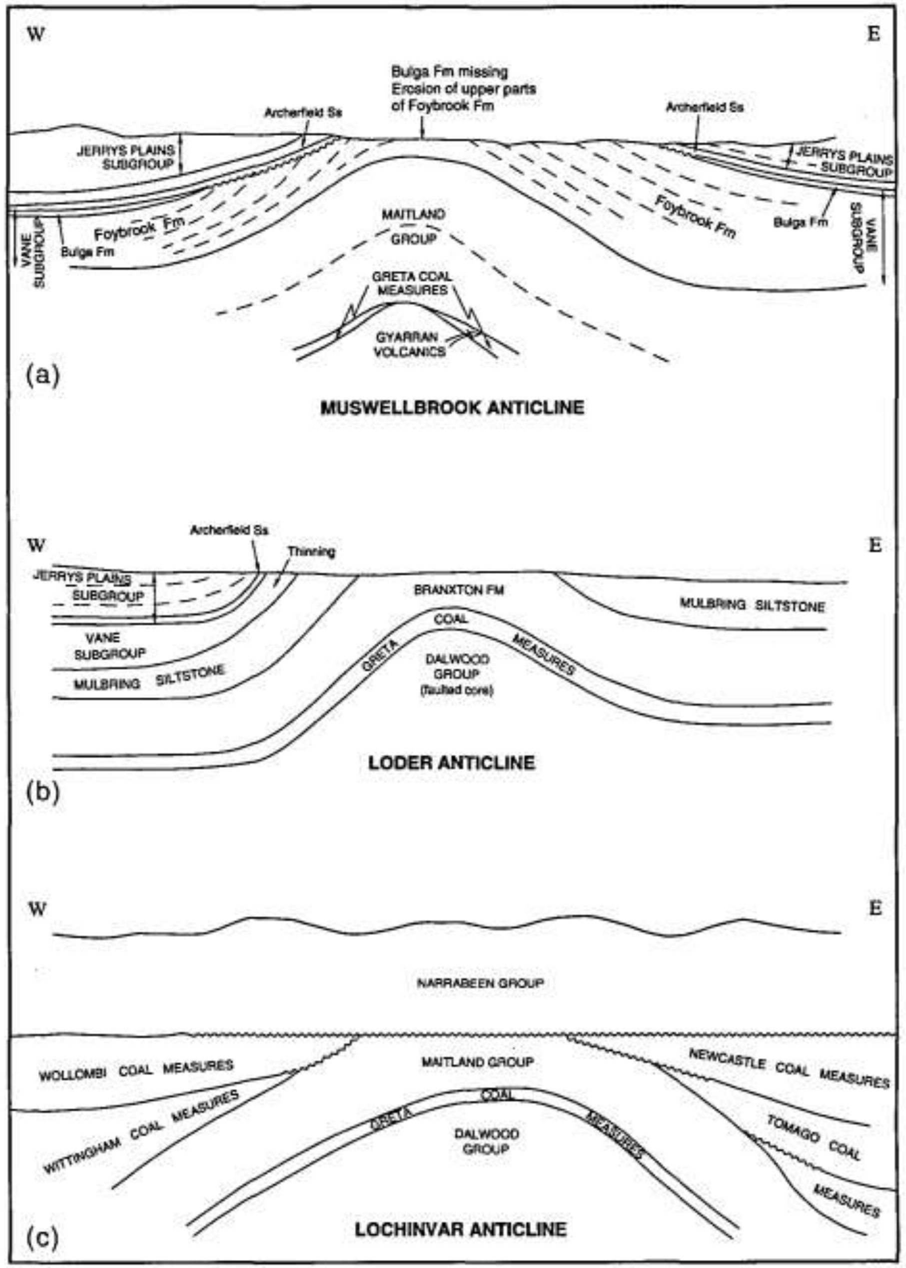




Towards the end of the Permian the re-establishment of a west dipping subduction zone results in compression and produces uplift to the North of the Sydney Basin, in the NEO.

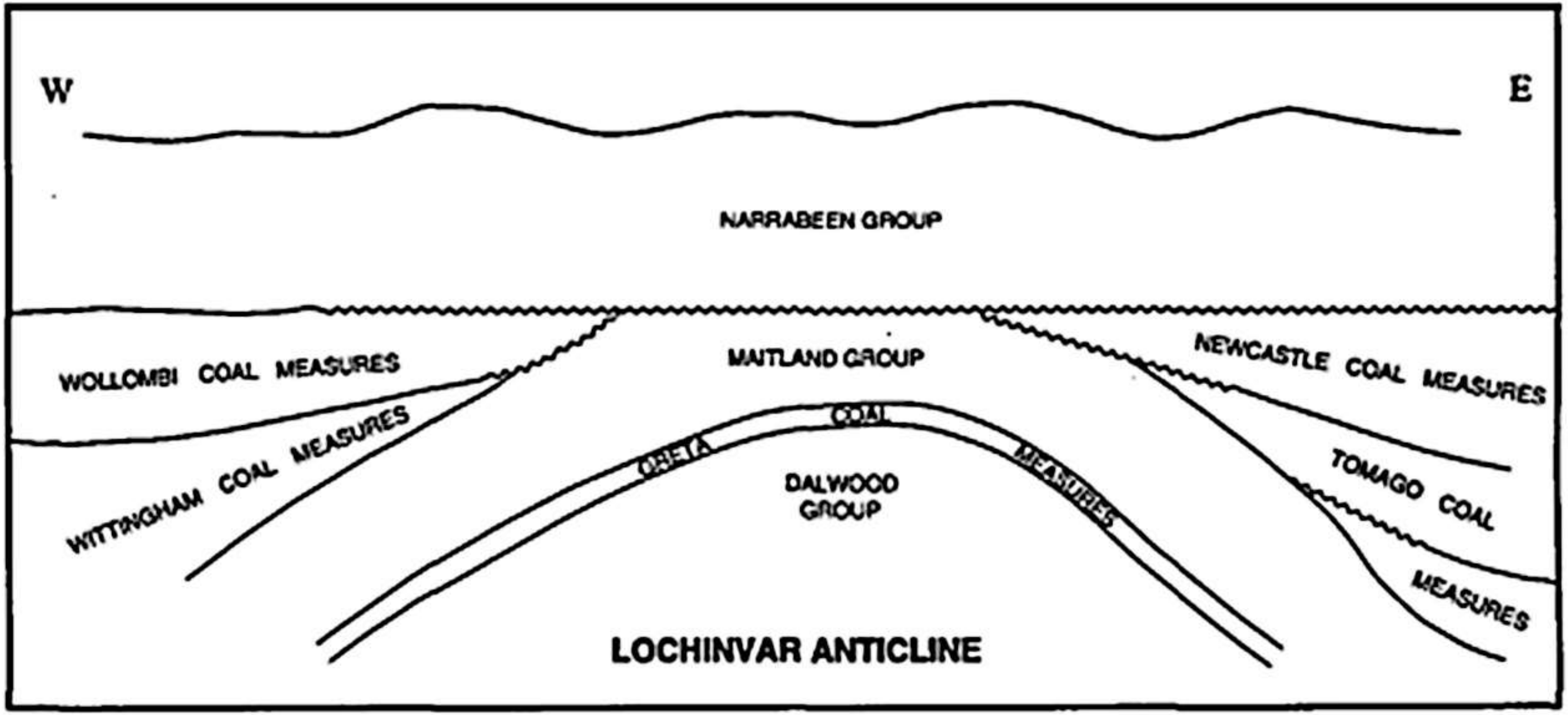


Cross-sections from Tectonic cycles of the New England Orogen: A Review Jessop et al 2019



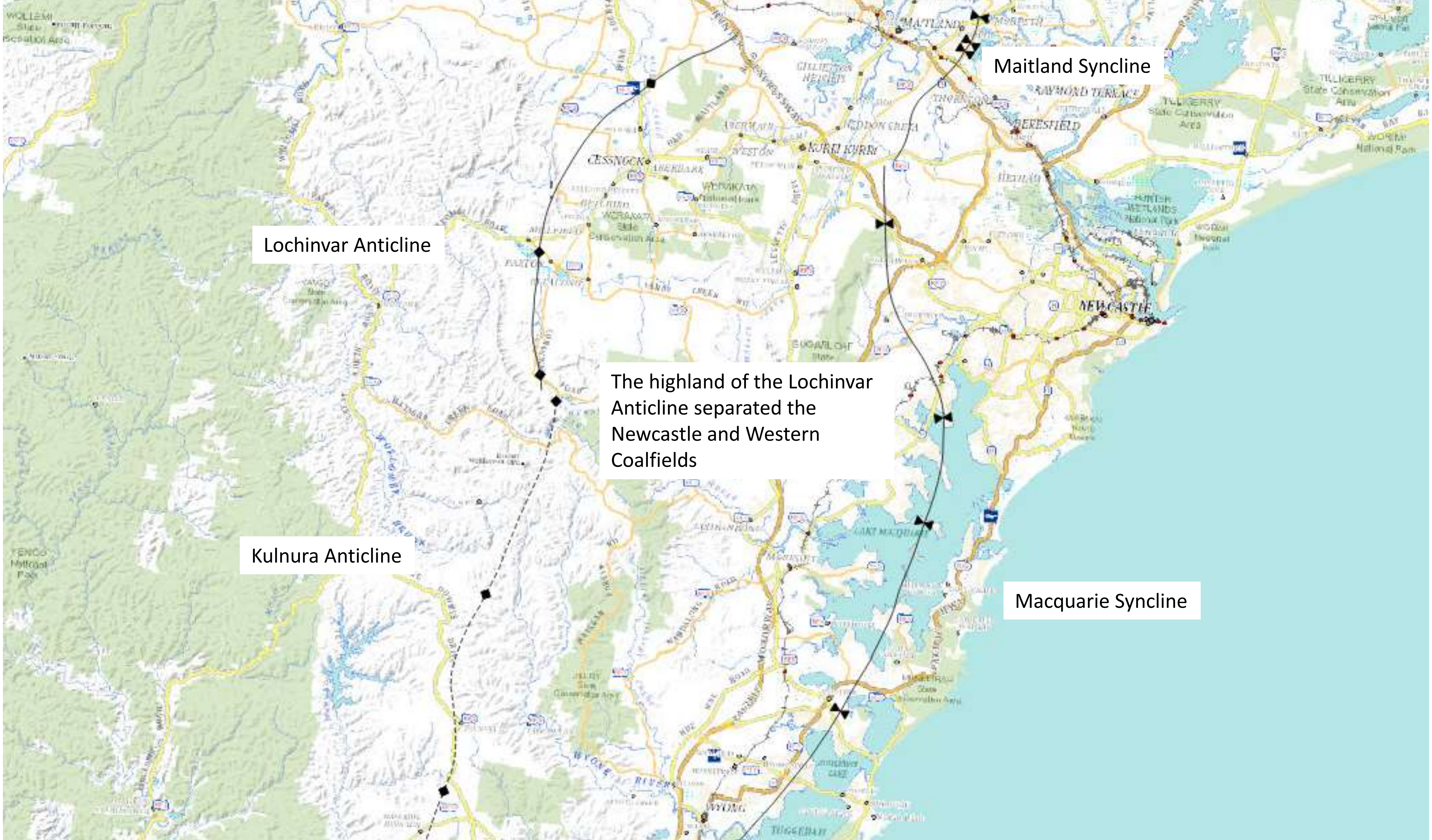
The contraction produced a number of folds in the Hunter and Central Coast and these influenced the development of later coalfields.

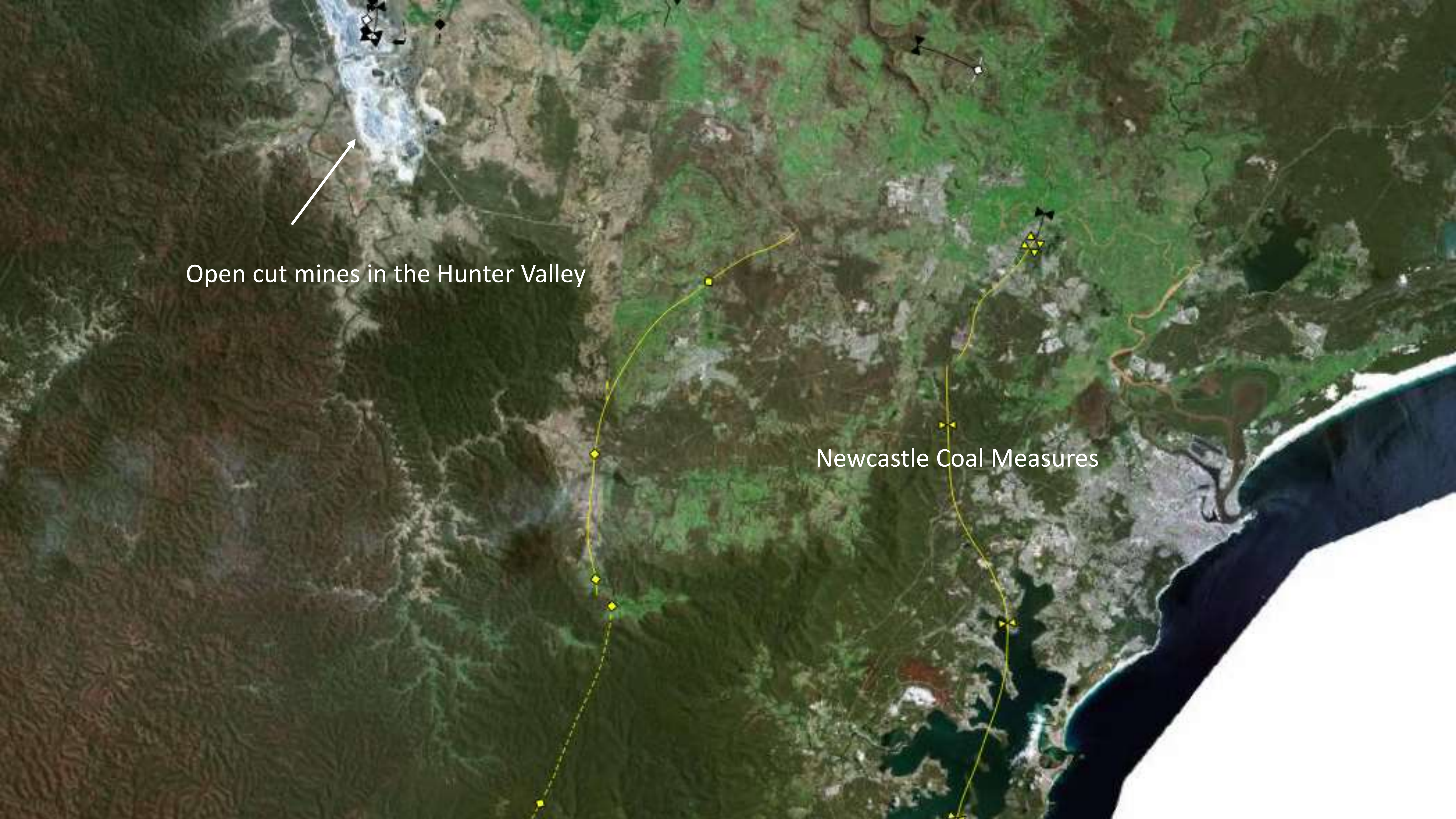
The longest fold, the Lochinvar Anticline, separated the Newcastle and Hunter Coalfields (R. A. Glen & J. Beckett (1997))

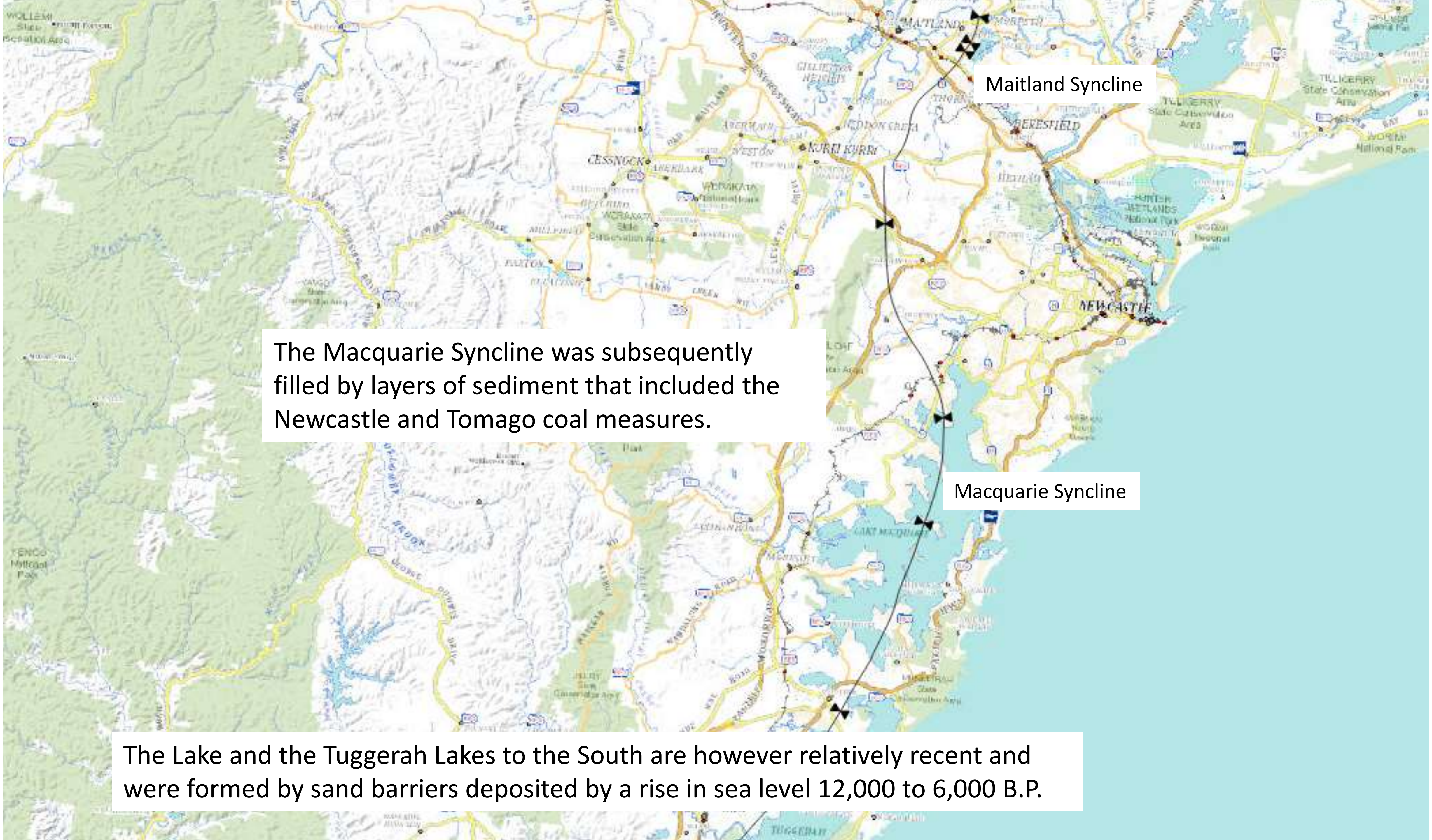


The Maitland Group (Muree Sandstone) and Greta Coal Measures overly the Lochinvar Anticline conformably and so preceded its formation. It separates the Newcastle Coalfields in the East from the Hunter fields in the West.

To the East of the Lochinvar anticline is a corresponding syncline, the Macquarie Syncline


Maitland Syncline
Lochinvar Anticline
The highland of the Lochinvar Anticline separated the Newcastle and Western Coalfields
Kulnura Anticline
Macquarie Syncline
NEWCASTLE
MAITLAND
CESSNOCK
KURRI KURRI
WYONG


Open cut mines in the Hunter Valley
Newcastle Coal Measures



The Macquarie Syncline was subsequently filled by layers of sediment that included the Newcastle and Tomago coal measures.

The Lake and the Tuggerah Lakes to the South are however relatively recent and were formed by sand barriers deposited by a rise in sea level 12,000 to 6,000 B.P.

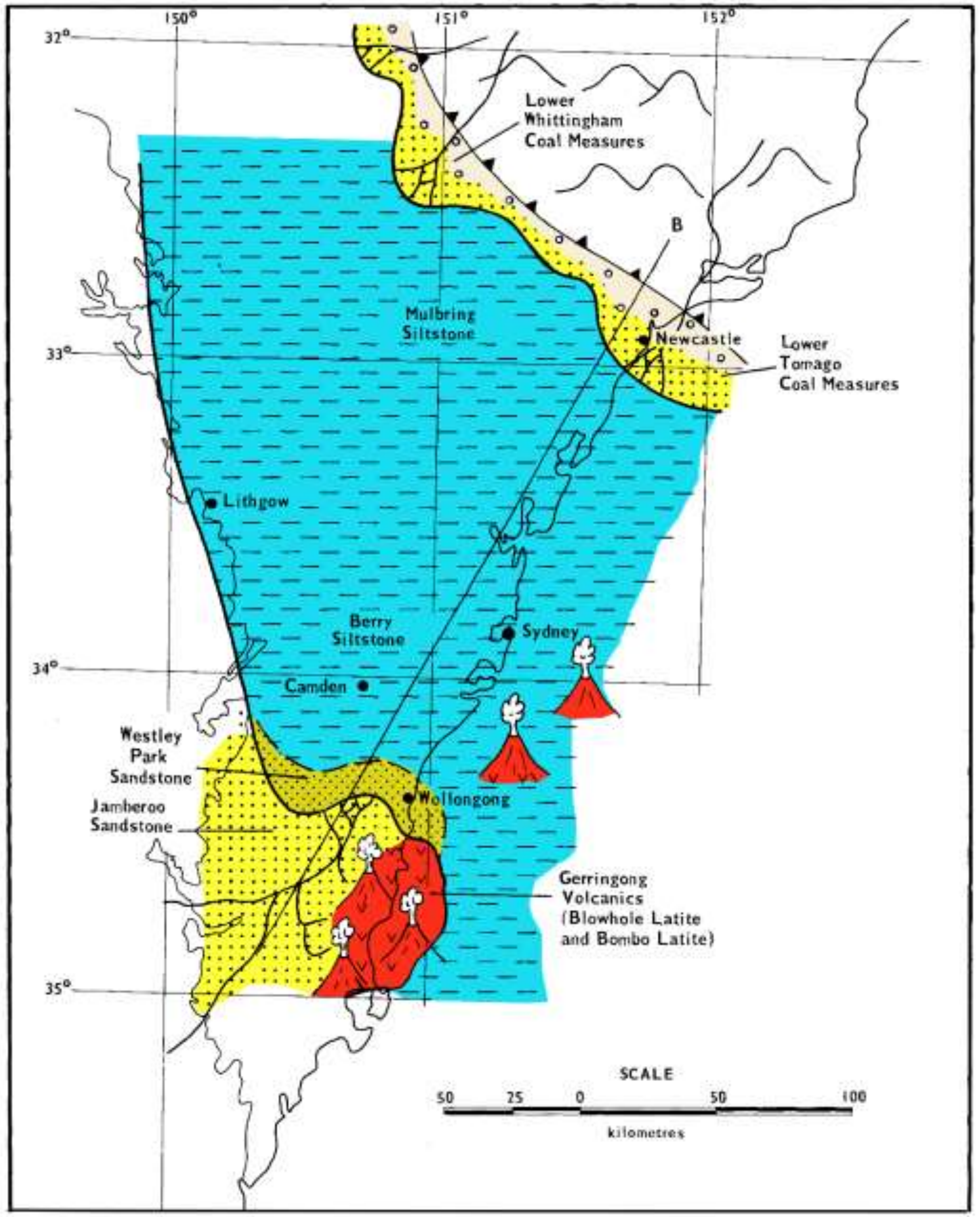
The Bowen Tectonic Stage Begins

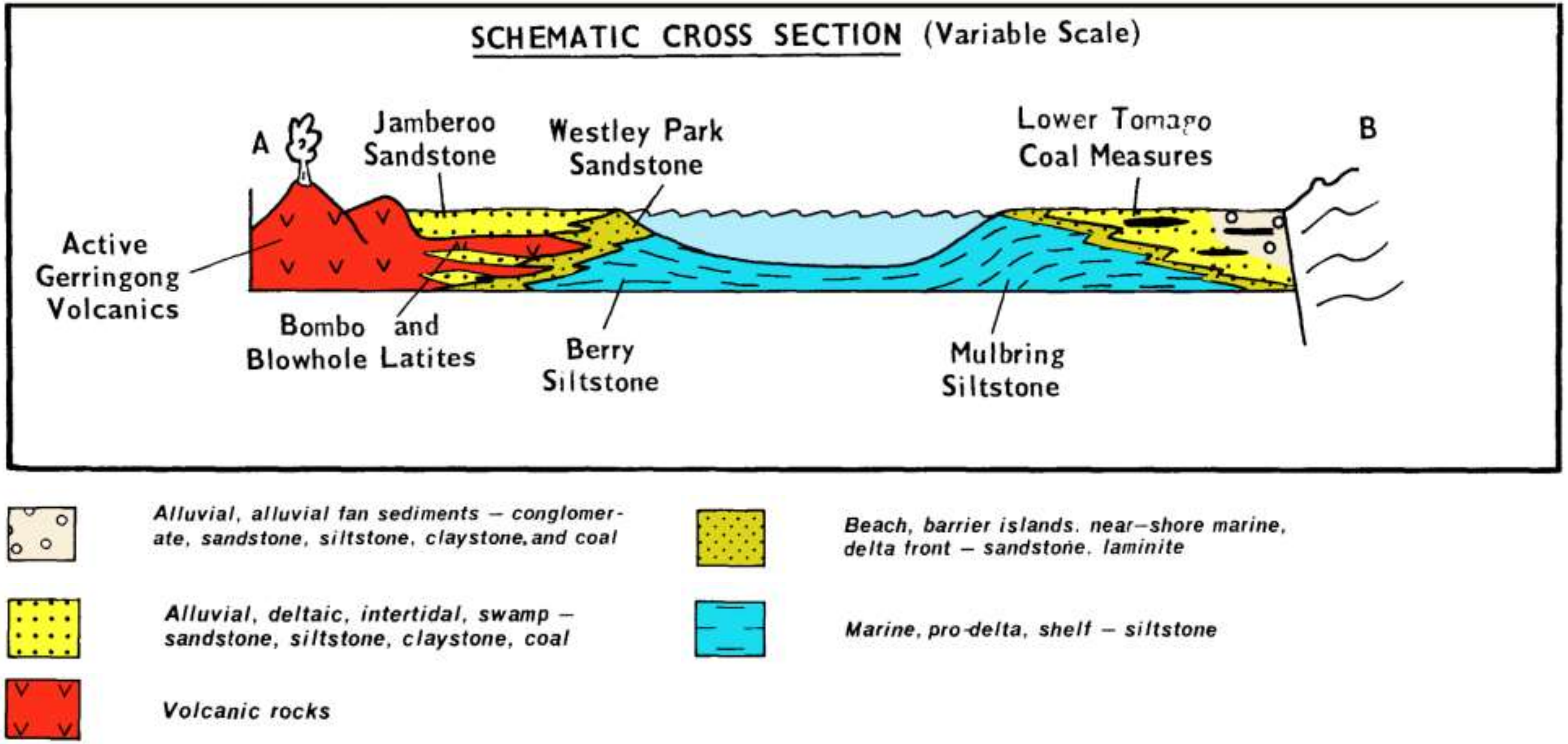
<u>Lower Tomago Depositional Episode - </u>Mid Permian 265-260 Ma

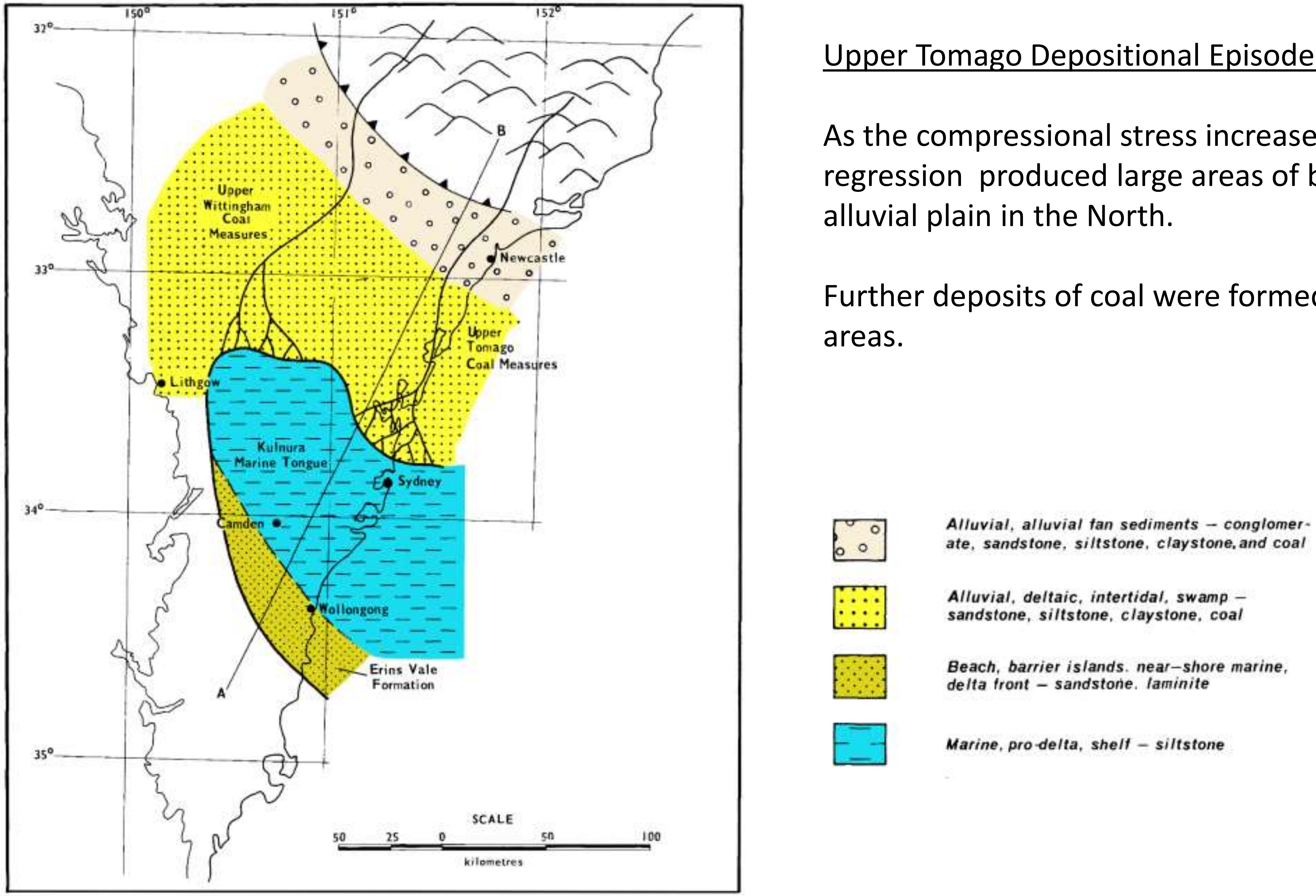
As a subduction zone re-established off the coast, erosion from the Hunter /Bowen Orogeny produced the Lower Tomago and Lower Whittingham coal measures.

The area covered by sea expanded In the initial stage and sediment was brought into the basin from both North and South.

In the North this was from the highlands created by the Hunter Mooki Thrust and in the South from the Gerringong Volcanoes, found near the Coast.



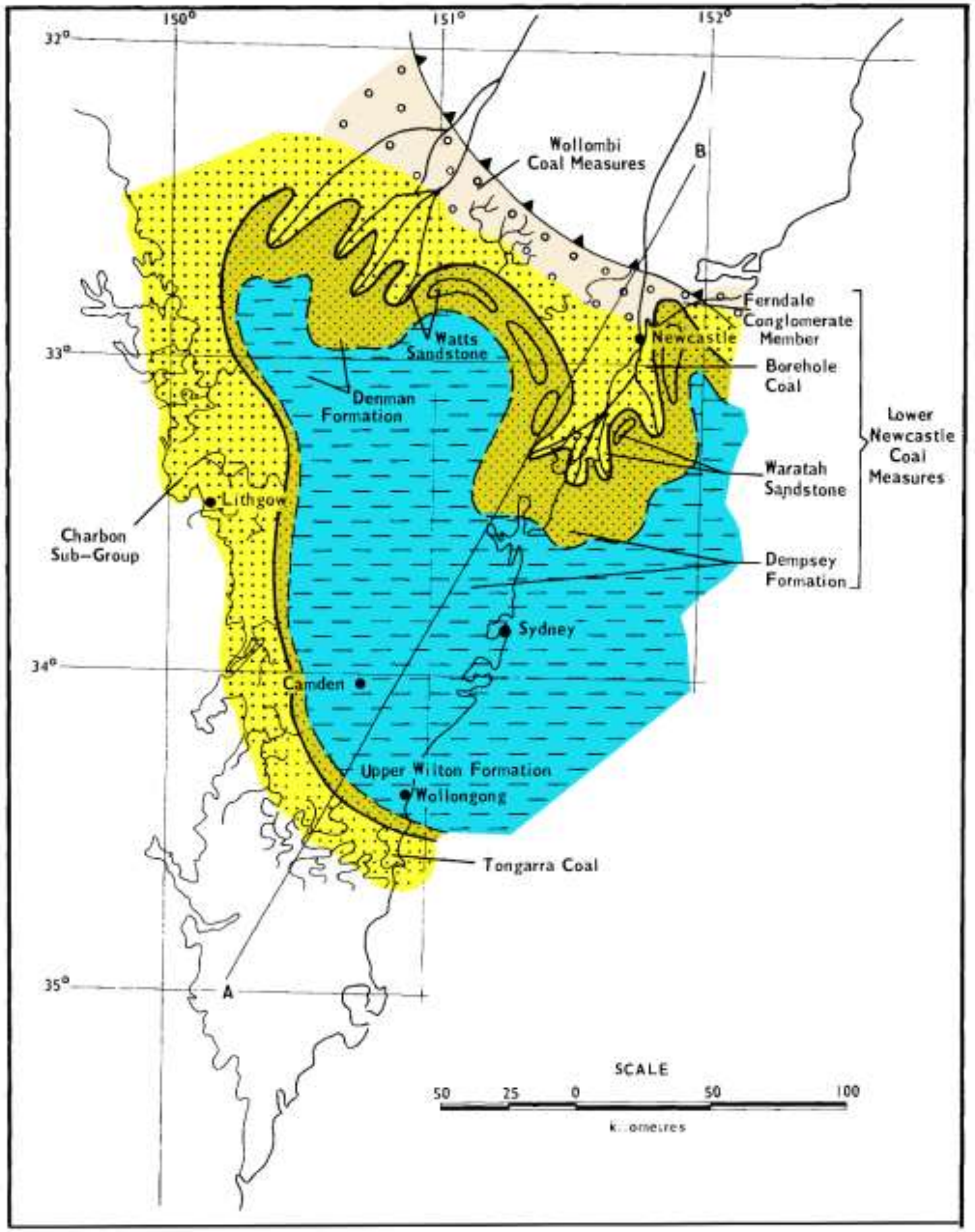

SCHEMATIC CROSS SECTION (Variable Scale)
A
B
Jamberoo Sandstone
Westley Park Sandstone
Lower Tomago Coal Measures
Active Gerringong Volcanics
Bombo and Blowhole Latites
Berry Siltstone
Mulbring Siltstone
Alluvial, alluvial fan sediments — conglomerate, sandstone, siltstone, claystone, and coal
Beach, barrier islands, near–shore marine, delta front — sandstone, laminite
Alluvial, deltaic, intertidal, swamp — sandstone, siltstone, claystone, coal
Marine, pro-delta, shelf — siltstone
Volcanic rocks



<u>Upper Tomago Depositional Episode</u> - 257-256 Ma.

As the compressional stress increased marine regression produced large areas of beach, delta and alluvial plain in the North.

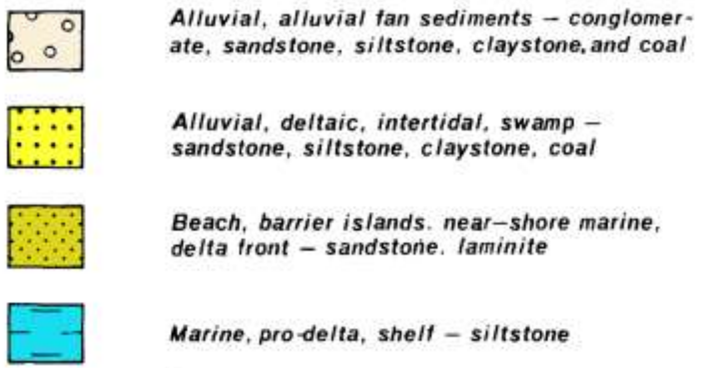
Further deposits of coal were formed in swampy areas.

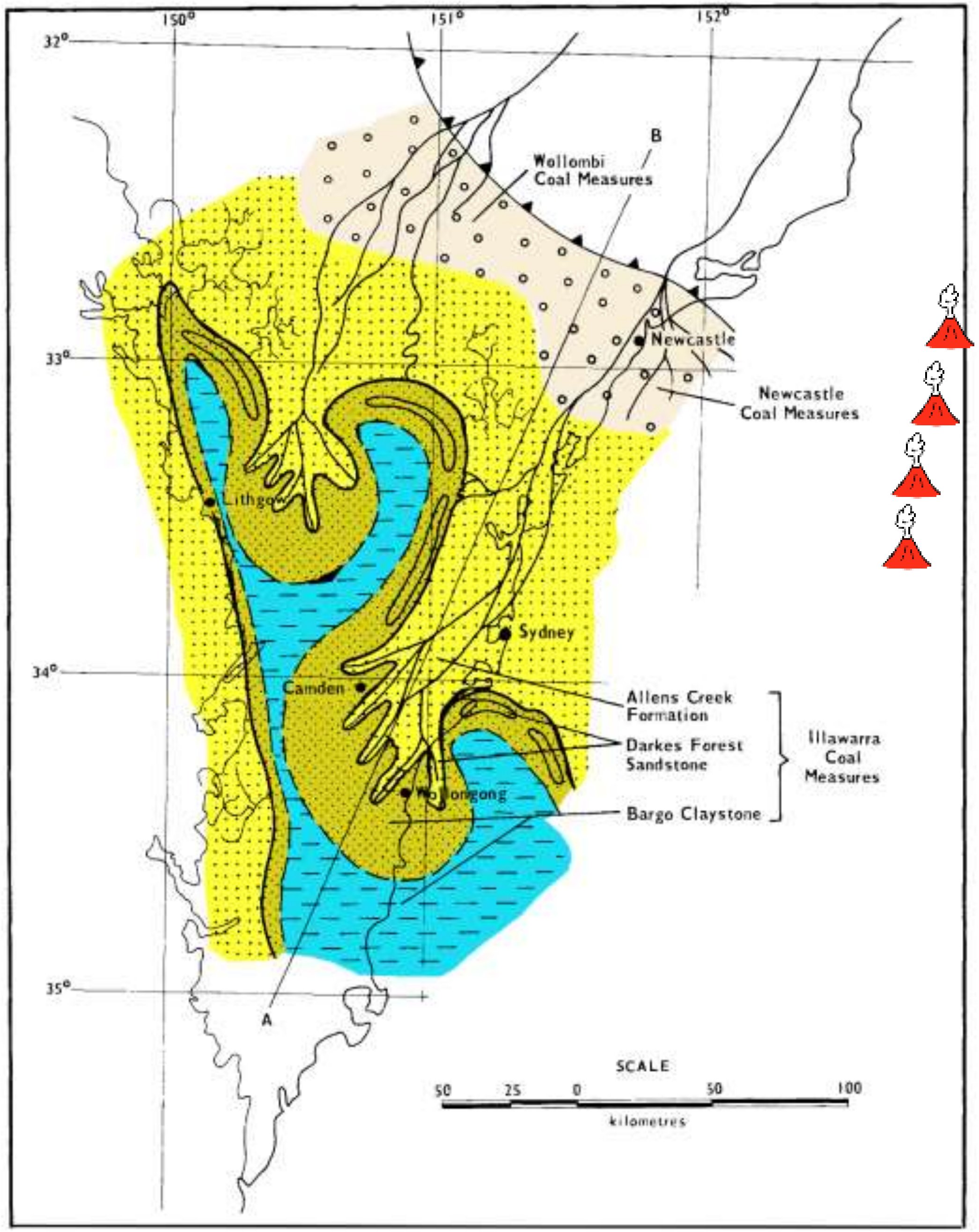


Early Newcastle Depositional Episode - 256-253 Ma

The New England Orogen continues to supply material to build large deltas and an offshore barrier system that aligned with the developing Macquarie Syncline and Lochinvar Anticline

Both these formations were produced by the re-establishment of compression and sediment supply during the Hunter/ Bowen Orogeny





<u>Late Newcastle Depositional Episode</u>

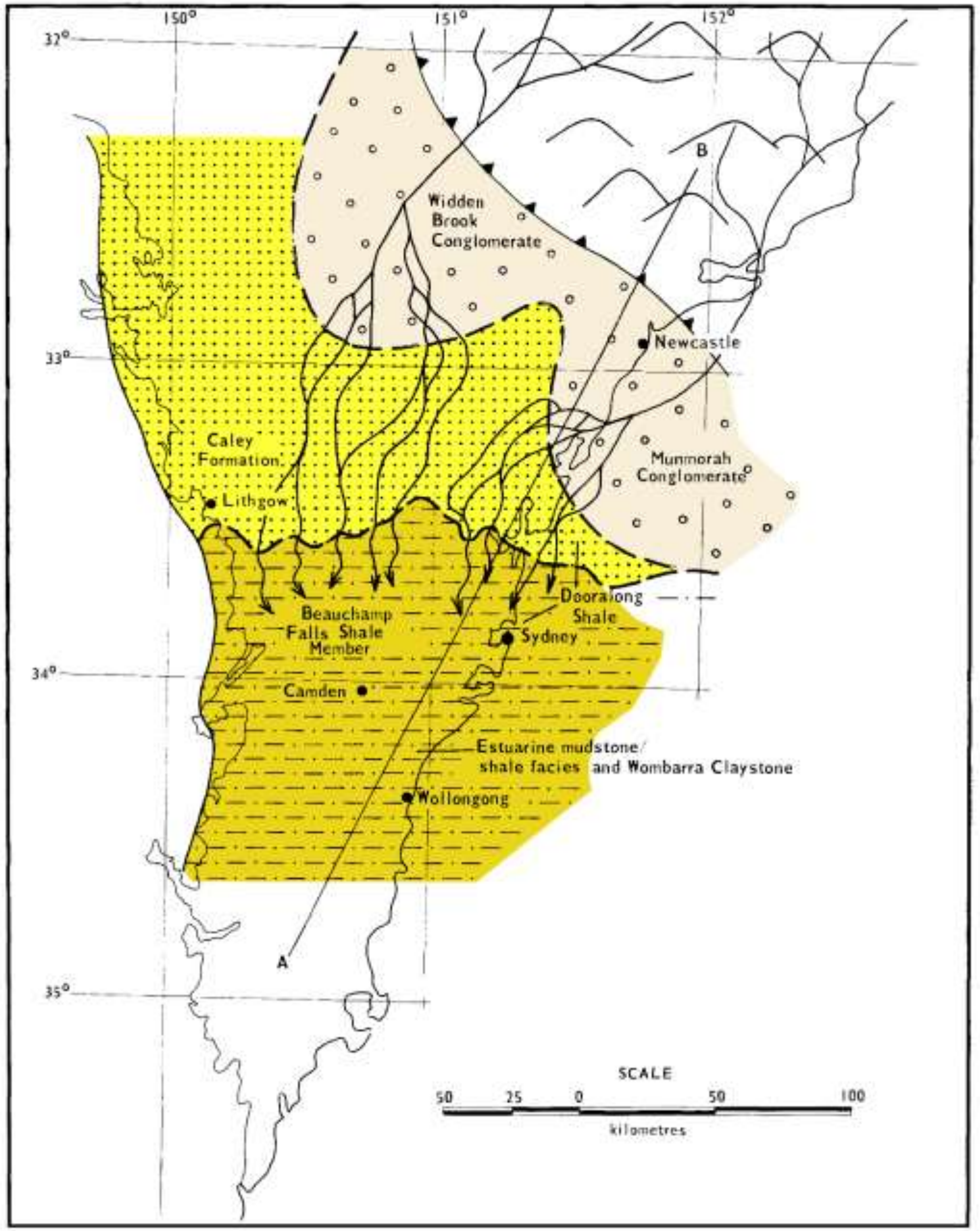
253 -252 Ma

The re-established subduction zone and ongoing uplift in the NEO continued to supply sediment from the North.

The deltaic environment created then extended from present Newcastle to Wollongong. A second delta on the western side of the Lochinvar Anticline produced the Wollombi Coal measures.

It is likely that a volcanic arc existed of the coast at this time. Six layers of Tuff have been recognised in the Newcastle Coal Measures and a petrified forest was created at Swansea Heads by an explosion similar to that of Mount St Helens in 1980.

http://coalfieldgeologycouncilnsw.org › 2021/05



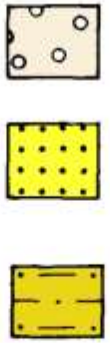
The Hawkesbury Tectonic Stage

Lower Narrabeen 251 Ma

At the end of the Permian the Sydney Basin of today was largely above sea level and sediment had covered the Lochinvar Anticline

During the Early Triassic sediment from the glaciated land of the NEO produced huge deposits of conglomerate over the Hunter Valley and Central Coast.

The Dooralong Shale was deposited at the time of the great Permian extinction and is the lowest formation in the Narrabeen Series.



Alluvial, alluvial fan sediments – conglomerate, sandstone, siltstone, claystone, and coal

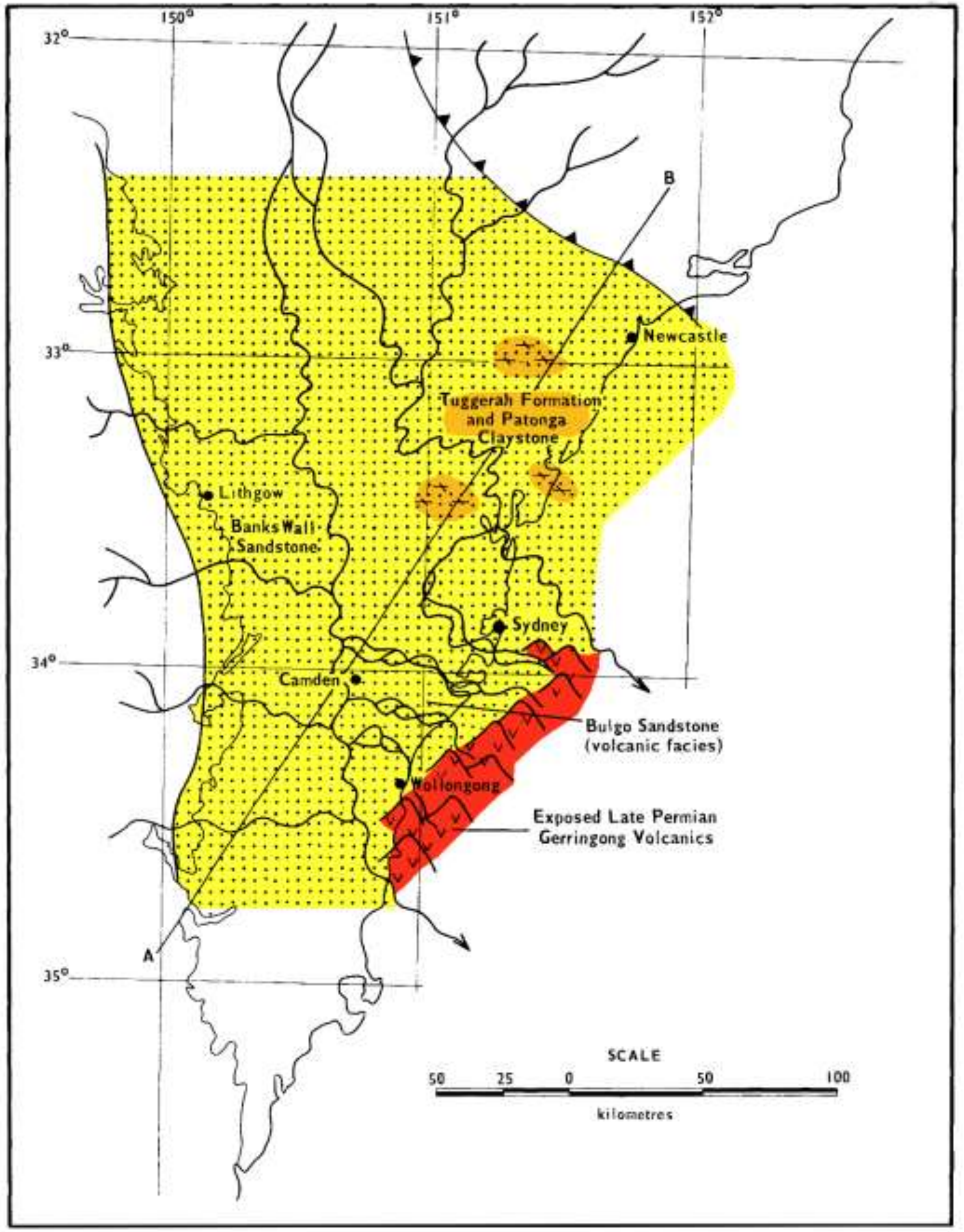
Alluvial, deltaic, intertidal, swamp – sandstone, siltstone, claystone, coal

Interbedded floodbasin sediments and subaqueous sediments, salinity of subaqueous sediments uncertain, but some evidence of marine influence – siltstone, sandstone, laminite

Middle Narrabeen

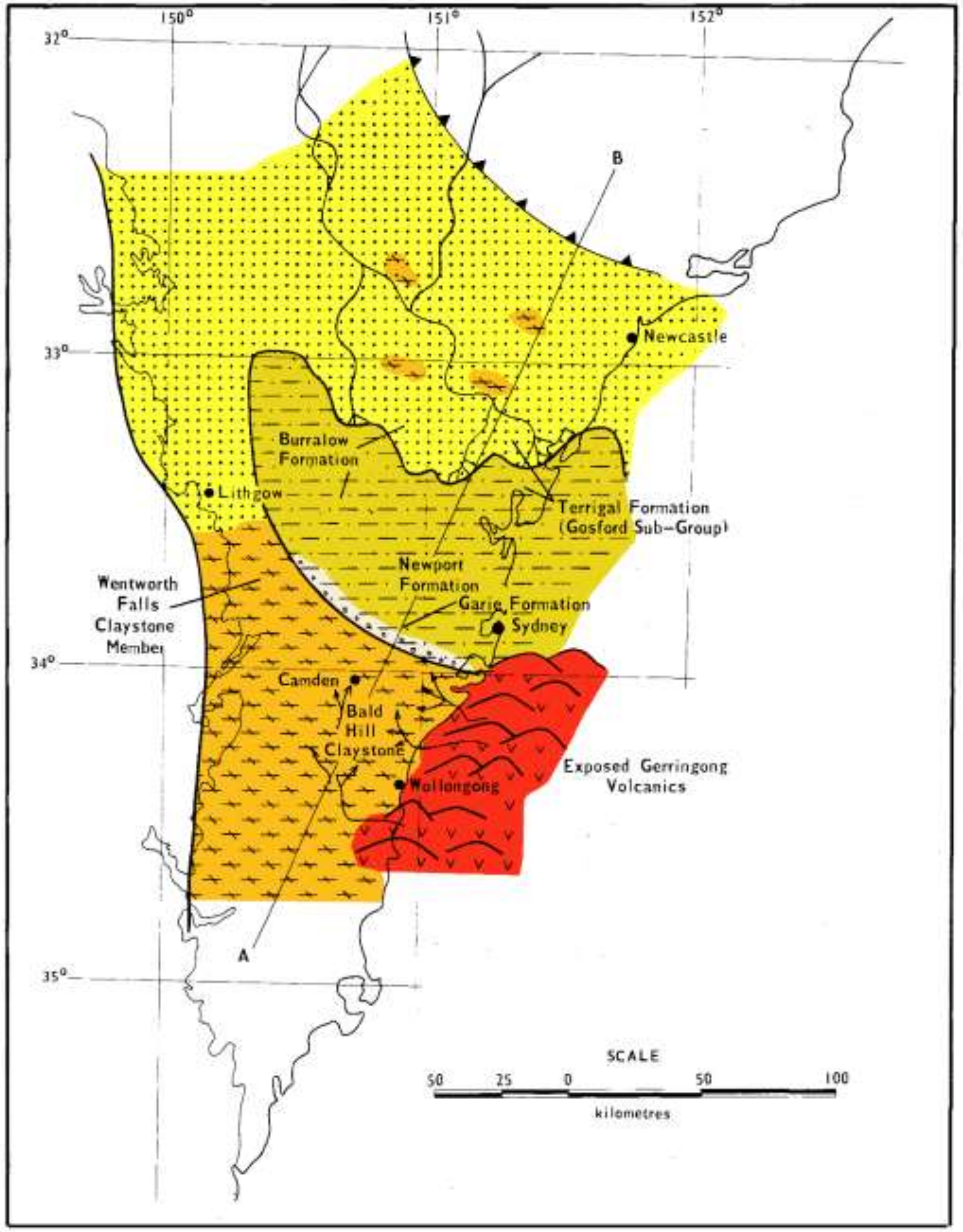
Sediment supply changes during this period, with more coming from the Lachlan Orogen in the West

Large areas of claystone are deposited in the North, in lakes and swamps on the flood plains



Upper Narrabeen c. 247 Ma

In this period sediment supply and drainage was down basin from the North West



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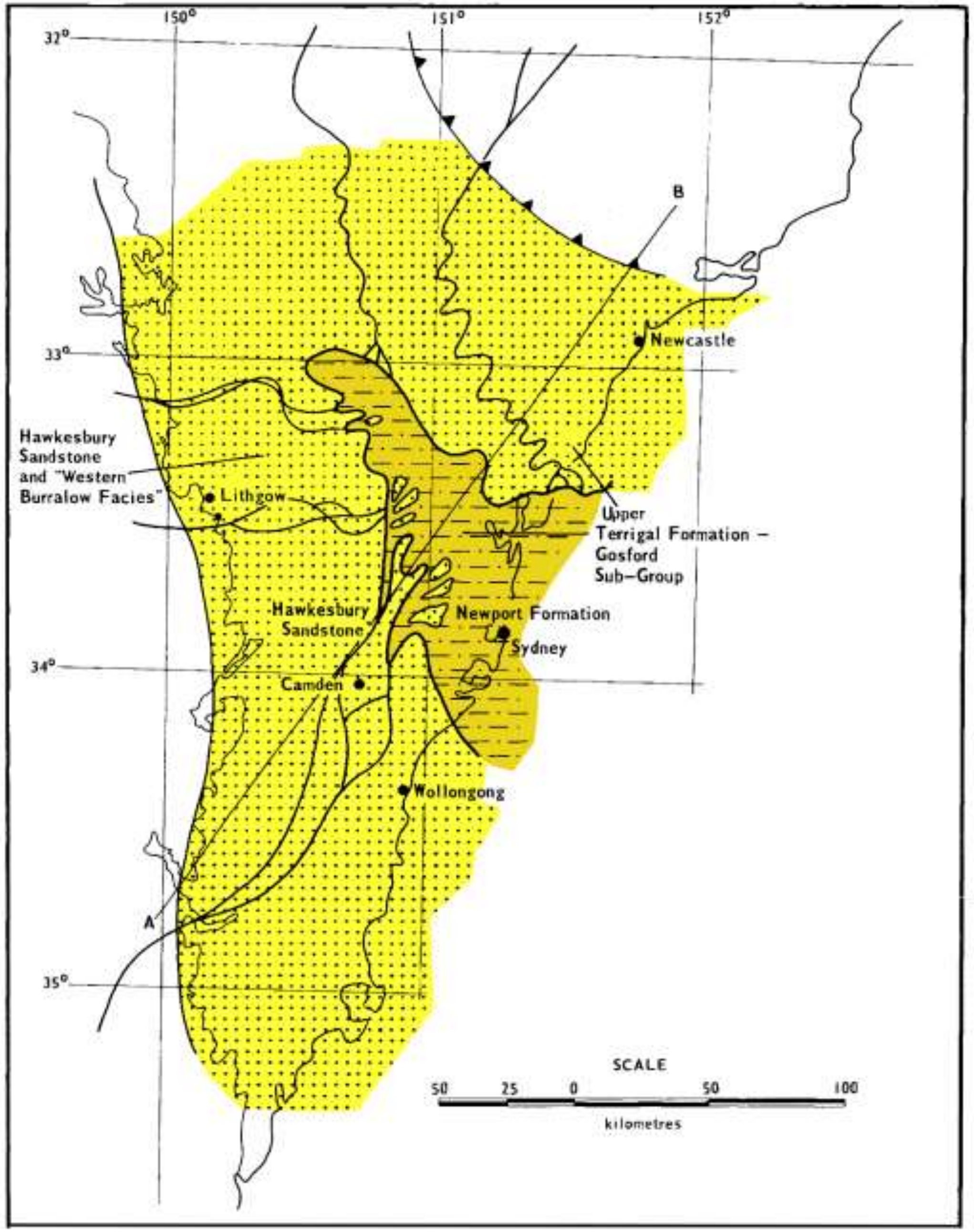
Claystone, red-brown

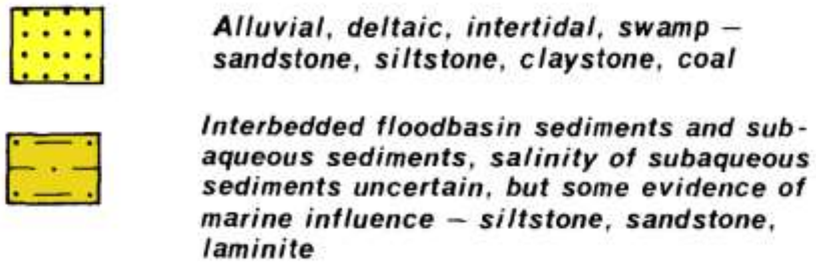
Volcanic rocks

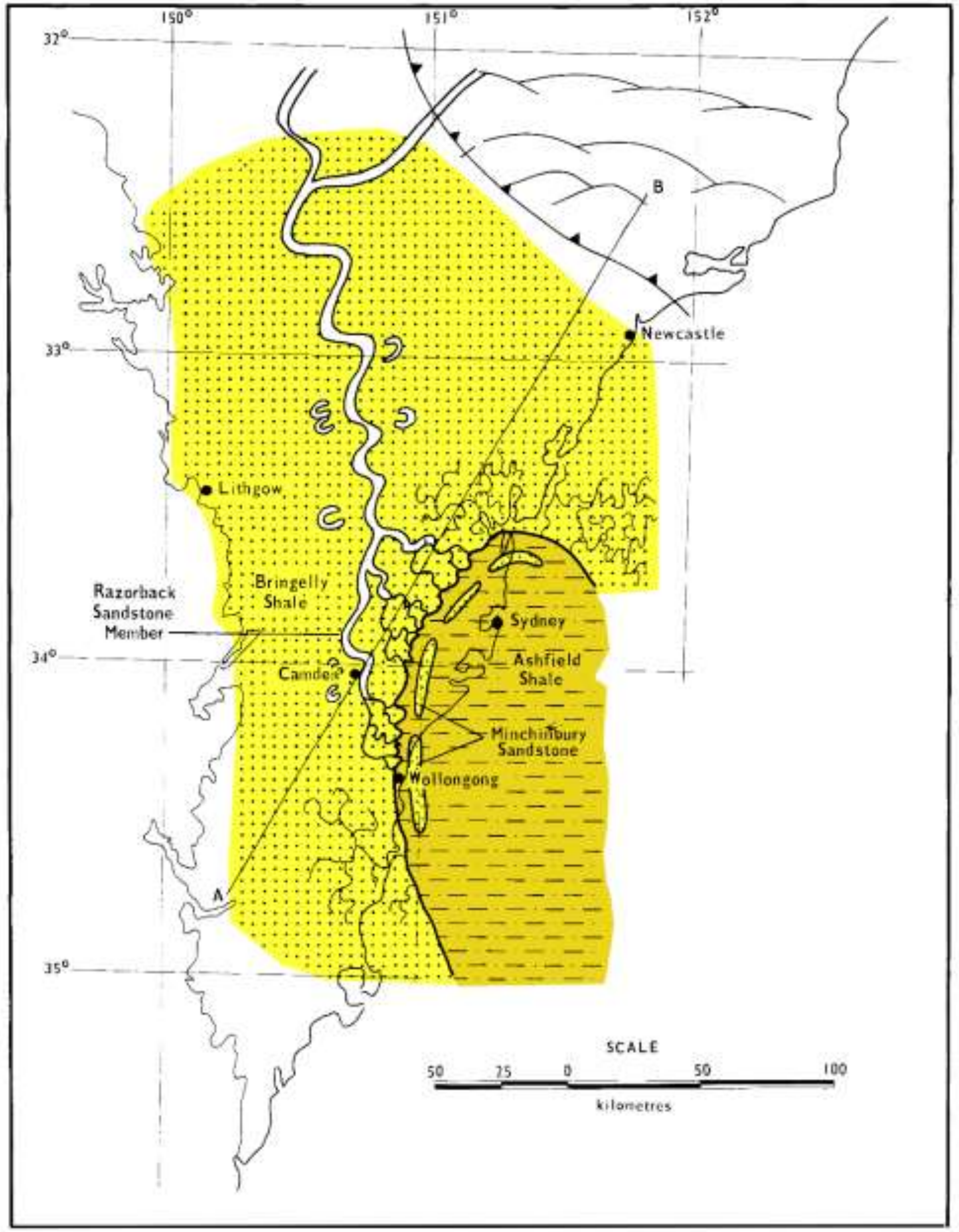


Late Narrabeen/ Early Hawkesbury c. 245 Ma

The drainage pattern continues to evolve with more sediment sourced from the area of the Lachlan Orogeny.

The Hawkesbury Sandstone eventually covered the Narrabeen series





Wianamatta Depositional Episode 235–201 Ma

In the Late Triassic a large coastal plain developed in the area between the Central Coast and Wollongong. Sea levels fluctuated covering and exposing this plain (G. Herbert 1997).

Deposition in the shallow marine environments was mainly of finer sediments and these produced the Ashfield Shales. The sediment forming these is relatively high in phosphorous. It appears this is contained in layers of phosphatic siderite nodules.

Fluctuating sea levels produced a barrier island system developed along the shoreline during these transgressions. These became the Minchinbury Sandstones.

The Bringelly Shales were developed last on floodplains and don't contain the same amount of phosphorous.

Alluvial, deltaic, intertidal, swamp – sandstone, siltstone, claystone, coal

Interbedded floodbasin sediments and sub-aqueous sediments, salinity of subaqueous sediments uncertain, but some evidence of marine influence – siltstone, sandstone, laminite

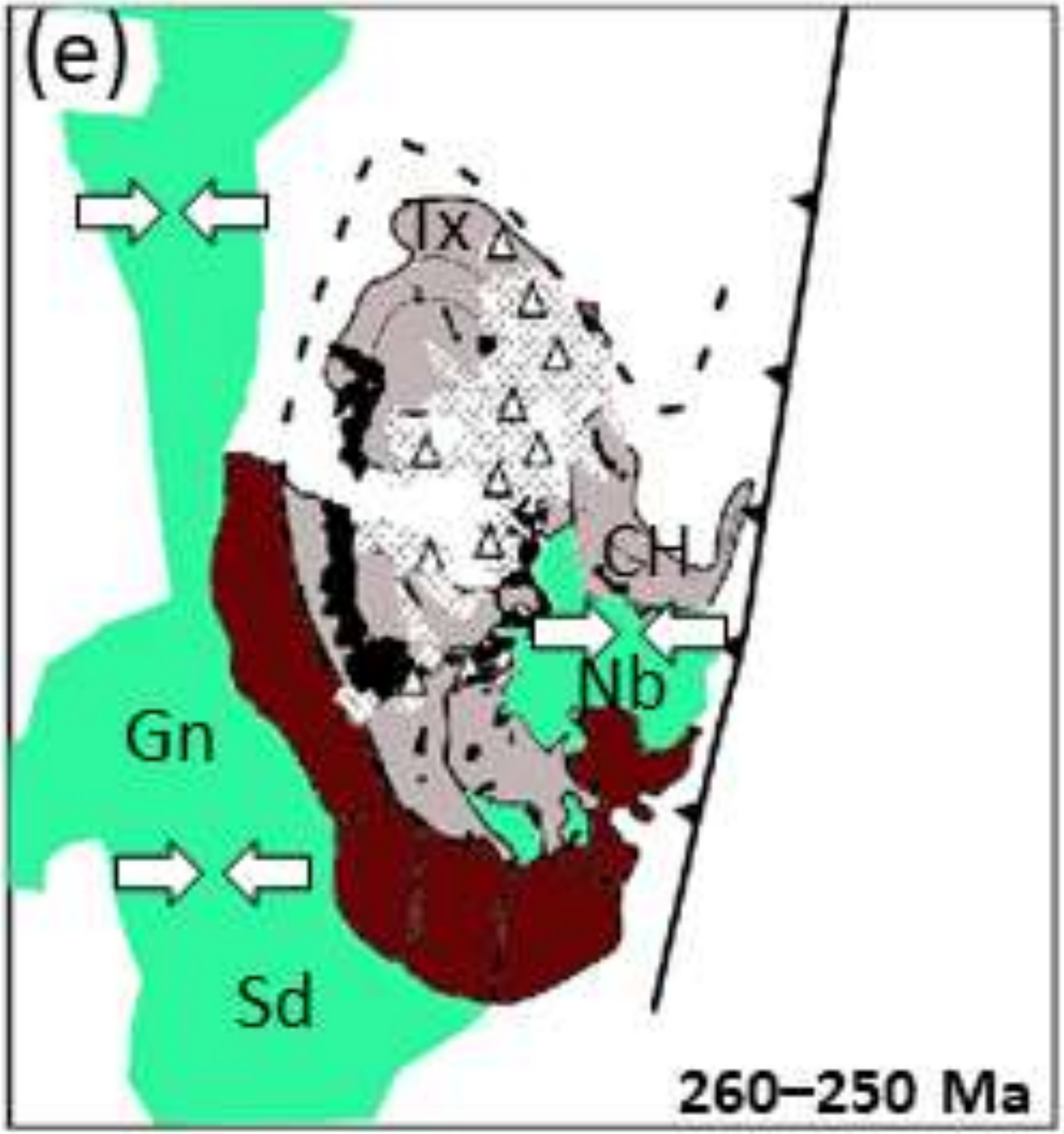
Ashfield Shales

When made into bricks the grey shale turns reddish and provides the distinctive colour of many Sydney buildings.

The relatively fertile shales were favoured by European settlers as they displaced the Aboriginal population.

Photo from https://www.step.org.au/index.php/item/214-wianamatta-group

During the Triassic the subduction zone off the coast produced widespread magmatism in the New England and Sydney Basin.



Late Permian – Triassic magmatism

Early Permian granitoids

Early Permian basins

Accretionary complex terranes

Forearc basin terranes

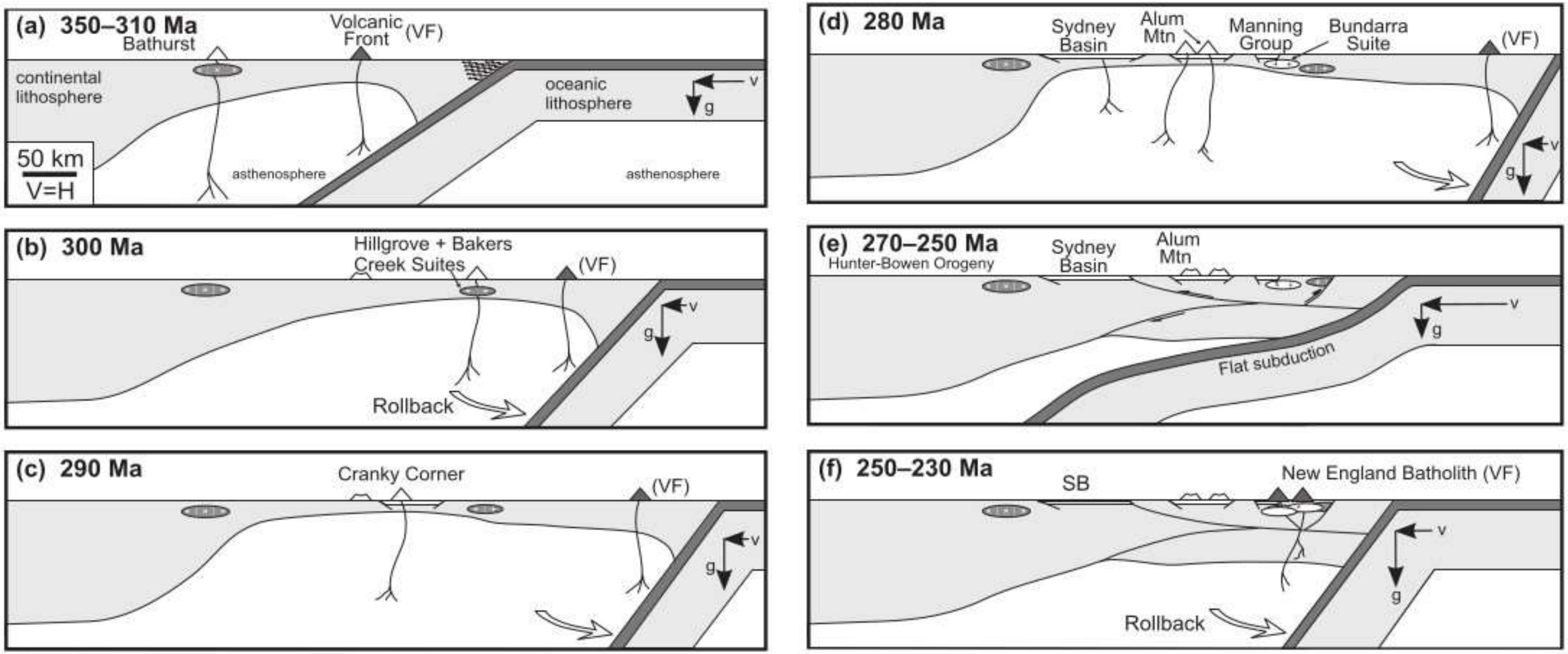
Serpentine Belt

Subduction rollback

Shortening

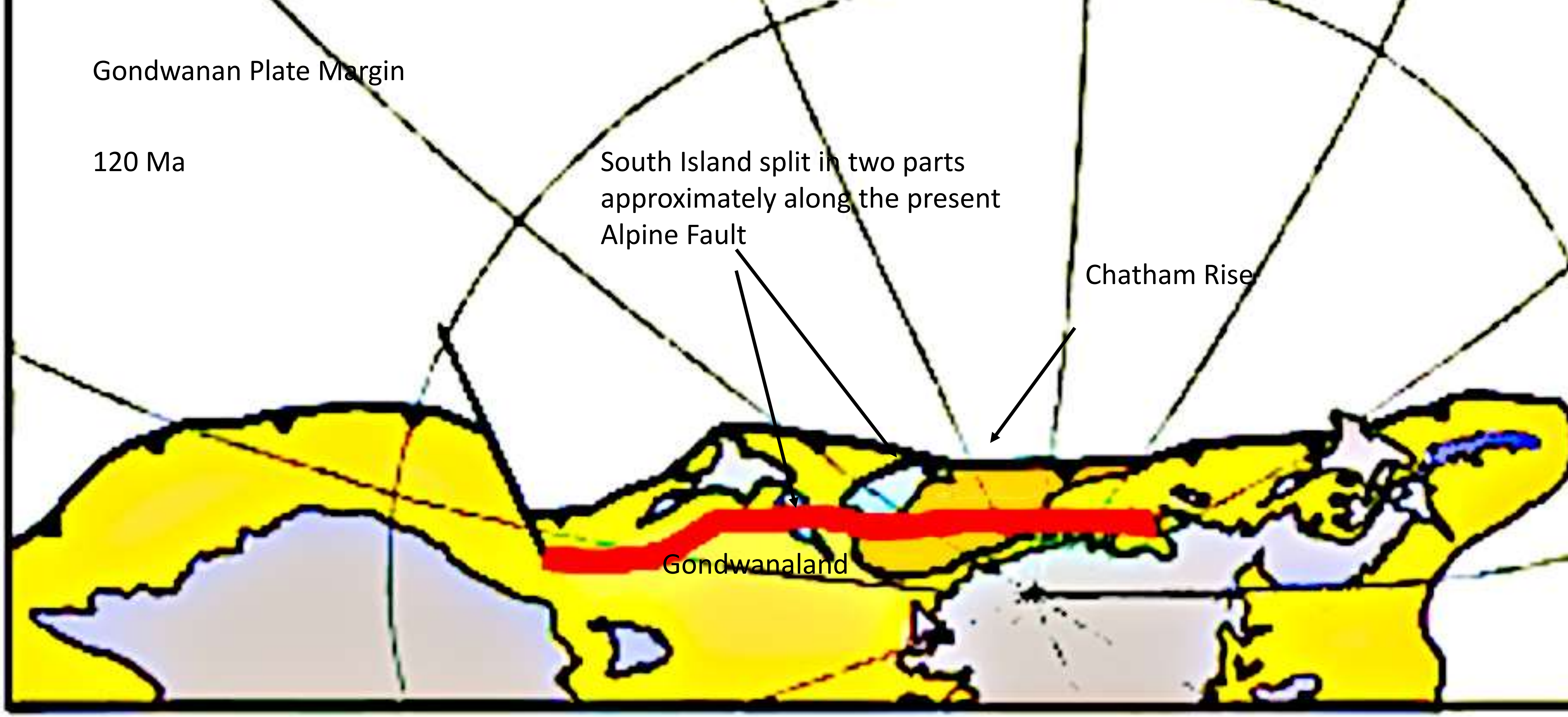
Extension

Active magmatism

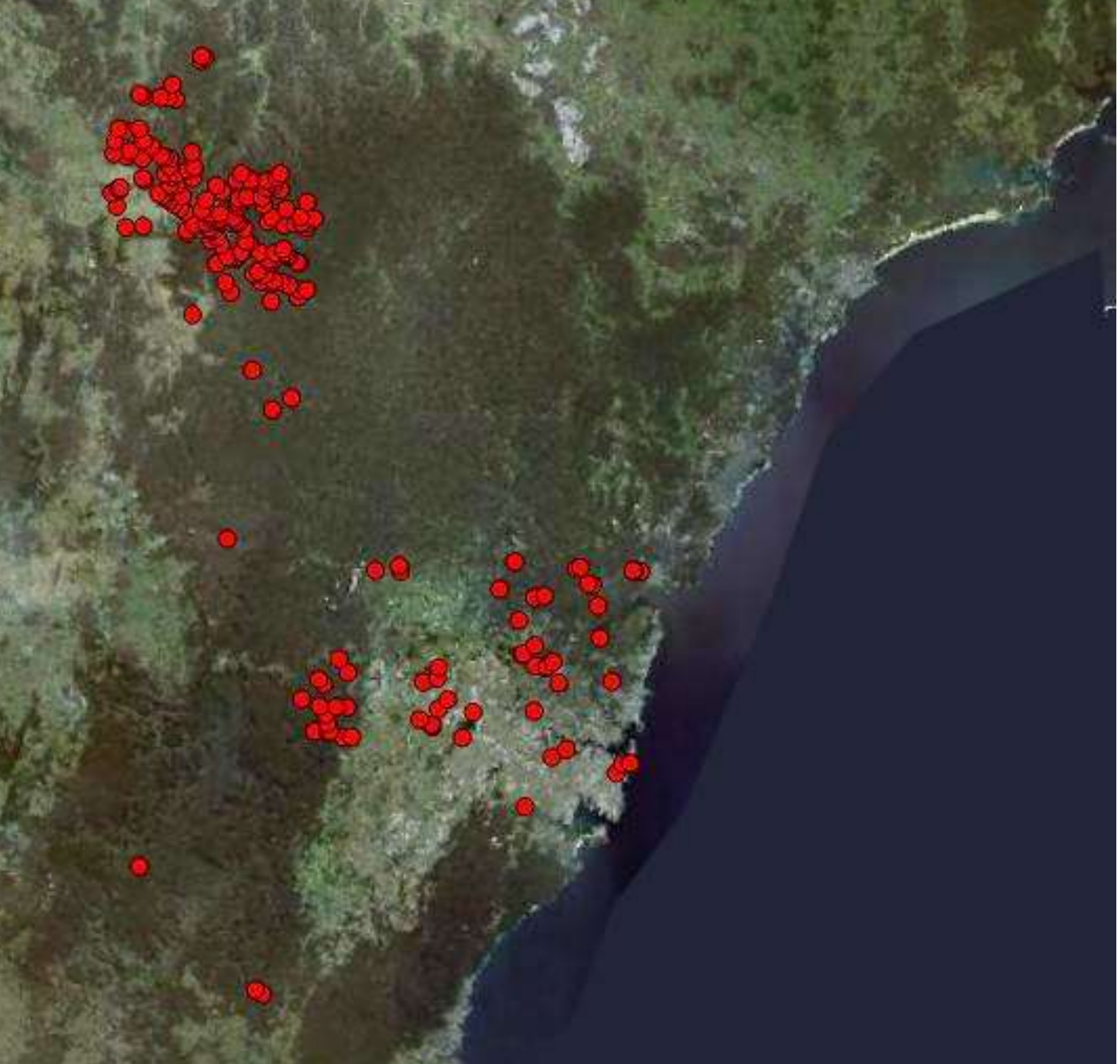


These sketches from R. B. Jenkins et al 2002 show how the thickness of the lithosphere varies with periods of advance and retreat (roll back) in the subduction zone off the coast. In periods of retreat the lithosphere thins and allows igneous intrusions with similar characteristics to Mid-ocean Ridge Basalts (MORB). The Alum Mountain Volcanics near Buladelah appear to be part of this process.

During the Jurassic period the subduction zone rolled back and re-established off the East Coast as seen below.



P Betts 2020 https://www.youtube.com/watch?v=_Dy4wwVPgxE



The Red dots show the location of 130 diatremes that occurred in the Sydney Basin at this time. As many have burst through Wianamatta Shales, they are thought to have occurred in the Jurassic.

Also originating at this time was the large Prospect Hill Laccolith (172 Ma)

Much of the material relating to this and the following slides is based on material in Branagan, D.F., and Packham, G.H., 2000 and https://australianmuseum.net.au/learn/minerals/shaping-earth/the-sydney-basin/

The Prospect dolerite intrusion near Parramatta in a suburb now called Pemulwuy is shown below. Dolerite is a type of basalt found in shallow dykes, sills and laccoliths.

Photo from Wikipedia

Photo from Prospect Heritage Trust

The Dolerite has been extensively mined and part of the old mine workings were submerged when an earth filled dam, to act as a water reservoir for Sydney, was made on Prospect Creek.

Volcanic activity in the Sydney Basin includes the formation of many dykes, the position of which are shown on the map.

While some of the dykes were formed before the opening of the Tasman Sea most along the coast are in the 80 – 60 Ma range.

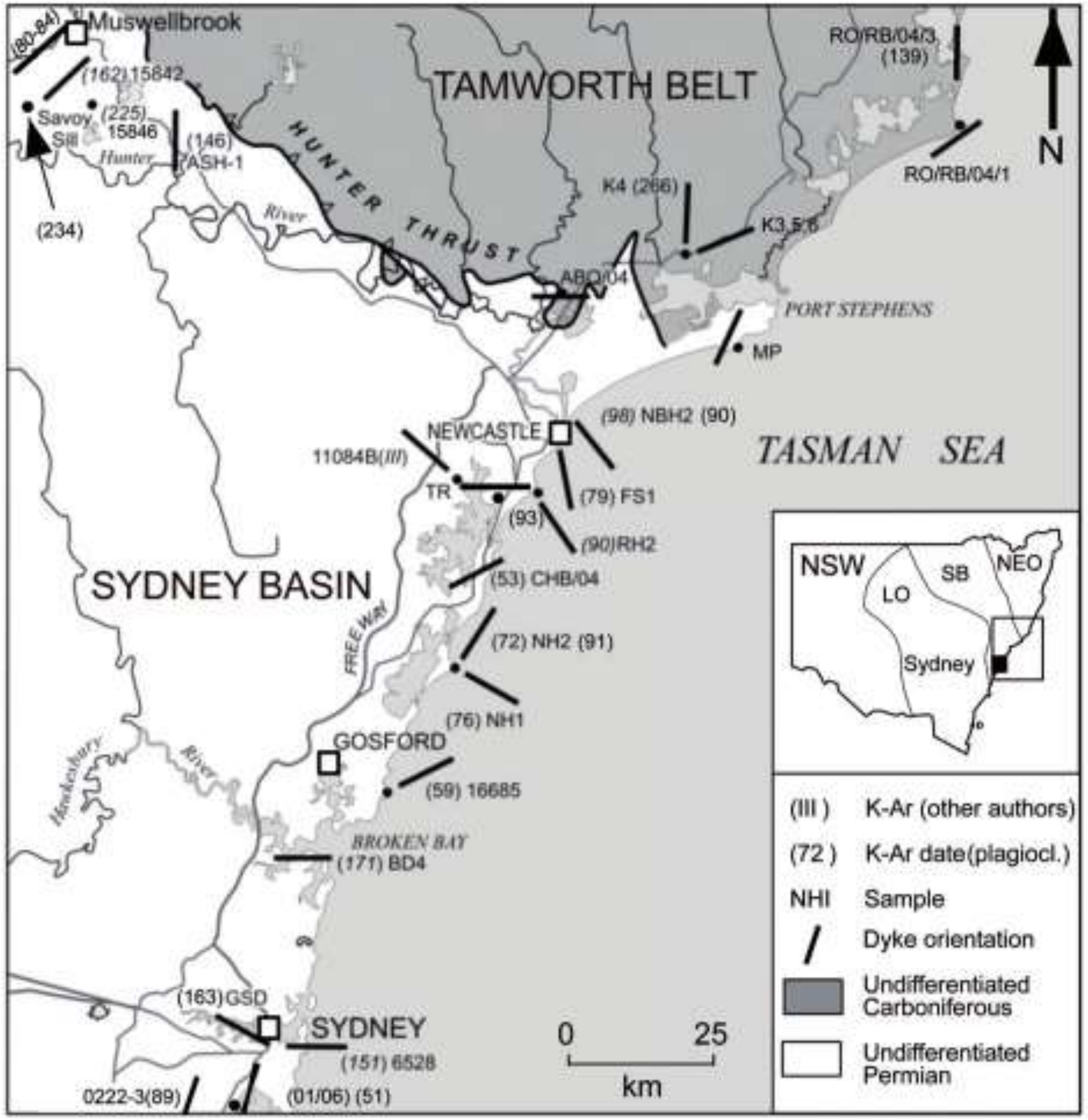
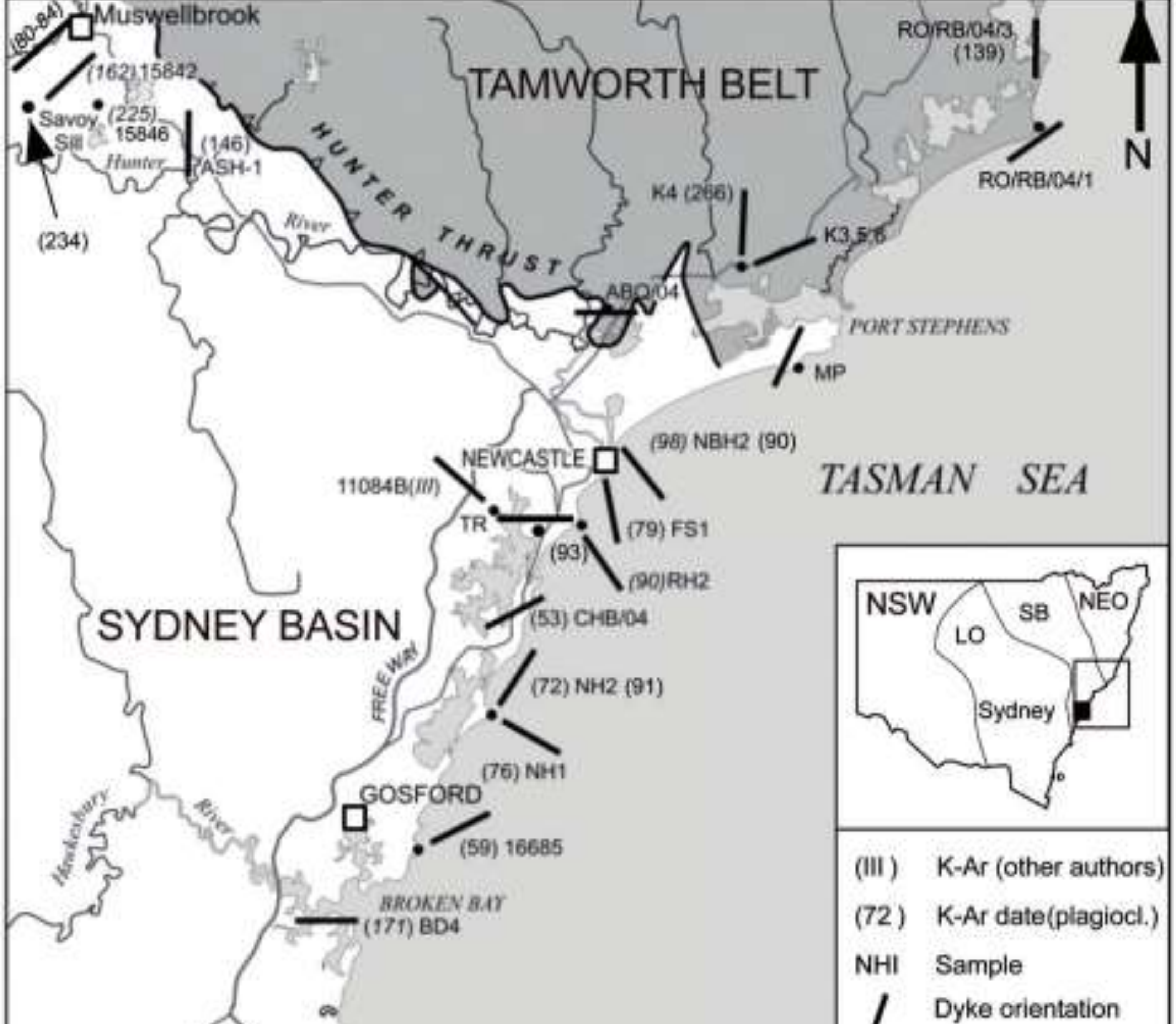


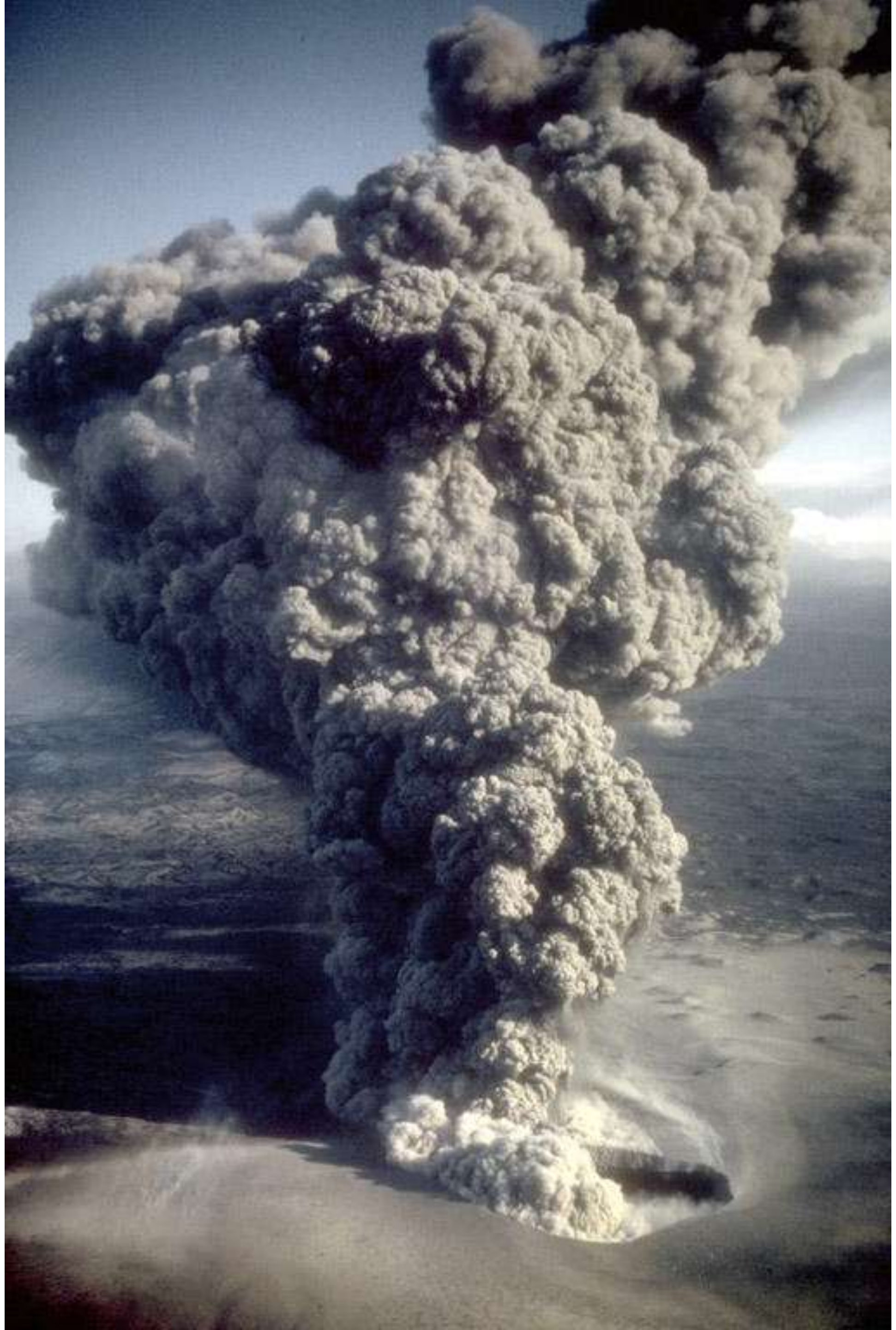
Figure 1. Simplified geological map of the northern Sydney Basin, showing the orientation of the dykes and ages of those mentioned in this study. Data for Savoy Sill (15846) and (15842) are from Harrington (1998); 11984B, BD4, and RH2 from Embleton *et al.* (1985) and Great Sydney Dyke from Och *et al.* (2009). GSD, Great Sydney Dyke; FS, Fort Scratchley; NH, Norah Head; MP, Morna Point; NBH, Nobbys Head; K, Karuah; RH, Red Head; TR, Teralba Rail Cut; ASH, Ashton Coal, Hunter Valley; BB, North Bondi Beach. Inset: Location of the southern New England Orogen (SNEO), Lachlan Orogen (LO), Sydney Basin (SB) and Mt Dromedary complex (D).



Muswellbrook
(80-84)
(162) 15842
Savoy Sill
(225) 15846
(146) ASH-1
Hunter River
(234)
TAMWORTH BELT
HUNTER THRUST
RO/RB/04/3 (139)
RO/RB/04/1
N
K4 (266)
K3,5,6
ABO/04
PORT STEPHENS
MP
(98) NBH2 (90)
NEWCASTLE
11084B(III)
TR
(93)
(79) FS1
(90) RH2
TASMAN SEA
SYDNEY BASIN
(53) CHB/04
FREEWAY
(72) NH2 (91)
(76) NH1
GOSFORD
Hawkesbury River
(59) 16685
BROKEN BAY
(171) BD4
NSW
LO
SB
NEO
Sydney
(III) K-Ar (other authors)
(72) K-Ar date(plagiocl.)
NHI Sample
Dyke orientation

Cenozoic activity was mainly in the form of basalt flows. These now form cappings to formations such as the Barrington Tops in the Hunter Valley, Mount Banks and Mount Wilson in the Blue Mountains and Peats Ridge on the central coast of New South Wales.

Photo from Wikipedia



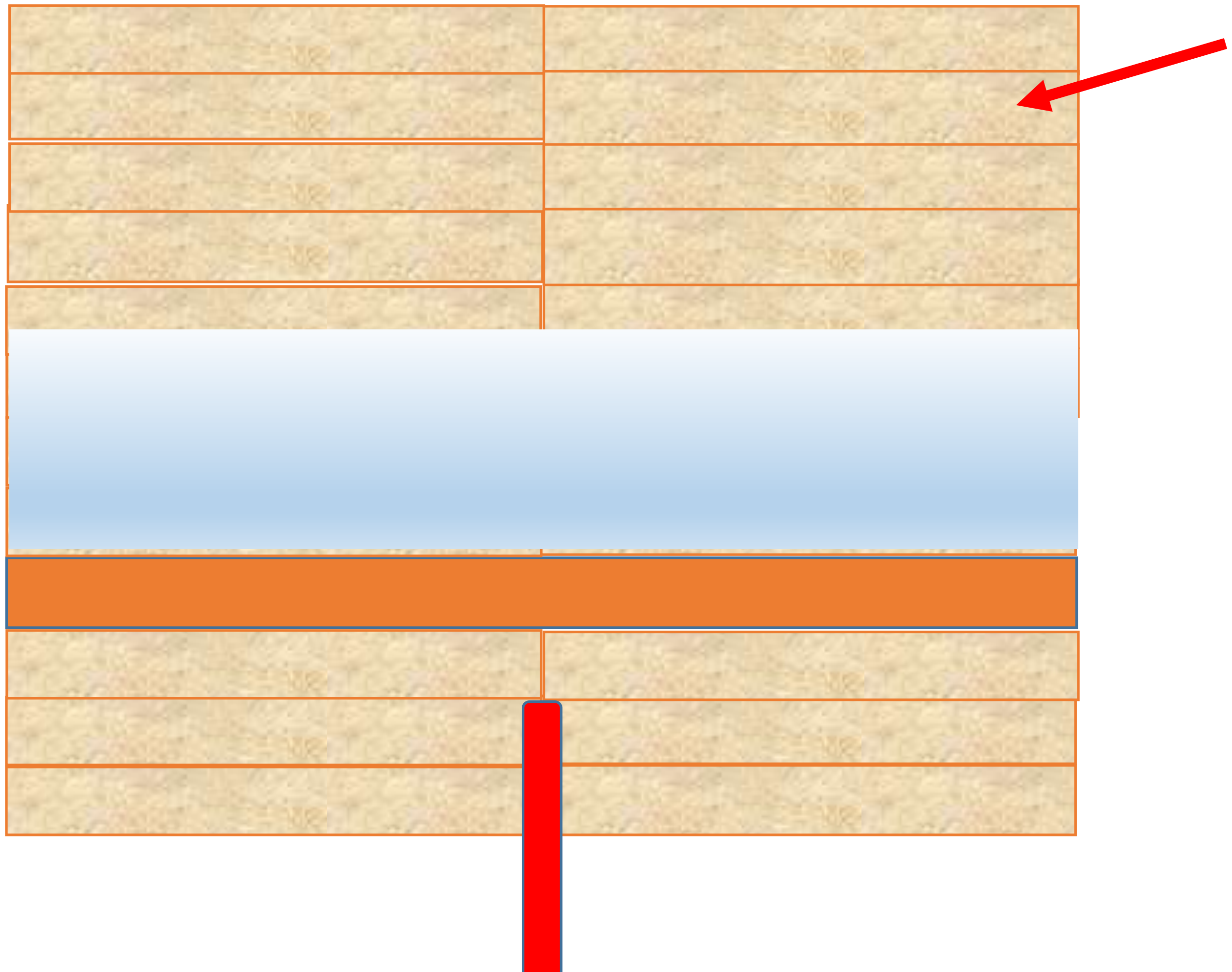
Diatremes form when magma, rising in a joint crack or weak spot in the rock layers near the surface, comes in contact with water in the rock. Each litre of water is turned into 1500 litres of steam and this causes an explosive eruption.

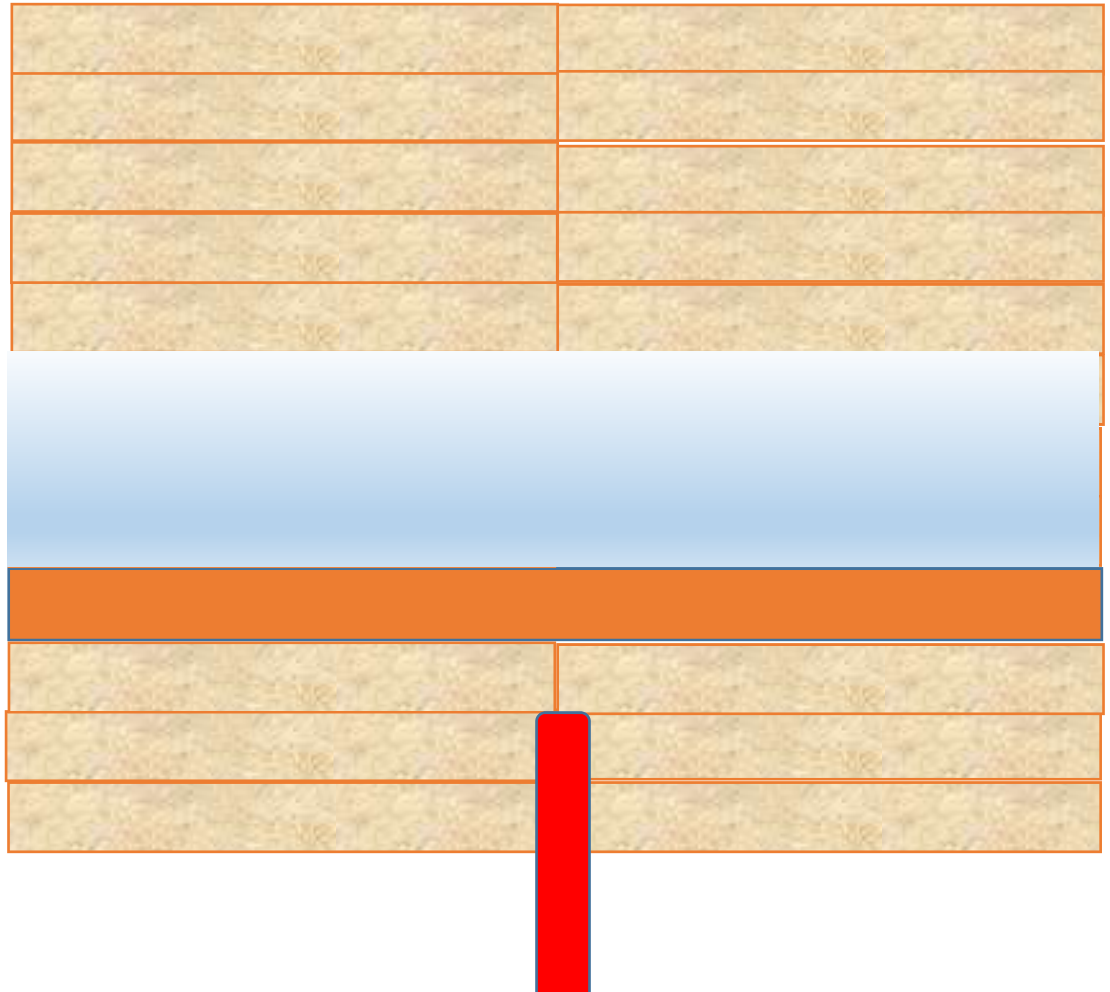
Geologists call this process Phreatomagmatic and this photo is an example of such an eruption in the east Ukinrek Maar crater, Alaska. The photo taken by C Russell.

The crater formed is termed a Maar and often contains a small lake.

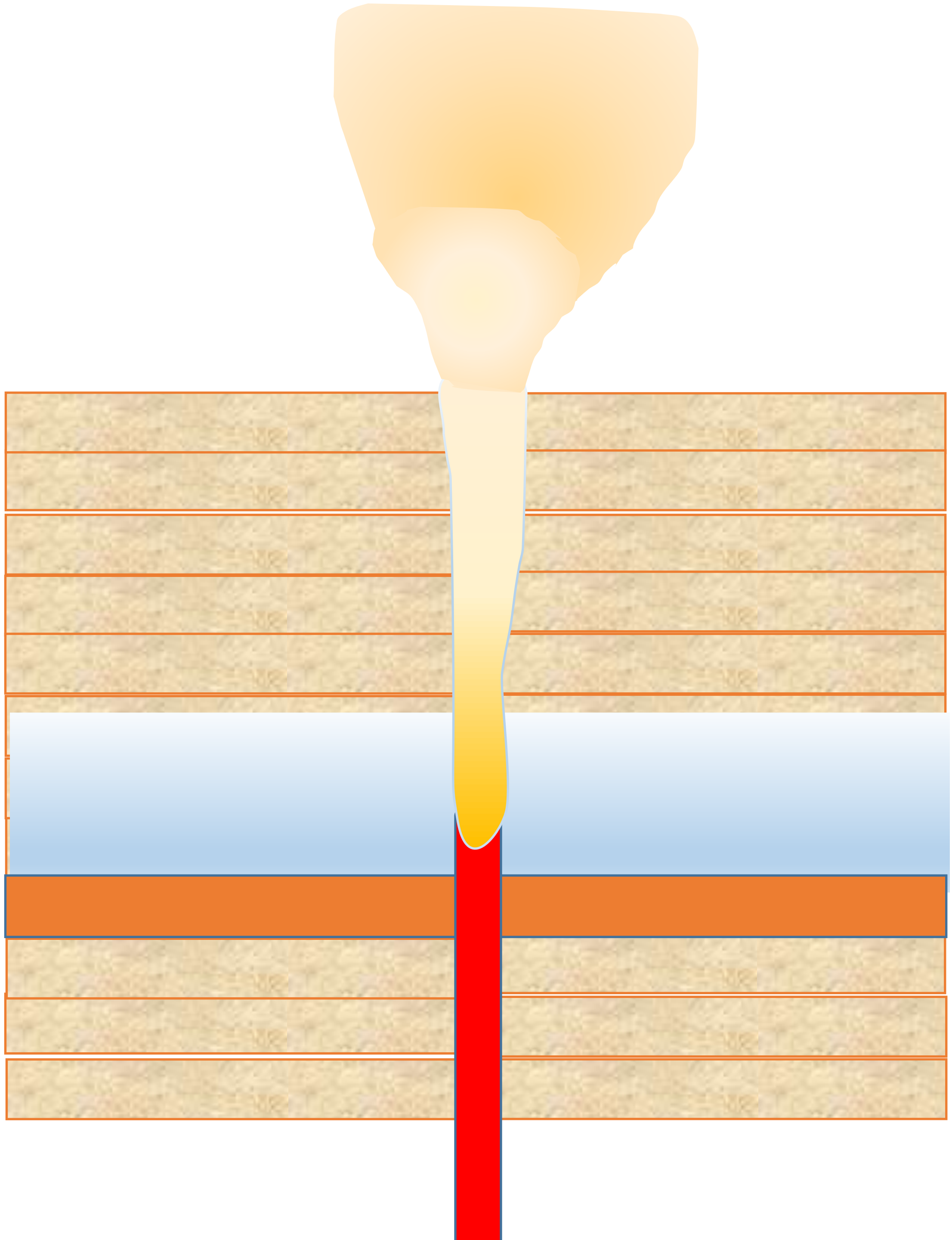
One of the largest and well known Maars near Sydney is the Hornsby Diatreme seen here. It has been extensively quarried but was recently used to dump the spoil from the North Connex tunnel.

Stages in the formation of a diatreme

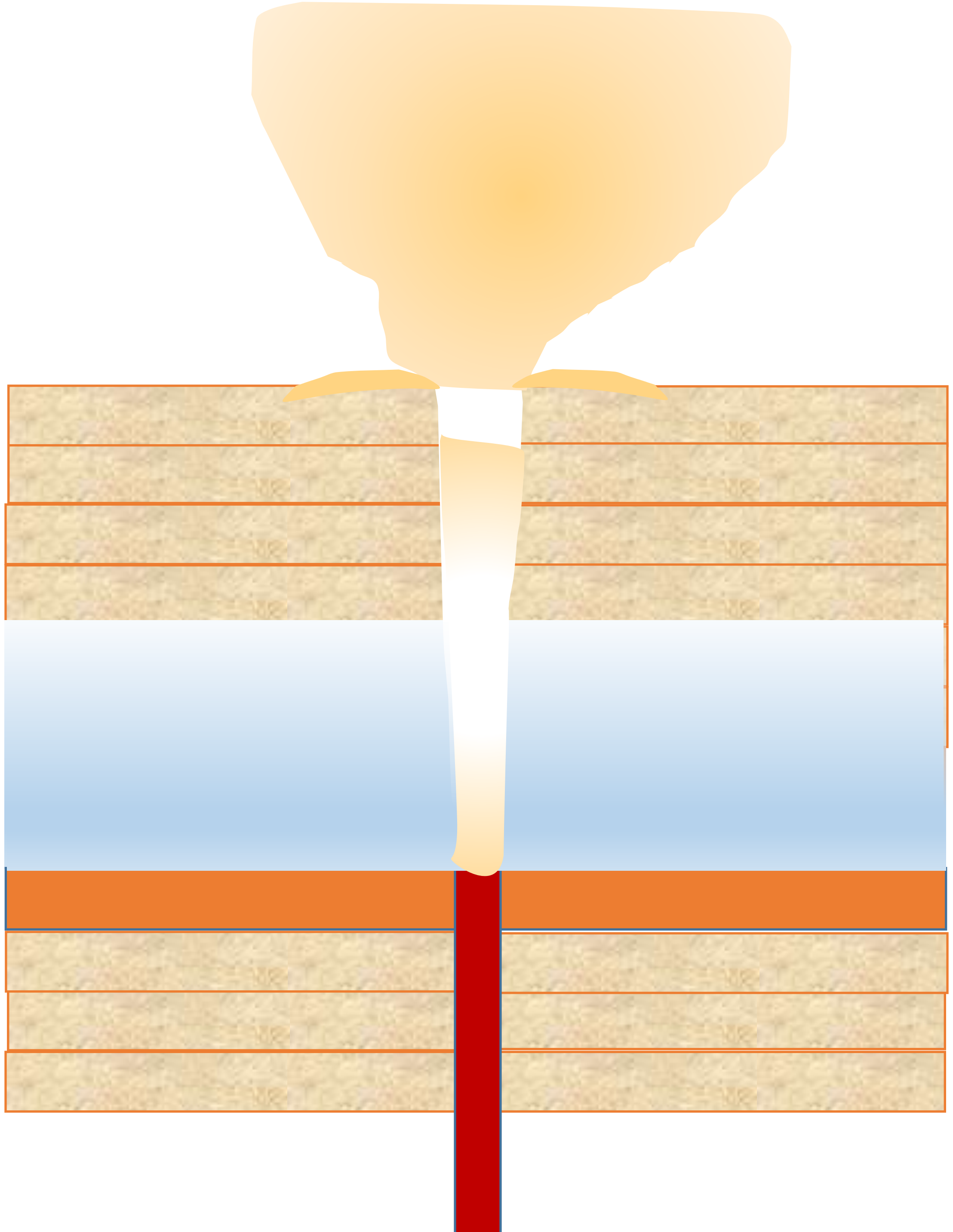




When lava contacts the ground water each litre is expanded into 1500 litres of steam

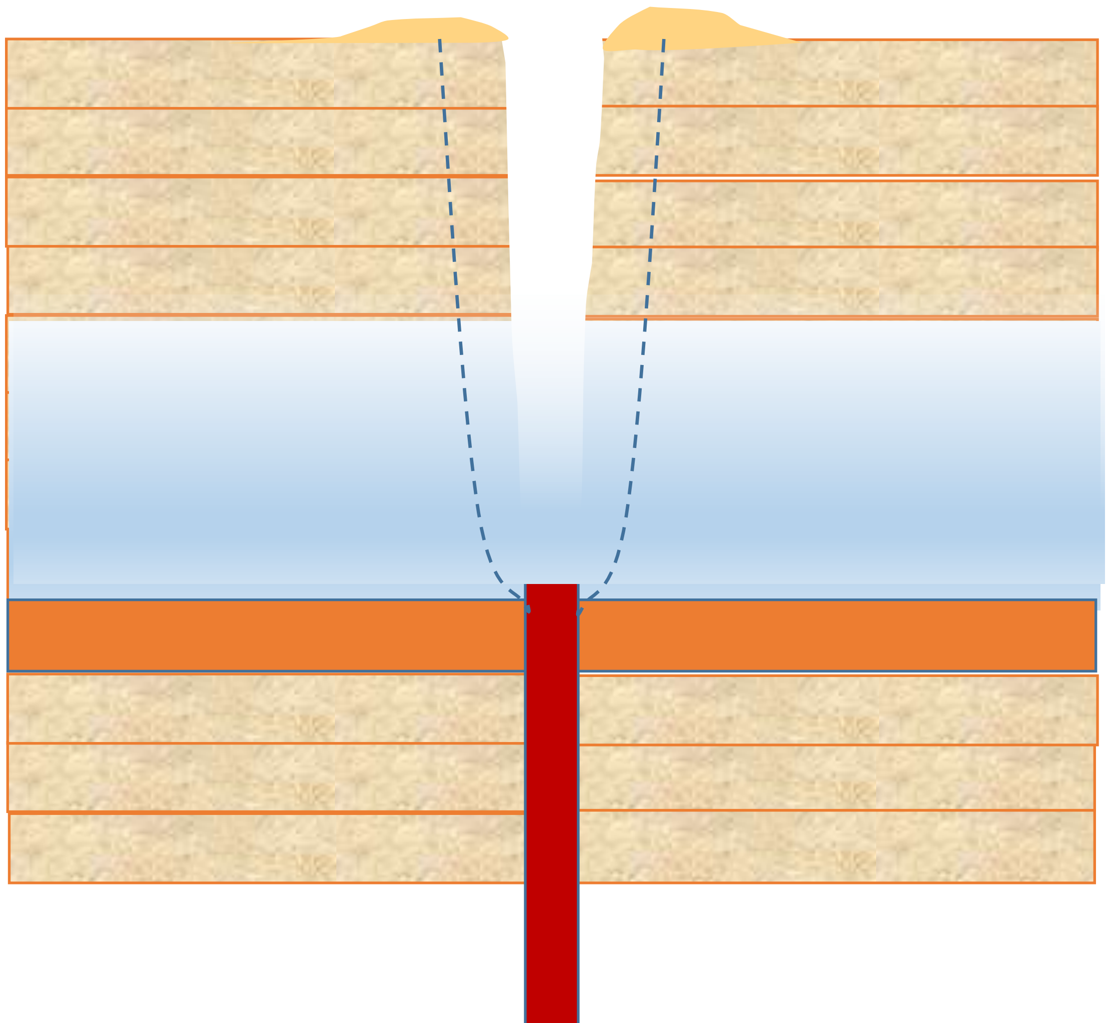


The expansion provides an explosive force that is transmitted along the relatively weaker joint crack to the surface.

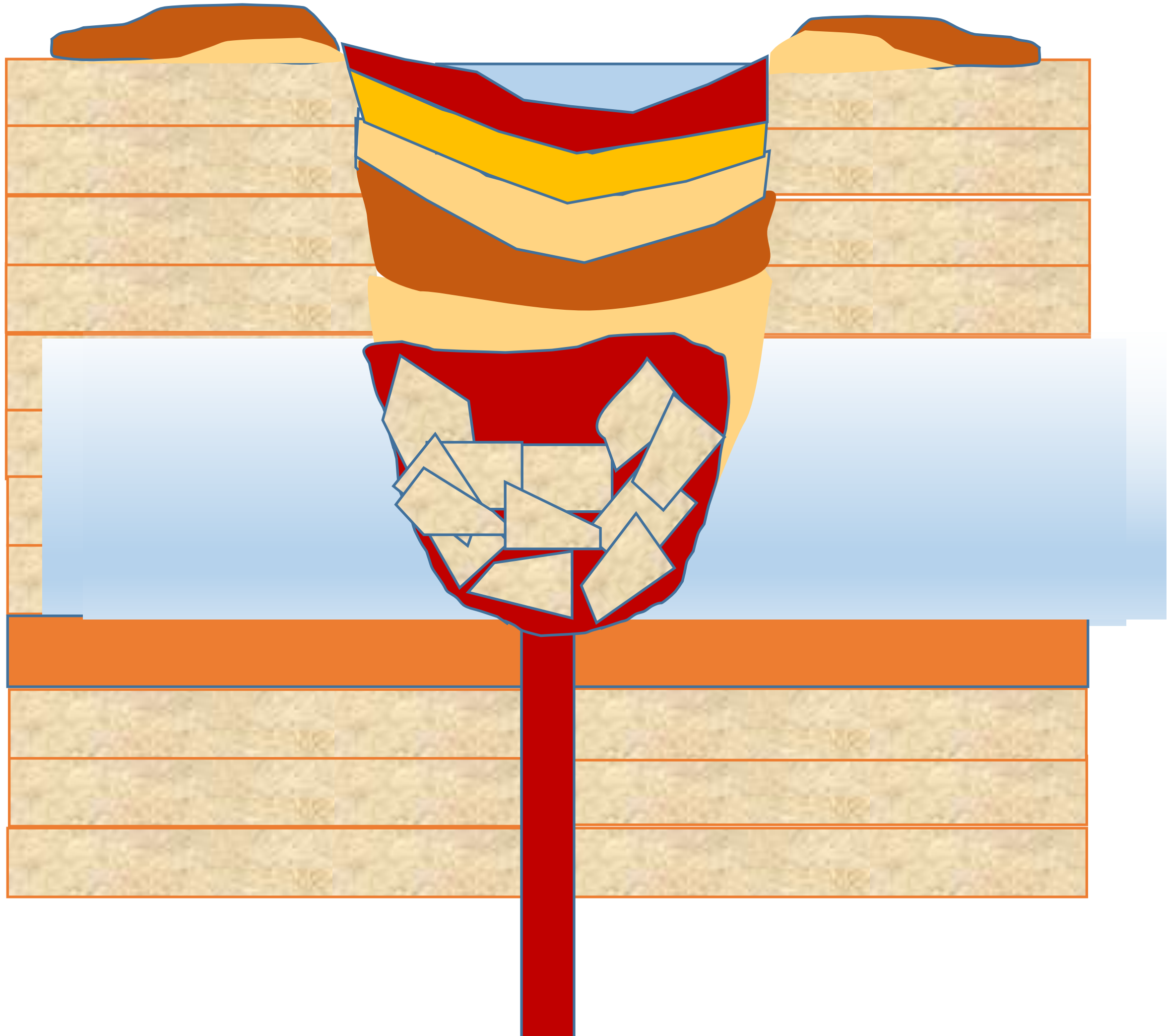


In the absence of strong winds the debris blown into the air sinks back down and forms layers of tuff around the vent.

Some debris sinks back into the pipe.



This and subsequent eruptions may form ring faults around the pipe. The material in these may collapse.



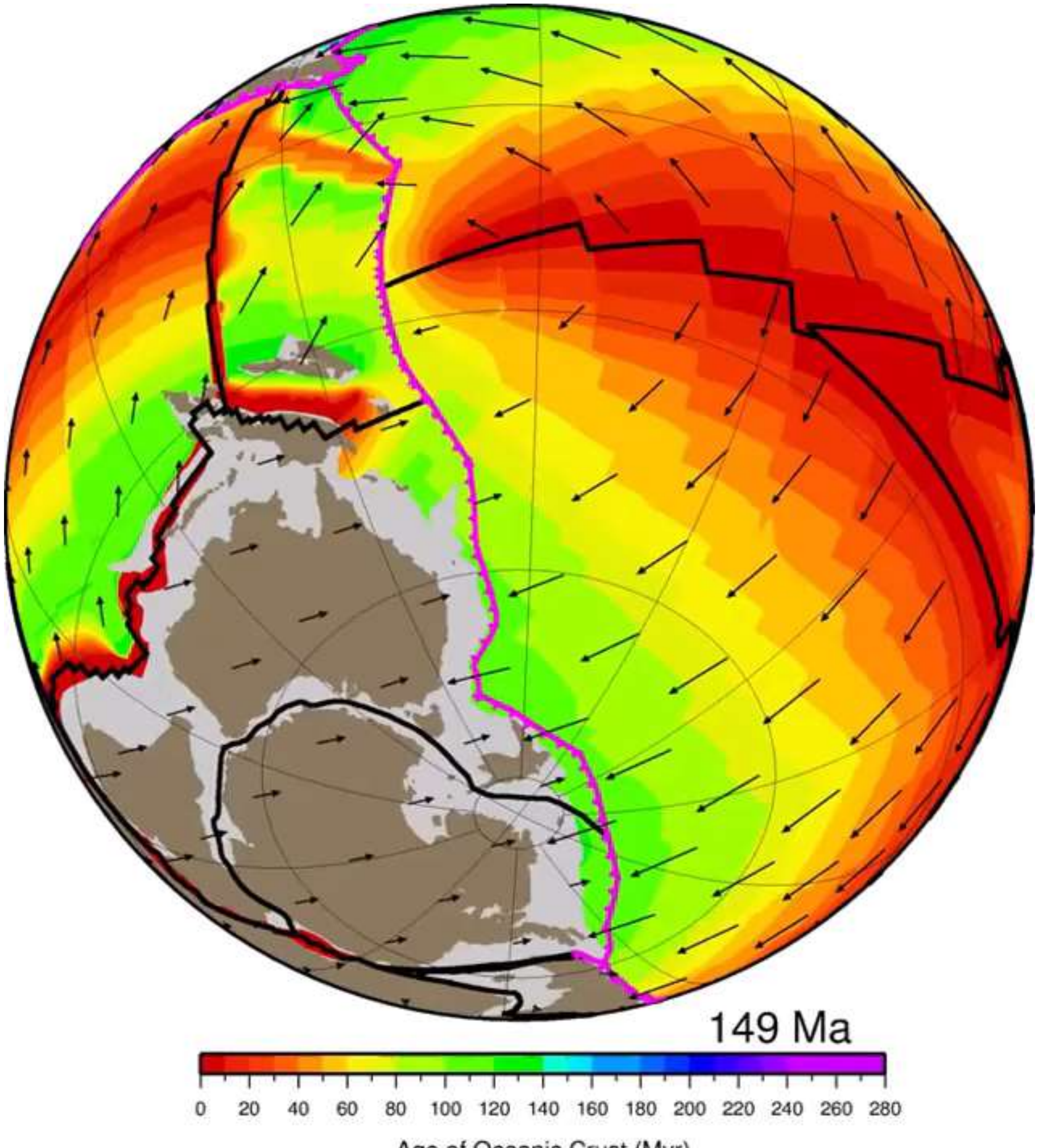
Further eruptions widen the vent and collapse of the ring faults partly fills the crater with layers of country rock and volcanic ejecta. These fall to form layers of breccia and these are often cup shaped

Basalt often flows into the crater consolidating the material.

Maar lakes may form in the crater

Cup shaped layers of breccia in the Hornsby diatreme.

Diatremes in Hawkesbury Sandstone tend to be eroded and form depressions while in the areas of Wianamatta Shales they are small rounded hills.



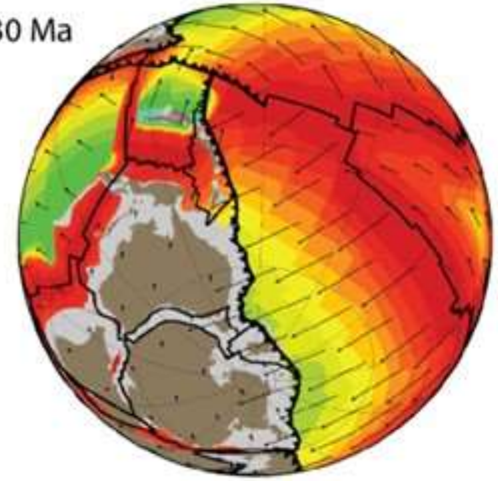
In the Cretaceous the opening of the Tasman Sea and the break up of Gondwanaland produced significant changes in the Sydney Basin.

This model from Earthbyte shows that the opening of the Tasman was followed by the break up of the Australian and Antarctic continents.

Click the diagram to begin the animation.

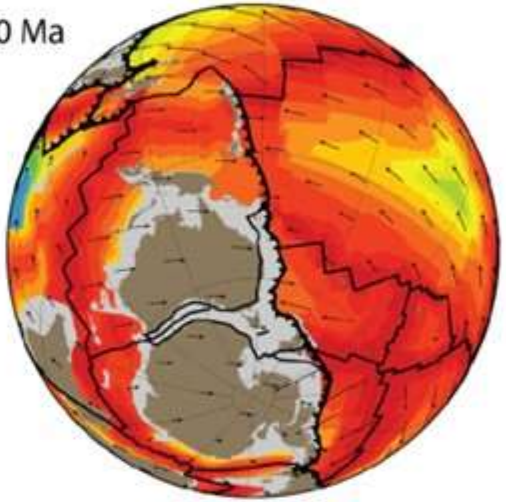
Mueller et al 2016. Earthbyte
https://www.youtube.com/watch?v=JoLQndZl2ZI

130 Ma



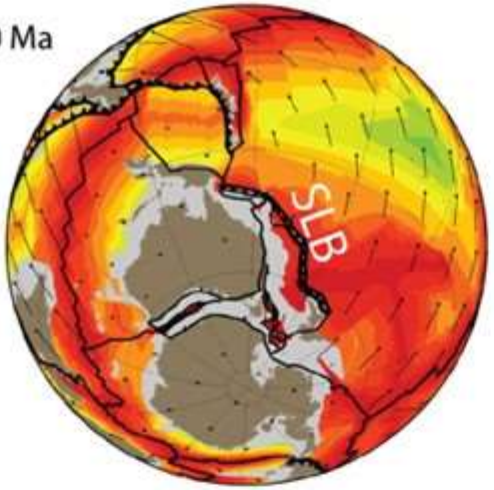
Eastern Gondwana initially moves north as split with India begins

100 Ma



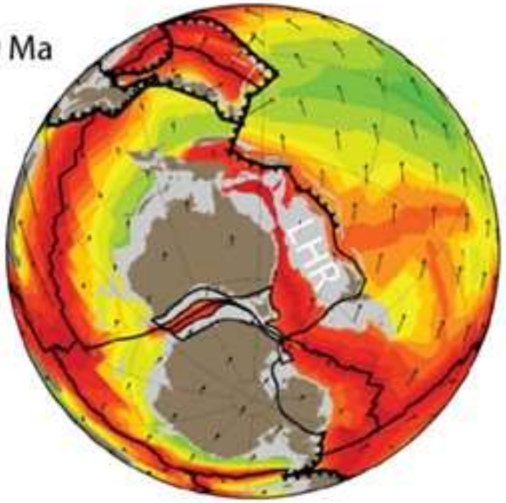
Eastern Gondwana moves east as the split with India widens

80 Ma

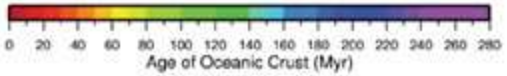


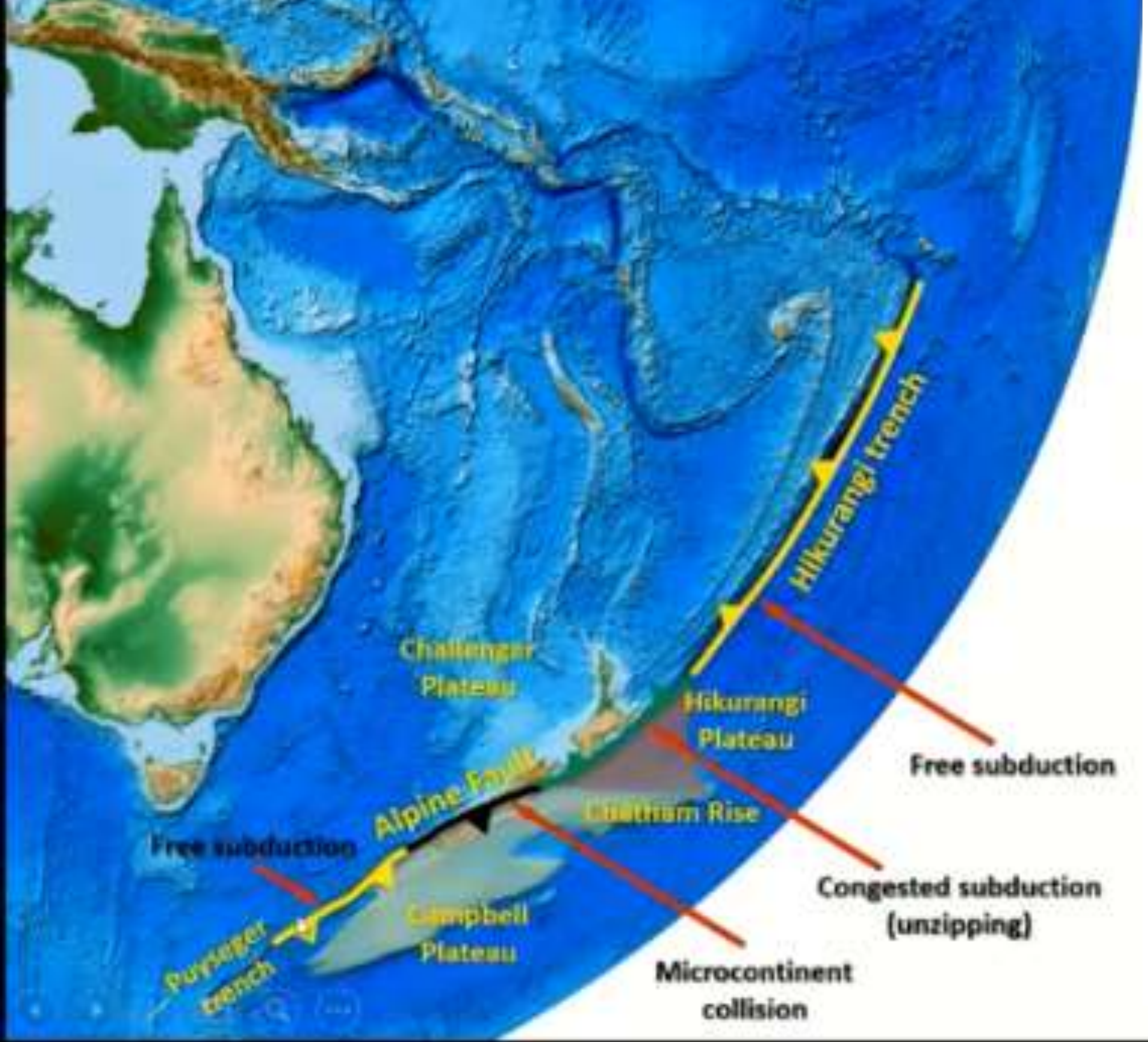
Australia and Antarctica begin to split and the Tasman Sea begins to open

50 Ma



Tasman Sea open and Australia moving north away from Antarctica



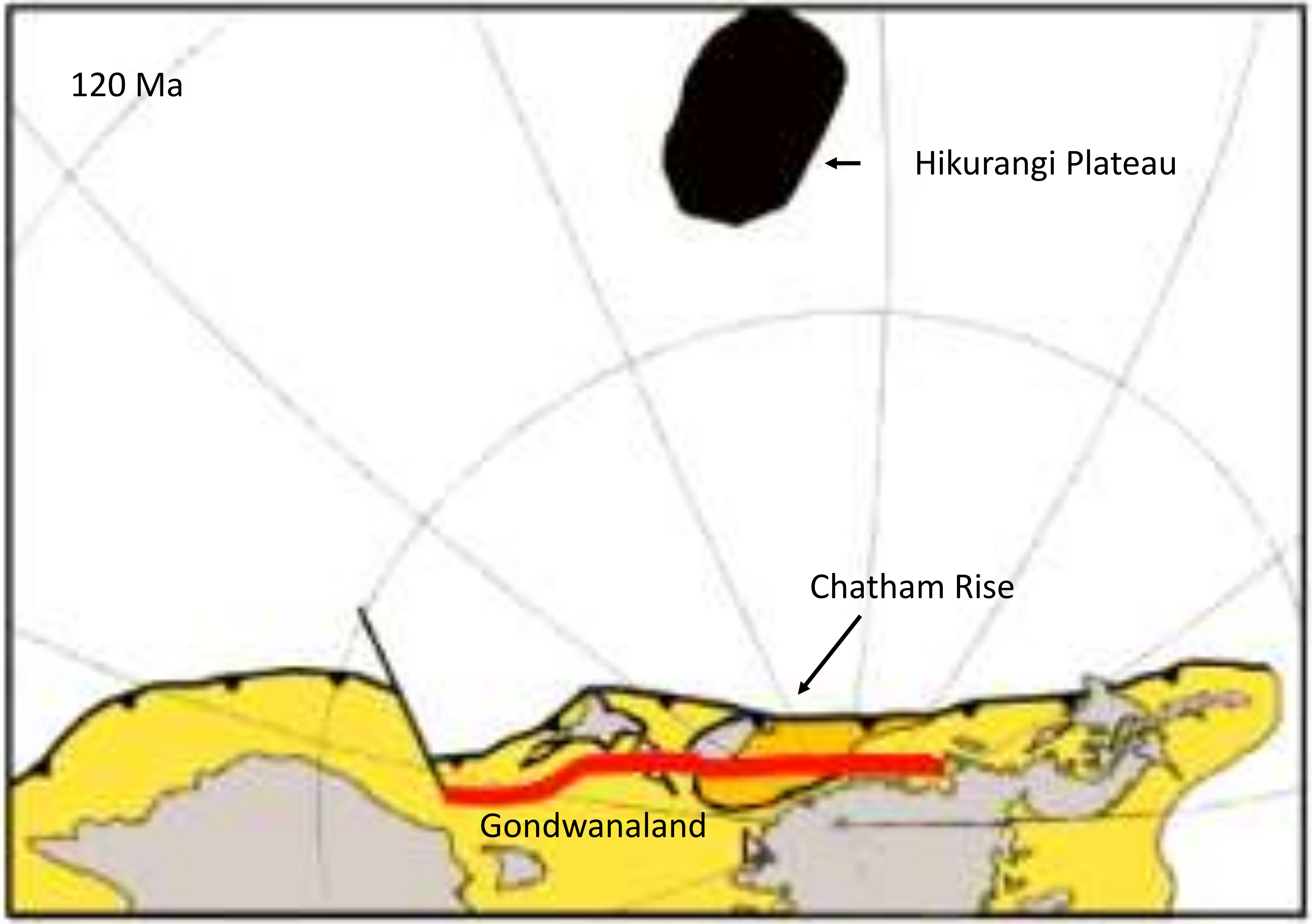


In the last two decades there has been considerable research in to the effects of congested subduction. Its effects on the Lachlan Orogen have been widely accepted and Ferguson (2019) outlined its contribution to the NEO.

Betts et al now suggest that congested subduction was the initiator for the opening of the Tasman Sea, the formation of the present arrangement of the NZ landmass.

The opening of the Tasman Sea had significant effects on the geomorphology of the Sydney Basin

Gondwanan Plate Margin



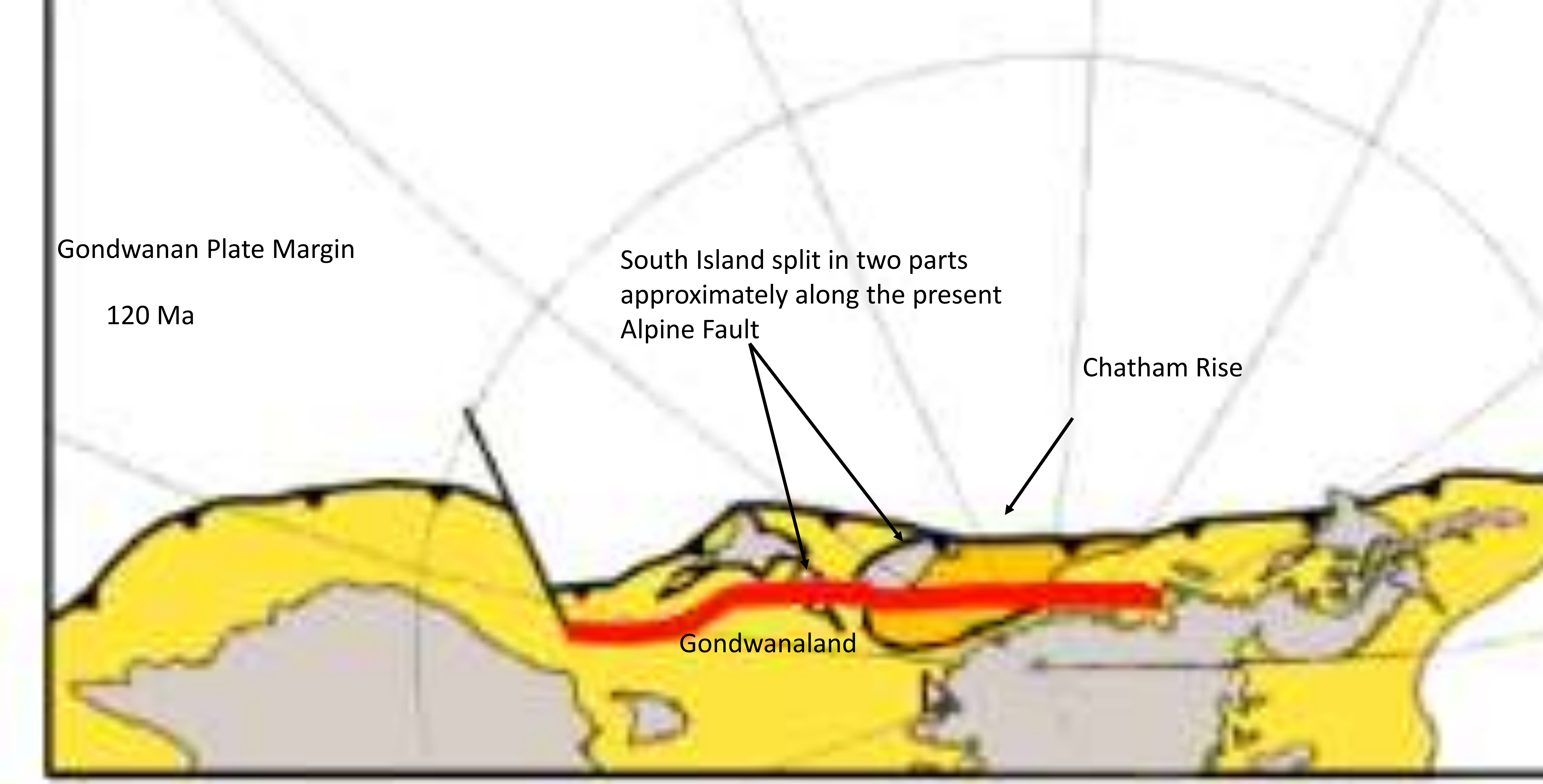
At approximately 120 Ma the subduction zone off the coast of eastern Australia had been retreating but was still relatively close and in the position shown on this map.

Note that the South Island was separated into two parts, approximately along the line of the present Alpine Fault.

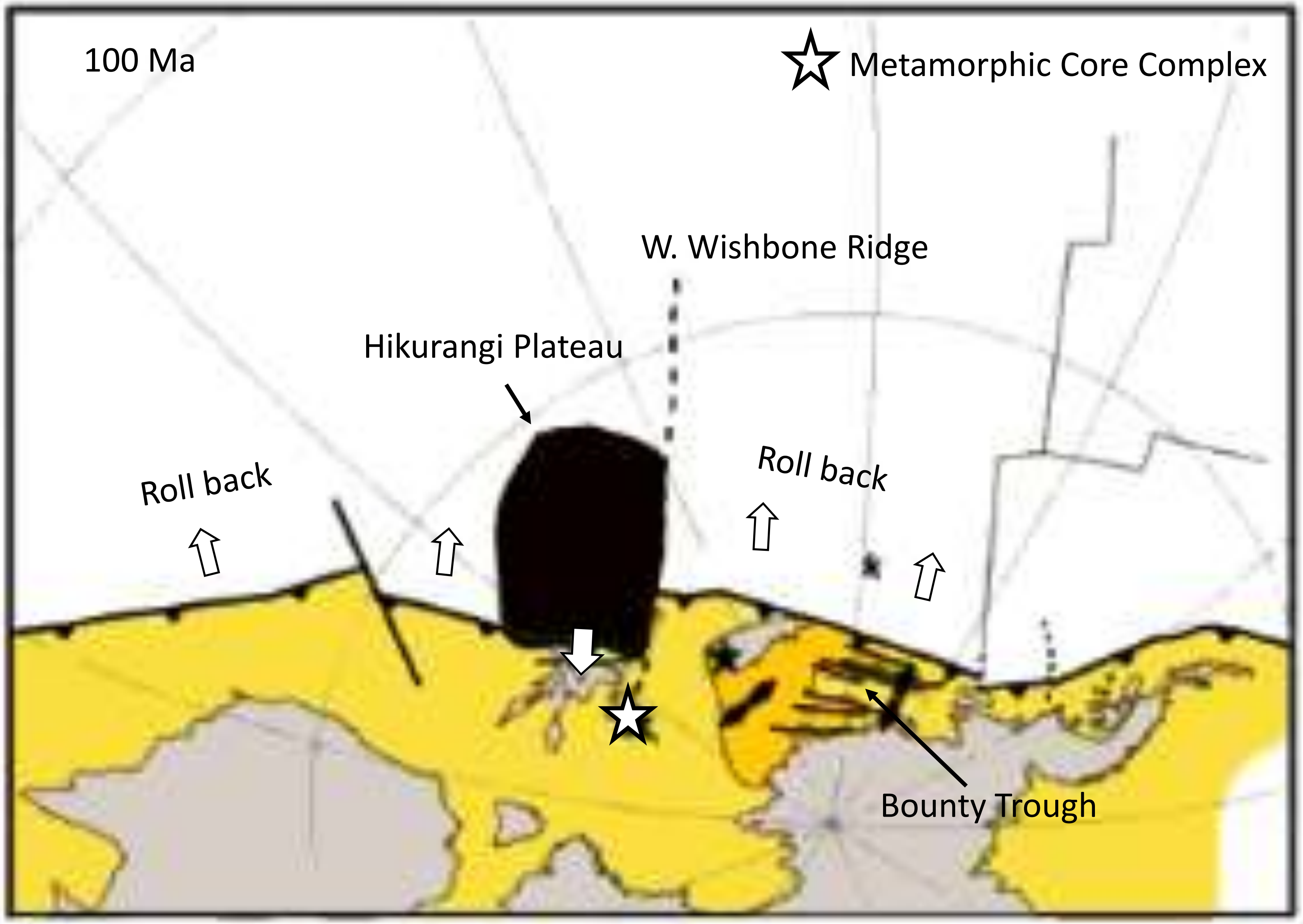
The Hikurangi Plateau was advancing towards Gondwanaland on a subducting plate.

Late Cretaceous Volcanics

This and the following slides are from P Betts 2020 https://www.youtube.com/watch?v=_Dy4wwVPgxE


Gondwanan Plate Margin
120 Ma
South Island split in two parts approximately along the present Alpine Fault
Chatham Rise
Gondwanaland

Initial segmentation of the Gondwanan Plate Margin

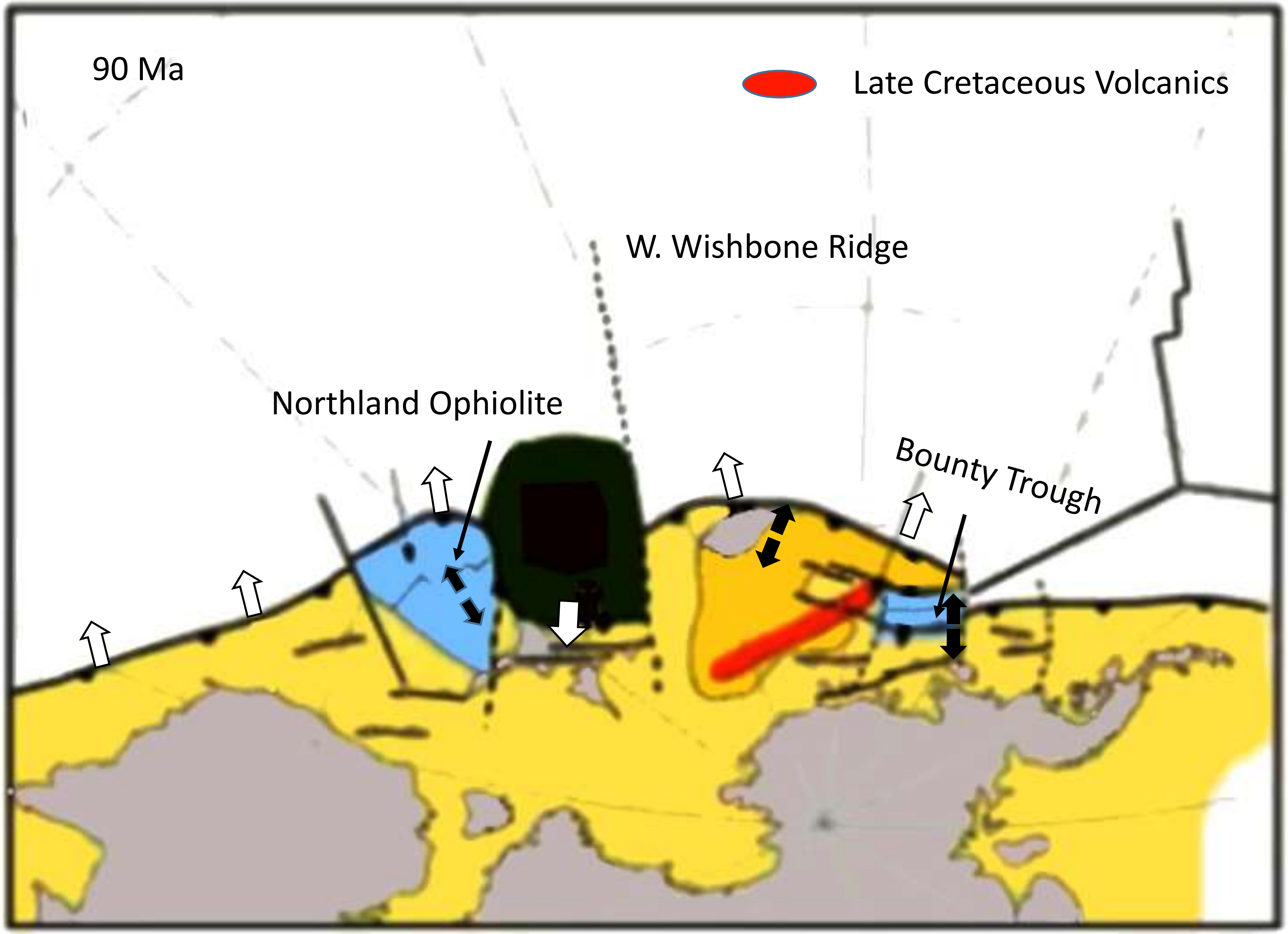


At approximately 100 Ma the Hikurangi Plateau collided with the North Island of NZ and the period of congested subduction began that persists to this day.

As explained in the Moresi modelling this produced roll back on either side of the congested subduction

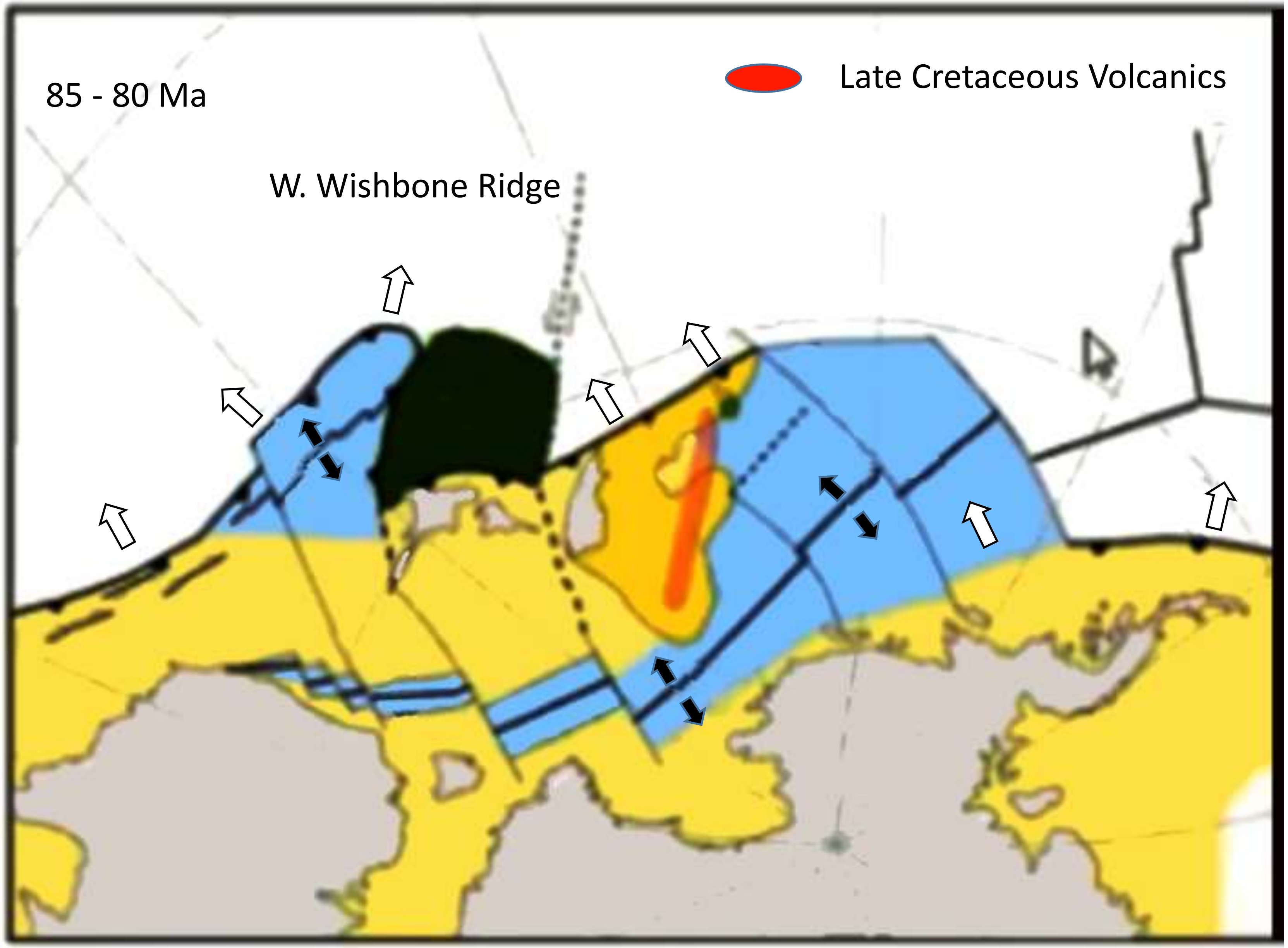
In the area off Antarctica, roll back initiates the Bounty Trough

Onset of plate re-organisation



As the Bounty Trough widens the Chatham Rise is split from Antarctica and it begins to rotate.

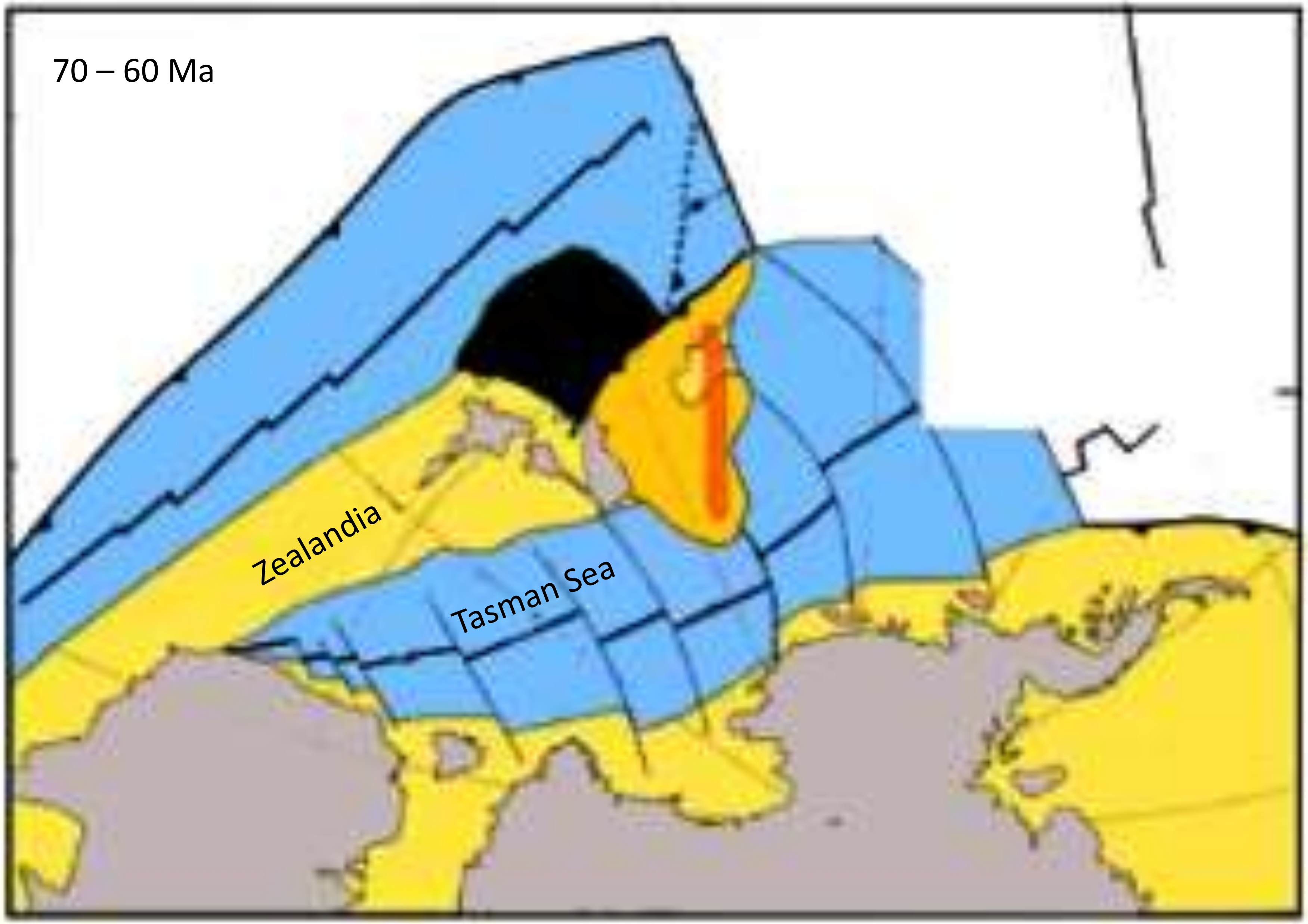
The Northland Ophiolite, which had been forming as a foreland basin, expands on the other side of the area of congested subduction.



At this stage the combination of shortening as the Hikurangi Plateau collides with the North Island and rotation in the roll back in the Chatham Rise brings the two together.

The West Wishbone Ridge become the proto Alpine Fault.

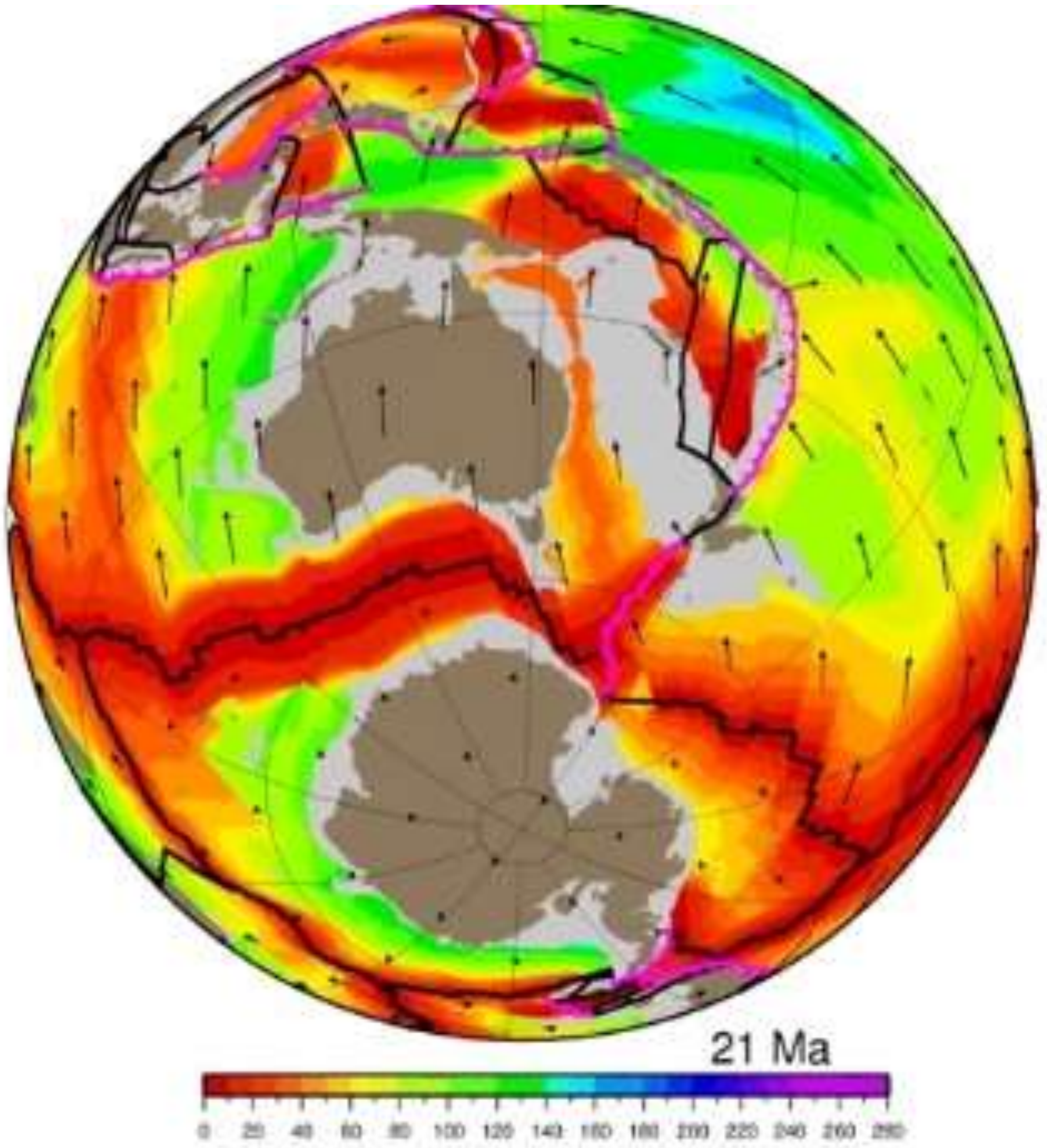
The divergence beginning in the Bounty Trough has spread along the coast of present day Australia and Antarctica.



Continued roll back against the congested margin rotates the larger section of the South Island against the North Western part until they both meet along the Alpine Fault and become part of the congested zone.

The establishment of a divergent margin off the coast exerts ridge push force on the Australian Continent.

Following this Australia and Antarctica diverge and the Australian Plate begins to move North.

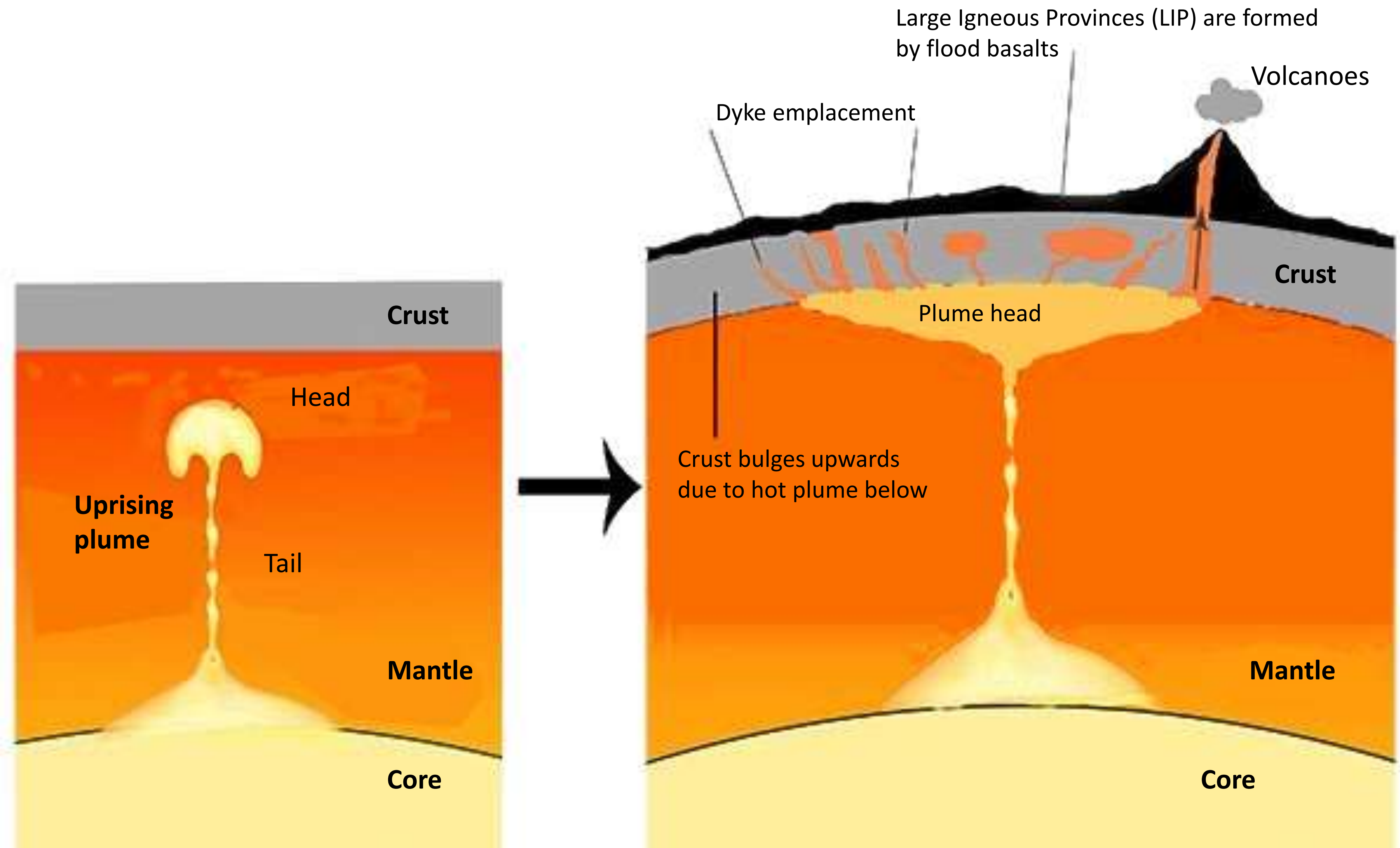


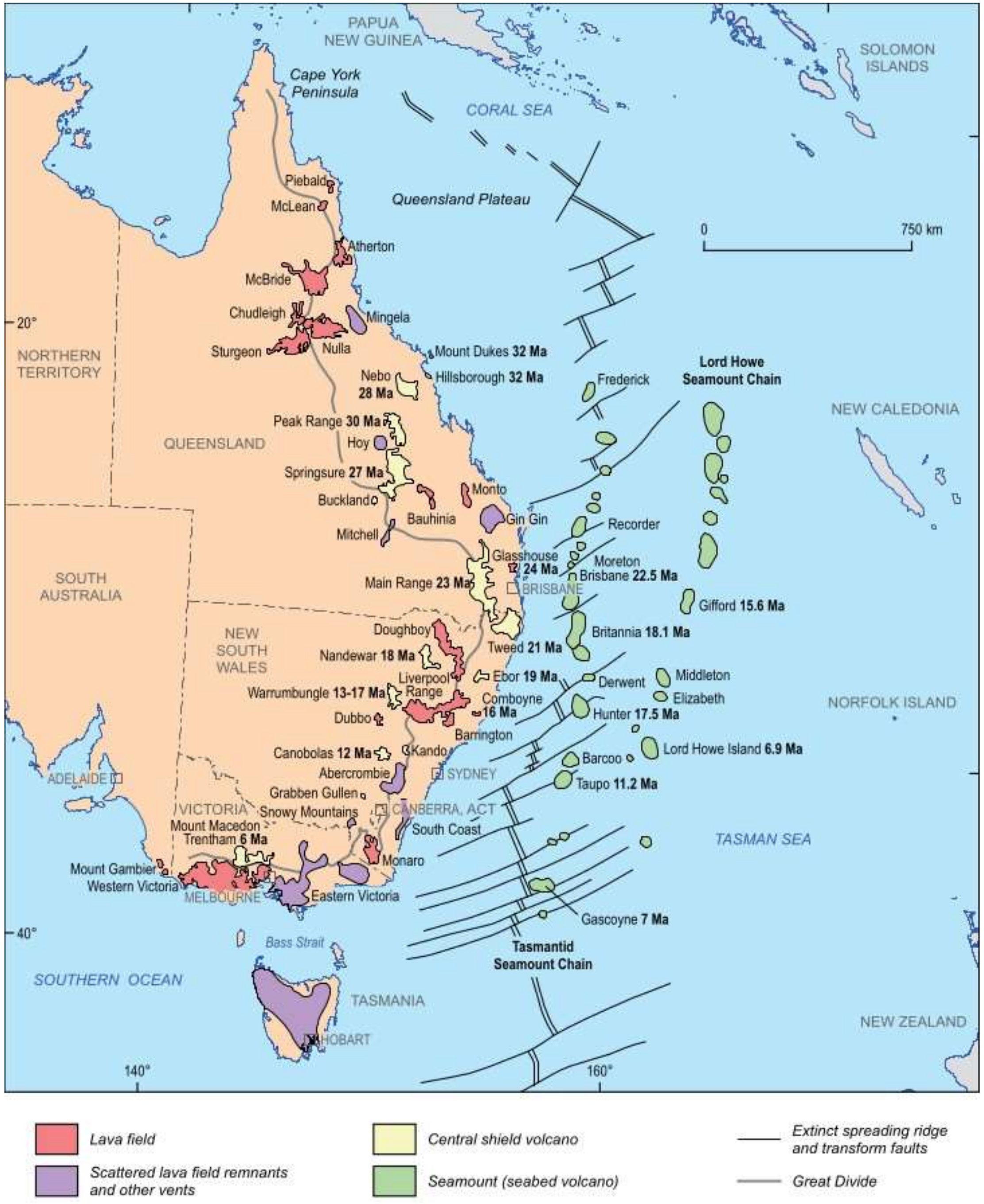
The East Coast of Australia was exposed to ridge push from the opening of the Tasman Sea and as the continent moved north it also travelled over volcanic plumes or “hot spots” of varying sizes.

These produced a series of intraplate volcanoes

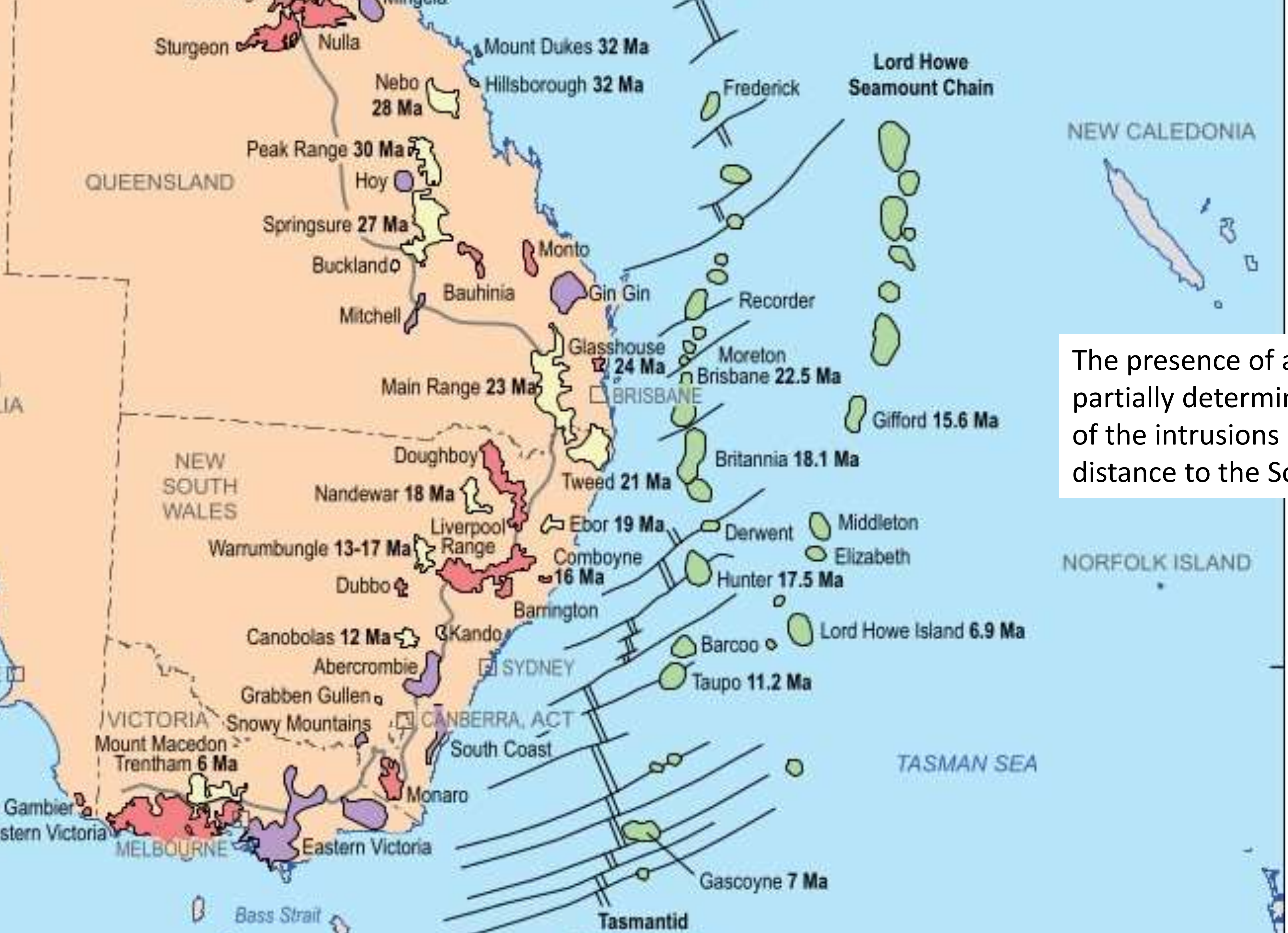
The following 11 slides contain material from a presentation by Prof Rhodri Davies from the ANU. https://science.anu.edu.au/news-events/events/cenozoic-intra-plate-volcanism-eastern-australia-role-mantle-plumes-plate-motion

Mueller et al 2016.
https://www.youtube.com/watch?v=JoLQndZl2ZI

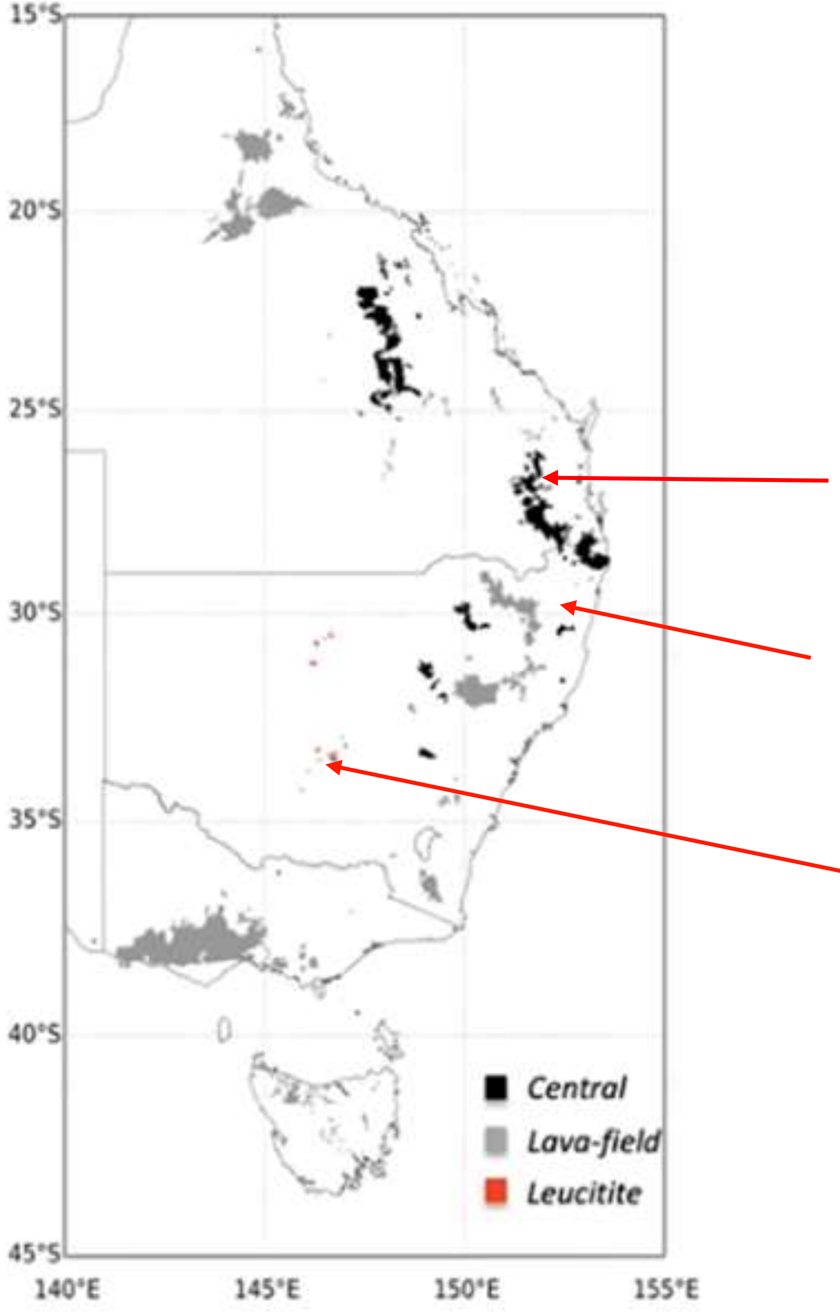

Crust
Head
Uprising plume
Tail
Mantle
Core
Large Igneous Provinces (LIP) are formed by flood basalts
Volcanoes
Dyke emplacement
Crust
Plume head
Crust bulges upwards due to hot plume below
Mantle
Core



The volcanic plumes produced lines of sea mounts, volcanoes and lava fields.



The presence of a plume or “hot spot” is partially determined by the fact that the age of the intrusions becomes younger with distance to the South in each chain.

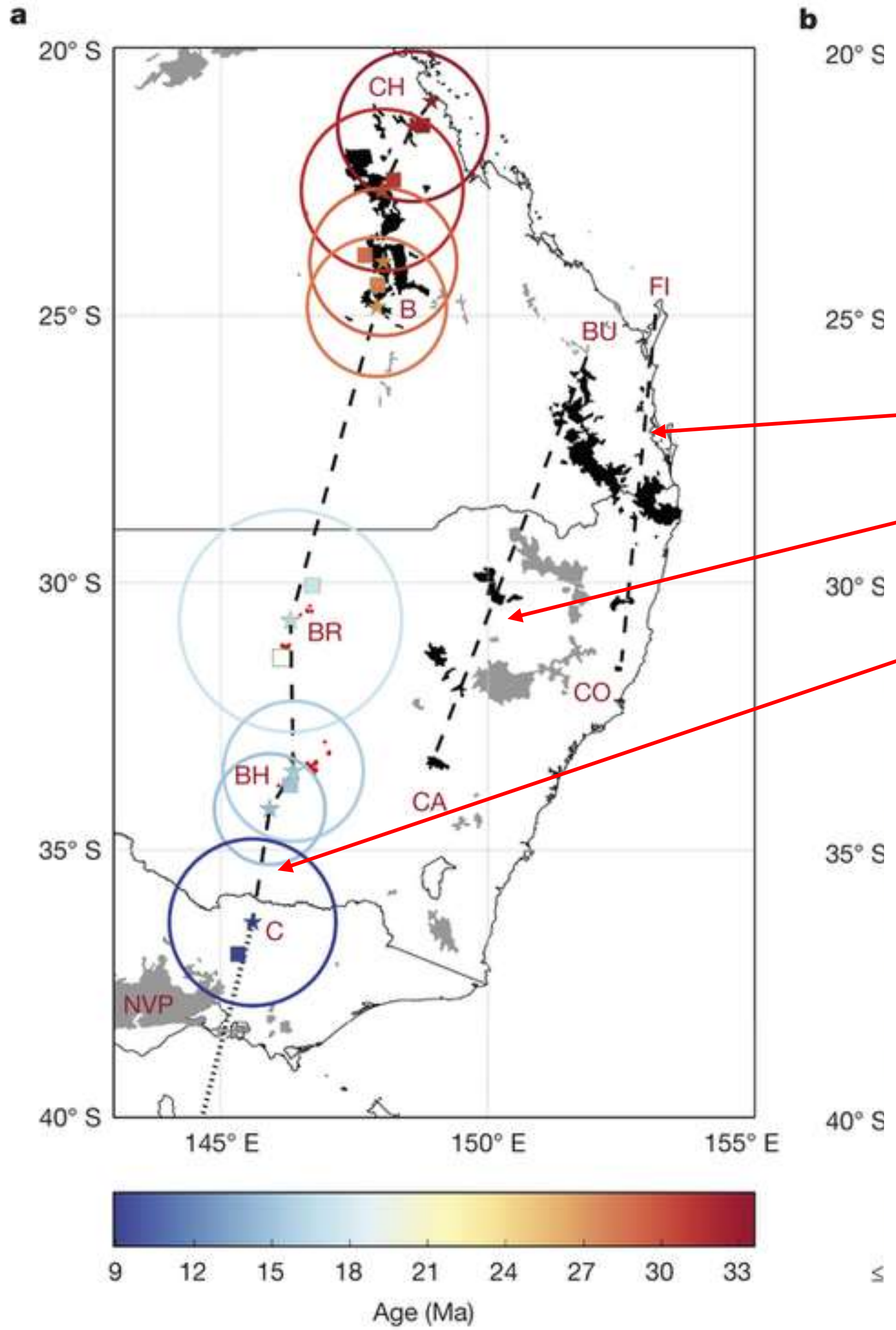


Volcanoes can be divided into three types (Wellman and Macdougall 1974):

1) Central volcanoes, which predominantly have a basaltic composition though they have felsic lava flows or intrusions, with lavas typically being produced from central vents, which often build large volcanic complexes. Shown here in black

2) Lava fields, which are basaltic, extensive and thin, and are often characterised by an abundance of small scoria, lava cones and maars. Shown here in dark grey.

3) The leucitite suites, dominated by low volume, leucitite bearing lavas which are rich in potassium. Shown here in red.



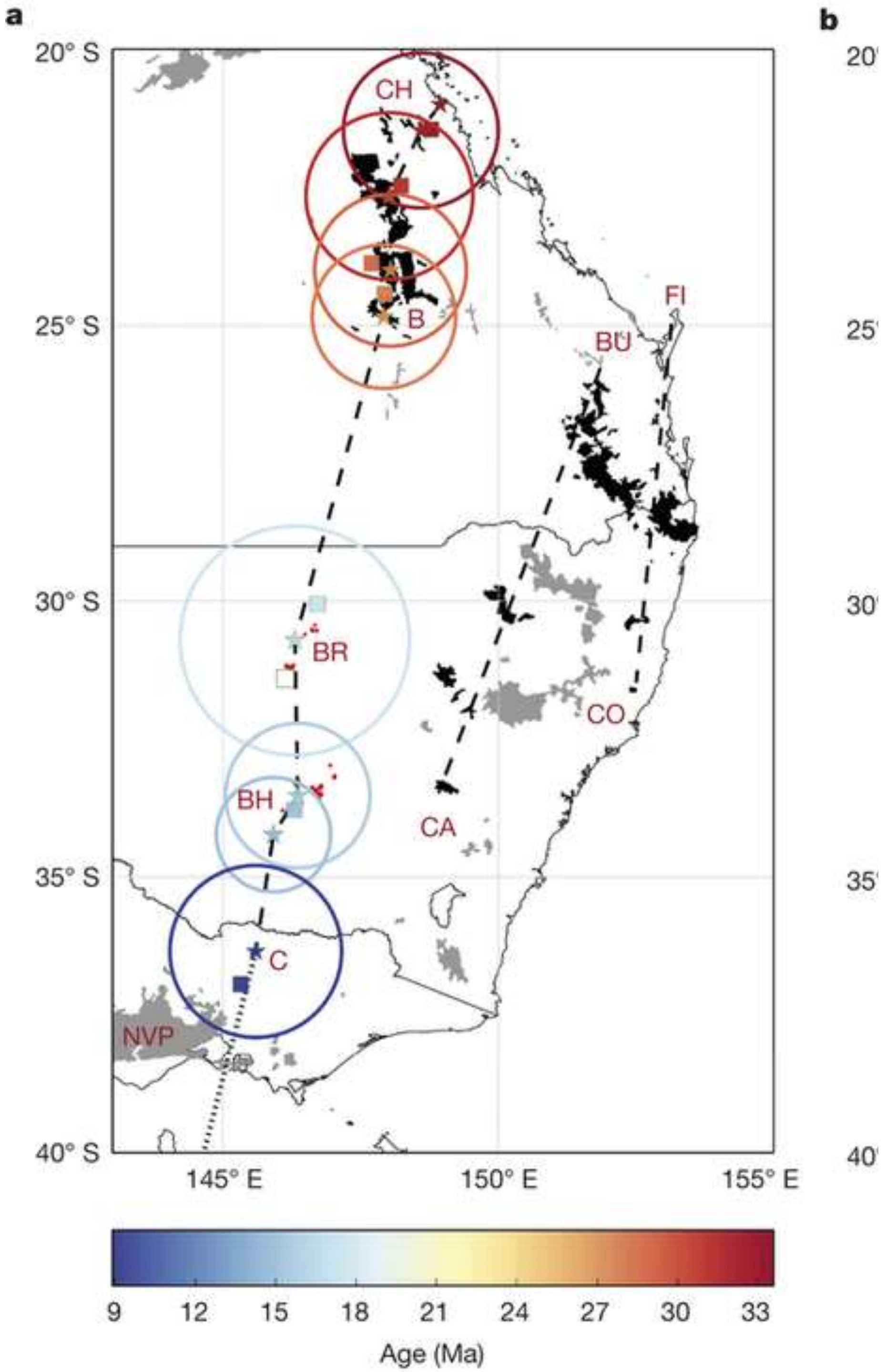
Three major lines of volcanoes have been identified in Eastern Australia.

They are:

The Comboyne Track

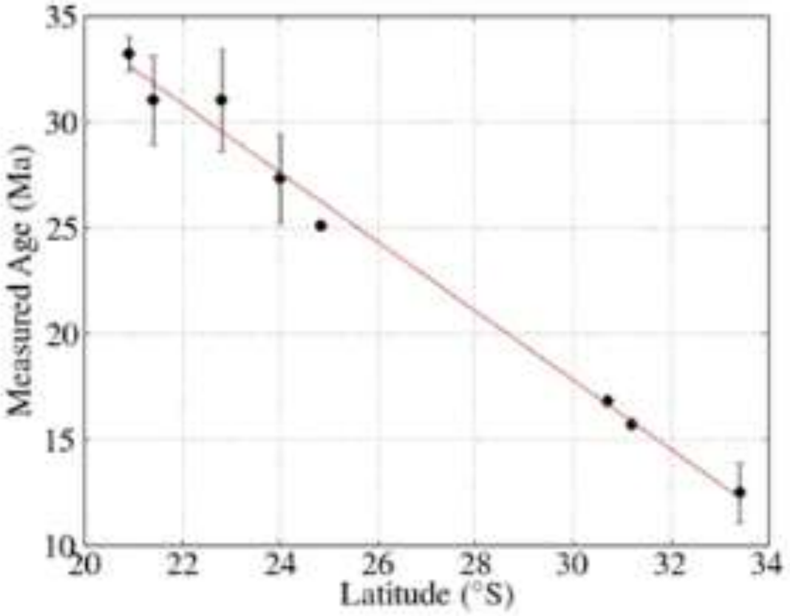
The Canobolas Track

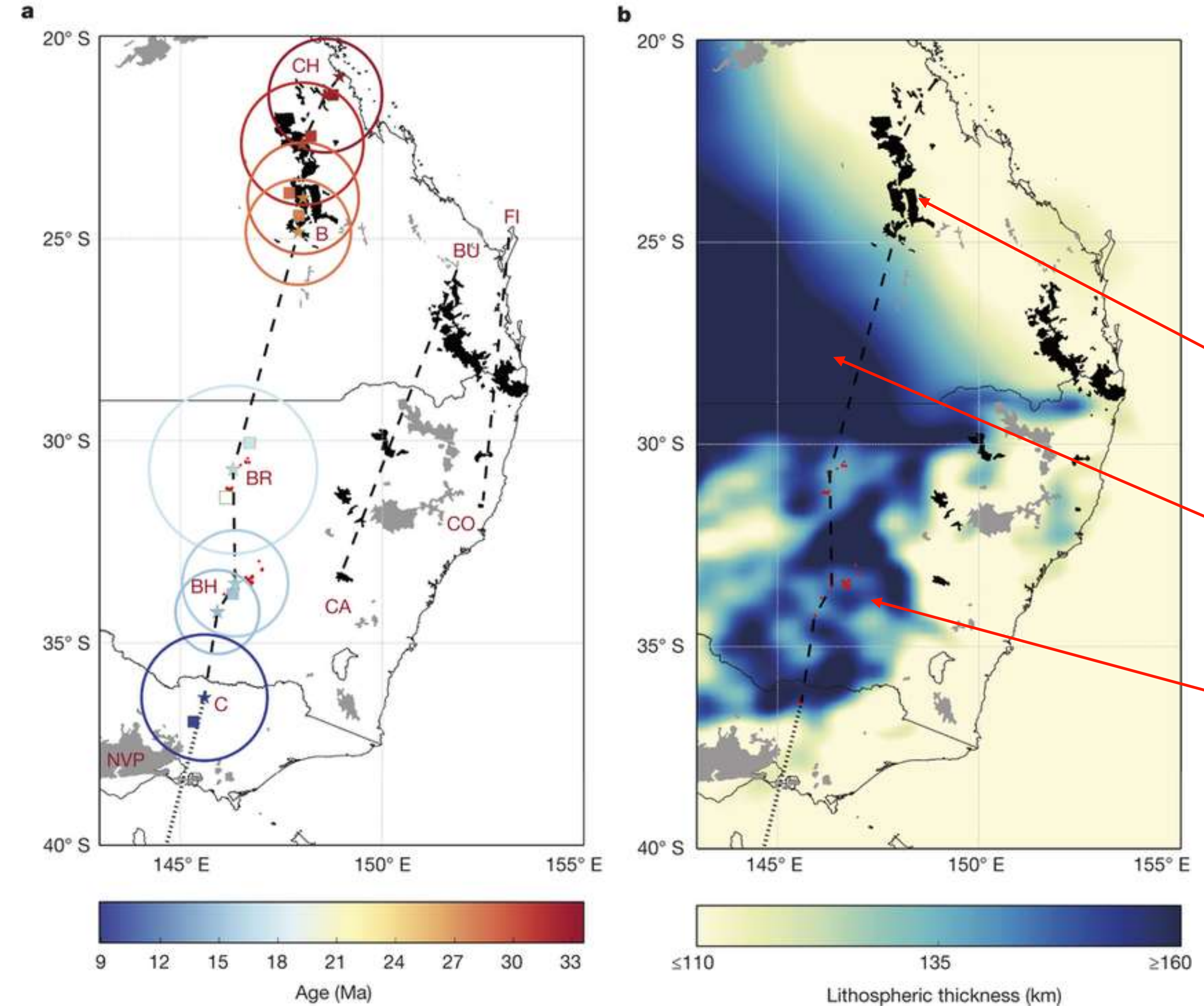
The Cosgrove Track



The Cosgrove track has only recently been recognised. It was thought to be two separate tracks as the southern section does not have central volcanoes but is composed of low volume extrusive leucitite lavas and there is a gap of more than 650 km between the tracks.

Davies (2014) showed that the age progression of the volcanoes in the northern track could predict the location of the leucatite eruptions in the south track.



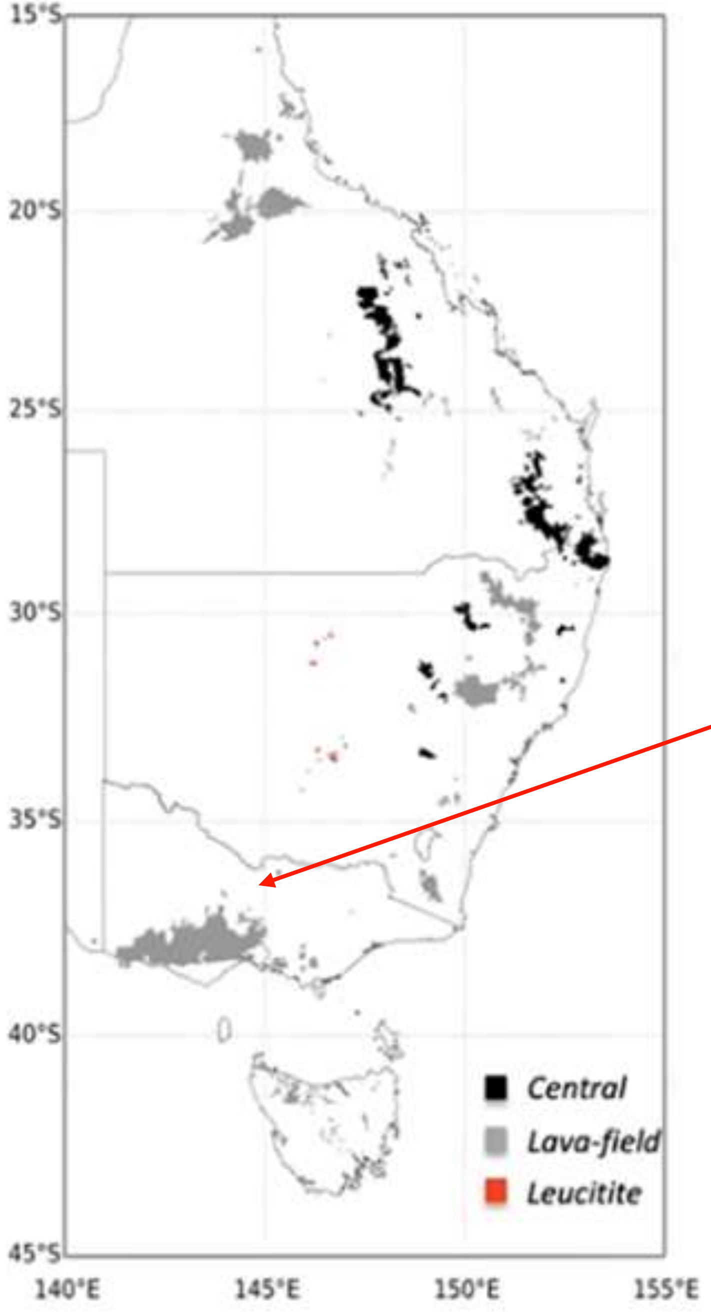


Davies (2014) also showed that the gap in the central section of the Cosgrove Track was associated with areas of thicker lithosphere.

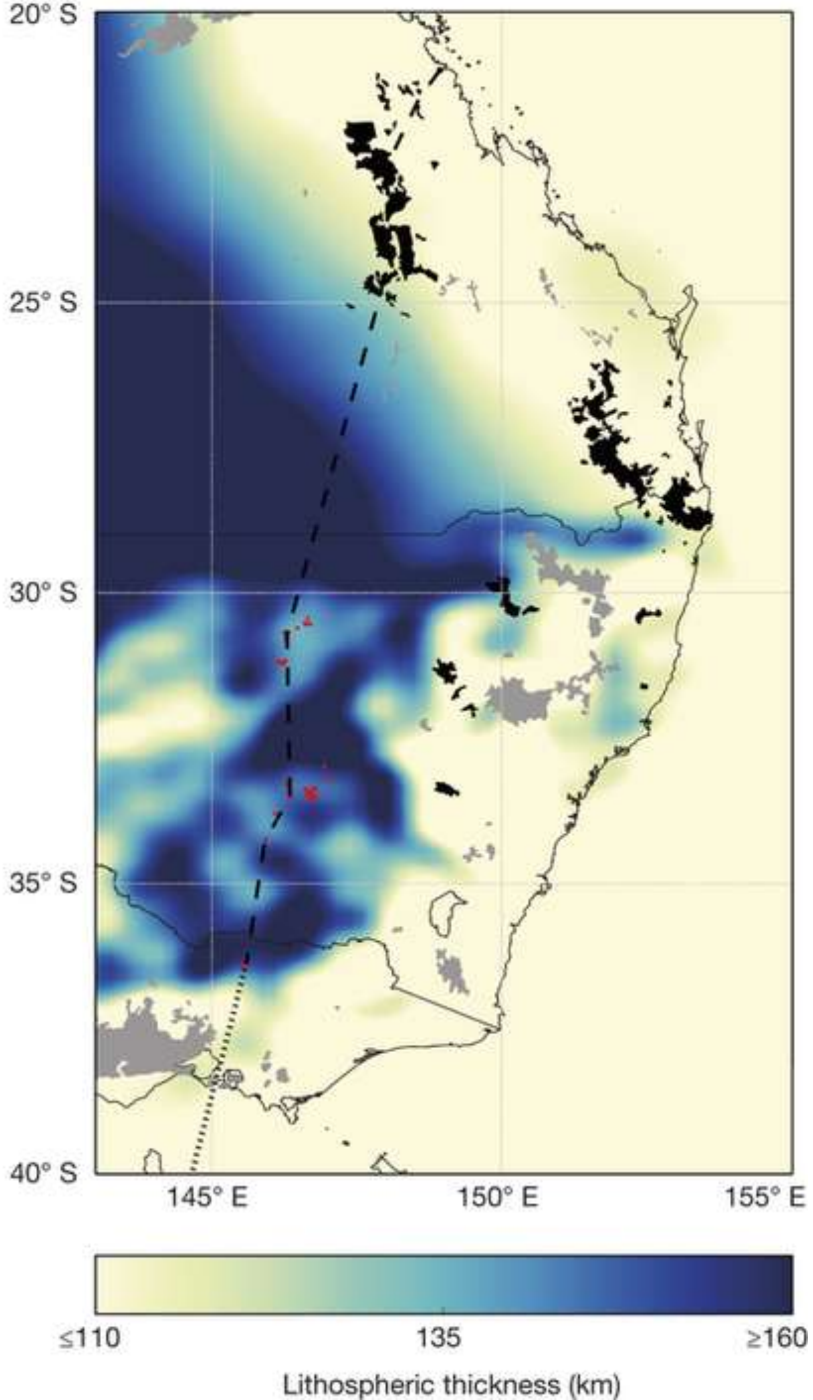
Central volcanoes occur where the lithosphere is < 110 km thick.

Surface volcanism was absent in areas where the lithosphere was thicker than 150 km.

In the areas of intermediate thickness only partial decompression melting could occur and this gave rise to the leucitite suites



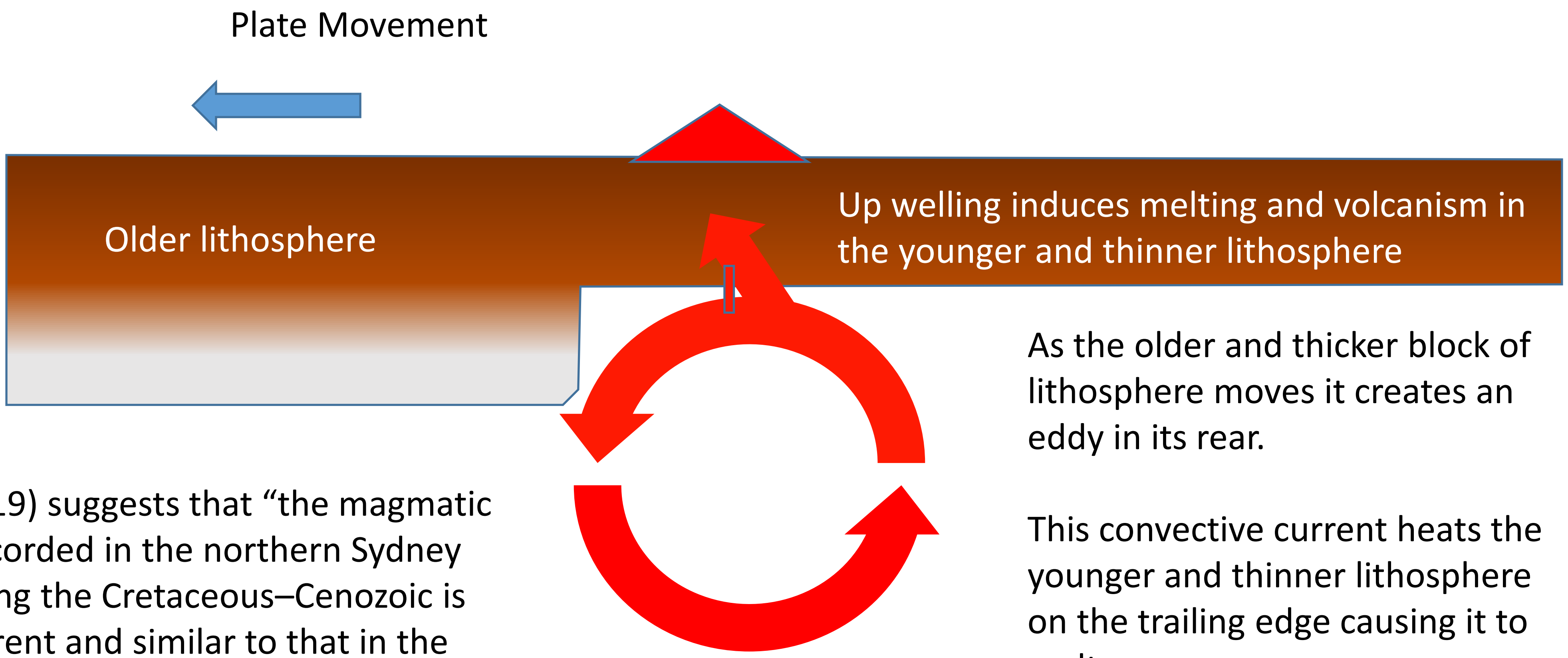
Davies says that many of the lava fields such as the New Volcanic Province (NVP) cannot be explained by passage over a hot spot.



Davies suggests that they are the result of a process termed Edge Driven Convection (EDC).

As the Australian Plate moves north convection currents are formed on the trailing edge of the thicker cratonic lithosphere, shown here in blue.

Upwelling heats the thinner younger lithosphere.



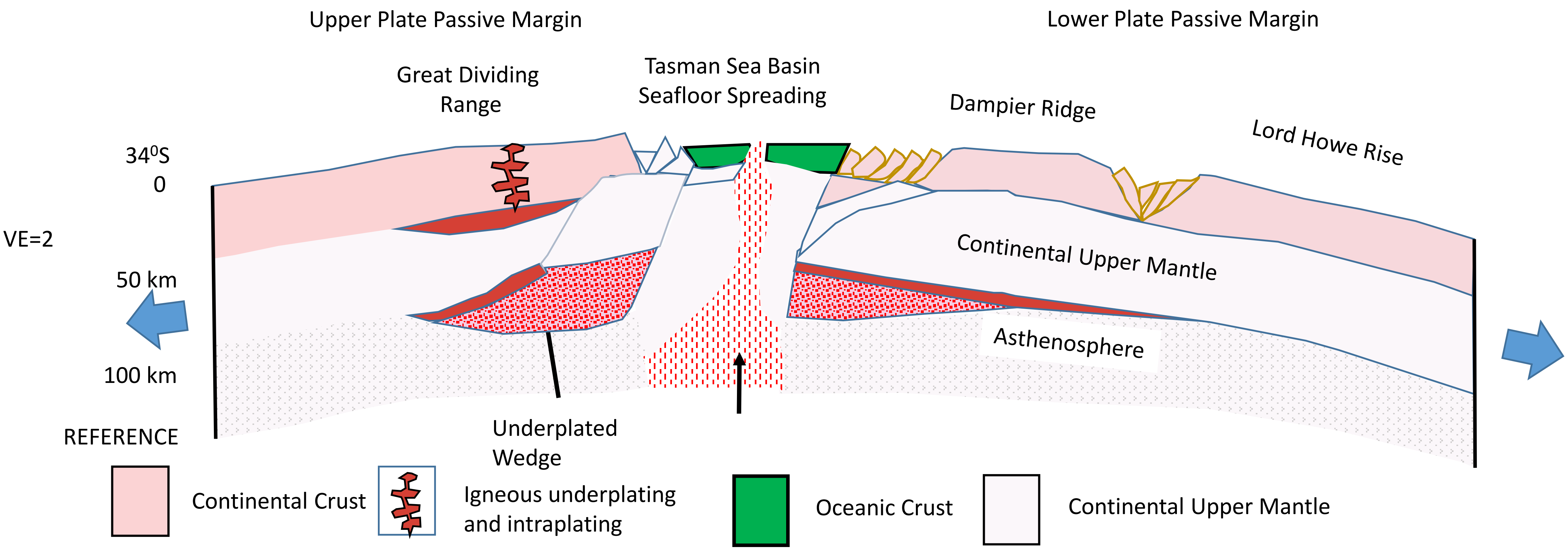
As the older and thicker block of lithosphere moves it creates an eddy in its rear.

This convective current heats the younger and thinner lithosphere on the trailing edge causing it to melt.

Offler (2019) suggests that “the magmatic history recorded in the northern Sydney Basin during the Cretaceous–Cenozoic is both different and similar to that in the northeast margin of the Australian continent—a silicic LIP (Large Igneous Province) is absent but intraplate alkali volcanism is well developed.

The localisation of the volcanic activity in this region and the SNEO may be due to edge driven convection (Davies & Rawlinson, 2014) where step changes in lithospheric thickness cause small scale convective instability in the mantle.”

Hypothetical Lithospheric Section along Latitude 34^{0}S in NSW
at the start of seafloor spreading beginning in the Late Cretaceous (98 – 65 Ma)

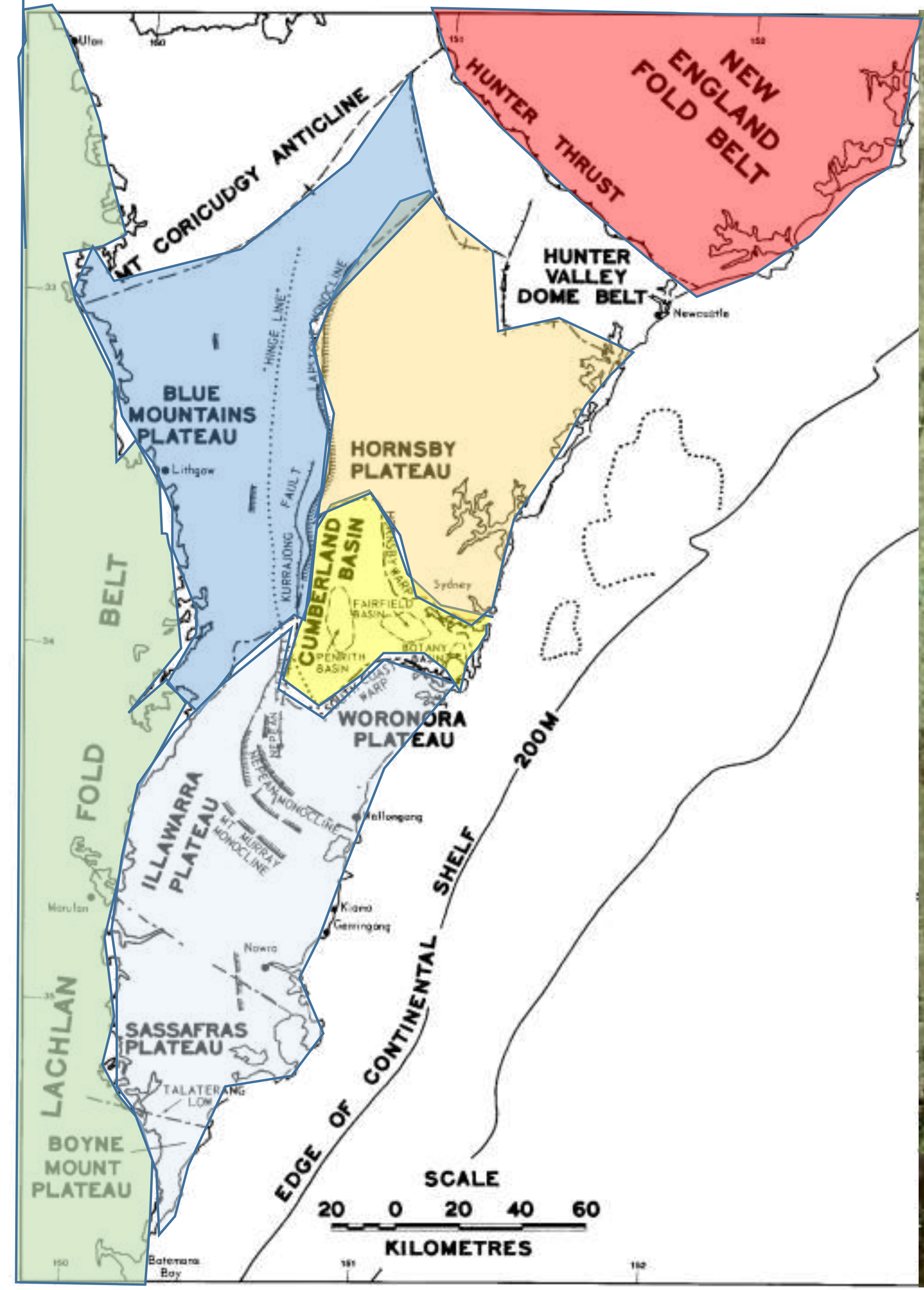


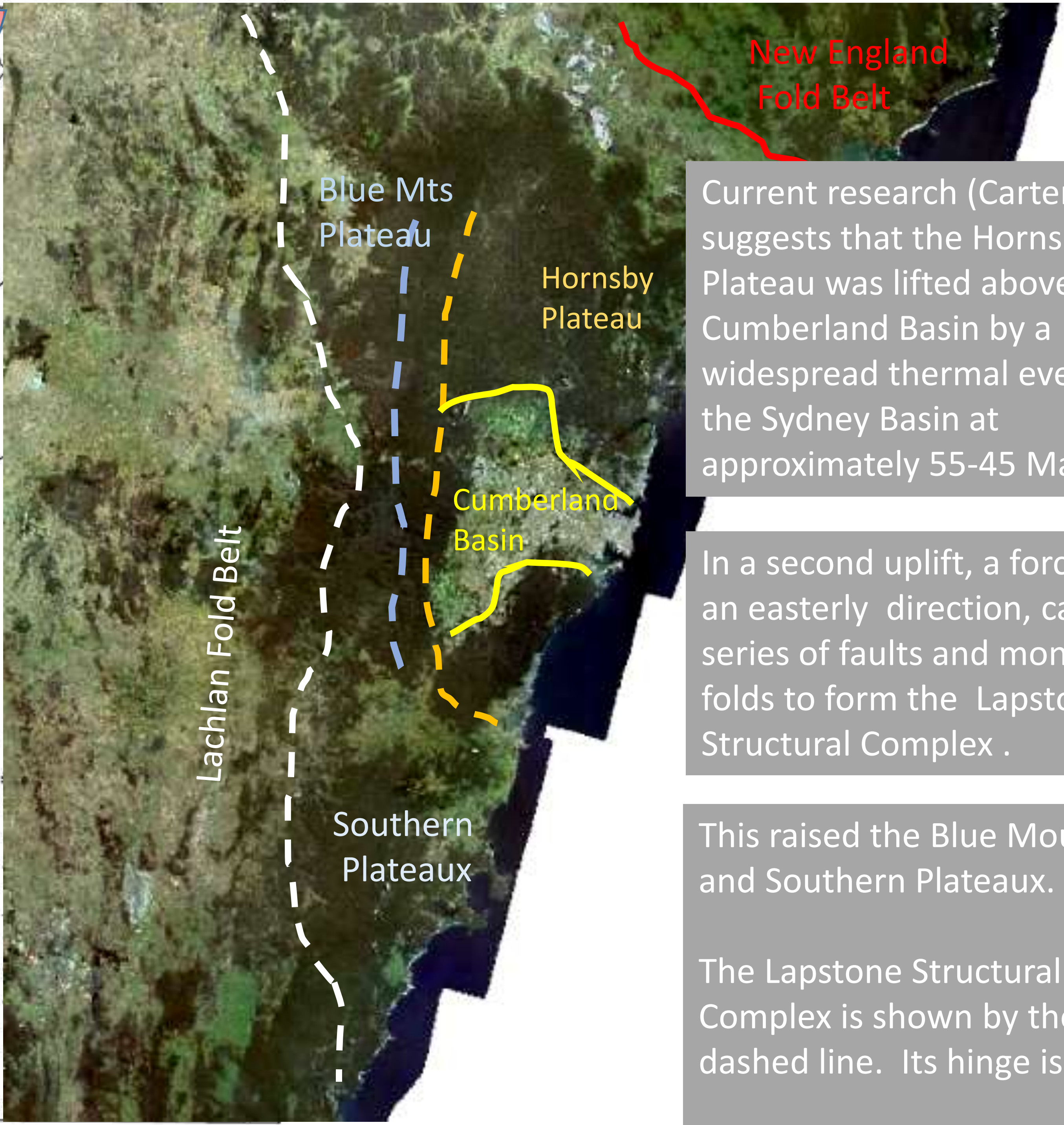
Geodynamic modelling of the uplift and erosional history of Australia's eastern highlands by Czarnota et al. (2014),Mueller et al. (2016) and Salles et al. (2017) suggests that the first phase of uplift that led to the initial formation of the eastern highlands and the Great Dividing Range was at ca 130 – 80 Ma and prior to the spreading event.

Quigley et al 2010 explain that geomorphology is influenced by currents in the mantle that operate on large, medium and small scales.

They suggest that at the smallest scale (10^1 km), fault-related deformation driven by far off stresses has changed surface topography at places in Australia at rates of up to approximately 170 m in a year and are responsible for more than 30–50% of the contemporary topographic relief between some of Australia's highlands and adjacent plains.

Much of the present landforms of the Sydney Basin can be explained by the presence of small scale currents in the mantle.





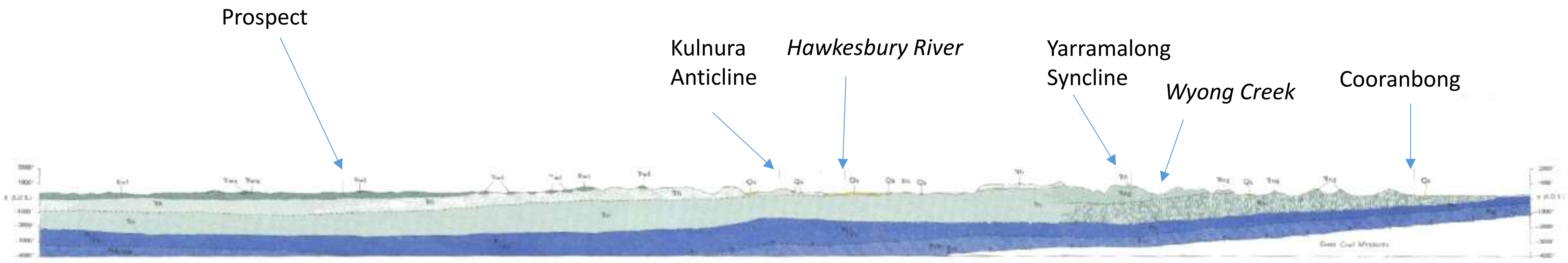
Current research (Carter 2011) suggests that the Hornsby Plateau was lifted above the Cumberland Basin by a widespread thermal event in the Sydney Basin at approximately 55-45 Ma.

In a second uplift, a force from an easterly direction, caused a series of faults and monoclonal folds to form the Lapstone Structural Complex .

This raised the Blue Mountains and Southern Plateaux.

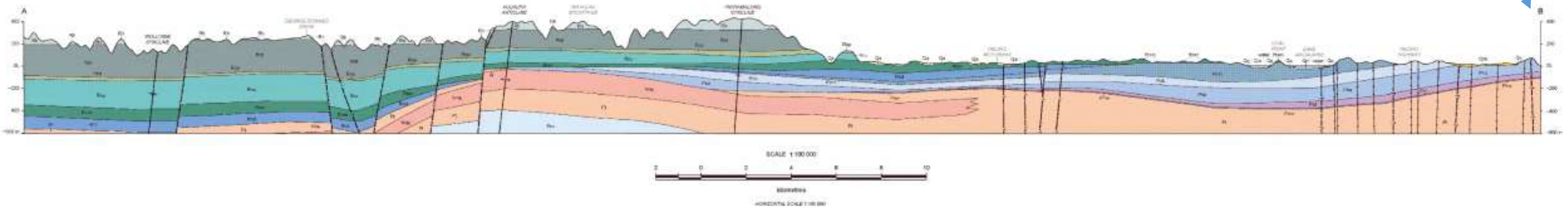
The Lapstone Structural Complex is shown by the brown dashed line. Its hinge is in blue.

The Hornsby Plateau has no evidence of major deformation, with only a gentle 2^0 slope to the South. This is consistent with an origin purely from uplift (Carter 2011).



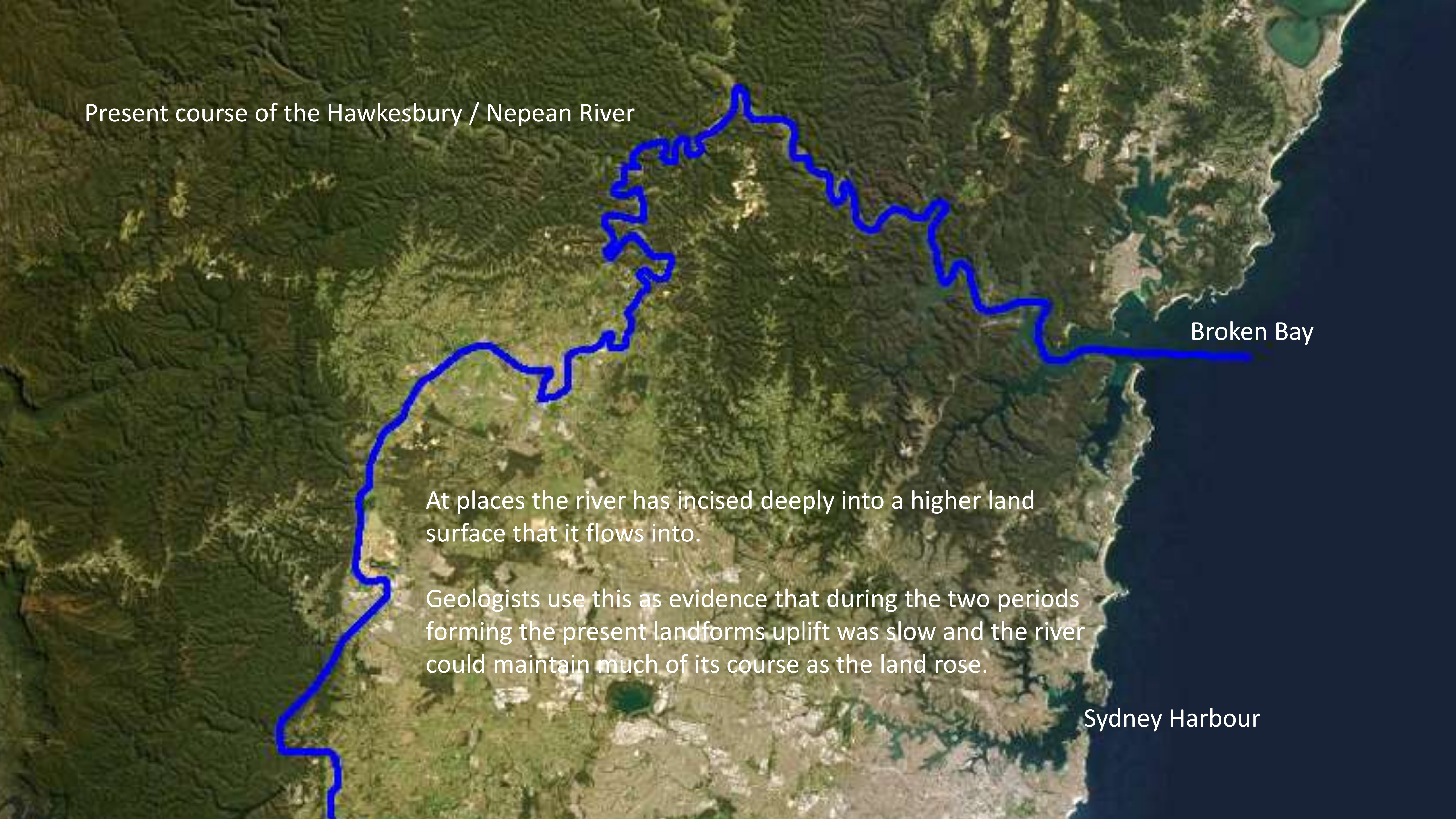
Bala Range
33^0 8.595’ S
151^0 1.686’ E

Red Head
33^0 0.607’ S
151^0 43.842’ E



Hornsby Plateau


Hornsby Plateau
Blue Mountains Plateau
Cumberland Basin


Present course of the Hawkesbury / Nepean River
Broken Bay
At places the river has incised deeply into a higher land surface that it flows into.
Geologists use this as evidence that during the two periods forming the present landforms uplift was slow and the river could maintain much of its course as the land rose.
Sydney Harbour


It re-emerges near Penrith
Fairlight Gorge
The river flows back into the highland of the Blue Mountains Plateau in these places
In these sections the Nepean River is flowing along its present floodplain
Warragamba Dam
Gulguer Gorge


Hornsby Plateau
Here again the river flows back into highland of the Hornsby Plateau.
It eroded the plateau as it rose and, with some halt, continued on its existing course to the sea.
Richmond
Windsor

In many areas the present course of the Hawkesbury River is substantially the same as it was approximately 60 Ma. At that time the river flowed out of the Lachlan Fold Belt from South to North.

Associated with its course were deposits of alluvium called the Rickabys Creek Gravels. They are very significant as today some of them can be found on top of high cliffs, hundreds of metres above the river. This has been used as evidence that the river has cut down (incised) as the land was uplifted.

This uplift is thought by Carter to have occurred at about 45 Ma and associated with a widespread thermal event in the Sydney Basin. To the North, in the Hunter, the large Barrington Shield Volcano erupted about 50 Ma

The Hornsby Plateau was uplifted first, partially damming the River and resulting in the deposition of the Londonderry Clay Formation. As the uplift was slow, the river was able to erode the Plateau and continue to the sea, largely in its present course.

As erosion progressed to base level it was able to drain the dammed area.

The northward movement of the Australian plate over mantle hot spots resulted in a second uplift event in the Blue Mountains. This event began at about 30 Ma. It led to the development of large knickpoints on the Wollondilly, Coxs and Kowmung Rivers. These are similar to those on the Shoalhaven River and other rivers flowing from the eastern highlands and they have retreated a considerable distance.

Van der Beek found that there was no more than 250m vertical relief and that there was a gentle tilt to the northeast .

The Lapstone Structural Complex then began to form and lift the Blue Mountains Plateau. Hatherly (2020) puts this at 10-5Ma. Again this was relatively slow. Evidence for this is the incised course of the river through the Gulguer and Fairlight (Nepean River) Gorges. The river flowing along its present floodplain flows into the Plateau and the back into the plain. At the Fairlight Gorge this occurs for about 16 km, before emerging near Penrith.

Stages in the formation of the Cumberland Plain (based on Carter 2011)

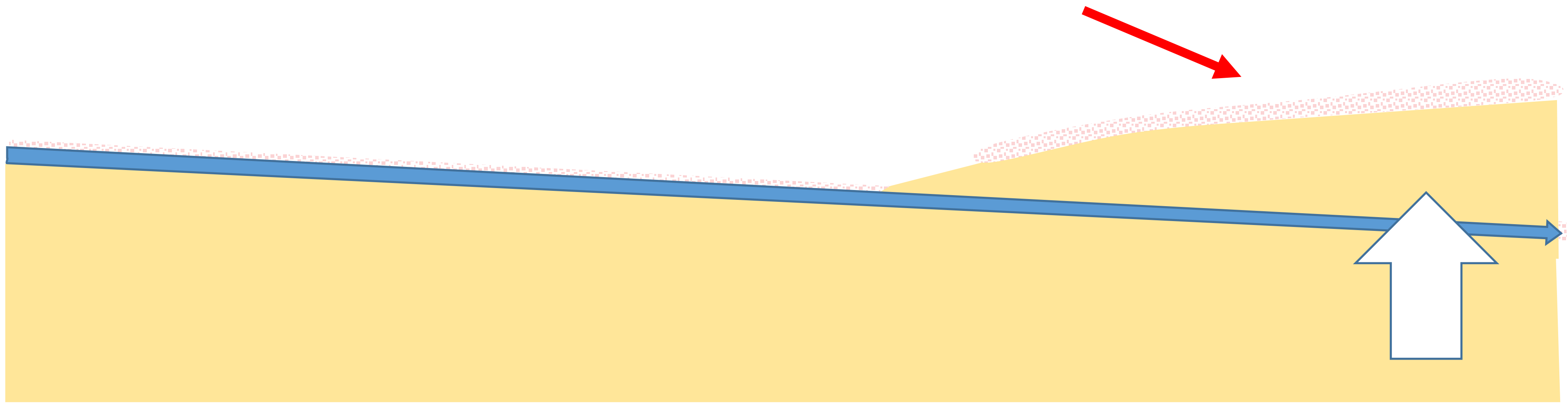
1. About 60 Ma a large braided river channel flowed out of the Lachlan Fold Belt towards the North

2. Inside its course, it built up a deposit of coarse alluvium known as the Rickabys Creek Gravels.

3. Uplift of the Hornsby Plateau occurred from about 45 Ma; probably as a result of increased thermal activity associated with the opening of the Tasman Sea.

4. This uplift was slow enough that the river could maintain its course despite the rising land.

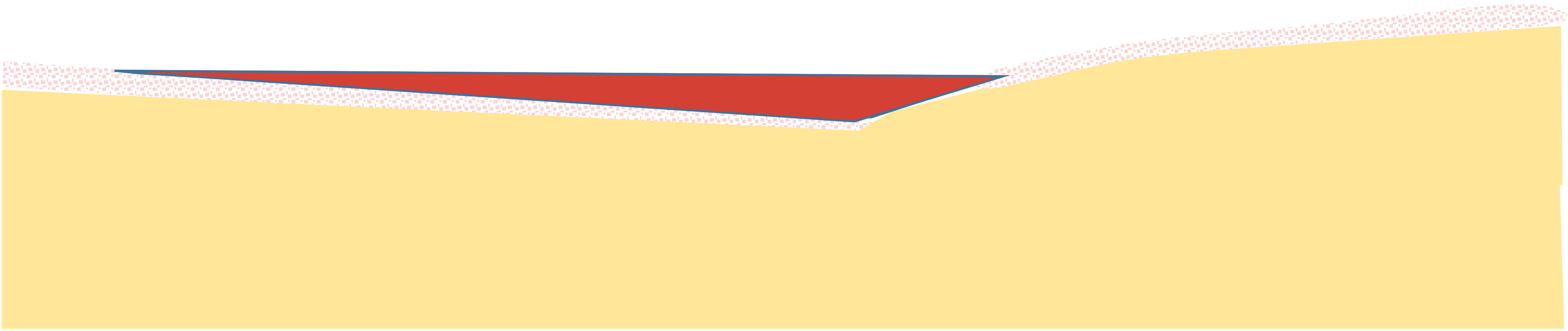
Some of the Rickabys Creek Gravels were now left raised on the Hornsby Plateau



5. The rising Hornsby Plateau initially dammed the river. Overtopping and subsequent erosion in the lower reaches eventually restored the flow.

6. Damming meant that the Rickabys Creek gravels could not be carried far into the flooded area and the thickness of their deposit began to decrease towards the Plateau.

7. Finer sediments carried by the river were deposited in the dammed water and began to create the Londonderry Clay



Rickabys Creek Gravels

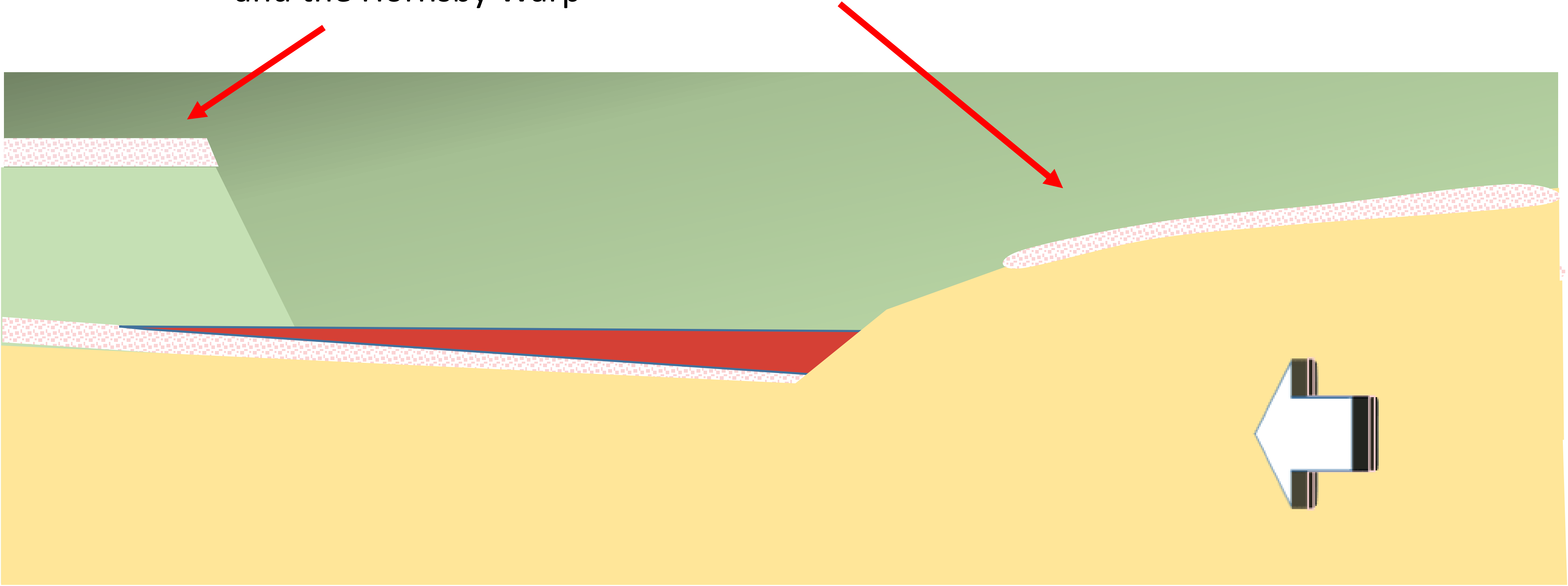
Londonderry Clay

Stages in the formation of the Cumberland Plain

8. A third period of uplift occurred from a period of compression. Recent research by Hatherly puts it at about 10-5 Ma and suggests further movement in the Quaternary.

9. This produced a series of monoclonal folds and faults now known as the Lapstone Structural Complex. This also raised the plateaux in both the West and South and increased the uplift in the Hornsby Warp

Some deposits of the Rickabys Creek Gravels were now on the Blue Mountains Plateau and the Hornsby Warp

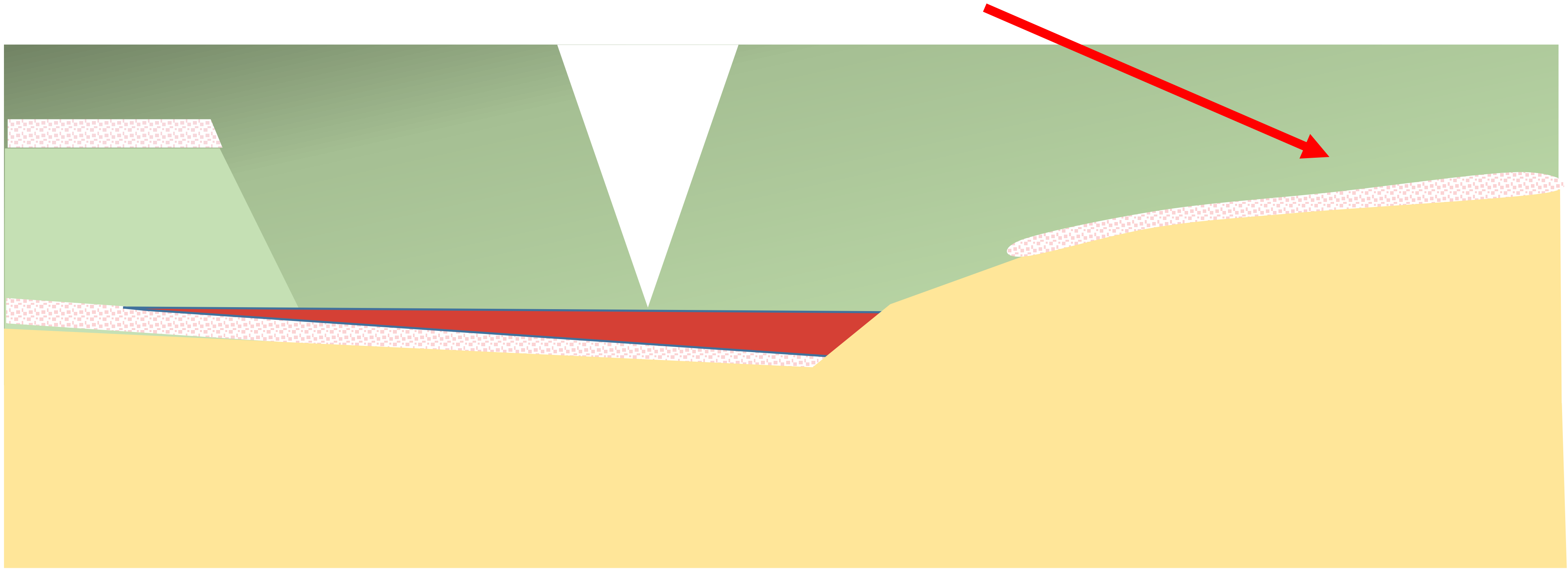


10. Since the uplift much of the Rickabys Creek Gravels have been eroded and tributary streams have incised deep valleys in the Plateaux.

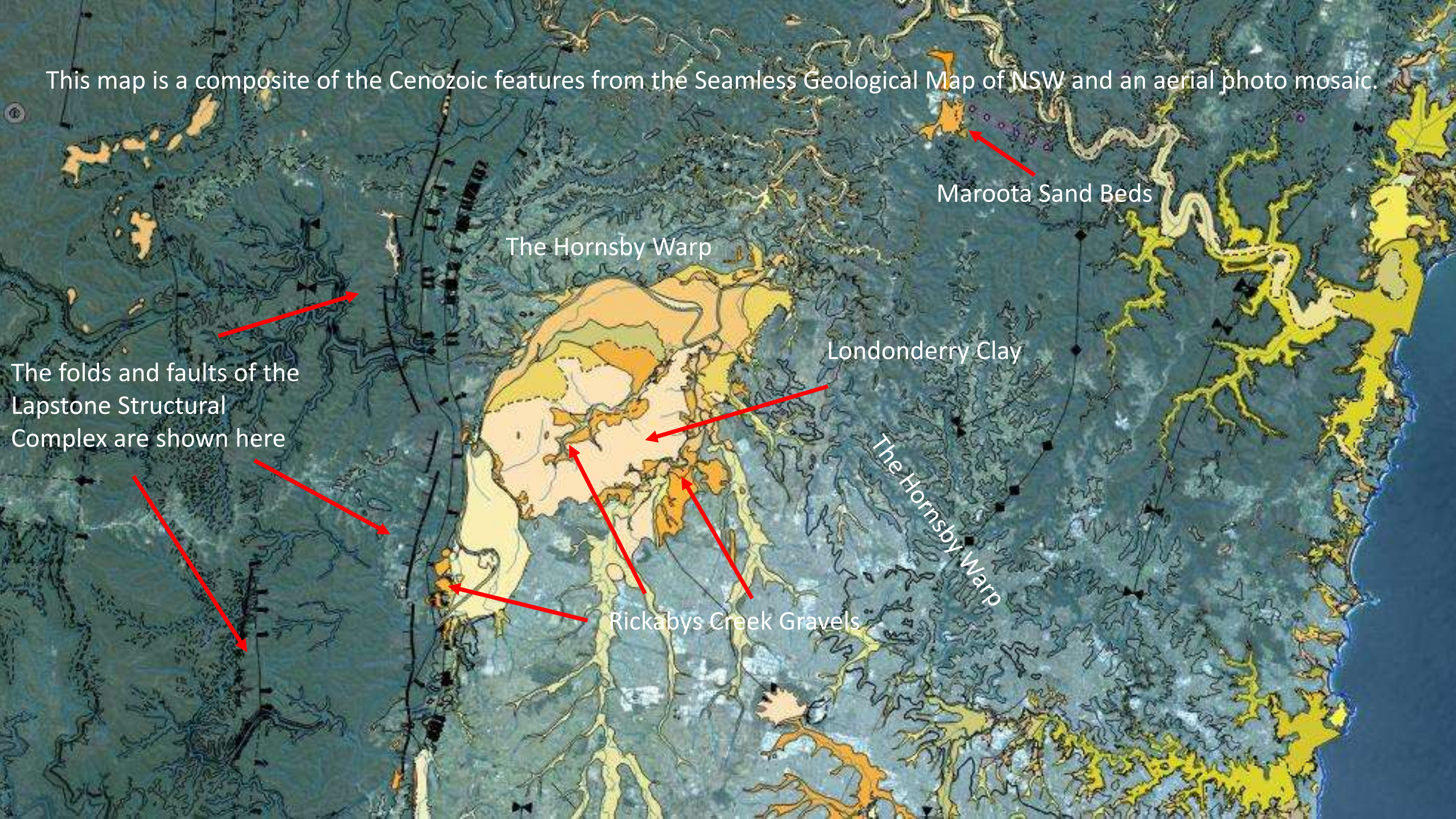
Remaining on the Hornsby Plateau are some alluvial and aeolian sand deposits associated with deposition during the pre-uplift course of the river.

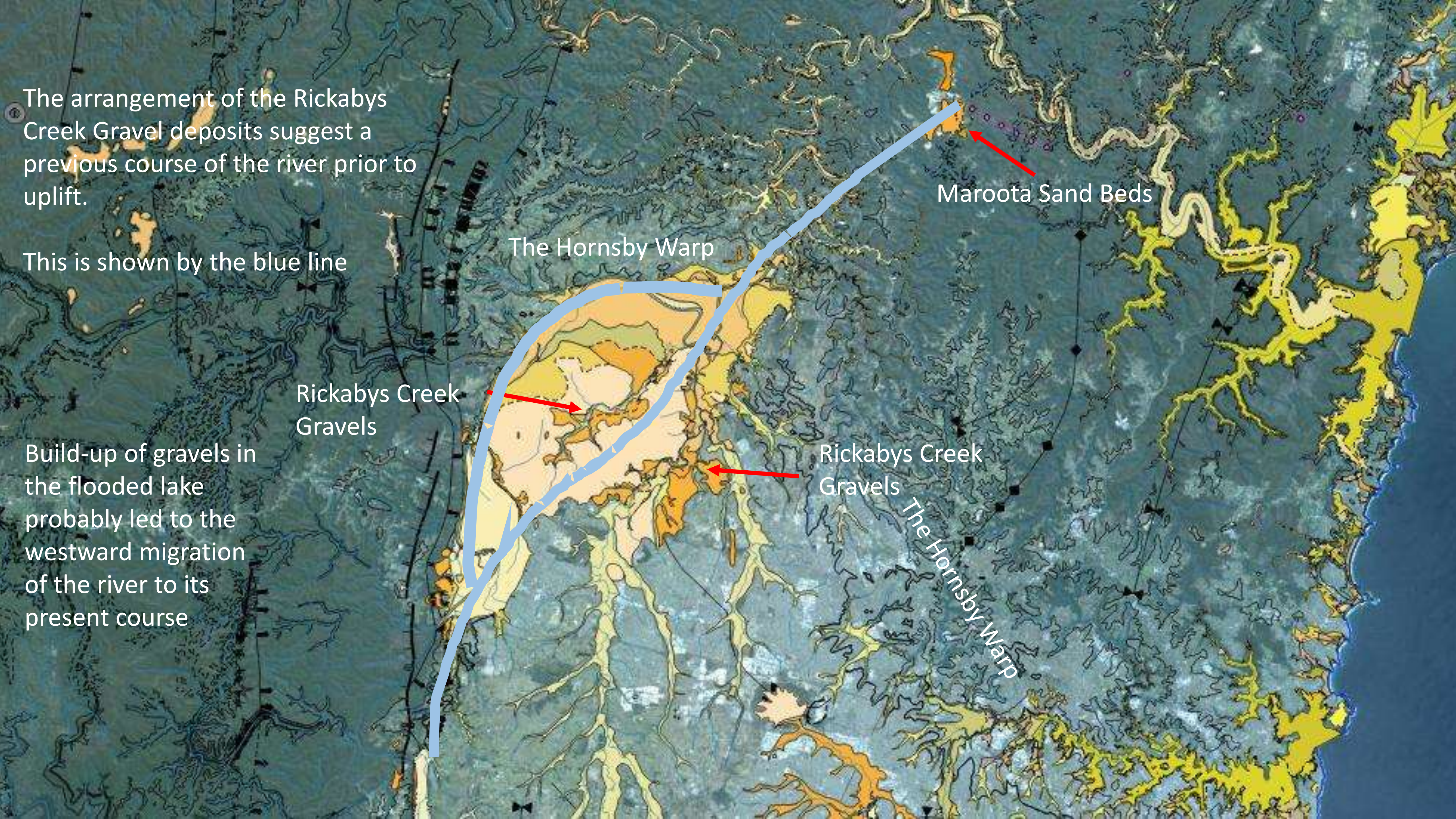
These are the Maroota Sand Beds and they are currently being mined to supply building sand for Sydney.

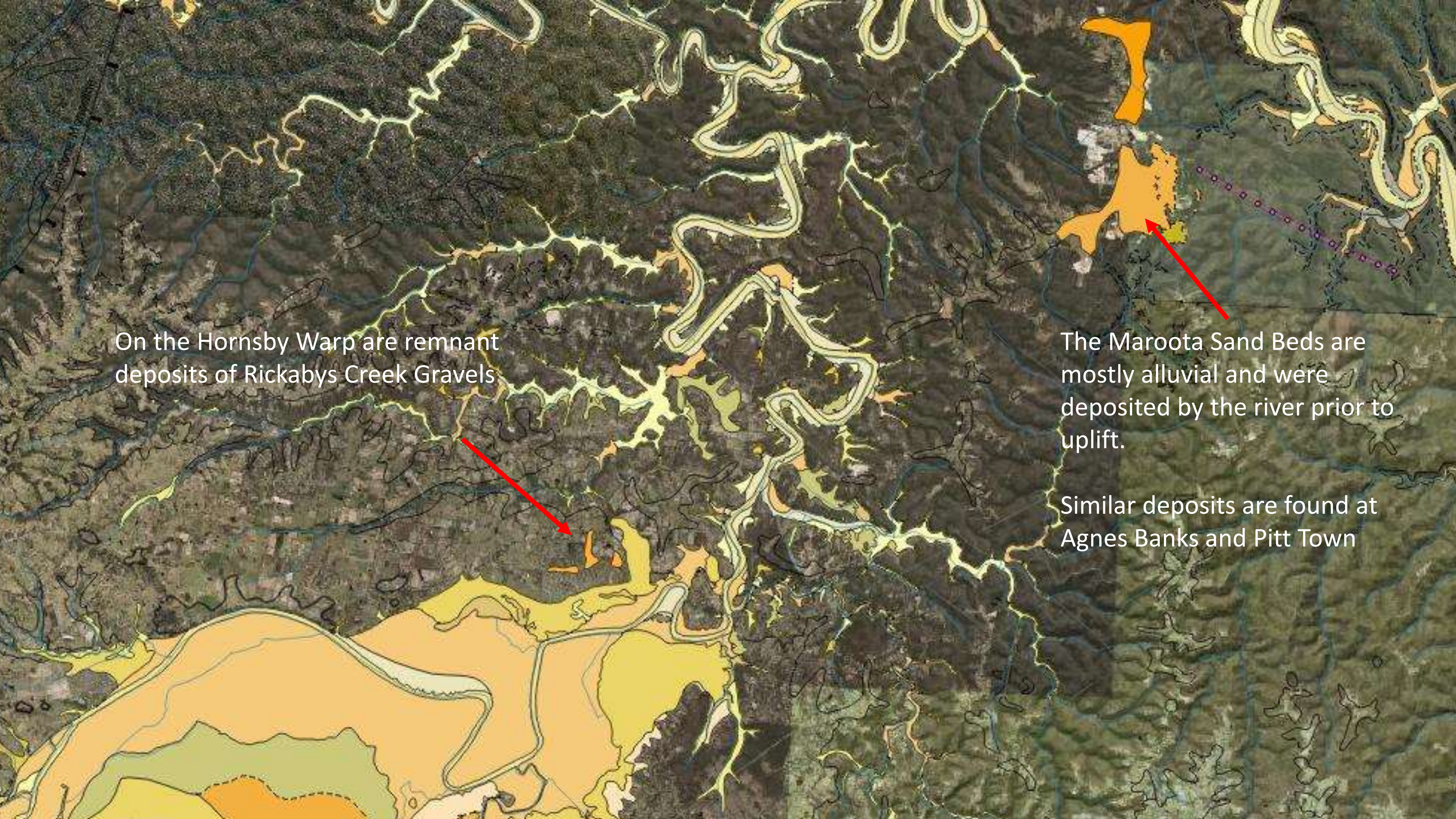
Other deposits can be found at Agnes Banks.

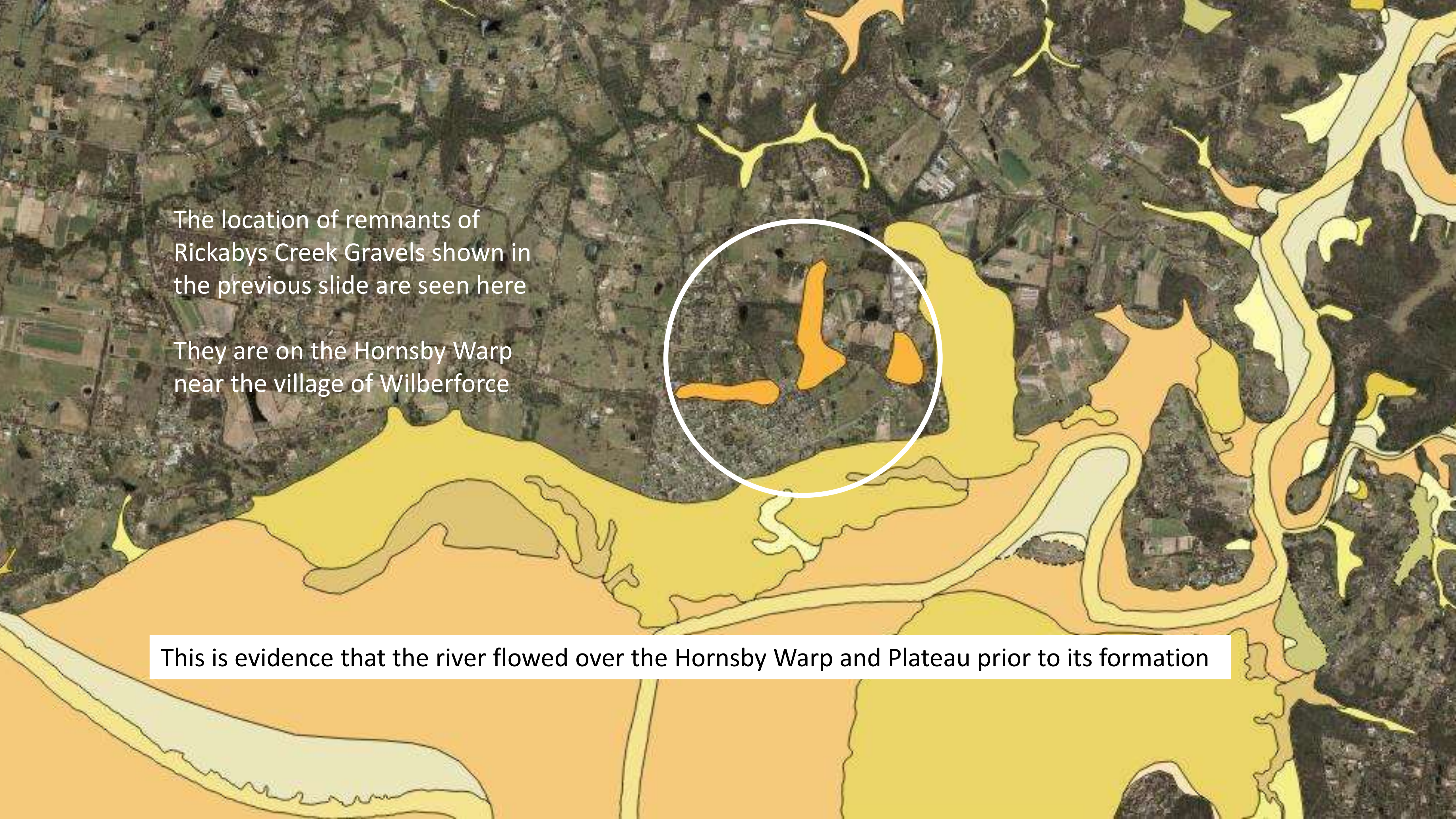


What is the evidence to support this process?


This map is a composite of the Cenozoic features from the Seamless Geological Map of NSW and an aerial photo mosaic.
Maroota Sand Beds
The Hornsby Warp
Londonderry Clay
The folds and faults of the Lapstone Structural Complex are shown here
The Hornsby Warp
Rickabys Creek Gravels


The arrangement of the Rickabys Creek Gravel deposits suggest a previous course of the river prior to uplift.
This is shown by the blue line
The Hornsby Warp
Maroota Sand Beds
Rickabys Creek Gravels
Rickabys Creek Gravels
Build-up of gravels in the flooded lake probably led to the westward migration of the river to its present course
The Hornsby Warp

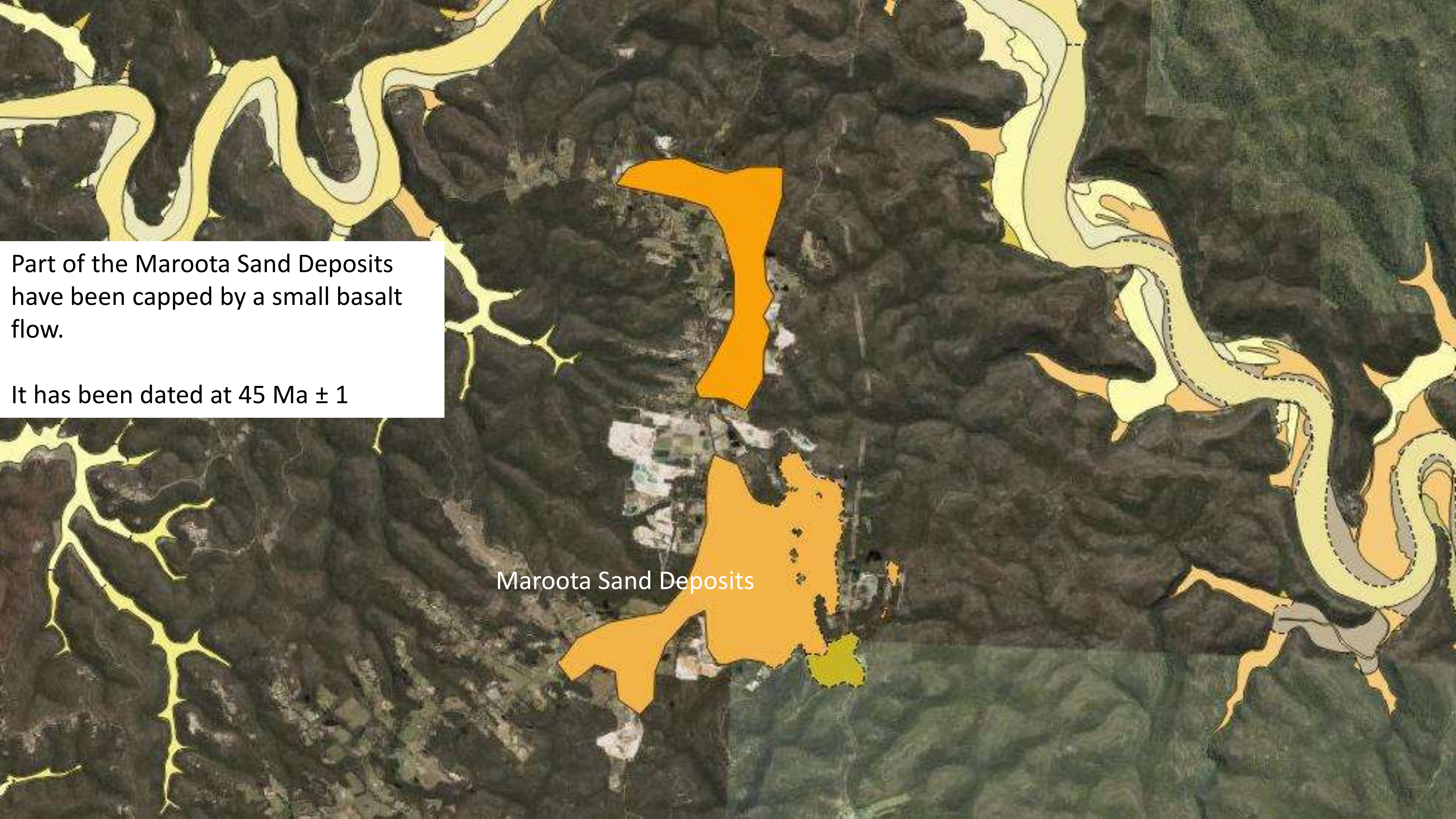

On the Hornsby Warp are remnant deposits of Rickabys Creek Gravels
The Maroota Sand Beds are mostly alluvial and were deposited by the river prior to uplift.
Similar deposits are found at Agnes Banks and Pitt Town


The location of remnants of Rickabys Creek Gravels shown in the previous slide are seen here
They are on the Hornsby Warp near the village of Wilberforce
This is evidence that the river flowed over the Hornsby Warp and Plateau prior to its formation


Some of the quarries mining the Maroota sand deposit and the adjacent Hawkesbury sandstone can be seen as white areas
This is the hamlet of Maroota

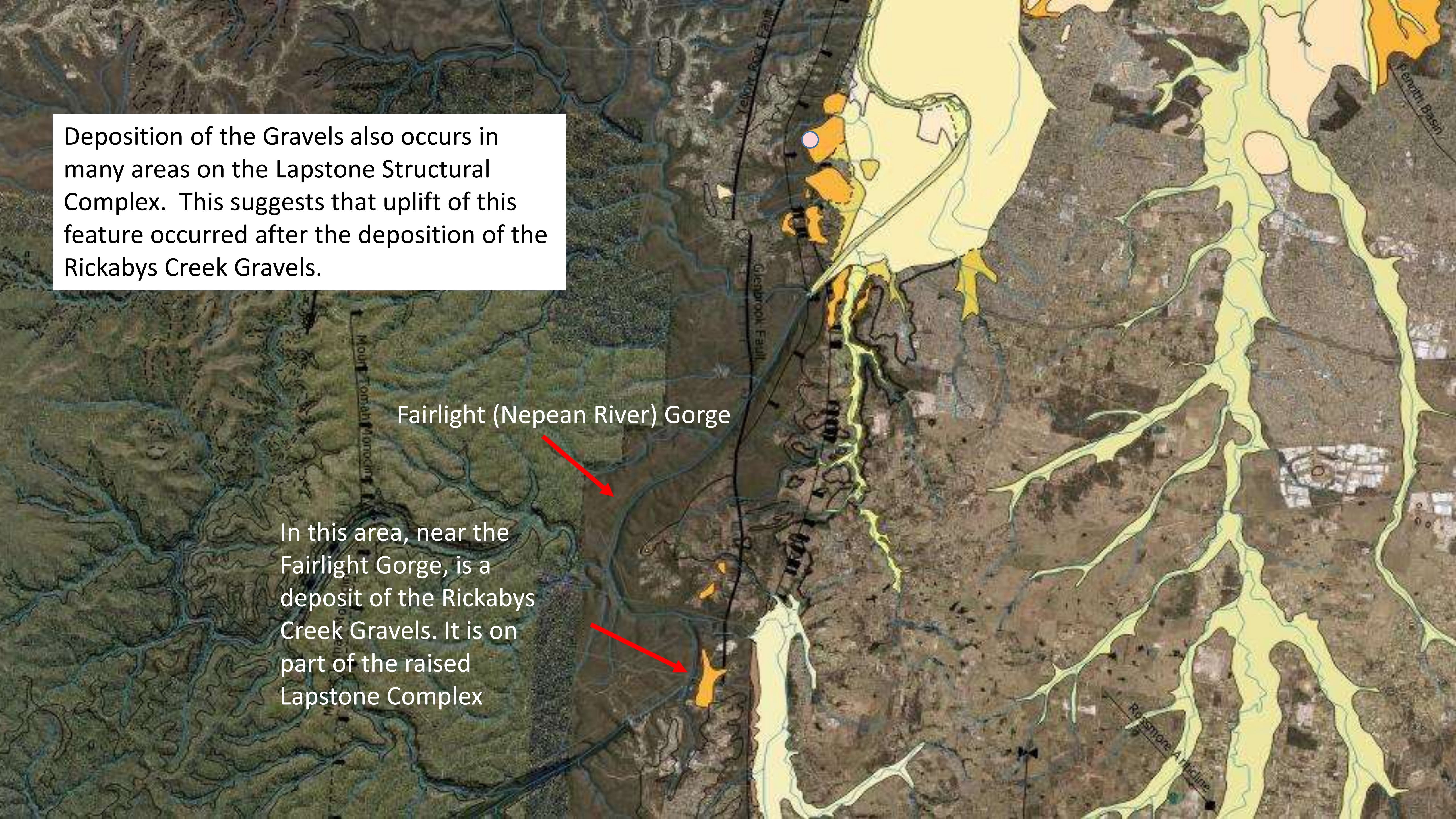
Part of the Maroota Sand Deposits have been capped by a small basalt flow.

It has been dated at 45 Ma ± 1




At 45 Ma +/- 1 the direction of flow and position of this basalt flow suggests uplift of this area subsequent to this date.
MZul_b
G__s
Maroota Sands
G__s

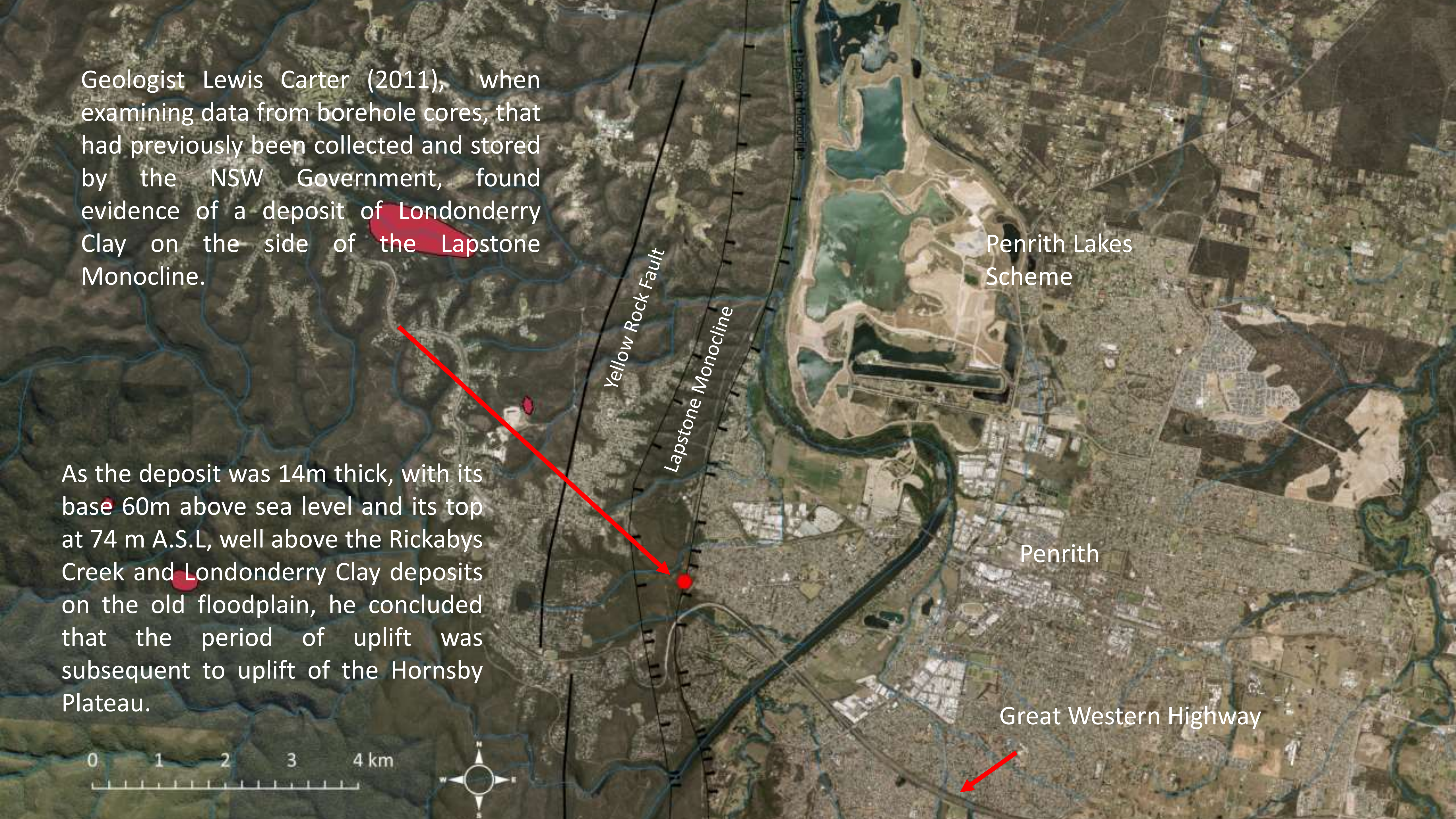
Deposition of the Gravels also occurs in many areas on the Lapstone Structural Complex. This suggests that uplift of this feature occurred after the deposition of the Rickabys Creek Gravels.



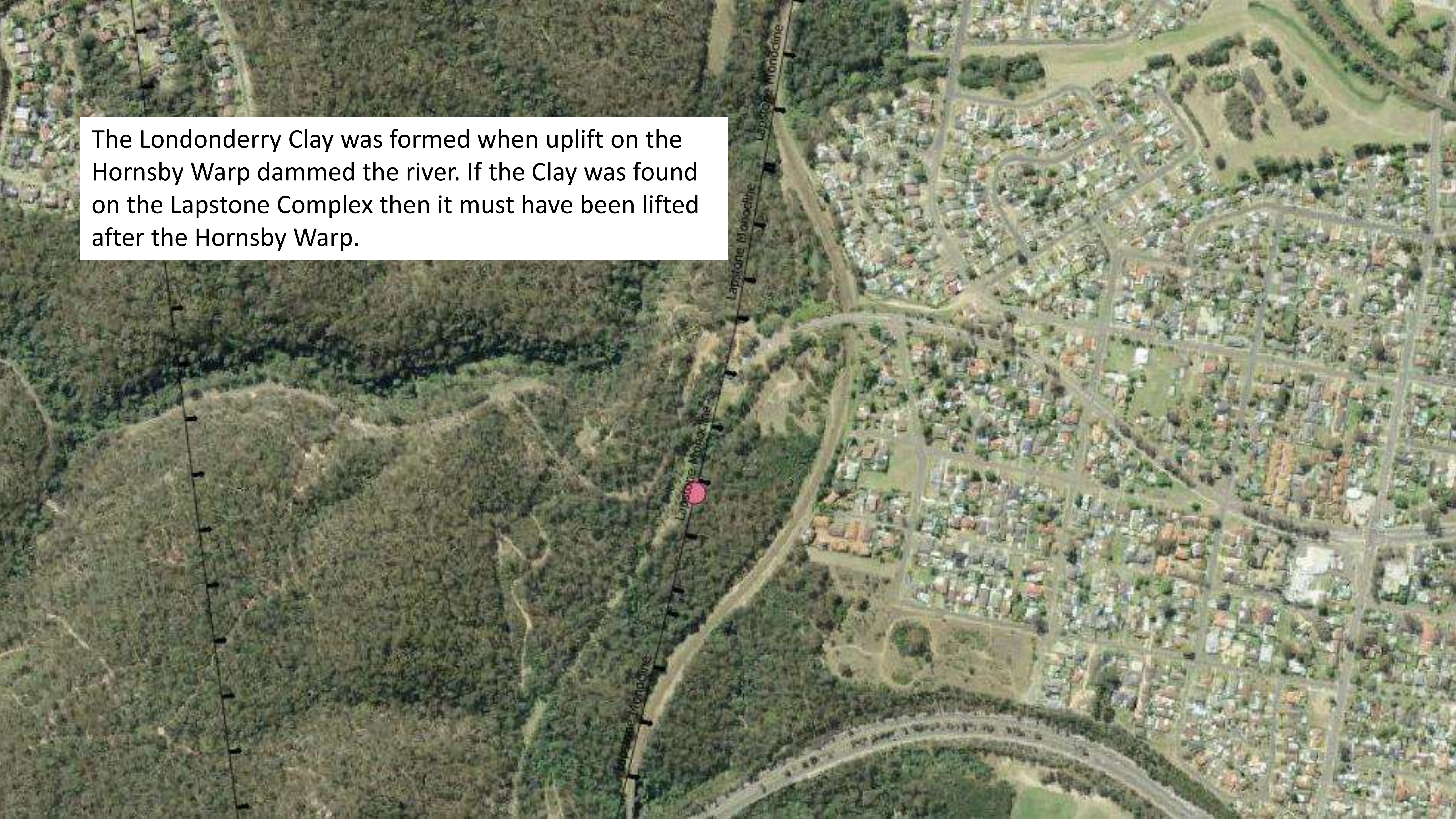
In this area, near the Fairlight Gorge, is a deposit of the Rickabys Creek Gravels. It is on part of the raised Lapstone Complex

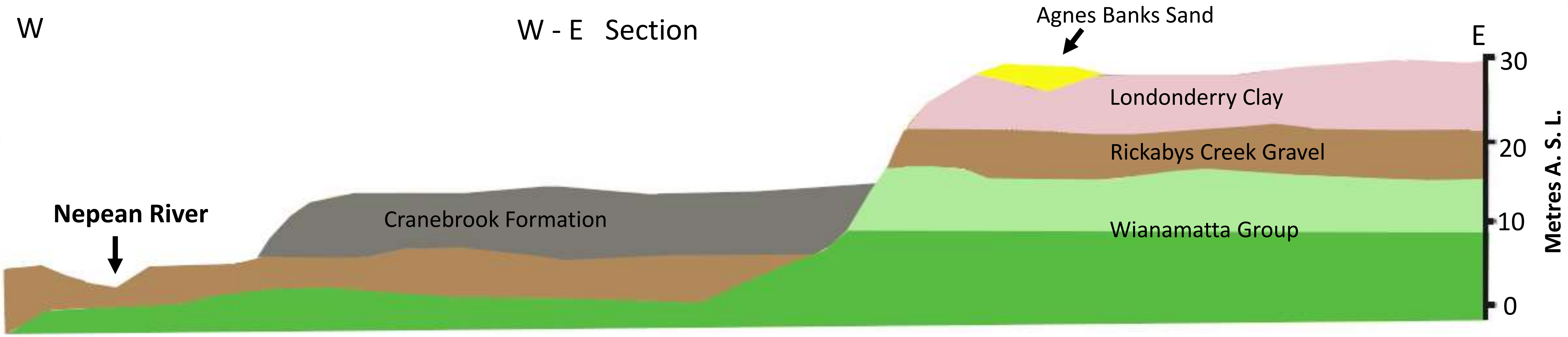
Geologist Lewis Carter (2011), when examining data from borehole cores, that had previously been collected and stored by the NSW Government, found evidence of a deposit of Londonderry Clay on the side of the Lapstone Monocline.

As the deposit was 14m thick, with its base 60m above sea level and its top at 74 m A.S.L, well above the Rickabys Creek and Londonderry Clay deposits on the old floodplain, he concluded that the period of uplift was subsequent to uplift of the Hornsby Plateau.



The Londonderry Clay was formed when uplift on the Hornsby Warp dammed the river. If the Clay was found on the Lapstone Complex then it must have been lifted after the Hornsby Warp.



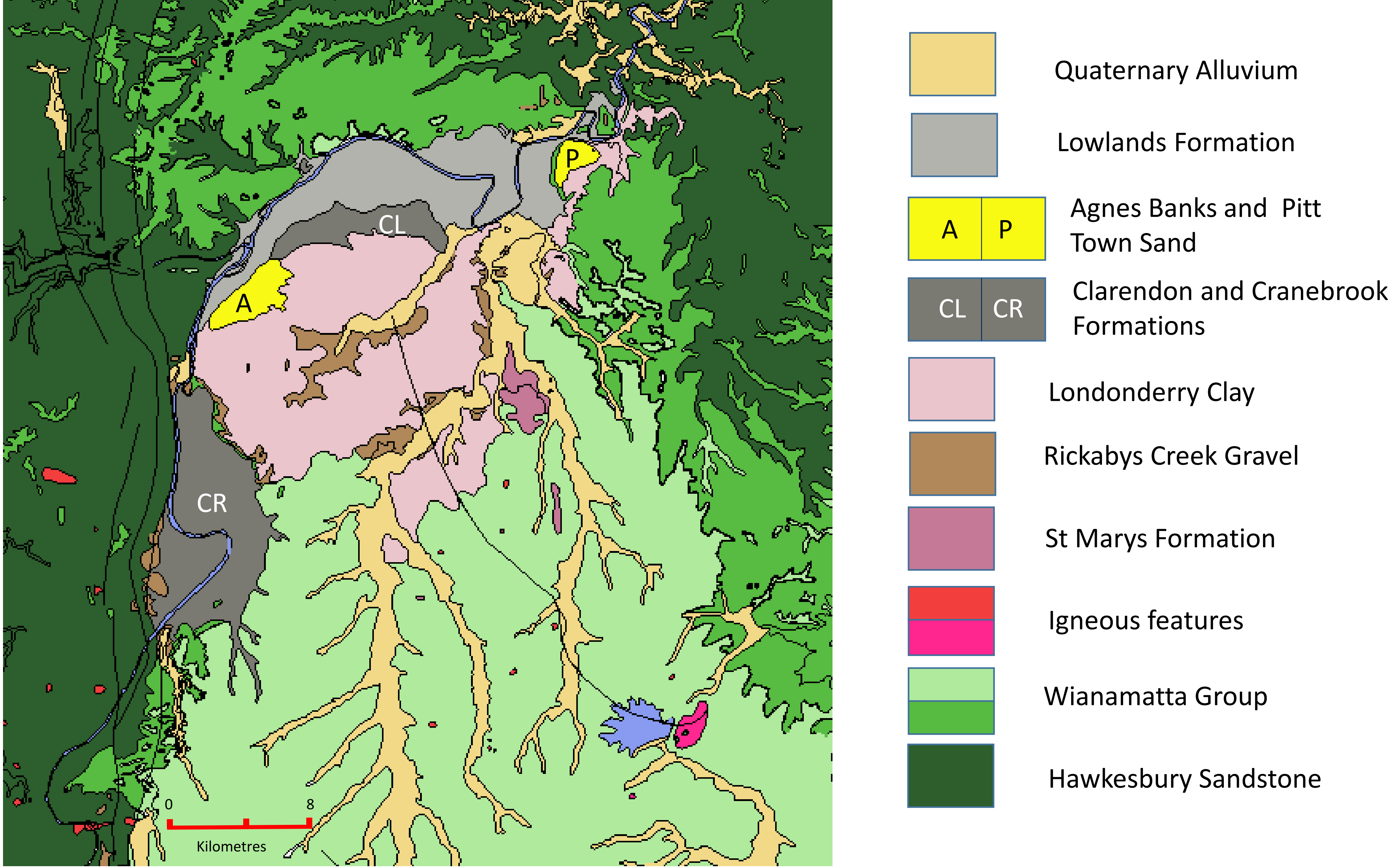


In the northern section of the Sydney Basin the process of uplift and fluvial processes have produced a series of terraces as shown in this stylized cross-section.

Since the damming of the river by the rise of the Hornsby Plateau the river has cut down though the deposits of Londonderry Clay and Rickabys Creek Gravel into the underlying rocks of the Wianamatta Group.

The changing river course first produced the Cranebrook and Clarendon Terraces; these were mostly made by reworking the previous deposits. Further erosion and migration of the river channel produced the Lowlands Formation. Currently the river is working on a new floodplain.

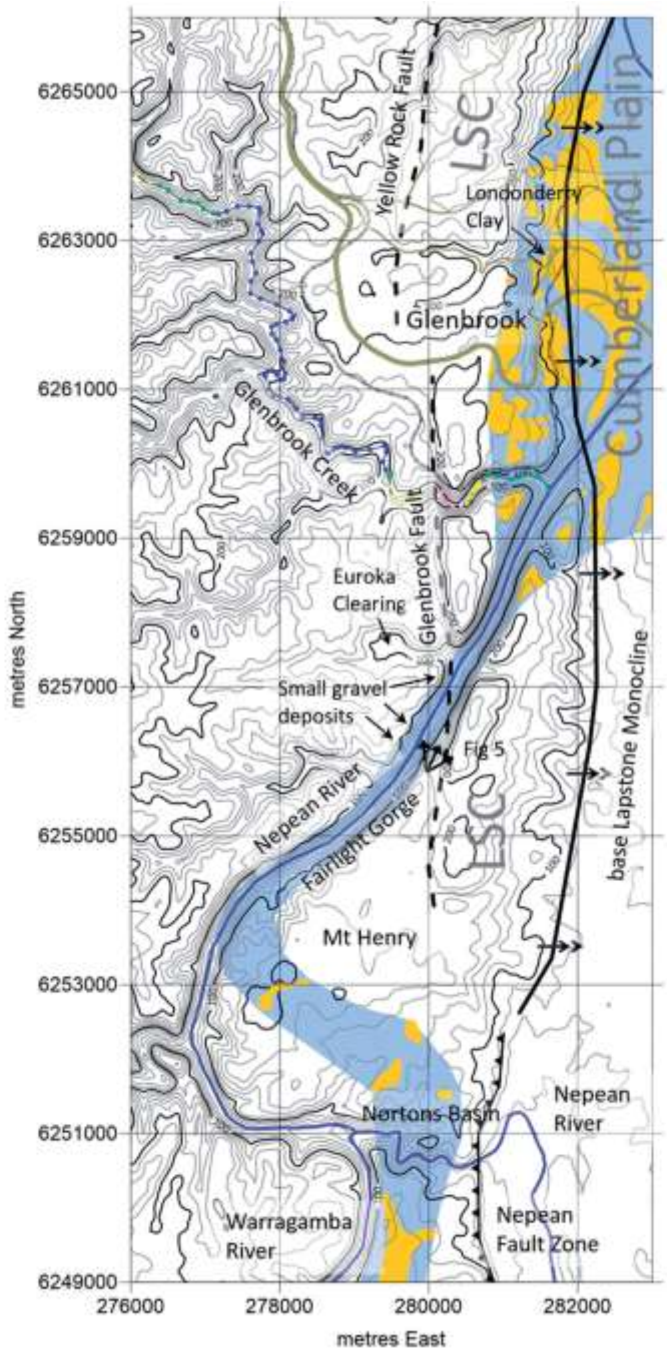
Based on the nomenclature and classification by the Geological Survey of NSW in Quarterly Survey Notes 32


CL
A
P
CR
0
8
Kilometres
Quaternary Alluvium
Lowlands Formation
A
P
Agnes Banks and Pitt Town Sand
CL
CR
Clarendon and Cranebrook Formations
Londonderry Clay
Rickabys Creek Gravel
St Marys Formation
Igneous features
Wianamatta Group
Hawkesbury Sandstone

Recent research by P. J. Hatherly (2020) involving knick points in streams associated with the Lapstone Structural Complex (LSC), associated basalt flows and the distribution of Rickabys Creek Gravels, has produced new evidence confirming the timing of the formation of the Blue Mountains and the LSC.

Fieldwork by Hatherly found that the Rickabys Creek Gravels were even more widespread on the heights of the LSC near the Fairlight Gorge than previously thought.

He produced this map of his findings.



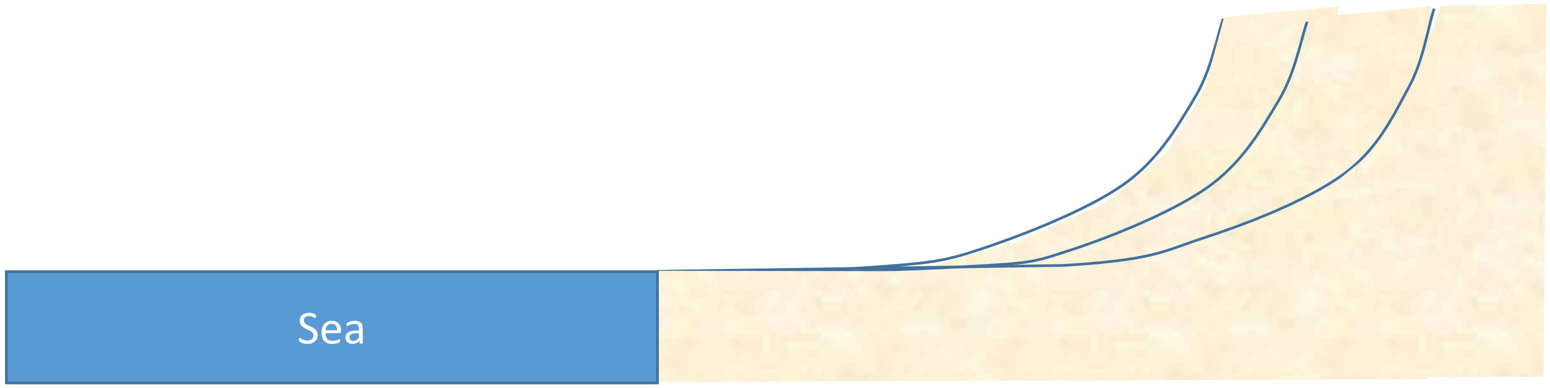
He cites this and the fact that the Nepean River flows into and out of the LSC as evidence that the rivers course was antecedent (prior) to the uplift.

Hatherly examined the thalwegs of the rivers associated with the LSC looking for the presence of knick points and knick zones in their profiles. These can be used to judge if the uplift that initiated them was relatively recent.

<u>River profiles and knick points</u>

Over time, in uniform lithology, rivers will erode their channels to sea (base) level. In doing this they develop concave longitudinal profiles as seen in this sketch. At this stage they are considered “mature”.

As erosion proceeds the profile retreats, all things being equal creating a flat plain, level with the sea (a peneplain).



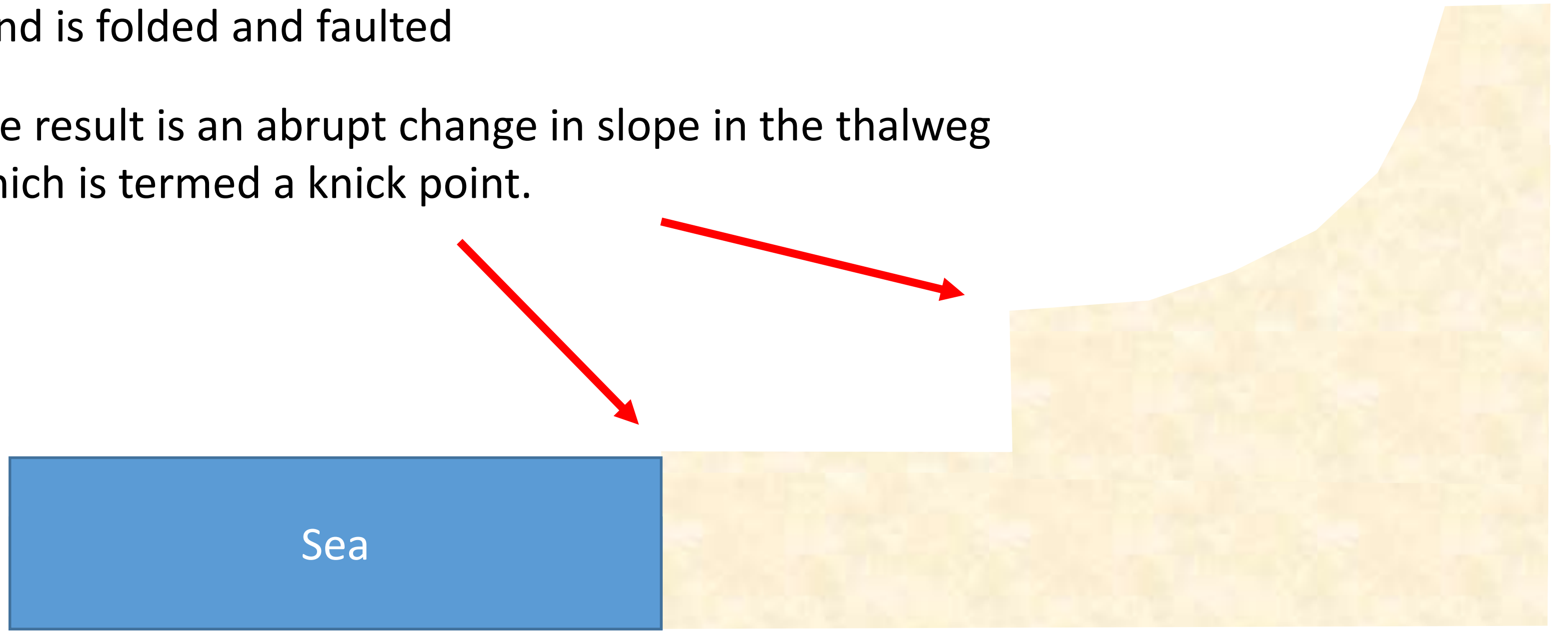
Successive profiles, known as Thalwegs, when graphed during this process, would appear like this.

The process of peneplanation is rarely achieved.

Sea levels rise and fall

Land is folded and faulted

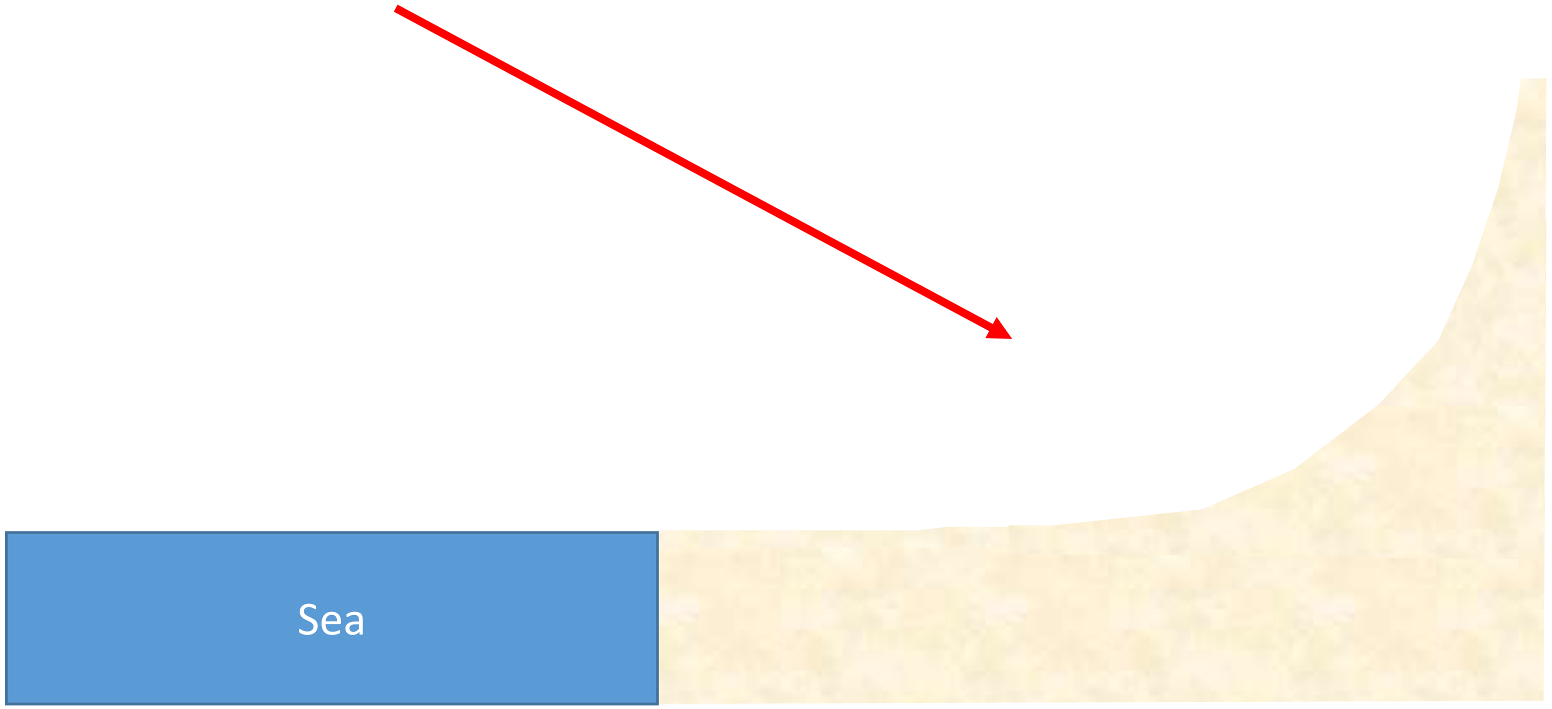
The result is an abrupt change in slope in the thalweg which is termed a knick point.



Knick points appear as waterfalls and rapids

The increase in steam velocity at the knick point will increase the rate of erosion and it will retreat until the river resumes its concave profile

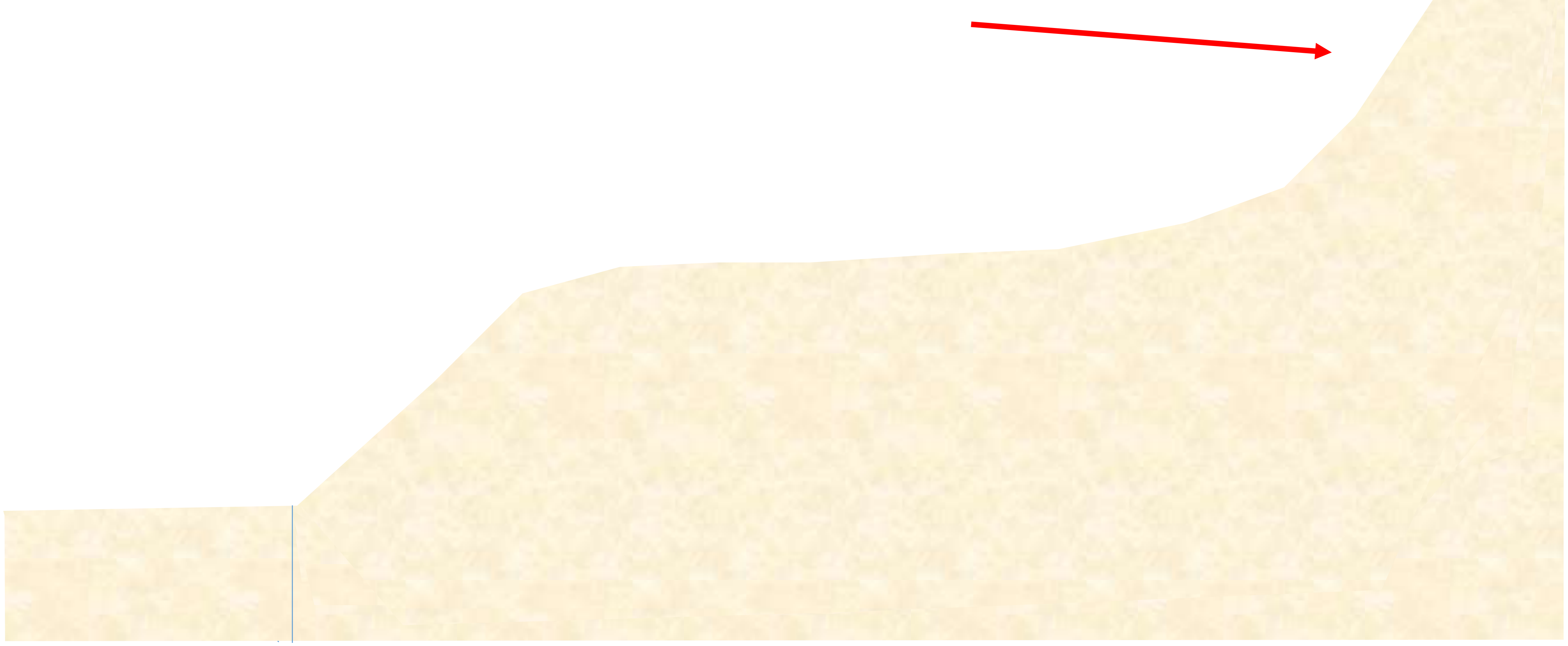
The area of steepened gradient is known as a knick zone



If a block is slowly uplifted for a period the thalweg will be pinned at the fault line.

After uplift ceases the influence of the knick point will still be apparent for some time before a mature concave profile is achieved. This may never occur.

This concave section in the headwater remains from the original “mature” profile



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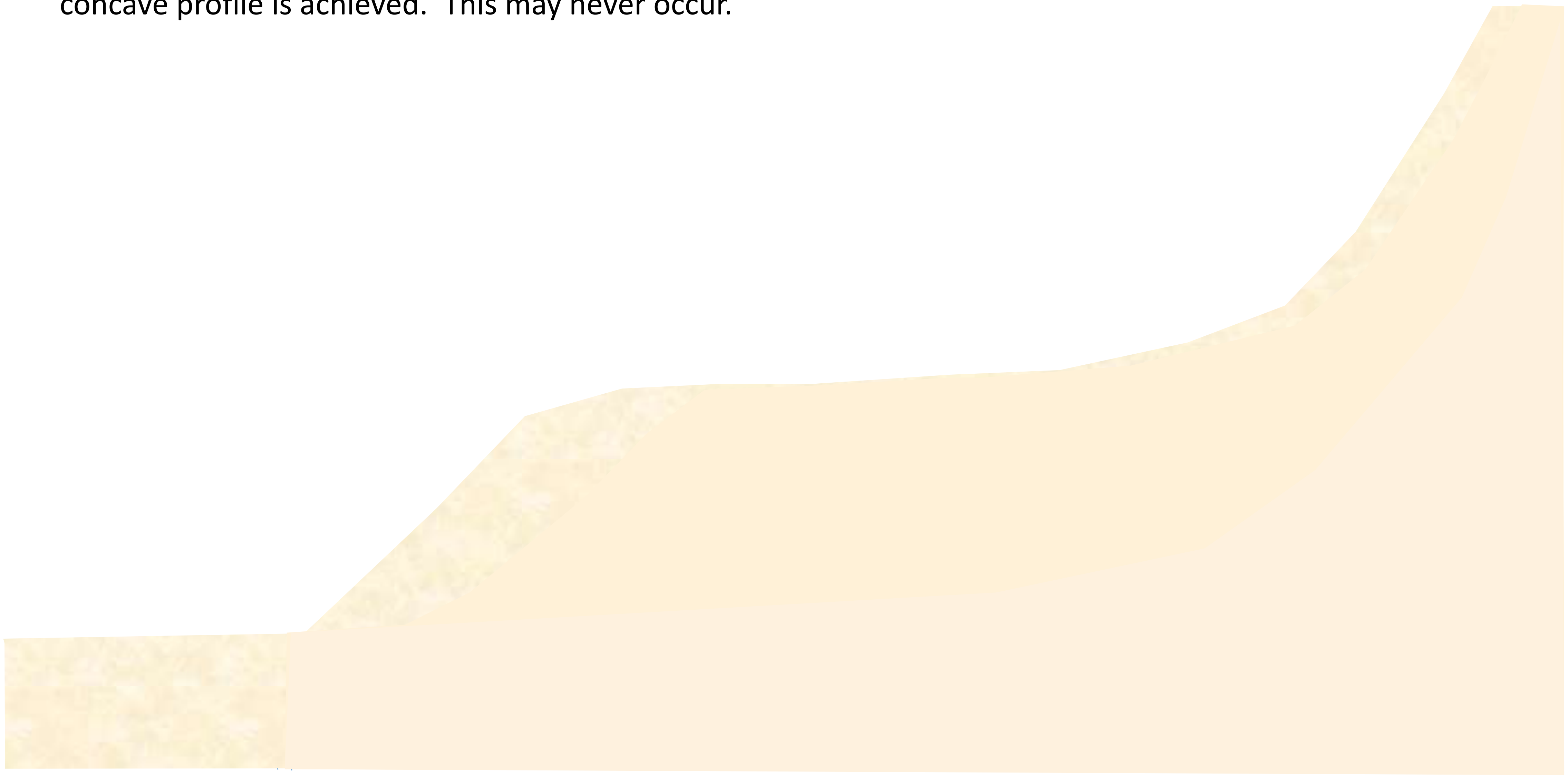
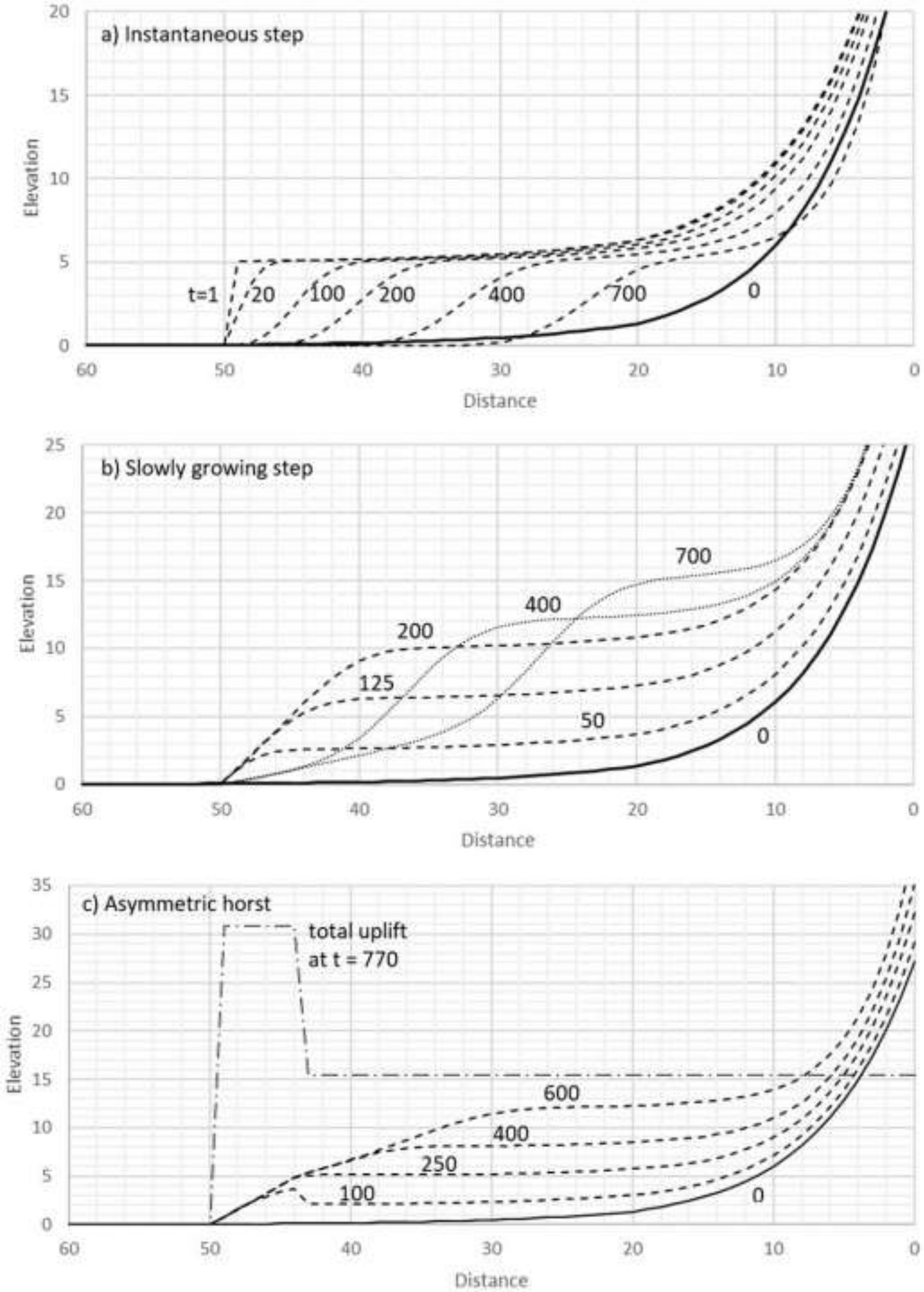
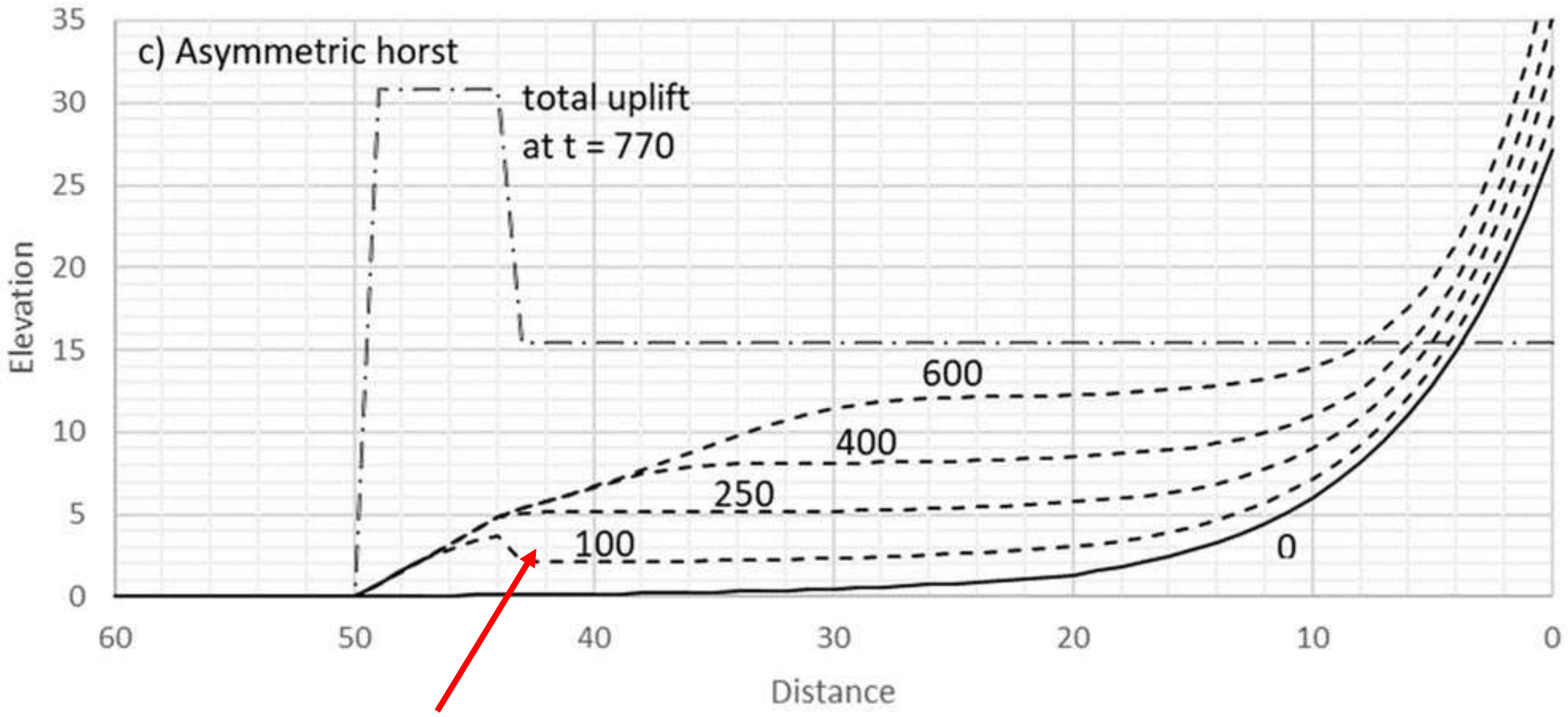




Hatherly illustrates this behaviour of knickpoints and zones with three diagrams (seen here).

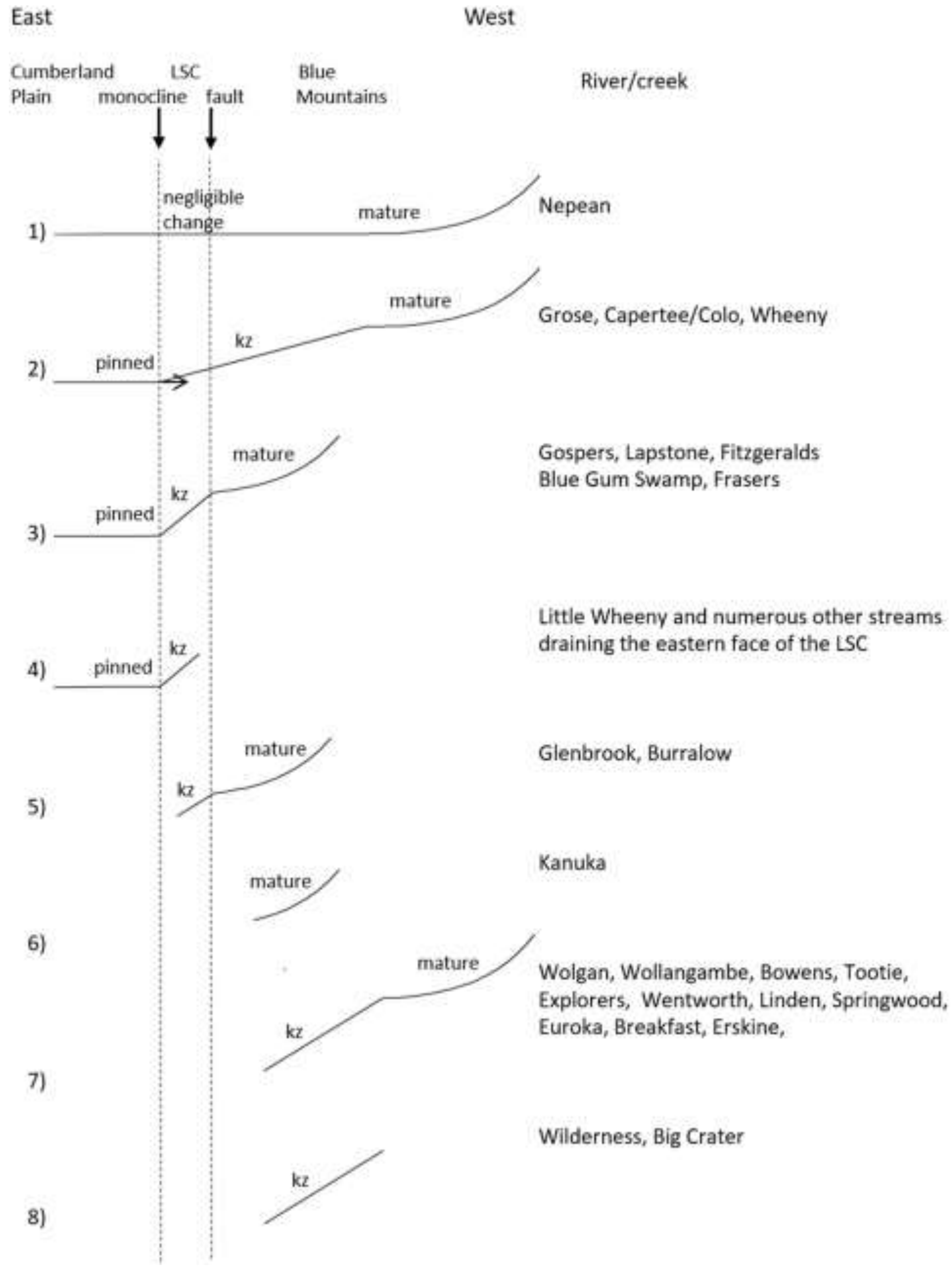
The t figures are time steps.

The third diagram shows the behaviour of a stream under an asymmetrical horst, which he says is similar to the form of the LSC



Until the stream breaks through the area of initial uplift, water will pool behind the higher land/fault and deposition, a lacustrine deposit, will form. Once breached the stream erosion may match the uplift but pinning the thalweg to the fault.

This process is suggested by Carter for the development of the Londonderry Clays and was also found in relation to the LSC at Burralow Creek and Mountain Lagoon.



Longitudinal stream profiles from Hatherly 2020

Hatherly found that the main rivers that appear to have been antecedent to the LSC have concave profiles in their headwaters; consistent with having been in place for a considerable time prior to its uplift.

The knickzones associated with these streams in the lower reaches, however, are tied to or closely tied to the LSC indicating a relatively recent uplift.

This is consistent with the existence of three periods of uplift in the area of the Blue Mountains

Hatherly’s research led him to conclude that the Blue Mountains, in the area drained by the Hawkesbury/Nepean River and its tributaries, were subject to three periods of uplift.

The first was a widespread uplift that occurred about 130 -80 Ma and helped form much of the Great Dividing Range. It would have been at some but an undetermined distance from the LSC.

At approximately 30 Ma a further and more localised uplift began in the area. The northward movement of the Australian plate over mantle hot spots resulted in this second uplift event. He says that it is progressively younger towards the south and in the vicinity of the Blue Mountains this event began at about 30 Ma. It led to the development of large knickpoints on the Wollondilly, Coxs and Kowmung Rivers. These are similar to those on the Shoalhaven River and other rivers flowing from the eastern highlands and they have retreated a considerable distance.

At approximately 10-5 Ma another uplift produced the Lapstone Structural Complex (LSC). This raised extensive areas of Rickabys Creek Gravel, while being slow enough to allow the Nepean River to erode its course in time with the uplift.

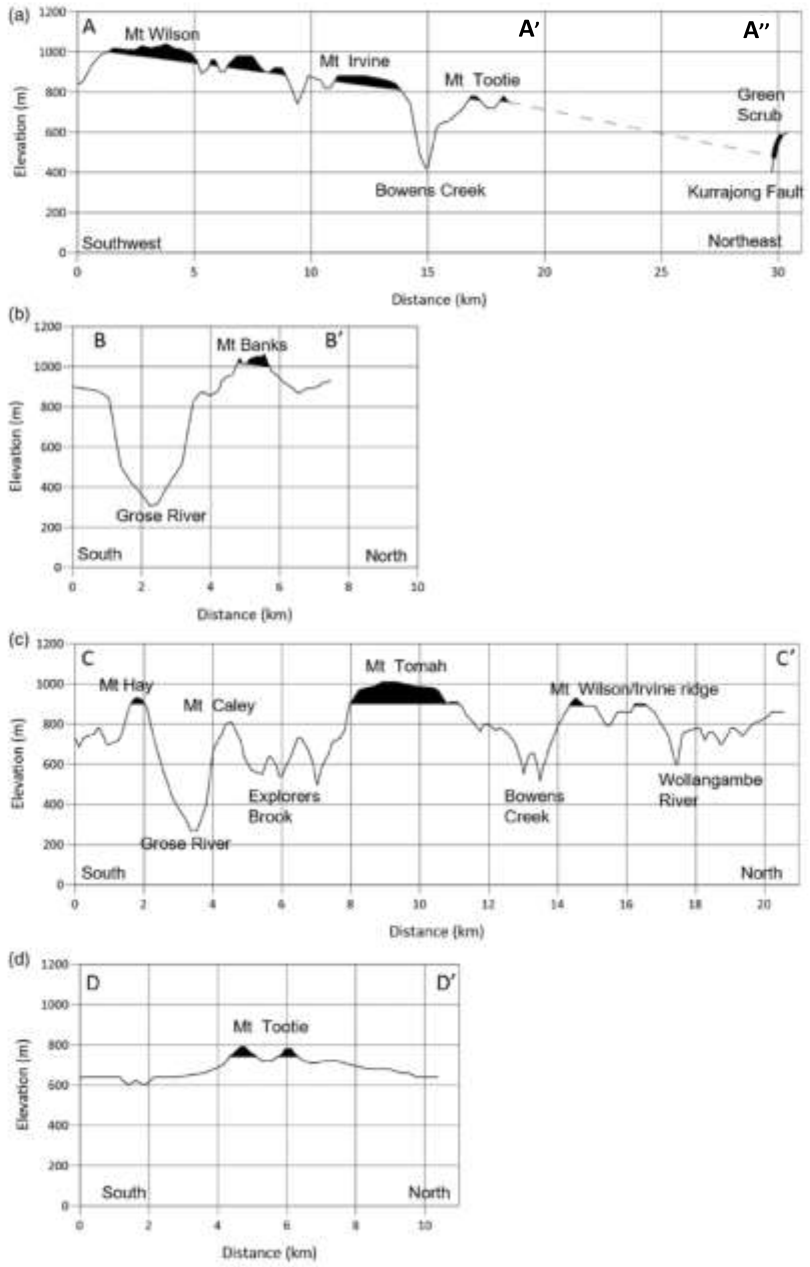
Hatherly found that major tributary streams that drain into the Hawkesbury/Nepean all have knick zones that are pinned or close to being pinned to the LSC. Evidence for the timing of this period of uplift comes from Basalt flows over much of the eastern plateau.

South North

The panorama above (Hatherly 2020) shows most of the Basalt caps located to the west of the LSC from Bowen Mountain. Geologists (David 1896) have suggested that these caps were related and that river gravels occur beneath the basalts at Mt Irvine and Mt Tootie (Carne, 1908). They have been used as proof that the formation of the LSC was after 14 Ma.

The suggestion that the basalts were once continuous was made by van der Beek et al. (2001) through mapping the base of the basalts and from geochemical analysis and dating, This built on work by Wellman and McDougall (1974).

Van der Beek found that there was no more than 250m vertical relief at the time of extrusion and that there was a gentle tilt to the northeast. Pickett (1984) also identified an east-northeast-trending valley beneath the basalts at Mt Tomah. Multiple flows are also indicated because the basalts at the top of the basalt caps are younger than at the base (van der Beek et al., 2001).

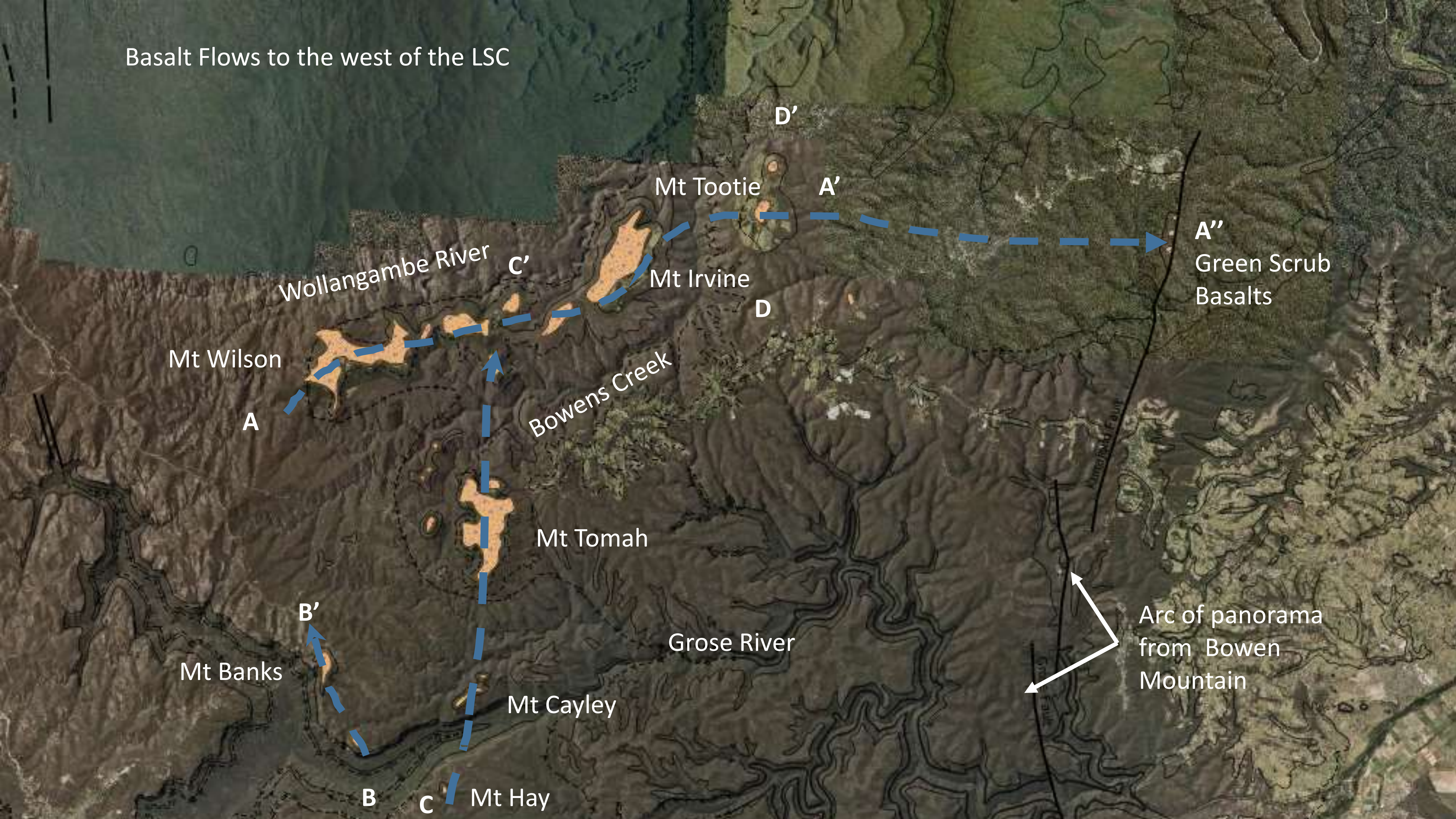


These cross-sections of the basalt caps (from Hatherly 2020) show that they have a gentle 0.85^0 slope to the North East.

It is thought that the Green Scrub Basalts originally flowed over the position of the Kurrajong Fault but have been moved/rotated since deposition.

The gentle but constant decline in the elevation of the basalts, over a distance of approximately 20–30 km, is consistent with the basalts all being part of the one series of flows.

They have been dated at 20.1–14.5 Ma (van der Beek 2001)



Basalt Flows to the west of the LSC
D'
Mt Tootie
A'
A''
Green Scrub
Basalts
Wollangambe River
C'
Mt Irvine
D
Mt Wilson
A
Bowens Creek
Mt Tomah
B'
Mt Banks
Grose River
Arc of panorama
from Bowen
Mountain
Mt Cayley
B
C
Mt Hay

Hatherly concludes that there was limited relief within the paleo-Hawkesbury river system at the time the Rickabys Creek Gravel was deposited and this was prior to the extrusion of the basalts. These would have flowed in a northeastly direction into a region of lesser relief; approximately following cross section A, A', A''

Given the evidence from Carter (2011) that the Hornsby Plateau had already been formed a stream flowing into the area of the Green Scrub Basalts would have flowed onto it and probably then down the warp.

Hatherly also suggests that erosion rates in the antecedent streams that flow beside and across the basalt flow are consistent with this process. Significant plateau lowering would have only commenced after initiation of uplift on the LSC. In the west, however, the relief would have been greater when the basalts were extruded, and the denudation of the plateau would already have commenced.

Uplift on the LSC is not uniform. Chris Fergusson (2006) provides these two stylised cross sections to show the difference in form between the two areas.

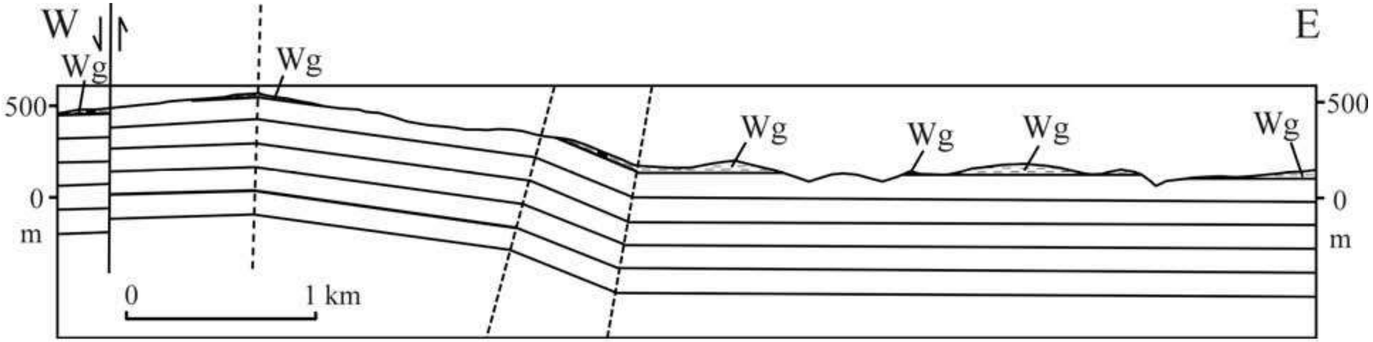


Figure 2 West to east cross section through the Lapstone Structural Complex at Kurrajong Heights. Wg = Wianamatta Group (underlying units not labelled). Vertical scale = horizontal scale. Cross section is constrained by the contact between the Wianamatta Group and the underlying Hawkesbury Sandstone as shown on the Penrith 1:100 000 Geological Sheet (Clarke & Jones 1991).

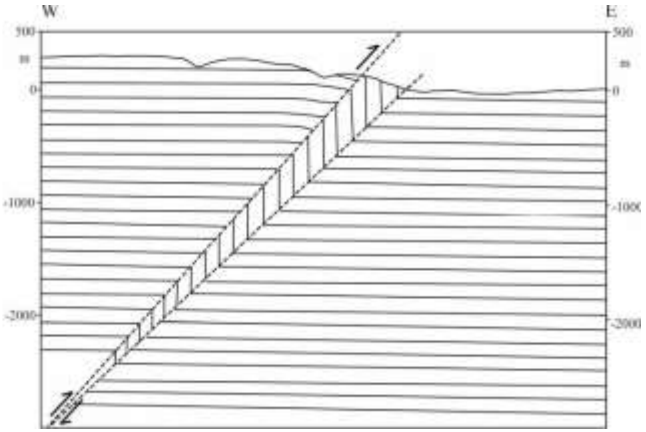
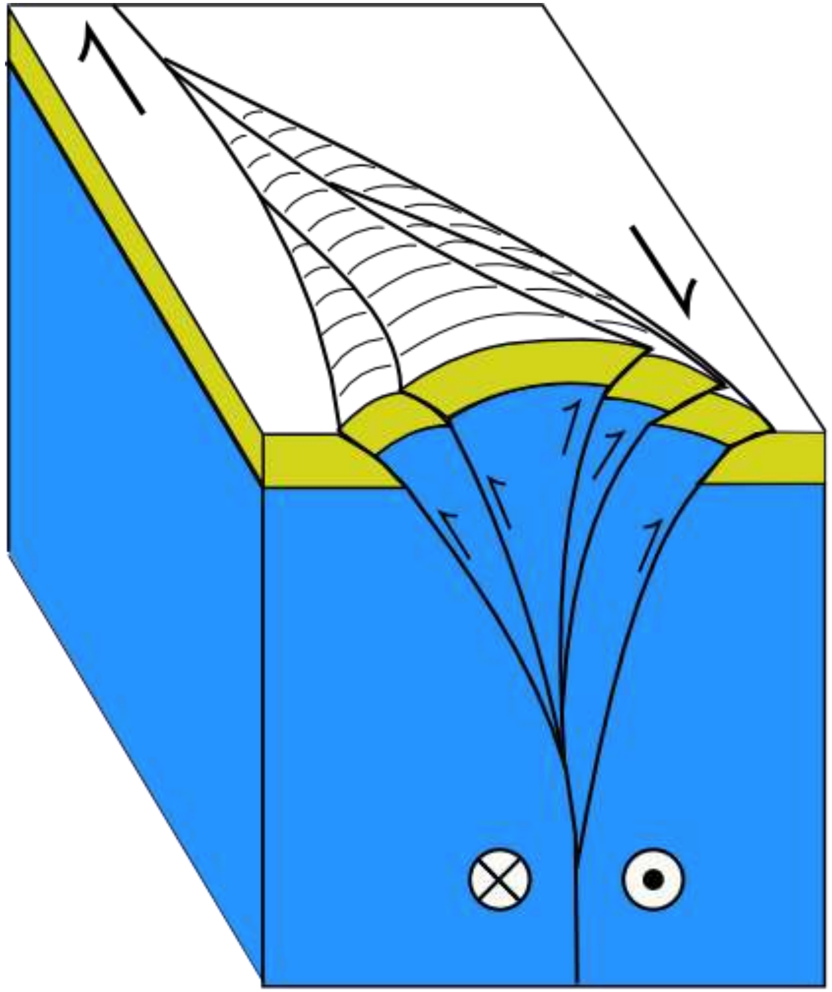


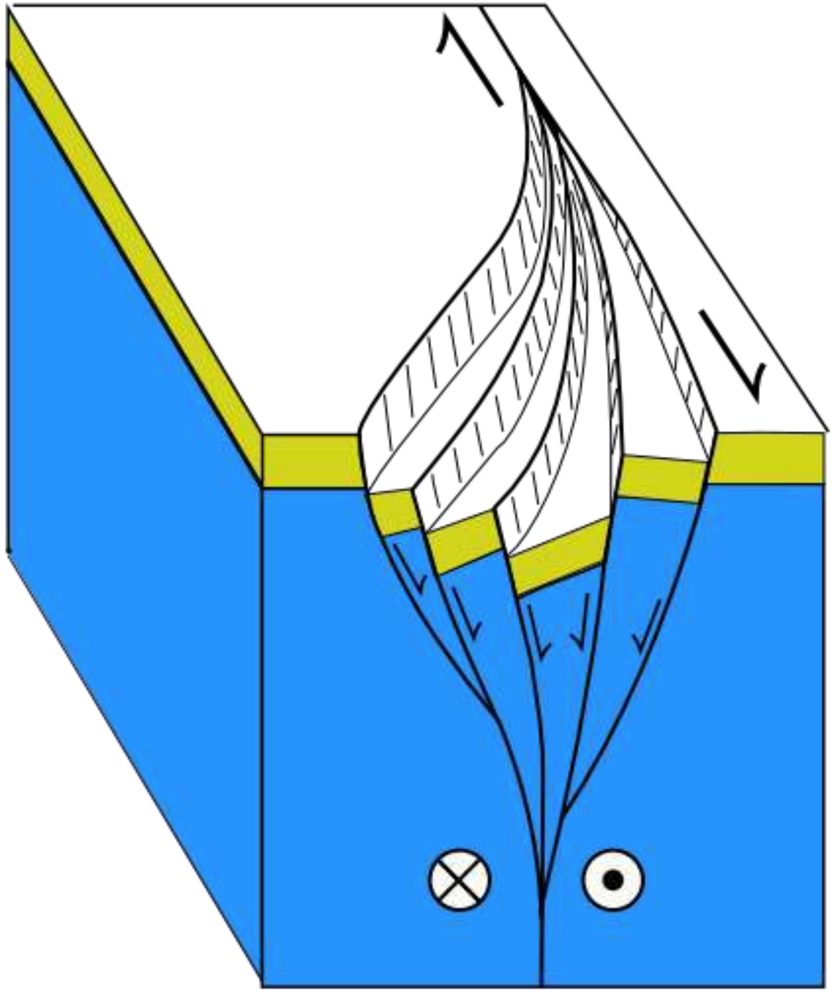
Figure 3. *West to east cross section through the Lapstone Structural Complex at the Hawkesbury Lookout (note that stratigraphy is omitted but the surface exposure is in the Hawkesbury Sandstone). Vertical scale = horizontal scale.*

He suggests that the difference can be explained by the existence of the en-echelon geometry of these faults in the Kurrajong area. This implies a strike-slip component in the areas geomorphology.

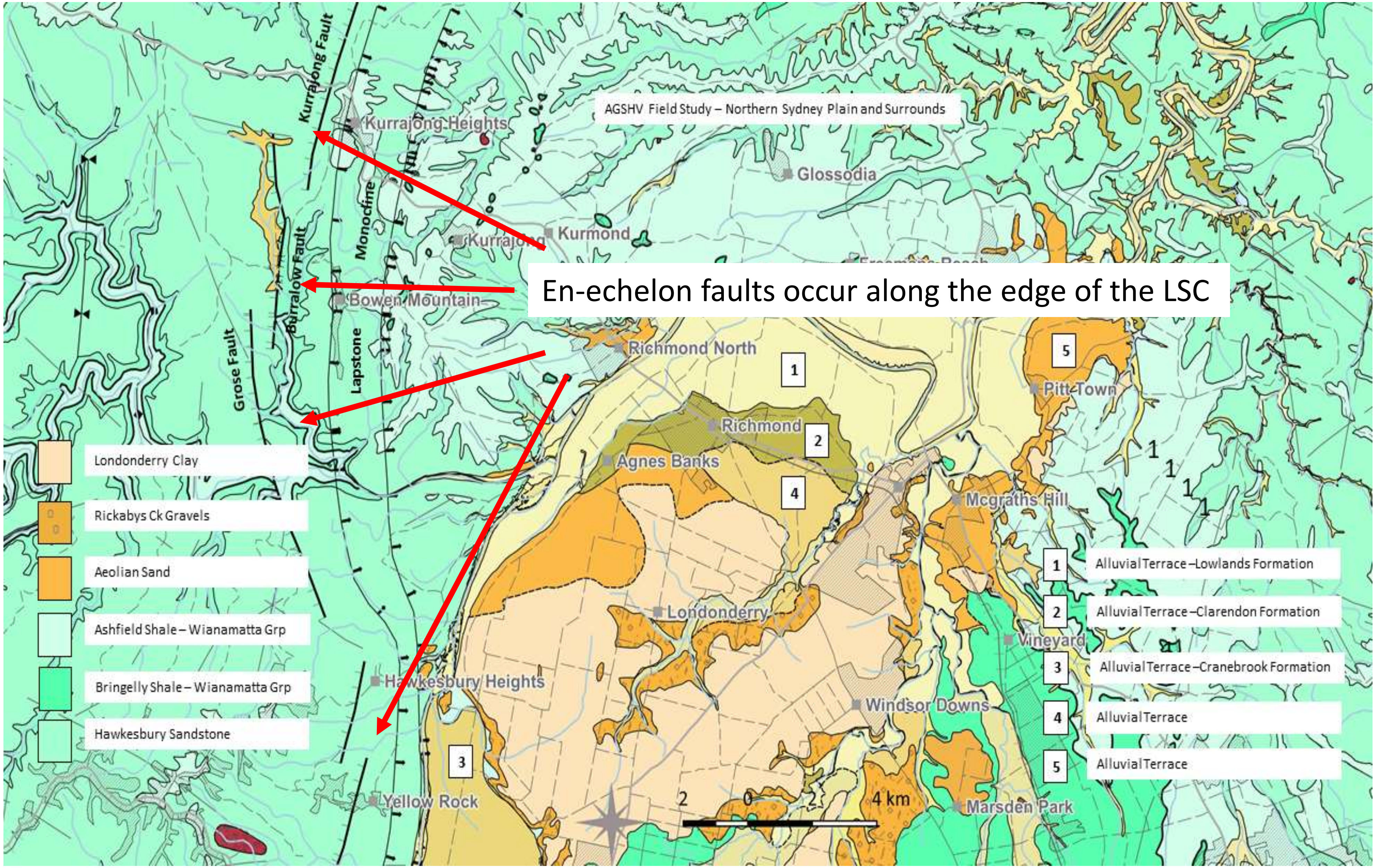
Strike slip movement can produce Flower Faults as seen in the following diagrams (Wikipedia).



Positive Flower



Negative Flower

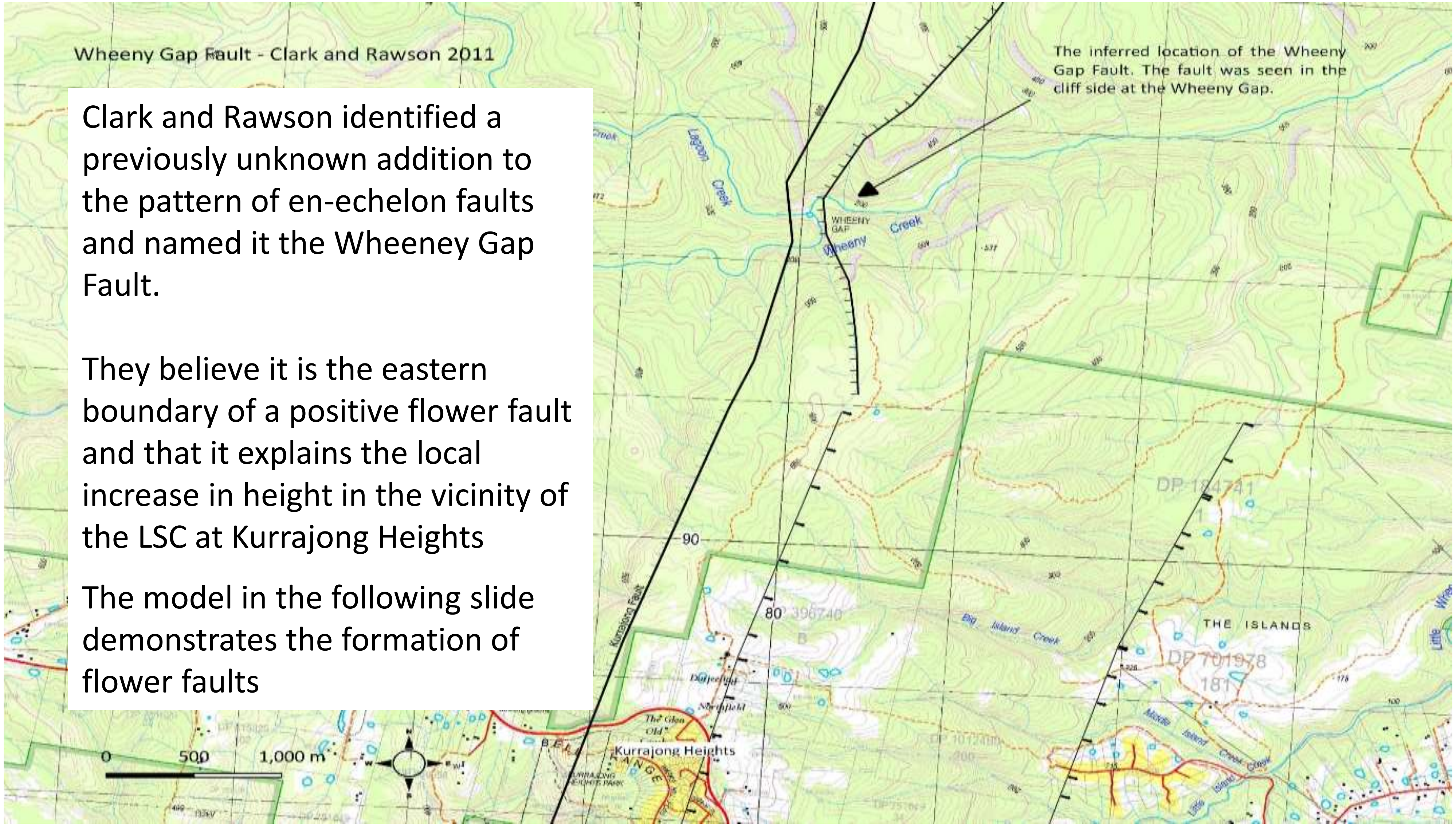


AGSHV Field Study – Northern Sydney Plain and Surrounds
En-echelon faults occur along the edge of the LSC
Kurrajong Fault
Burralow Fault
Grose Fault
Monocline
Lapstone
Kurrajong Heights
Glossodia
Kurmond
Kurrajong
Bowen Mountain
Richmond North
Richmond
Agnes Banks
Pitt Town
Mcgraths Hill
Londonderry
Vineyard
Hawkesbury Heights
Windsor Downs
Yellow Rock
Marsden Park
2 0 2 4 km
Londonderry Clay
Rickabys Ck Gravels
Aeolian Sand
Ashfield Shale – Wianamatta Grp
Bringelly Shale – Wianamatta Grp
Hawkesbury Sandstone
1 Alluvial Terrace – Lowlands Formation
2 Alluvial Terrace – Clarendon Formation
3 Alluvial Terrace – Cranebrook Formation
4 Alluvial Terrace
5 Alluvial Terrace

Clark and Rawson identified a previously unknown addition to the pattern of en-echelon faults and named it the Wheeney Gap Fault.

They believe it is the eastern boundary of a positive flower fault and that it explains the local increase in height in the vicinity of the LSC at Kurrajong Heights

The model in the following slide demonstrates the formation of flower faults



Map of Wheeny Gap Fault (inferred Clark and Rawson 2011)

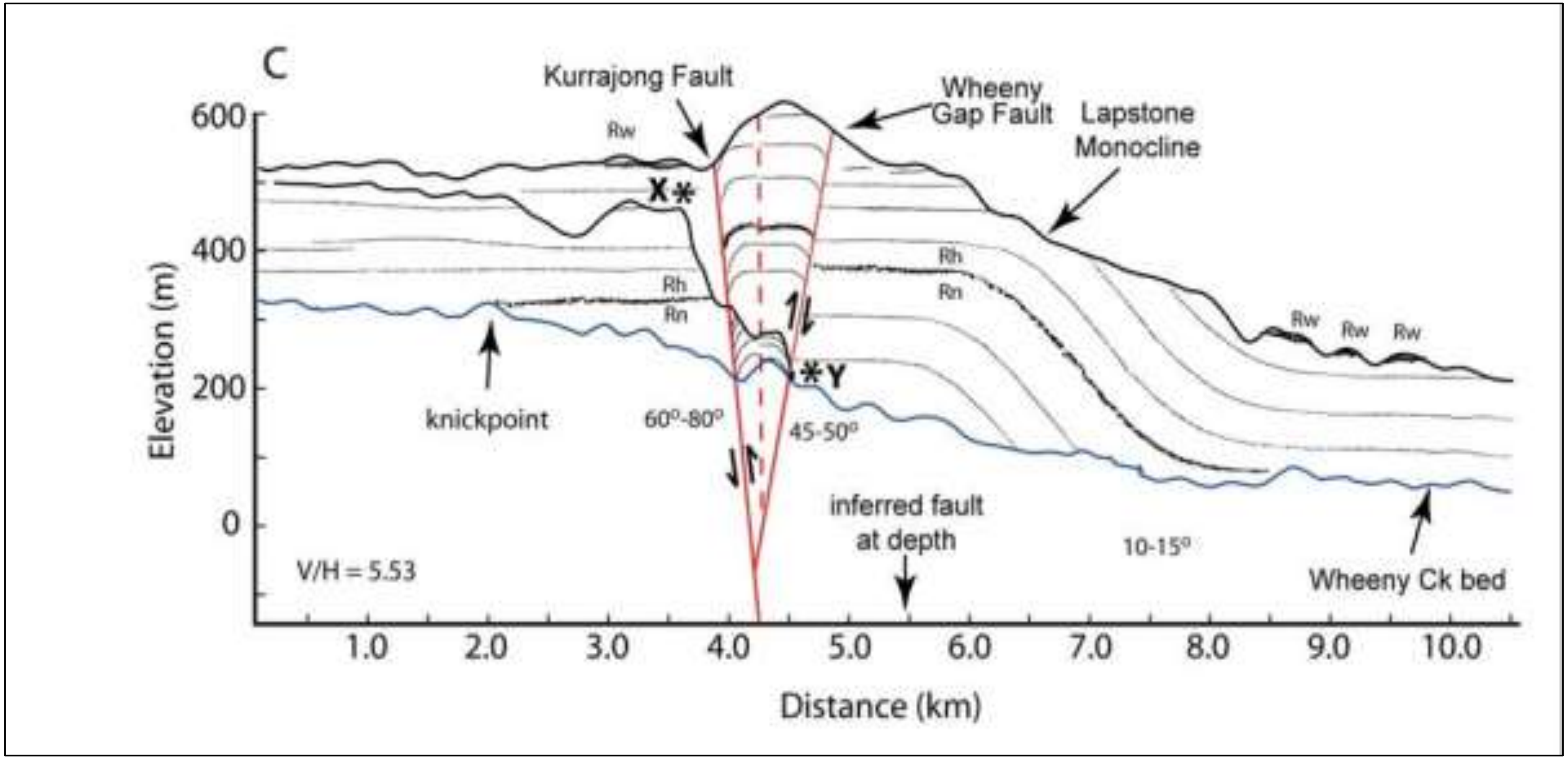


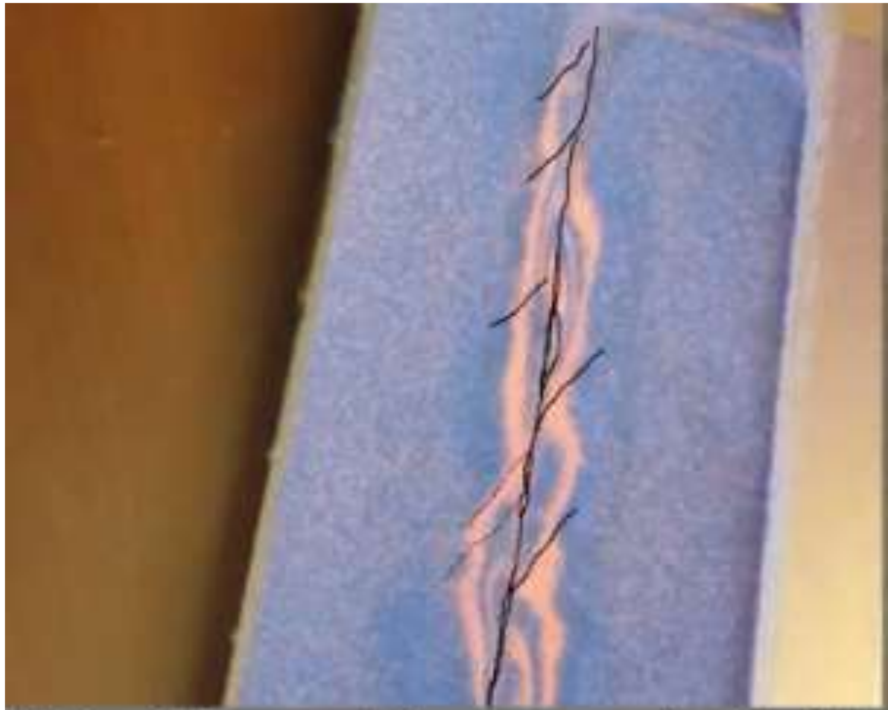
Figure 4. *Cross Section at Wheeny Gap. Rh =Hawkesbury Sandstone Rn= Narrabeen Group Sandstone. Clark and Rawson 2005.*

Model presented by

Virginia Tech
Active Tectonics and Geomorphology Lab

Model Setup

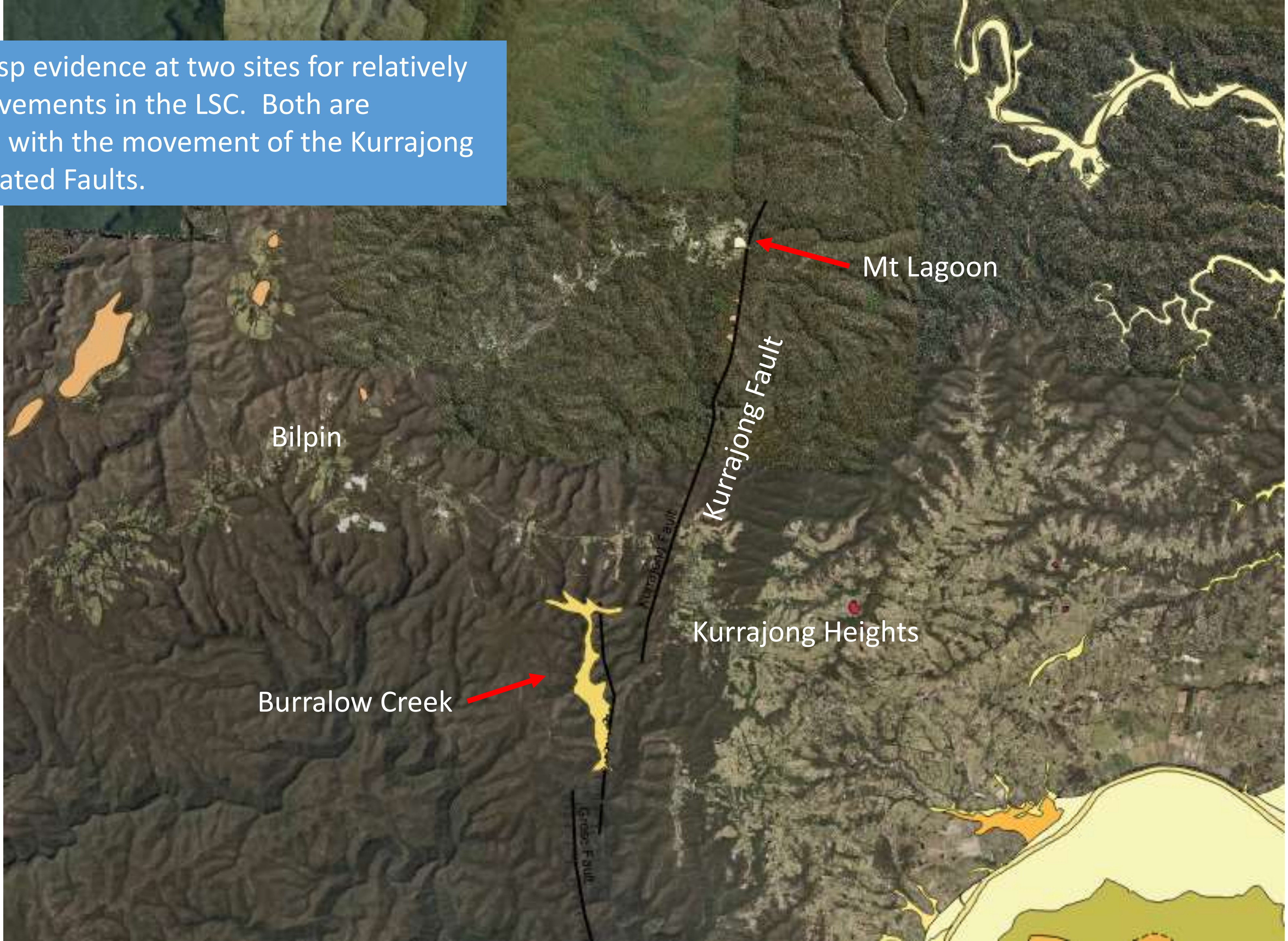
Philip Prince



This video provides a more detailed look at the pure strike-slip deformation model presented in the Strike-Slip Preview video. This model was prepared using an all-sand layer pack, with half of the layer pack resting on a high-friction base to permit it to be pulled and displaced relative to the other half of the layer pack. Construction of the model simulates a basement strike-slip fault whose motion deforms kilometers of overlying sedimentary strata. The uplifted area along the fault zone is eroded as it rises, exposing the outcrop pattern produced by the deformation.


Dextral (top right)
motion

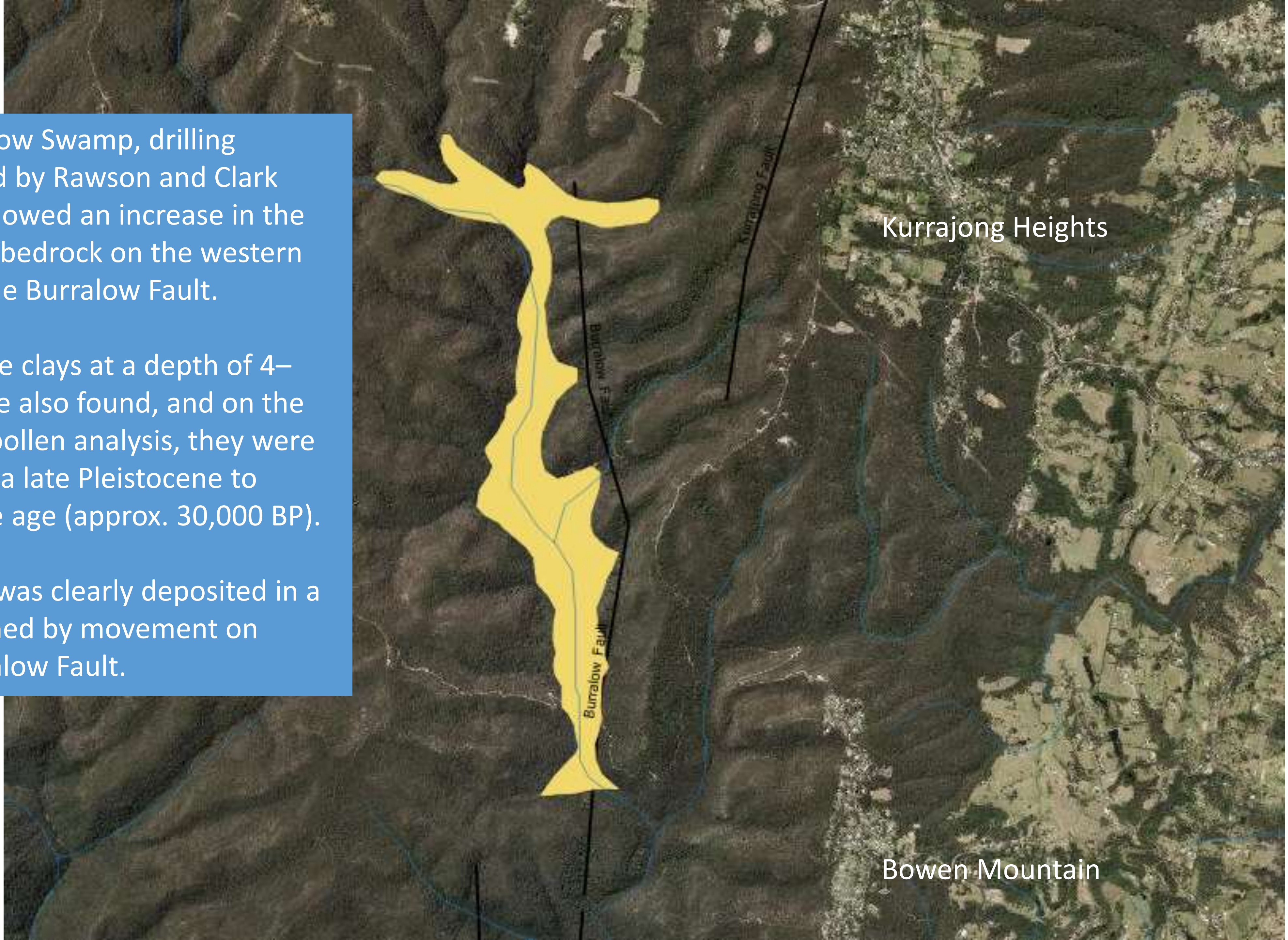
There is alsp evidence at two sites for relatively recent movements in the LSC. Both are associated with the movement of the Kurrajong and associated Faults.



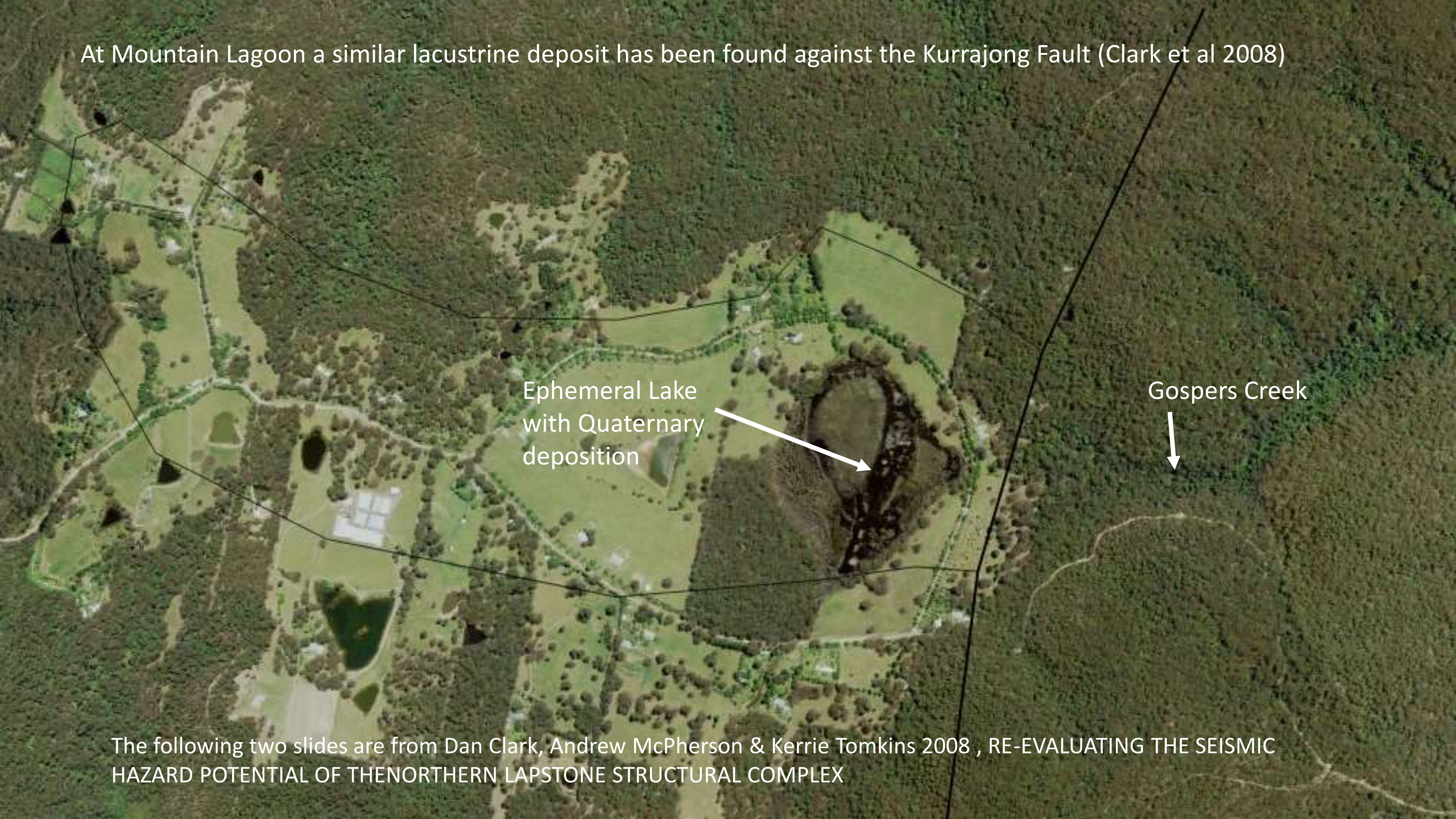
At Burralow Swamp, drilling described by Rawson and Clark (2009) showed an increase in the depth to bedrock on the western side of the Burralow Fault.

Lacustrine clays at a depth of 4–10m were also found, and on the basis of pollen analysis, they were assigned a late Pleistocene to Holocene age (approx. 30,000 BP).

The clay was clearly deposited in a lake formed by movement on the Burralow Fault.



At Mountain Lagoon a similar lacustrine deposit has been found against the Kurrajong Fault (Clark et al 2008)



The following two slides are from Dan Clark, Andrew McPherson & Kerrie Tomkins 2008 , RE-EVALUATING THE SEISMIC HAZARD POTENTIAL OF THENORTHERN LAPSTONE STRUCTURAL COMPLEX

Clark et al conducted drilling on the eastern margin of the Mt Lagoon and confirmed that the deposition is the result of damming against the Kurrajong Fault . They found a deposit with fifteen metres of layered lake clays, alluvial fan sands and sandy colluvial sediments that were overlying a shale bedrock.

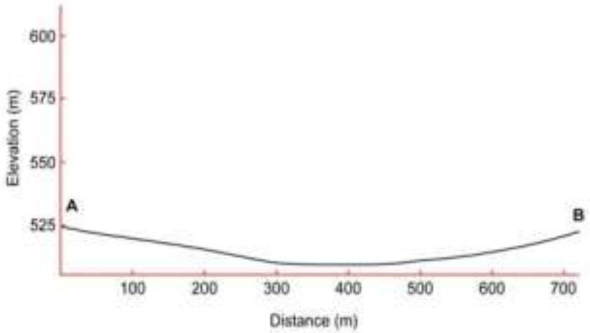
Prior to the uplift in the Fault Gospers Creek had sufficient power to erode a steep V shaped valley as can be seen in the cross-sections in the following slide.

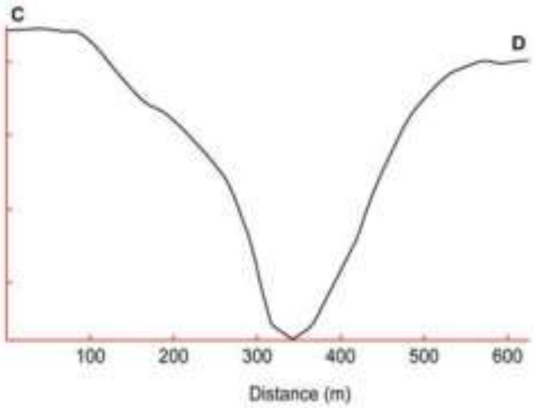
Since the damming the creek has had insufficient power to erode the sandstone bar associated with the Fault.

Clark et al have, as yet, not been able to date the sediments.

Clark et al drilled bores in a cross–section from E to F ; from the Lagoon and across the Kurrajong Fault

The deposition has covered what was originally a steep sided valley on Gospers Creek





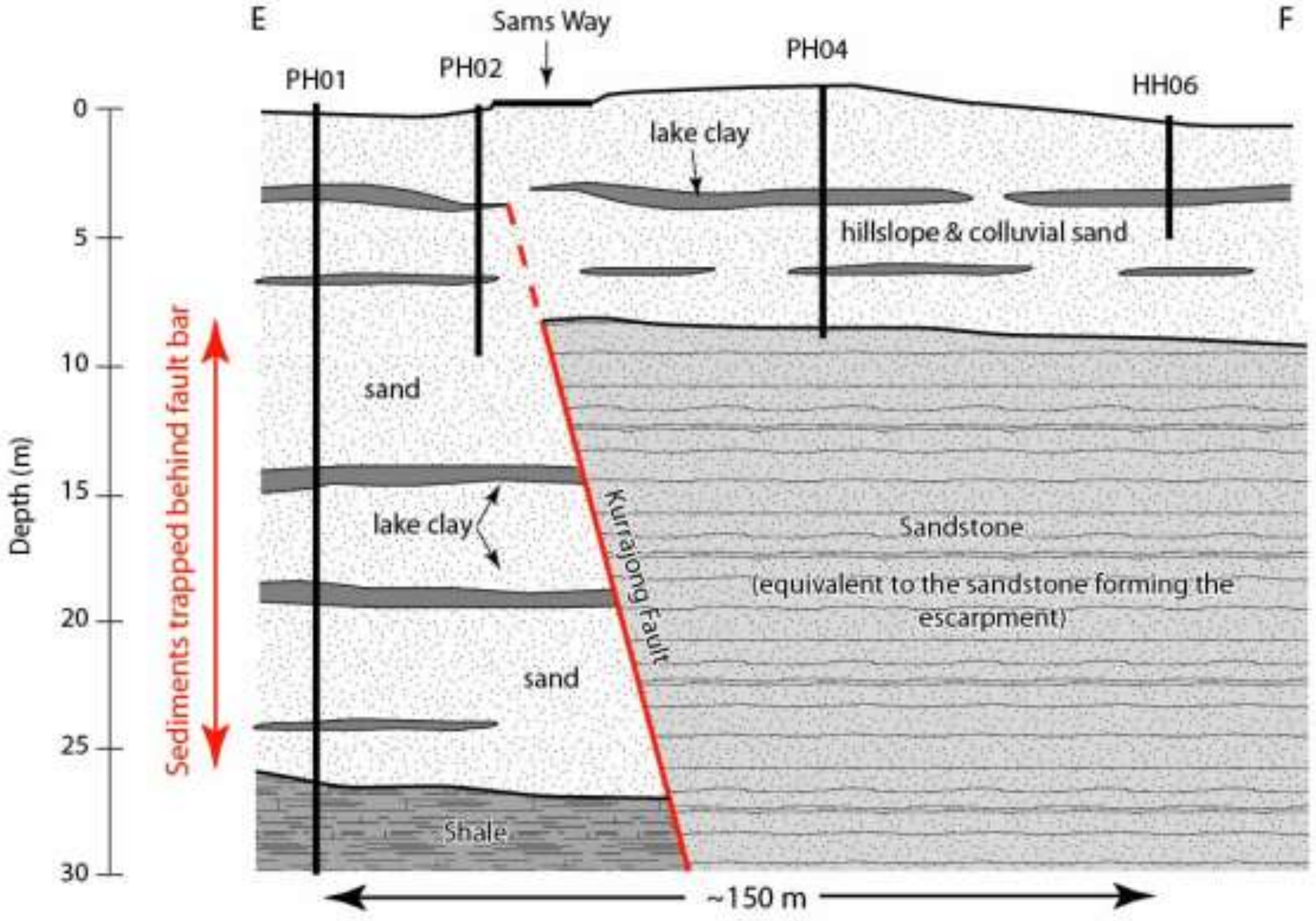


Diagram from Clark et al showing the position and results of their boreholes and the movement on the Fault

References

Branagan, D.F., and Packham, G.H., 2000. *Field Geology of New South Wales*. 3rd Edition. New South Wales Department of Mineral Resources, Sydney.

Herbert, C., 1983. *Geology of the Sydney Basin 1: 100 000 sheet 9130*. New South Wales Department of Mineral Resources, Sydney.

Carter, Lewis. 2011. Tectonic Control of Cenozoic Deposition in the Cumberland Basin, Penrith/Hawkesbury Region, New South Wales. Hons Thesis. University of Wollongong

Czarnota, K., Roberts, G., White, N., Fishwick, S., 2014. Spatial and temporal patterns of Australian dynamic topography from River Profile Modeling. J. Geophys. Res., Solid Earth119, 1384–1424.

Davies, Prof Rhodri, ANU. June 2021. https://science.anu.edu.au/news-events/events/cenozoic-intra-plate-volcanism-eastern-australia-role-mantle-plumes-plate-motion

Betts P., Willis D., Moresi L., Miller M. and Whittaker J.. Congested Subduction: Lessons from the Australian-Pacific convergent margin (NZ). 2020 . https://www.youtube.com/watch?v=_Dy4wwVPgxE

Fergusson, C. L. (2019). Subduction accretion and orocline development in modern and ancient settings: Implications of Japanese examples for development of the New England Orogen of eastern Australia. Journal of Geodynamics, 129 117-130.

Glen R. A. & Beckett J. (1997) Structure and tectonics along the inner edge of a foreland basin: The Hunter Coalfield in the northern Sydney Basin, New South Wales, Australian Journal of Earth Sciences, 44:6, 853-877, DOI: 10.1080/08120099708728359

Glen R. A., The Tasmanides of eastern Australia Geological Survey of New South Wales, Department of Primary Industries, PO Box 344, Hunter Region Mail Centre, New South Wales, 2310 Australia

Hatherly P. J. (2020) Landscape evolution of the Blue Mountains revealed by longitudinal river profiles and Cenozoic basalts and gravels, Australian Journal of Earth Sciences

Herbert, Chris and Helby, Robin. A guide to the Sydney Basin. 1980. Geological Survey of NSW. Bulletin 26.

Henderson R. and Johnson D. The Geology of Australia 3rd Ed. Cambridge University Press.

Jenkins R. B. , Landenberger B. & Collins W. J. (2002) Late Palaeozoic retreating and advancing subduction boundary in the New England Fold Belt, New South Wales, Australian Journal of Earth Sciences, 49:3, 467-489, DOI: 10.1046/j.1440-0952.2002.00932.x

Jessop K. , Daczko N. R. and Piazolo S. . Tectonic cycles of the New England Orogen, eastern Australia: A Review. Australian Journal of Earth Sciences' February 2019

Moresi Louis. Professor of Geophysics Australian National University Canberra, Australia +61 4 0333 1413. https://www.youtube.com/watch?v=cVulRP2tUGM

Müller, R. D, Seton, M., Zahirovic, S., Williams, S.E., Matthews, K.J., Wright, N.M., Shephard, G.E., Maloney, K.Y., Barnett-Moore, N., Hosseinpour, M., Bower, D.J., Cannon, J., 2016, Ocean basin evolution and global-scale plate reorganization events since Pangea breakup, Annual Review of Earth and Planetary Science, Vol 44, 107-138. https://www.youtube.com/watch?v=JoLQndZl2ZI

Muller, R Dietmar; Flament, Nicolas; Matthews, Kara J.; Williams, Simon E.; and Gurnis, Michael, "Formation of Australian continental margin highlands driven by plate-mantle interaction" (2016). Faculty
of Science, Medicine and Health - Papers: part A. 4195. https://ro.uow.edu.au/smhpapers/4195

Offler R. , Zwingmann H. , Foden J. , Sutherland F. L. and Graham I. T. , Age and composition of dykes emplaced before and during the opening of the Tasman Sea—source implications. Australian Journal of Earth Sciences 2019, Vol. 66, No. 8

Quigley, Mark C. , Clark, Dan & Sandiford, Mike. Tectonic geomorphology of Australia, Geological Society, London, Special Publications 2010; v. 346; p. 243-265

Rawson, A., & Clark, D. (2009). Geomorphological evidence for neotectonic activity on the northern Lapstone Structural Complex. In D. Clark (Ed.), Potential geologic sources of seismic hazard in the Sydney Basin (pp. 19–30). Geoscience Australia Record 2009/11.

Rosenbaum G., Pengfei Li, Rubatto D. The contorted New England Orogen (eastern Australia): New evidence from U-Pb geochronology of early Permian granitoids. First published: 03 February 2012 Tectonics I Volume 31, Issue 1 https://doLorg/1 0.1 029/2011 TC002960

Salles, T., N. Flament, and D. Muller (2017), Influence of mantle flow on the drainage of eastern Australia since the Jurassic Period, AGU Publications.Geochem. Geophys. Geosyst., 18, 280–305, doi:10.1002/2016GC006617.

Scheibner, Erwin. The geological evolution of New South Wales : a brief review. Editors: Helena Basden, Dorothy Pearson. NSW Dept. of Mineral Resources, c1999

The Australian Museum. The Sydney Basin, Discover and Learn.
https://australianmuseum.net.au/learn/minerals/shaping-earth/the-sydney-basin/