Using Permian glacials and Paleocene-Eocene Thermal Maximum regolith as time markers to constrain and understand the uplift history and landscape evolution of the Australian Alps

Ross Cayley, Geological Survey of Victoria.

Tom Andrews, Geological Survey of Victoria.

Australian Earth Sciences Convention
3 February 2025

RESOURCES VICTORIA

We acknowledge and respect Victorian Traditional Owners as the original custodians of Victoria's land and waters, their unique ability to care for Country and deep spiritual connection to it.

We honour Elders past and present whose knowledge and wisdom has ensured the continuation of culture and traditional practices.

Resources Victoria is committed to genuinely partnering with Victorian Traditional Owners and Victoria's Aboriginal community to progress their aspirations.

Talk Outline

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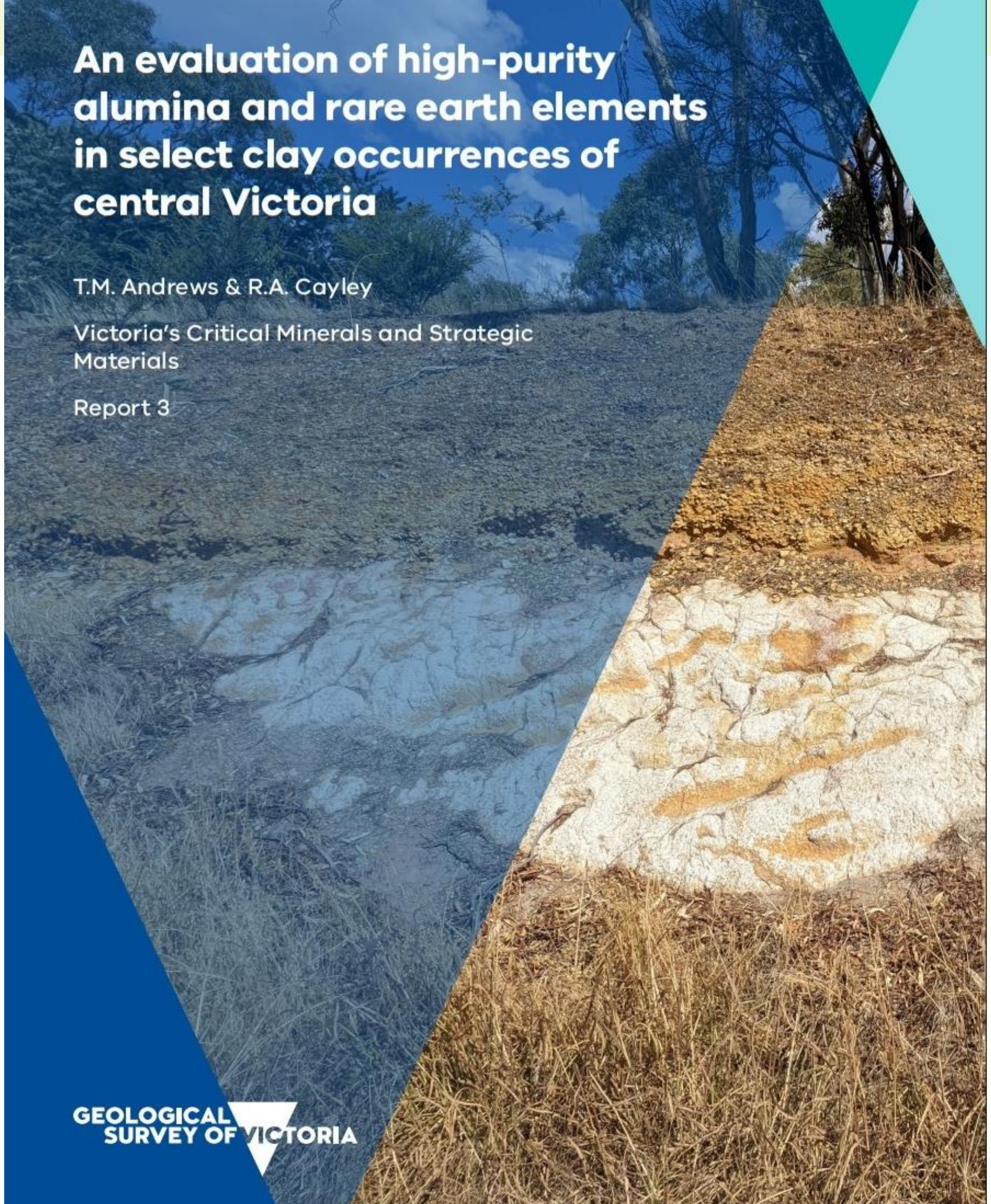
An evaluation of high-purity alumina and rare earth elements in select clay occurrences of central Victoria
T.M. Andrews & R.A. Cayley
Victoria's Critical Minerals and Strategic Materials
Report 3
GEOLOGICAL SURVEY OF VICTORIA

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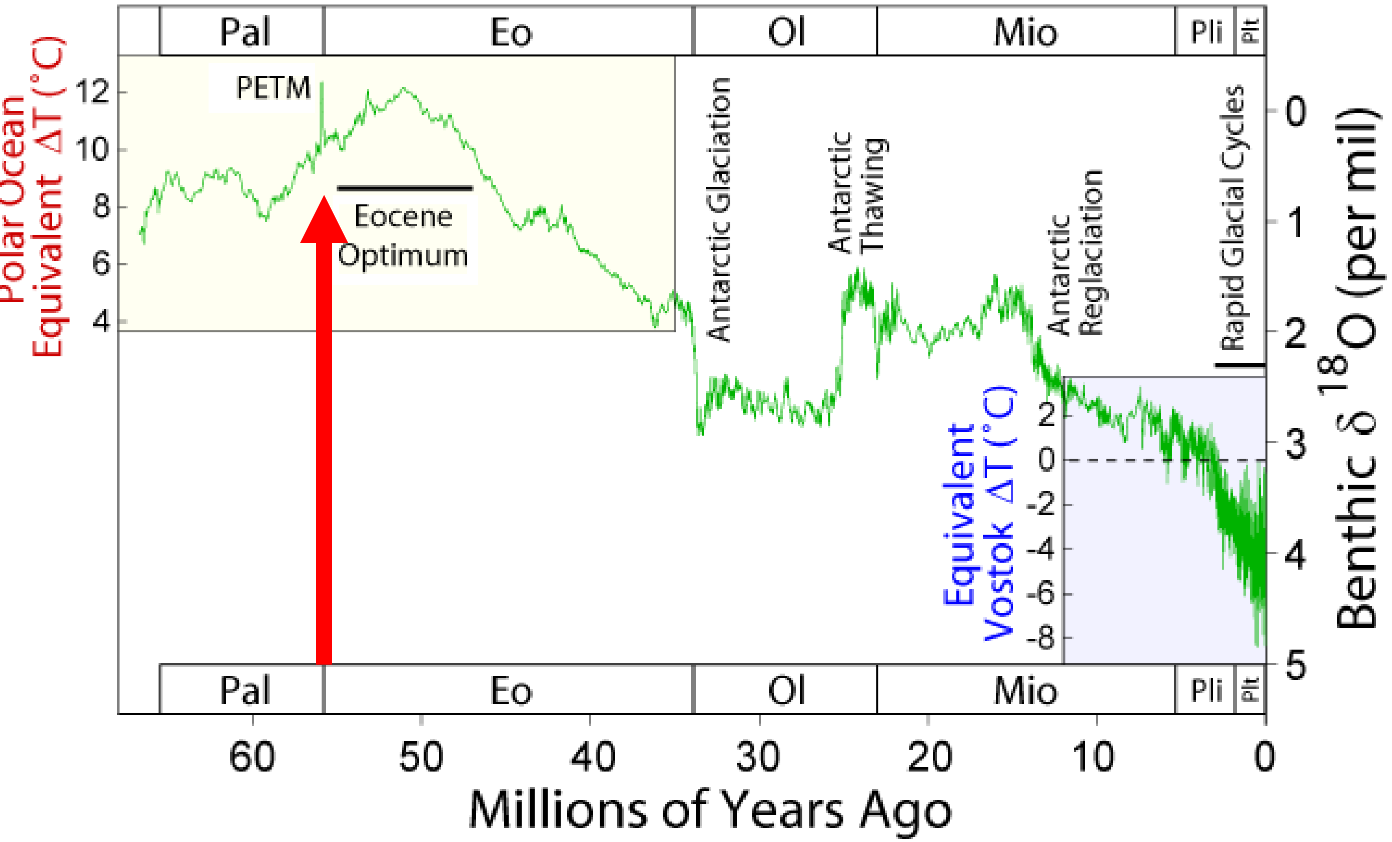
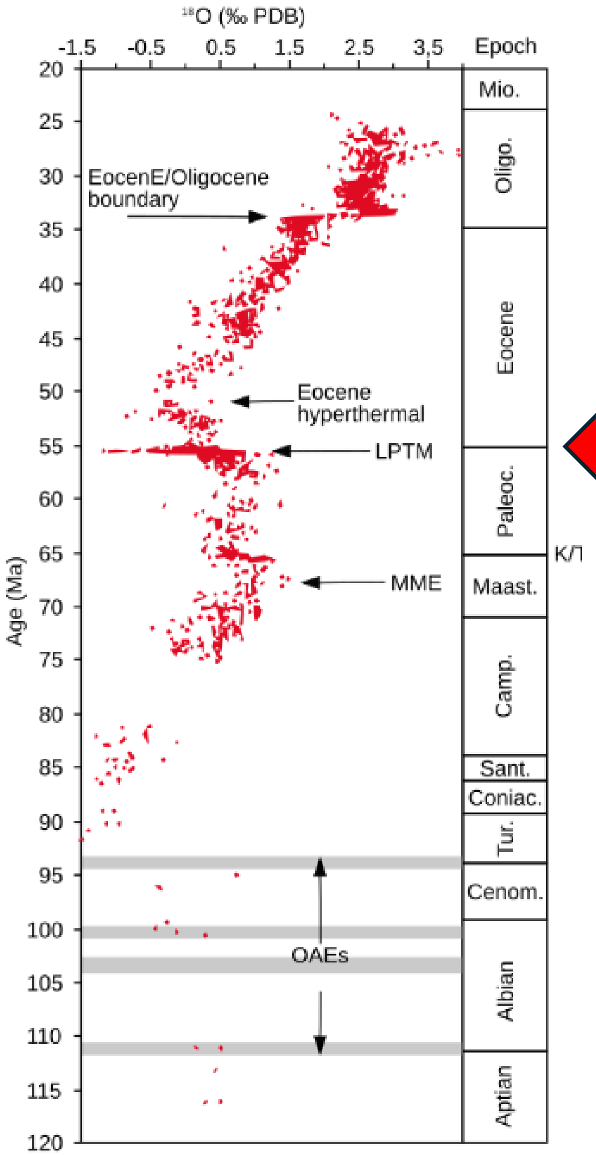
The Paleocene – Eocene Thermal Maximum. What is it?



By Robert A. Rohde - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=466265



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Global mean surface temperature at peak PETM: 27.2-34.5° C. (Inglis et al., 2020)

Sea surface temperatures in the East Tasman Plateau (located ~65° S at ~57 Ma) were **33° C**! (estimated from sediment core samples; Sluijs et al., 2011)

For ~200 thousand years Victoria was both subpolar and rampantly ‘tropical’, with a sustained semi-tropical climate persisting for the next ~10 million years!

PETM significance for constraining Victoria's landscape evolution history:

We can assign thick, tropical-style paleo-regolith profiles in Victoria to the PETM with confidence because:

- the preceding +ve temperature excursion of similar magnitude (Cretaceous Thermal Maximum at ~90 mya) is too old to explain thick in-situ tropical-style regolith profiles developed in Paleocene fluvial units in Victoria.

- Eocene strata in Victoria are similarly weathered but with slightly less intensity (consistent with the sustained 'Eocene Optimum' that followed the PETM).

- Olicocene and younger strata in Victoria preserve no evidence of tropical-style weathering (but locally incorporate reworked PETM remnants -kaolinitic clays / lateritic clasts – but intermixed with unweathered materials)

- there has been no comparable global +ve thermal excursion since the Eocene – so no younger 'tropical' regolith here.

We consider the **PETM is a fantastic time-marker**.

- PETM regolith: indiscriminate and thick (uneroded PETM regolith profiles extend to ~80m deep in Palaeozoic bedrock).
- Super easy and unambiguous to recognise
- Given the global context and Statewide remnant distribution of PETM in Victoria,
  we expect this event affected every rock exposed in Victoria at that time.

Therefore:

- Where PETM regolith and / or coeval stratigraphy are substantially or even intermittently preserved,
  it dates the local land-surface to Late Paleocene (at a minimum).
- Where PETM regolith and / or coeval stratigraphy are entirely absent, it is an indication that the local land-surface is younger than the PETM (ie: has been subjected to a significant (~50m +) denudation post-Eocene)

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PETM clay localities (commercial)

PETM regolith best preserved in river valley flanks and floors (minor younger exceptions)

PETM regolith only preserved on high plateau surface remnants (where locally protected).
PETM entirely absent from river valley flanks and floors (very minor exceptions)

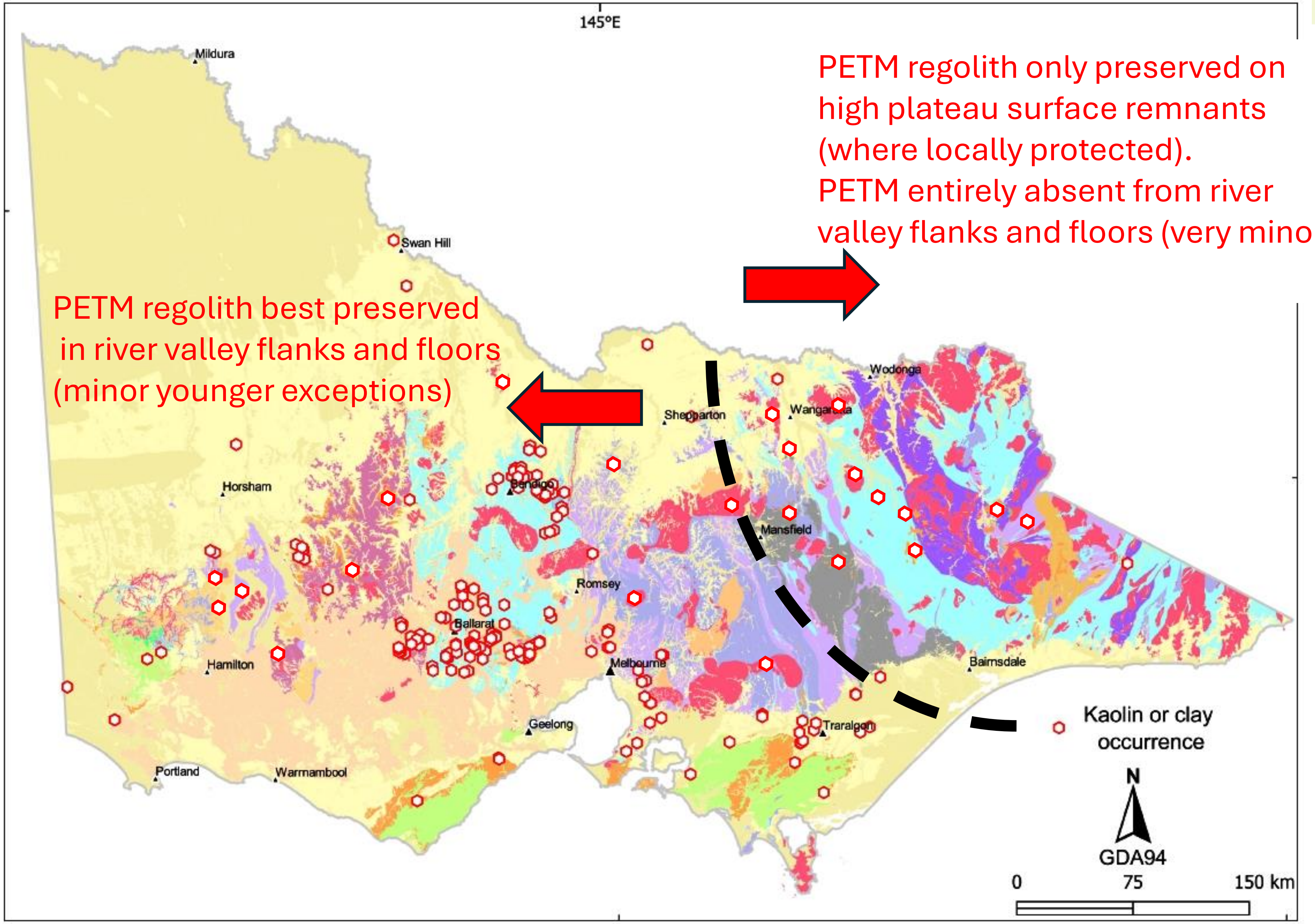
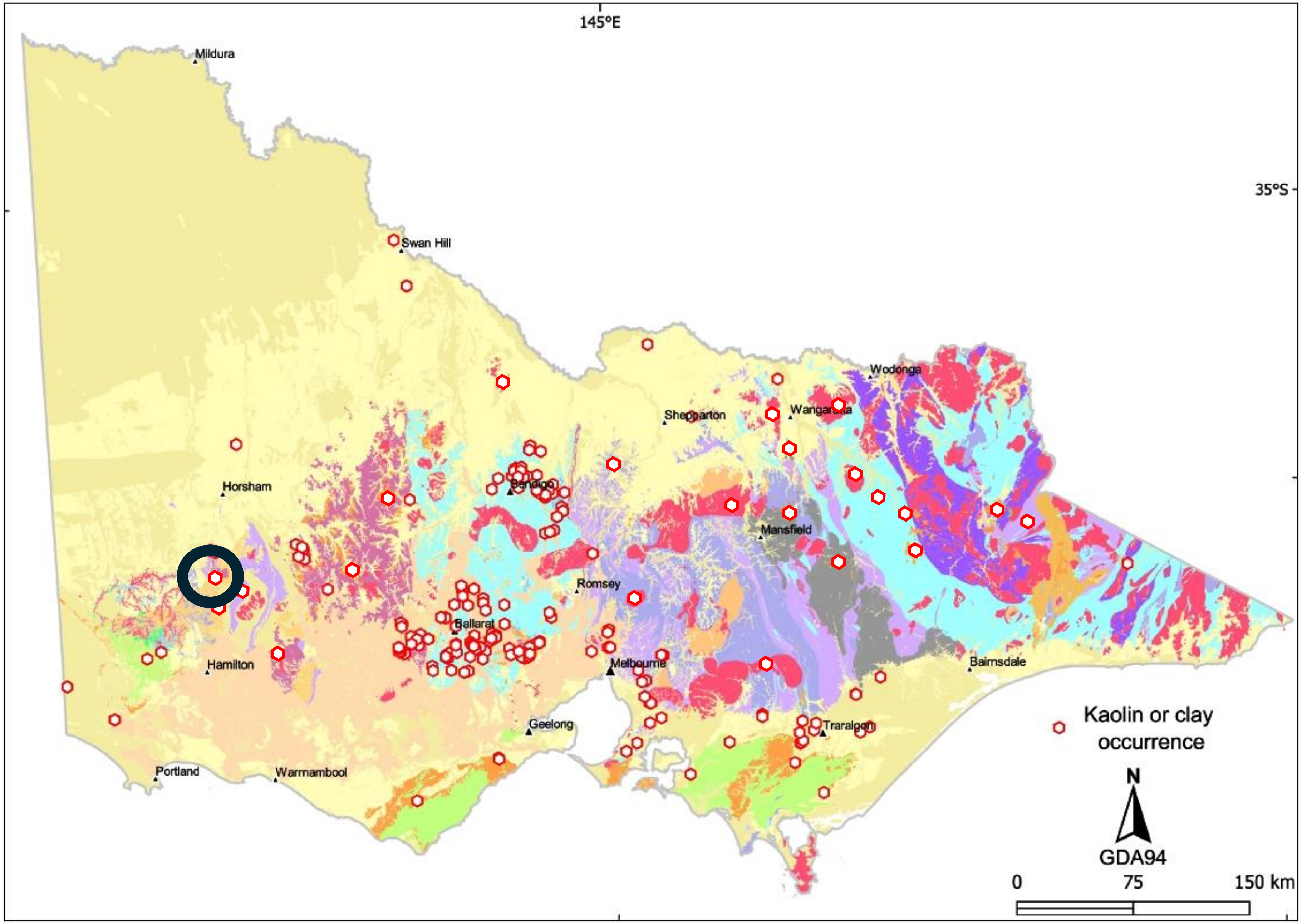


Figure 2.2 Mineral occurrences listing kaolin and clay as the primary production commodity on Victoria's Seamless Geology (simplified after Welch et al., 2011).



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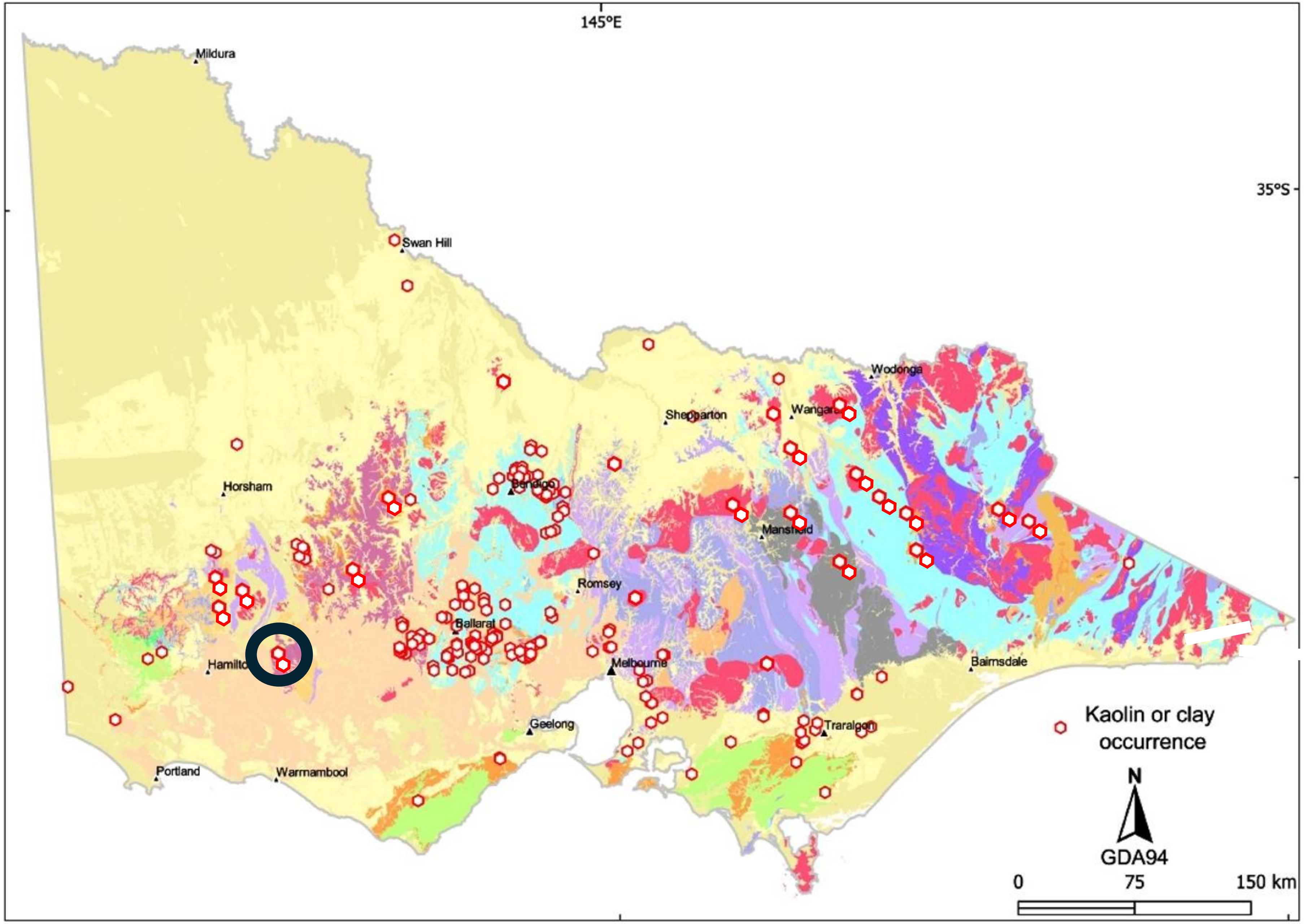
Black Range / Rocklands Reservoir
AESC February 2026



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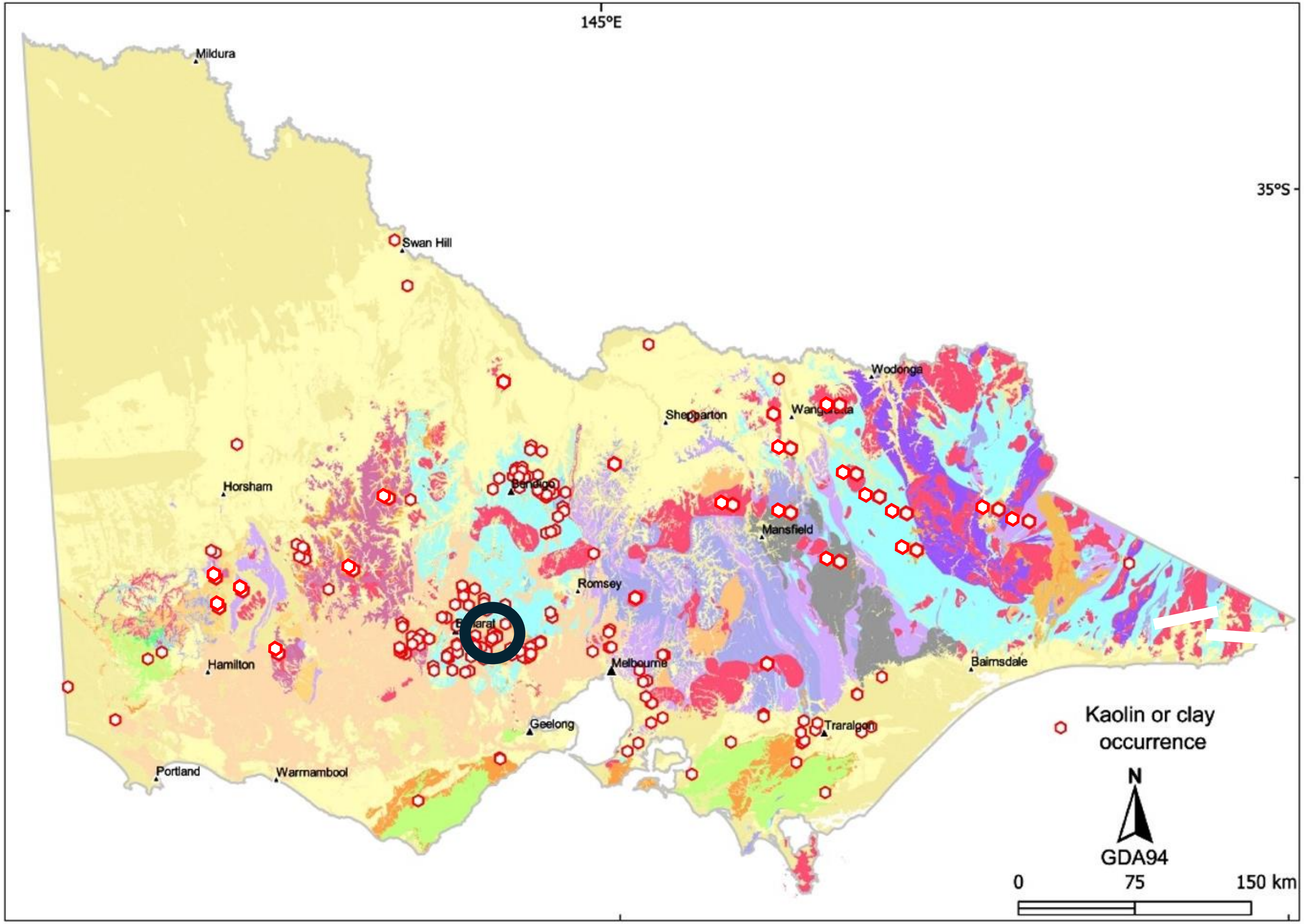
Glenthompson



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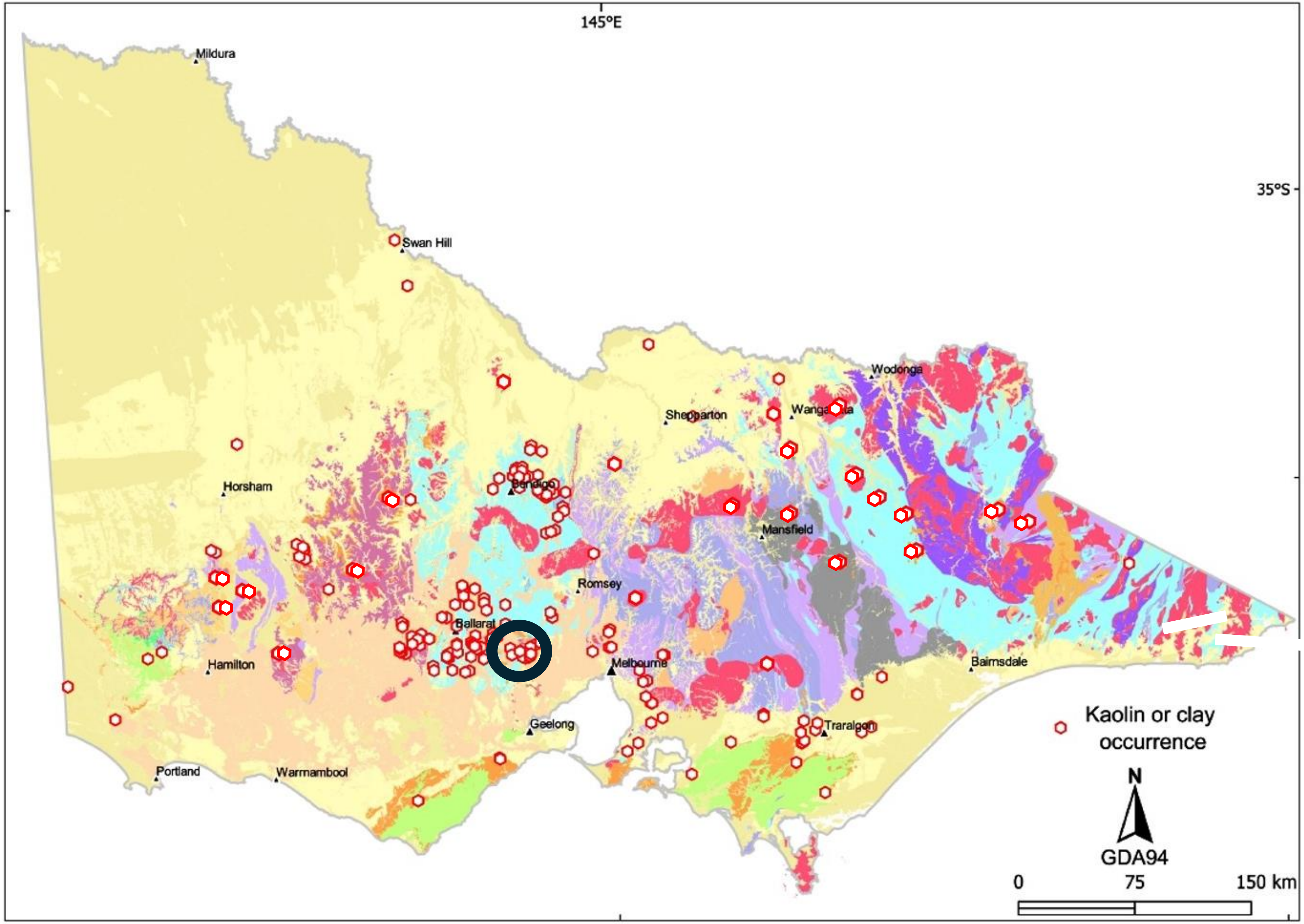
Egerton / Lal Lal



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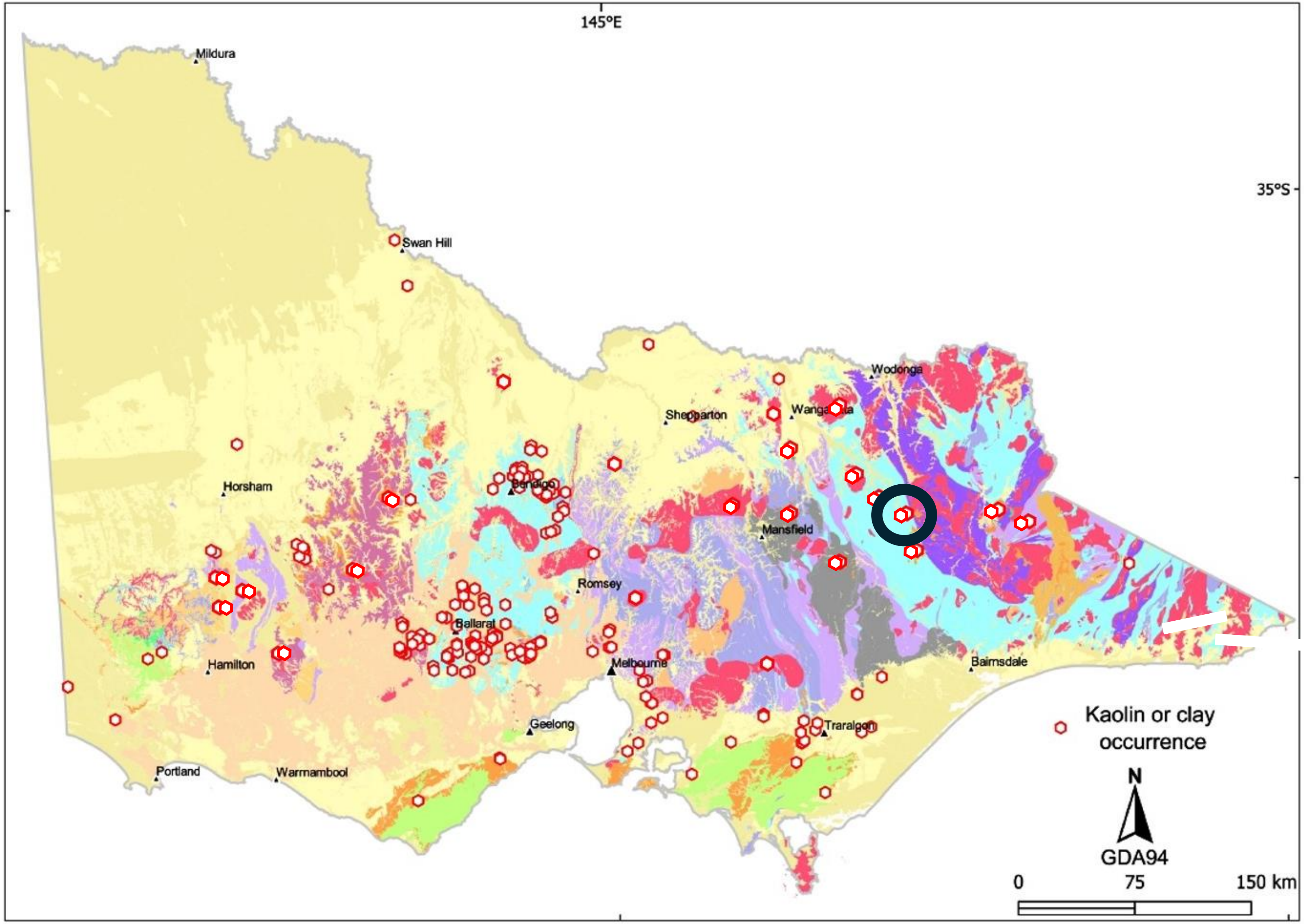
Ingliston Gorge, Bacchus Marsh
(Werribee Formation)



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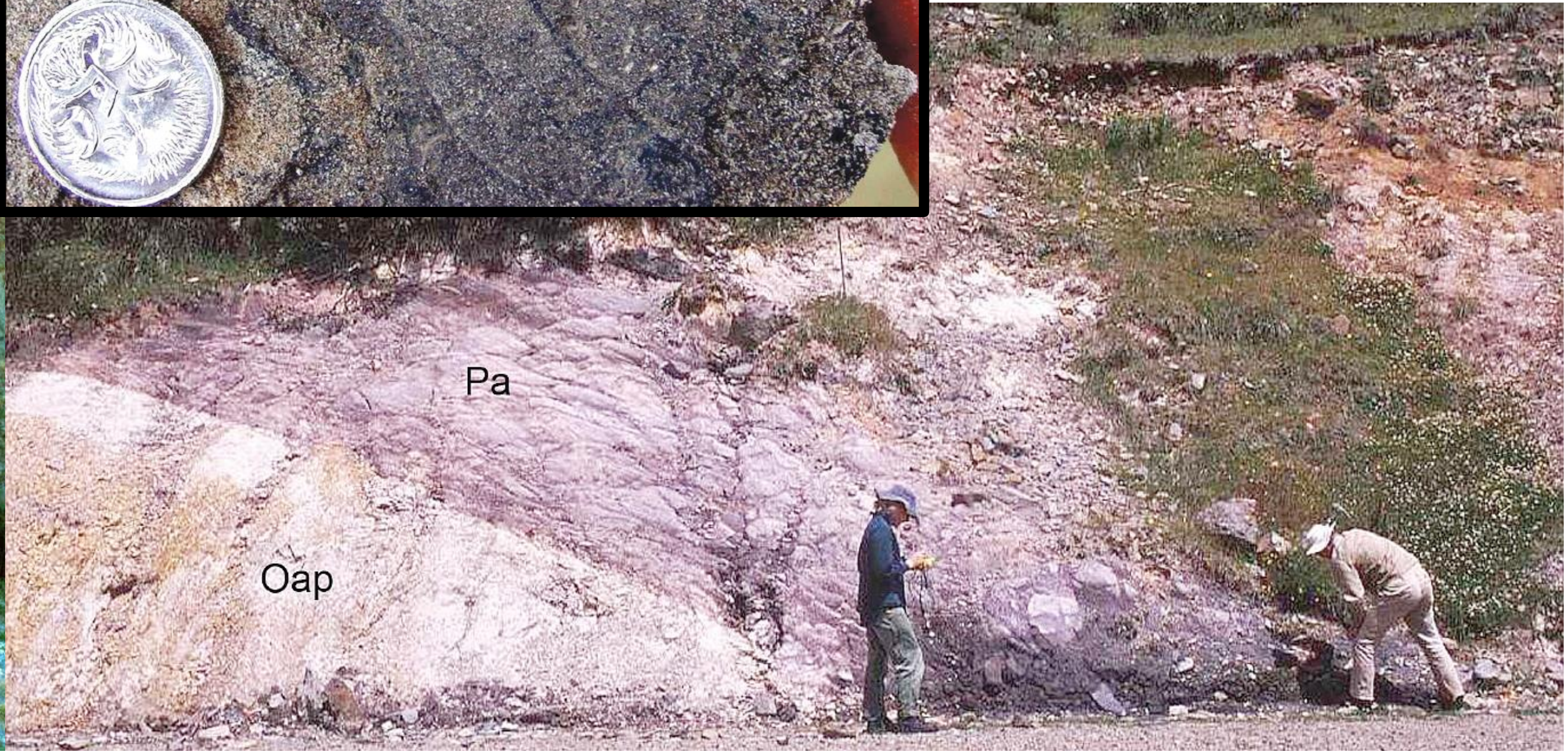
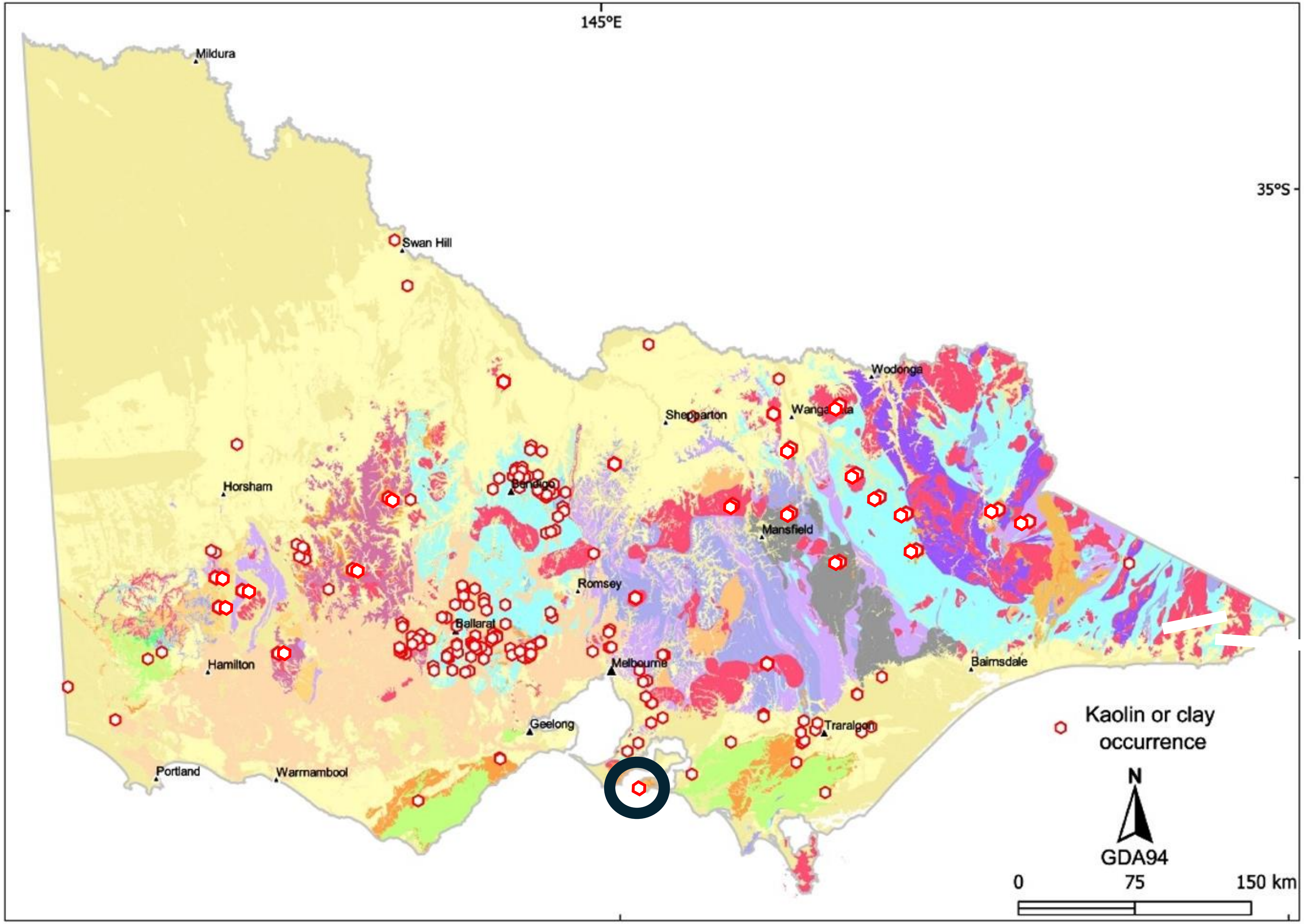
Mount Fainter

Alpine vegetation
(e.g. Greenwood et al., 2017)
implication: plateau uplift
preceded the Paleocene.

Mount Little Higginbotham
(Mt Hotham; Morand et al., 2005)





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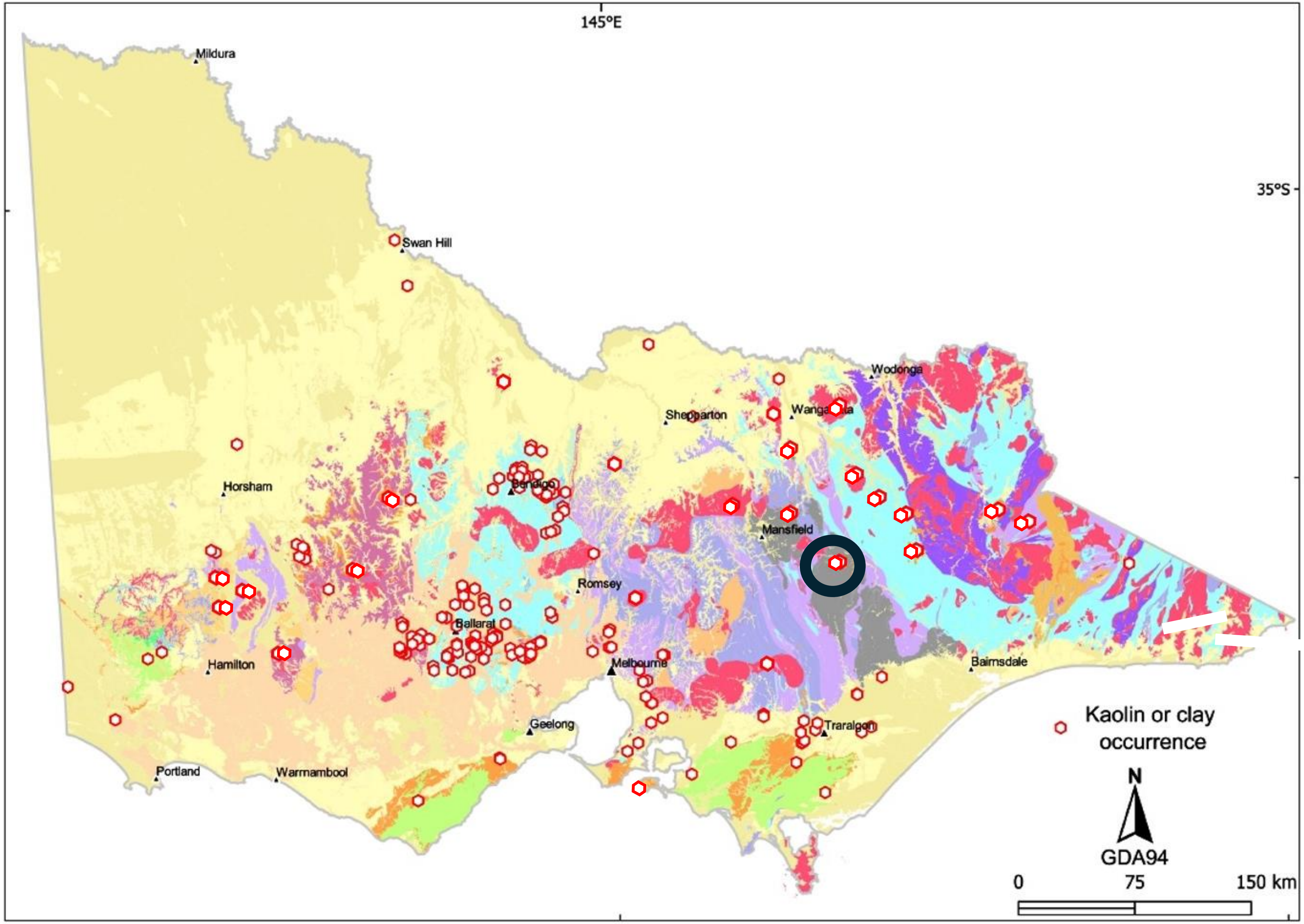
‘The Nobbies’
Phillip Island


Kitty Miller Bay, Phillip Island



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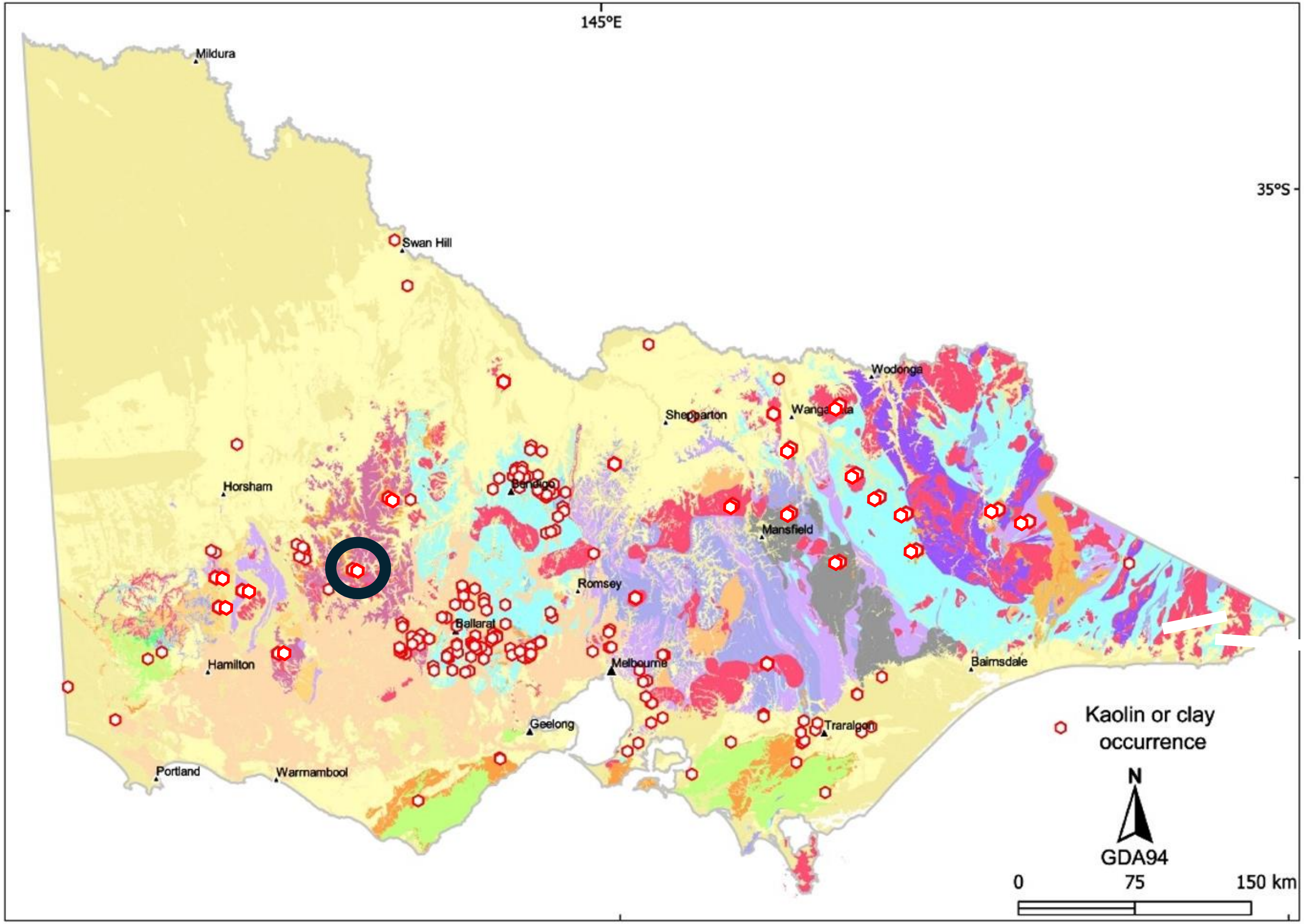
Mount Clear (King Billy in the distance)

Zeolite amygdales
('Eocene Optimum' regolith trace)



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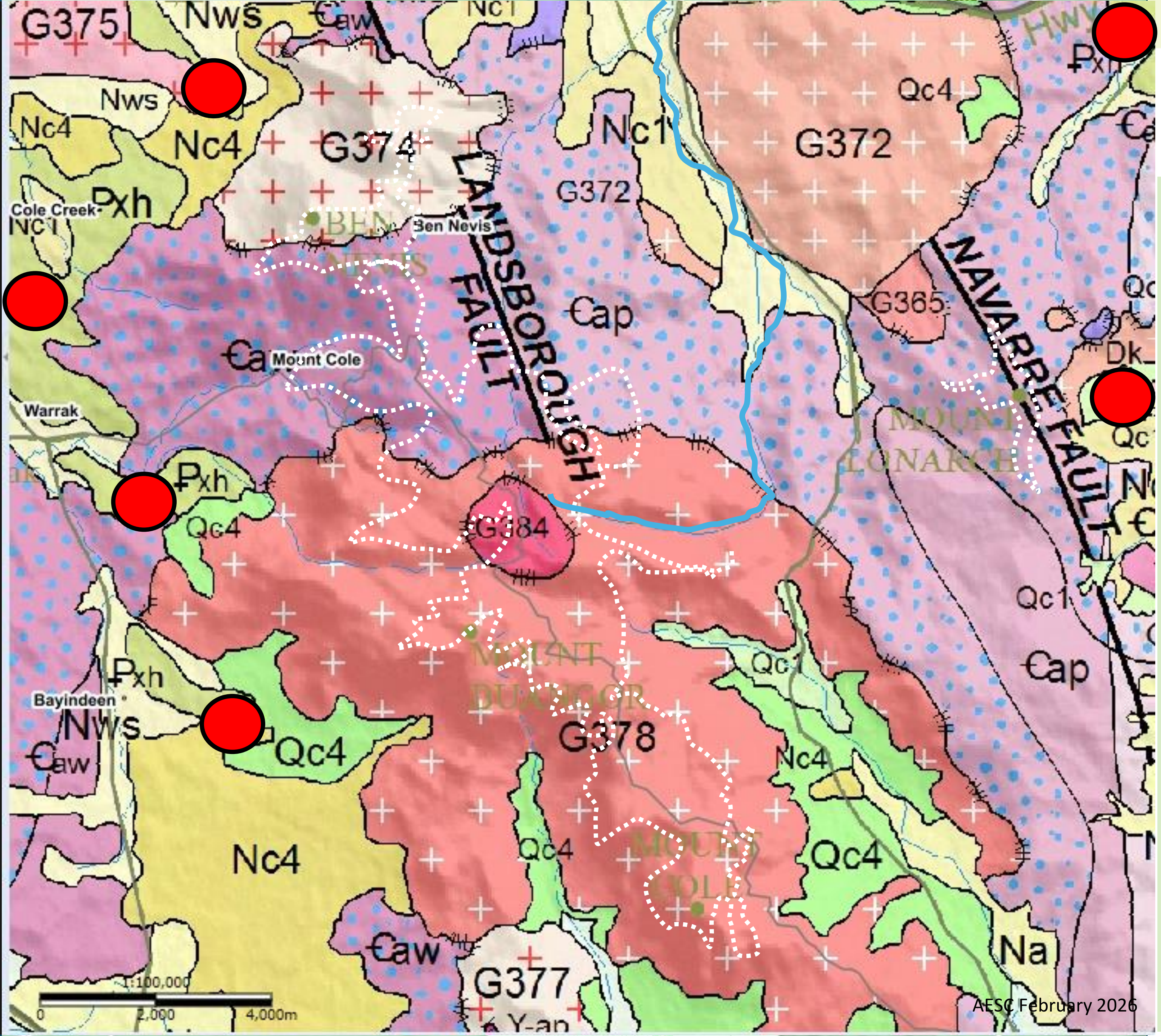
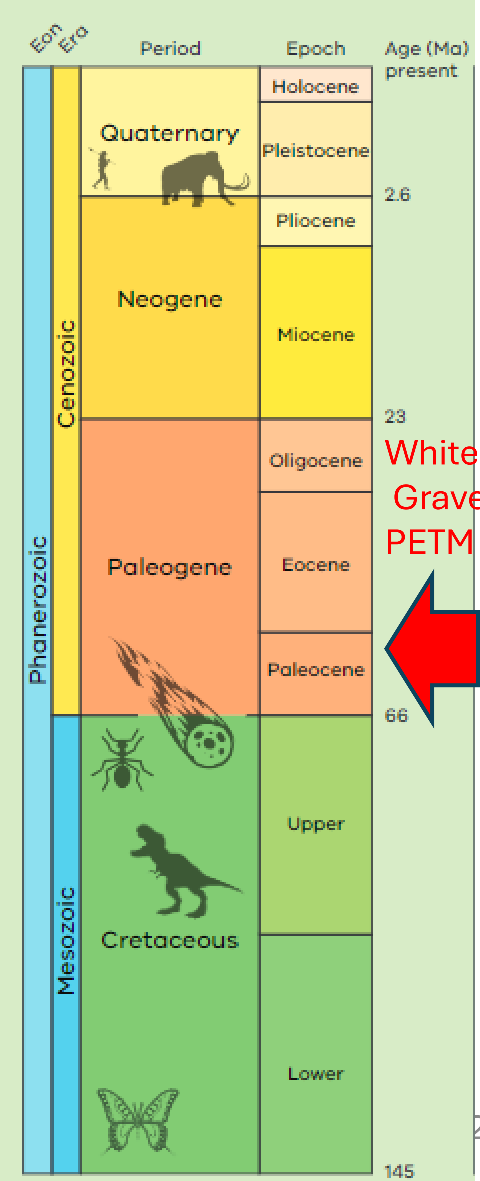
Cayley & McDonald, 1995

Mount Cole / Ben Nevis / Pyrenees Range

remnants of the same ancient, Uplifted alpine land surface, but in Western Victoria





White Hills Gravel

PETM regolith

Cayley & McDonald, 1995

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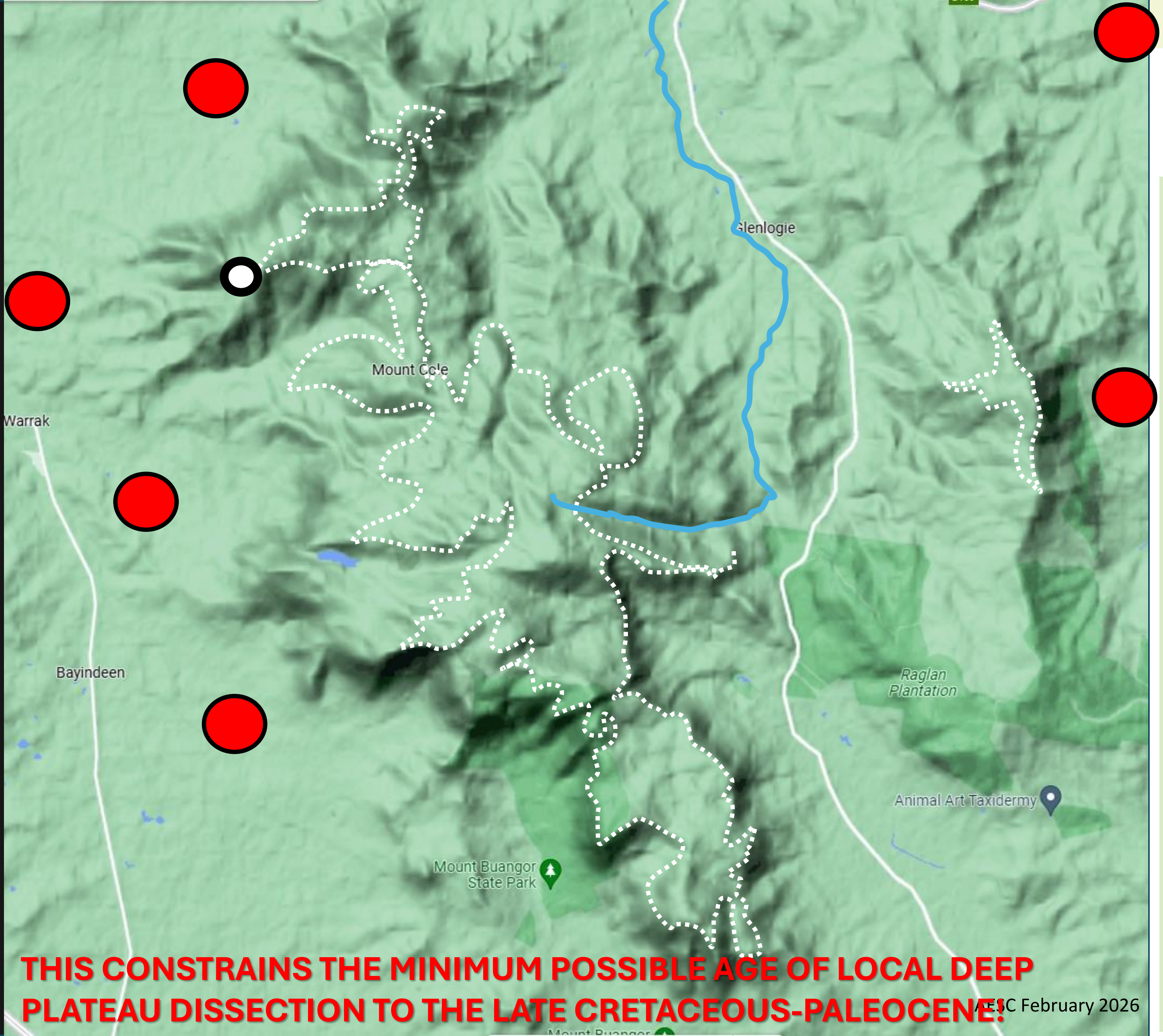
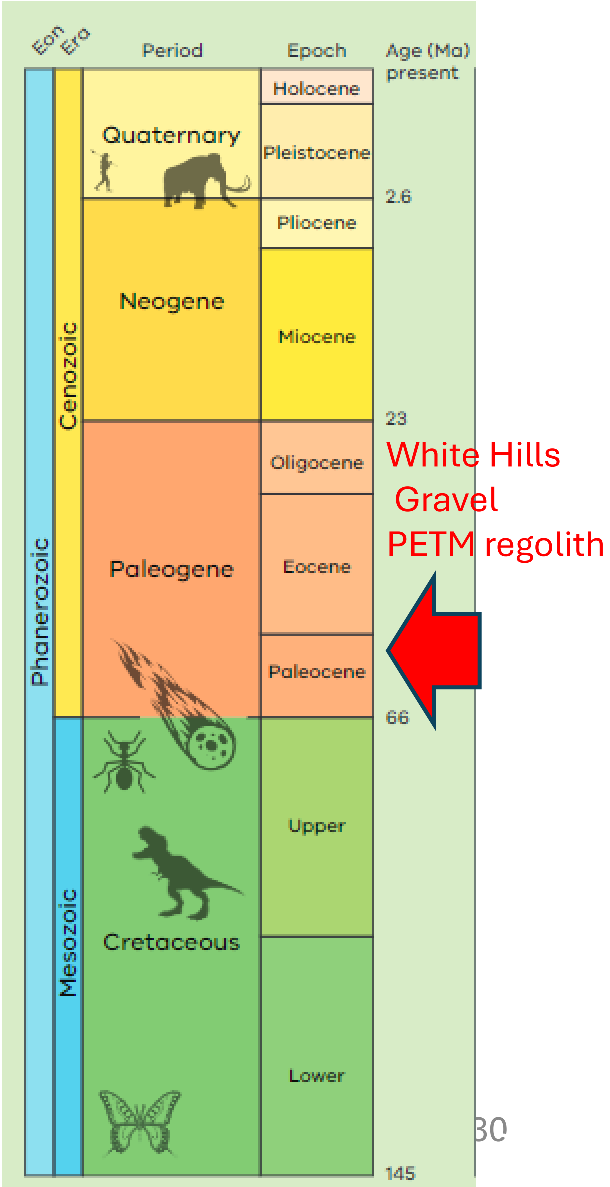
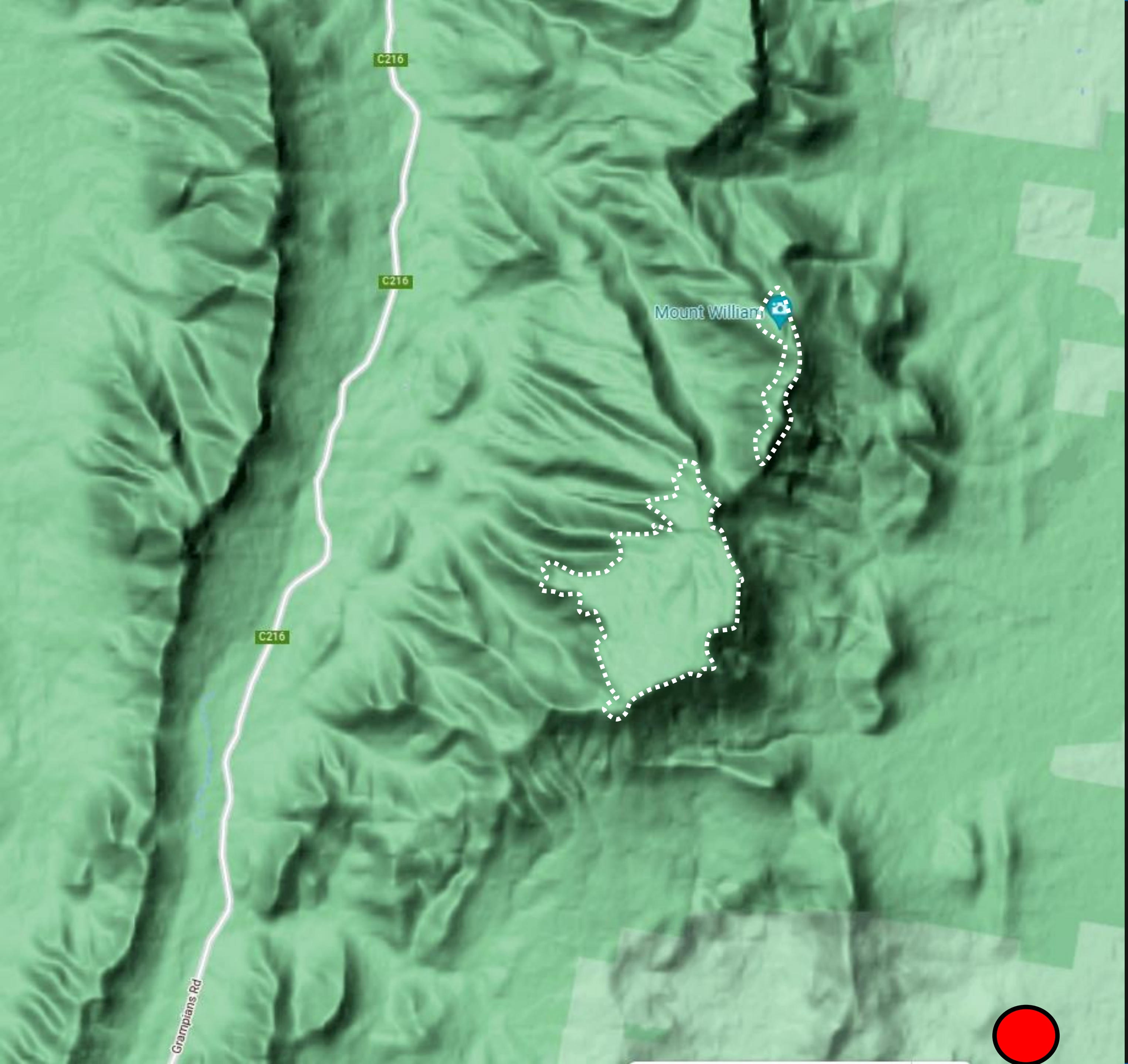




THIS CONSTRAINS THE MINIMUM POSSIBLE AGE OF LOCAL DEEP PLATEAU DISSECTION TO THE LATE CRETACEOUS-PALEOCENE!


Ben Nevis
~ 900m ASL
~ 300m ASL



Gariwerd - Major Mitchell Plateau – one of several remnants of the old uplifted land surface deeply dissected prior to the Paleocene and PETM

Cayley & Taylor, 1997

White Hills Gravel and thick PETM regolith

The deep dissection that dissects and surrounds Mount Cole / Pyrenees / Gariwerd is pre-PETM.
But is there a maximum age constraint for this palaeo-land surface uplift?

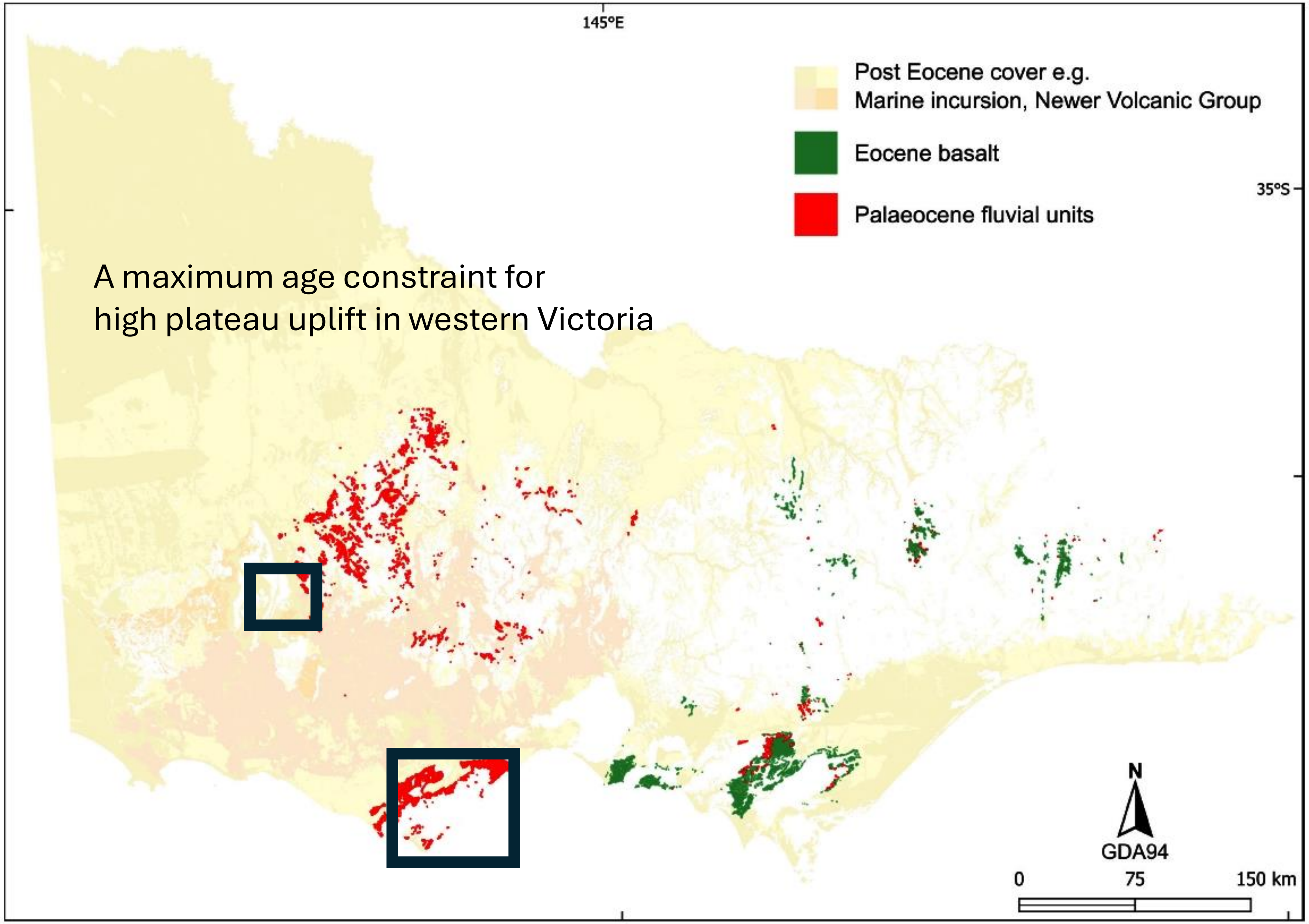
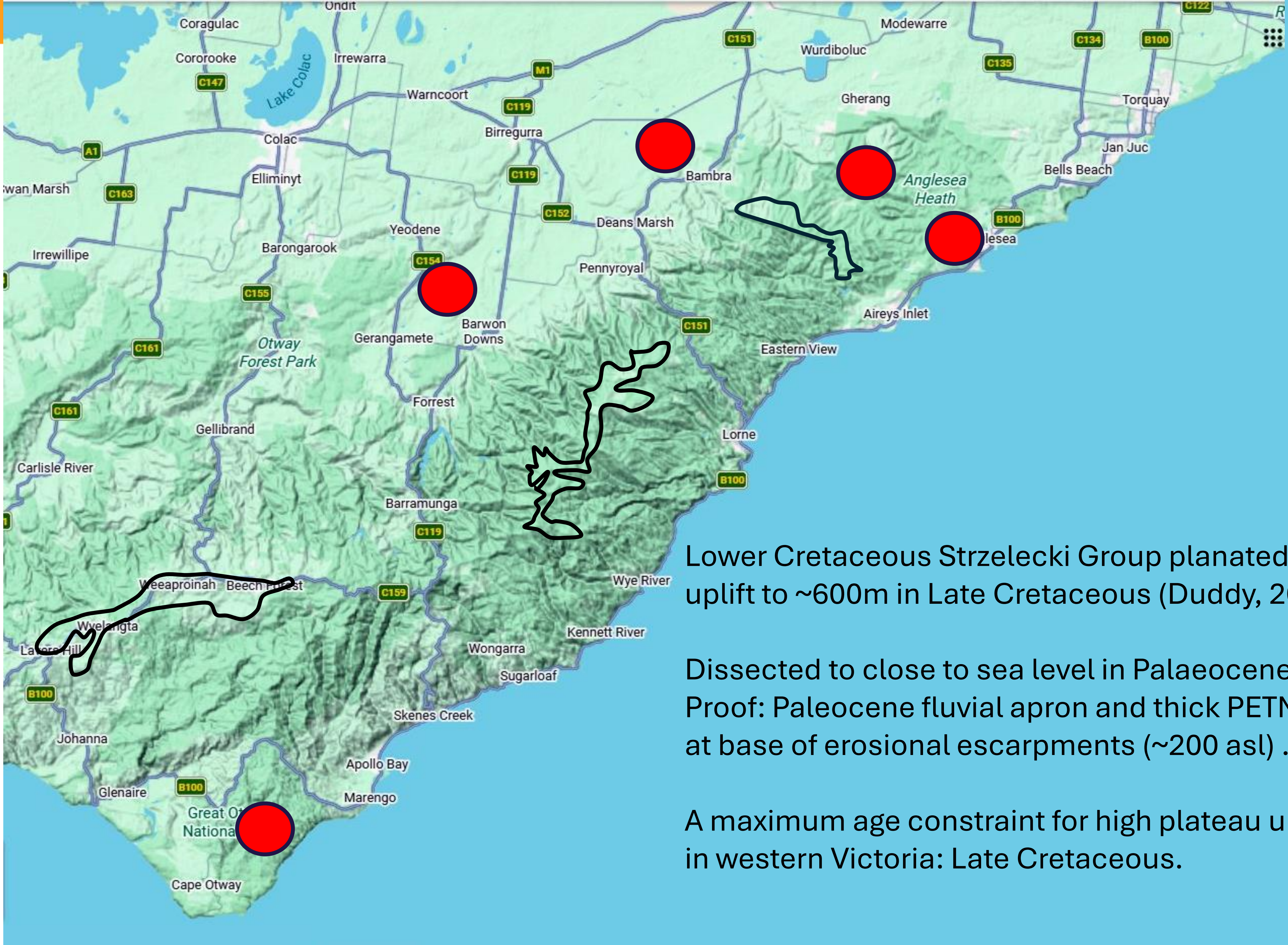


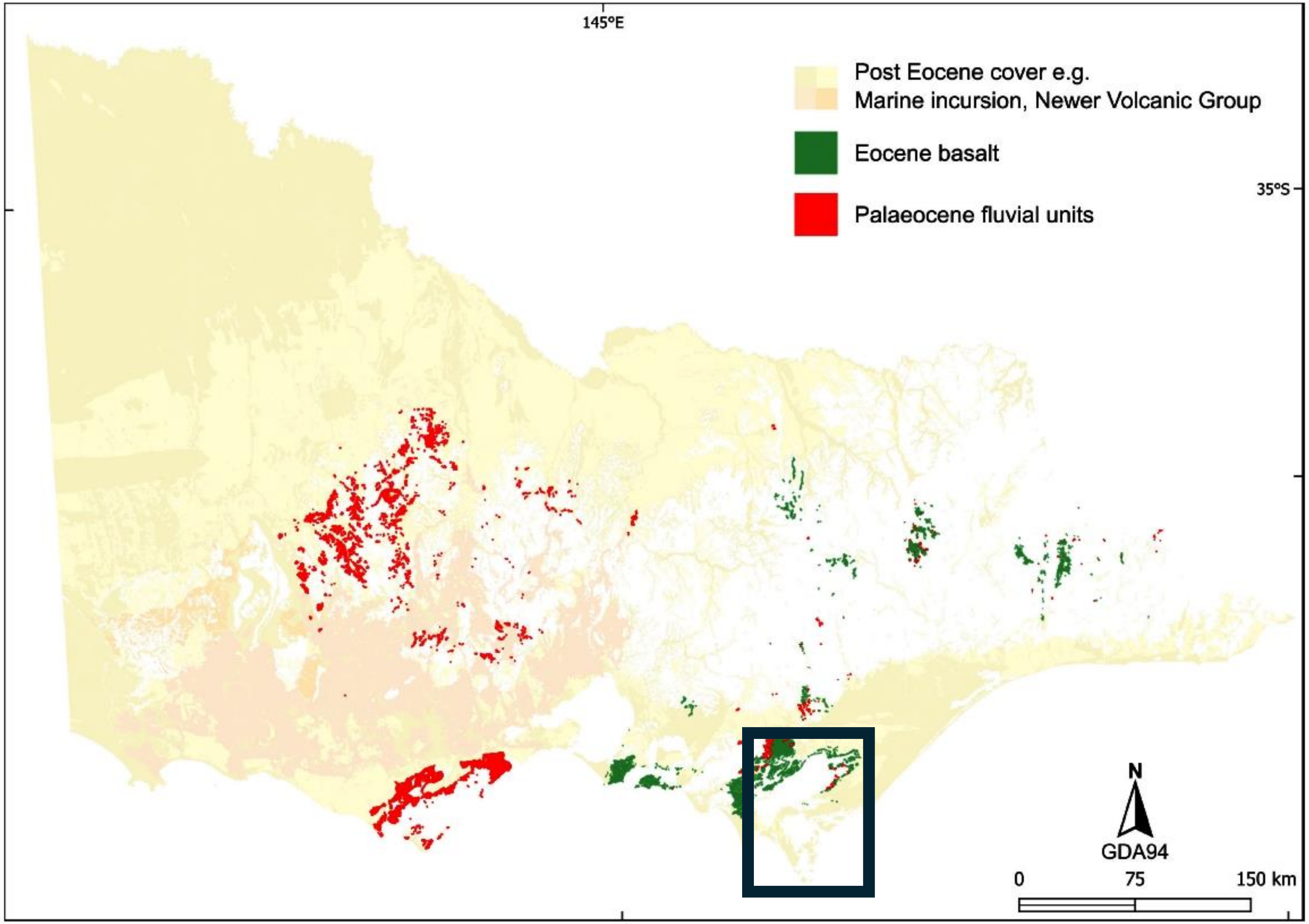
Figure 3.5 Distribution of Palaeocene fluvial, Eocene basalt, and post Eocene units. The Palaeocene fluvial and Eocene basalt deposits are proxies for local preservation of Palaeocene – Eocene thermal maximum regolith, and therefore increased critical minerals in clay prospectivity. Post Eocene units either destroy or overlie Palaeocene – Eocene regolith.



Lower Cretaceous Strzelecki Group planated prior to uplift to ~600m in Late Cretaceous (Duddy, 2003)

Dissected to close to sea level in Palaeocene – Proof: Paleocene fluvial apron and thick PETM profiles at base of erosional escarpments (~200 asl) .

A maximum age constraint for high plateau uplift in western Victoria: Late Cretaceous.



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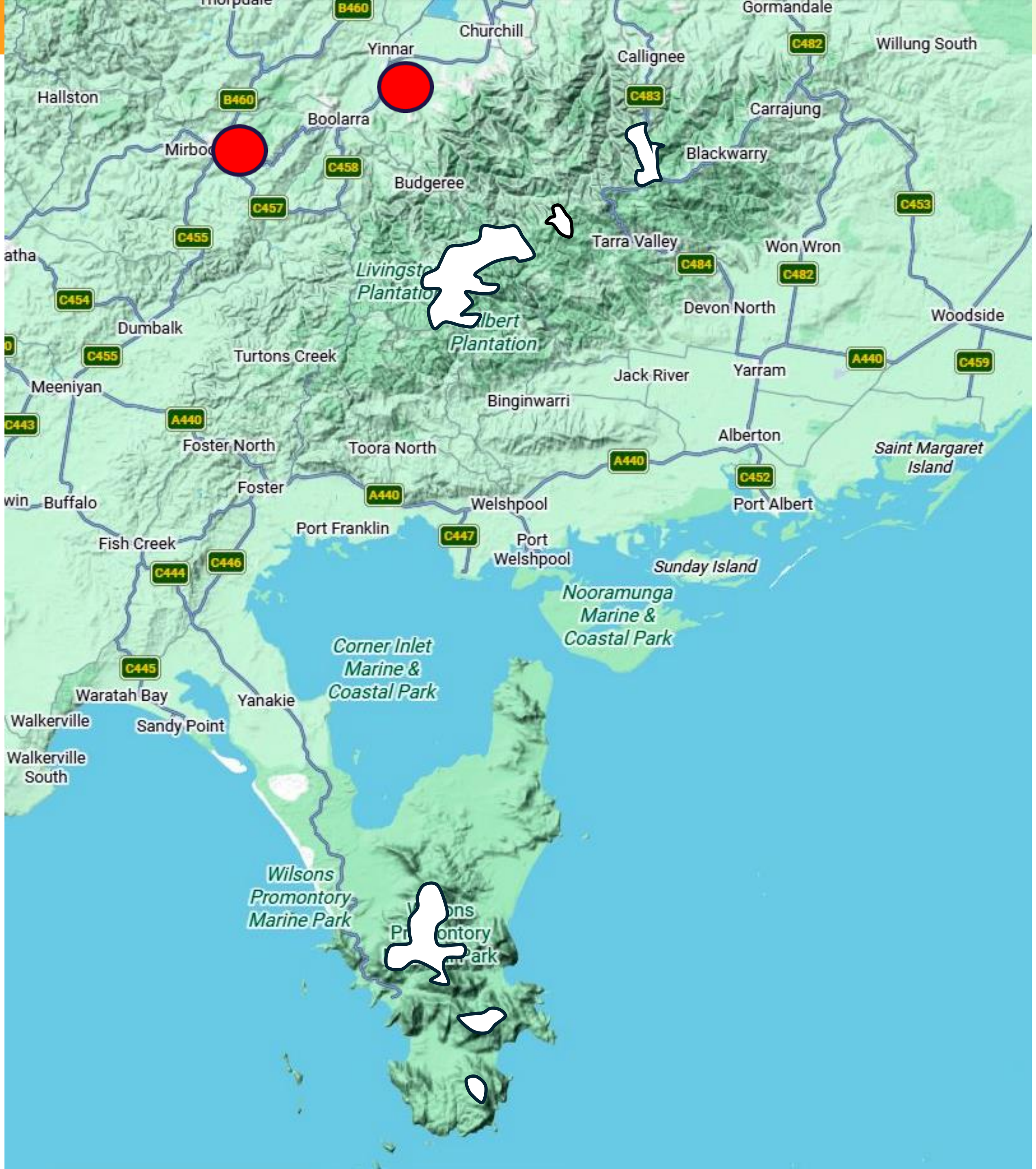

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Profiles at base of erosional escarpments
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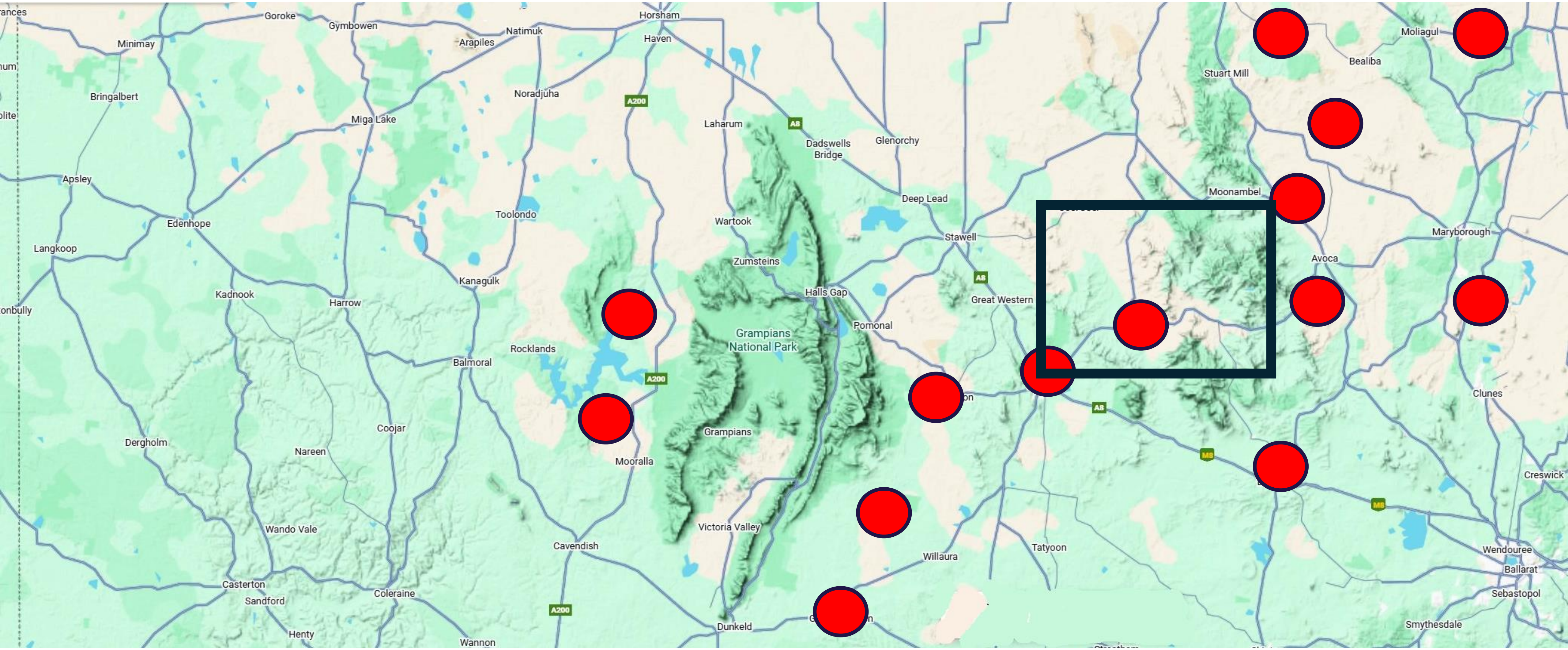
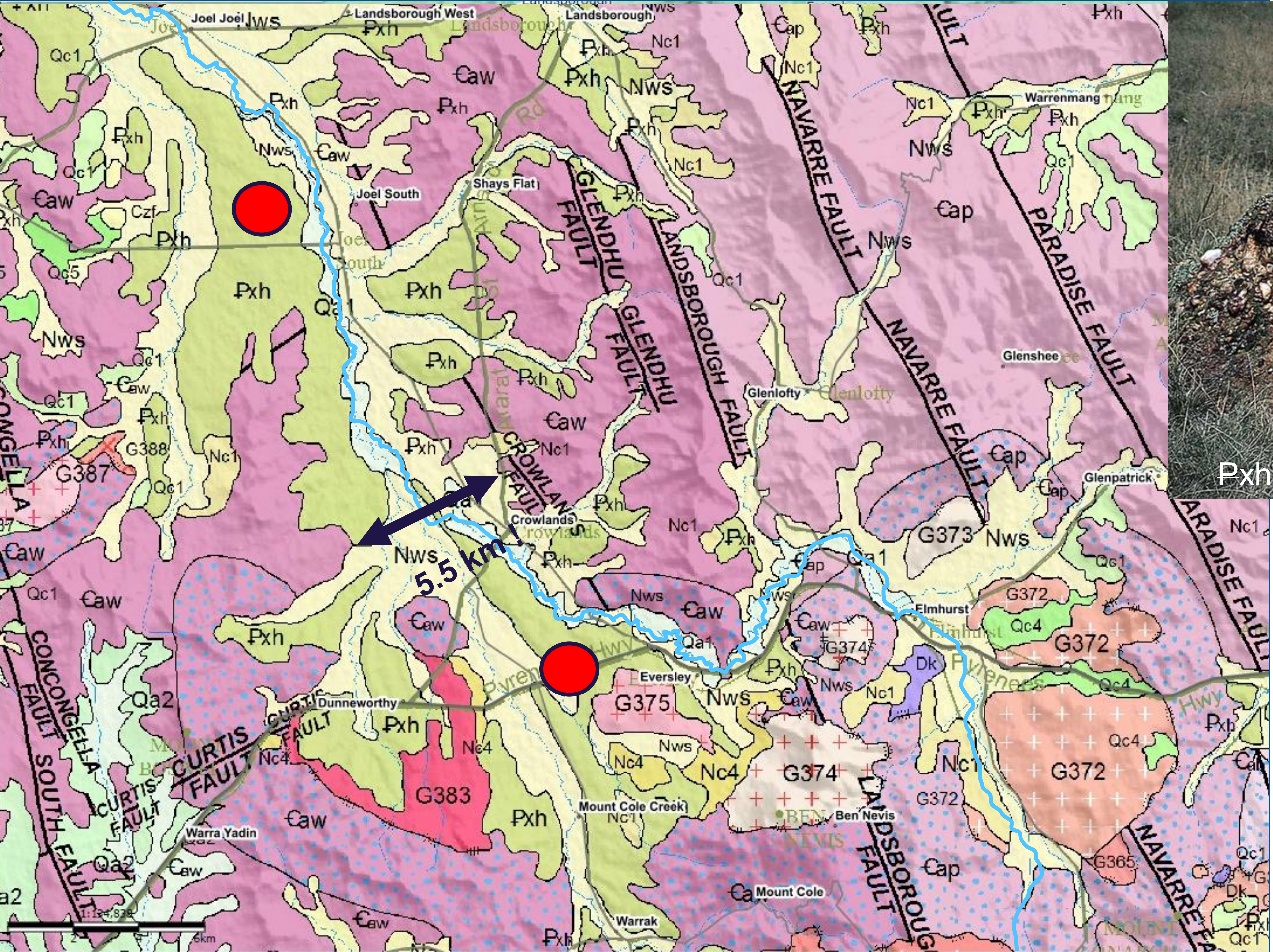
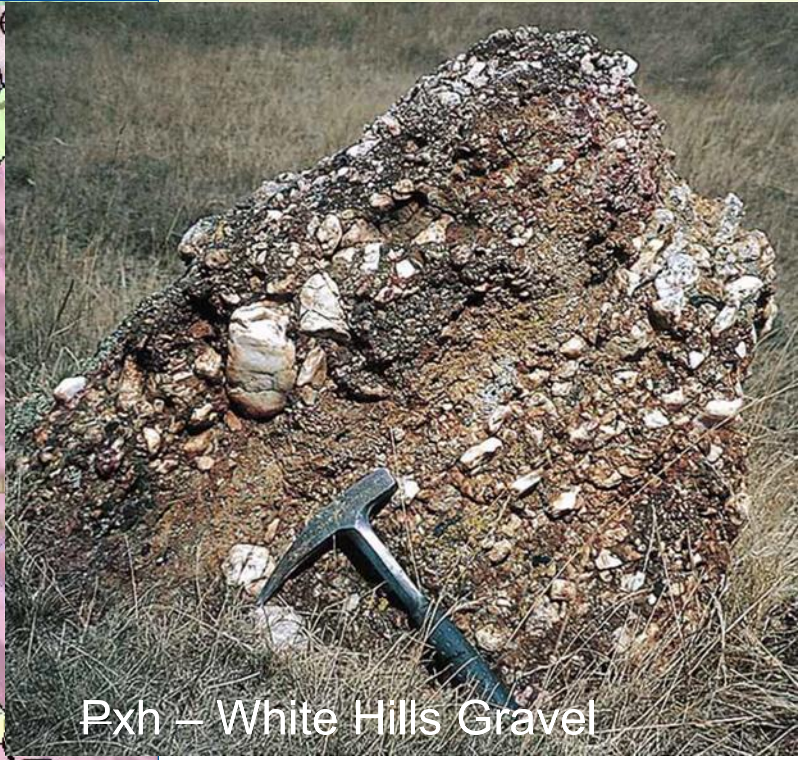
A maximum age constraint for high plateau uplift in southeastern Victoria: Late Cretaceous.

A minimum age constraint for high plateau uplift and deep dissection in southeastern Victoria: Palaeocene (pre-PETM).



Paleocene fluvial 'White Hills Gravel' overprinted in-situ by deep PETM regolith





The modern Wimmera River
Tiny, ephemeral.

Massively underfit in its valley

Conclusions:

western Victoria was WET in the Paleocene!

Erosion of the uplifted high plateau was rapid and aggressive.

Paleocene rivers were wide and highly energetic and eroded broad, mature braidplain valleys.

The modern rivers are all underfit.

Plateau erosion has barely advanced since the Eocene.

Why and how did this change?

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The Victorian Alps are different: pre-Palaeocene uplift, but little Paleocene erosion

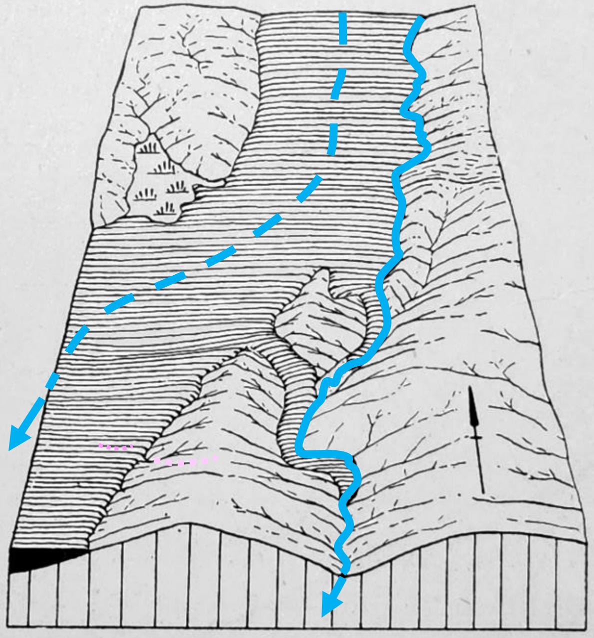
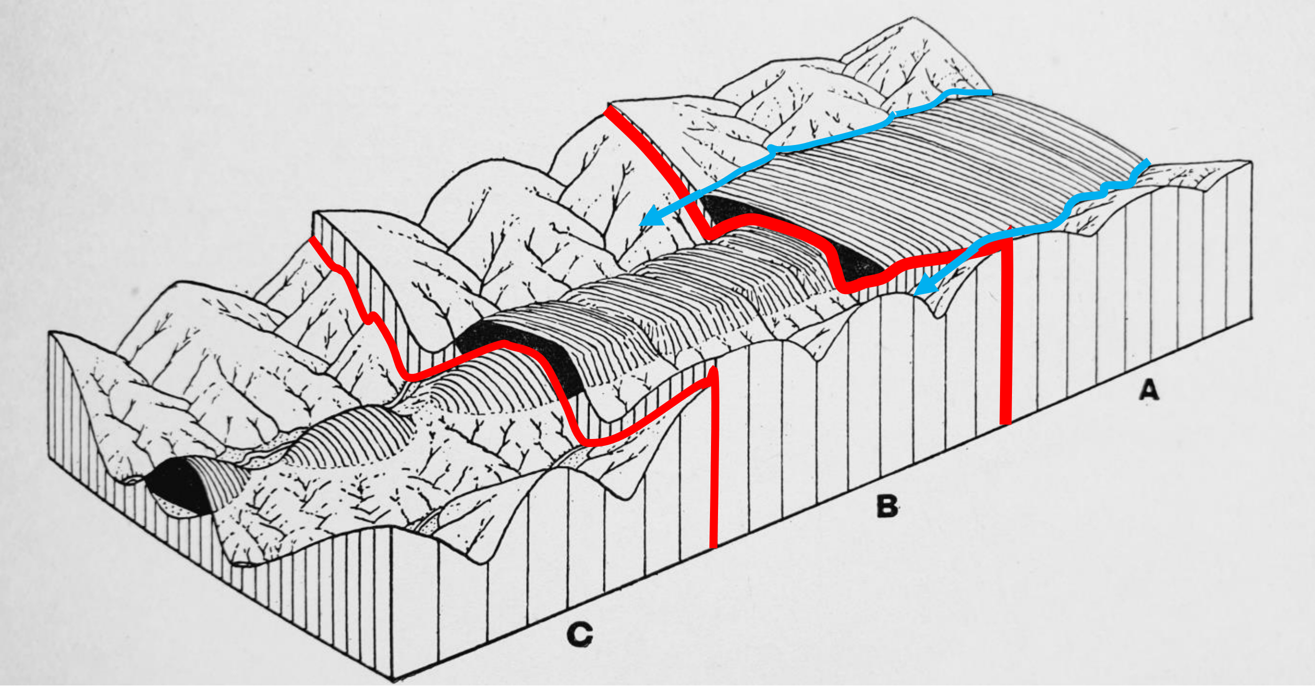


Fig. 259—Block diagram showing the diversion of the Plenty River from its lava-filled valley, at South Morang. [*After Jutson*



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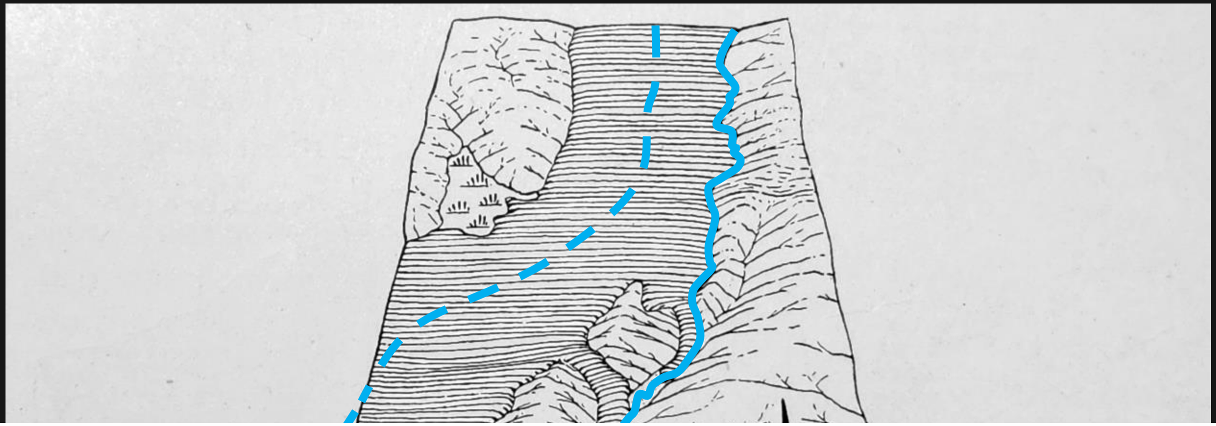
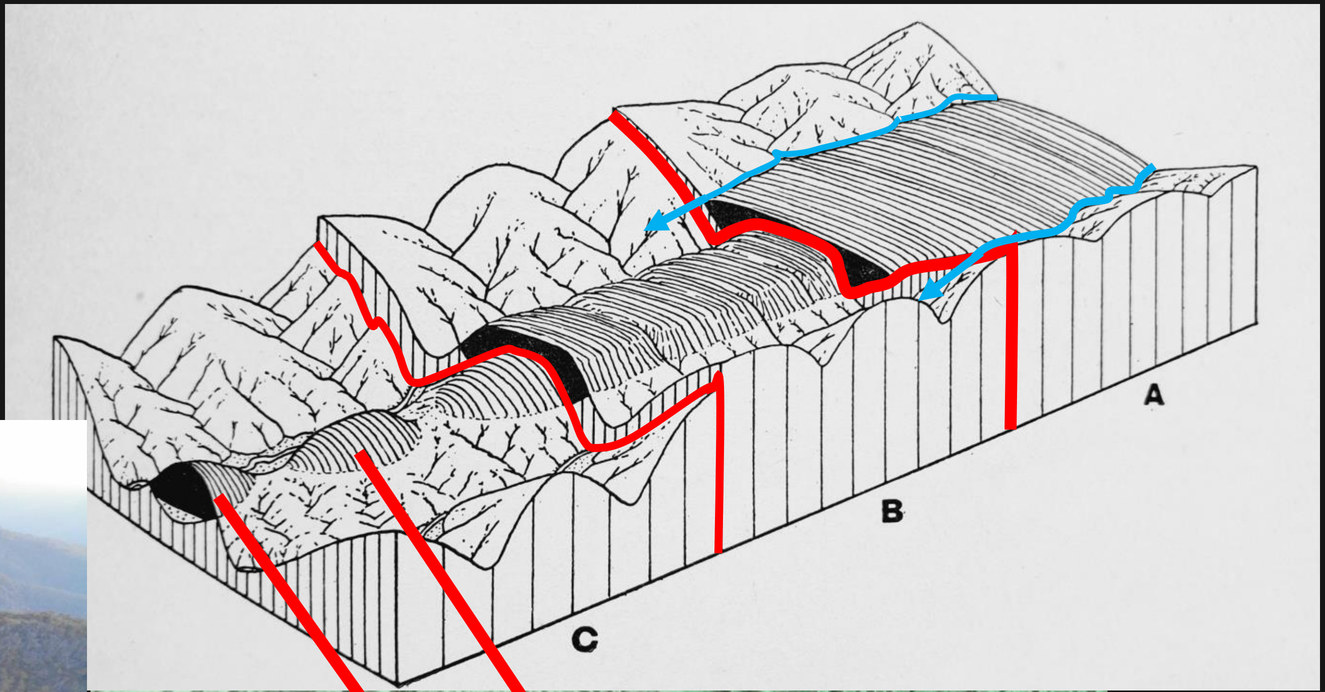
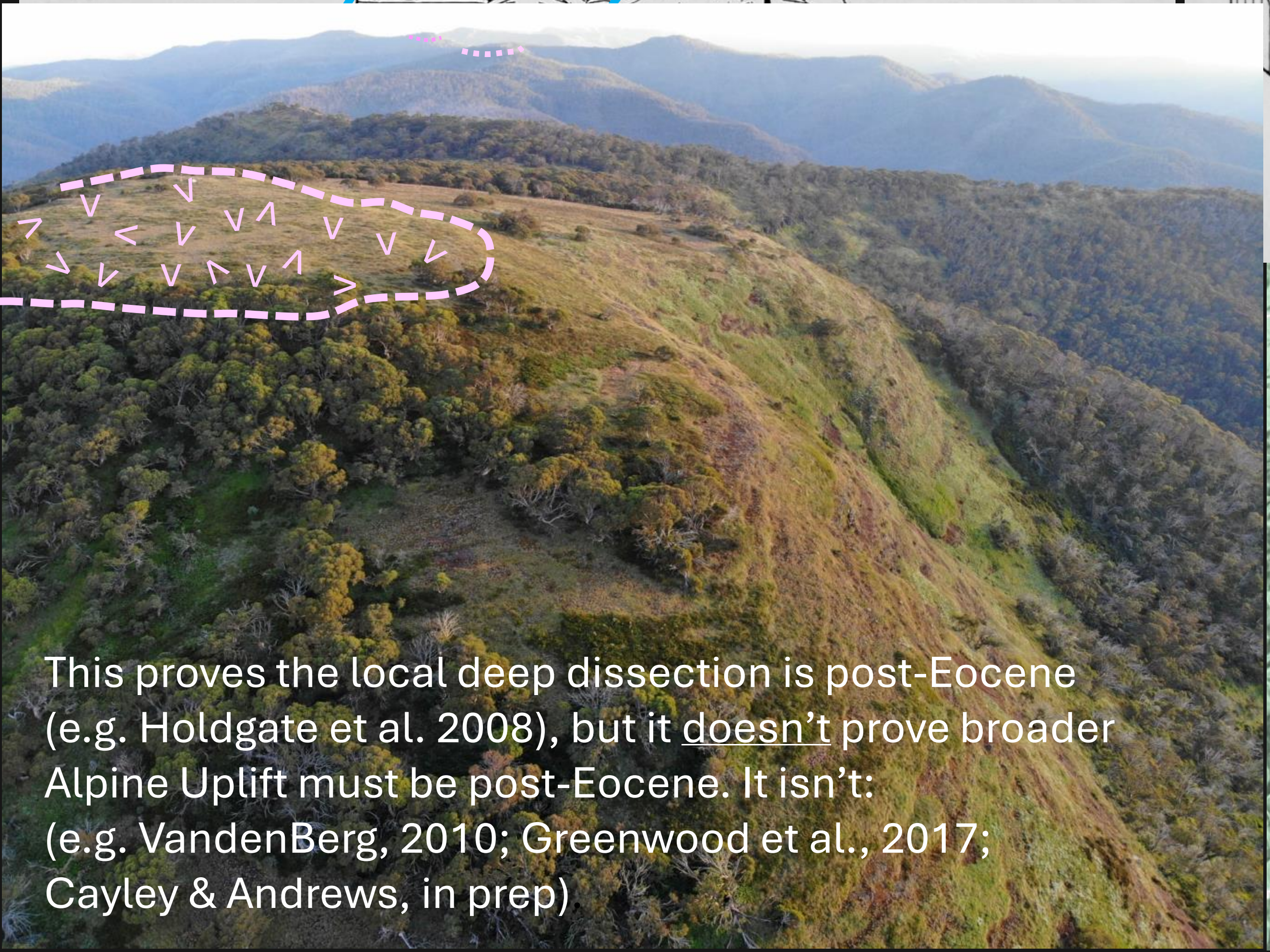
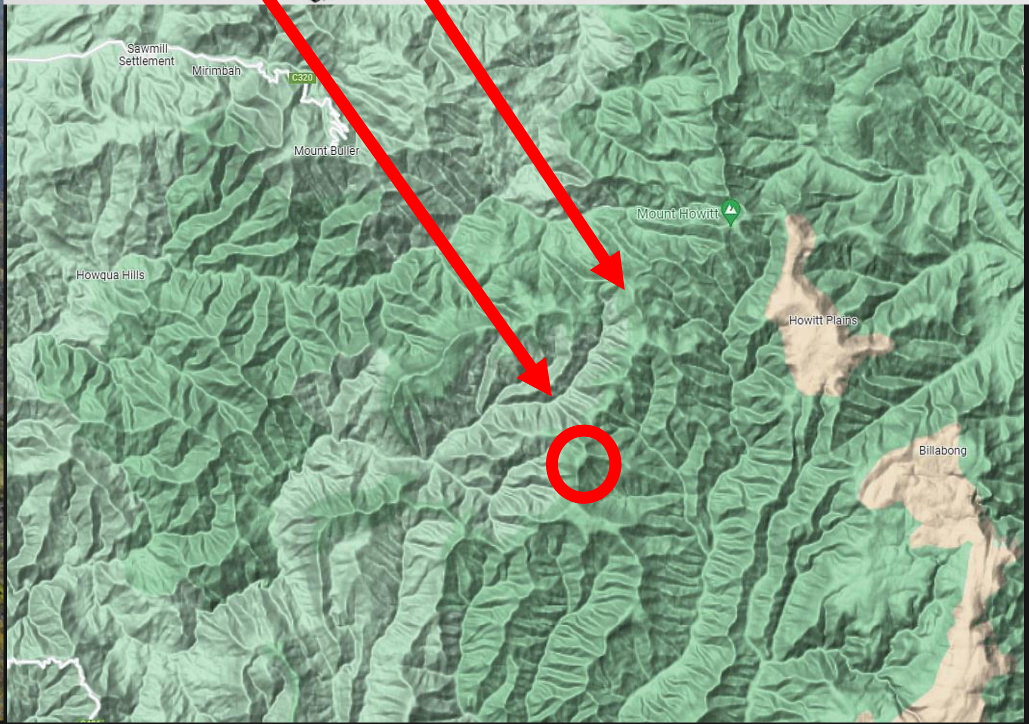


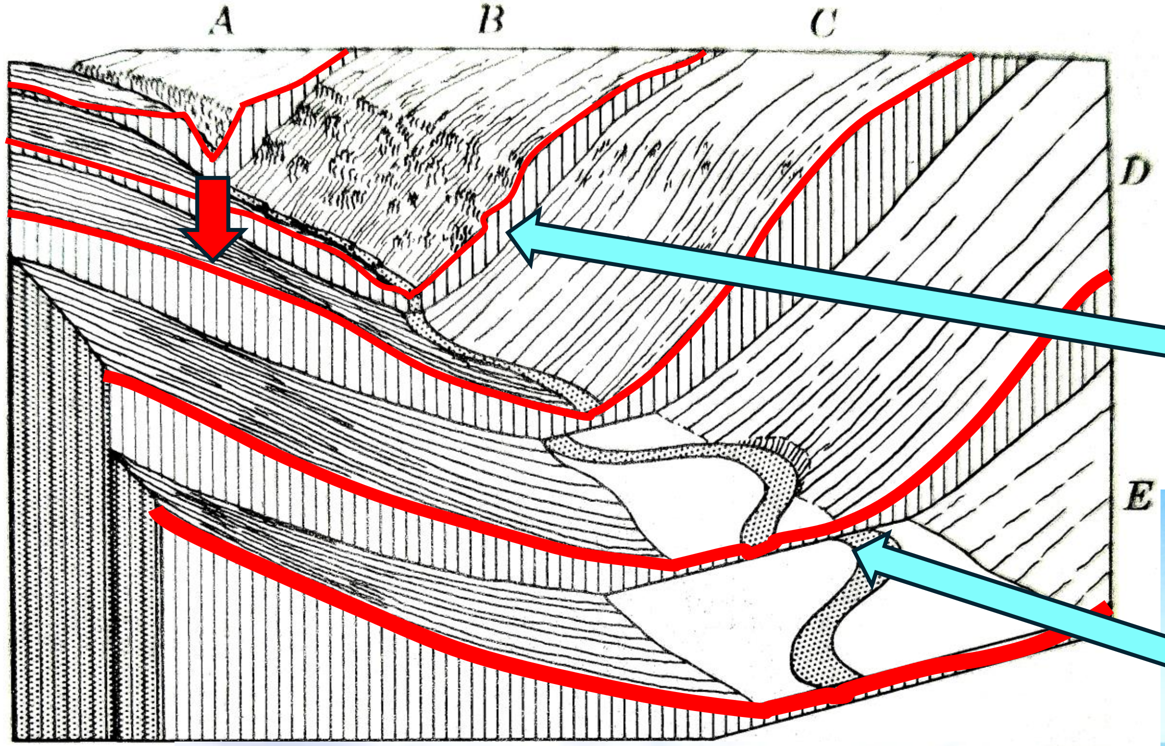




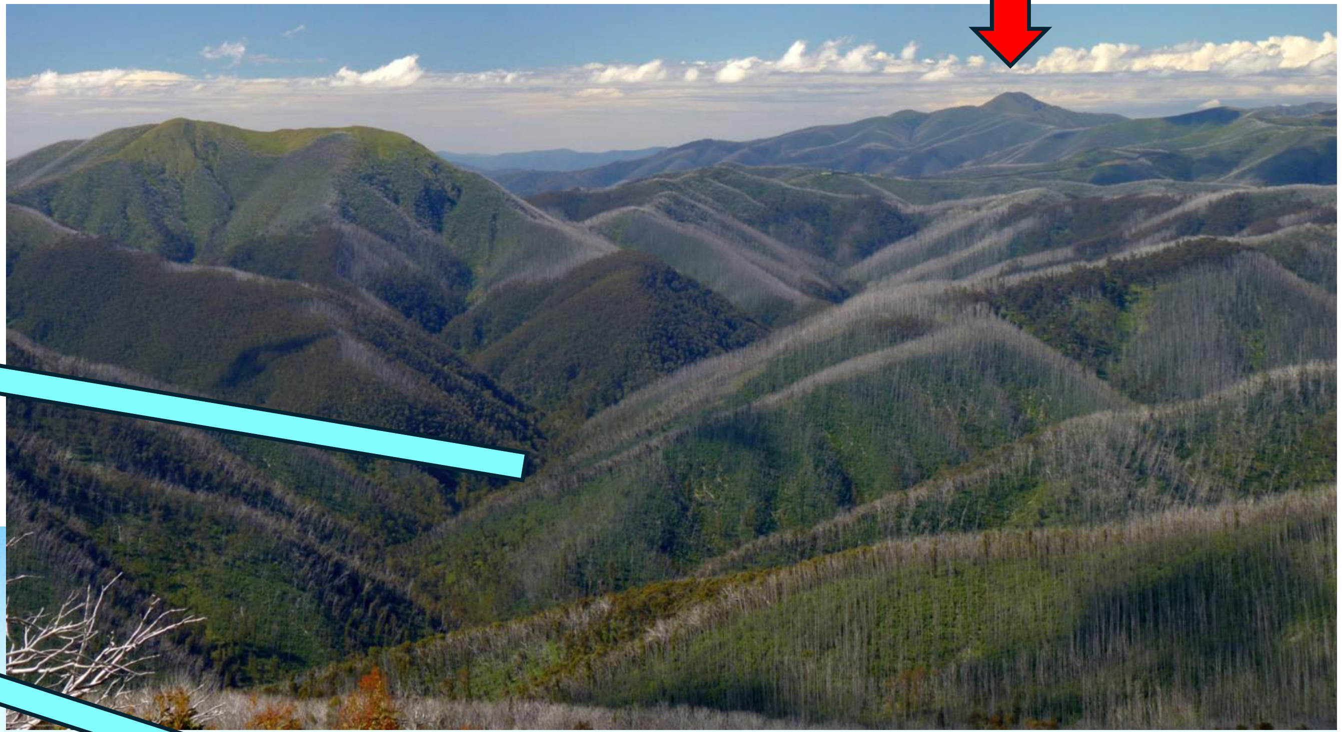
This proves the local deep dissection is post-Eocene (e.g. Holdgate et al. 2008), but it doesn't prove broader Alpine Uplift must be post-Eocene. It isn't:
(e.g. VandenBerg, 2010; Greenwood et al., 2017; Cayley & Andrews, in prep)

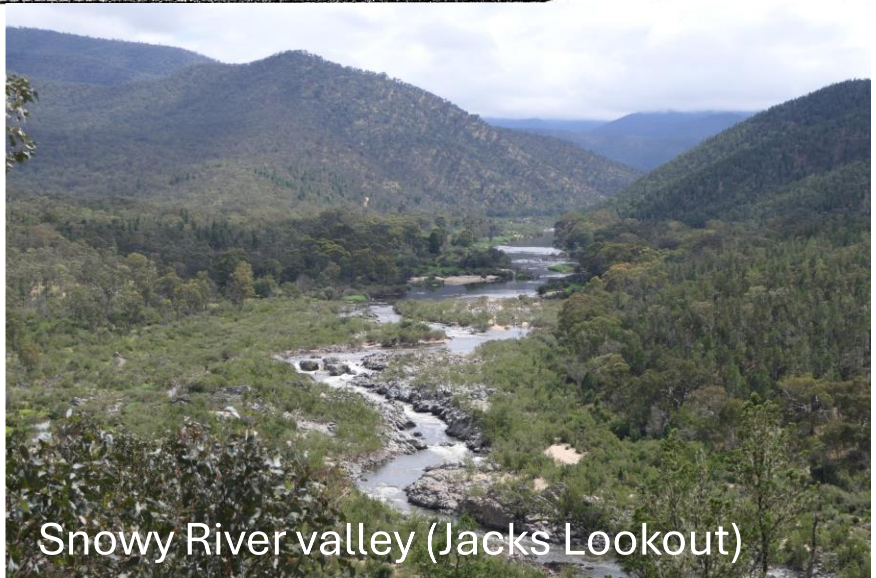


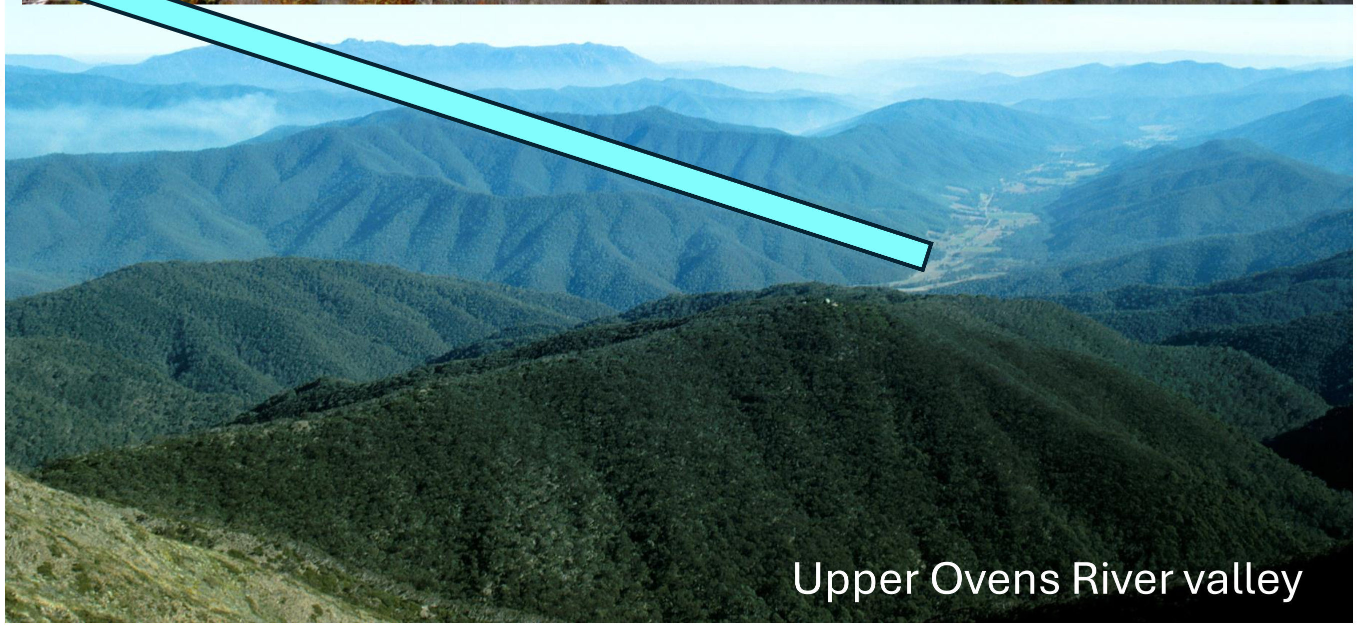
Strahler, 1951



Mount Feathertop







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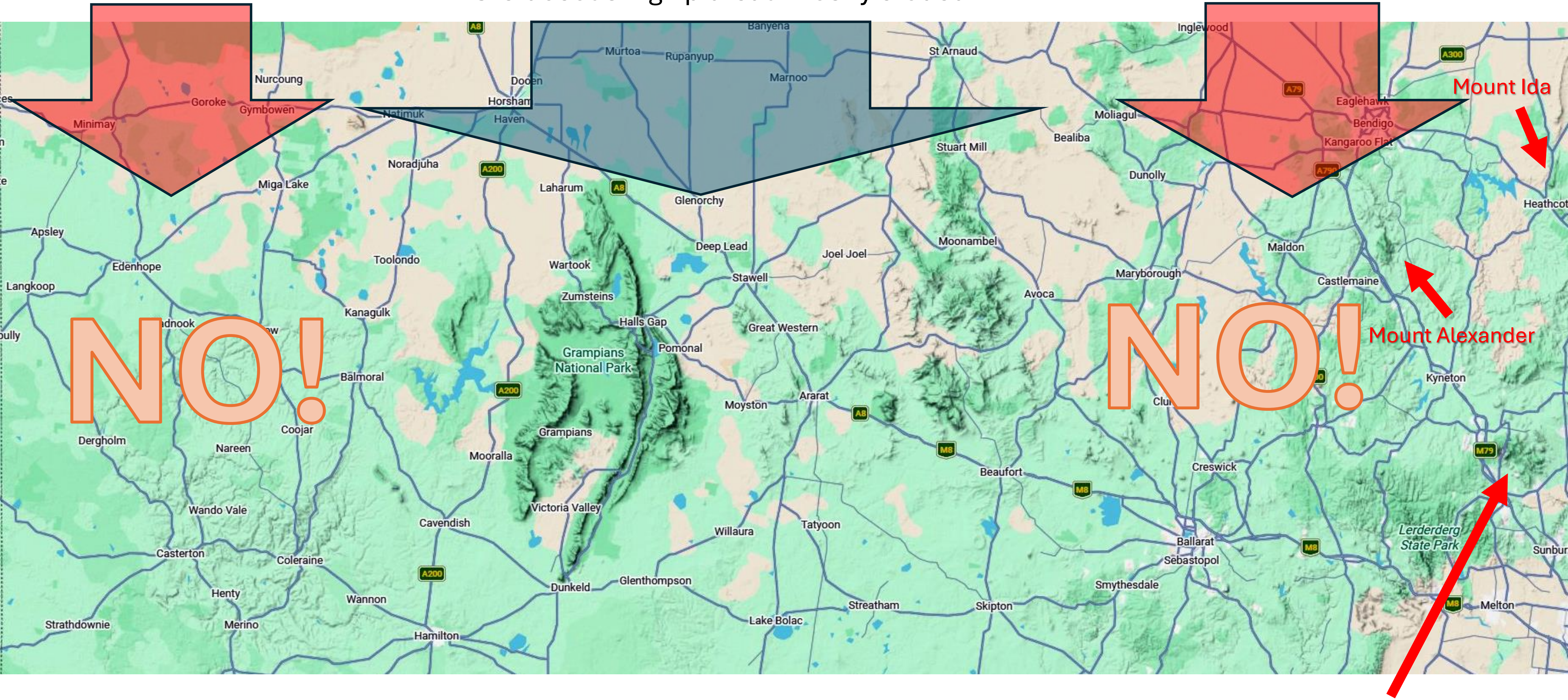
Cretaceous high plateau entirely eroded?

Cretaceous high plateau mostly eroded

Cretaceous high plateau entirely eroded?



Cayley & Andrews, in prep

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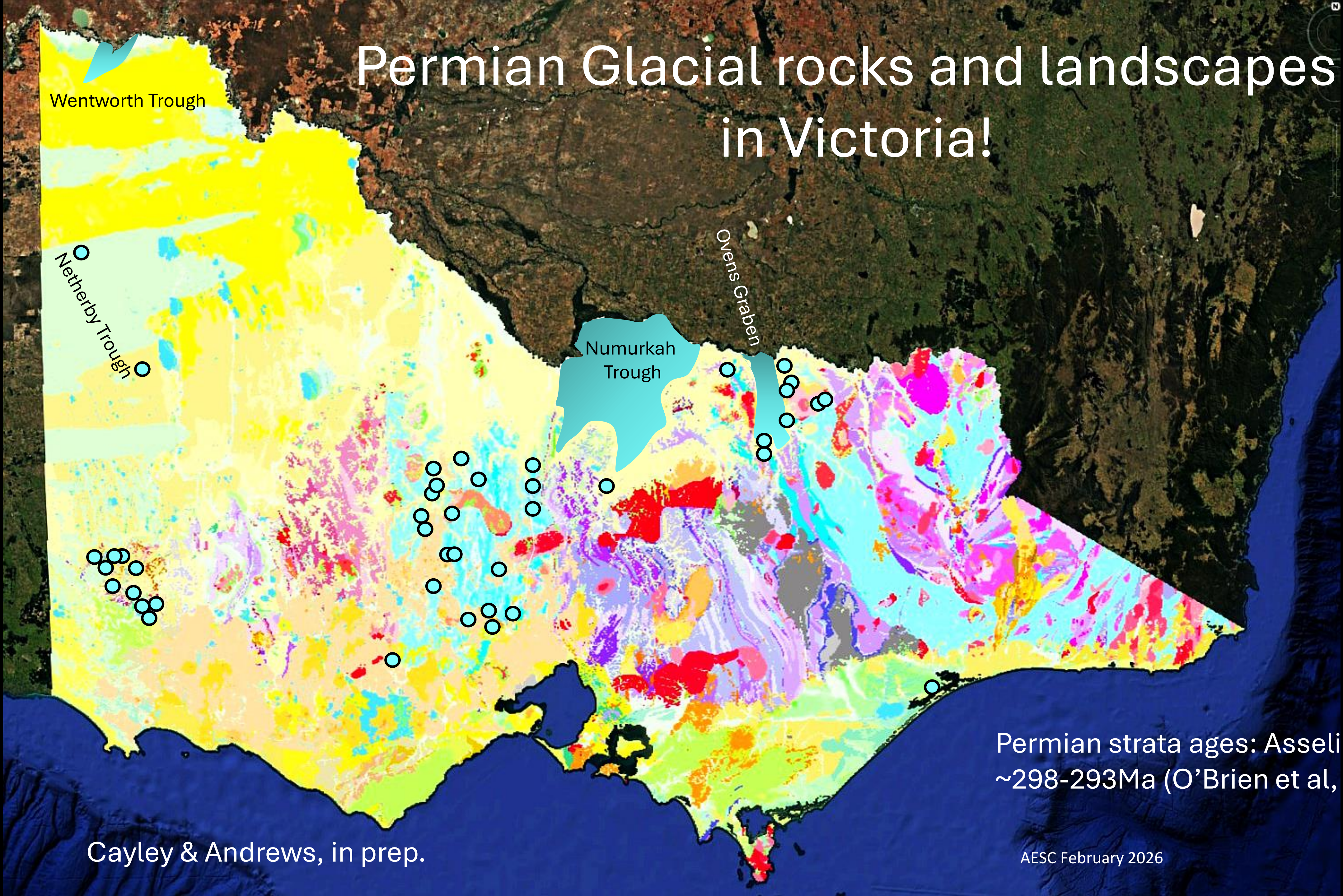
Permian Glacial rocks and landscapes in Victoria!



Permian strata ages: Asselian ~298-293Ma (O'Brien et al, 2003)

Cayley & Andrews, in prep.

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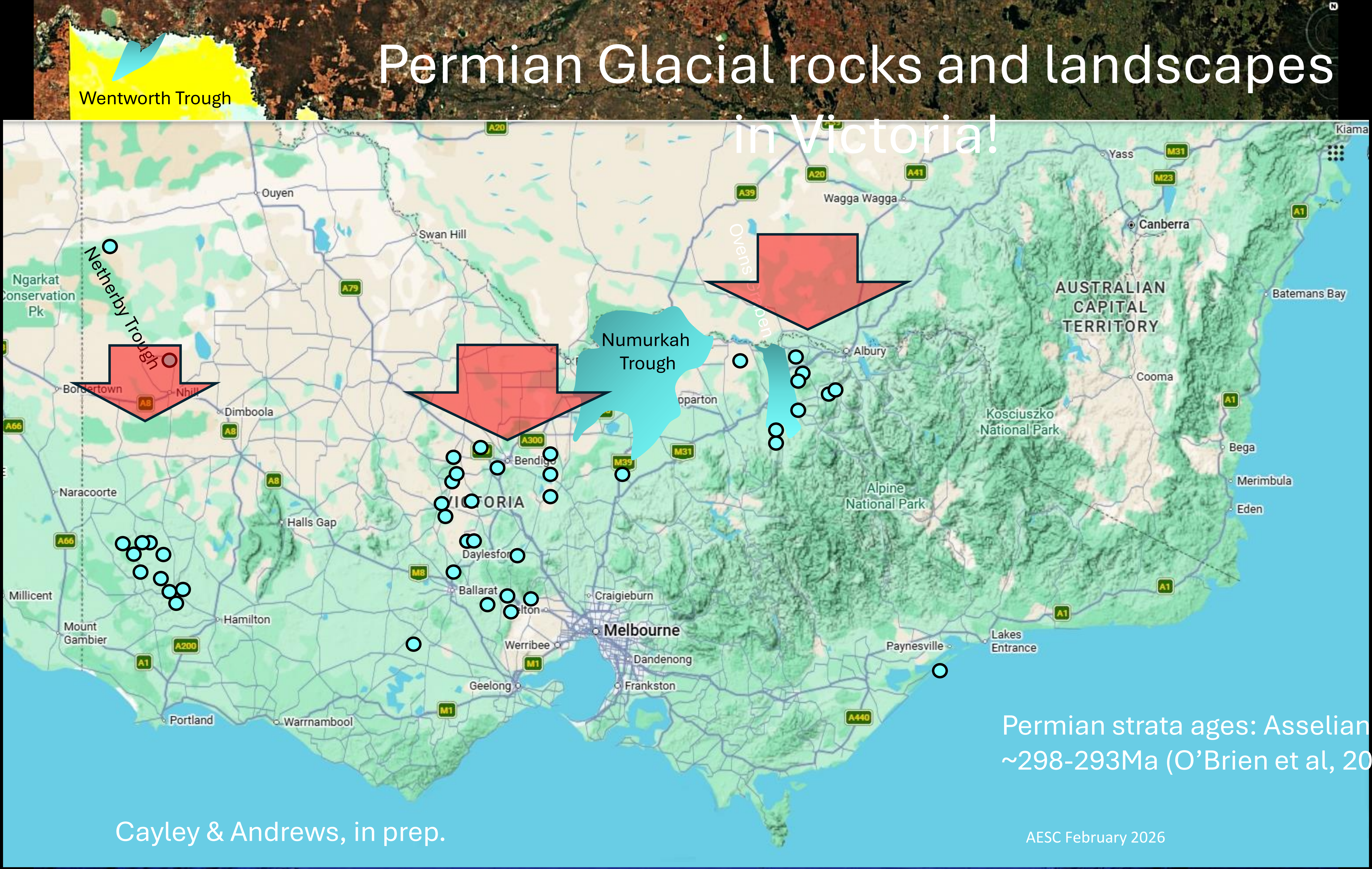

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No Cretaceous uplift
Limited erosion of
a Permian landscape

Cretaceous high plateau mostly eroded

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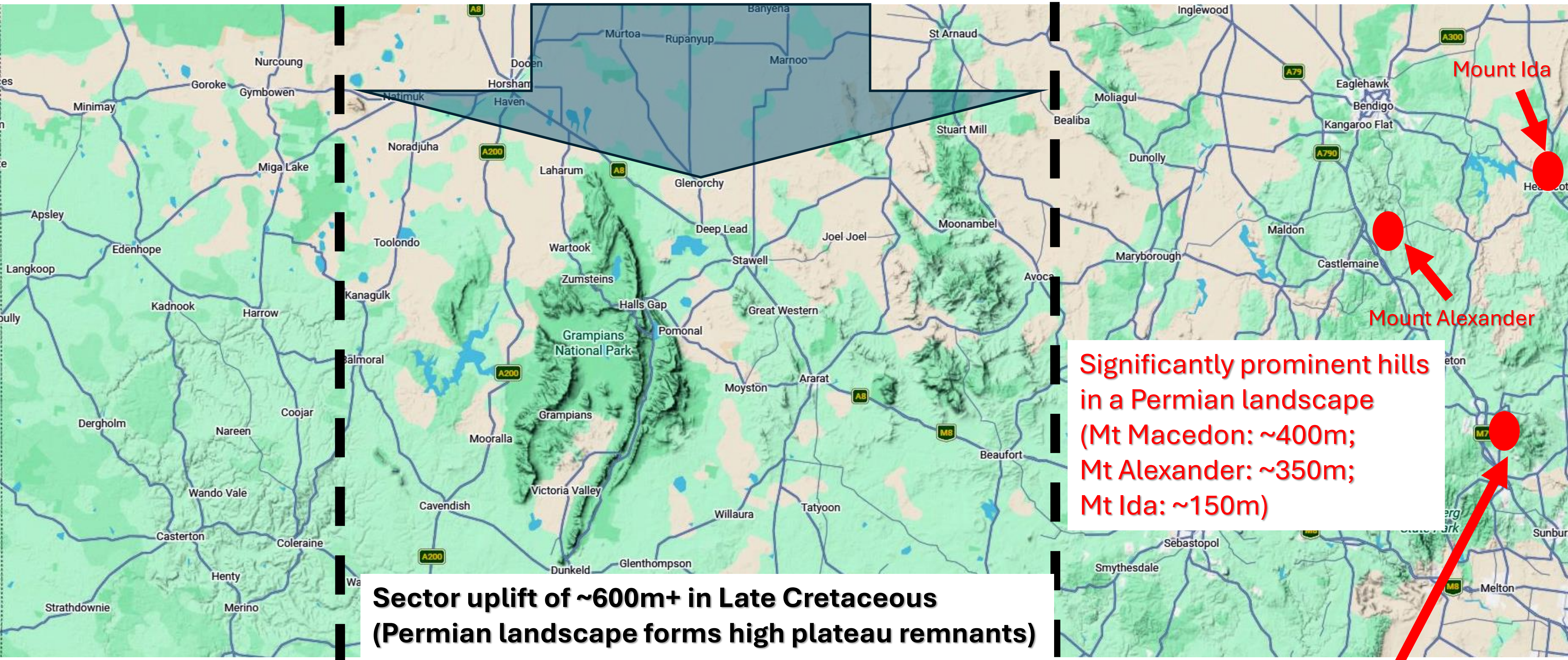

Sector uplift of ~600m+ in Late Cretaceous
(Permian landscape forms high plateau remnants)

Significantly prominent hills
in a Permian landscape
(Mt Macedon: ~400m;
Mt Alexander: ~350m;
Mt Ida: ~150m)

Cayley & Andrews, in prep.

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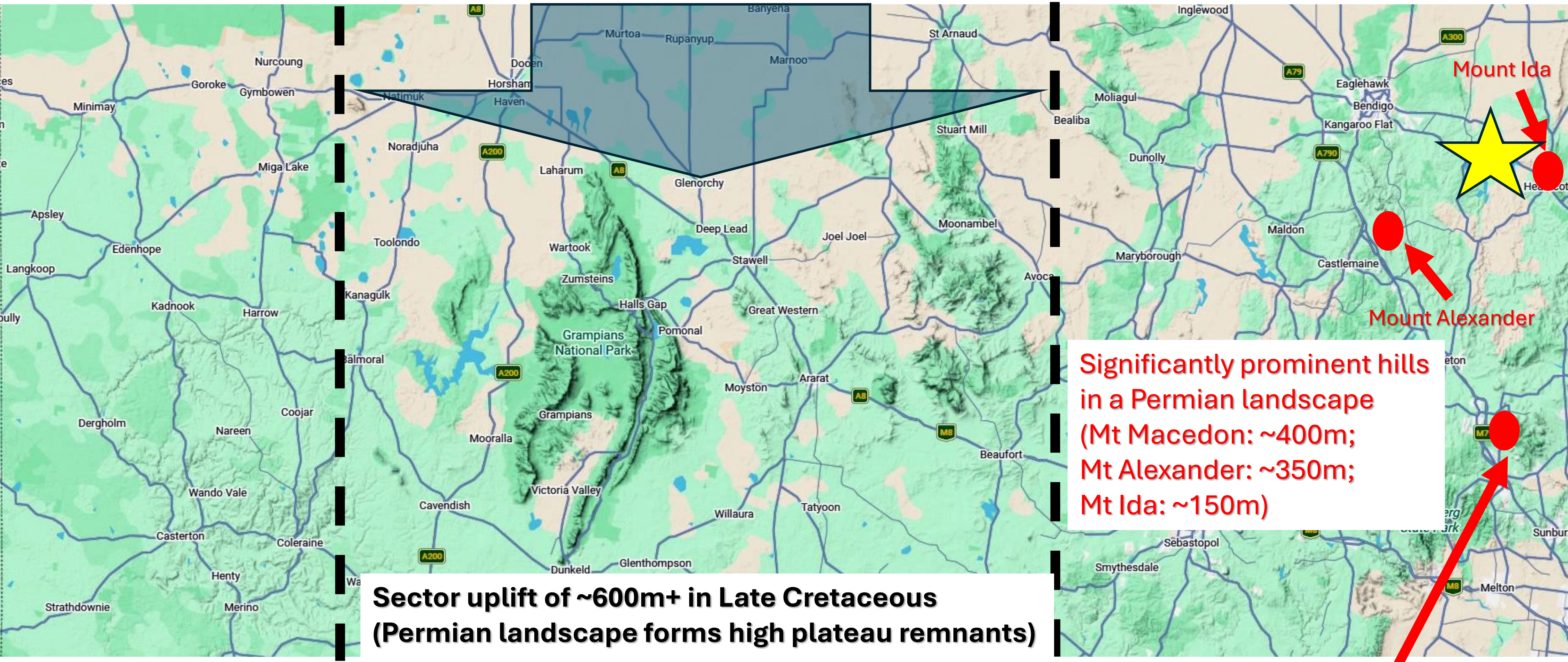

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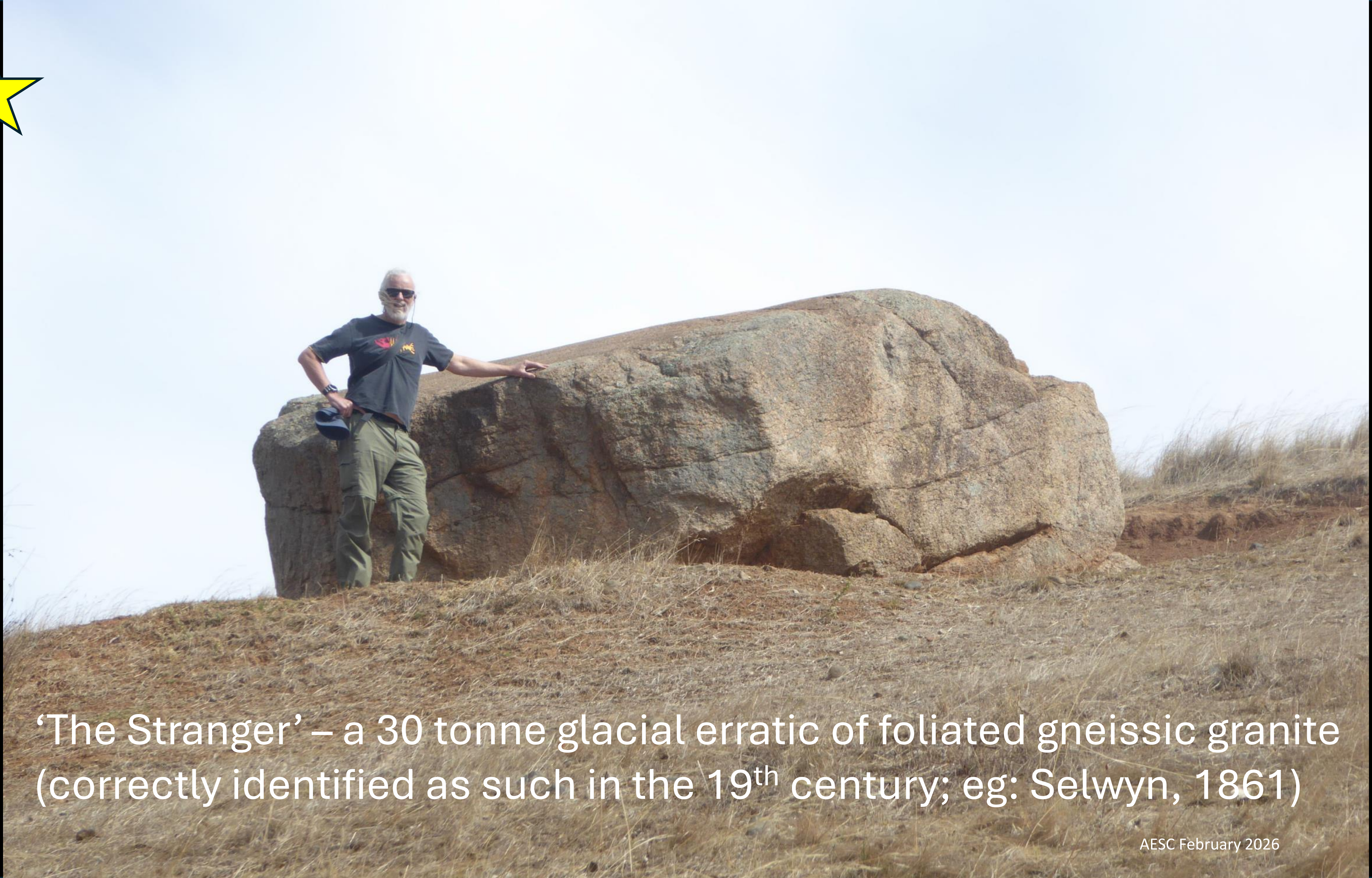
Derrinal / Eppalock


Derrinal / Eppalock



‘The Stranger’ – a 30 tonne glacial erratic of foliated gneissic granite (correctly identified as such in the 19th century; eg: Selwyn, 1861)

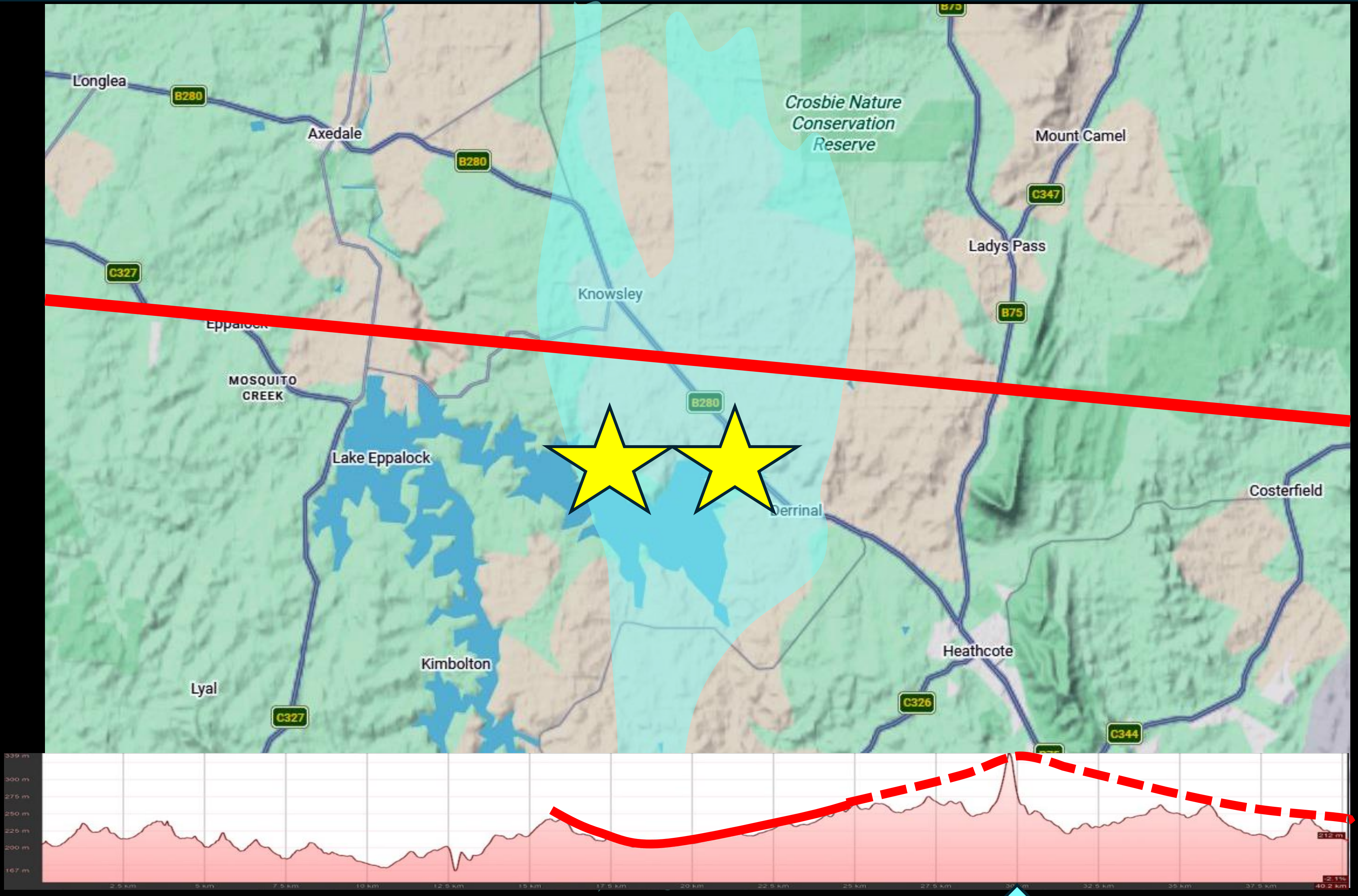

Consistent South-to-North and Southwest-to-Northeast
ice-sheet transport directions indicated Statewide

Correctly identified as a glacially excavated valley by David (1895)

Length of ice transport paths and aggressive nature of bedrock gouging Statewide require ice thicknesses in excess of 1 km (but not Polar scale).

It was a continental –scale ice sheet (e.g. O'Brien et al., 2003).

Analogues: Pleistocene northern Canada and Scandinavia



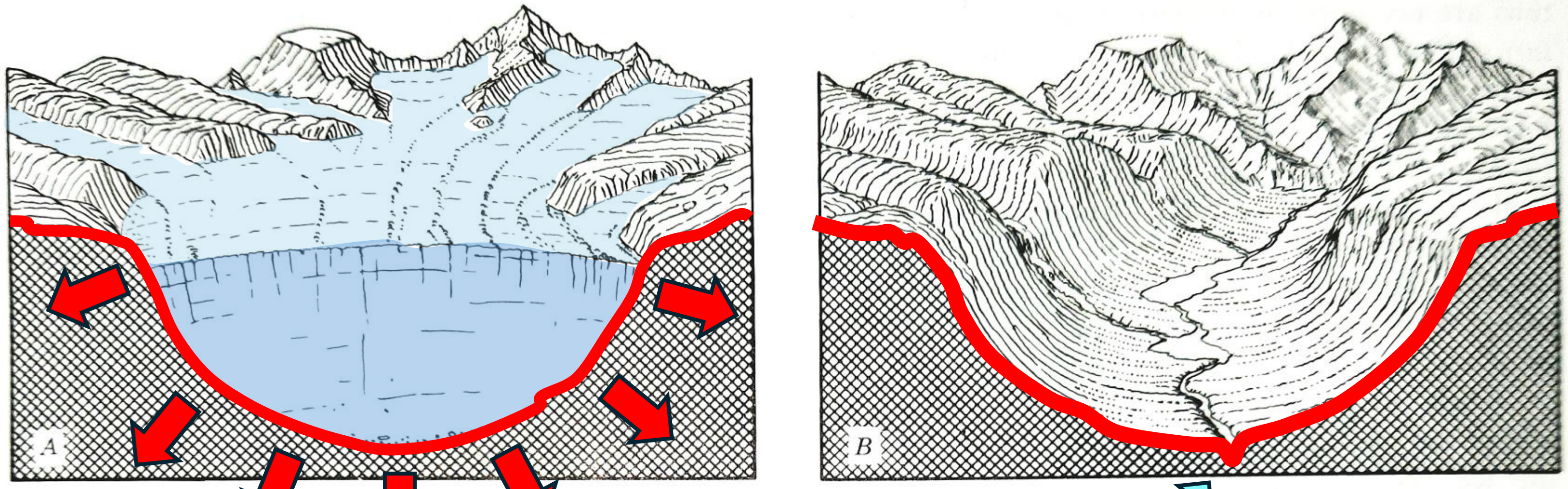
Permian glacials
In boreholes

Cayley & Andrews, in prep.

Broad, U-shaped depression

Similar U-shaped profiles across Permian-filled valleys at Tylden, Clunes (Chalks Lead)

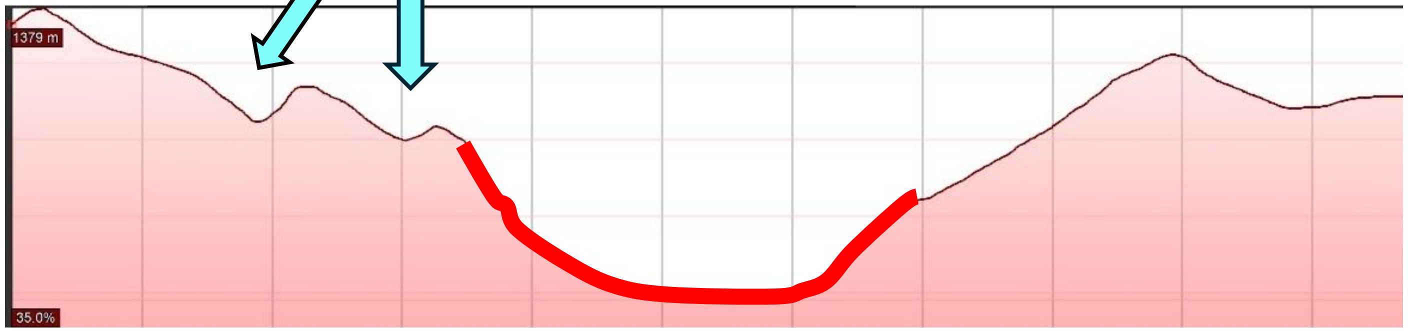
Permian subglacial ridge



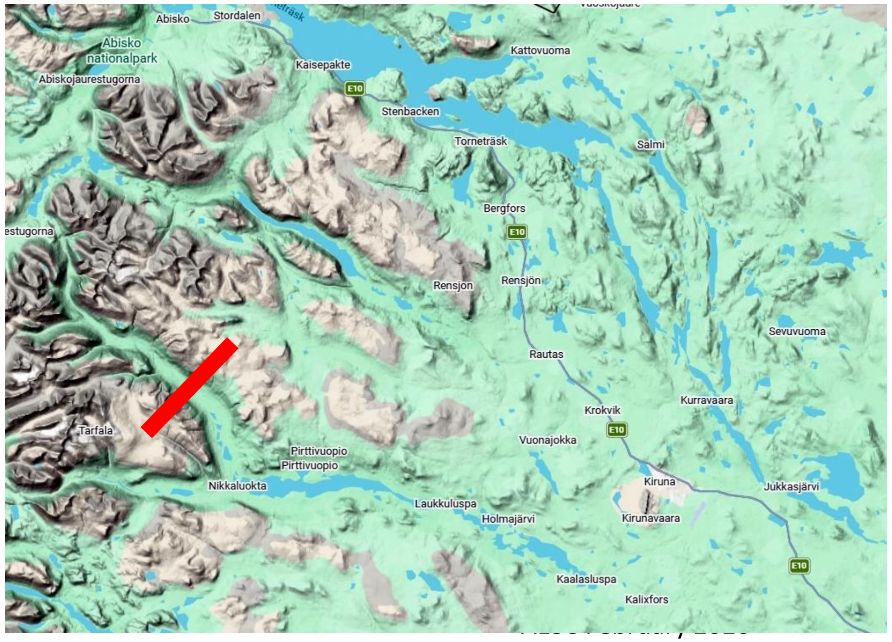
A. During maximum glaciation the U-shaped trough is filled by ice to the level of the small tributaries.

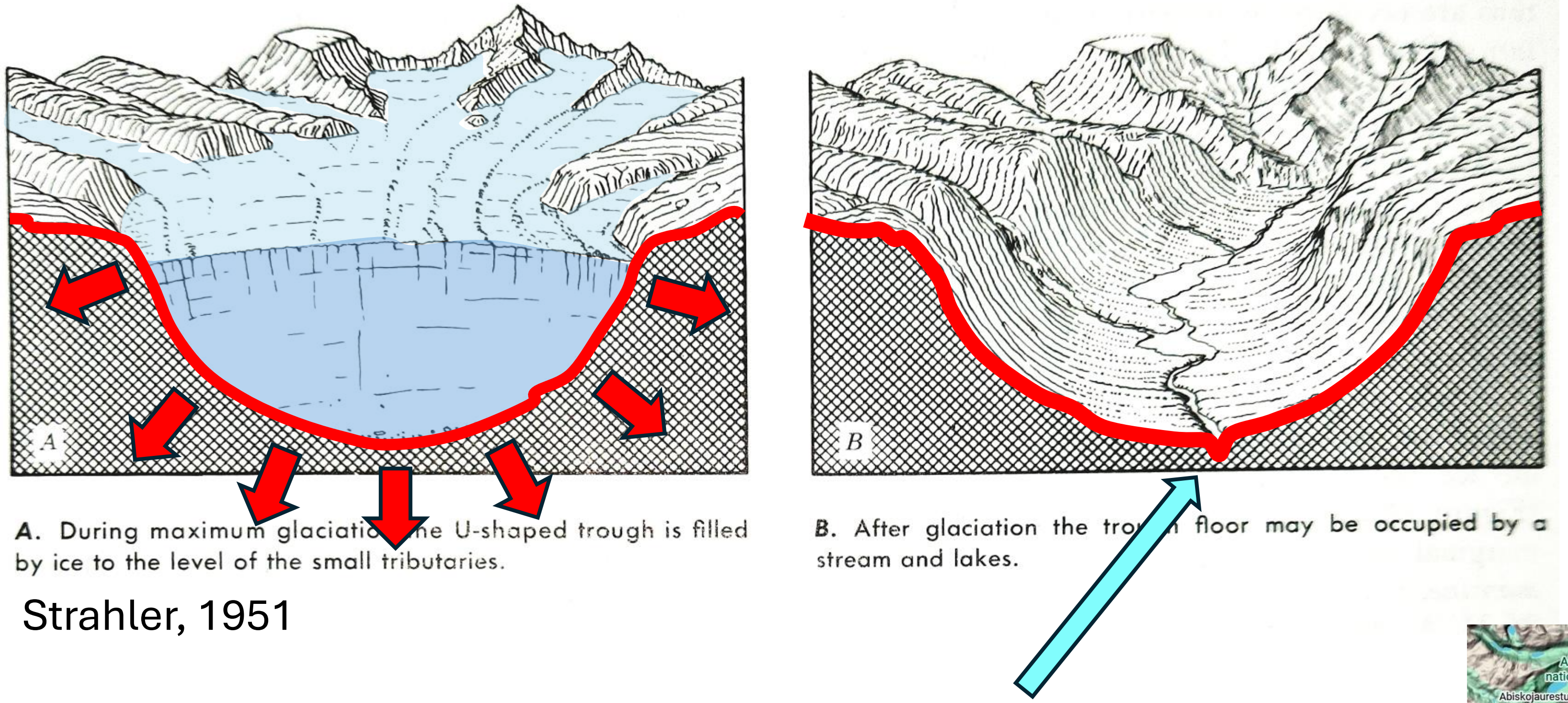
B. After glaciation the trough floor may be occupied by a stream and lakes.

Strahler, 1951

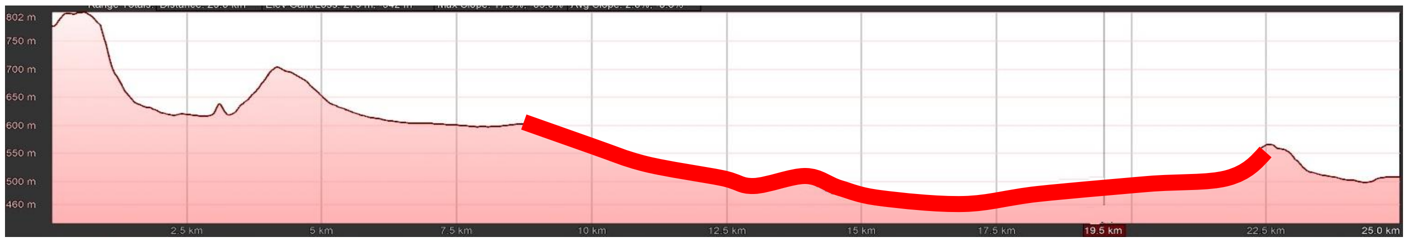


Cayley & Andrews, in prep.

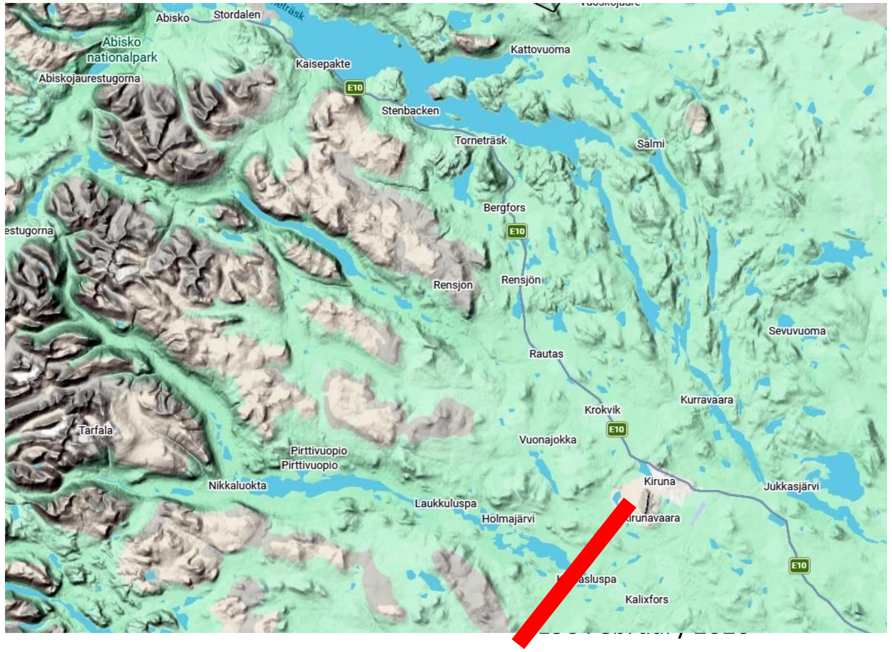




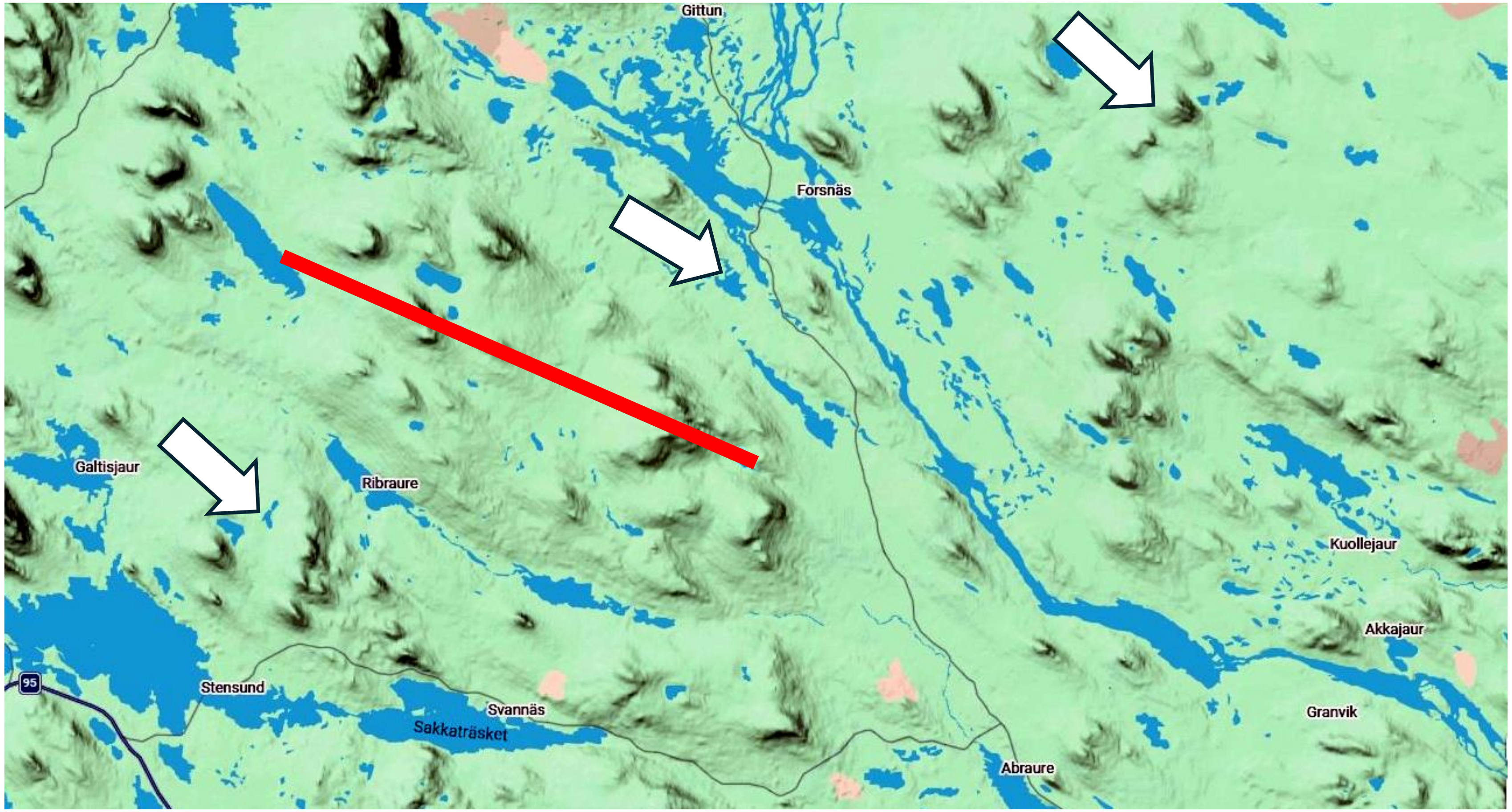
Strahler, 1951



Cayley & Andrews, in prep.



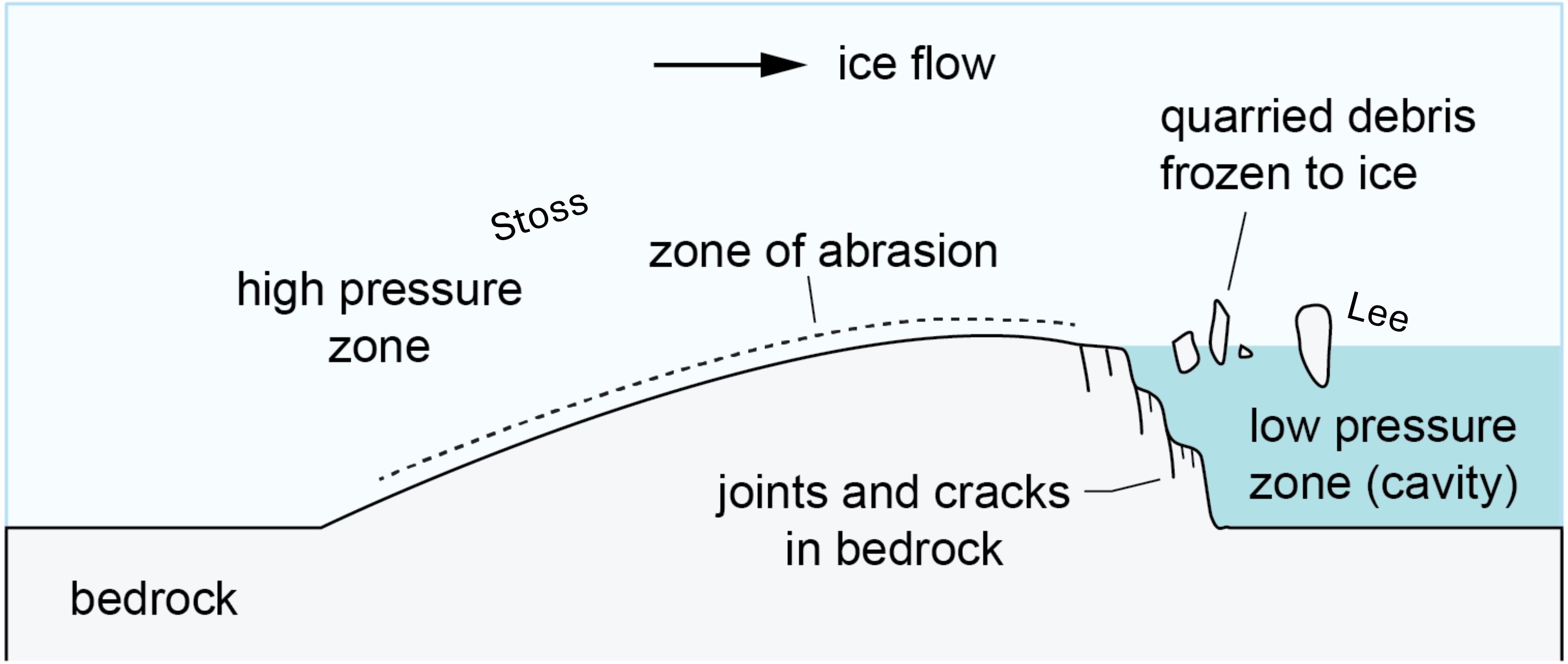
Roche moutonnée at Mia Mia.


Gittun
Forsnäs
Galtisjaur
Ribraure
Kuollejaur
Akkajaur
Stensund
Svannäs
Sakkaträsket
Granvik
Abraure
95

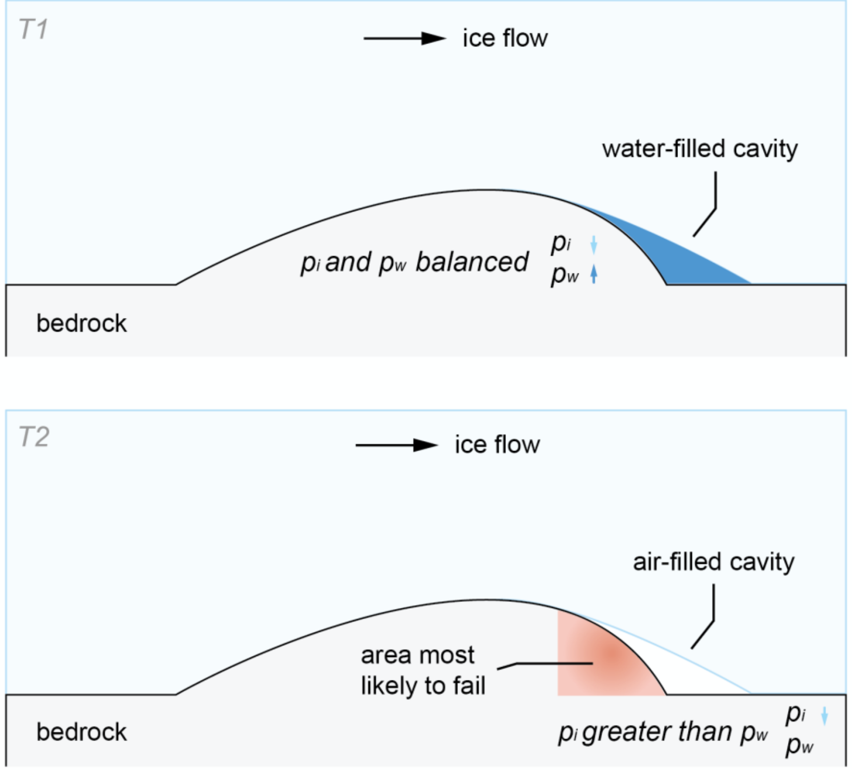

Sweden
Norway
Finland
Gulf of Bothnia
Oslo
Stockholm
St Petersburg
Санкт-Петербург
Estonia
Baltic Sea
Latvia
Denmark
Lithuania
Moscow
Москва

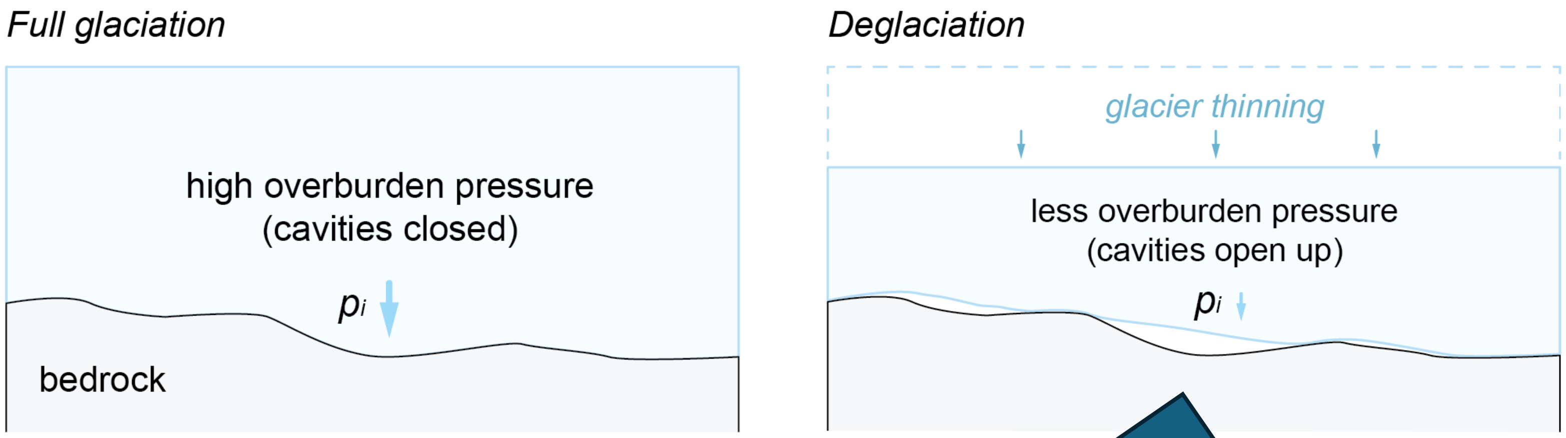

690m
520m
Stoss
Lee
Stoss
Lee

Subglacial peaks (Nunataks) also often exhibit a stoss-lee effect, with smooth, abraded lower angle upstream sides (stoss) and steeper plucked downstream side

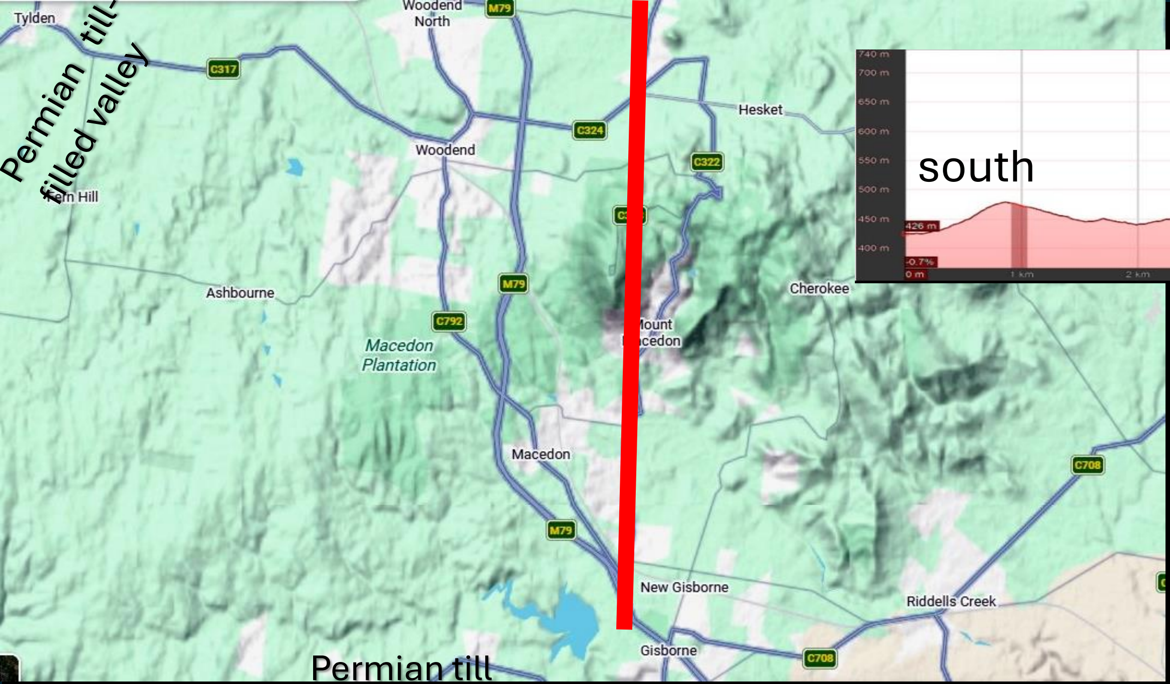


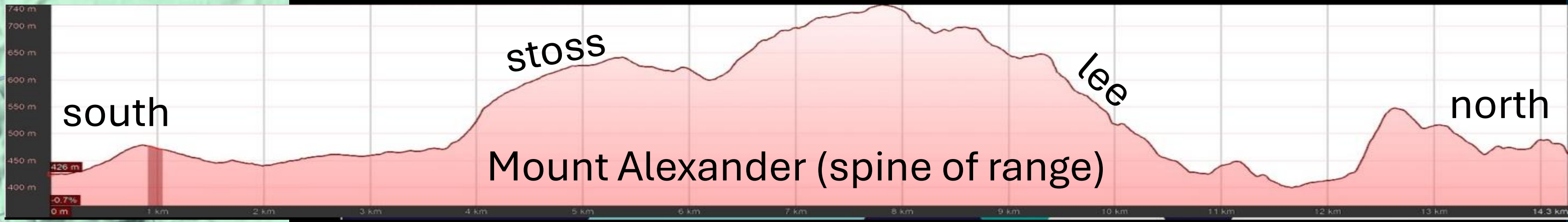
J. Bendle (2020)

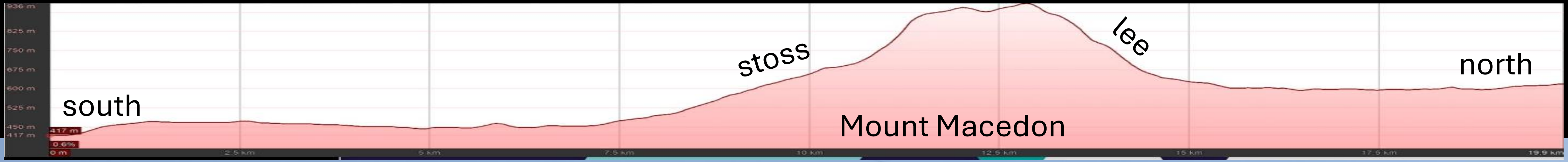




Rouche Moutonee develop more quickly beneath ice sheet margins and/or or during deglaciation when high differential stress zones can develop in lee zones more easily. (e.g. Roberts & Long, 2005)







Mount Macedon – a Permian subglacial peak (or nunatak)?

Cayley & Andrews, in prep.

AESC February 2026

Talk Outline

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- **And – Permian glacial landscapes are everywhere!**
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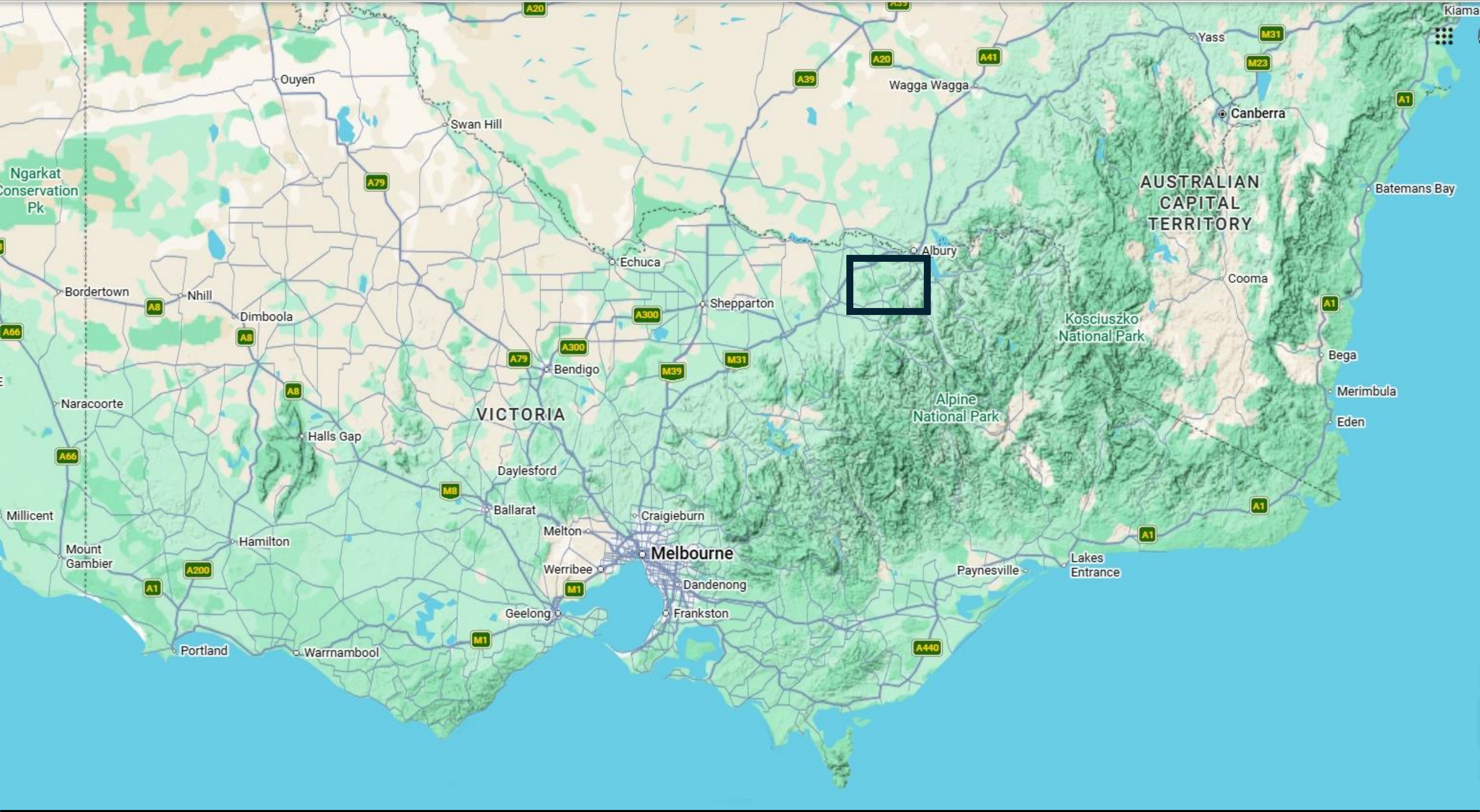
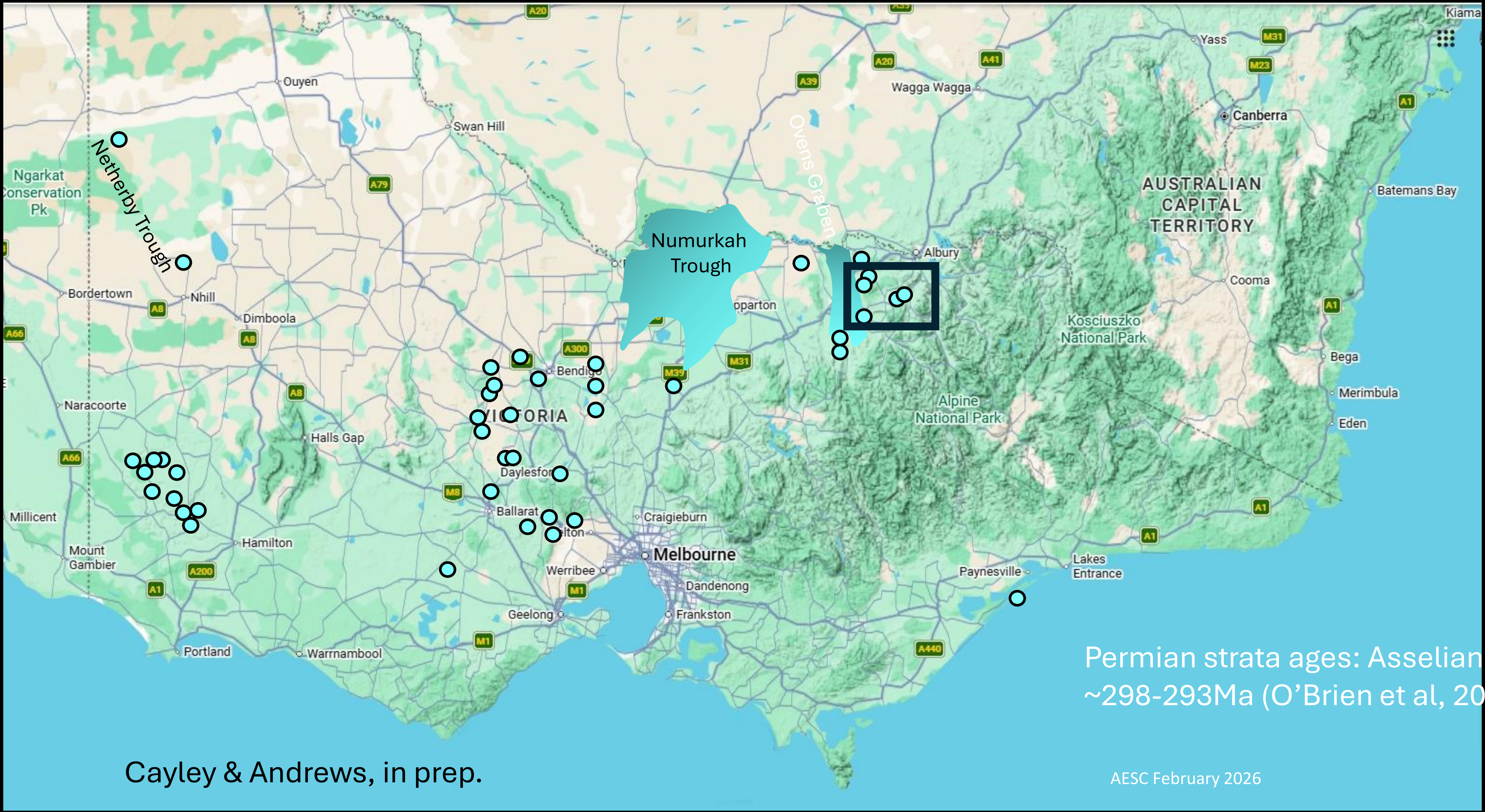
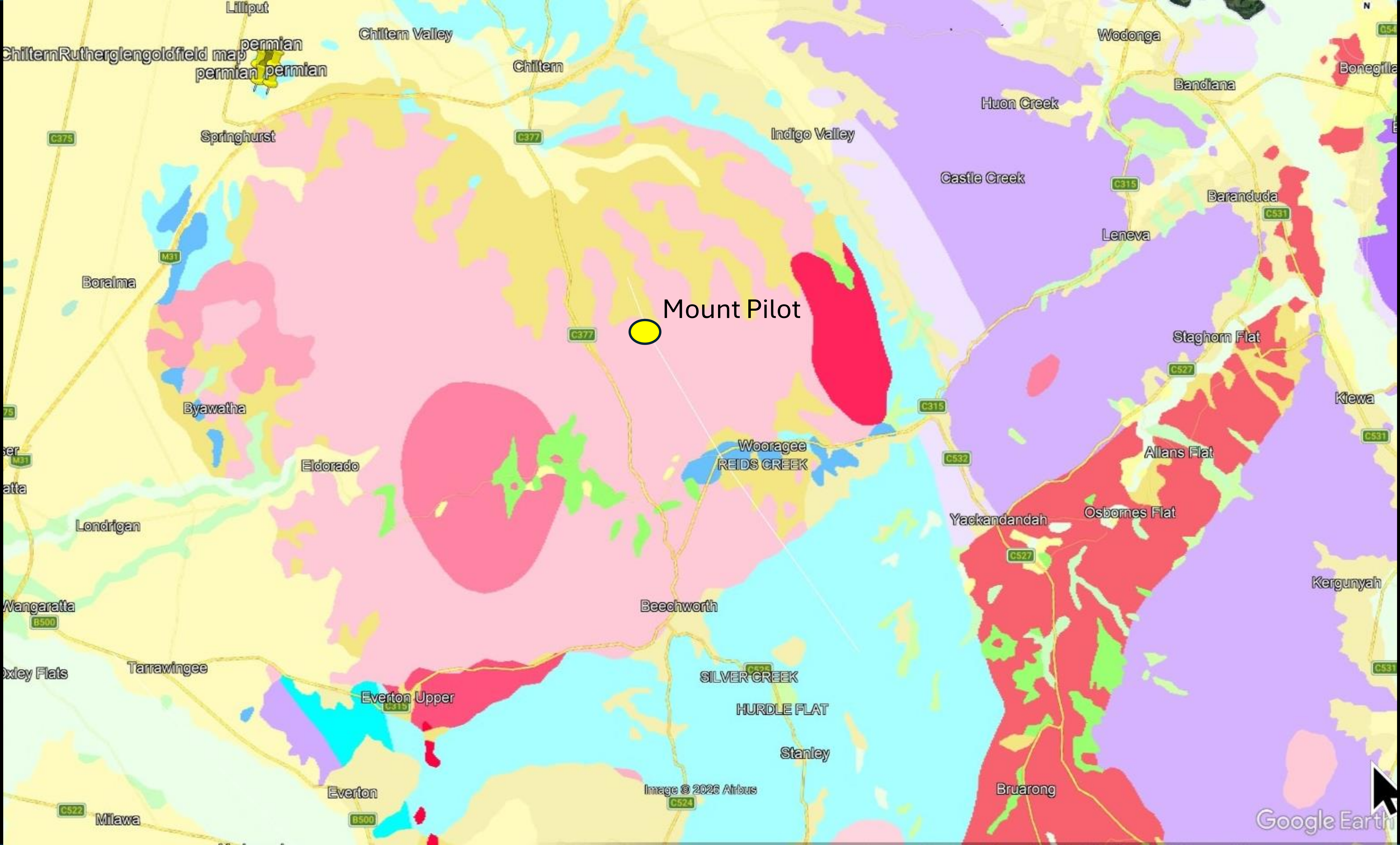

Ouyen
Swan Hill
Wagga Wagga
Yass
Canberra
Kiama
Ngarkat
Conservation
Pk
AUSTRALIAN
CAPITAL
TERRITORY
Batemans Bay
Albury
Echuca
Cooma
Bordertown
Nhill
Dimboola
Shepparton
Kosciuszko
National Park
Bendigo
Bega
Naracoorte
Alpine
National Park
Merimbula
Eden
Halls Gap
VICTORIA
Daylesford
Millicent
Ballarat
Craigieburn
Mount
Gambier
Hamilton
Melton
Melbourne
Lakes
Entrance
Werribee
Paynesville
Dandenong
Geelong
Frankston
Portland
Warrnambool
A20
A39
A41
M31
M23
A1
A79
A8
A66
A300
M39
M8
A200
M1
A440

Permian Glacial rocks and landscapes in Victoria!



Permian strata ages: Asselian ~298-293Ma (O'Brien et al, 2003)

Cayley & Andrews, in prep.


Mount Pilot
Lilliput
Chiltern Valley
ChilternRutherglengoldfield map
permian
permian
permian
Chiltern
Wodonga
Bonegilla
Bandiana
Huon Creek
Springhurst
C375
C377
Indigo Valley
Castle Creek
C315
Barandnuda
C531
Leneva
M31
Boralma
Staghorn Flat
C527
Kiewa
Byawatha
C315
Wooragee
REIDS CREEK
C532
Allans Flat
Eldorado
Londrigan
Yackandandah
Osbornes Flat
C527
Kergunyah
Wangaratta
B500
Beechworth
Tarrawingee
Oxley Flats
SILVER CREEK
Everton Upper
HURDLE FLAT
Stanley
Everton
Image © 2026 Airbus
C524
Bruarong
C522
Milawa
B500
Google Earth


AESC February 2026


Lilliput
Chiltern Valley
ChilternRutherglengoldfield map
permian
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Chiltern
Wodonga
Bandiana
Bonegilla
Huon Creek
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Indigo Valley
Castle Creek
Baranduda
Leneva
Boralma
Mount Pilot
Staghorn Flat
Kiewa
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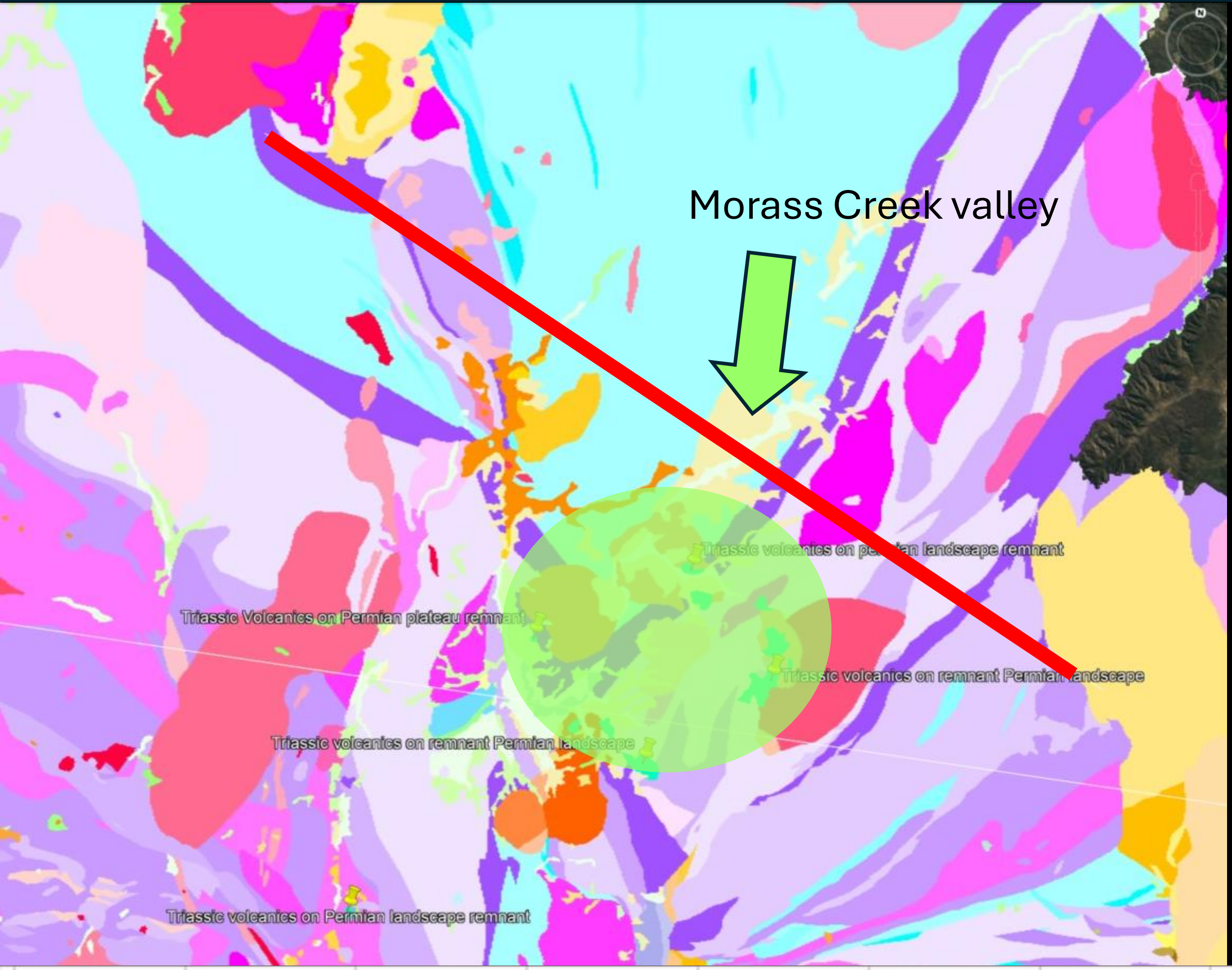
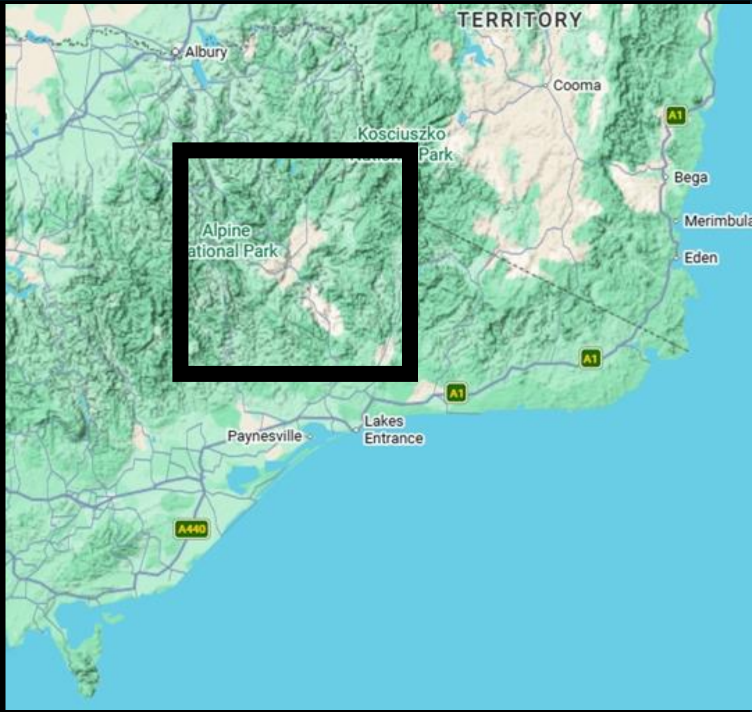
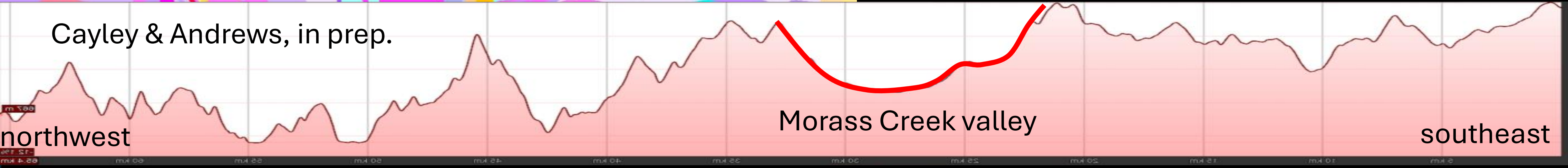
Wooragee
Allans Flat
Eldorado
Yackandandah
Osbornes Flat
Londrigan
Kergunyah
Wangaratta
Beechworth
Cayley & Andrews, in prep.
In-situ
Permian
glacials
south
north
Post-Eocene erosional escarpments





Triassic volcanics – Teapot Creek Formation

This whole region is a Permian landscape remnant- Benambra – Morass Ck is a sub-icecap depression…. now uplifted in the heart of the Victorian Alps



65 km long profile

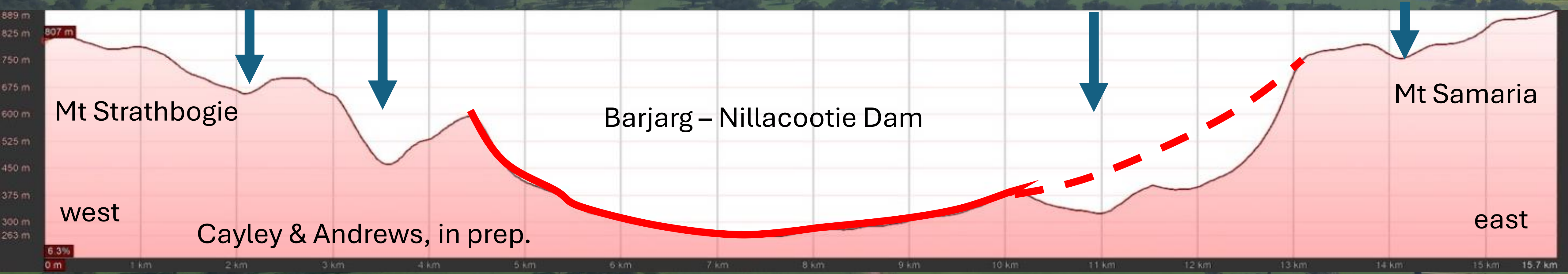
Benambra – a subglacial depression

Cayley & Andrews, in prep.


Wild Cat Trig – a subglacial rise flanking the Benambra subglacial depresson
Cayley & Andrews, in prep
AESC February 2026


Cayley & Andrews, in prep.

The entire *Mansfield Basin* is a broad Permian sublacial depression!
The Barjarg valley is an exit glacial valley (one of two we have identified)



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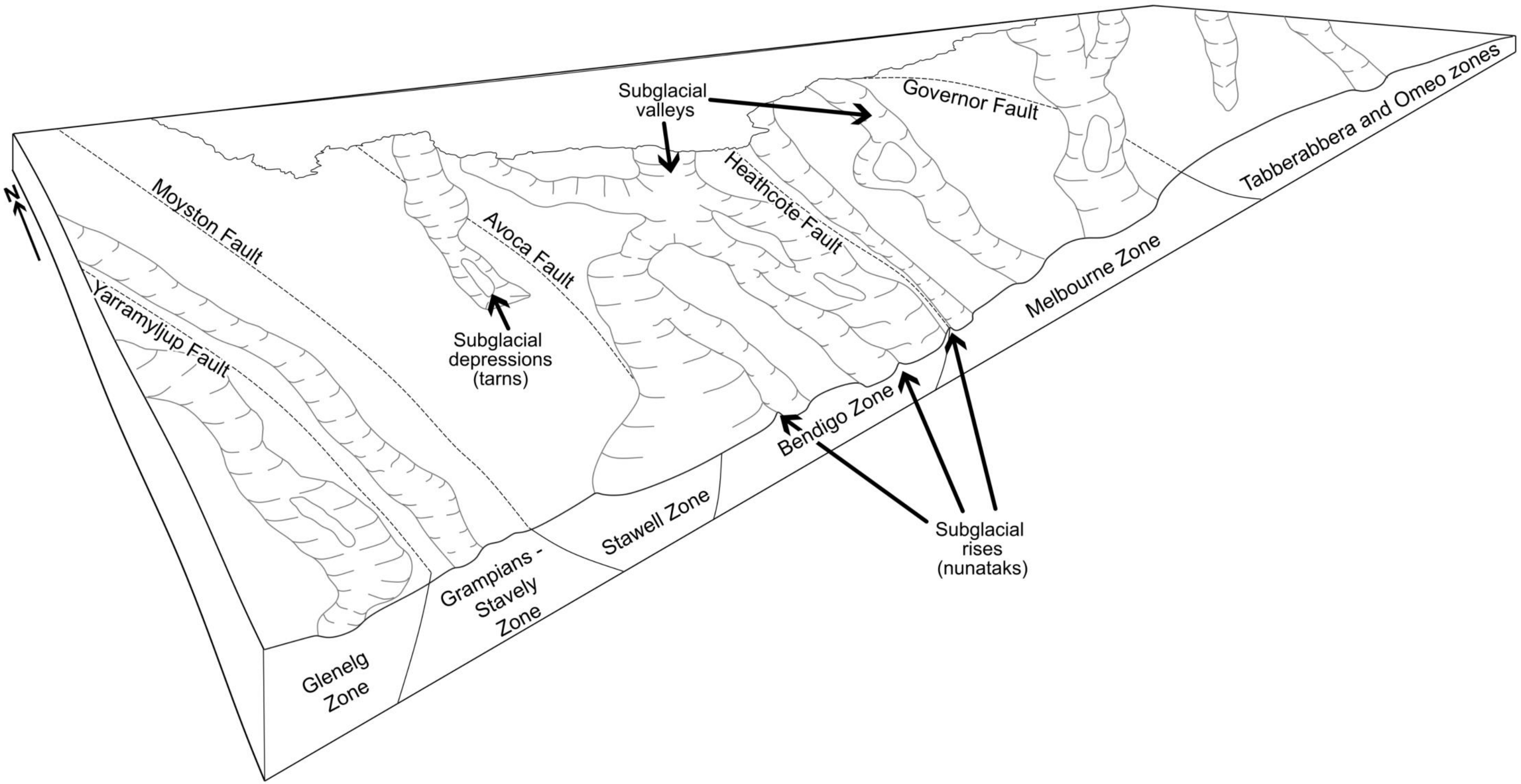
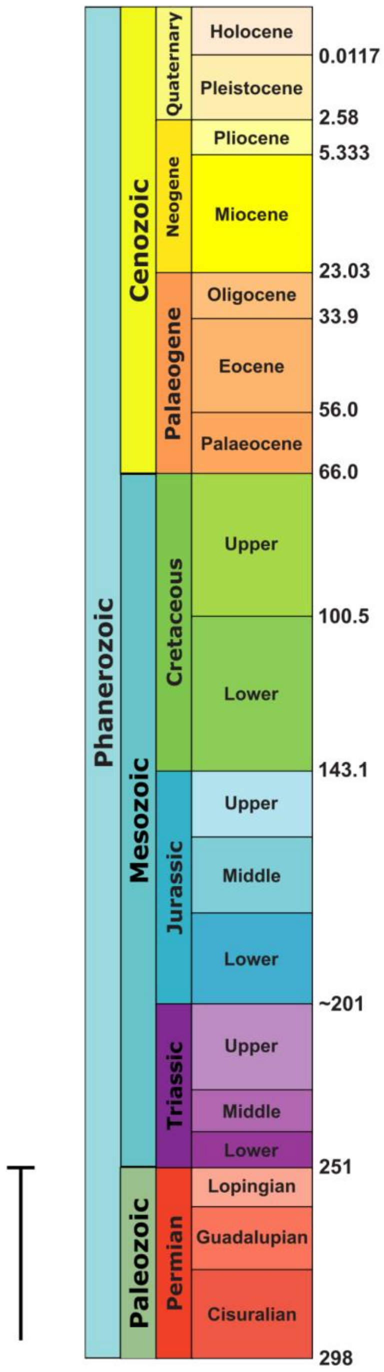
Iceland (AKA Victoria.....in the Permian)

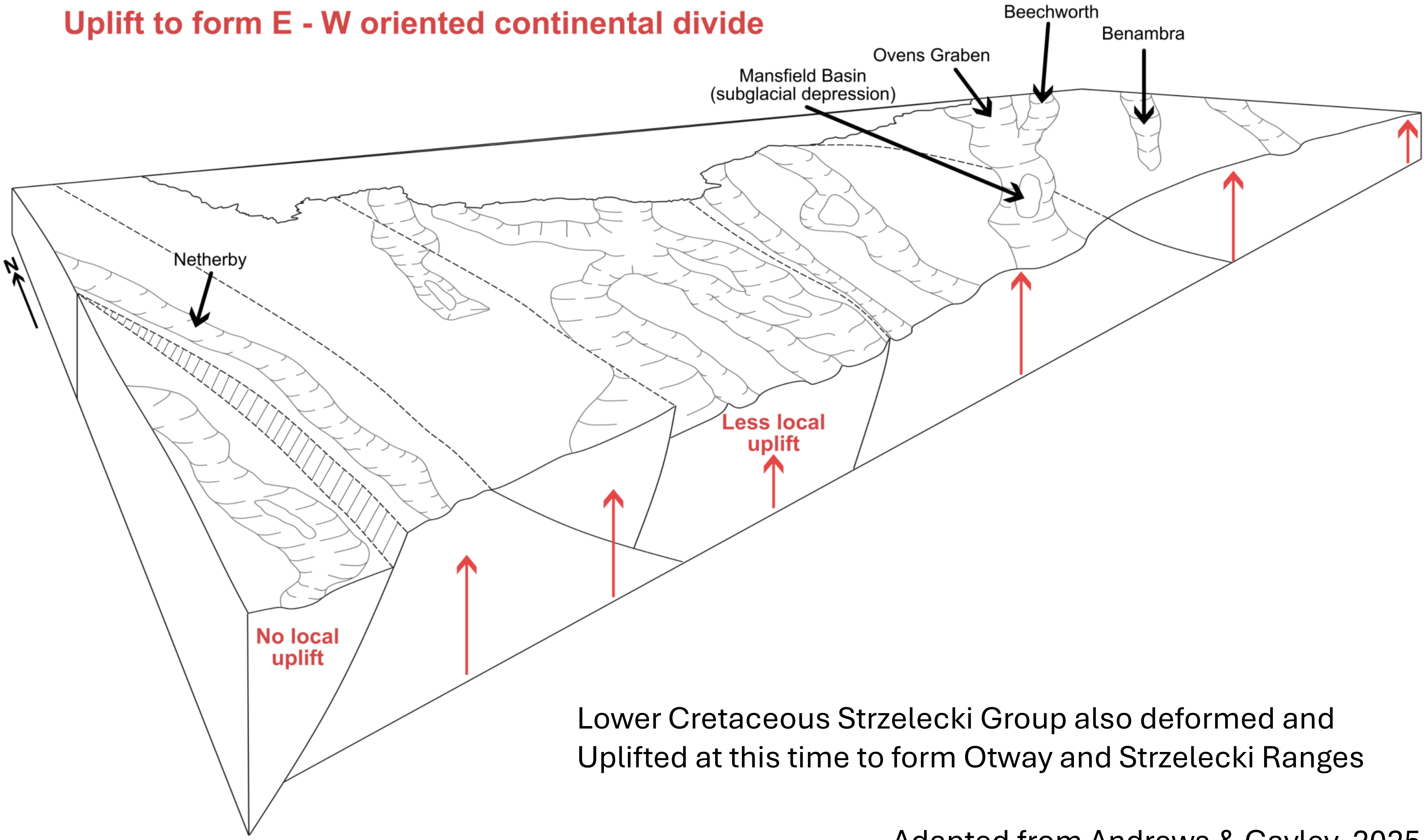
Undulating Permian landscape on Paleozoic bedrock

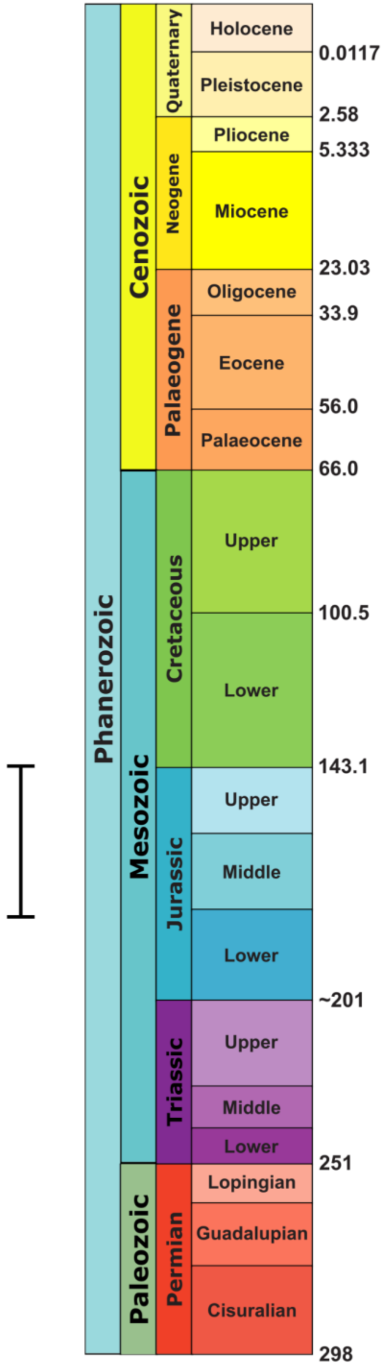


Adapted from Andrews & Cayley, 2025



Uplift to form E - W oriented continental divide



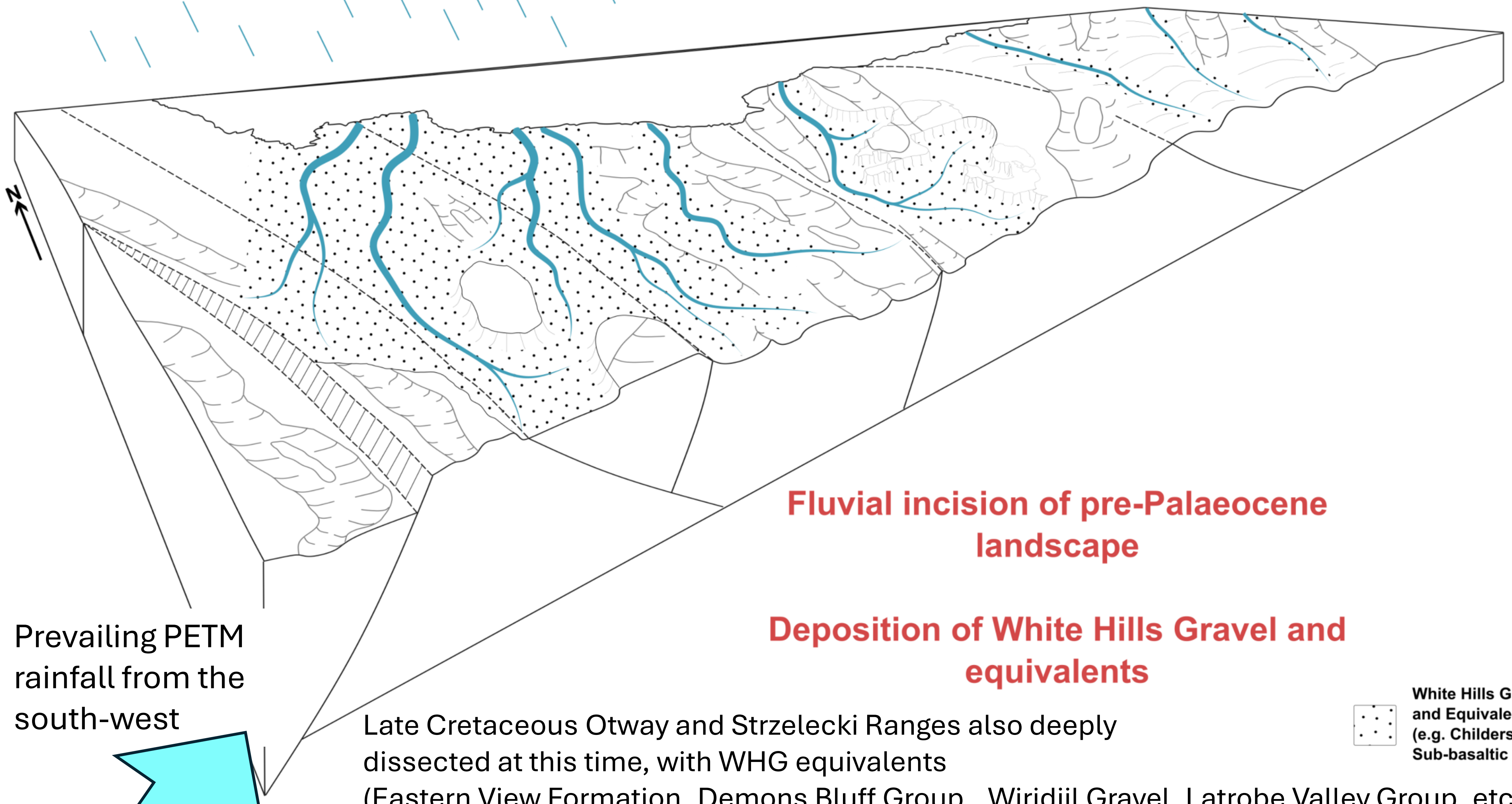


Lower Cretaceous Strzelecki Group also deformed and
Uplifted at this time to form Otway and Strzelecki Ranges

Adapted from Andrews & Cayley, 2025

Increased orographic rainfall in central - western Victoria

Eastern Victoria rainshadow



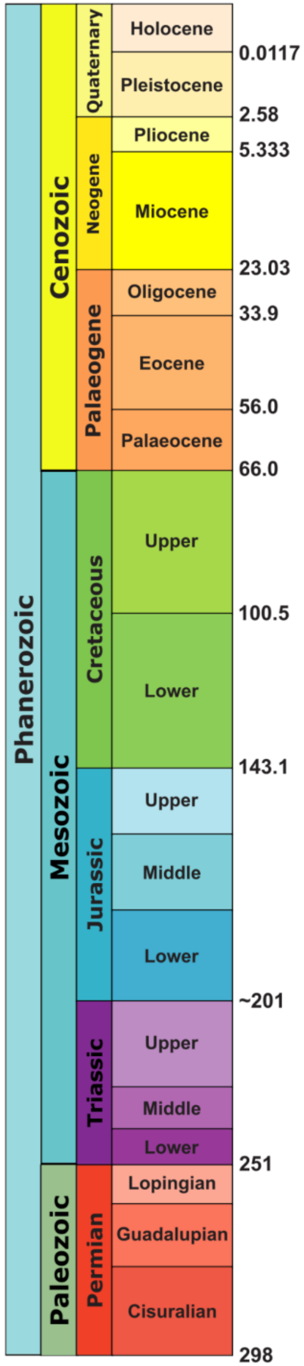
Fluvial incision of pre-Palaeocene landscape

Deposition of White Hills Gravel and equivalents

Prevailing PETM rainfall from the south-west

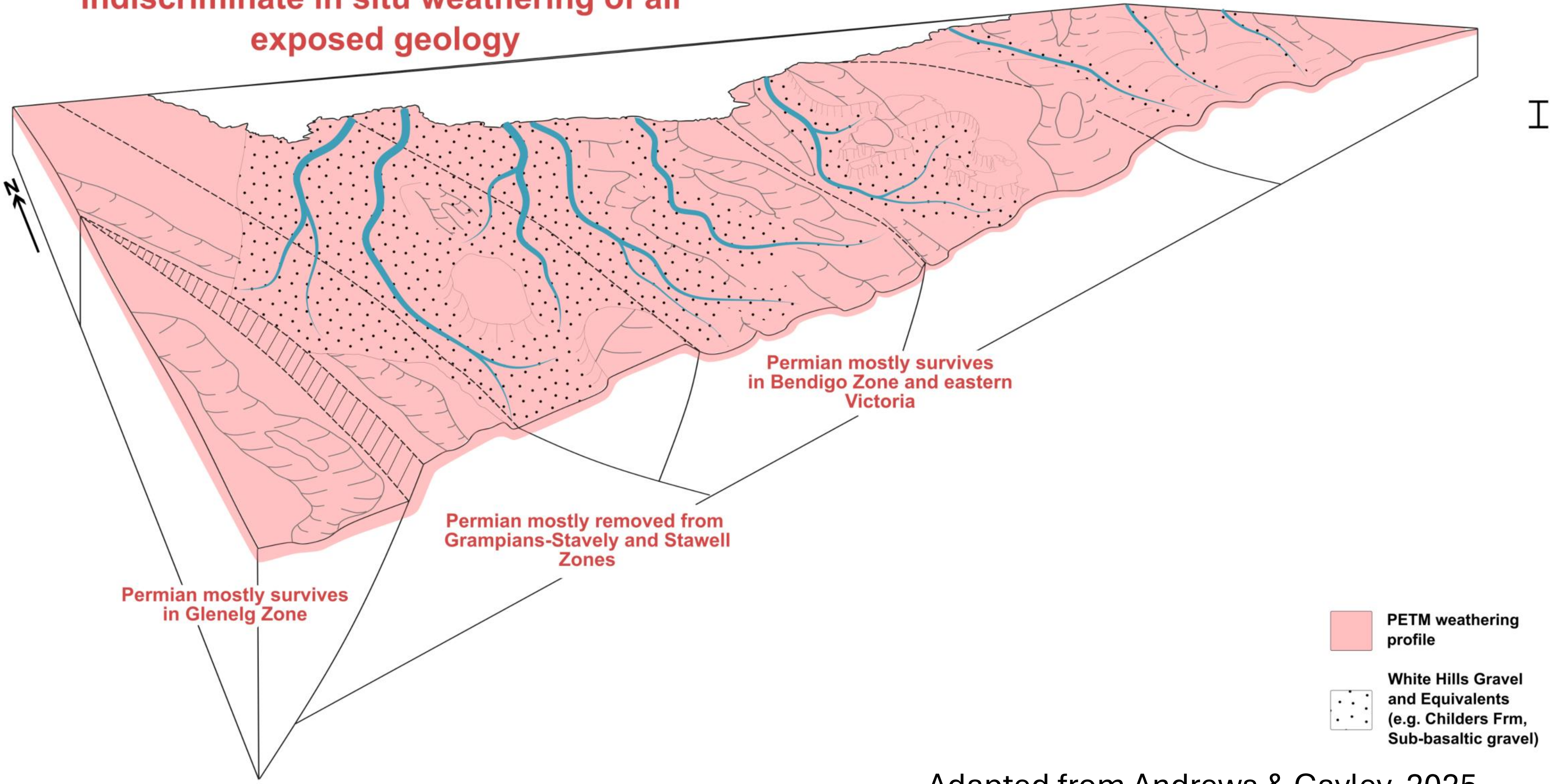
Late Cretaceous Otway and Strzelecki Ranges also deeply dissected at this time, with WHG equivalents (Eastern View Formation, Demons Bluff Group,, Wiridjil Gravel, Latrobe Valley Group, etc.) deposited at bases of erosional escarpments

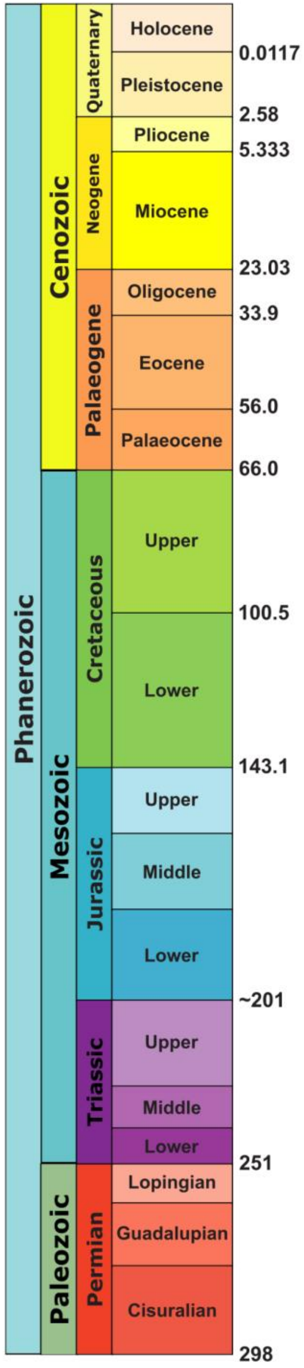
White Hills Gravel and Equivalents (e.g. Childers Frm, Sub-basaltic gravel)



Palaeocene - Eocene Thermal Maximum

Indiscriminate in situ weathering of all exposed geology

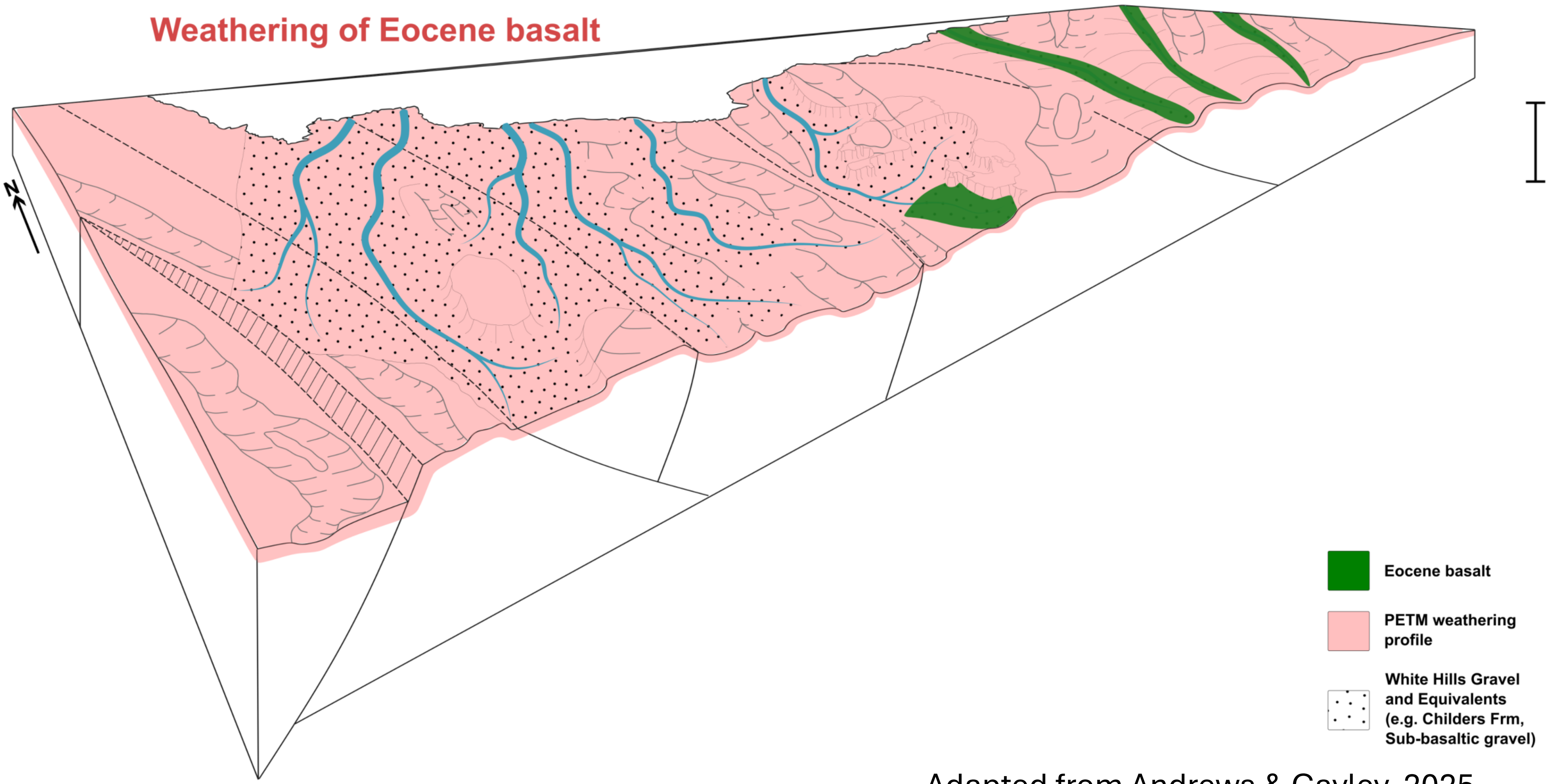




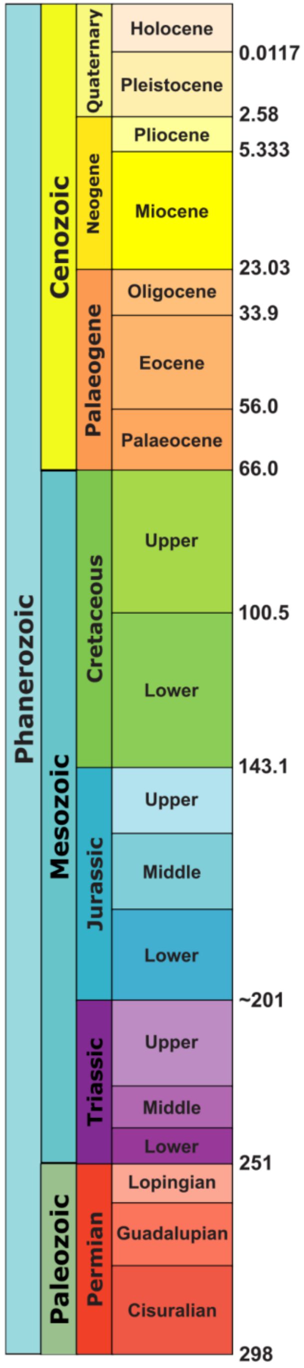
Adapted from Andrews & Cayley, 2025

Eruption of Eocene basalt onto White Hills Gravel

Weathering of Eocene basalt



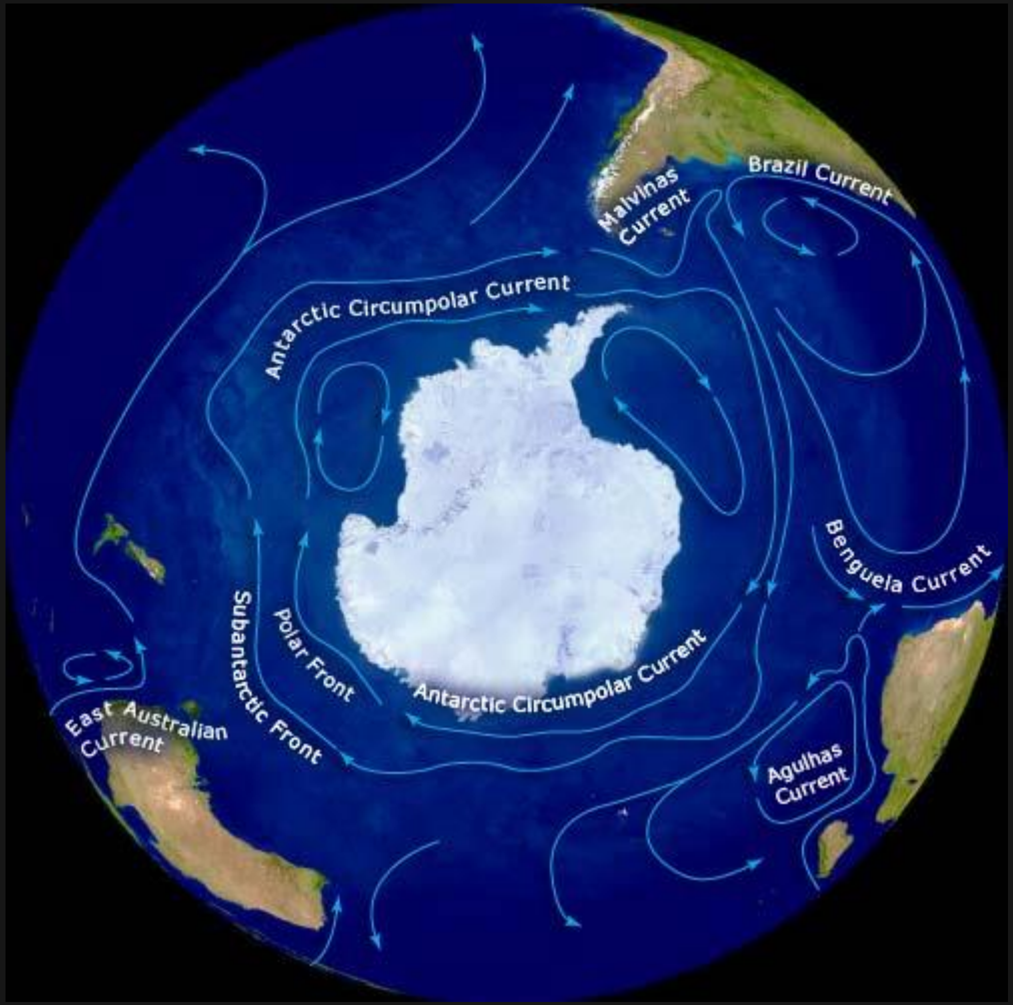
Adapted from Andrews & Cayley, 2025



South America – Australia – Antarctica separations finally allowed full development of Circum-Antarctic ocean circulation.

This polarised global temperatures and exposed southern Australia to a cold ocean.

Cold ocean = dry climate. Victoria dried out in the Oligocene. Virtually no erosion evident anywhere.

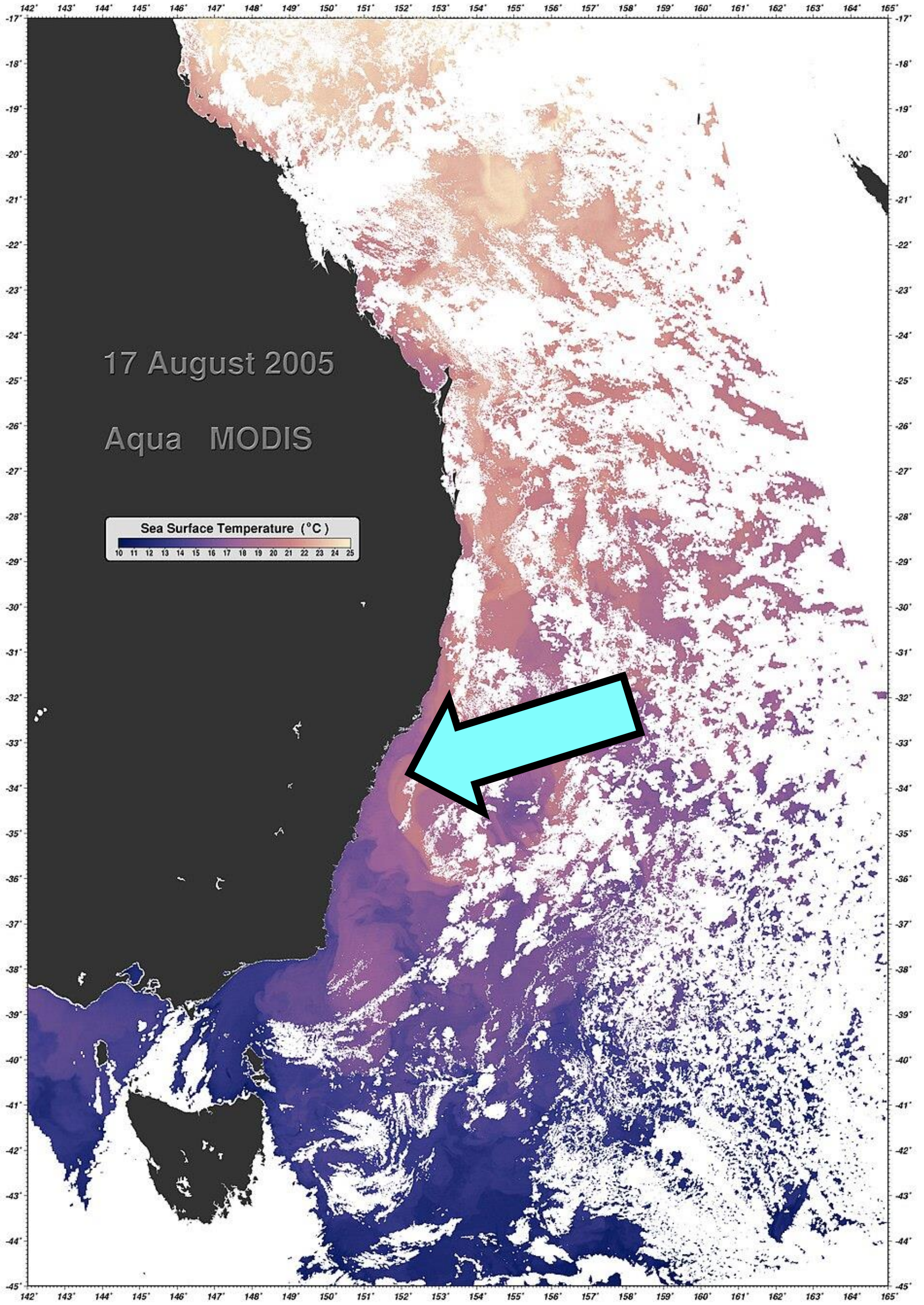


But then.....

East Australian Current (EAC) – initiated in the Miocene.
(e.g. Eberli 2022)

The imposition of a completely new rainfall regime for SE Australia, from the East!

Now its western Victoria's turn to be in a rain shadow!



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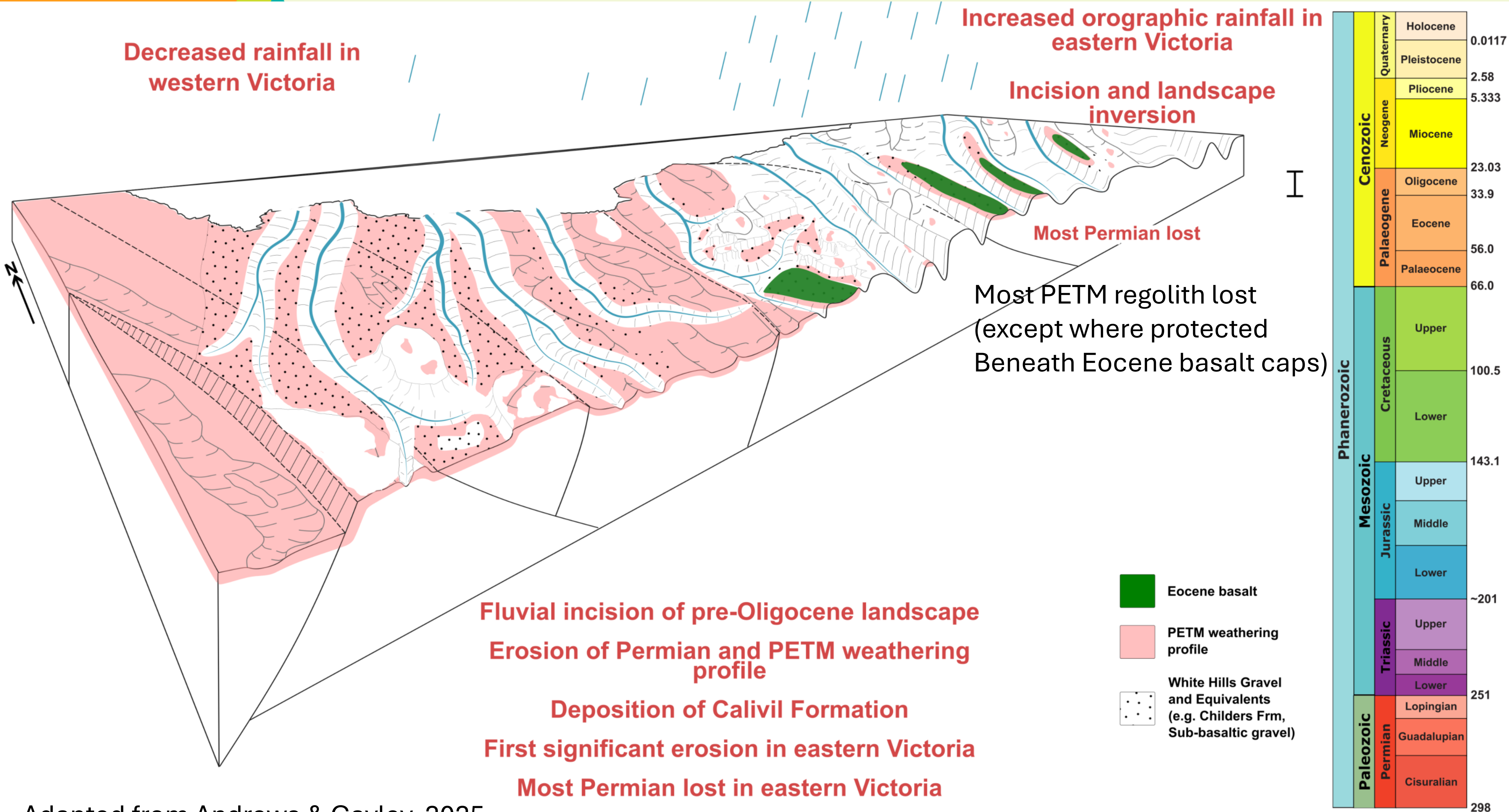
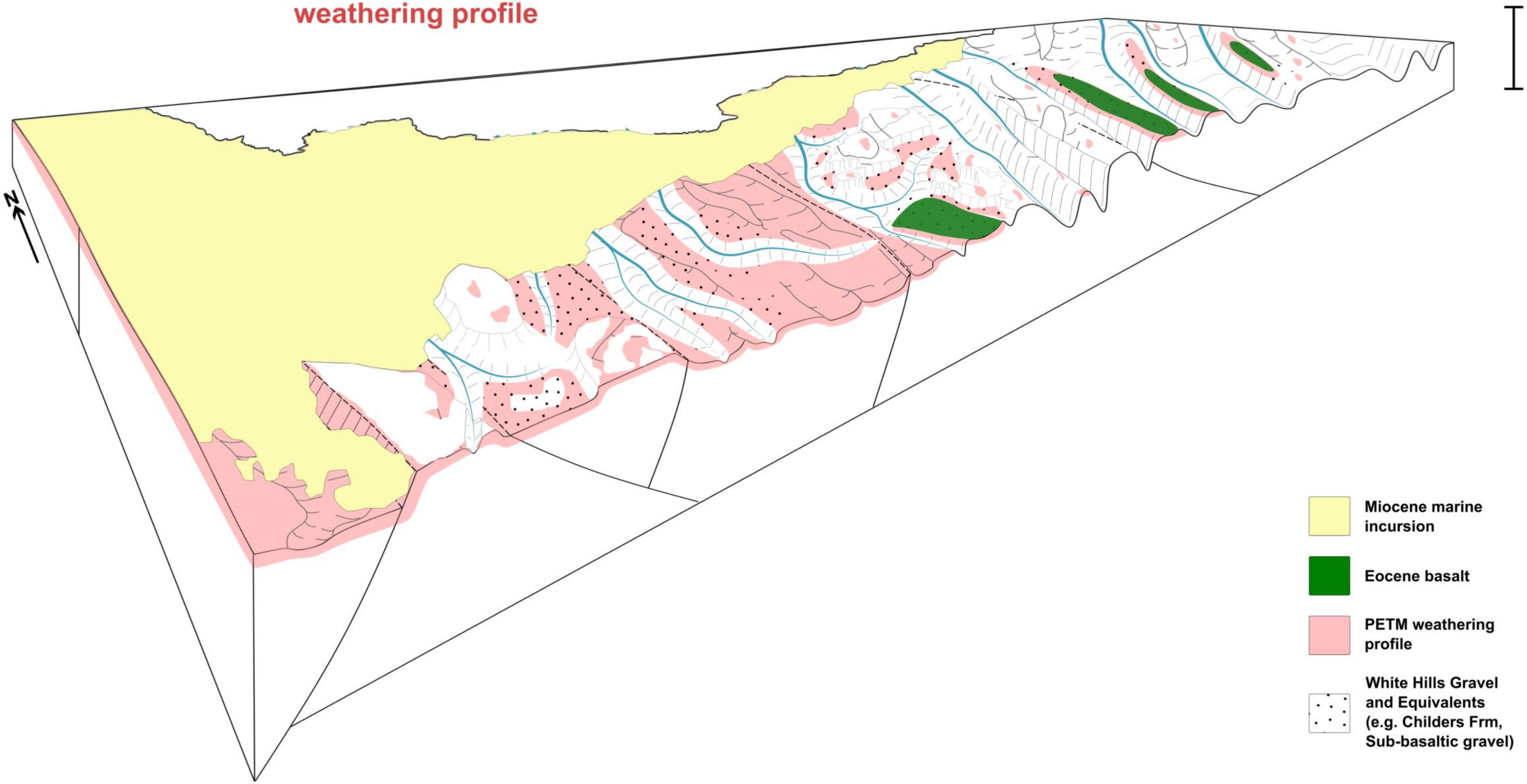
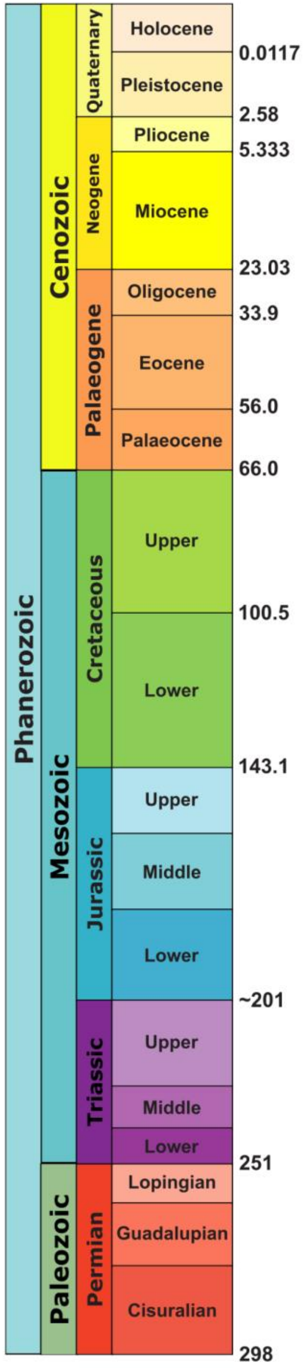


Adapted from Andrews & Cayley, 2025

Regional subsidence and marine incursion

Burial and destruction of Permian and PETM weathering profile

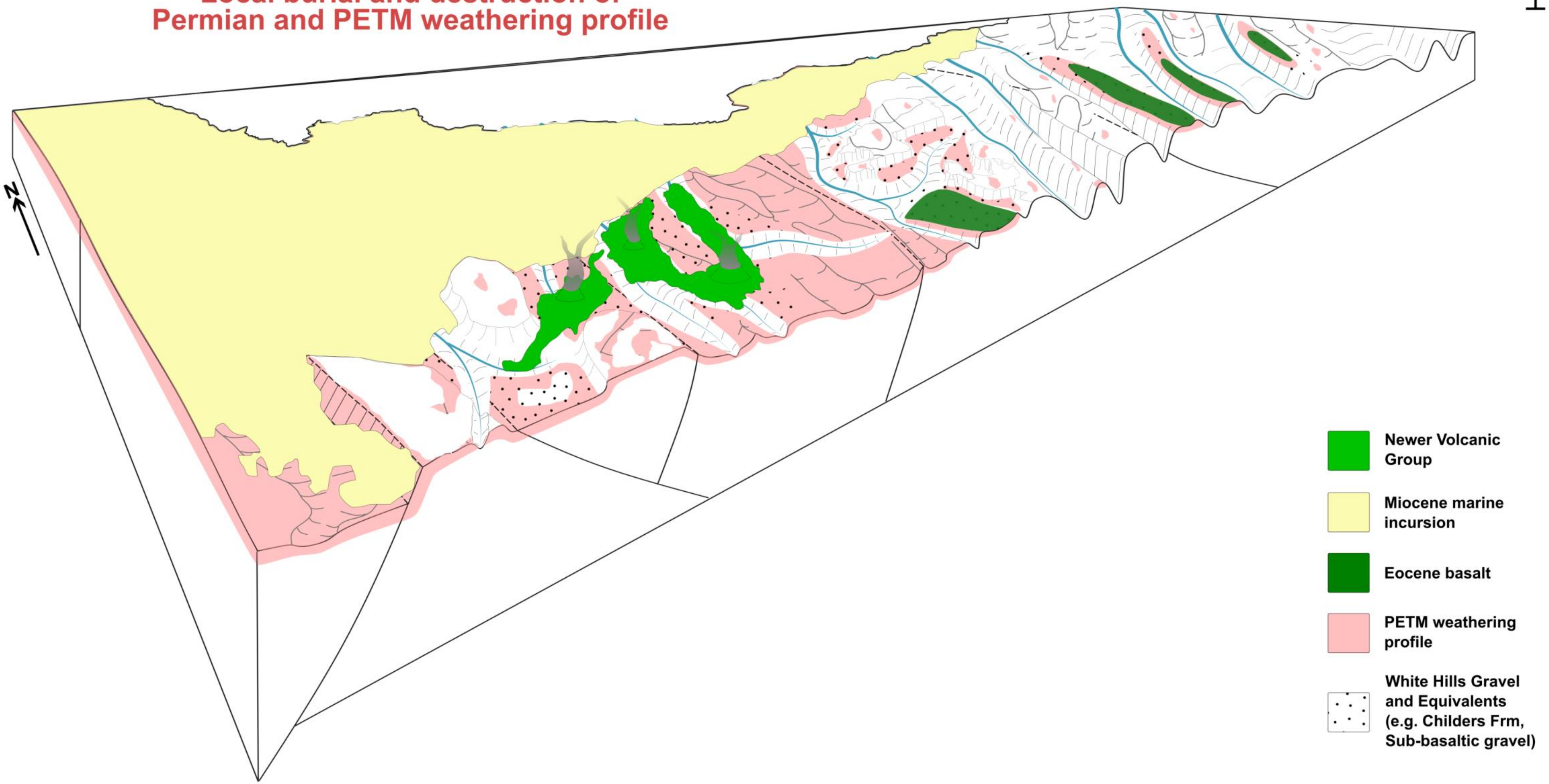


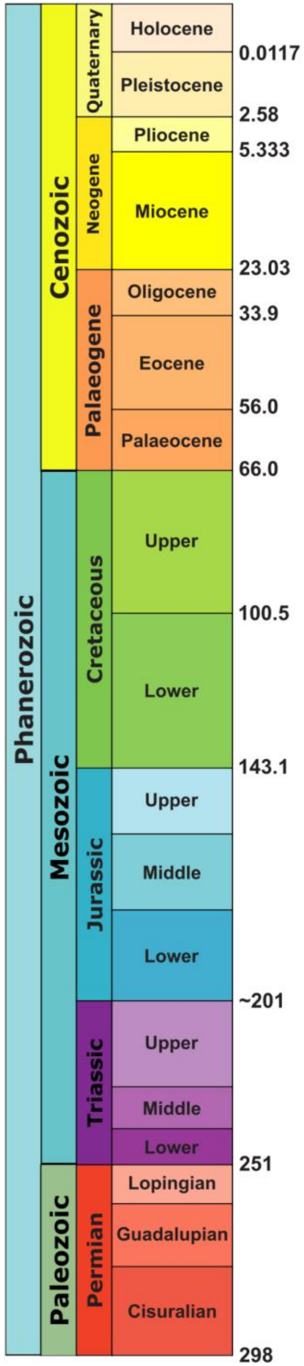


Adapted from Andrews & Cayley, 2025

Eruption of Newer Volcanic Group

Local burial and destruction of Permian and PETM weathering profile





Adapted from Andrews & Cayley, 2025