Astrobiology
AT THE UNIVERSITY OF WASHINGTON

Squeezing Blood from a Stone

Inferences into the Life & Depositional Environments

of the Early Archaean

University of St. Andrews

September MMXII

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Overview

Objective		
Context	Geological Time	
	The Rock Record	Field areas
		Greenstone belts
	‘Organic’ Matter	
Depositional Settings	Isua meta-turbidite	
	Coonterunah meta-carbonate	
	Strelley Pool Chert	Bedded units
		Neptunian fissures
	Hooggenoeg Formation	
Synthesis	Carbon cycling	
Conclusion	Astrobiological implications	

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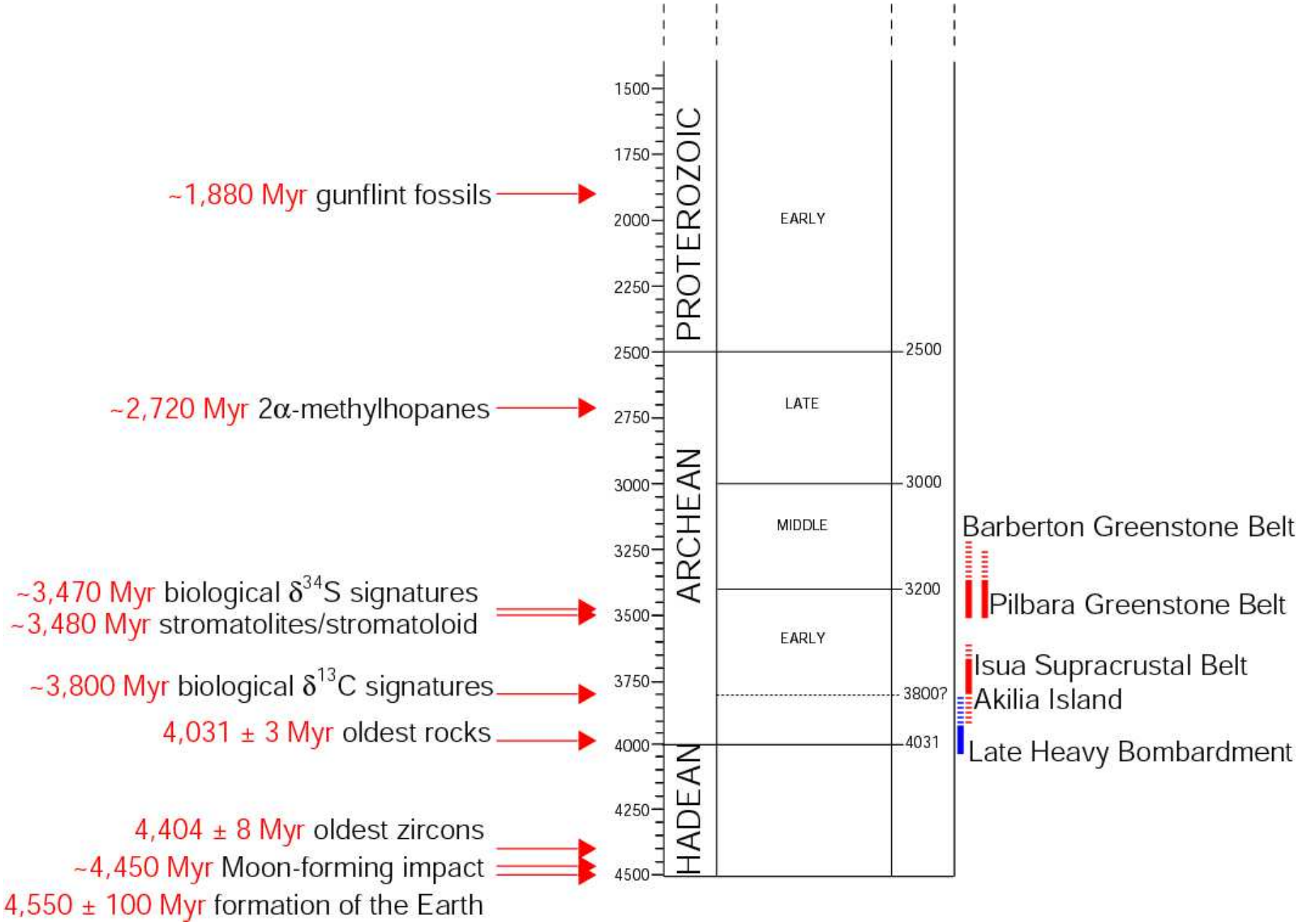
Objective

Search the oldest well-preserved sedimentary rocks for geological evidence of/for:

- biological processes
- the nature of depositional environments

Geological Time



Geological Time

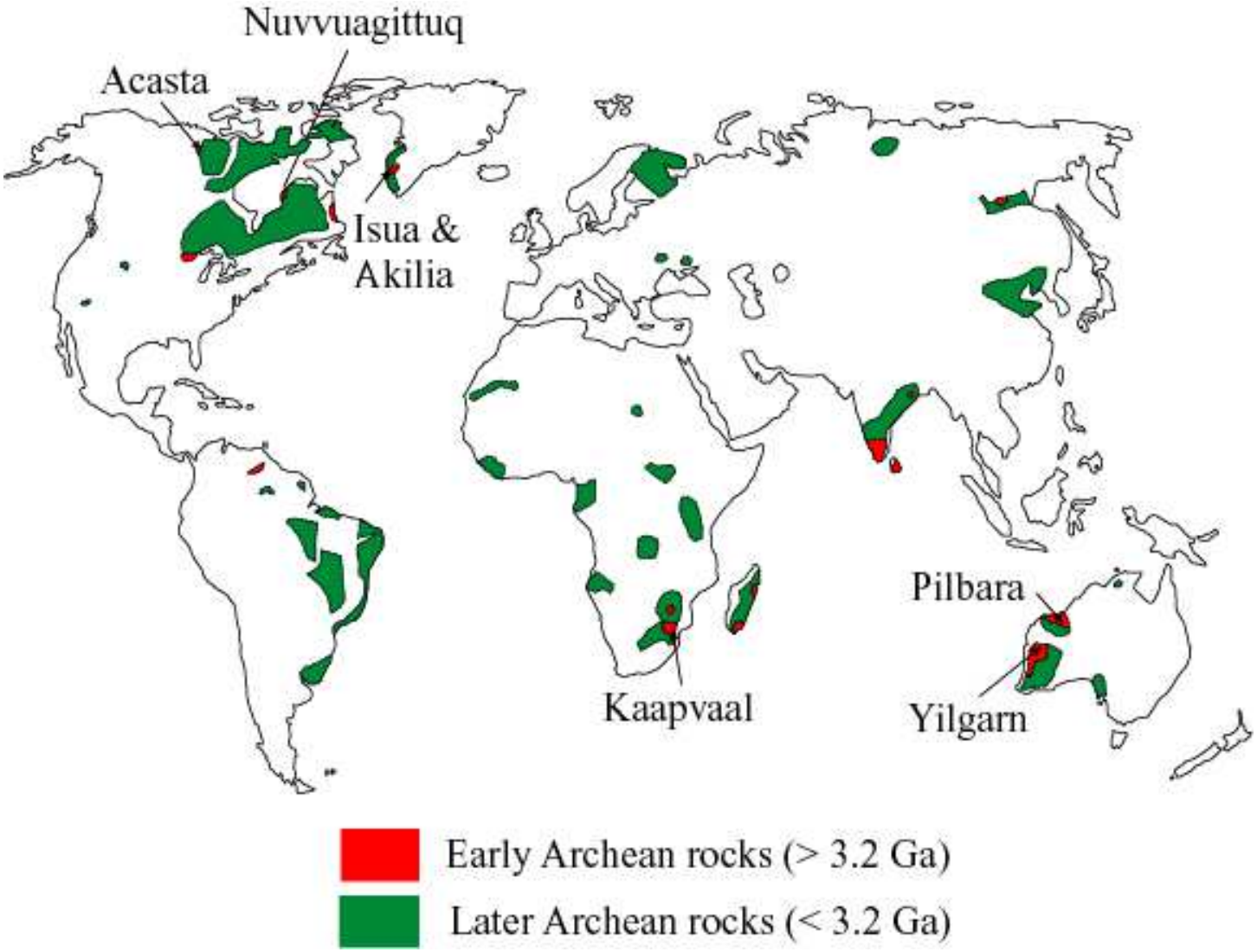
"An attempt to explain the former changes of the Earth's surface by reference to causes now in operation"

- Subtitle to Charles Lyell (1830-1833), *Principles of Geology*

"[In geology] no powers are to be employed that are not natural to the globe, no action to be admitted except those of which we know the principle."

- James Hutton (1785)

The Rock Record



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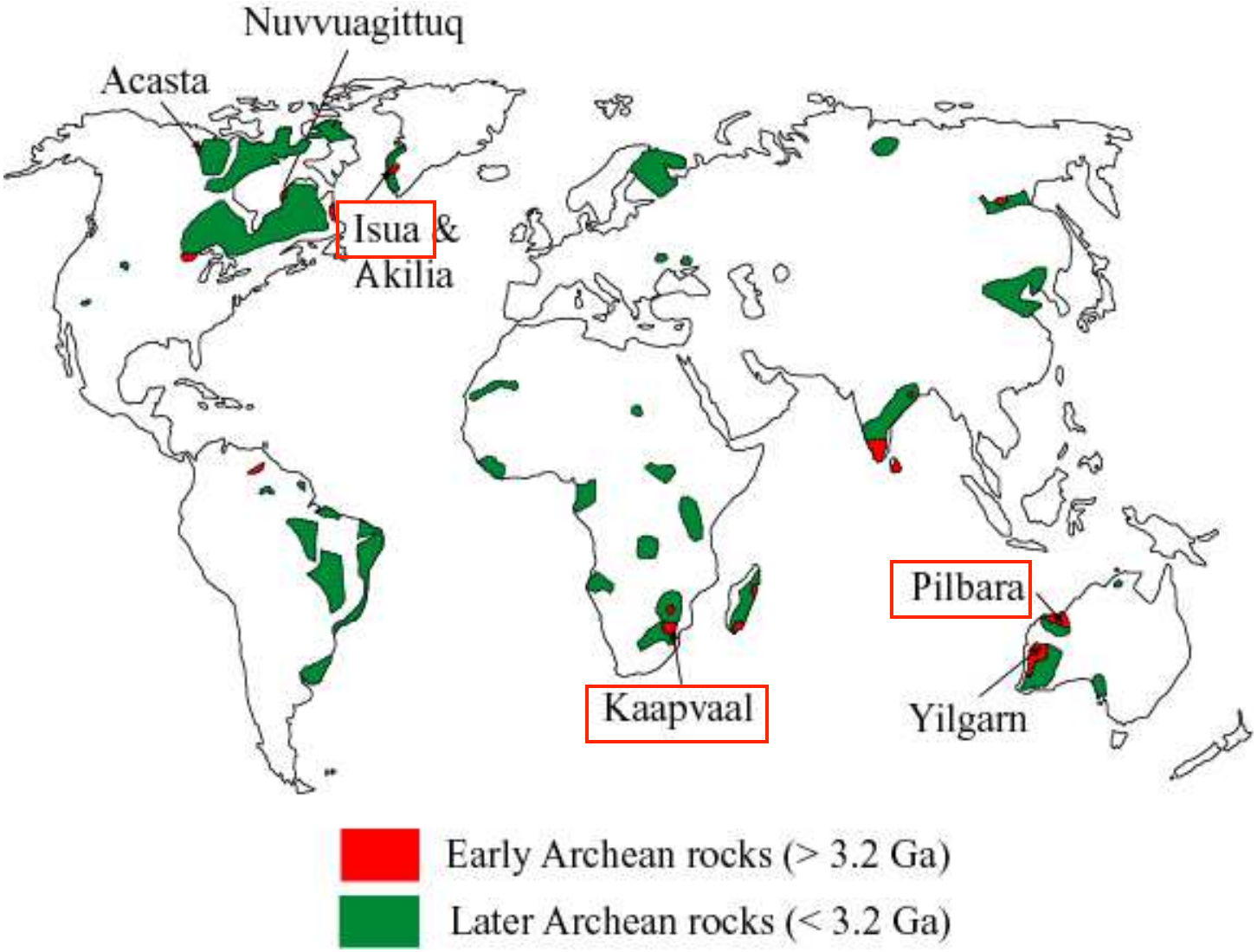
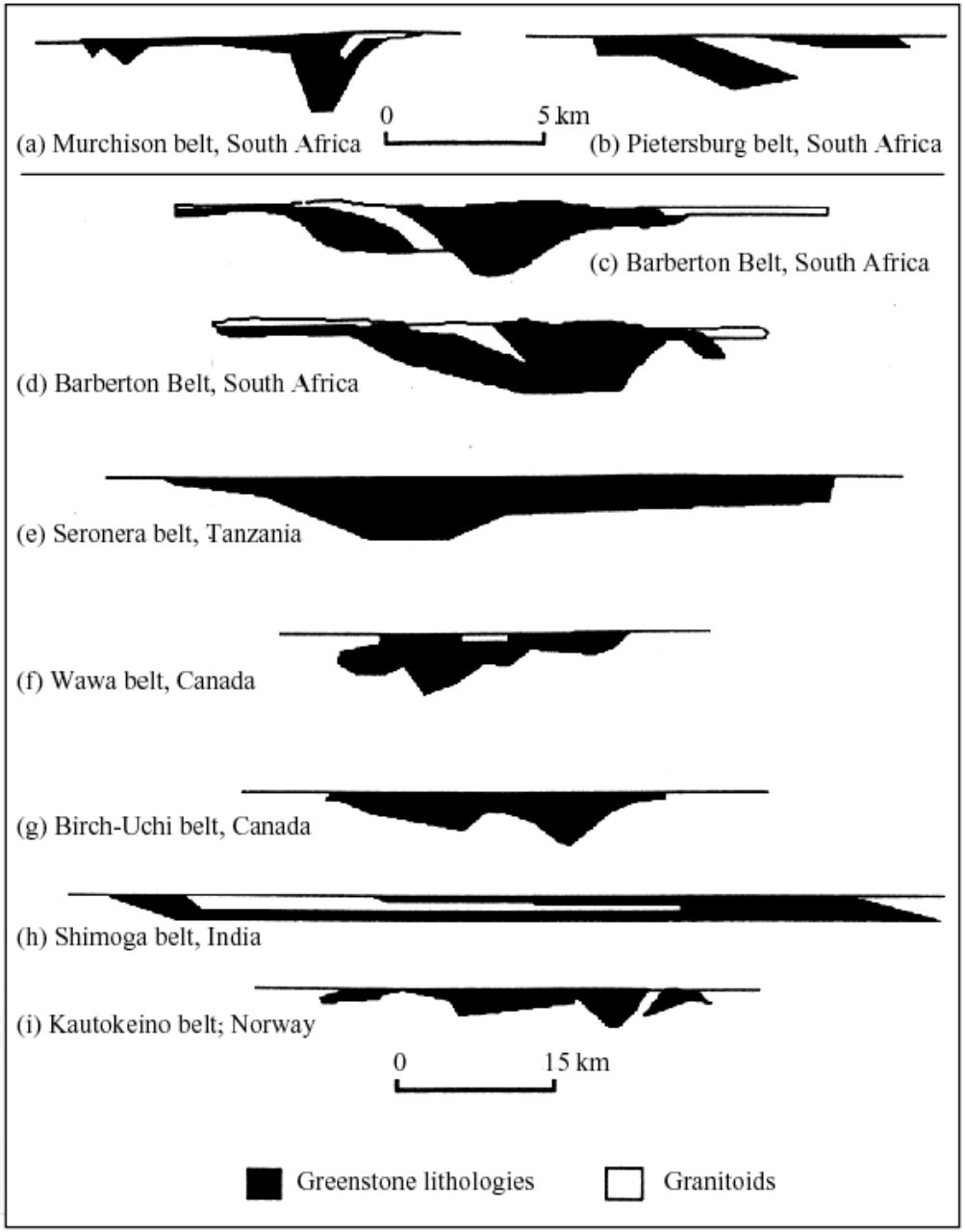


Greenstone Belts

Greenstone Belts



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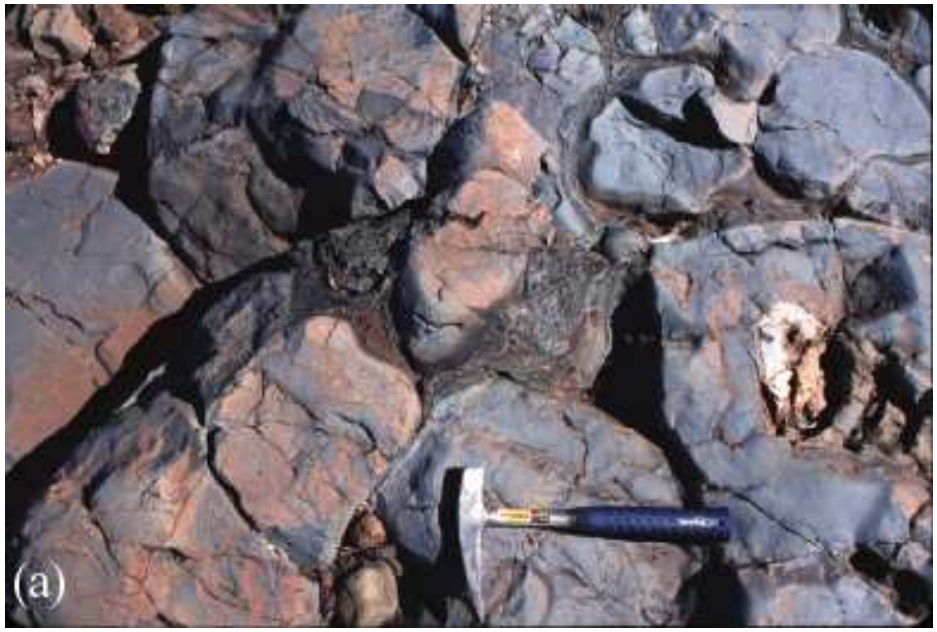
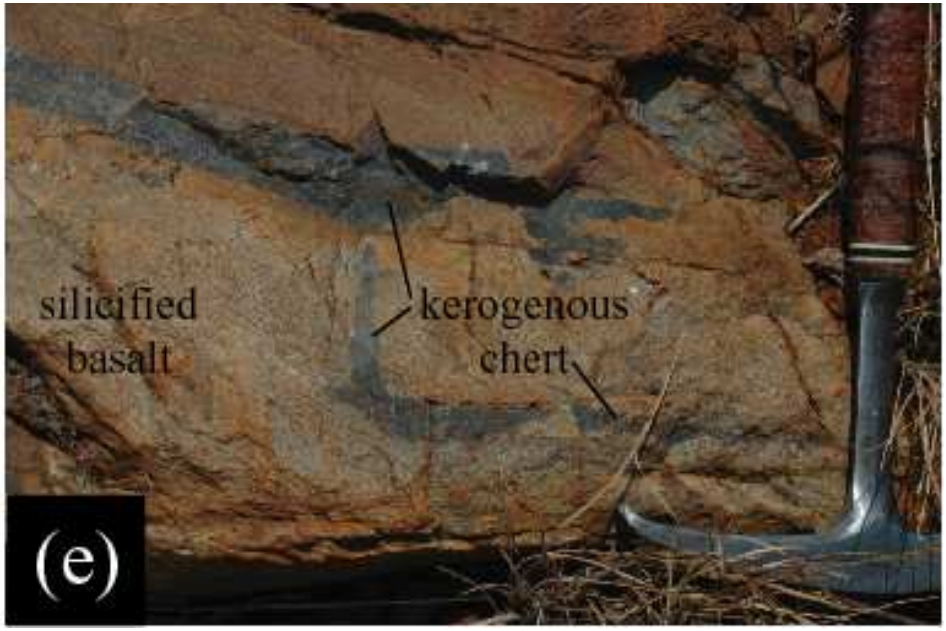


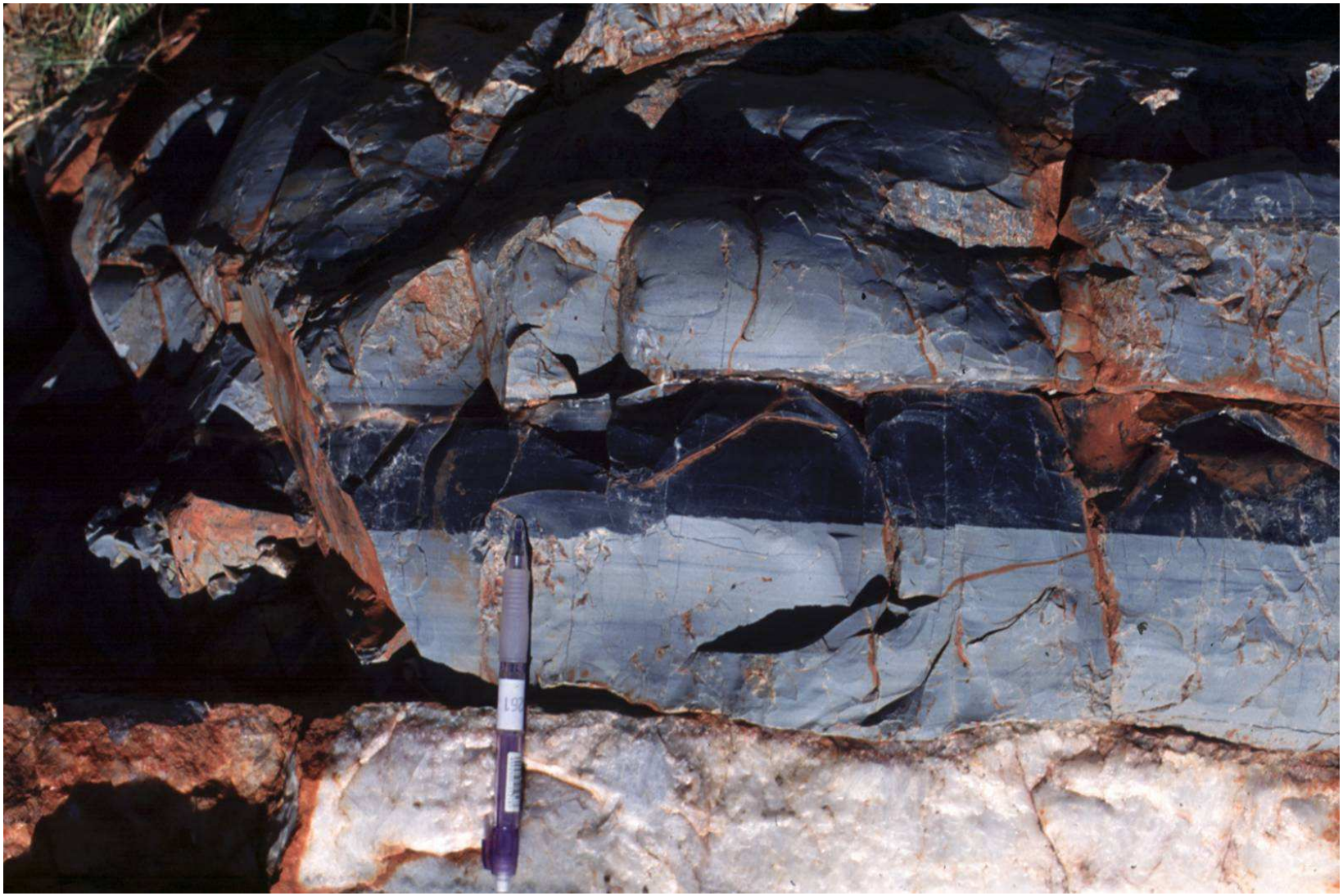
‘Organic’ Matter

H2C banded chert member, Hooggenoeg Fm., Barberton



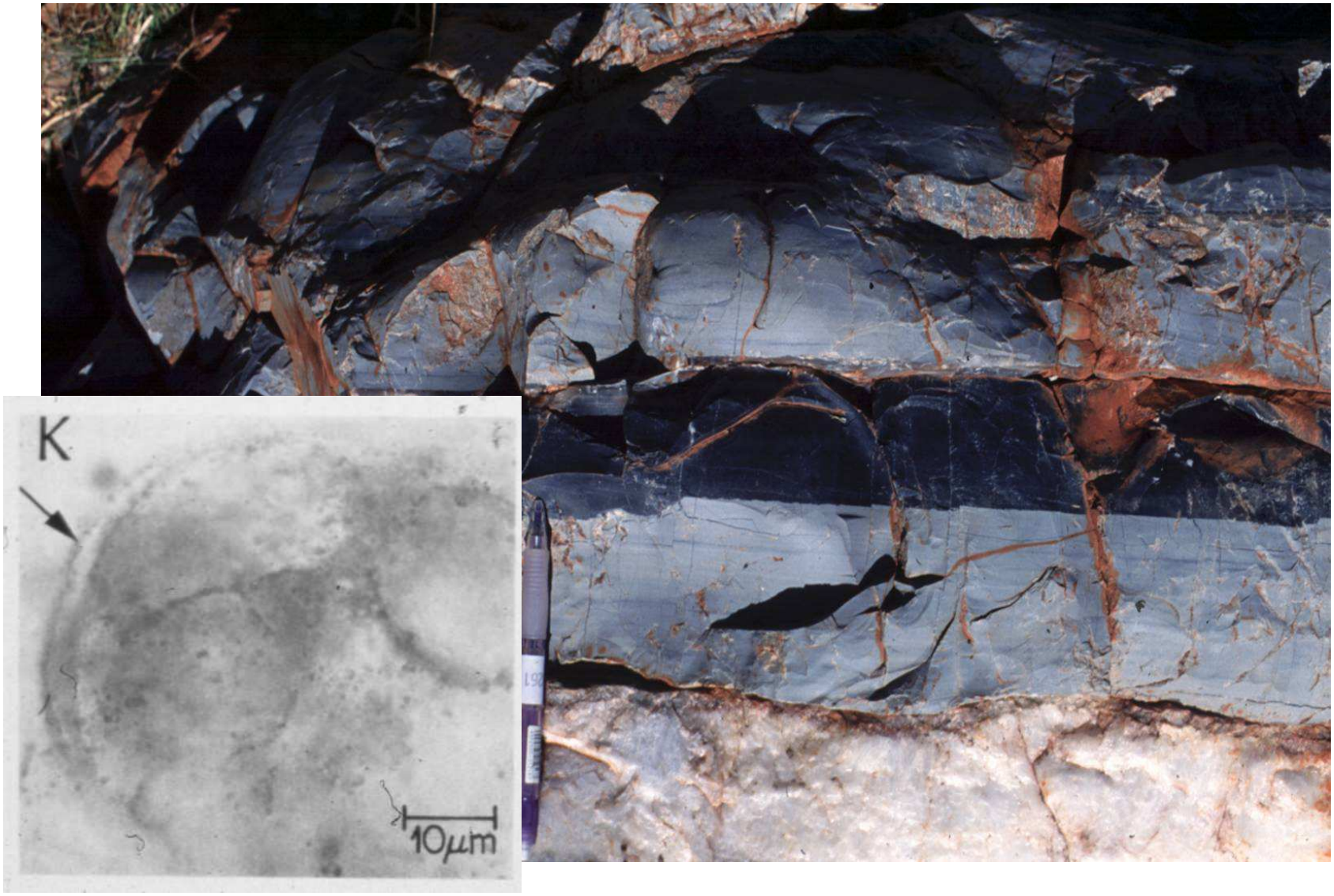
- Insoluble hydrocarbon material (kerogen) is common
- Much of it is post-sedimentary

‘Organic’ Matter



Putative microfossil locale in Euro Basalt, Pilgangoora Belt

‘Organic’ Matter



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Syn-sedimentary kerogen, Coucal Fm., Pilbara

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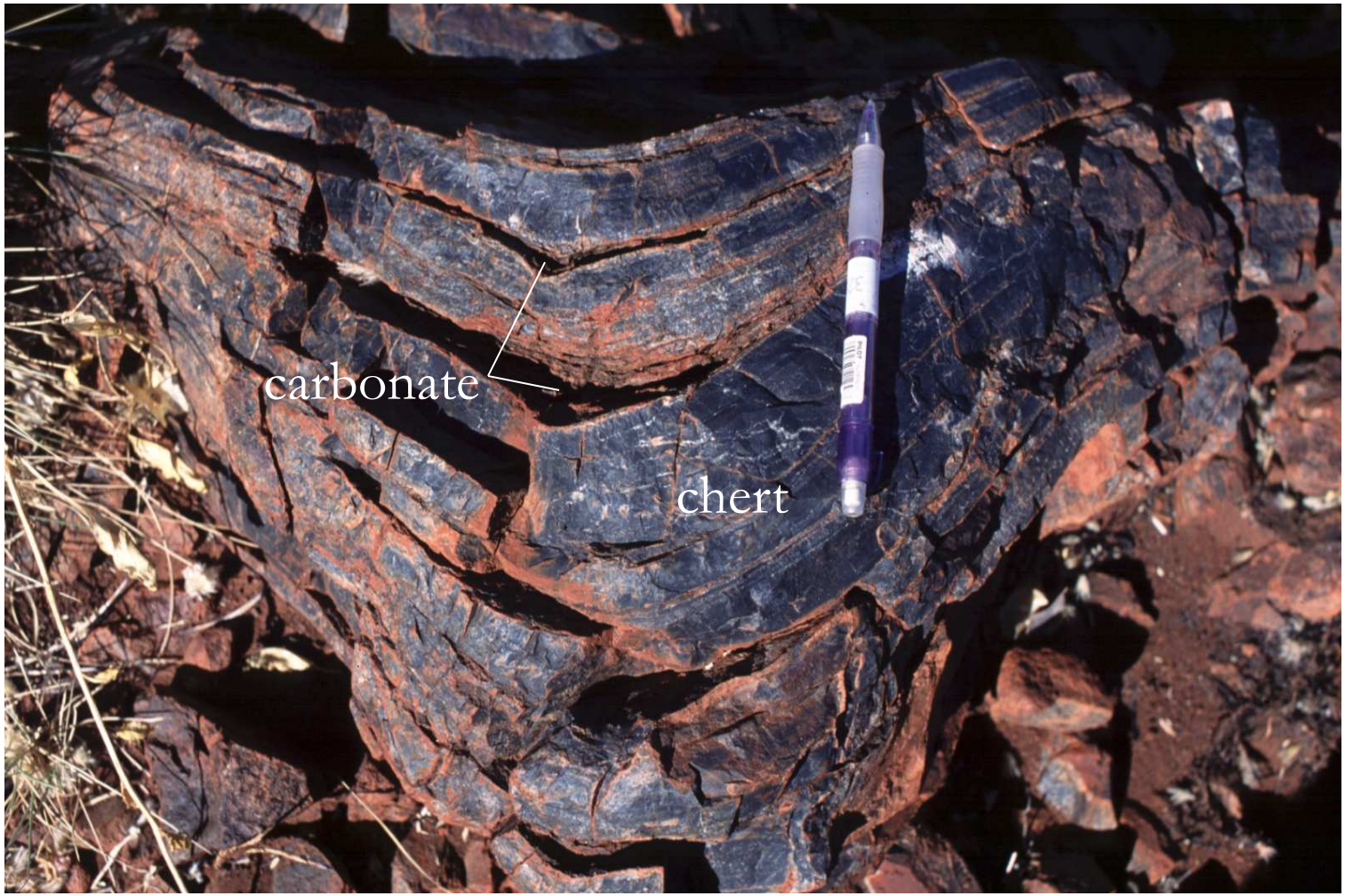
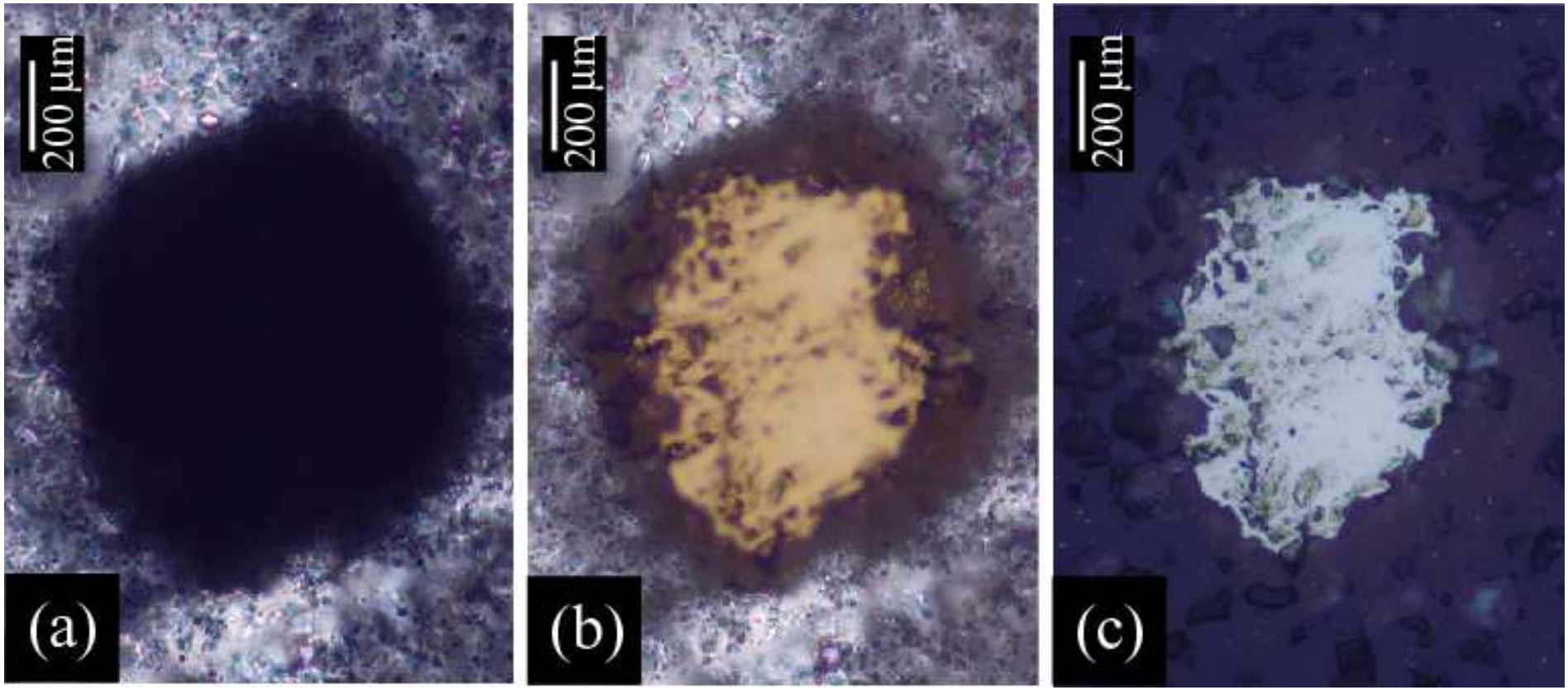
Syn-sedimentary kerogen, Coucal Fm., Pilbara



- Carbonate replacement by silica
- Requires carbonate dissolution and high [Si(aq)]

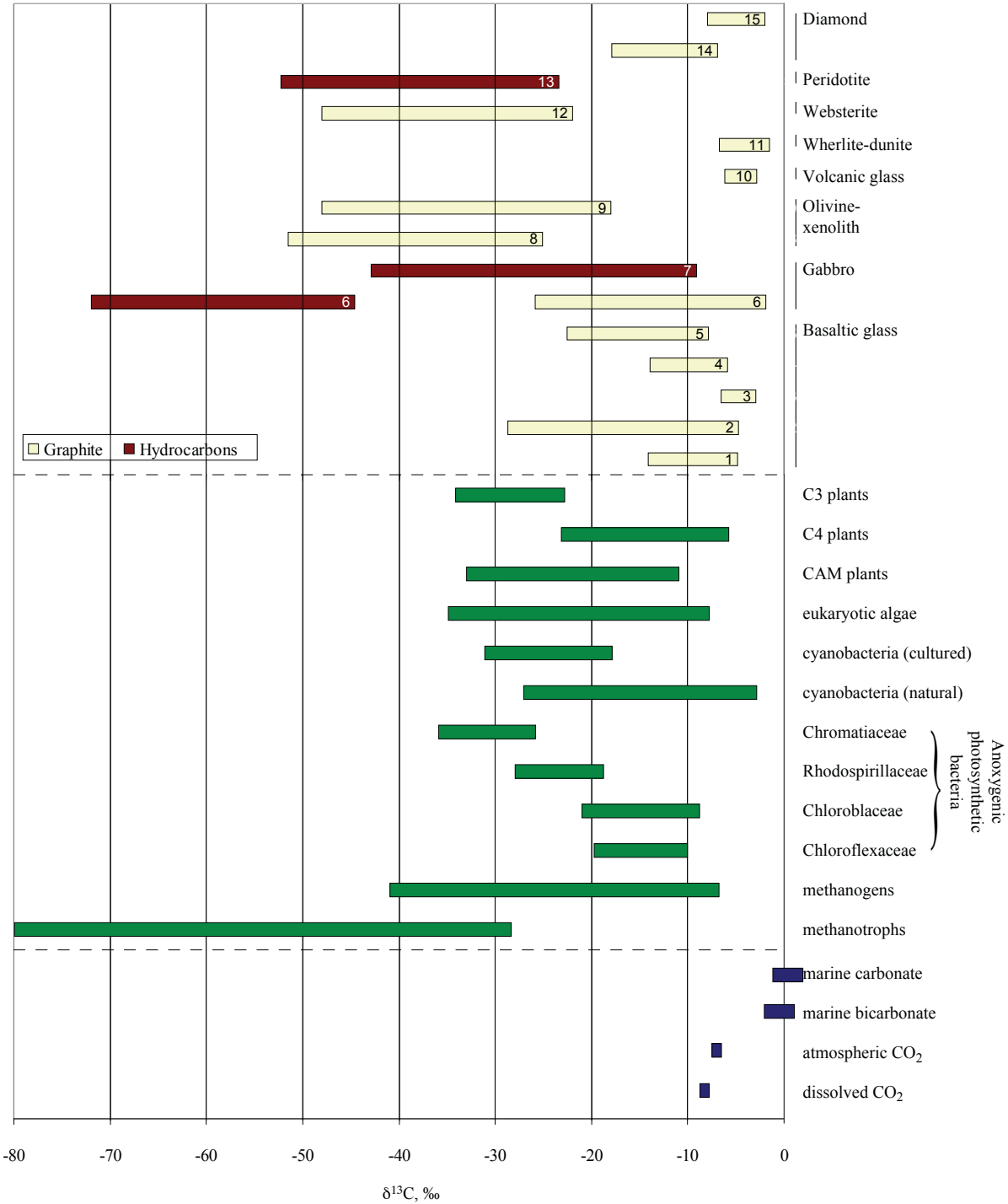
‘Organic’ Matter

Kerogen-coated pyrite, Strelley Pool Chert, Pilbara



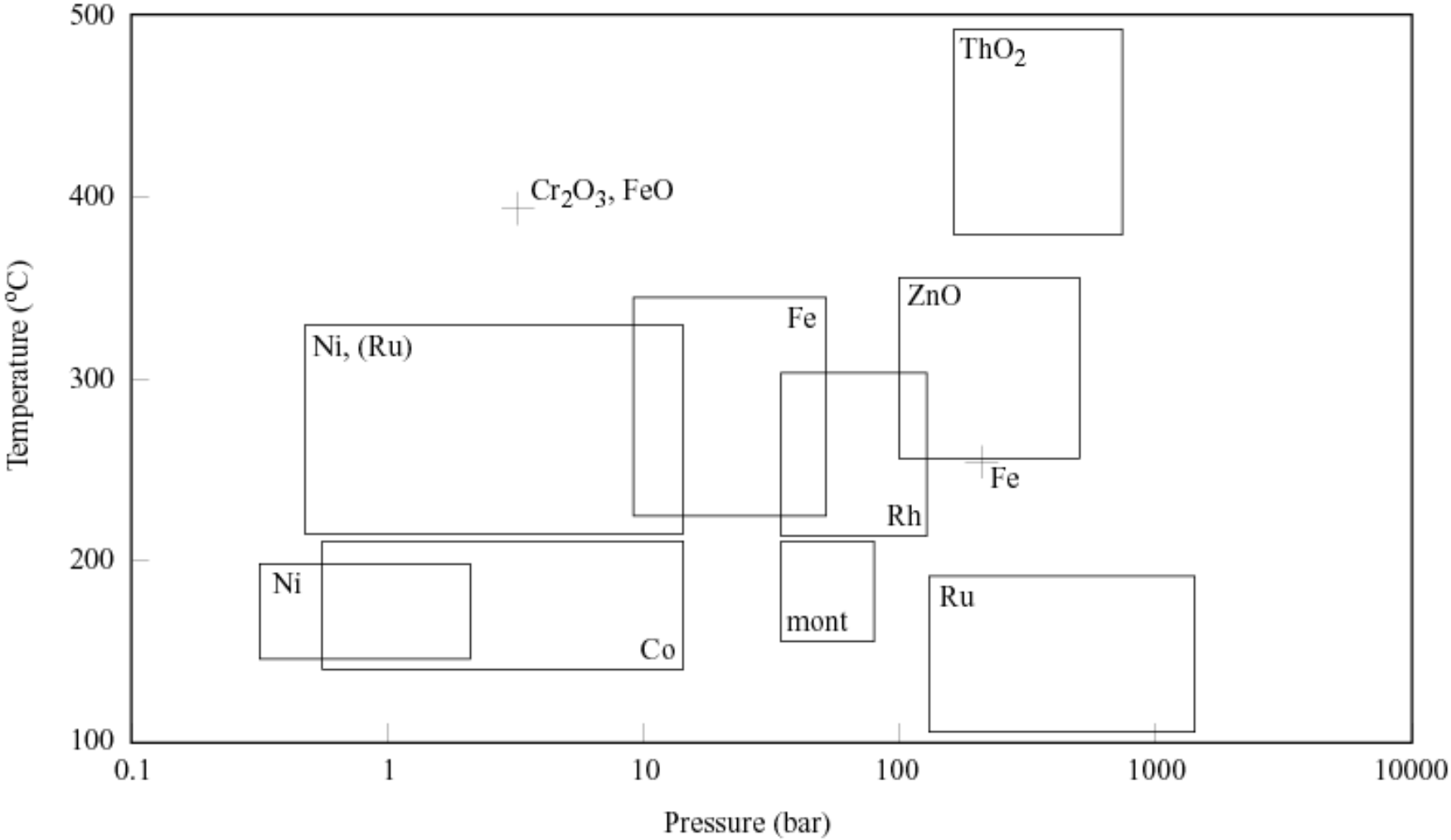
- Common diagenetic association

Carbon Isotopics



Fischer-Tropsch Synthesis

$$n\,CO + (2n+1)\,H_2 \rightarrow C_nH_{(2n+2)} + n\,H_2O$$



- Organic matter ≠ Life

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Field Areas

Craton / Terrain	Belt	Location	Age (Ga)	Formation	Setting
Isua	Isua Supracrustal Belt	S.W. Greenland	3.7 – 3.8	[to be named]	Deep marine
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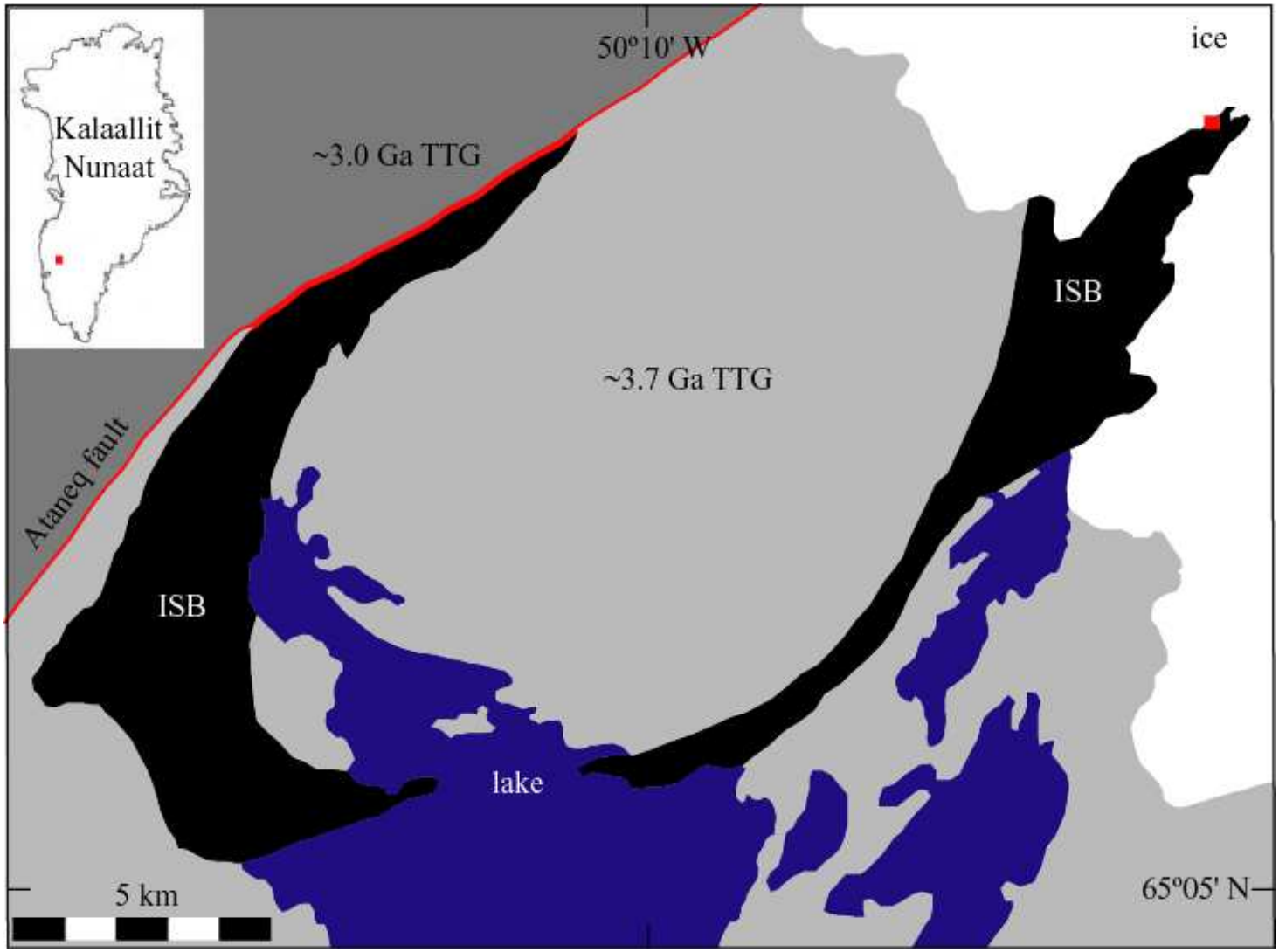
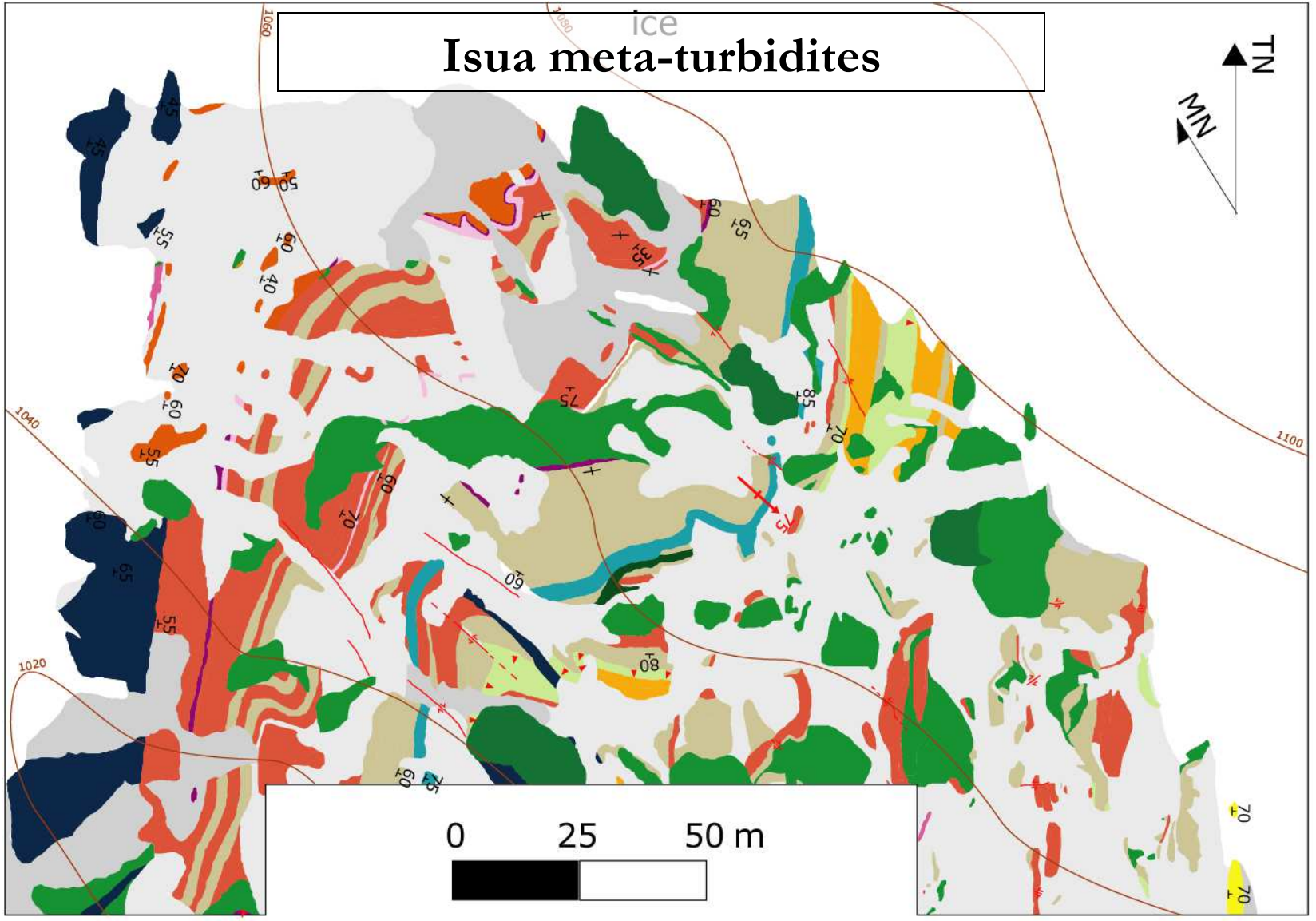
Isua Supracrustal Belt

Isua Supracrustal Belt



- Dominantly lower to upper amphibolite facies
- Nature of protoliths controversial



Post-Archean

- Ice
- Scree
- Moraine
- Carbonate

Metasediments

- Banded iron formation
- Biotite-chlorite schist
- Greywacke
- Sandstone
- Siltstone
- Quartzite
- Conglomerate
- Silicified greywacke

Metaintrusives

- Amphibolite
- Ultramafic
- Gabbro
- Mafic dyke
- Quartz dyke

Miscellaneous

- 1080 Contours and elevation (m)
- Fault
- Sedimentary grading
- Antiform trace
- Dip & strike

Isua meta-turbidites

Banded magnetite-chert clast in conglomerate

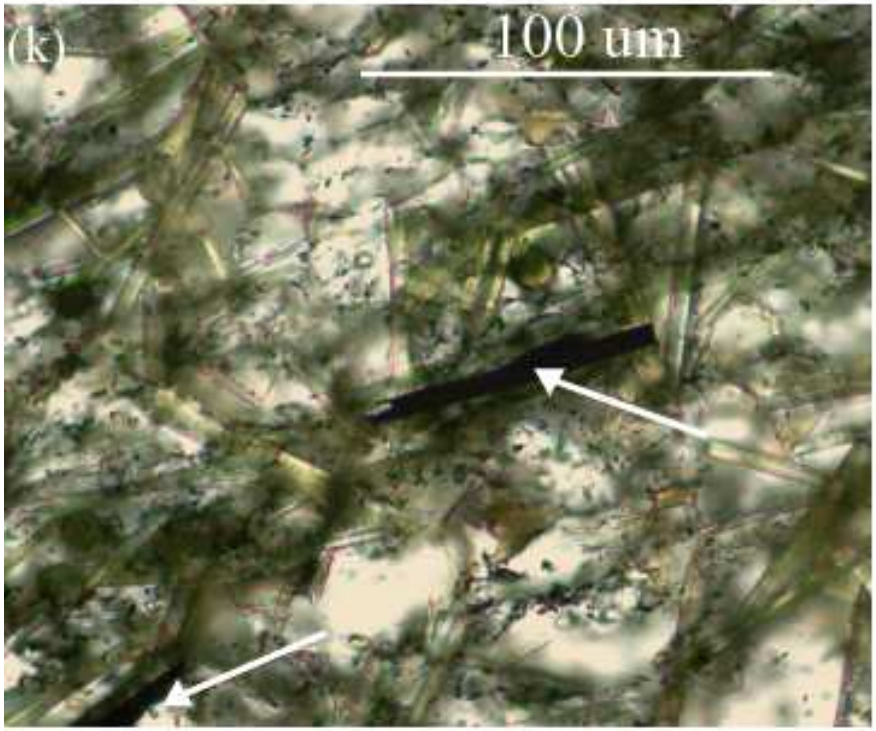
- Well-preserved clastic sedimentary textures
- High Fe, Si

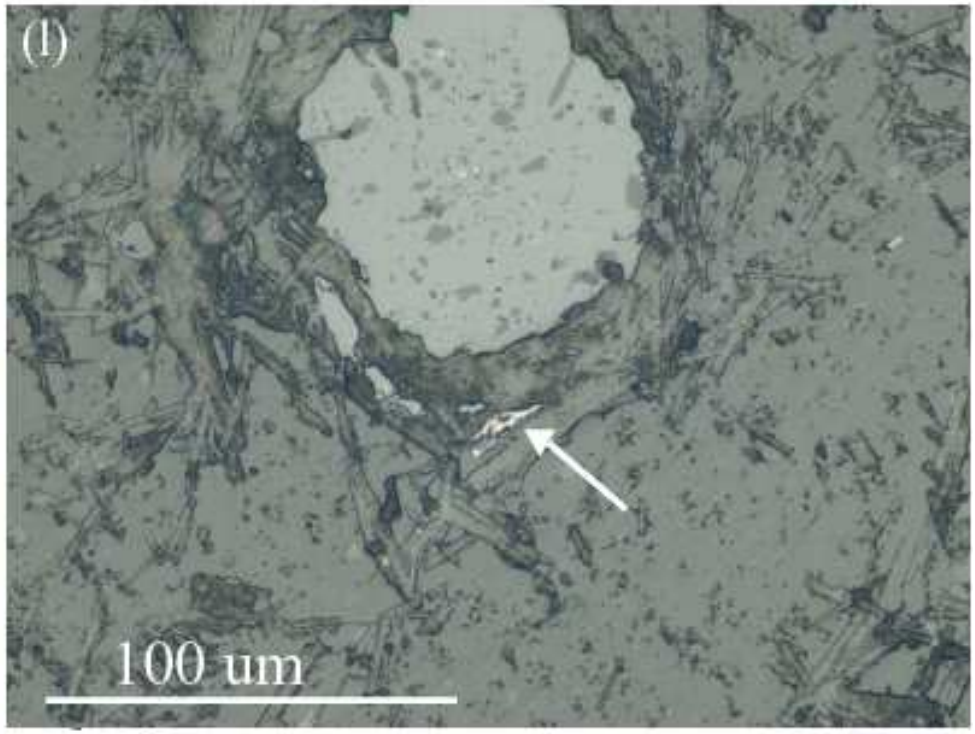
Isua meta-turbidites

Wavy-laminated biotite-chlorite-quartz schist

- K-feldspar → chlorite weathering
- Detrital zircon U-Pb date: 3817 ± 3 Ma

Isua graphite





- Graphite present in small amounts
- Not associated with carbonate
- Metasomatic vein graphite $\delta^{13}C_{org}$ = -12.1 ± 0.1‰
- Meta-turbidite graphite $\delta^{13}C_{org}$ = -19.6 ± 0.3‰ (best value)

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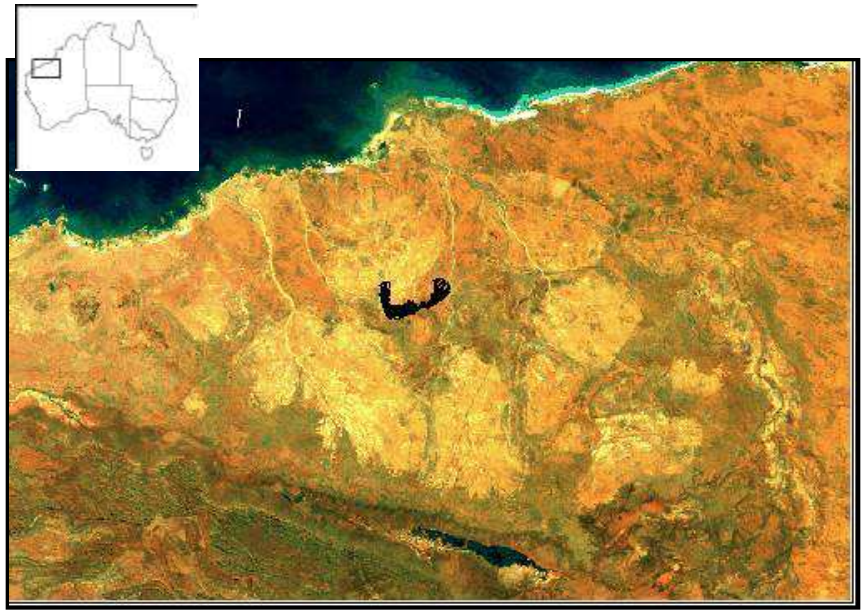
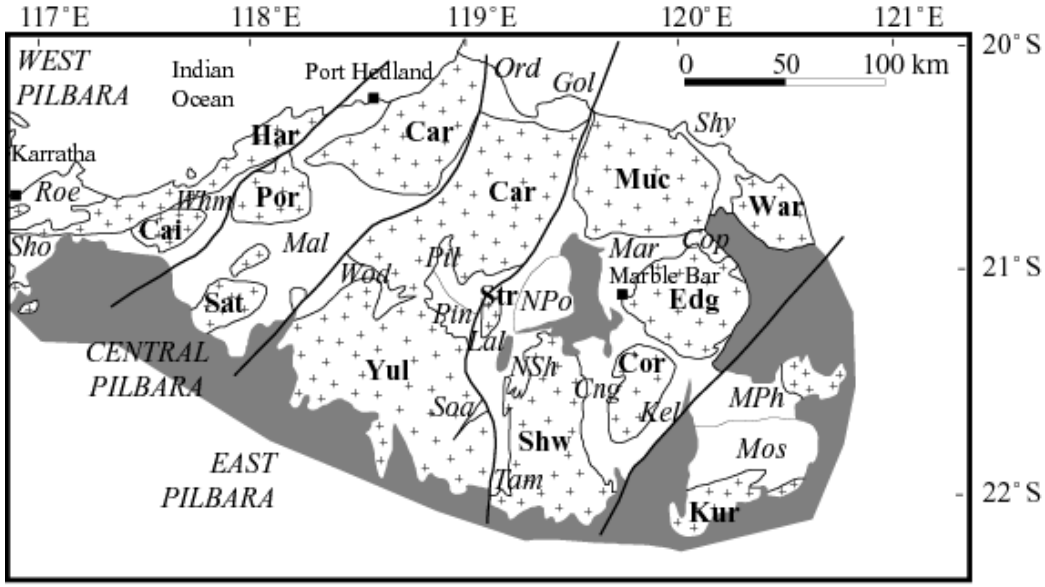
Pilgangoora Belt & Environs

Pilbara granite-greenstone belts





Fortescue Group

Granitoid Suites / Gneiss Complexes

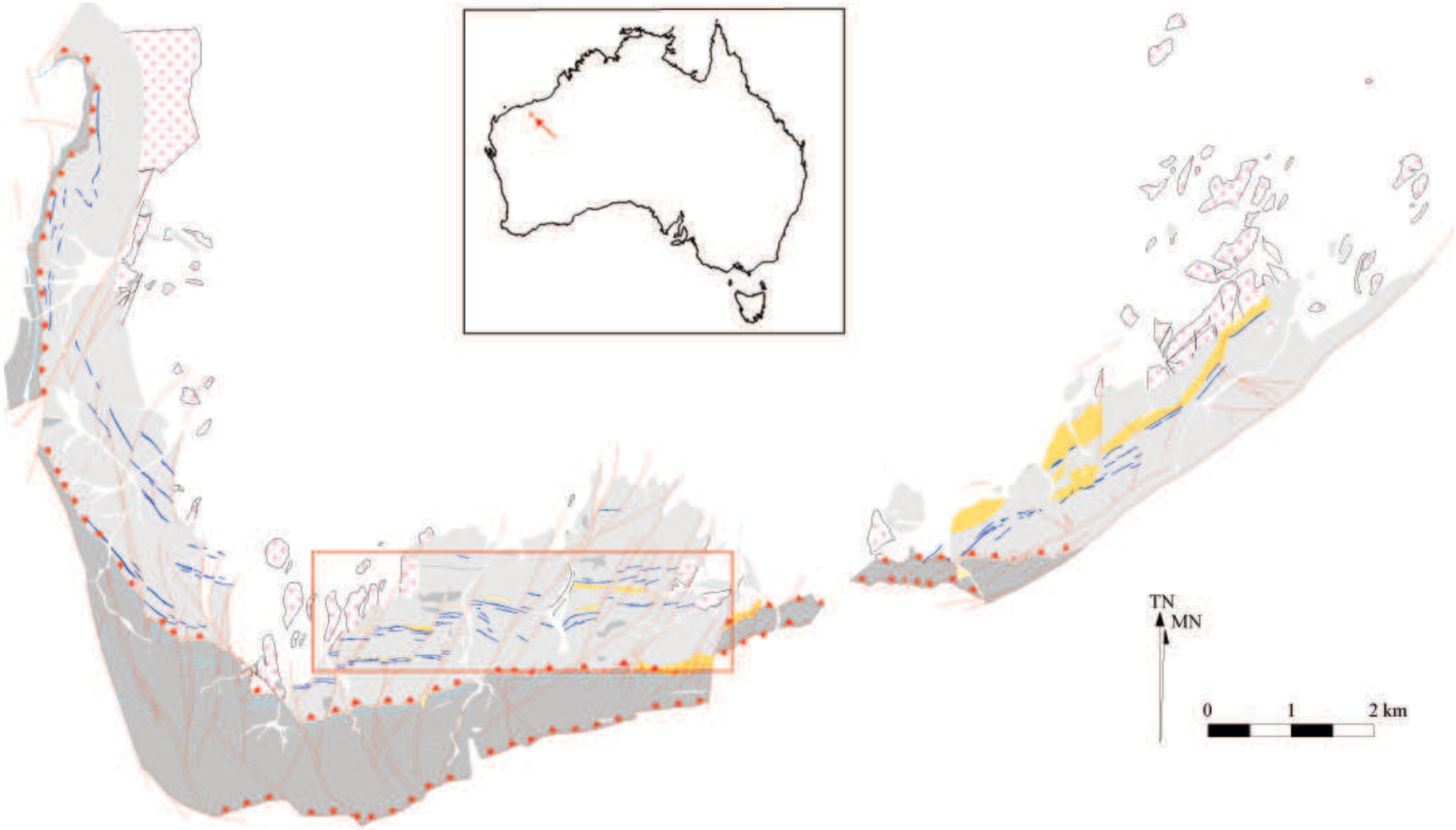
Cai	Caines Well	**Por**	Porree
Car	Carlindi	**Sat**	Satirist
Cor	Corunna Downs	**Shw**	Shaw
Edg	Mount Edgar	**Str**	Strelley
Har	Harding	**War**	Warrawagine
Kur	Kurrana	**Yul**	Yule
Muc	Muccan		

Greenstone Belts

Cng	Coongan	*Ord*	Ord
Cop	Coppin Gap	*Pil*	Pilgangoora
Gol	Goldsworthy	*Pin*	Pincunah
Kel	Kelly	*Roe*	Roebourne
Lal	Lalla Rookh	*Shy*	Shay Gap
Mar	Marble Bar	*Sho*	Sholl
Mal	Mallina	*Soa*	Soanesville
MPh	McPhee	*Tam*	Tambina
Mos	Mosquito Creek	*Whm*	Whim Creek
NPo	North Pole	*Wod*	Wodgina
NSh	North Shaw		

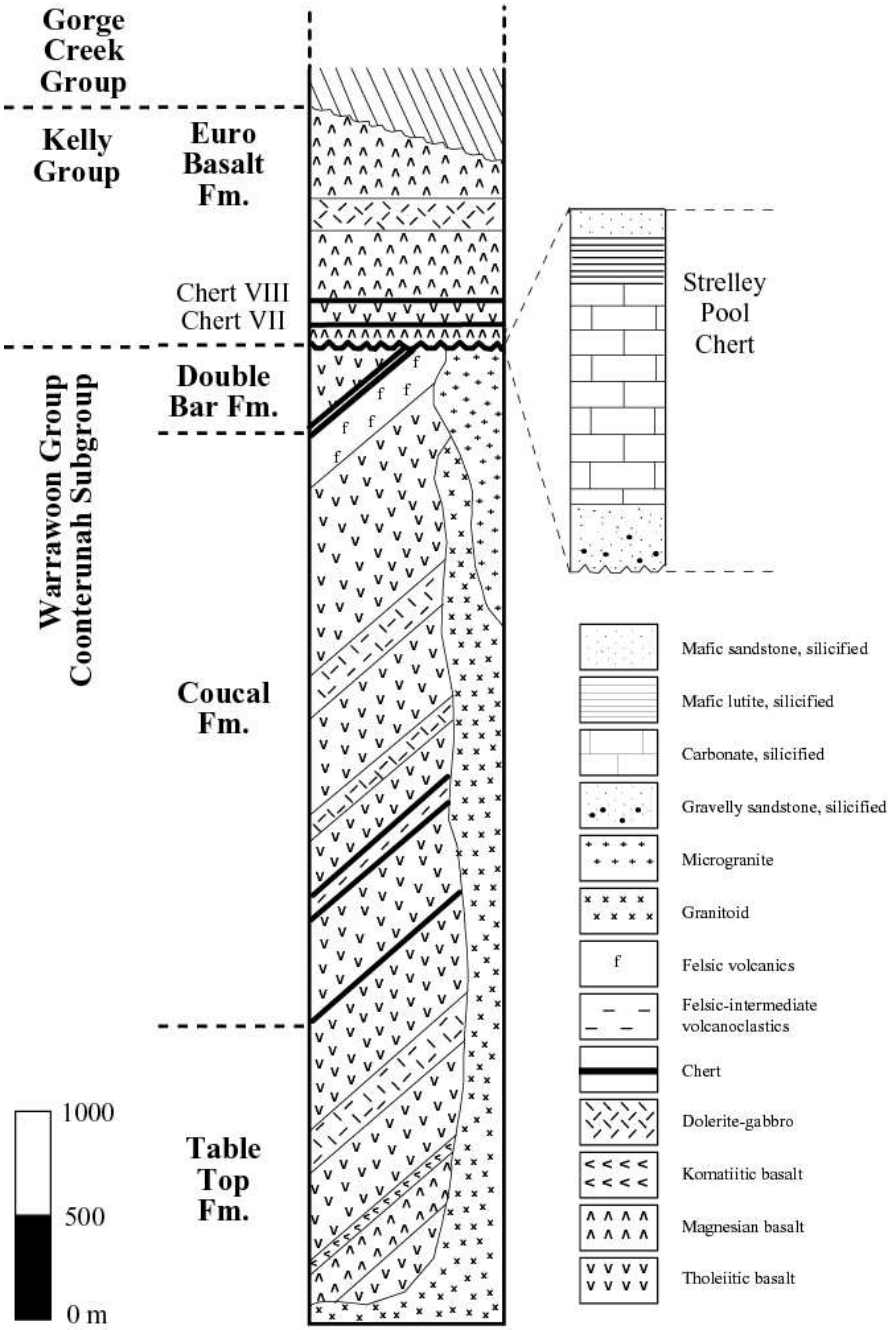
The Pilgangoora Belt

The Pilgangoora Belt

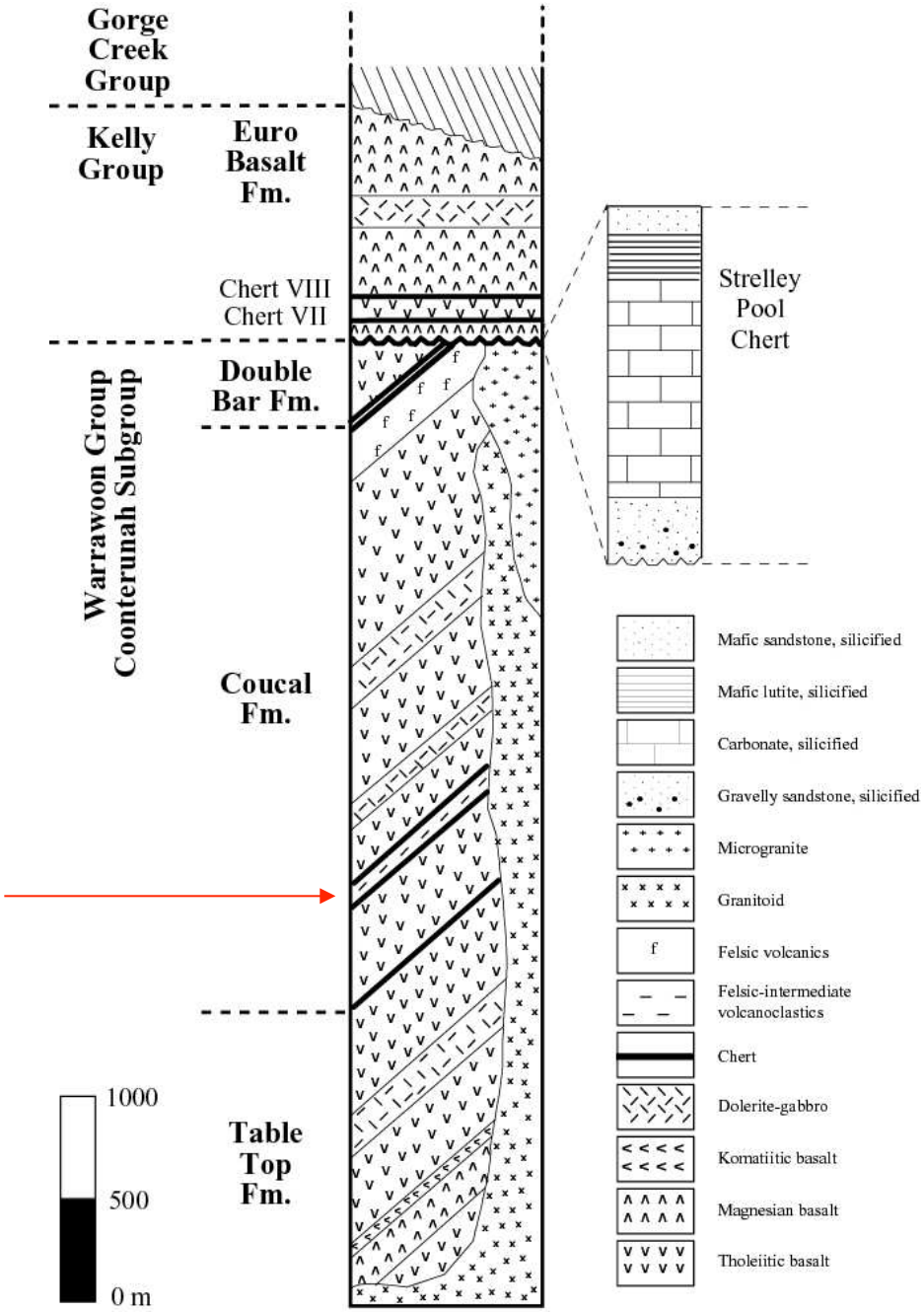


	IGNEOUS ROCKS	SEDIMENTARY ROCKS	STRUCTURAL FEATURES
Kelly Group	Mafic rocks	Strelley Pool Chert Euro Basalt cherts	Fault
Warrawoona Group	Mafic rocks	Coonterunah Chert	Unconformity
	Granitoid		
	Felsic volcanic		

The Pilgangoora Belt



Coonterunah Carbonate



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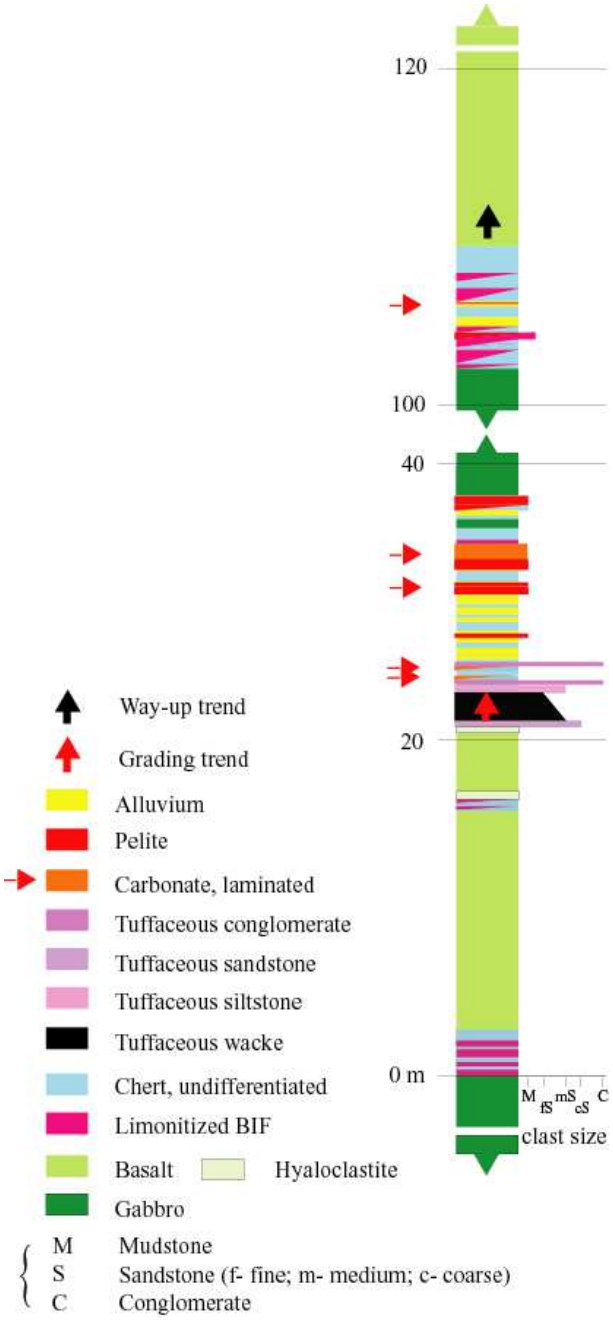

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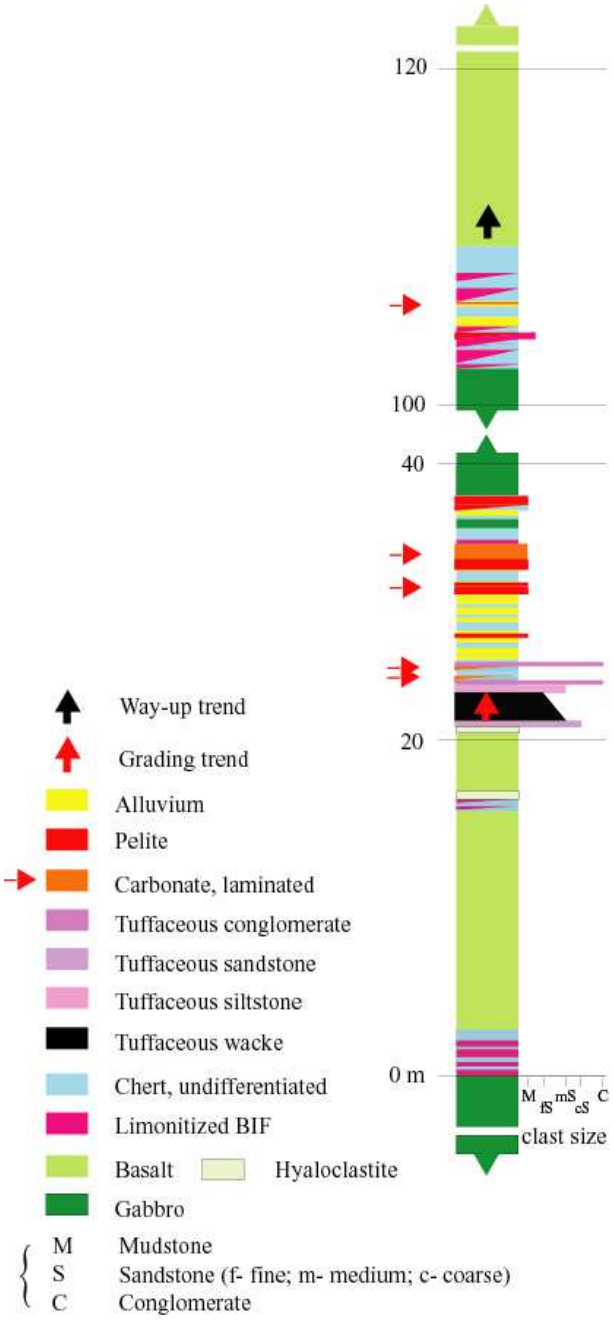
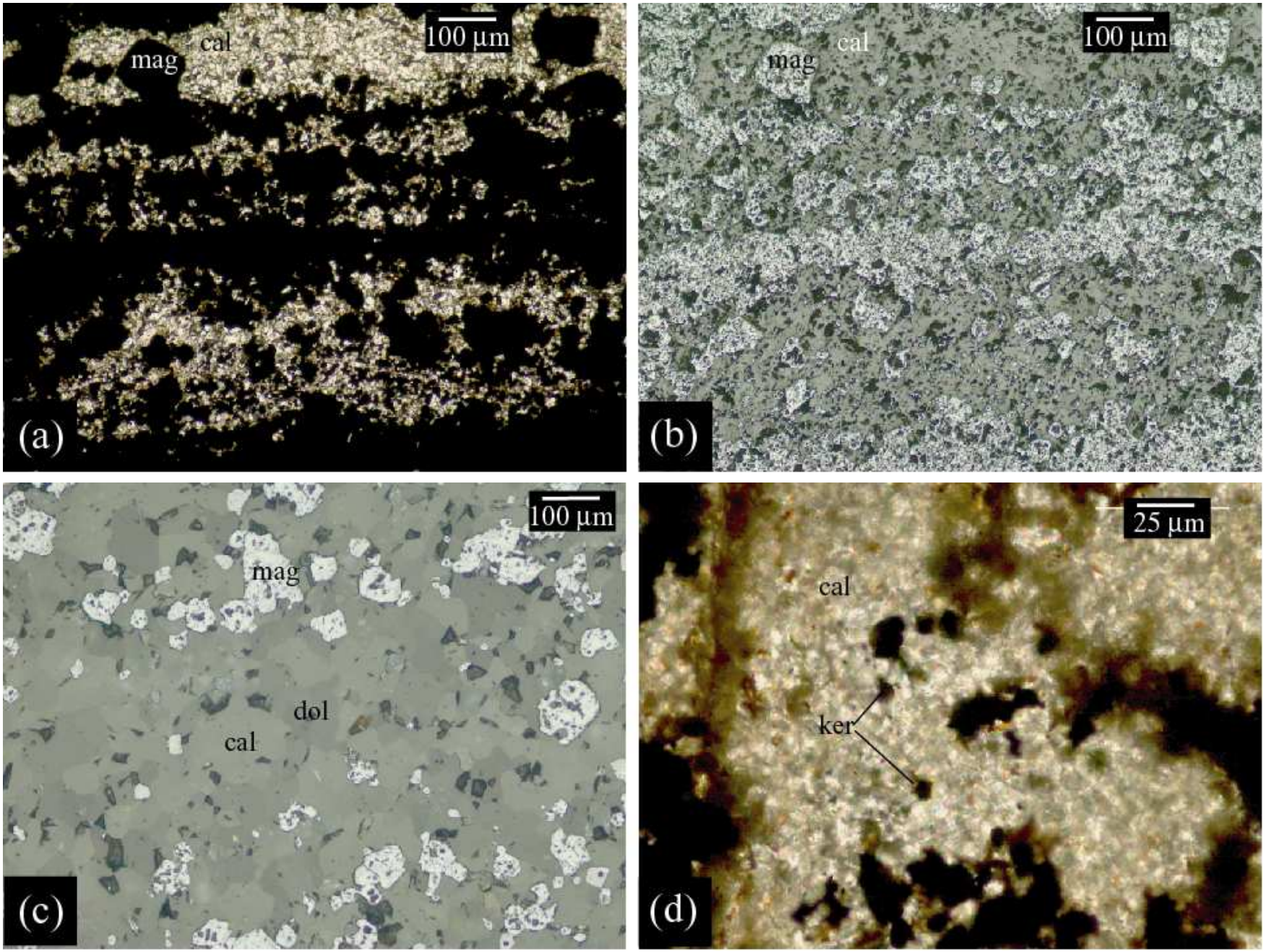


- ~35m of rhyolite-andesite tuffs
- Very low terrigenous clastic input
- No hydrothermal overprint

Coonterunah Carbonate

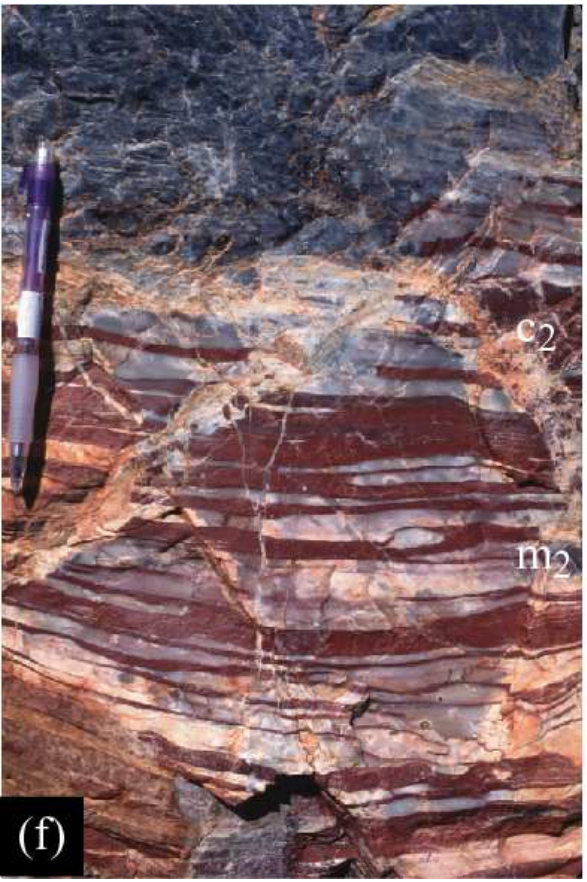
- Laterally extensive, ~ 5km
- Rare magnetite-calcite mineralogy
- Variably dolomitized
- Precipitate origin for carbonate
- Kerogenous, $\delta^{13}C_{org} = -26.1 \pm 2.4$ ‰

Coonterunah Carbonate



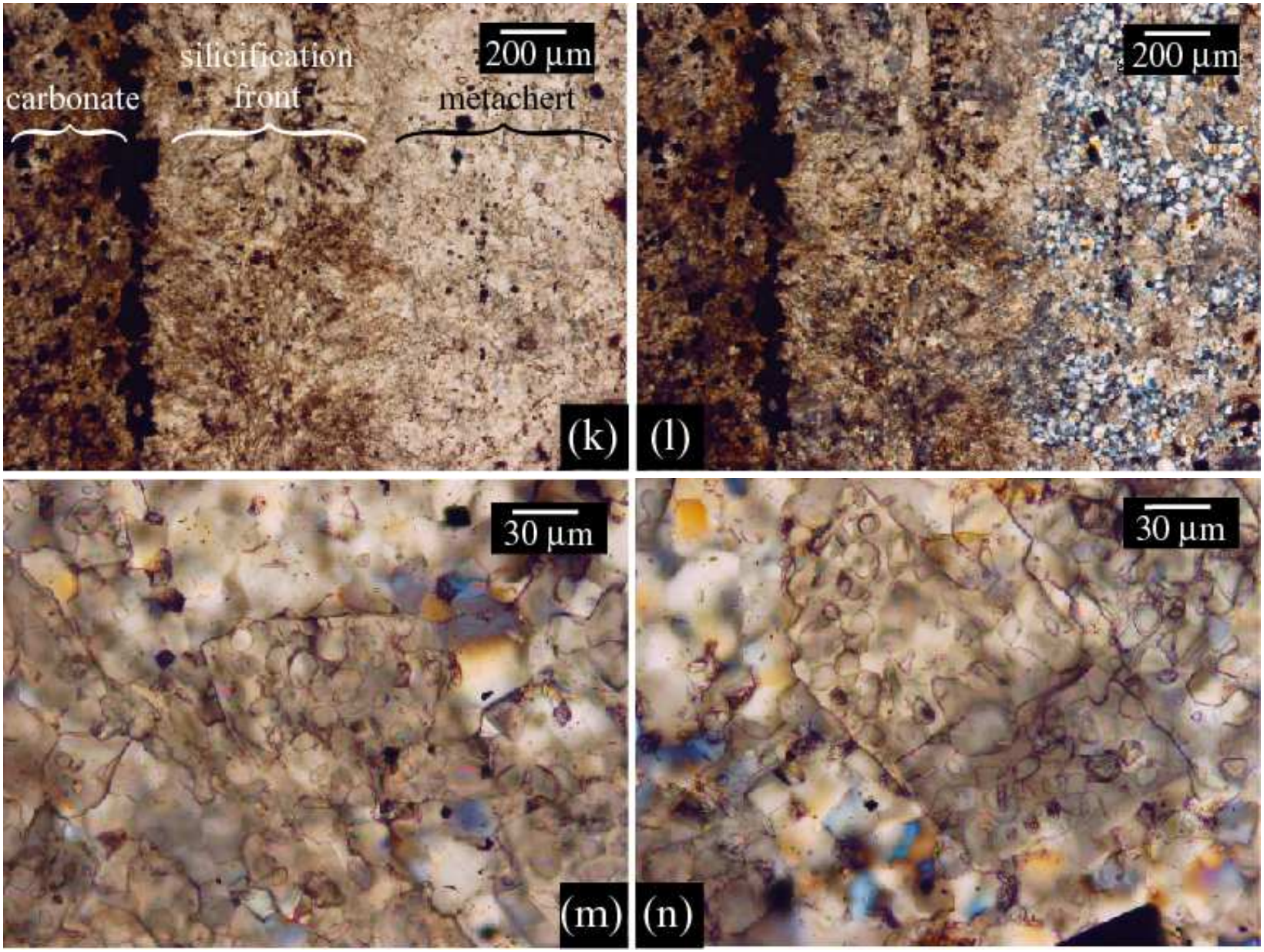
Coonterunah Carbonate

Post-metamorphic silification



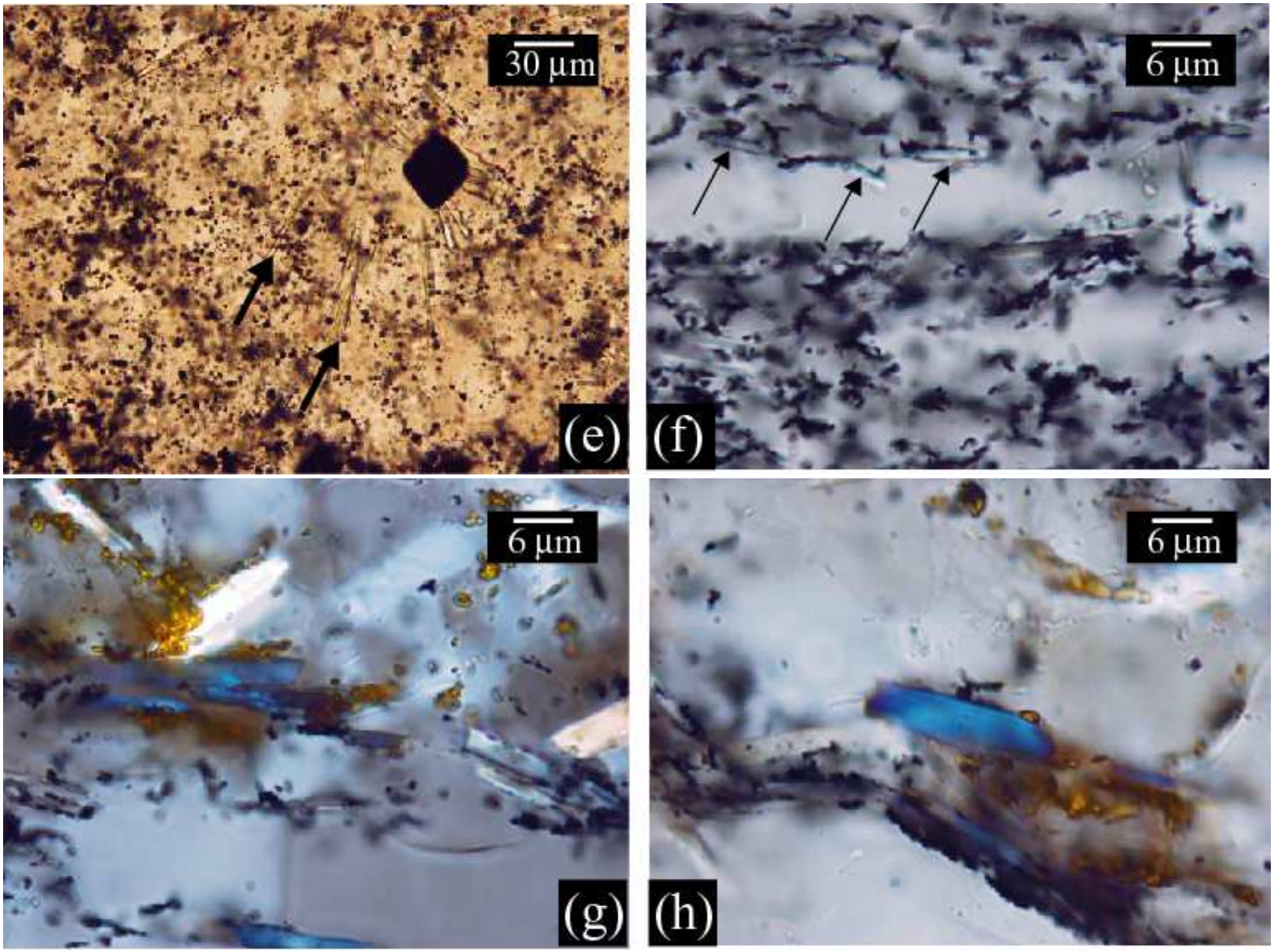
Coonterunah Carbonate

Pre-metamorphic silification



Coonterunah Carbonate

Metamorphosis



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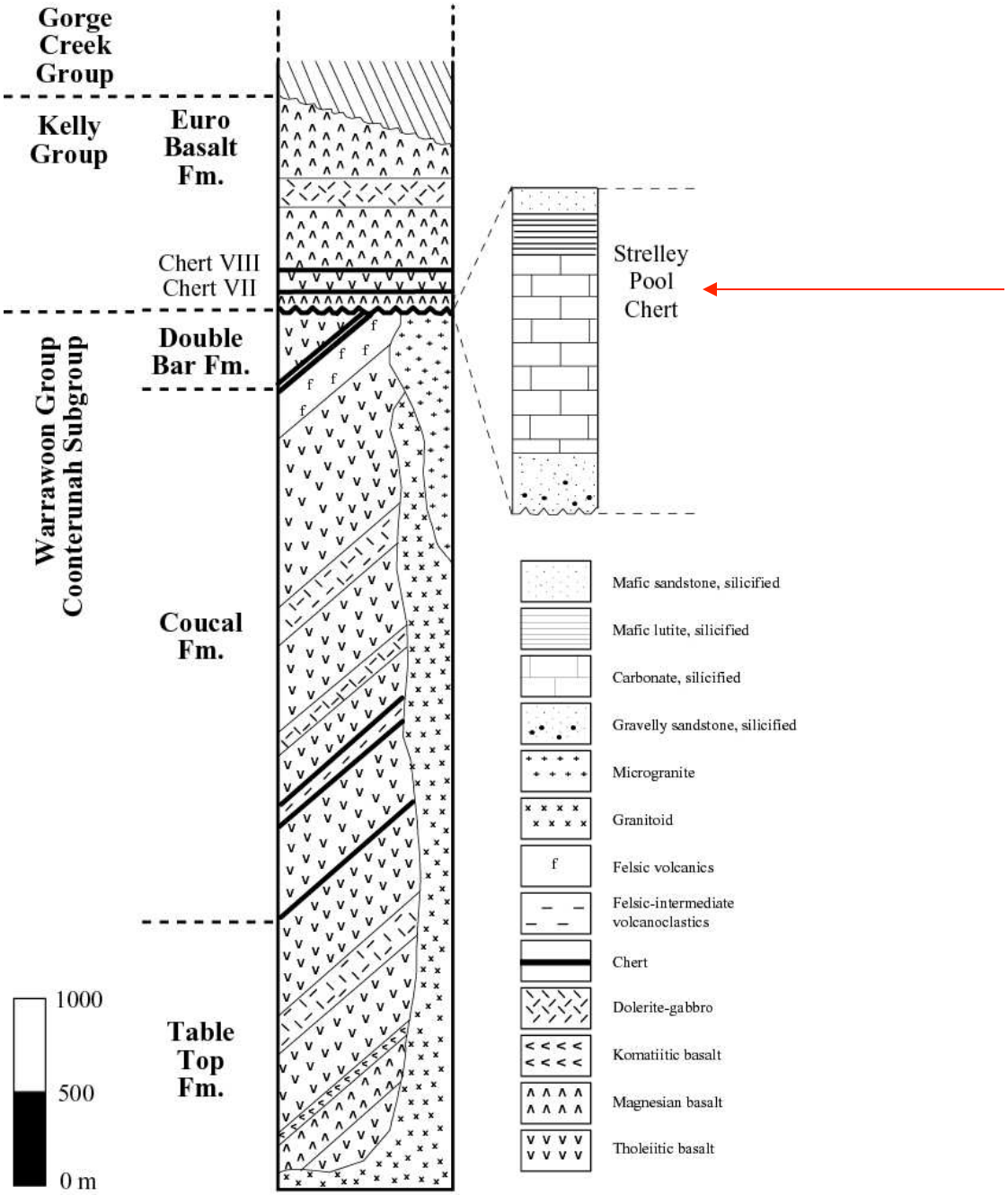
Strelley Pool Chert



Strelley Pool Chert

Bedded Units

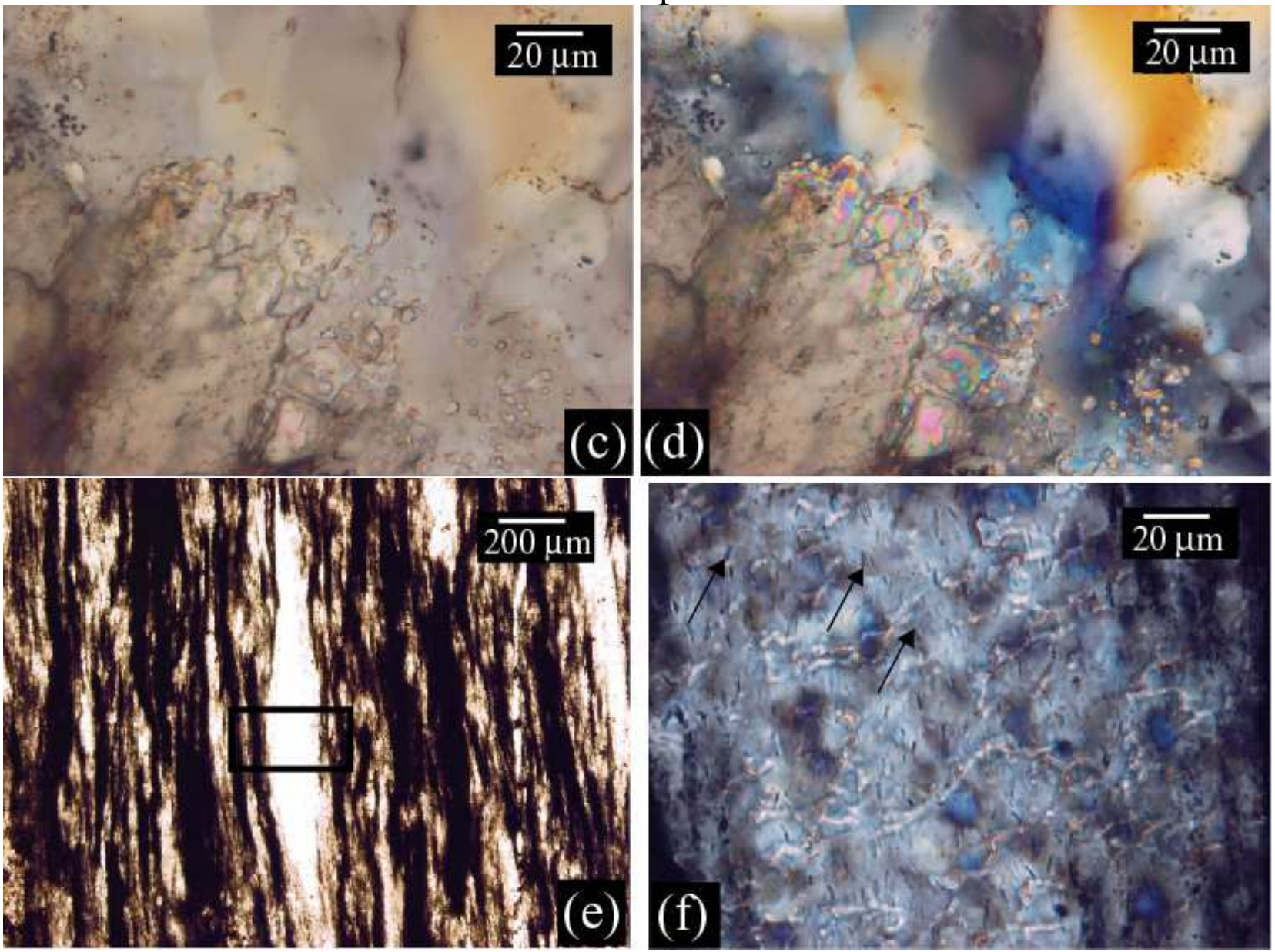
Silicified stromatoloids

Early dolomite replacement

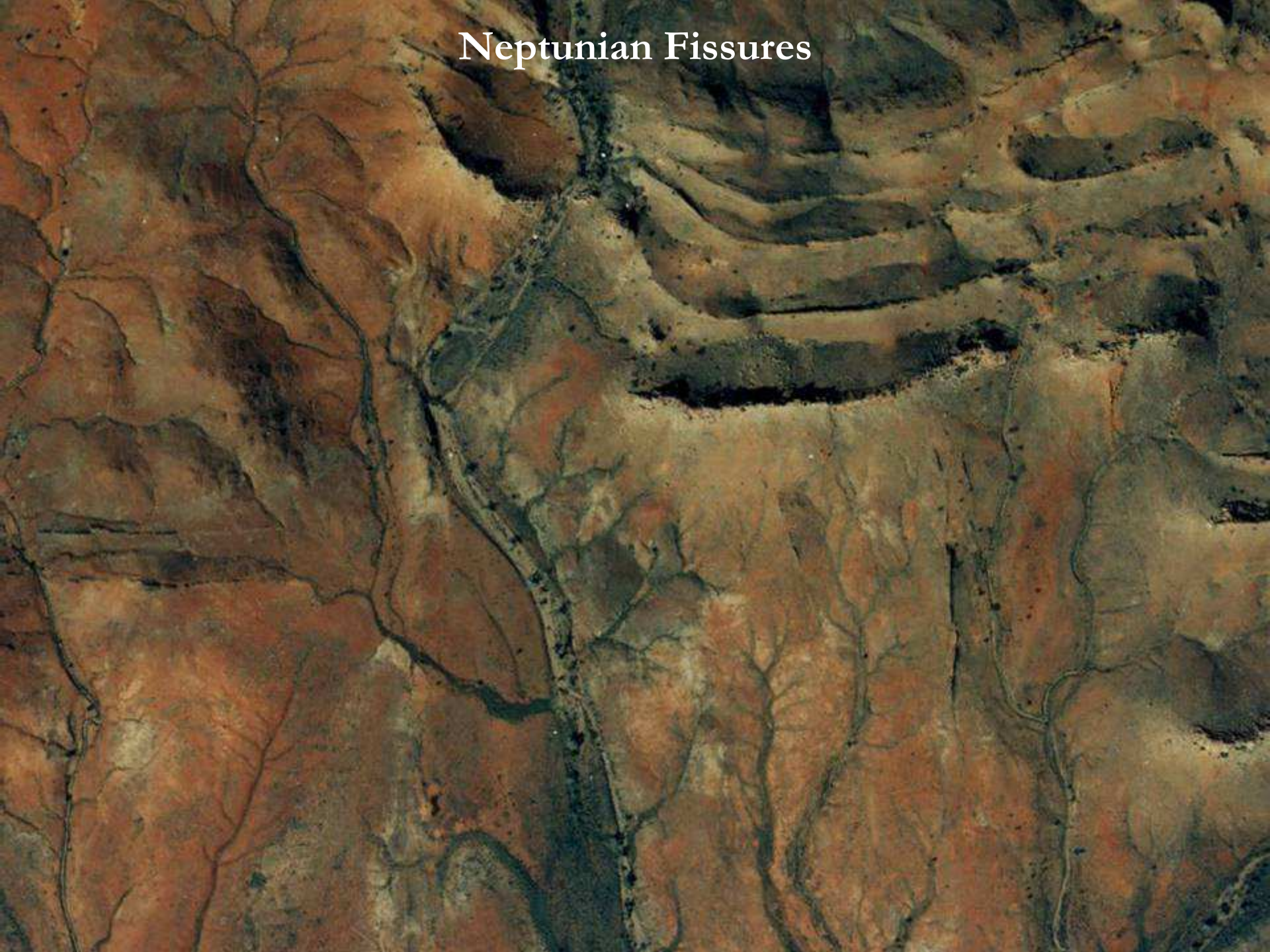
- Shallow marine
- Stromatolitic
- Patchy pre-metamorphic silicification

Strelley Pool Chert

Carbonate precursor



Neptunian Fissures



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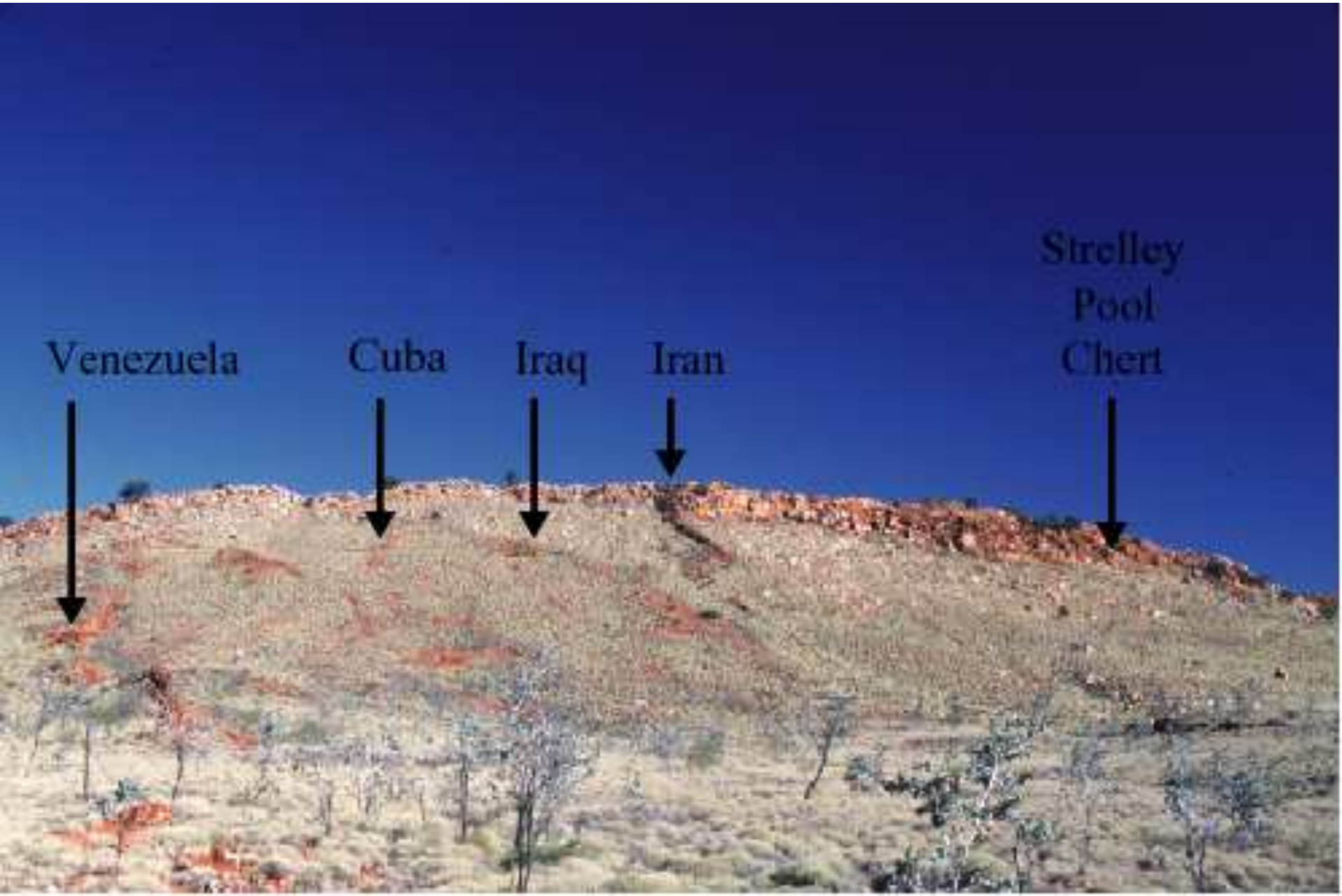

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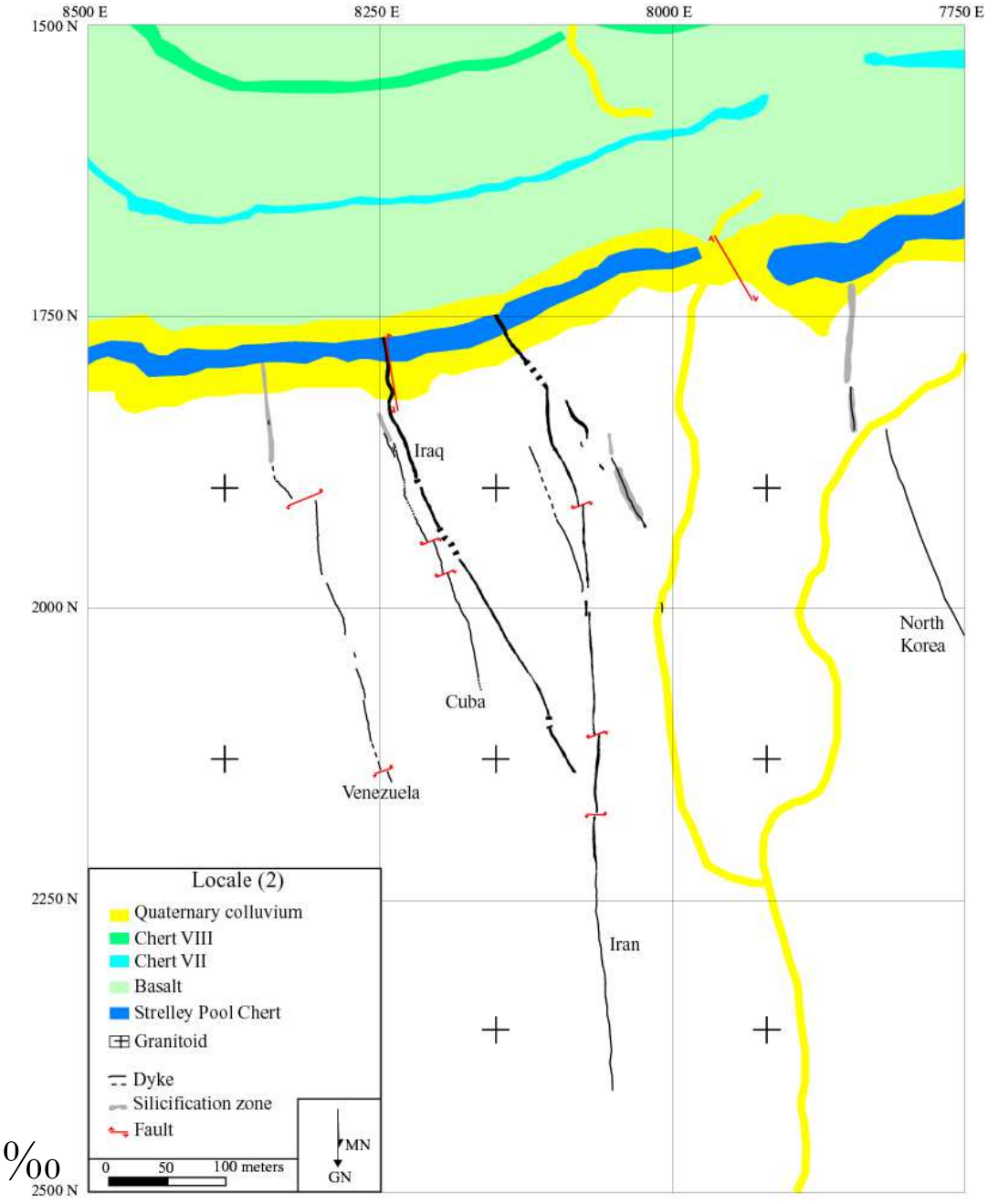
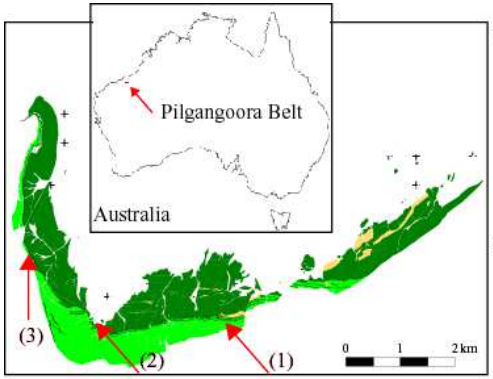
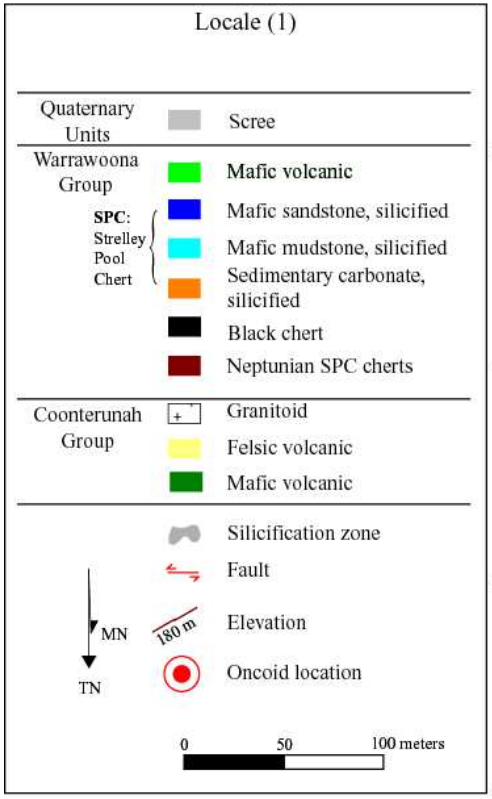
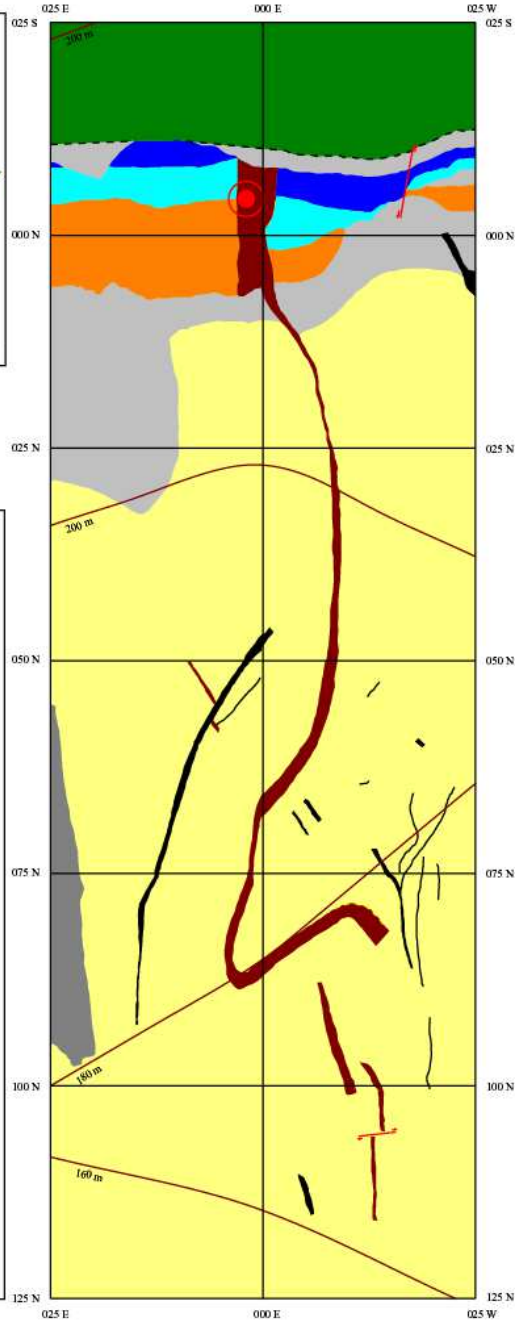


- Seafloor fissures
- Up to 750m deep
- Collected material from Strelley Pool Chert
- Abundant kerogenous chert
- Lowest $\delta^{13}C_{org} = -35.8 \pm 0.1‰$

Neptunian Fissures

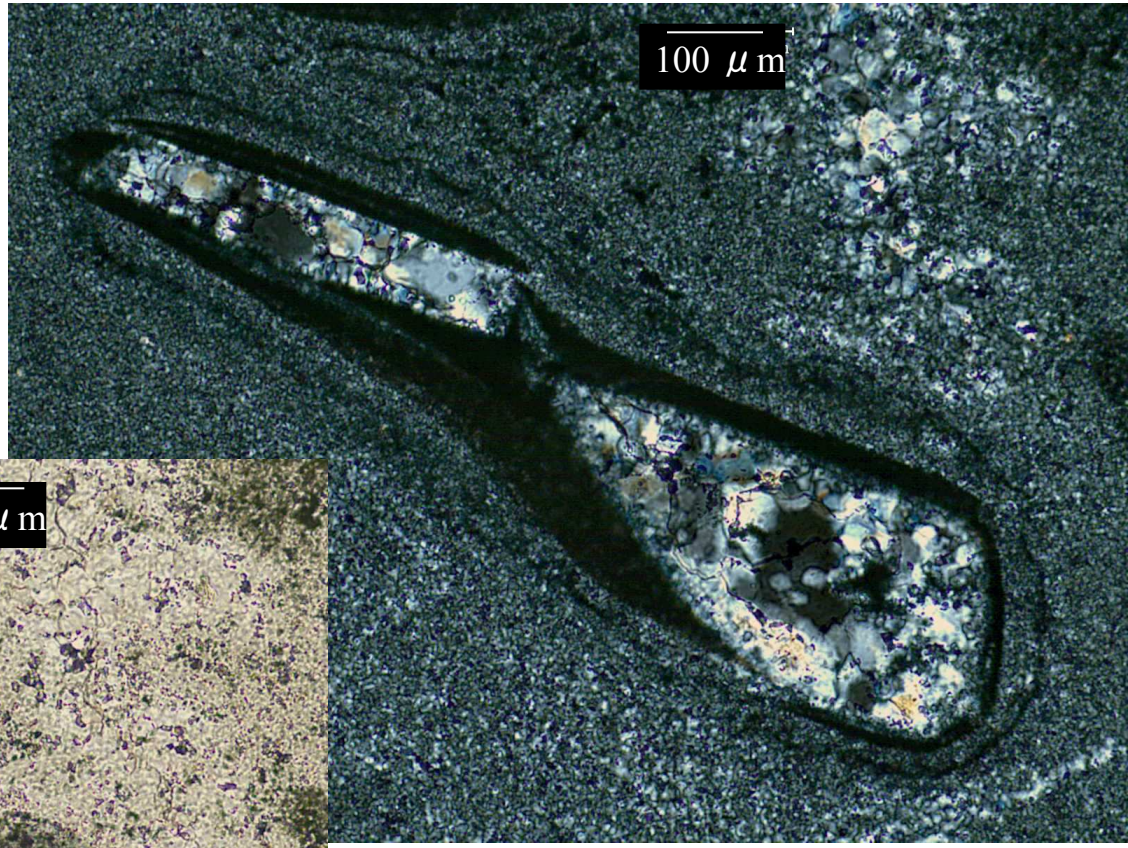


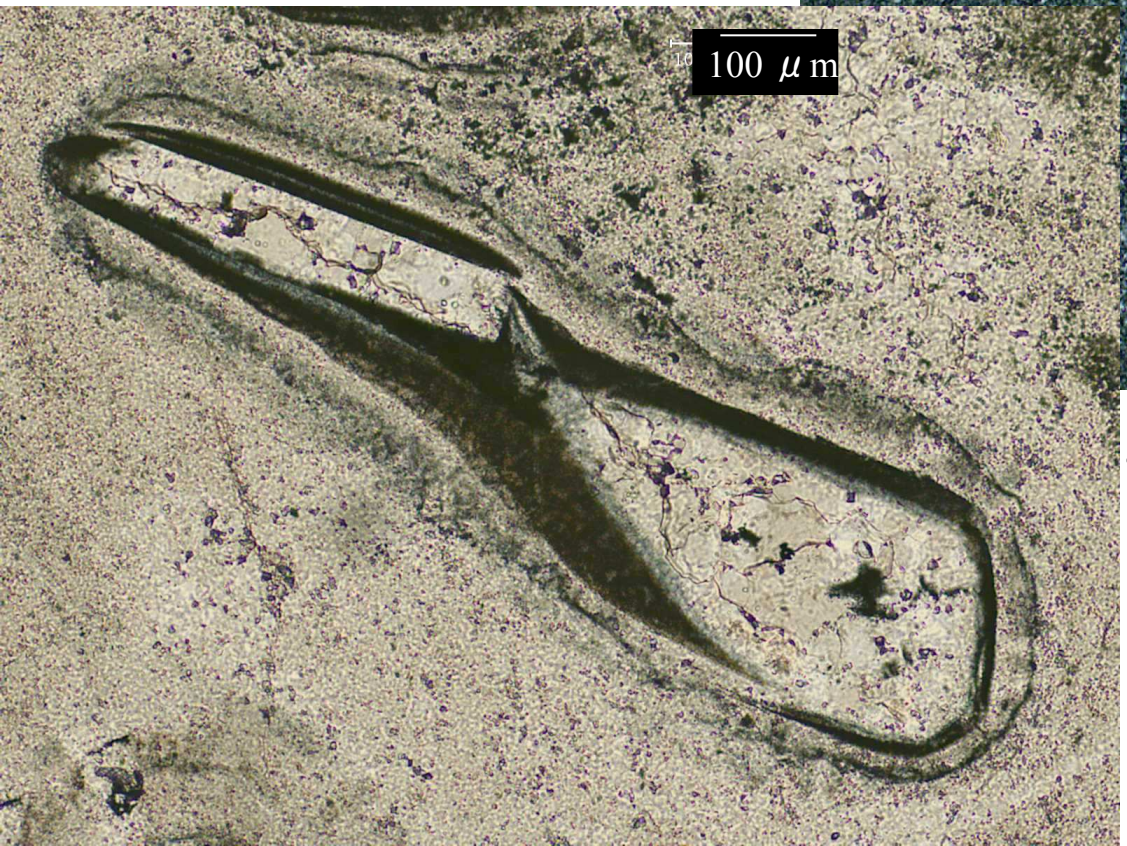




Neptunian Oncoids

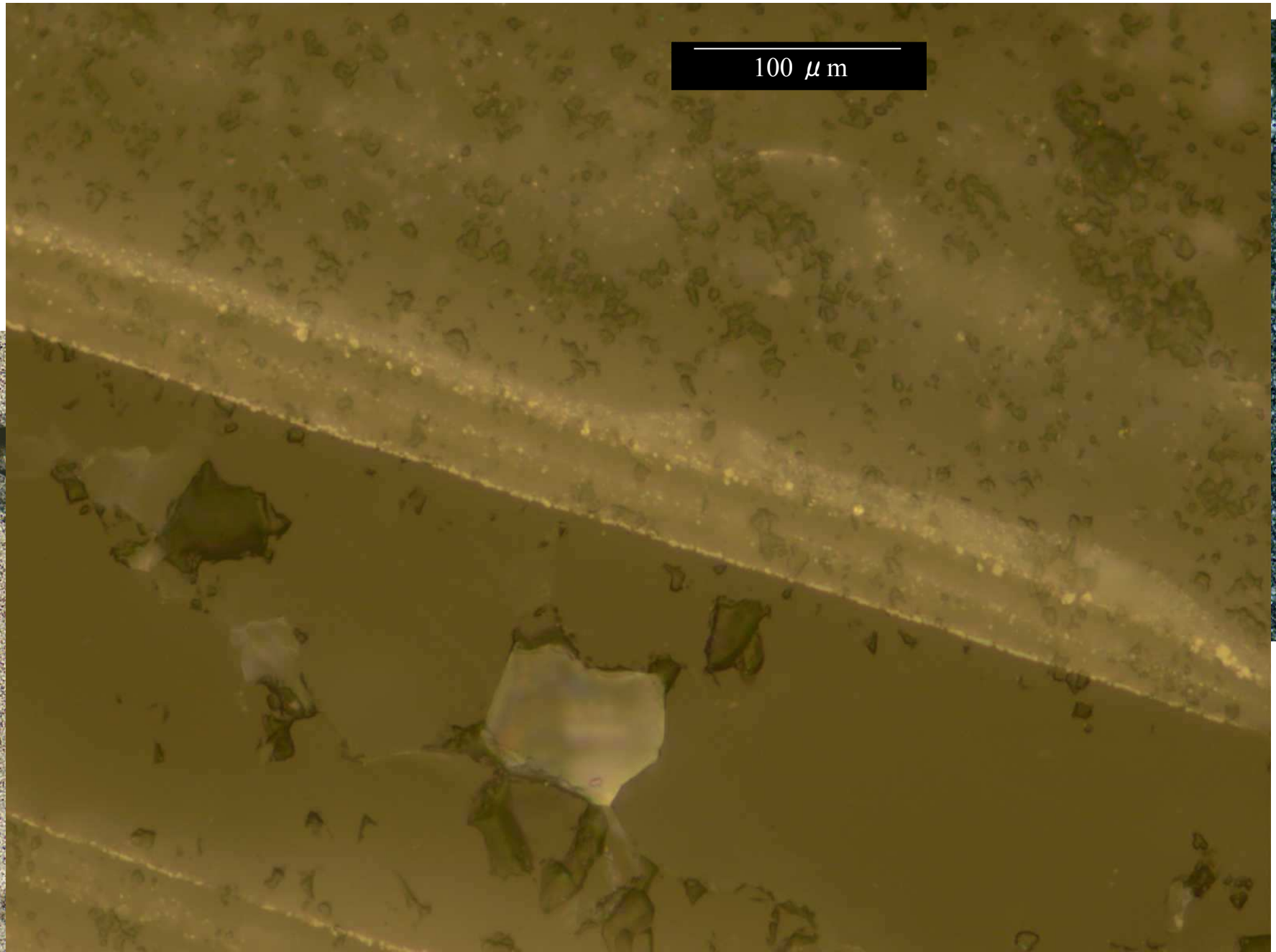
- Multi-laminar coated grains
- Microstromatolitic
- No abiotic analogue known





- $\delta^{13}C_{org} = -32.1 \pm 0.3‰$

Neptunian Oncoids

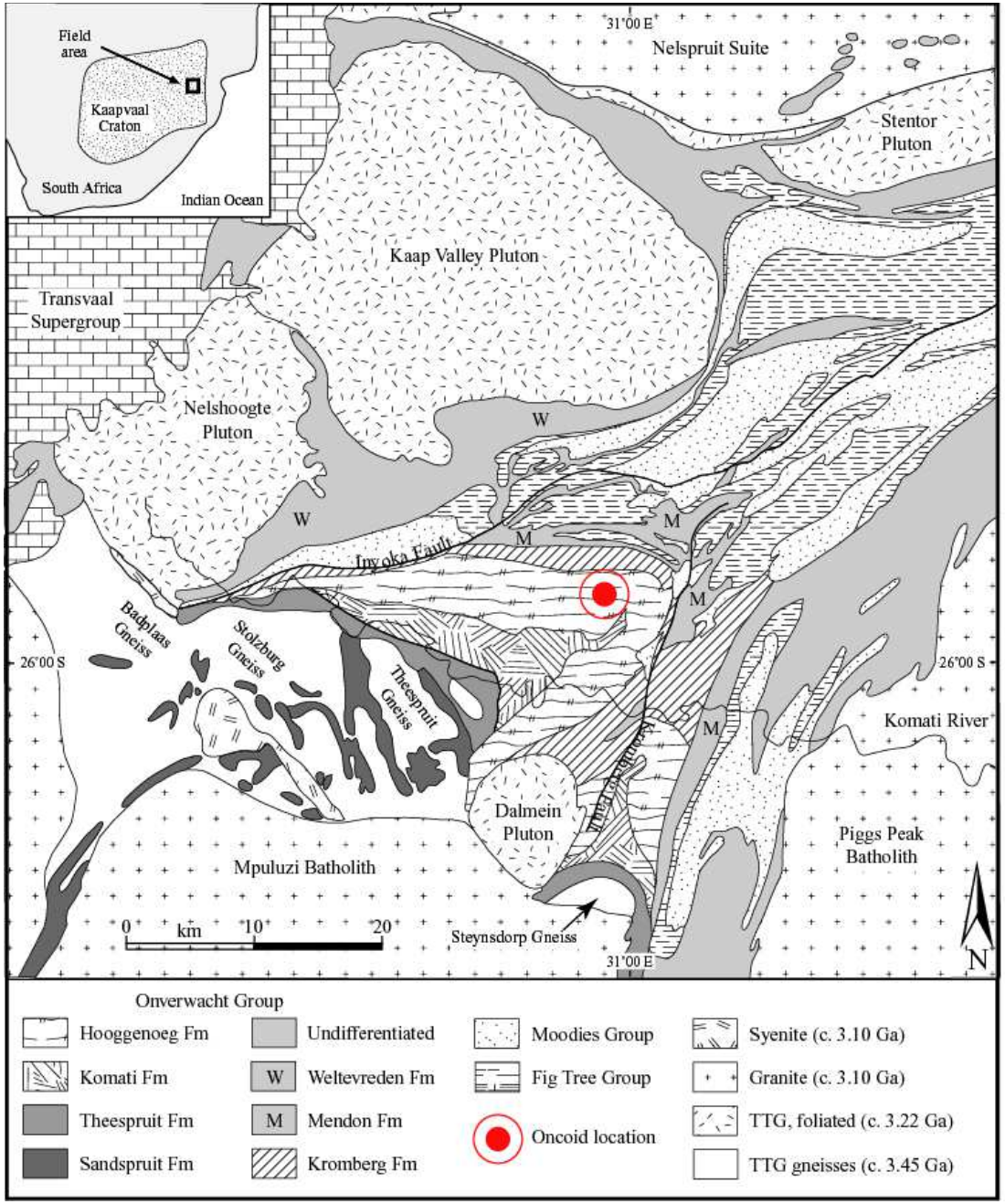


Neptunian Oncoids

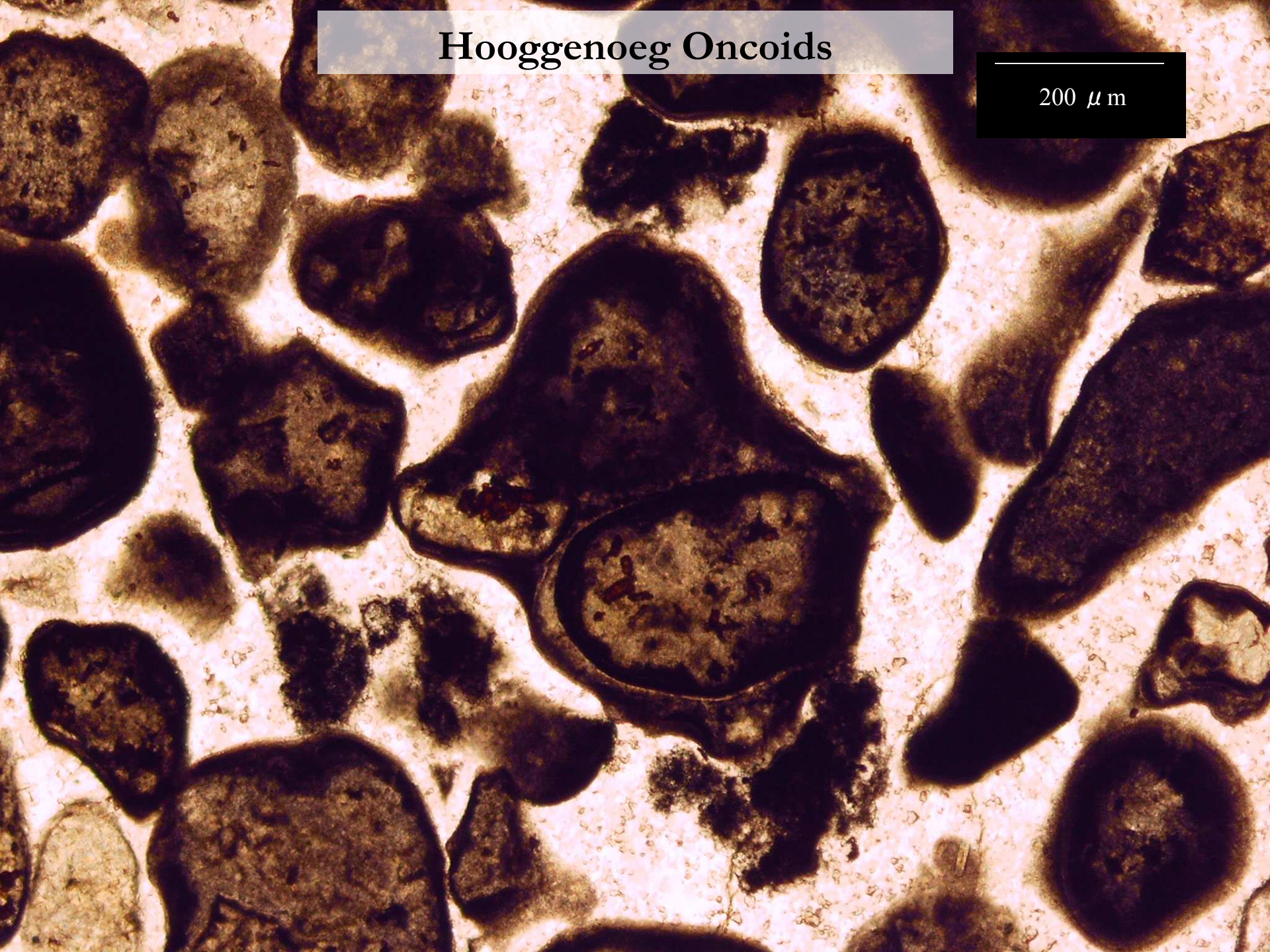
Field Areas

Craton / Terrain	Belt	Location	Age (Ga)	Formation	Setting
Isua	Isua Supracrustal Belt	S.W. Greenland	3.7 – 3.8	[to be named]	Deep marine
Pilbara	Pilgangoora Belt	N.W. Australia	3.52	Coucal Fm.	Deep marine
Pilbara	Pilgangoora Belt	N.W. Australia	3.42	Strelley Pool Chert Fm.	Shallow marine / Sub-aerial
Kaapvaal	Barberton Greenstone Belt	W. Swaziland / Mpumalanga, South Africa	3.45	Hooggenoeg Fm.	Shallow marine

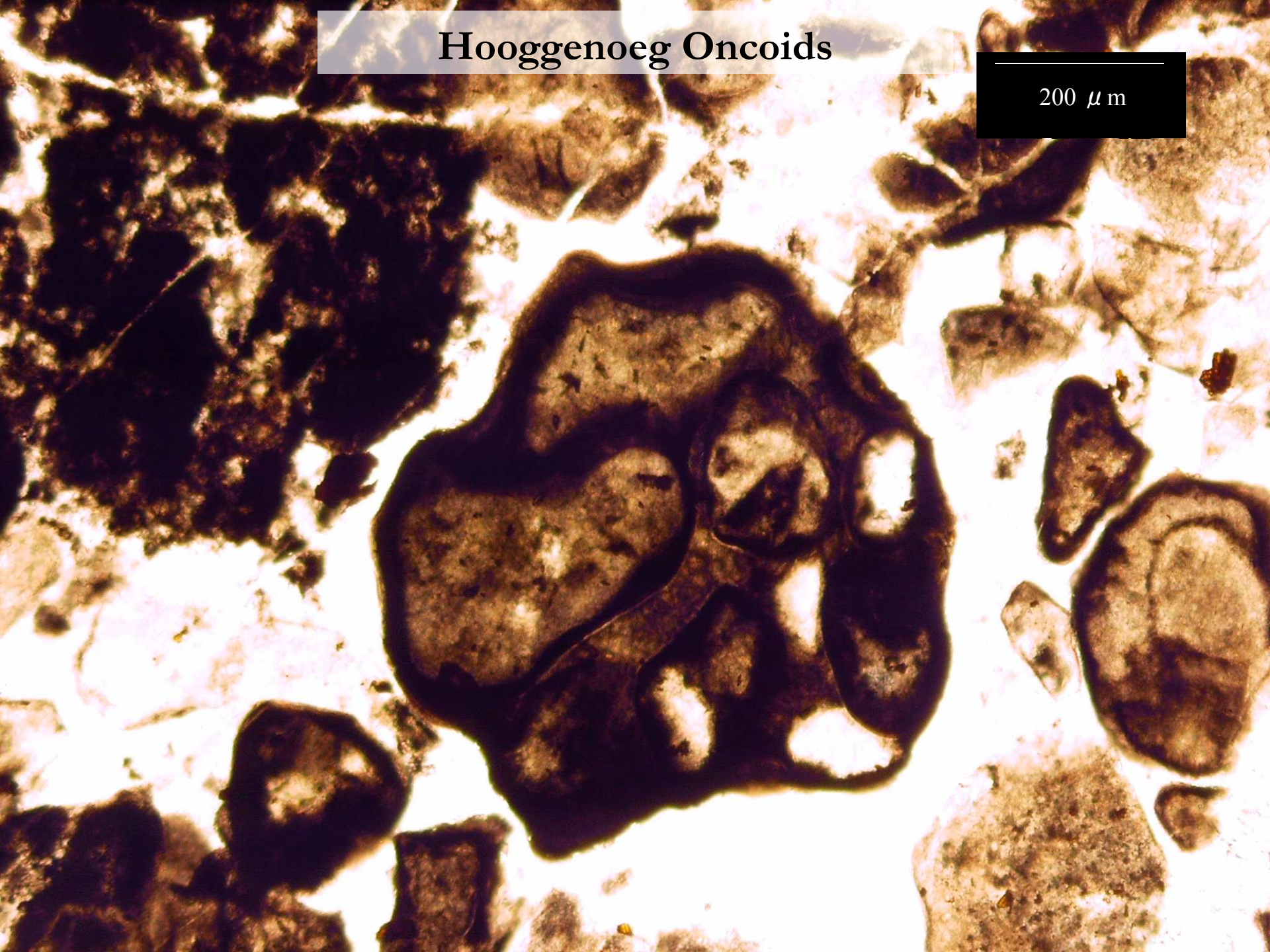
Barberton Greenstone Belt



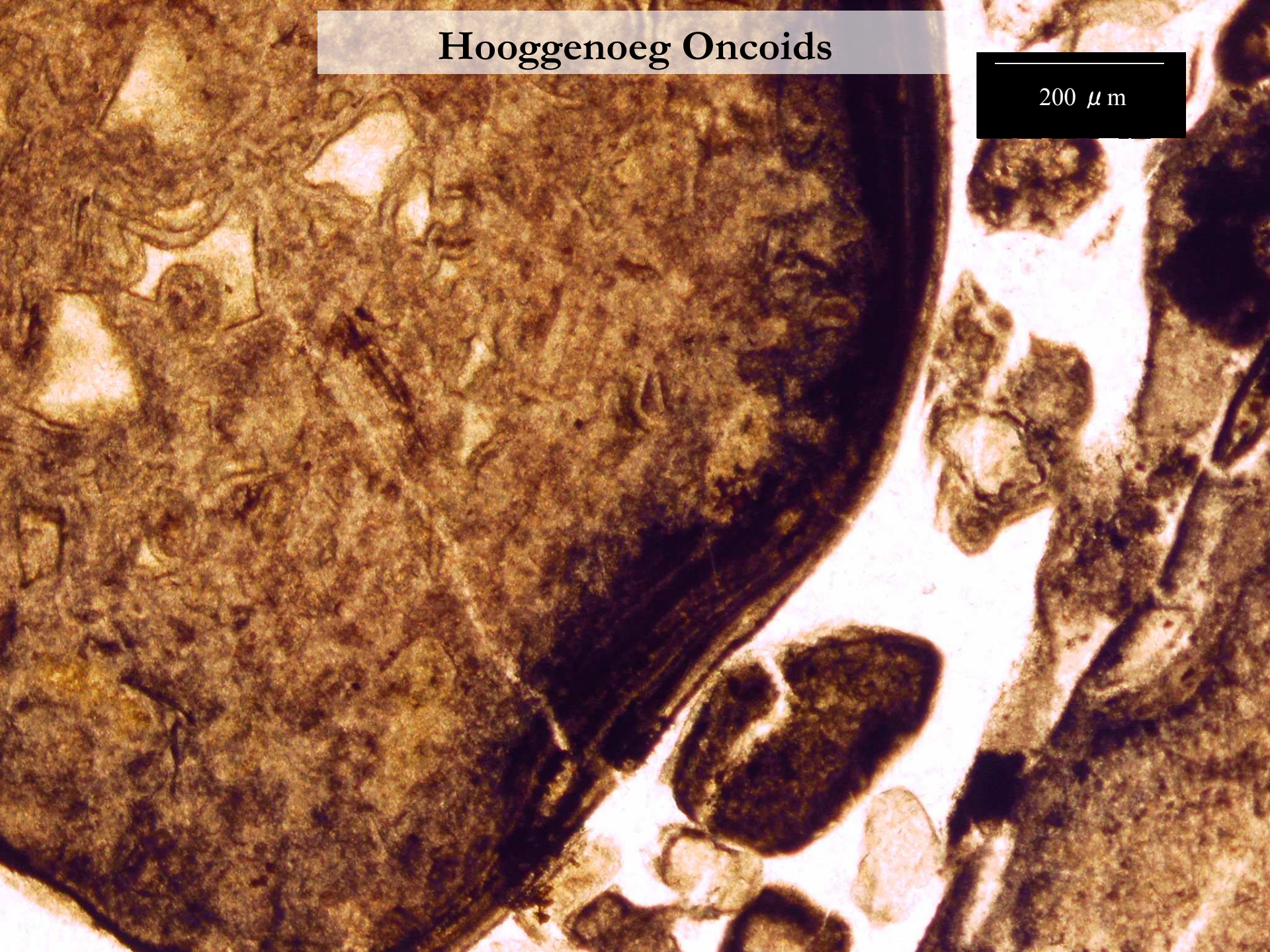
Hooggenoeg Oncoids



Hooggenoeg Oncoids



Hooggenoeg Oncoids



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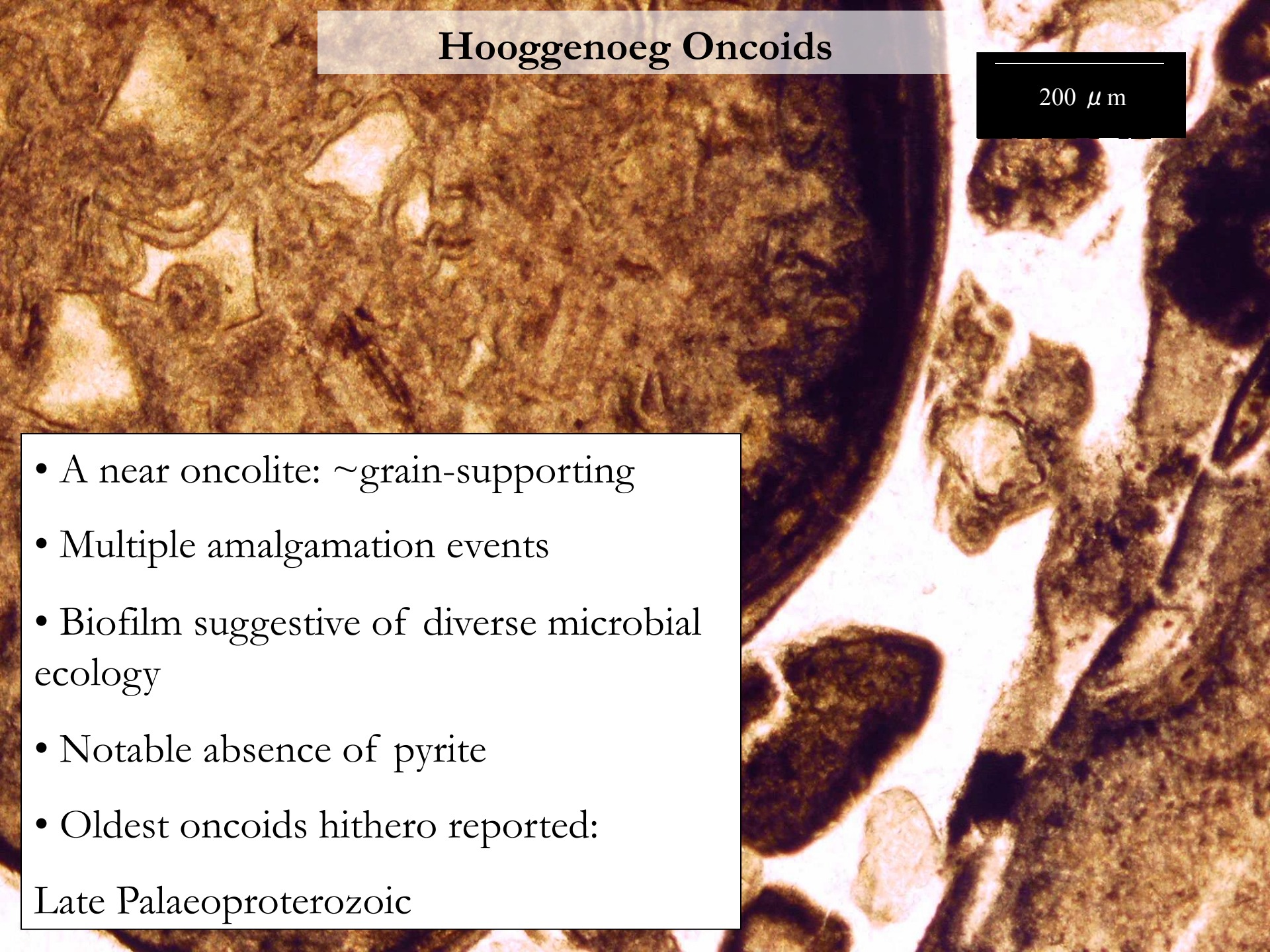


- A near oncolite: ~grain-supporting
- Multiple amalgamation events
- Biofilm suggestive of diverse microbial ecology
- Notable absence of pyrite
- Oldest oncoids hithero reported:

Late Palaeoproterozoic

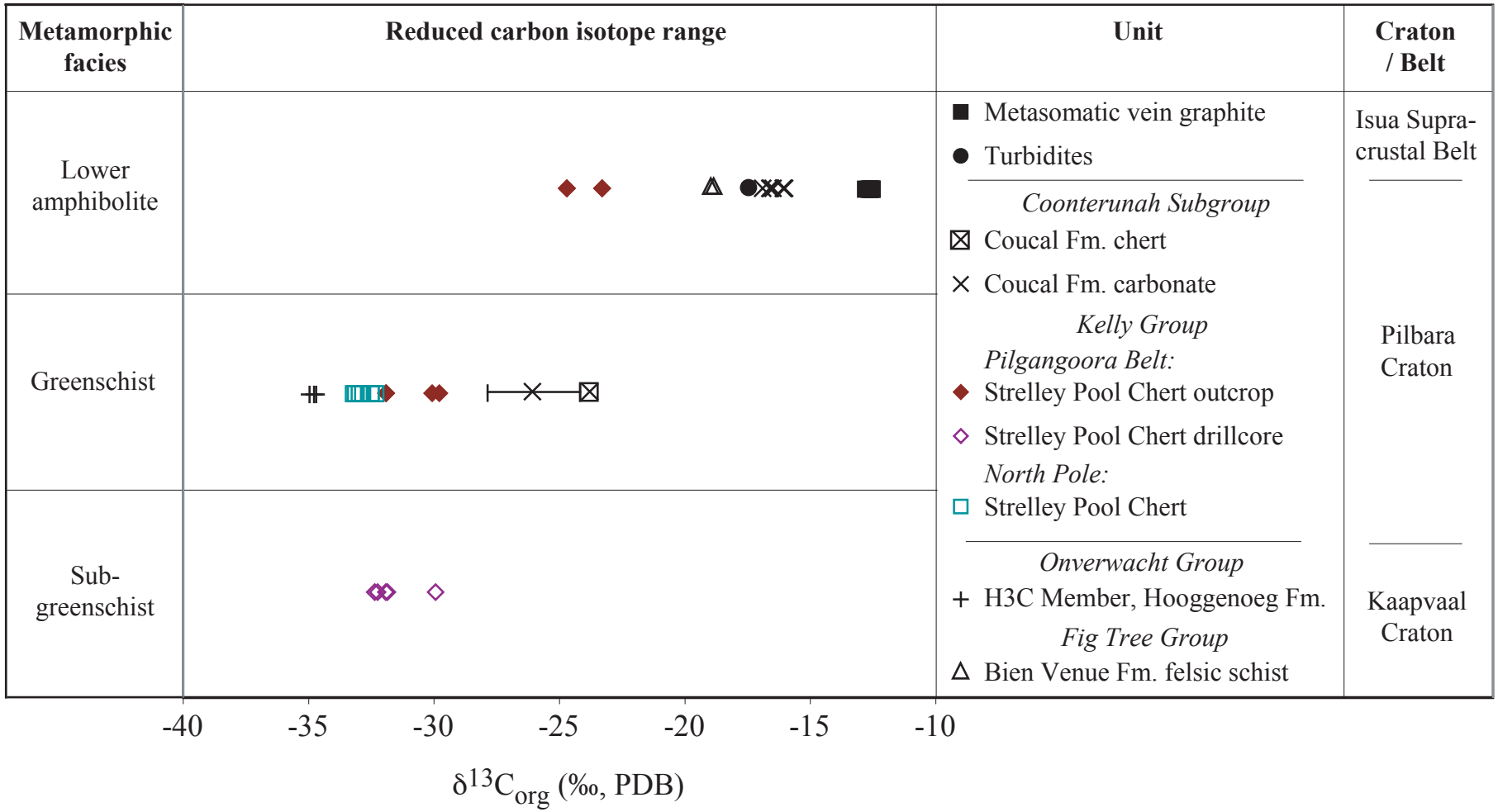
Neptunian Kerogen Isotopes

Formation	Member / Locale	Lithology	*n*	$d^{13}C_{PDB}$ (‰)	± 1σ (‰)	Oncoids?
Barberton Hooggenoeg	H3C	Black chert breccia	1	-24.5	0.1	√
Pilbara Strelley Pool Chert	Fissure 1	Bedded black chert*	1	-21.5	0.4	X
		Fissure chert breccia	2	-32.1	0.9	√
	Fissure 2(a)	Bedded black chert	2	-25.6	3.0	X
		Fissure chert breccia	3	-33.5	1.7	X
	Fissure 2(c)	Bedded black chert	1	-30.2	0.2	X
		Fissure chert breccia	1	-35.8	0.1	X
	Fissure 2(d)	Bedded black chert	2	-25.8	0.4	X
		Fissure chert breccia	2	-34.8	1.2	X
	Fissure 3	Bedded black chert	1	-25.1	0.1	X
		Fissure chert breccia	1	-35.8	0.1	X

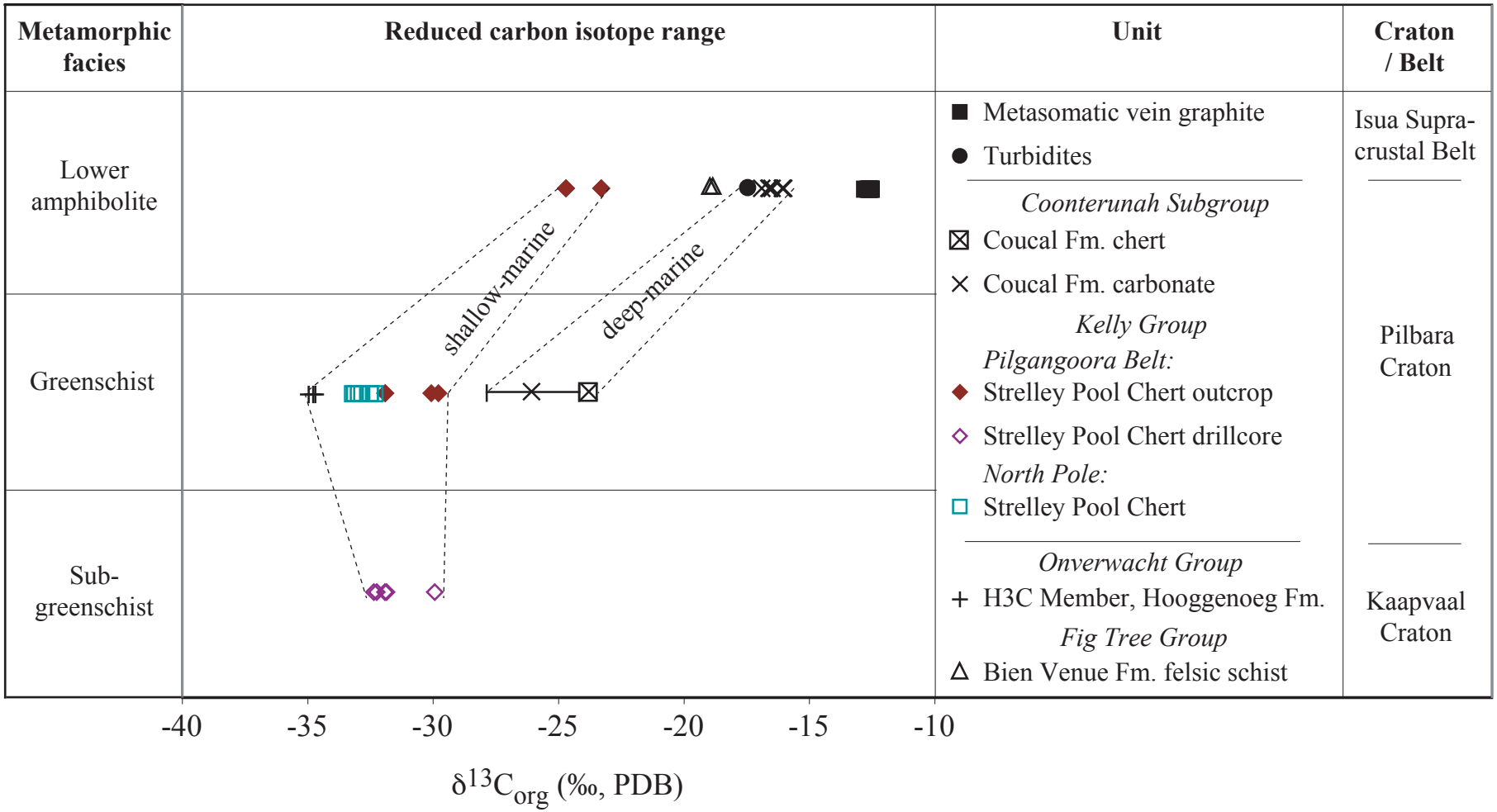
Overview

Objective		
Context	Geological Time	
	The Rock Record	Field areas
		Greenstone belts
	'Organic' Matter	
Depositional Settings	Isua meta-turbidite	
	Coonterunah meta-carbonate	
	Strelley Pool Chert	Bedded units
		Neptunian fissures
	Hooggenoeg Formation	
Synthesis	Carbon cycling	
Conclusion	Astrobiological implications	

Kerogen & Graphite Isotopes



Kerogen & Graphite Isotopes



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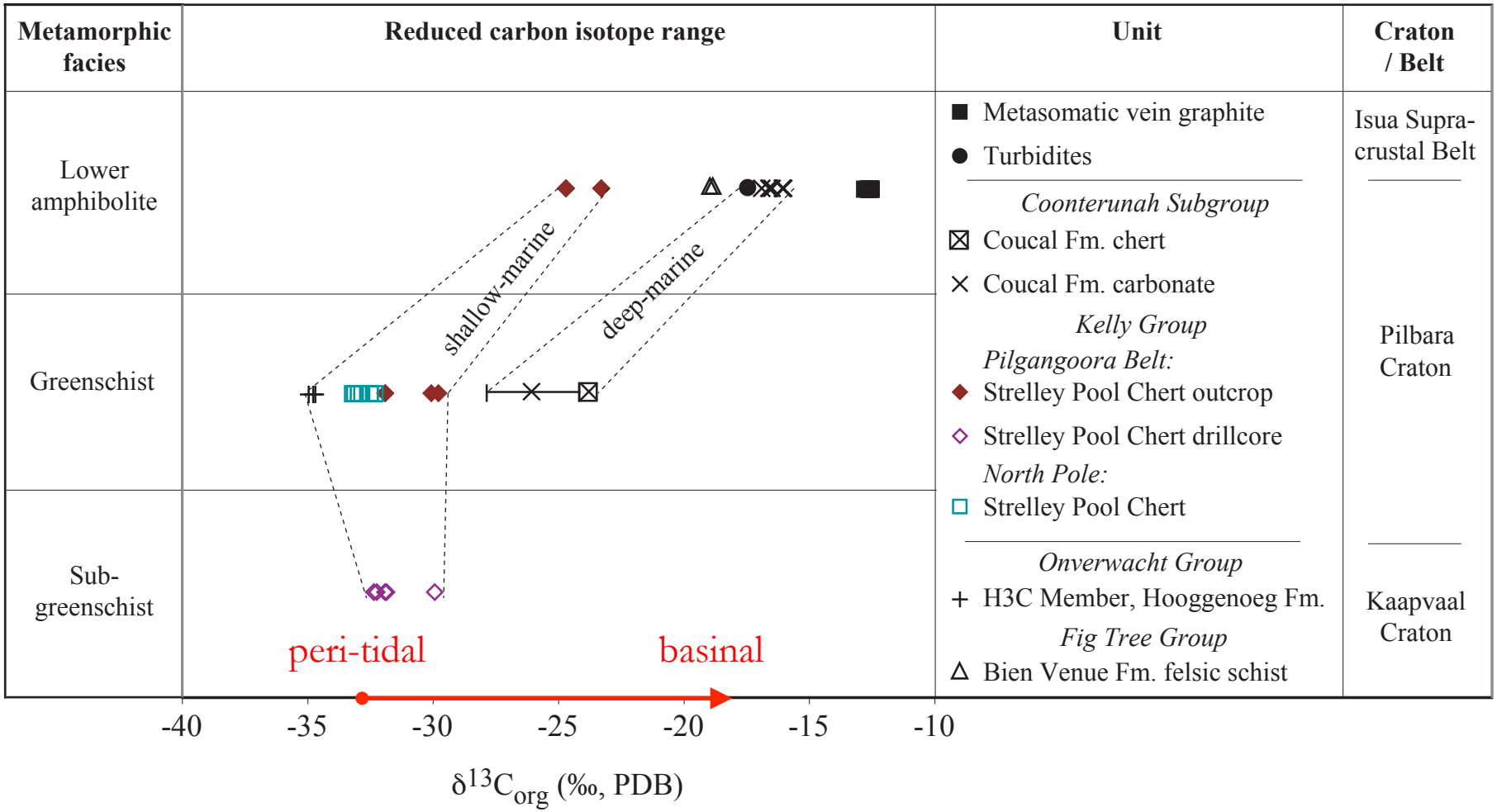


Early Archaean Carbon Cycling I

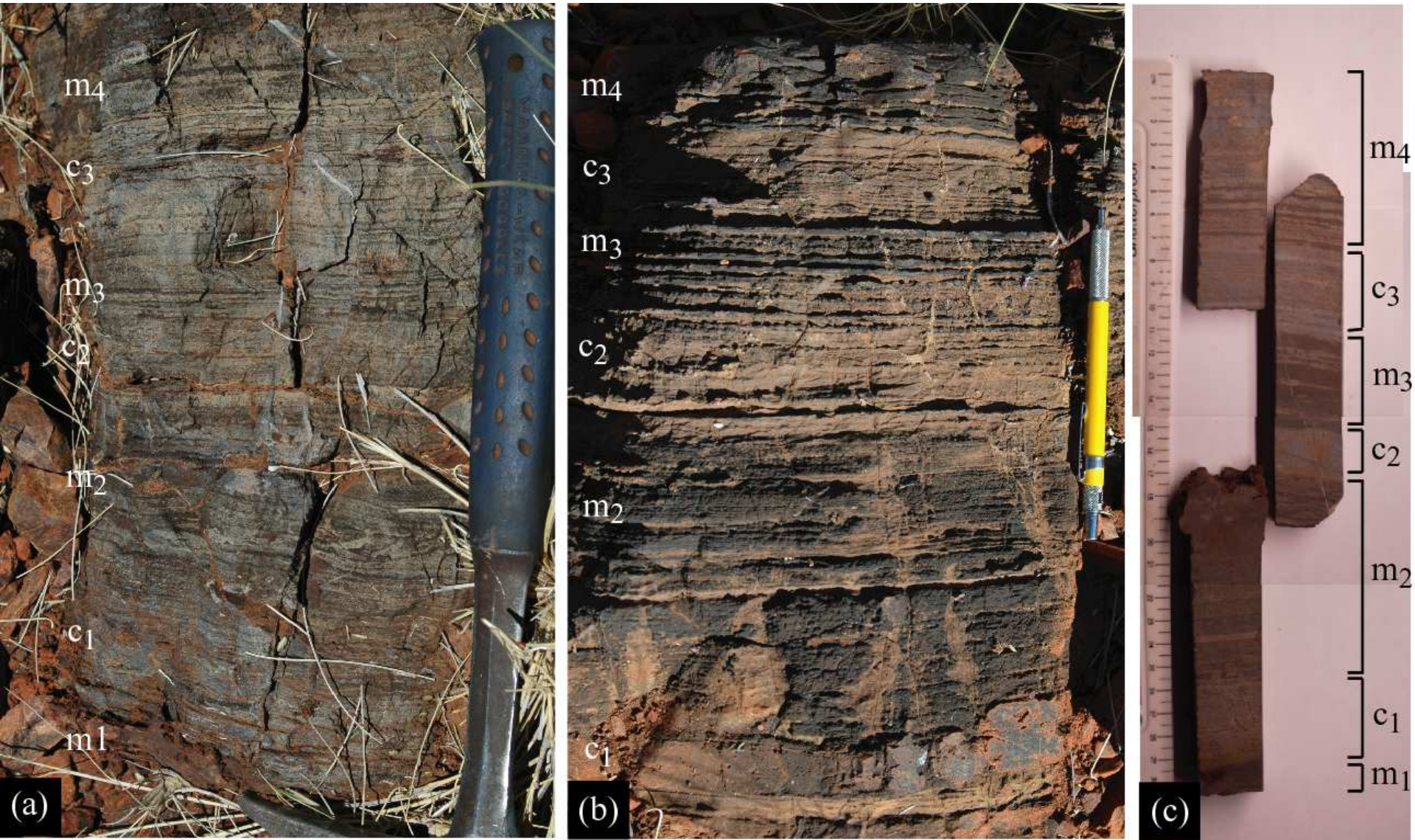
- Kerogen-graphite carbon isotope distributions vary systematically between depositional settings.

- Pilgangoora Belt $\delta^{13}C_{org}$ at lower greenschist facies varies with palaeodepth:
  - Deep-marine Coonterunah: -26.1 ± 2.4 ‰
  - Shallow marine Strelley Pool Chert: -29.5 to -32.9 ‰

- Although variable, sub-tidal settings sequestered distinctly **more** carbon (higher TOC%) than peri-tidal settings.

- These features are commensurate with biogeochemical control, and not with an abiotic Fischer-Tropsch synthesis origin.

Carbonate Isotopes



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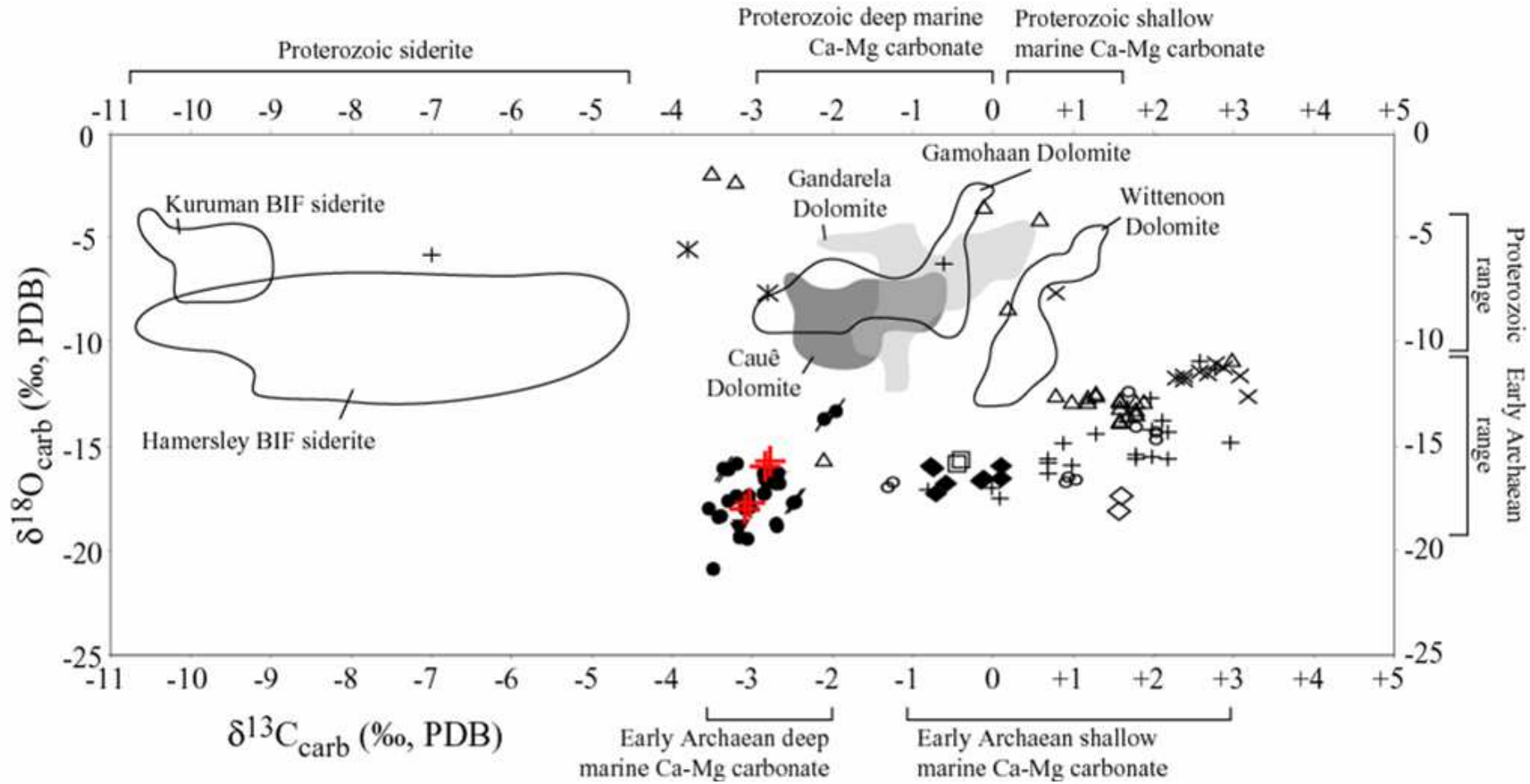
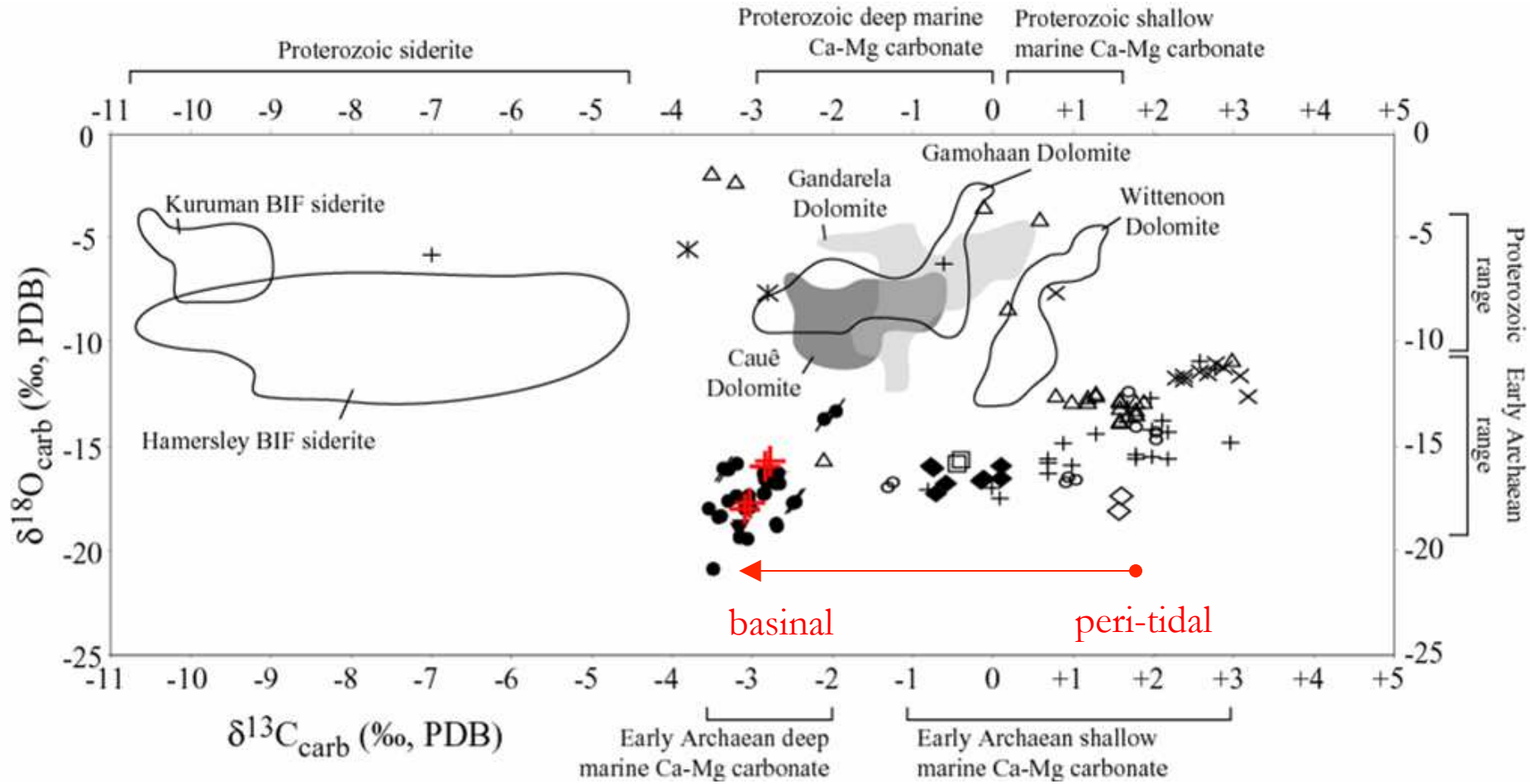


Basinal marine calcitic and dolomitic BIF					
Early Archaean	Pilbara Supergroup	Coonterunah Subgroup, Pilgangoora Belt	Double Bar Fm.	◆ Sparry dolomite (drillcore)	This study
			Coucal Fm.	▼ Prominent calcitic carbonate ● Prominent dolomitic carbonate + Prominent dolomitic carbonate, pervasively silicified Lesser dolomitic carbonate	
Palaeo-proterozoic	Minas Supergroup	Quadrilátero Ferrífero		Cauê Dolomite	Spier *et al.* (2007)

Shallow marine sedimentary calcite and dolomite					
Early Archaean	Pilbara Supergroup	Strelley Pool Chert	Pilgangoora Belt	◇ Sparry dolomite (drillcore) □ Laminated carbonate (neptunian breccia) ○ Laminated carbonate (outcrop)	This study
				+ Laminated carbonate (neptunian breccia and outcrop)	Lindsay *et al.* (2005)
			North Pole Dome	× Laminated carbonate	
		McPhee Formation	Marble Bar	✱ Laminated carbonate	Veizer *et al.* (1989)
	Swaziland Supergroup	(various localities)		△ Assorted bedded carbonate	
Palaeo-proterozoic	Hamersley Group	(various localities)		◯ Wittenoon Dolomite	Veizer *et al.* (1990)

Carbonate Isotopes



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Early Archaean Carbon Cycling II

- Like kerogen-graphite, carbonate isotope distributions also vary systematically with littoral environment.

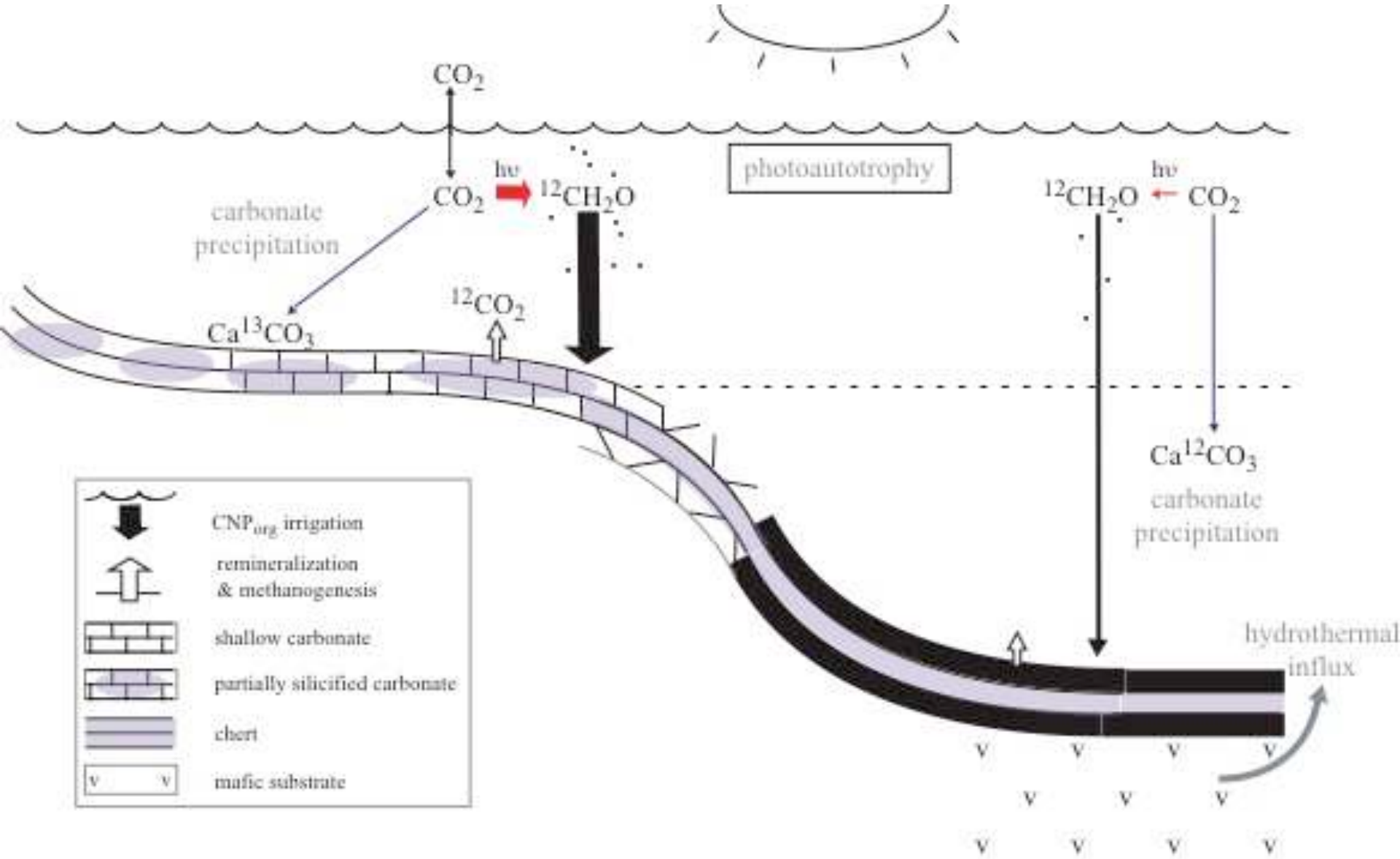
- $(\delta^{13}C, \delta^{18}O)_{carb}$ at or below lower greenschist facies:
  - Deep-marine Coonterunah:

    (-3.0 ± 1.0 ‰, -17.8 ± 0.2 ‰)
  - Shallow marine settings:

    (+3.0 ‰, -11.0 ‰) to (+1.0 ‰, -17.0 ‰)

- $\delta^{13}C_{\text{nearshore DIC}} - \delta^{13}C_{\text{open ocean DIC}} \approx +4$ to $+6$ ‰.

Early Archaean Carbon Cycling

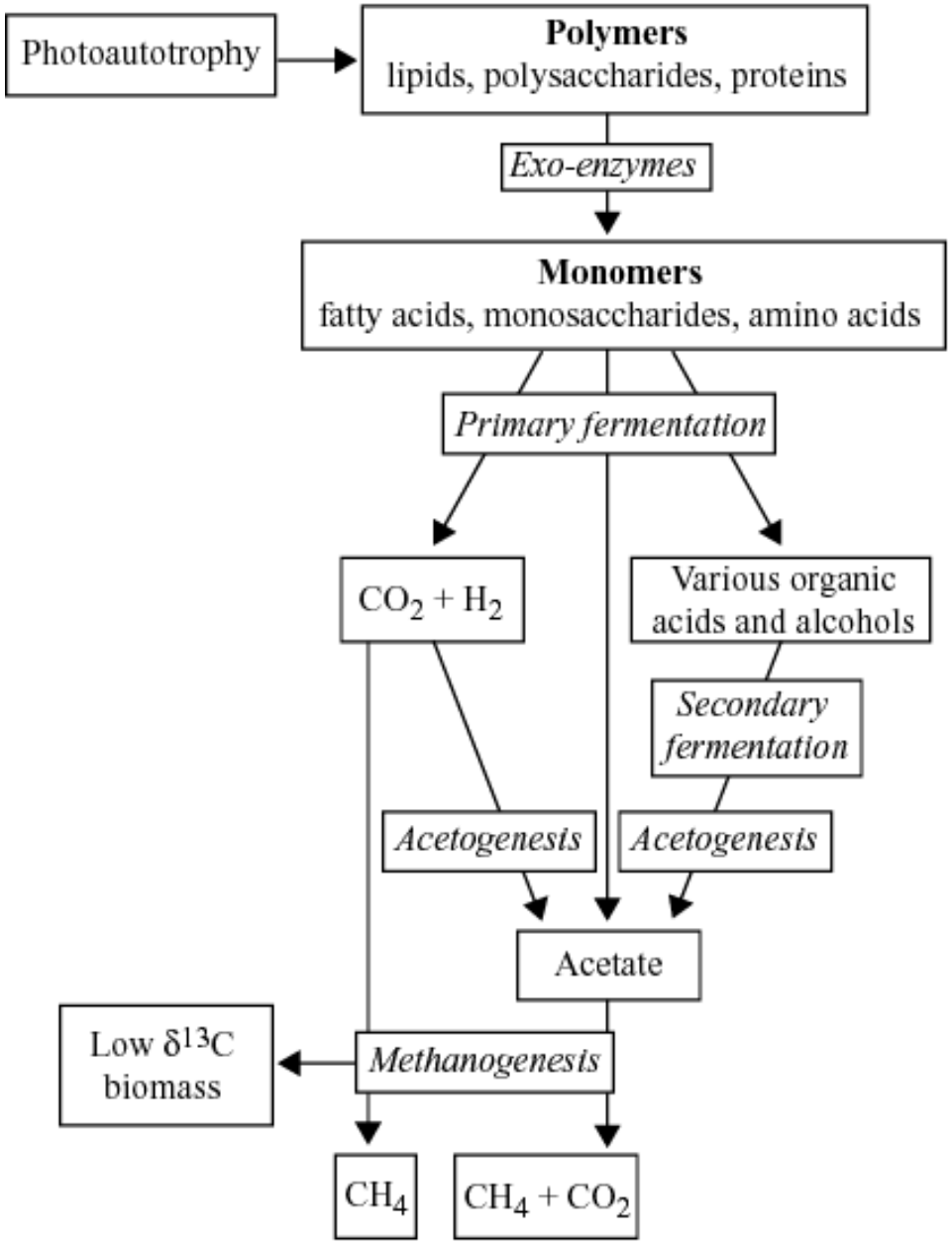


Early Archaean Carbon Cycling

- Carbonate isotope trends are compatible with organic export, rather than remineralization, control on marine $\delta^{13}C_{DIC}$.

- This fits well with inferred low availability of soluble electron acceptors: O_2, NO_x^-, SO_4^{2-}:
    - Little water-column respiration.
    - Benthic remineralization facilitated by metabolic processes using organic compounds as electron acceptors:
        - fermentation;
        - acetogenesis; and
        - methanogenesis.

Early Archaean Metabolism



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Conclusion

- At the time of the earliest recorded sedimentation, a diverse and abundant biosphere was already well established in a variety of environmental settings.

- If evolution was able to gain a foothold on and within these fragmented and volcanically active slivers of greenstone belt crust, then there exists reason to anticipate the ubiquity of life in habitable zones elsewhere.

Coonterunah Carbonate

Proto Banded-Iron Formation?

"It is through madness that the greatest good things have come to Greece."

Coonterunah Carbonate

Proto Banded-Iron Formation?

PROCEEDINGS

OF THE

GEOLOGICAL AND POLYTECHNIC SOCIETY

Of the West Riding of Yorkshire,

AT THE ~~FORTY-FIFTH~~ 51st MEETING, HELD IN THE

CUTLER'S HALL, SHEFFIELD, ON WEDNESDAY, JULY 30TH, 1856,

AT TWELVE O'CLOCK AT NOON.

Sorby (1856), 'On the origin of the Cleveland Hill ironstone'.

ACADÉMIE DES SCIENCES.

SÉANCE DU LUNDI 6 DÉCEMBRE 1909.

PRÉSIDENCE DE M. BOUCHARD.

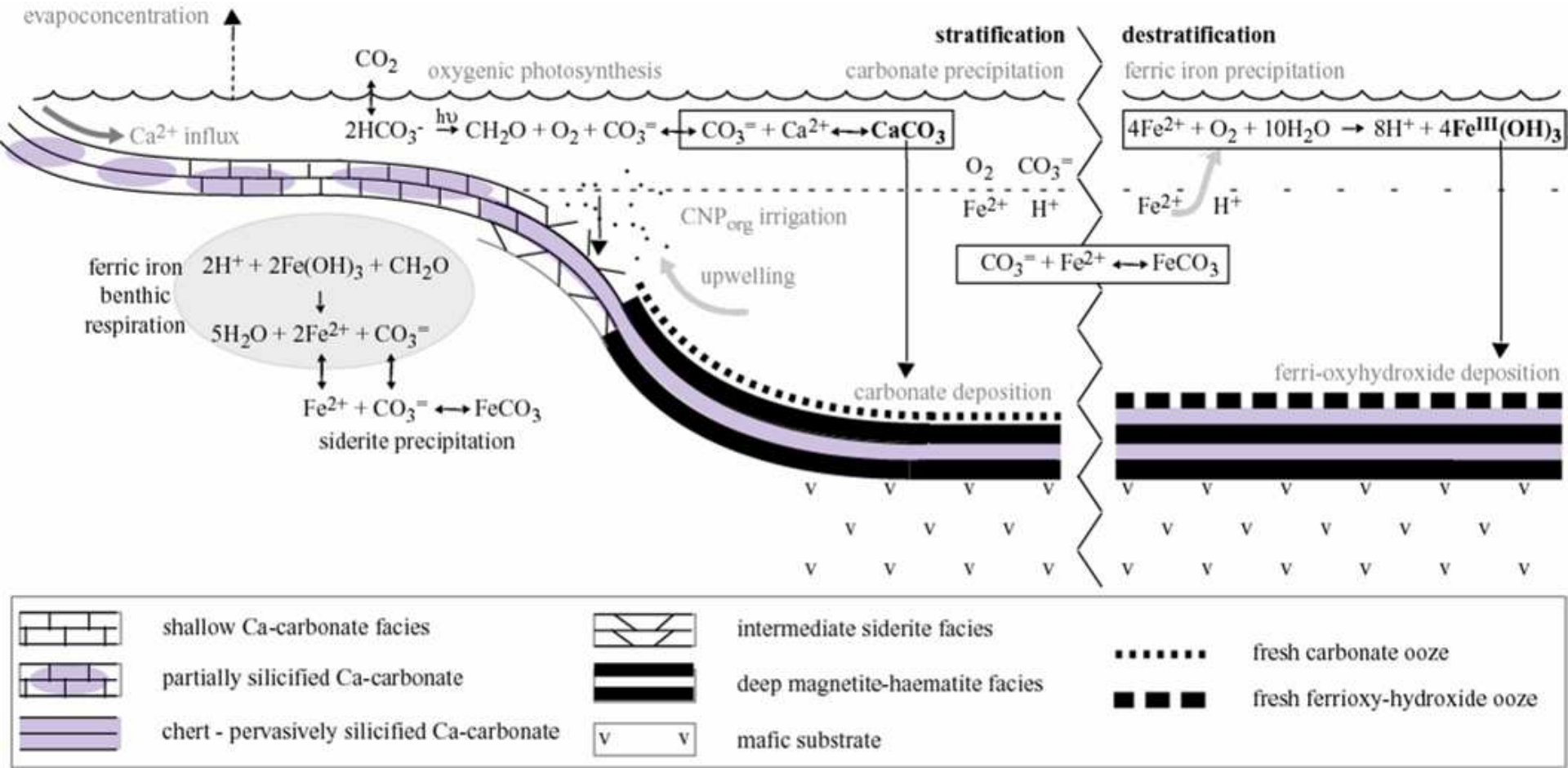
Cayeux (1909), 'Le quartz secondaire des minerals de fer oolithiques du silurien de France et son remplacement en profondeur par fer carbonate'.

Coonterunah Carbonate

Proto Banded-Iron Formation?

Coonterunah Carbonate

Proto Banded-Iron Formation?

Coonterunah Carbonate

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