Constraining the thermal history of carbonate reservoirs

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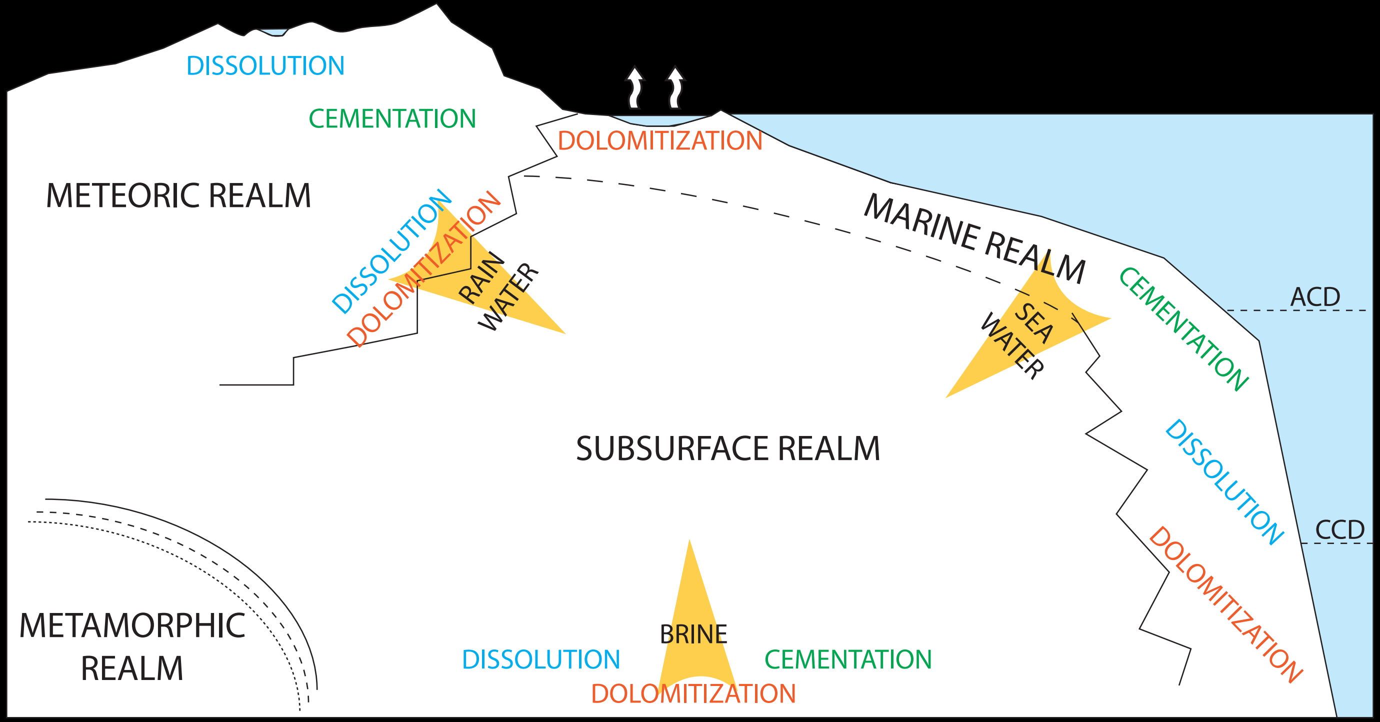
Petroleum Development Oman

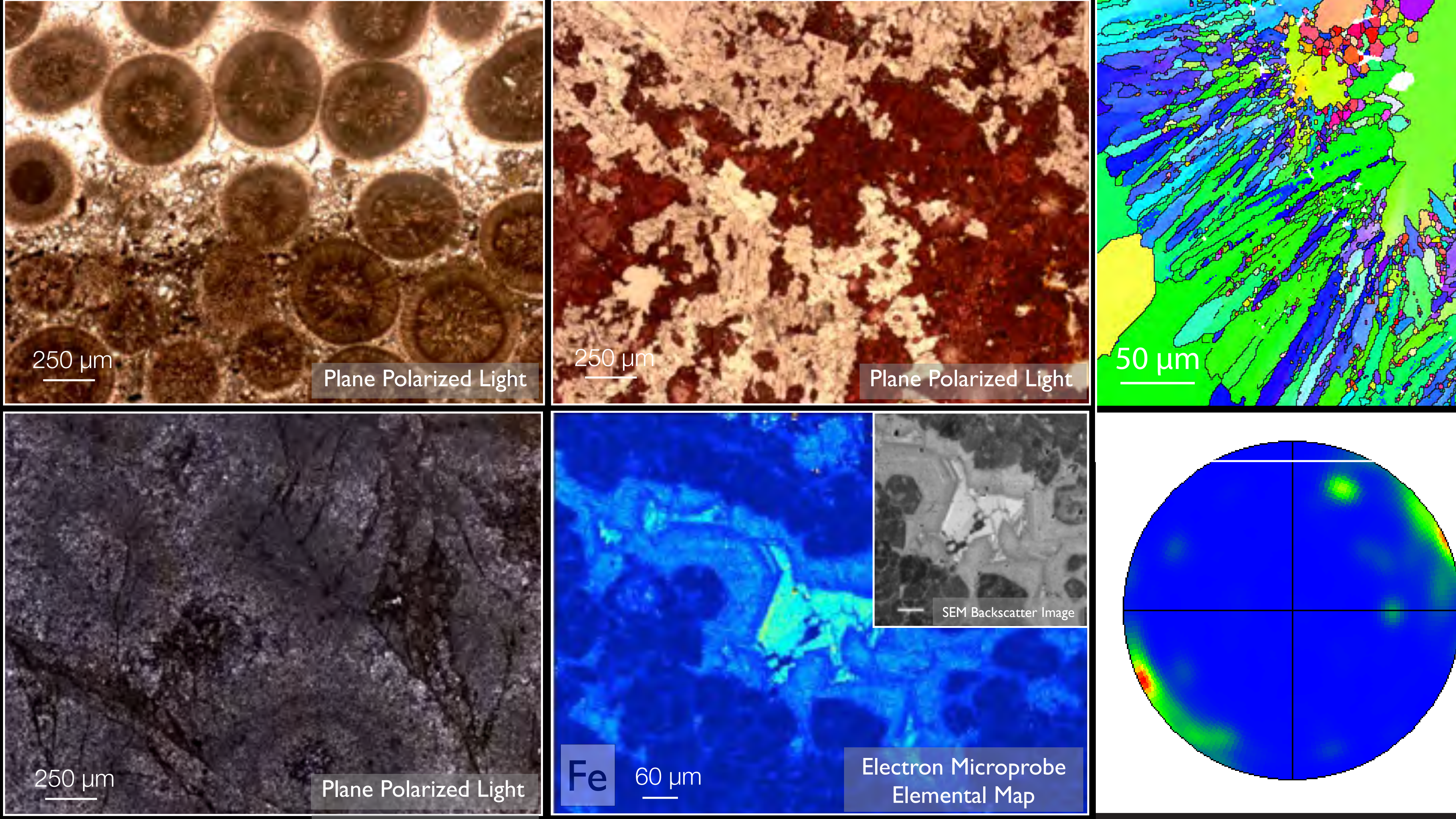
Massachusetts Institute of Technology

Earth Resources Laboratory

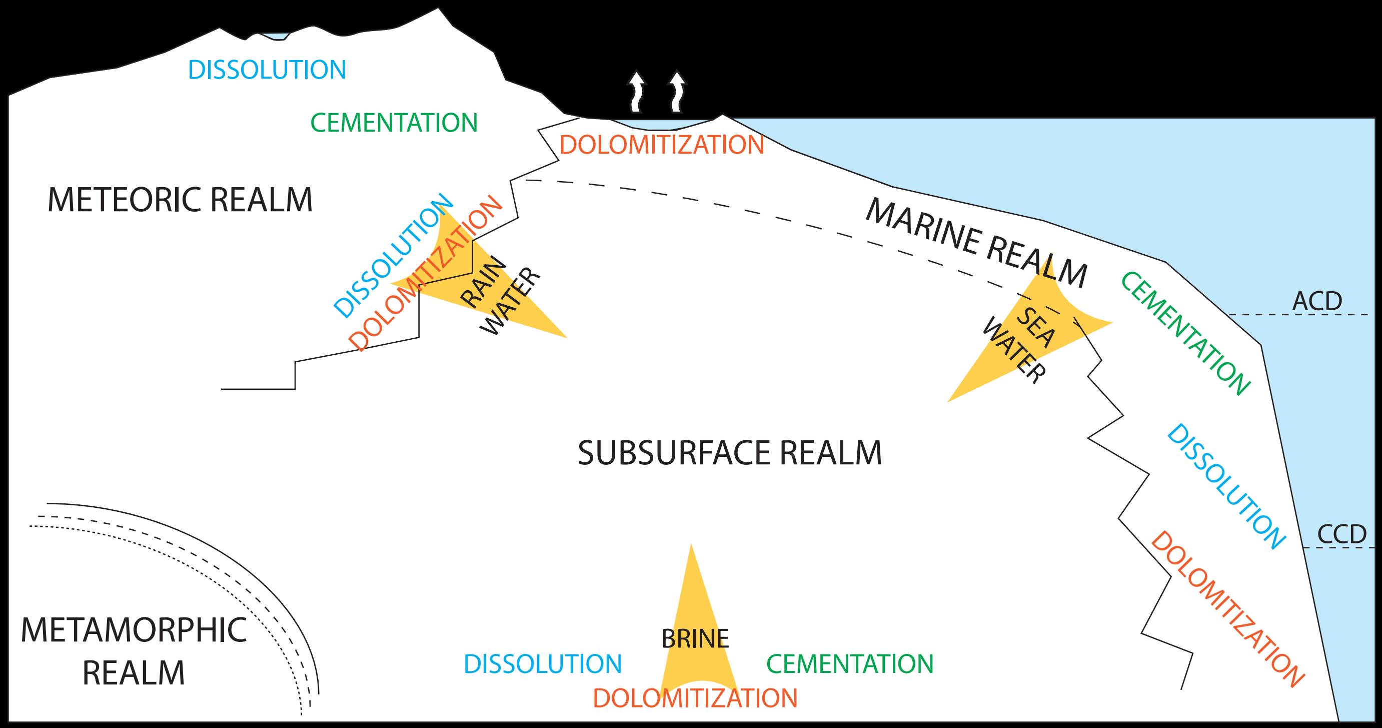
Carbonate reservoirs reflect shallow crustal processes that occlude or enhance porosity



(Modified from Moore, 1989)


250 µm
Plane Polarized Light
250 µm
Plane Polarized Light
50 µm
250 µm
Plane Polarized Light
Fe
60 µm
SEM Backscatter Image
Electron Microprobe Elemental Map

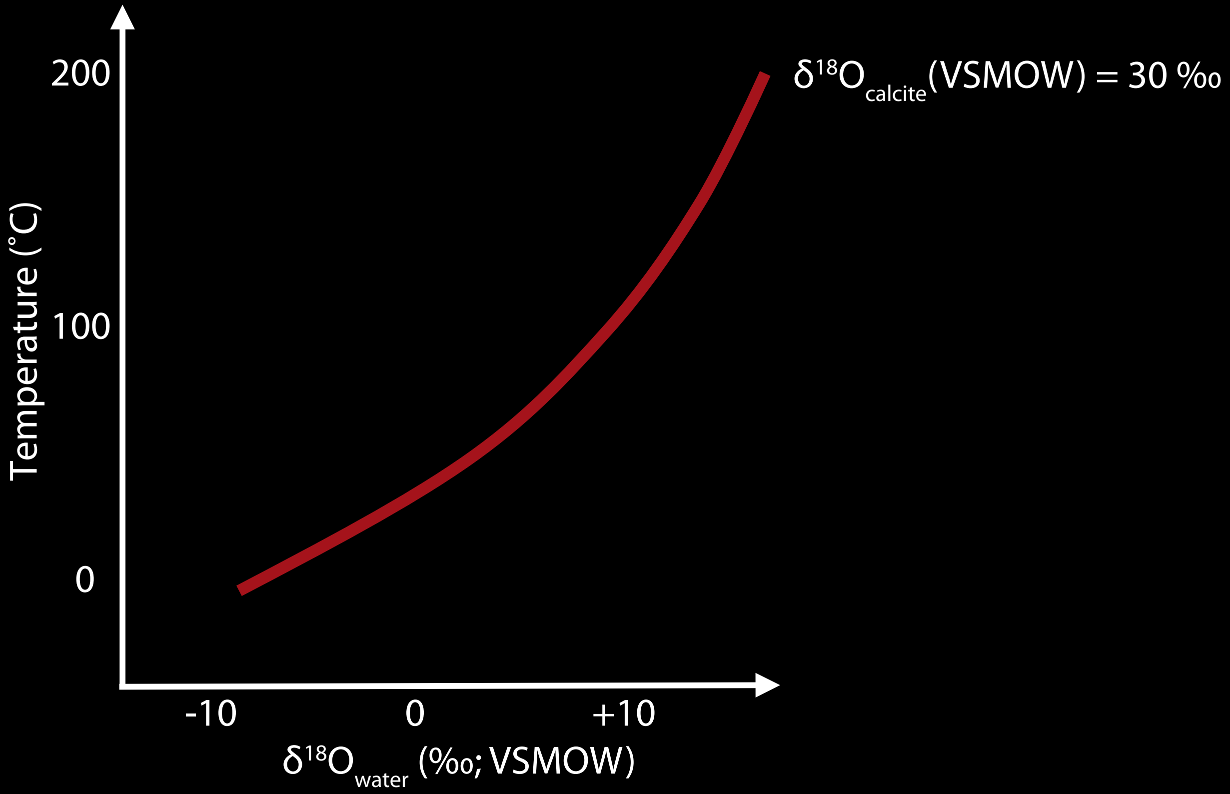
Tracking when and where key events occur is a function of T and W



(Modified from Moore, 1989)

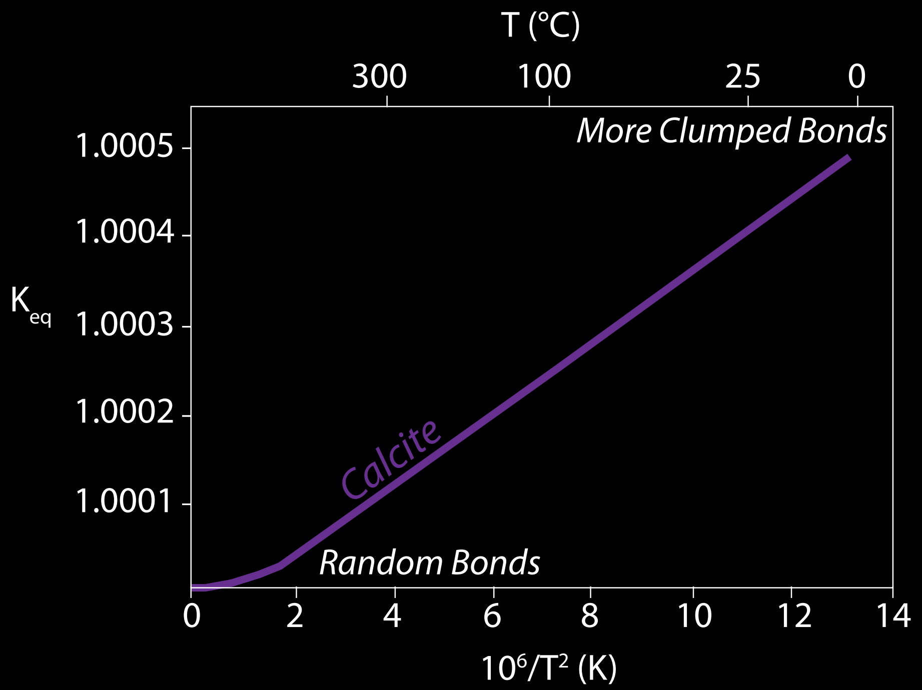
Traditional $\delta^{18}O$ measurements depend on both T and W

$$CaC^{16}O_3 + H_2{}^{18}O \xrightarrow{K_{eq}} CaC^{18}O^{16}O_2 + H_2{}^{16}O$$



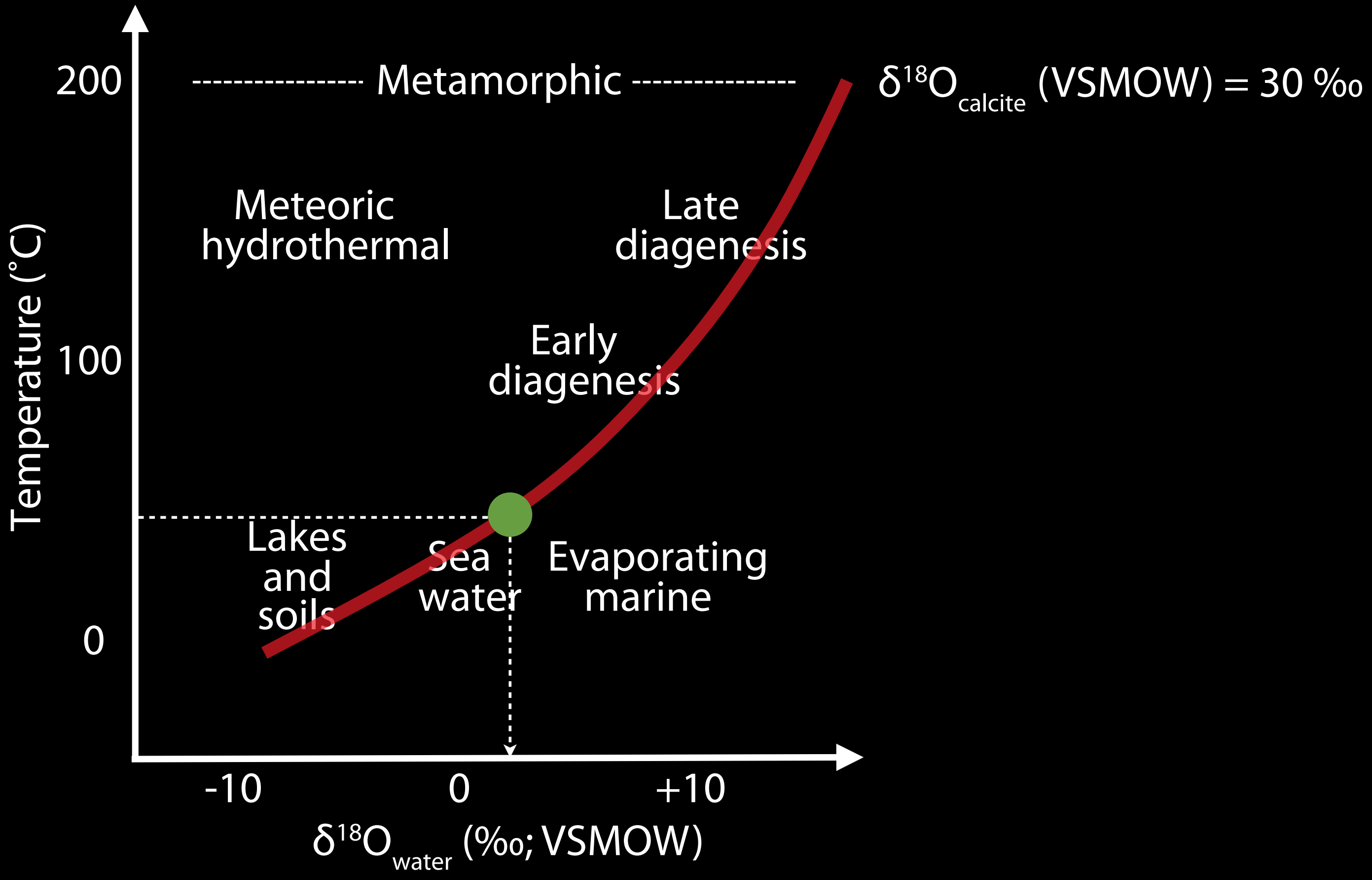
Clumped isotope thermometry primer

$$Ca^{13}C^{16}O_3 + Ca^{12}C^{18}O^{16}O \overset{K_{eq}}{\longleftrightarrow} Ca^{13}C^{18}O^{16}O_2 + Ca^{12}C^{16}O_3$$

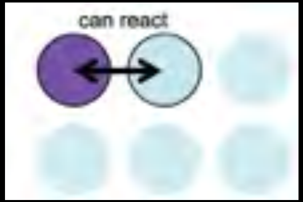


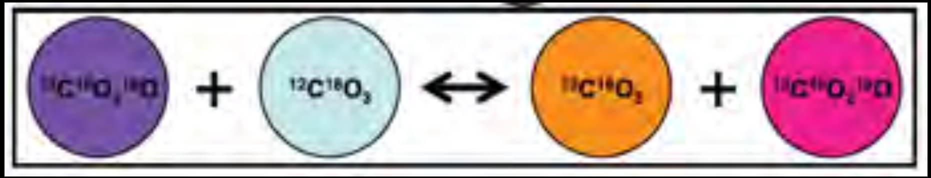
DFT Model of clumping in calcite from Schauble et al., 2006

$$CaC^{16}O_3 + H_2{}^{18}O \overset{K_{eq}}{\longleftrightarrow} CaC^{18}O^{16}O_2 + H_2{}^{16}O$$



Solid state reordering





Stolper and Eiler, 2015

- Apatite and aragonite will begin to reorder >100°C over 10^6 years (Stolper and Eiler, 2015 and Piasecki et al., 2015)

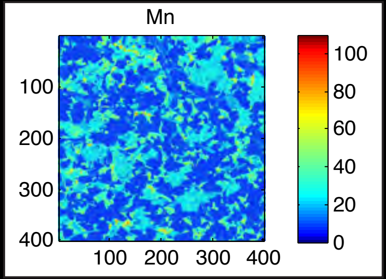
- Calcite will begin to reorder at >150°C over 10^6 - 10^8 years and fully-equilibrates above 200°C (Henkes et al., 2014; Stolper and Eiler, 2015)

- Dolomite does not reorder over ~ 250°C over 10^8 years (Lloyd and Eiler, 2014)

The Bergmann Lab approach

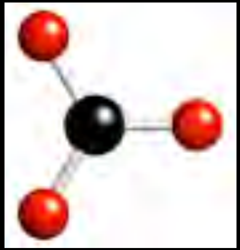
Sedimentological context and petrographic preservation

Field observations and EBSD mapping



Trace metal and isotopic heterogenetity

SIMS, Electron Microprobe, XRD, XANES, ICP-AES



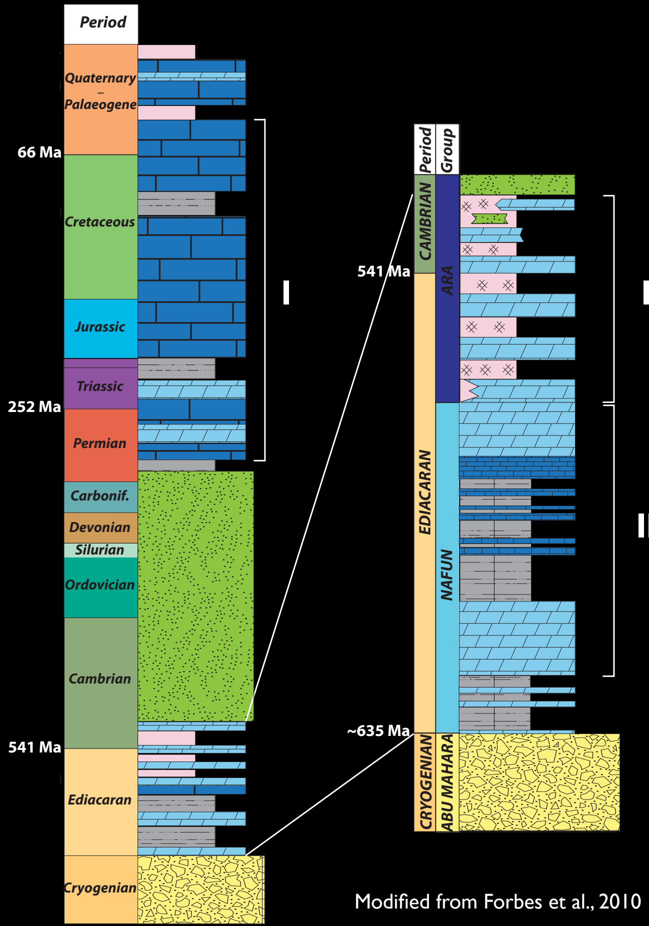
Precipitating temperature and fluid compositions

Clumped Isotope Thermometry





Diagenetic trends in marine carbonates
Sultanate of Oman



Group I: Eocene to Permian

- Thick limestones to mixed limestones and siliclastics
- Minor dolomite in the Permian
- Range of petrographic fabrics from micrite to grainstone with varying degrees of fossil preservation and cementation

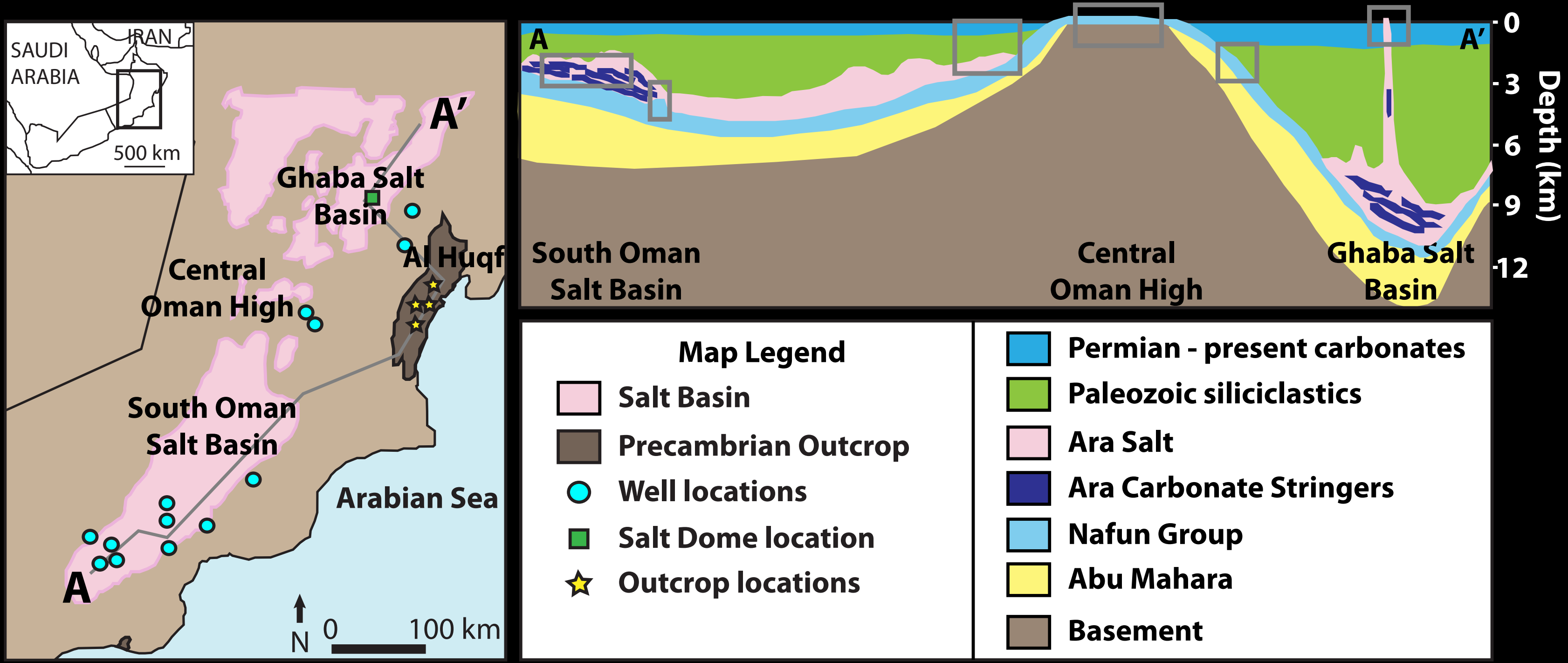
Group II: PC-C Ara Group

- Carbonate 'stringers' floating in evaporites
- Dominantly dolomite although some calcite
- Range of petrographic fabrics with fine to coarse grained interlocking recrystallized fabrics

Group III: Ediacaran Nafun Group

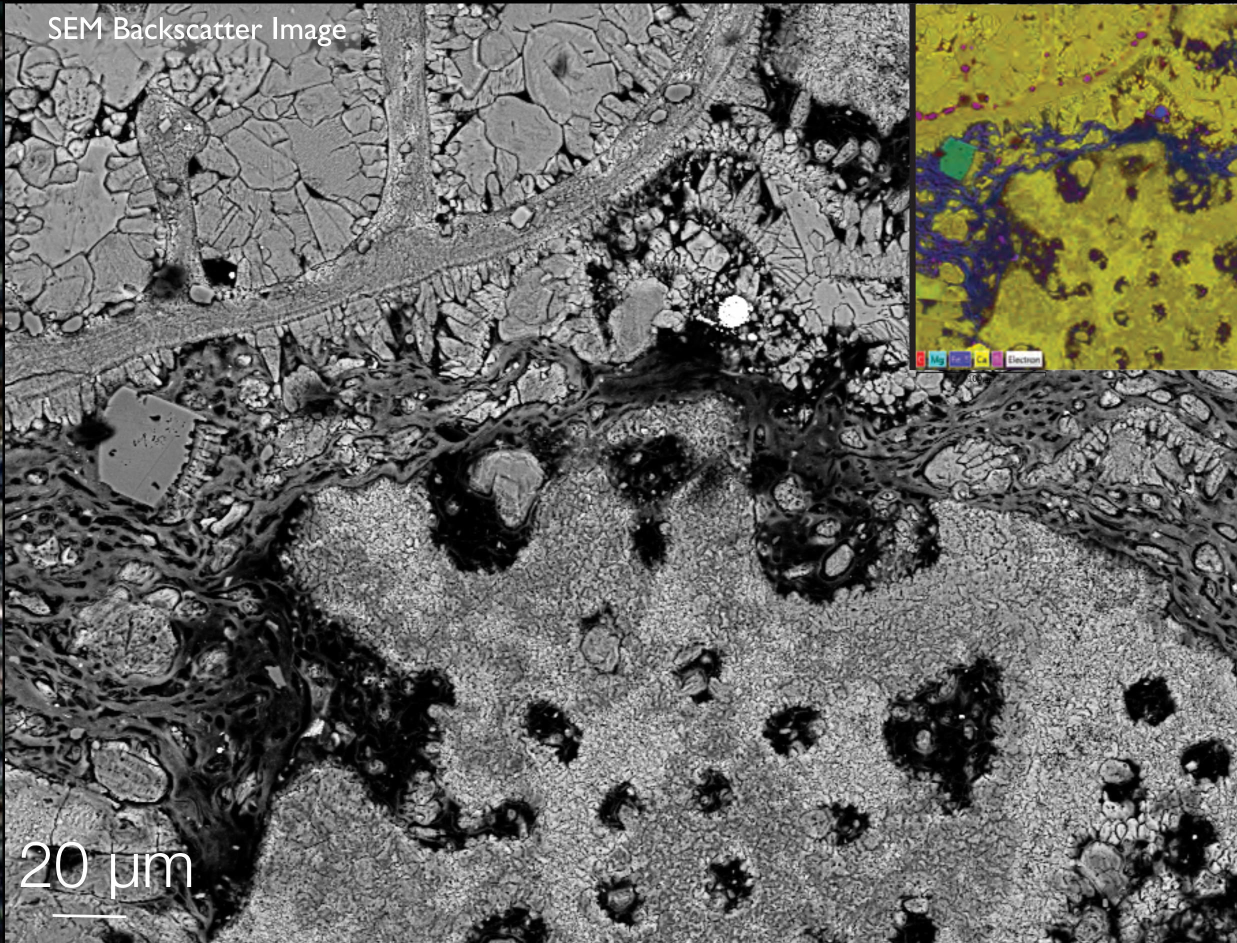
- Thick dolomites to mixed limestones and siliclastics
- Range of petrographic fabrics from micrite to grainstone to boundstone with similar preservation character to Group I

Diagenetic trends in marine carbonates: Cross section of central Oman

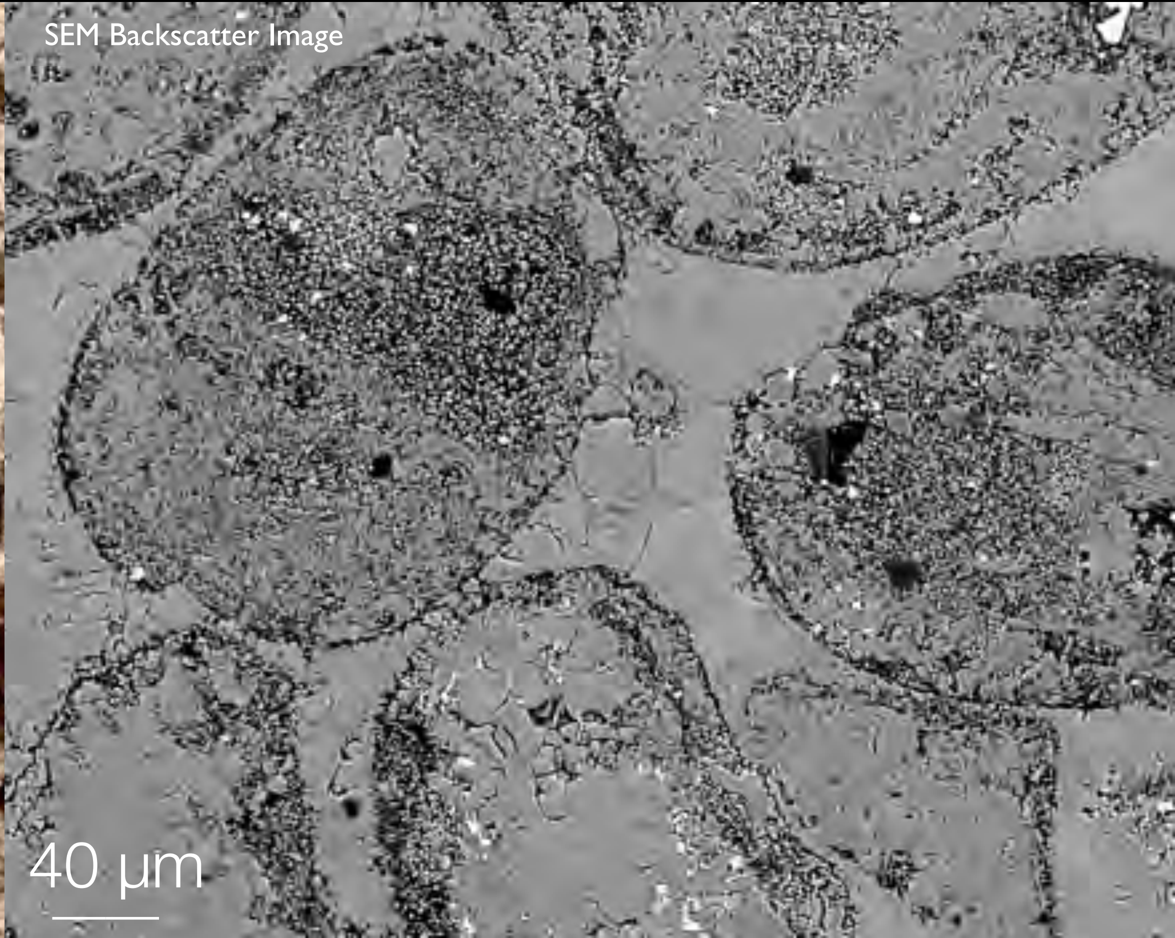


Modified from Al Siyabi, 2005

Eocene [357m, BT = 43°C]: T = 30 ± 2°C
$\delta^{18}O_{water}$ = 0.2 ± 0.5‰ (n=3)



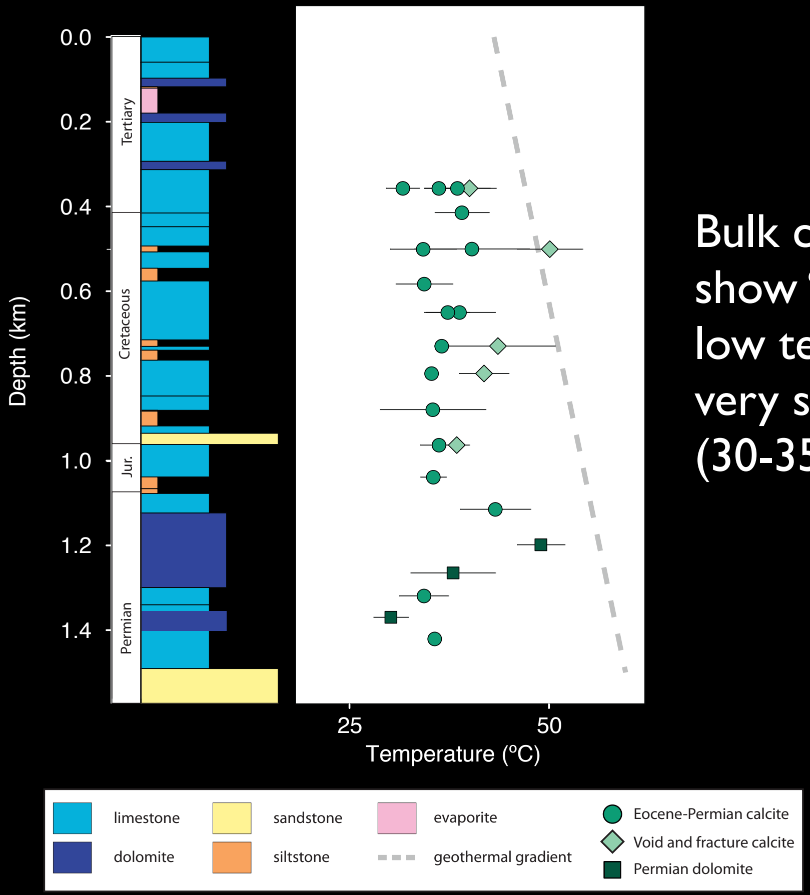
Jurassic [1038 m, BT = 54°C]: T = 34 ± 2°C
$\delta^{18}O_{water}$ = 0.3 ± 0.3‰ (n=2)



Cretaceous [500.8 m, BT = 49°C]: T = 32 ± 4°C

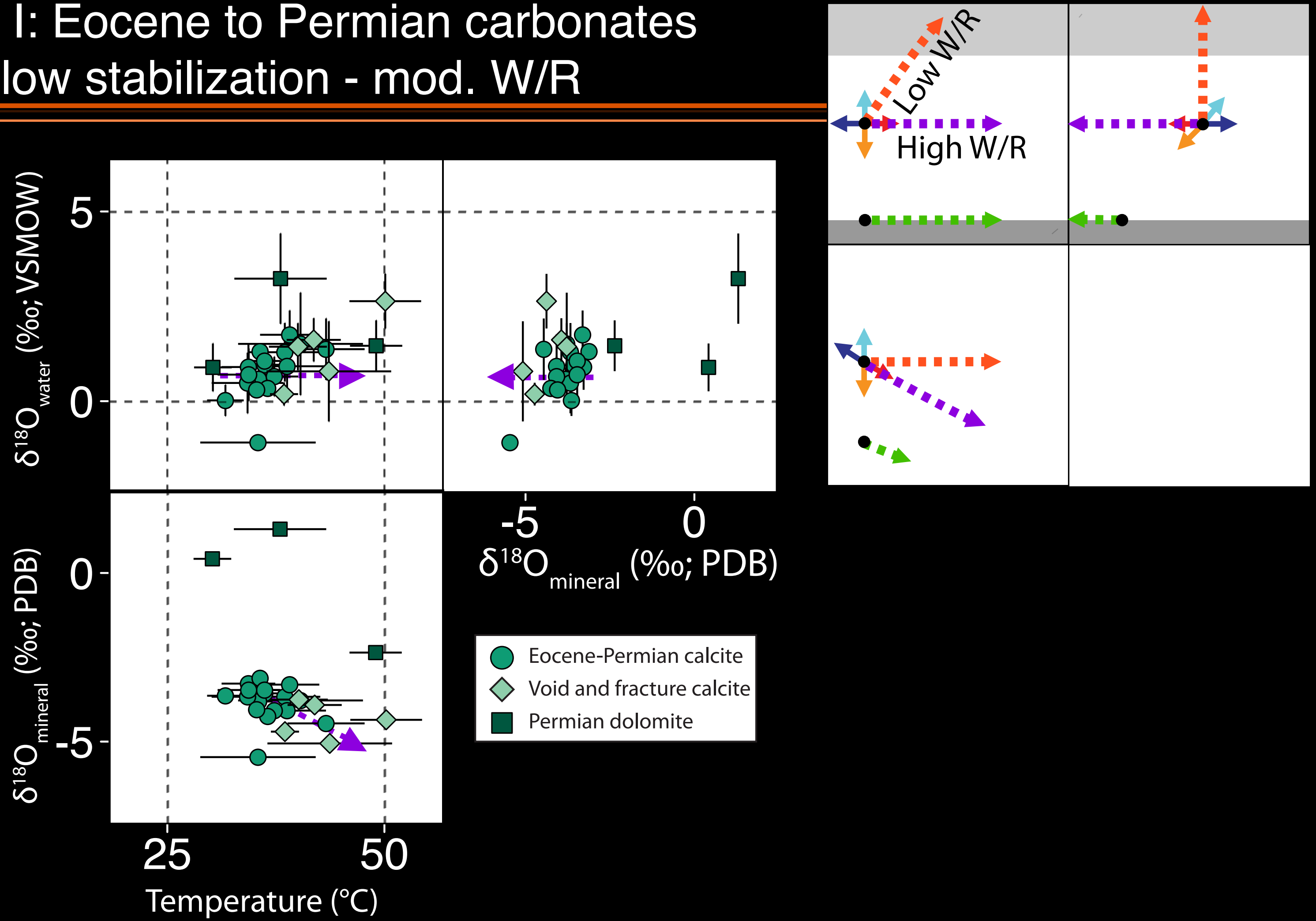
$\delta^{18}O_{water}$ = 0.2 ± 0.8‰ (n=2)

Group I: Eocene to Permian carbonates
A subsurface well

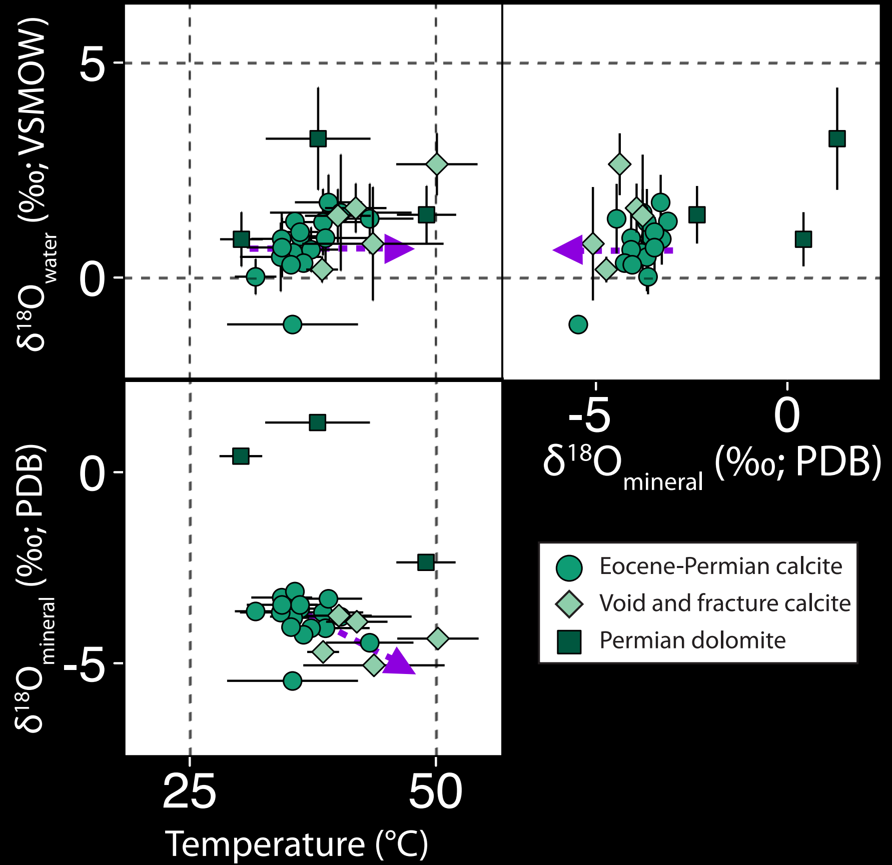


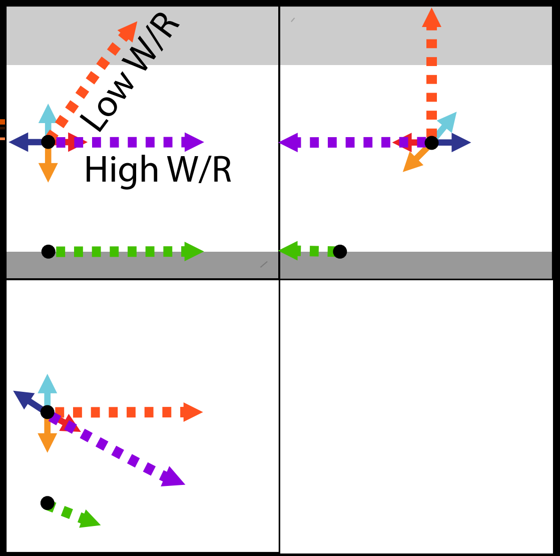
Bulk carbonates show 'stabilization' at low temperatures and very shallow depths (30-35°C)

Group I: Eocene to Permian carbonates
v. shallow stabilization - mod. W/R

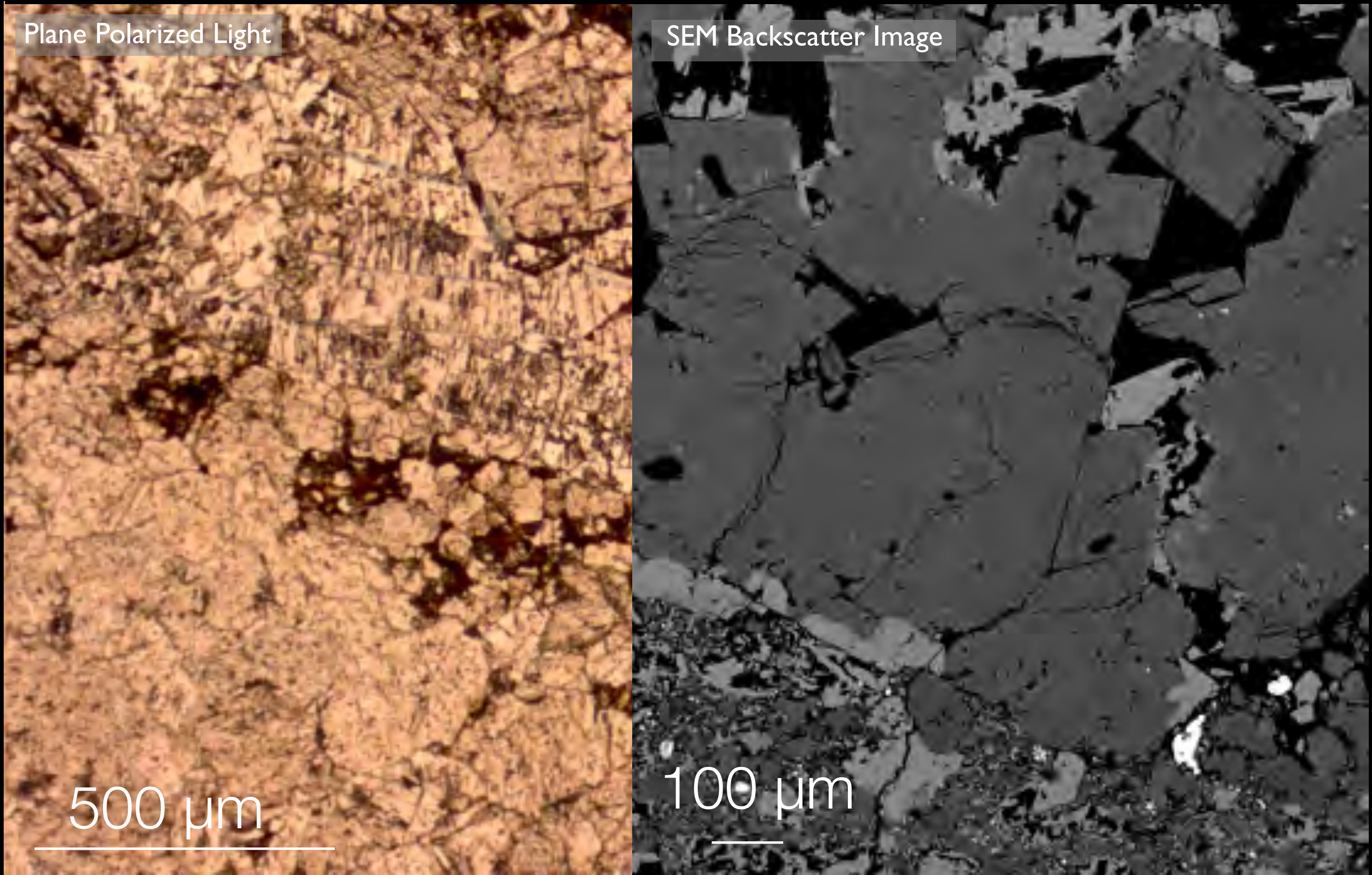


Group I: Eocene to Permian carbonates v. shallow stabilization - mod. W/R

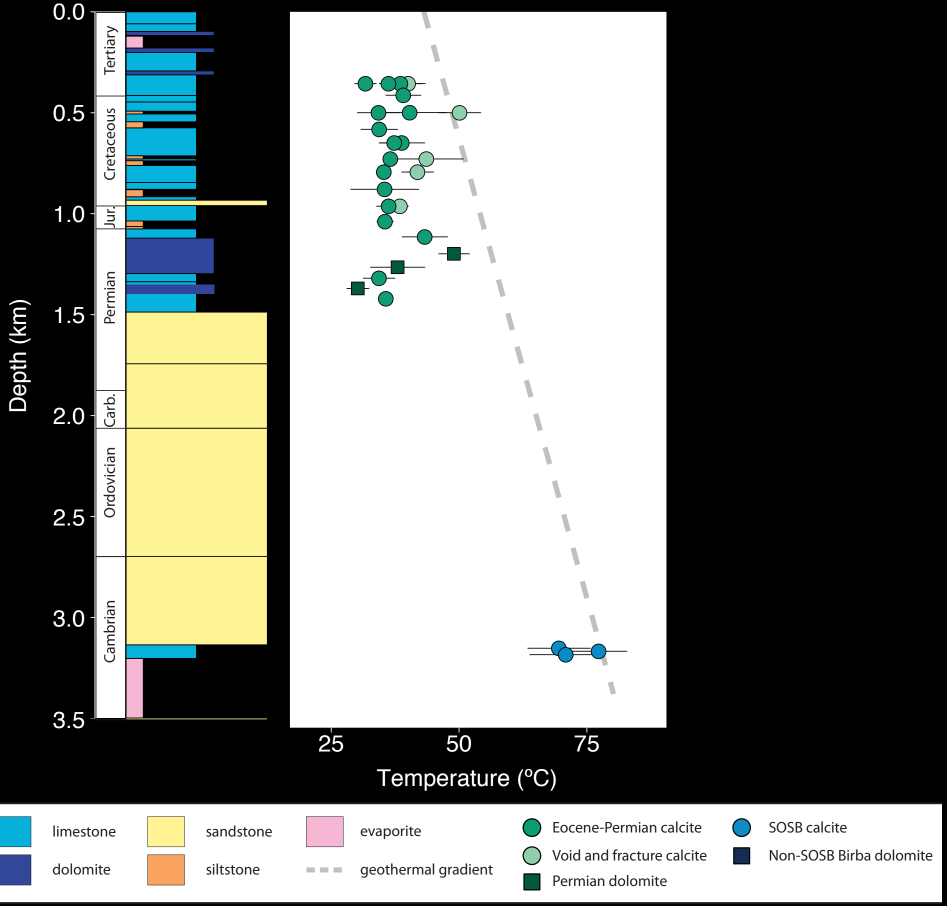




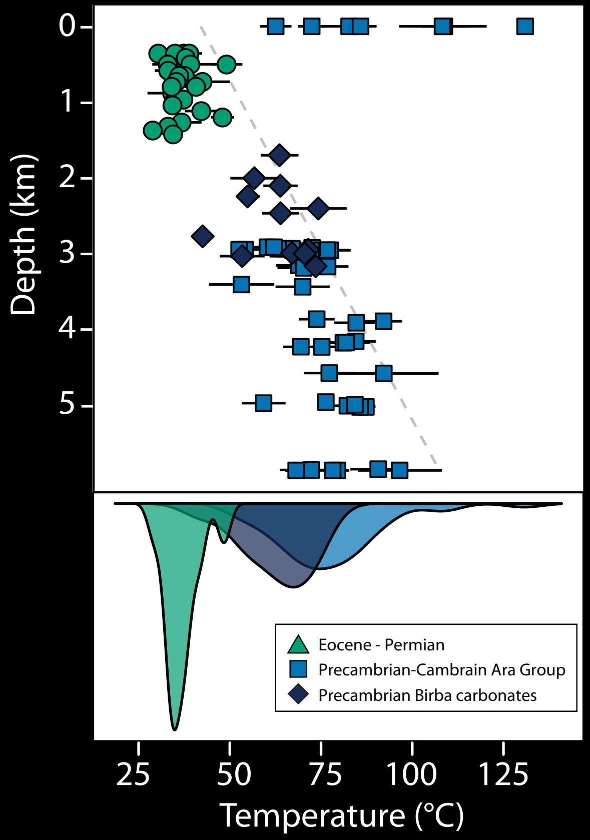
PC-C (Ara Group) [3148 m, BT = 77°C] T = 75 ± 5°C
$\delta^{18}O_{water}$ = 7 ± 1‰ (n=2)

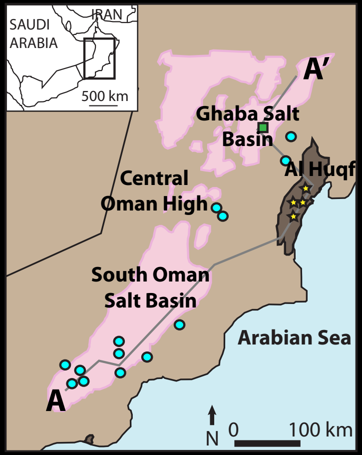


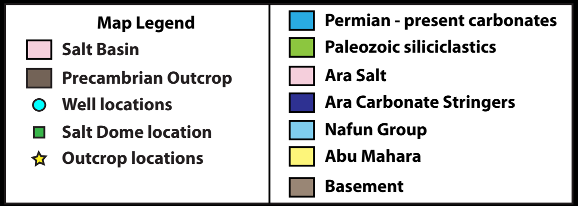
Group II: Precambrian-Cambrian Ara Group
A subsurface well

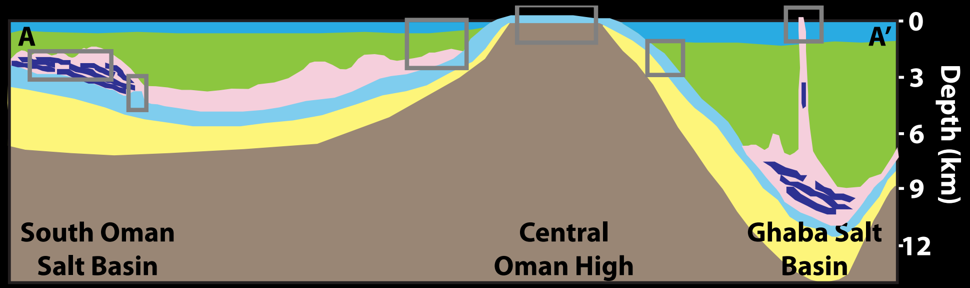


Group II: Precambrian-Cambrian Ara Group sample Ts approach the current geotherm

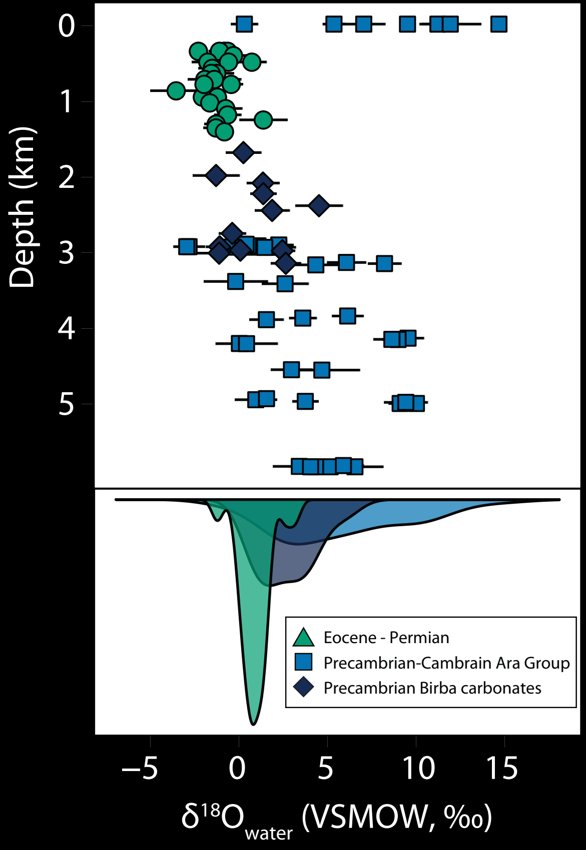


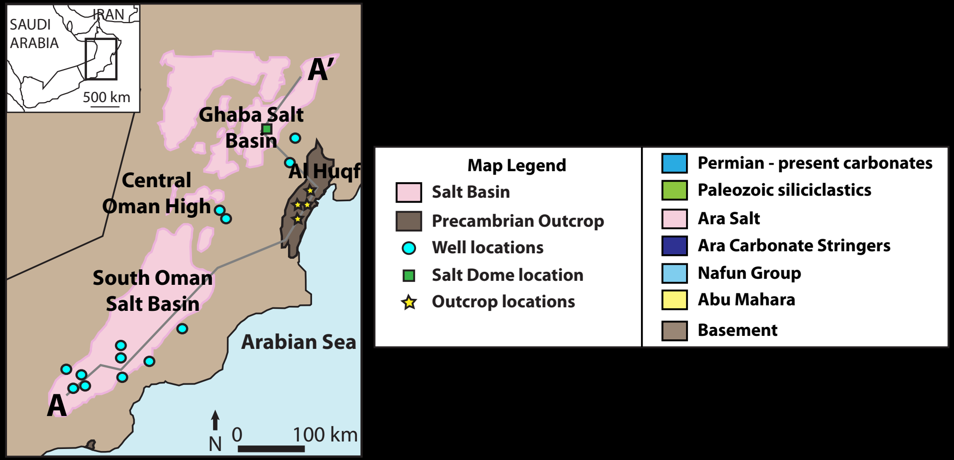


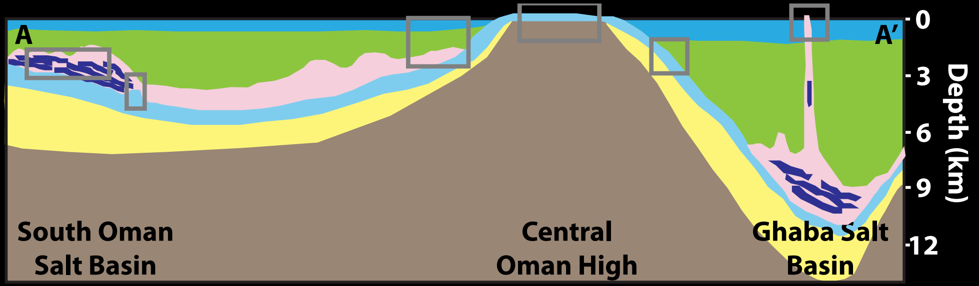




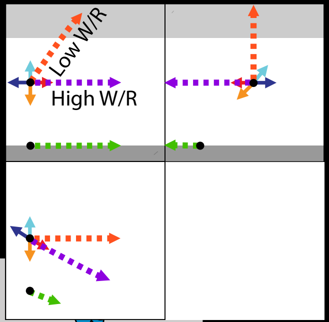
Group II: Precambrian-Cambrian Ara Group $\delta^{18}O_{water}$ compositions are enriched

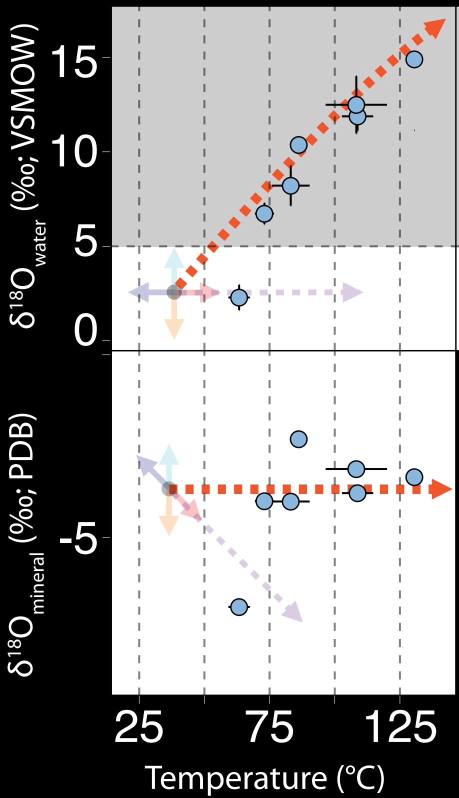


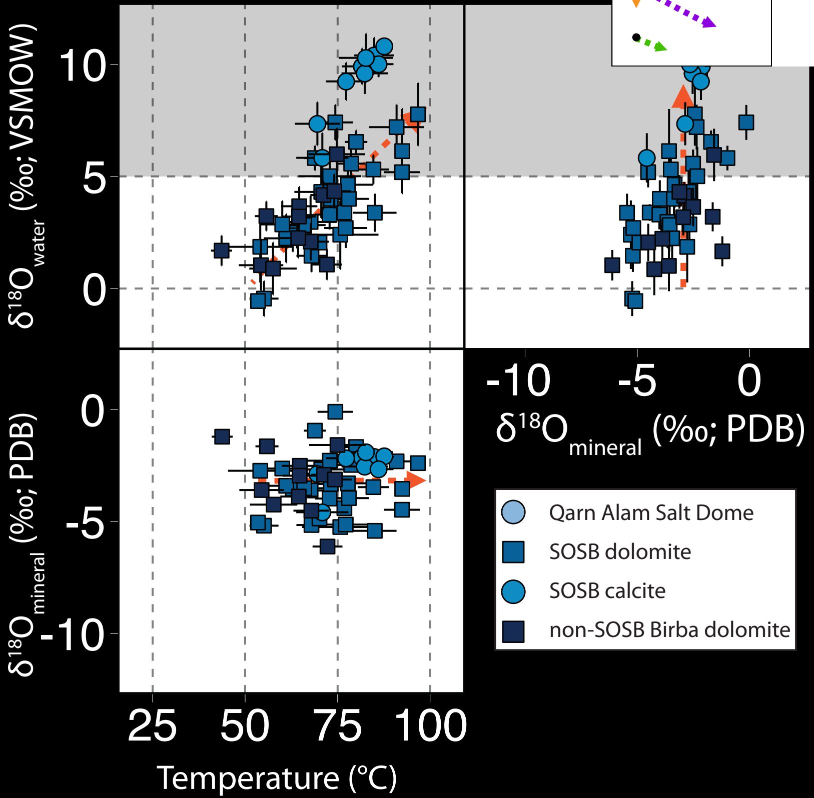




Group II: Precambrian-Cambrian Ara Group low W/R ratio

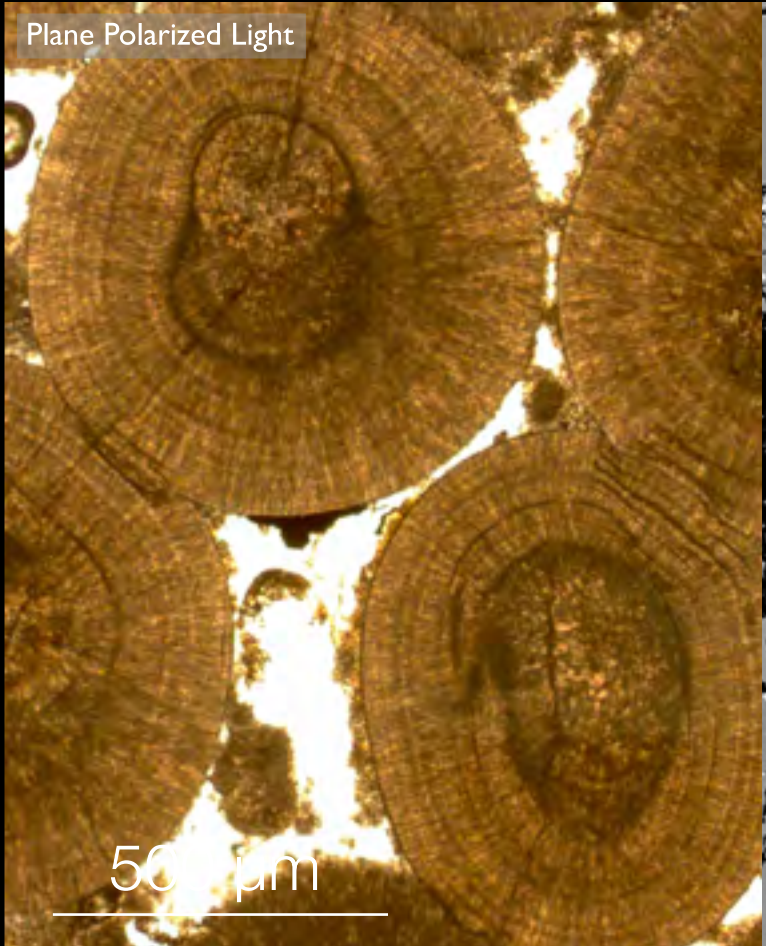


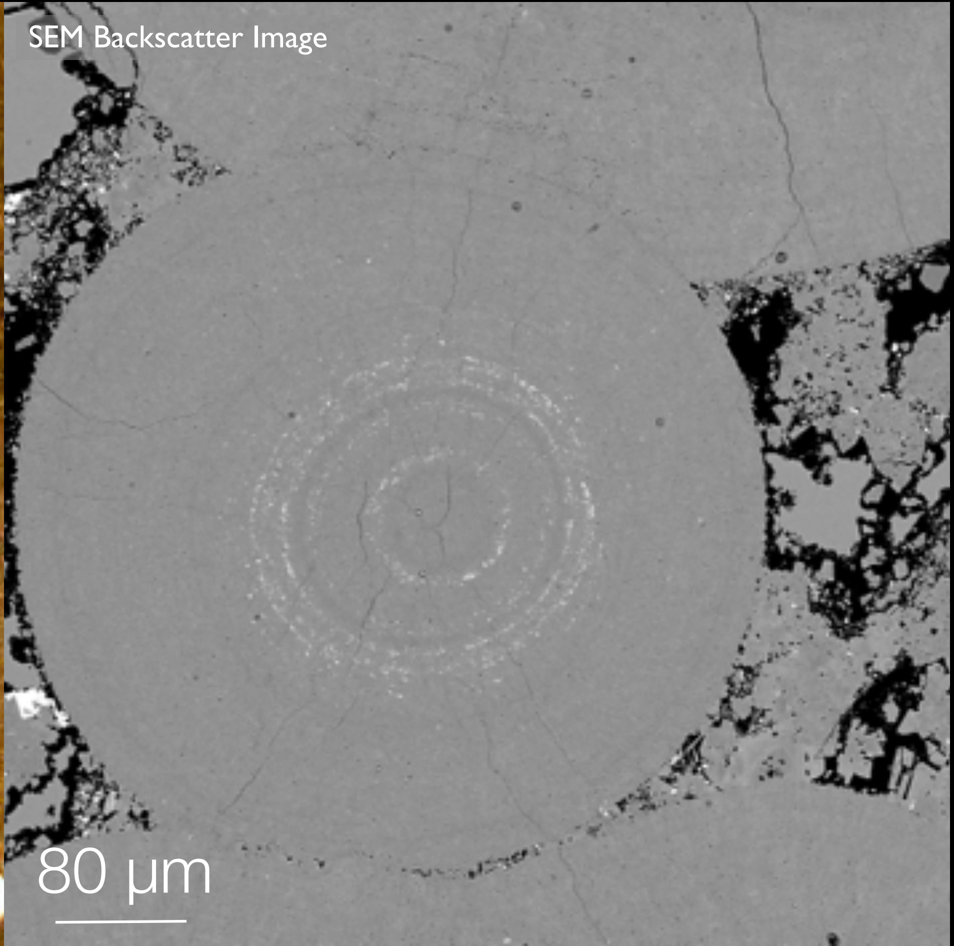




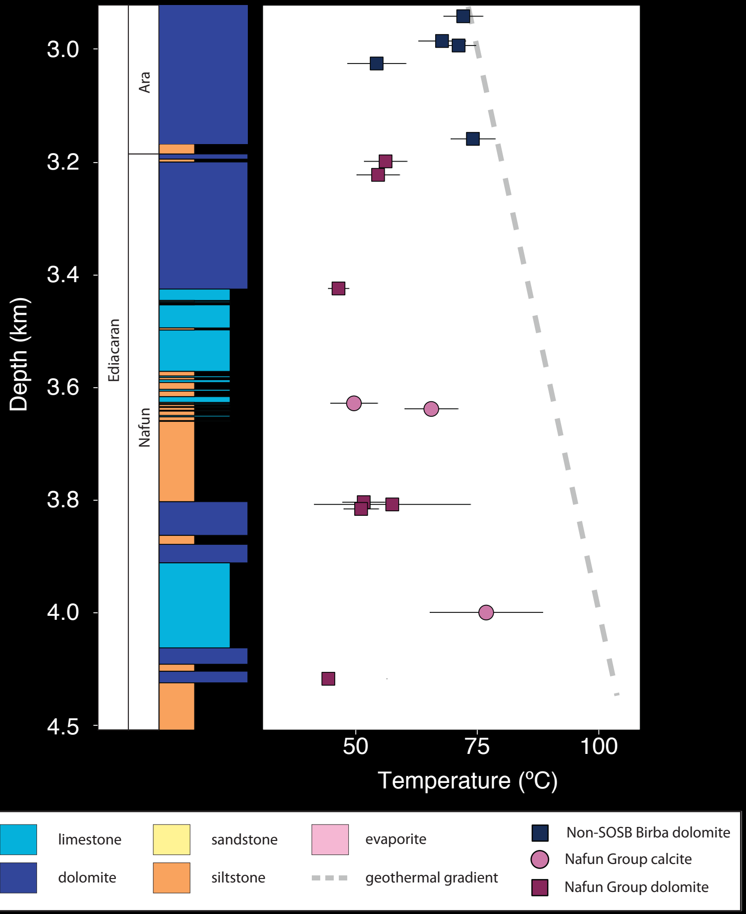
Ediacaran (Nafun Group) [surface, est. 1-2km max]

T = 55 ± 1°C, $\delta^{18}O_{water}$ = -1.6 ± 0.4‰ (n=3)

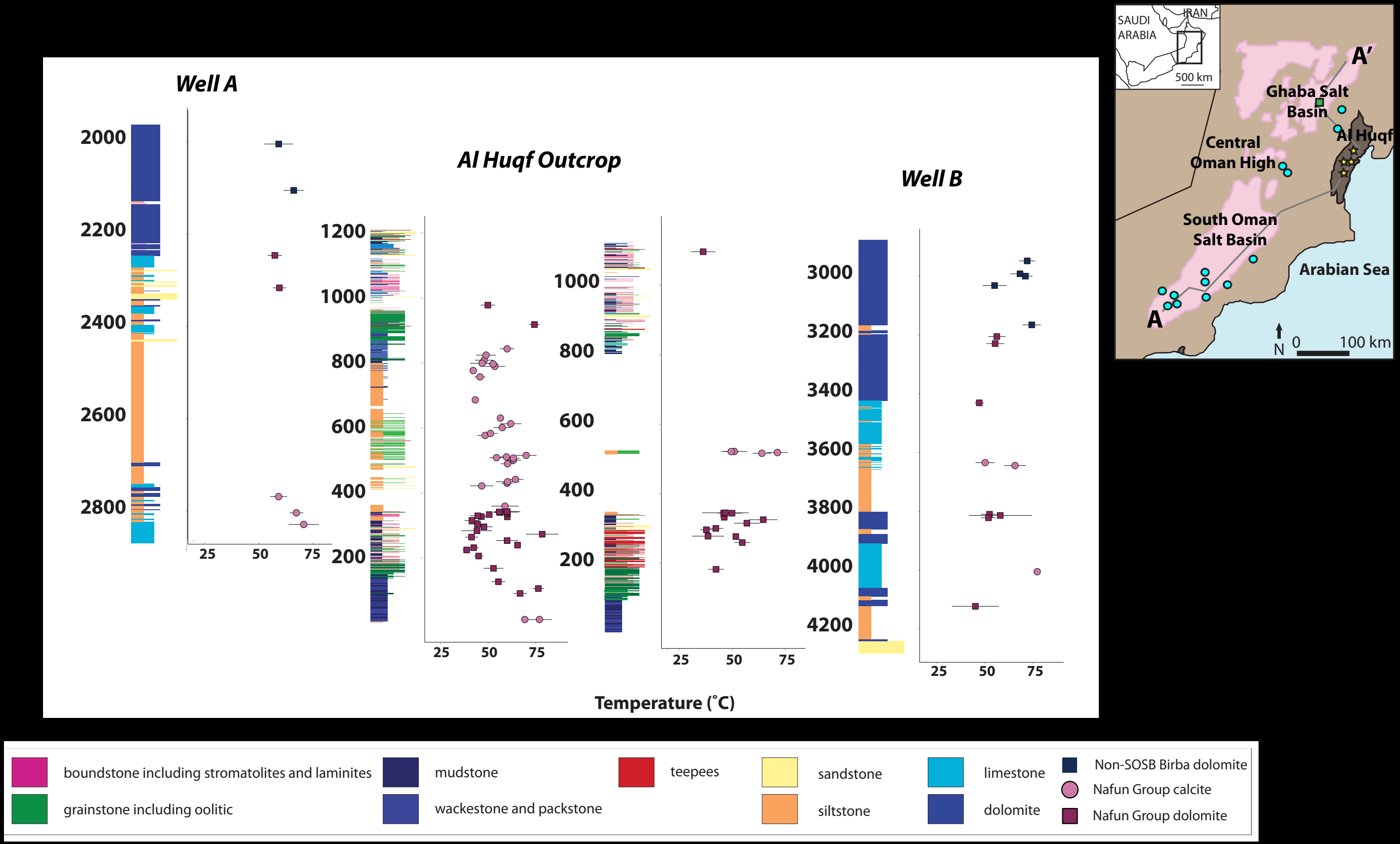




Group III: Ediacaran Nafun Group
A subsurface well

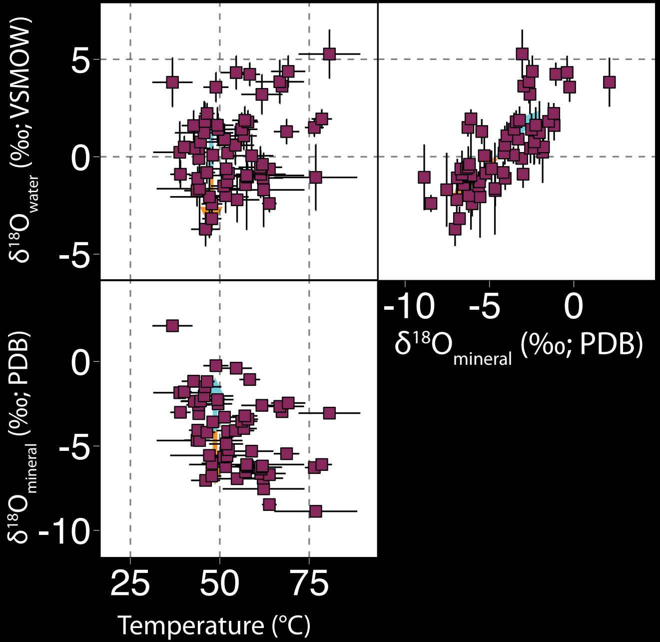


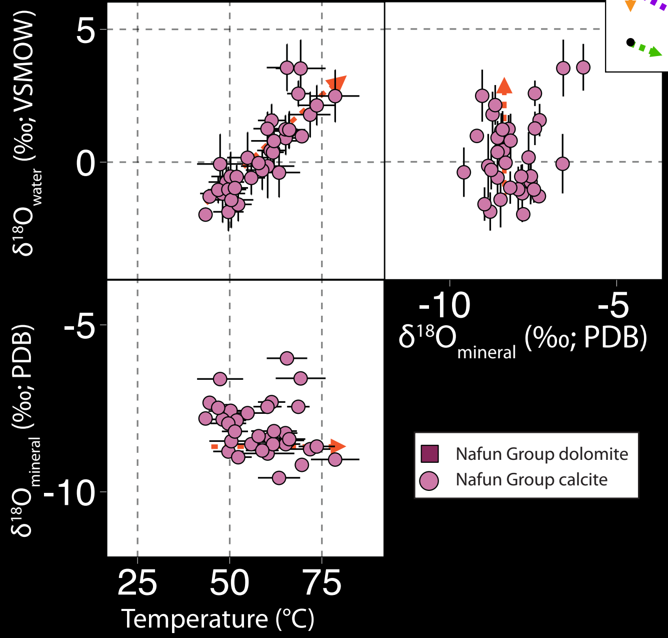
T range is spatially and stratigraphically consistent for both dolomite and calcite in Nafun Group

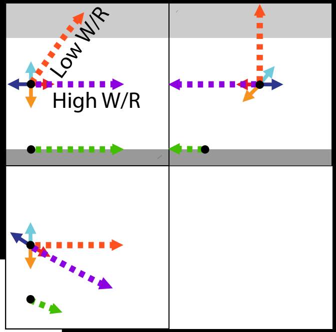


(sedimentology from Bergmann, 2013 and Osburn, 2013)

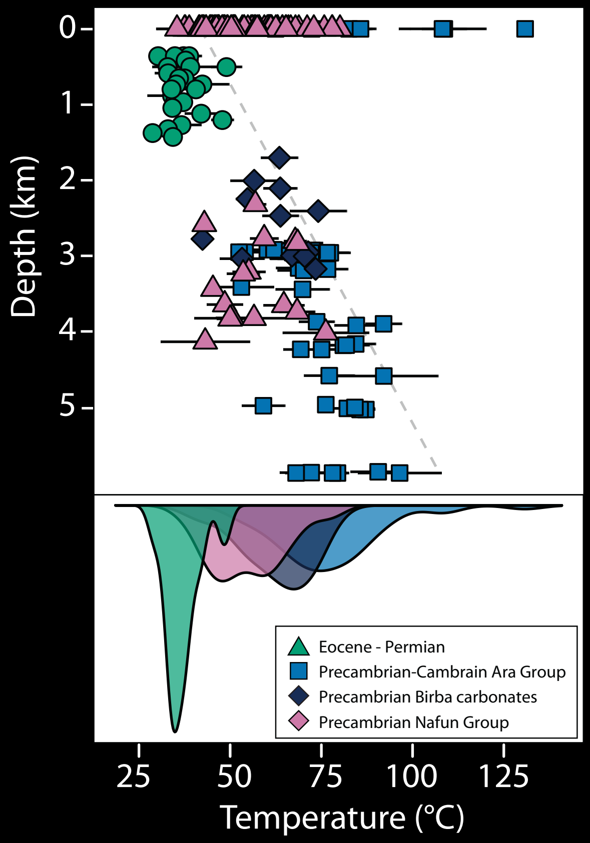
Group III: Ediacaran Nafun Group change in fluid comp., low W/R in calcite

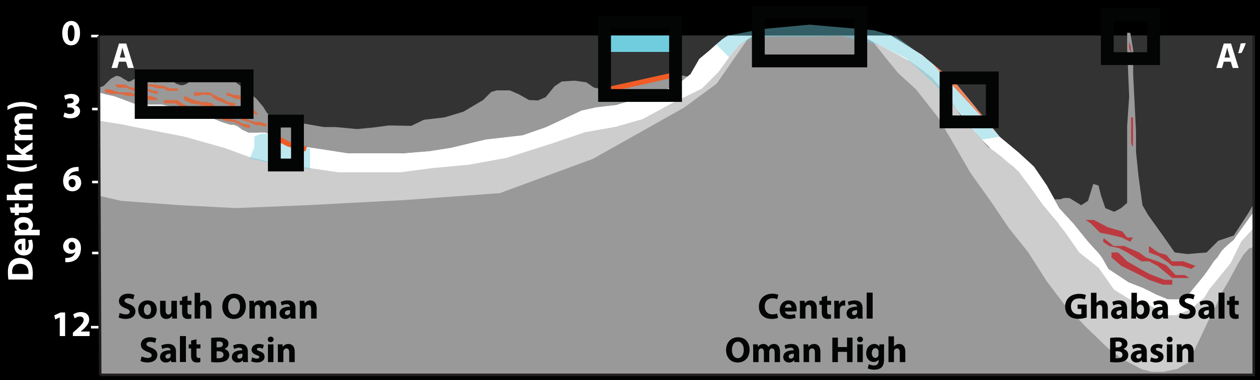




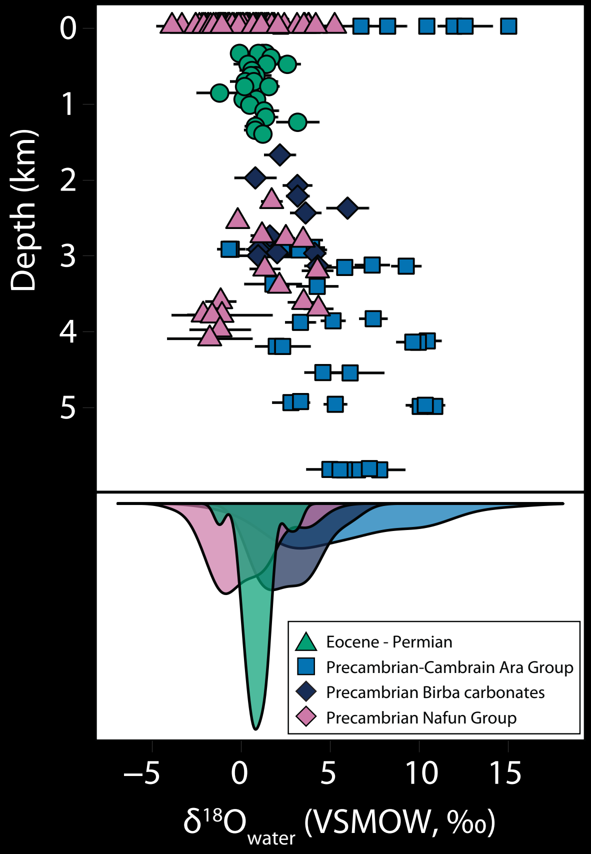


Group III: Ediacaran Nafun Group Ts in between Groups I & II





Group III: Ediacaran Nafun Group $\delta^{18}O_{water}$ marine-like



Observations:

- Nafun Group carbonates are petrographically well-preserved

- Co-occuring calcite and dolomite indicate similar T

- $\delta^{18}O_{water}$ compositions are seawater like for both calcite and dolomite

Options:

- partial solid state diffusion and long term change in $\delta^{18}O_{water}$
- change in temperature of shallow burial 'stabilization' or initial temperature

Summary

- Using a combination of petrographic, microanalytical and clumped isotope analyses of specific textures we can reconstruct the timing of events critical to the evolution of carbonate reservoirs and the thermal history of basins

- Results from Oman indicate dolomites and limestones are more susceptible to burial diagenetic processes than solid state diffusion between 0-6 km over geologic timescales.

- Group I of Eocene-Permian limestones and dolomites suggest very early 'stabilization'. Group II Ara Group limestones and dolomites show variable closed system behavior. Group III Nafun Group data are consistent with a higher temperature of 'stabilization' at very shallow depths which could indicate the Ediacaran was 5-20°C warmer than the recent Phanerozoic.