

# **Hydrothermal Dolomitization Paradigms and the Manetoe Dolomite: Are All HTDs Fault-Related?\***

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## **Abstract**

Recent work on hydrothermal dolomite masses has emphasized their close relationship to structural deformation and faulting. The source of dolomitizing fluids is considered to have been intimately and primarily related to the development of extensional, or strike-slip, wrench-style faults. This paradigm has been recently challenged by workers who have documented many occurrences of Paleozoic-hosted hydrothermal petroleum reservoir dolomites in North America that bear little, if any, overt relationship to faults. The gas-bearing Manetoe Dolomite of northern Canada is another spectacular example of a hydrothermal dolomite that does not exhibit a general spatial relationship to known faults. This laterally extensive HDT is encountered in nearly 70 wells across more than 25,000 km<sup>2</sup> in the little deformed subsurface east of the Mackenzie Mountains, as well as in outcrop across Liard Plateau and Mackenzie Mountains where it has been mapped as a discontinuous “formation” across six 1:250,000 scale geologic map areas, or over more than 20,000 km<sup>2</sup>. The Headless Shale aquiclude exerted a strong hydrodynamic control on the upward circulation of dolomitizing brines in Late Devonian time east of the mountain front across Slave Plain. The much greater depth to hydrodynamic basement west of the mountain front may have engendered more vigorous circulation of dolomitizing brines, as indicated by fluid inclusion and isotopic data. This enhanced convective brine circulation, in conjunction with local attenuation of the Headless Shale and the presence of carbonate shelf edge shoal grainstone facies, may have caused the development of the very thick Manetoe Dolomite masses, such as in the Liard gas fields and in the “Manetoe” shelf edge exposures at Ram River and Iverson Lake. Outcrop exposures of “HDT” zebra and boxwork fabrics in the Manetoe are best interpreted as the consequence of hydrothermal dissolution by heated evaporitic brines of seawater origin, and not as dilational breccia fabrics attendant upon extensional or wrench faulting.

## **Selected References**

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- Qing, H., 1998, Petrography and Geochemistry of Early-Stage, Fine- and Medium Crystalline Dolomites in the Middle Devonian Presqu'ile Barrier at Pine Point, Canada: Sedimentology, v. 45, p. 433-446.
- Roedder, E., 1968, Temperature, Salinity, and Origin of the Ore-Forming Fluids at Pine Point, Northwest Territories, Canada, from Fluid Inclusion Studies: Economic Geology, v. 63/5, p. 439-450.

Saller, A.H., and J.A.D. Dickson, 2011, Partial Dolomitization of a Pennsylvanian Limestone Buildup by Hydrothermal Fluids and its Effect on Reservoir Quality and Performance: AAPG Bulletin, v. 95, p. 1745-1762.

# Hydrothermal dolomitization paradigms and the Manetoe Dolomite: are all HTDs fault-related?

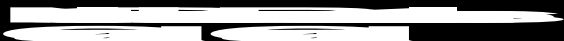


David Morrow, GSC

Obvious  
Dilational  
Fracturing and  
Brecciation?



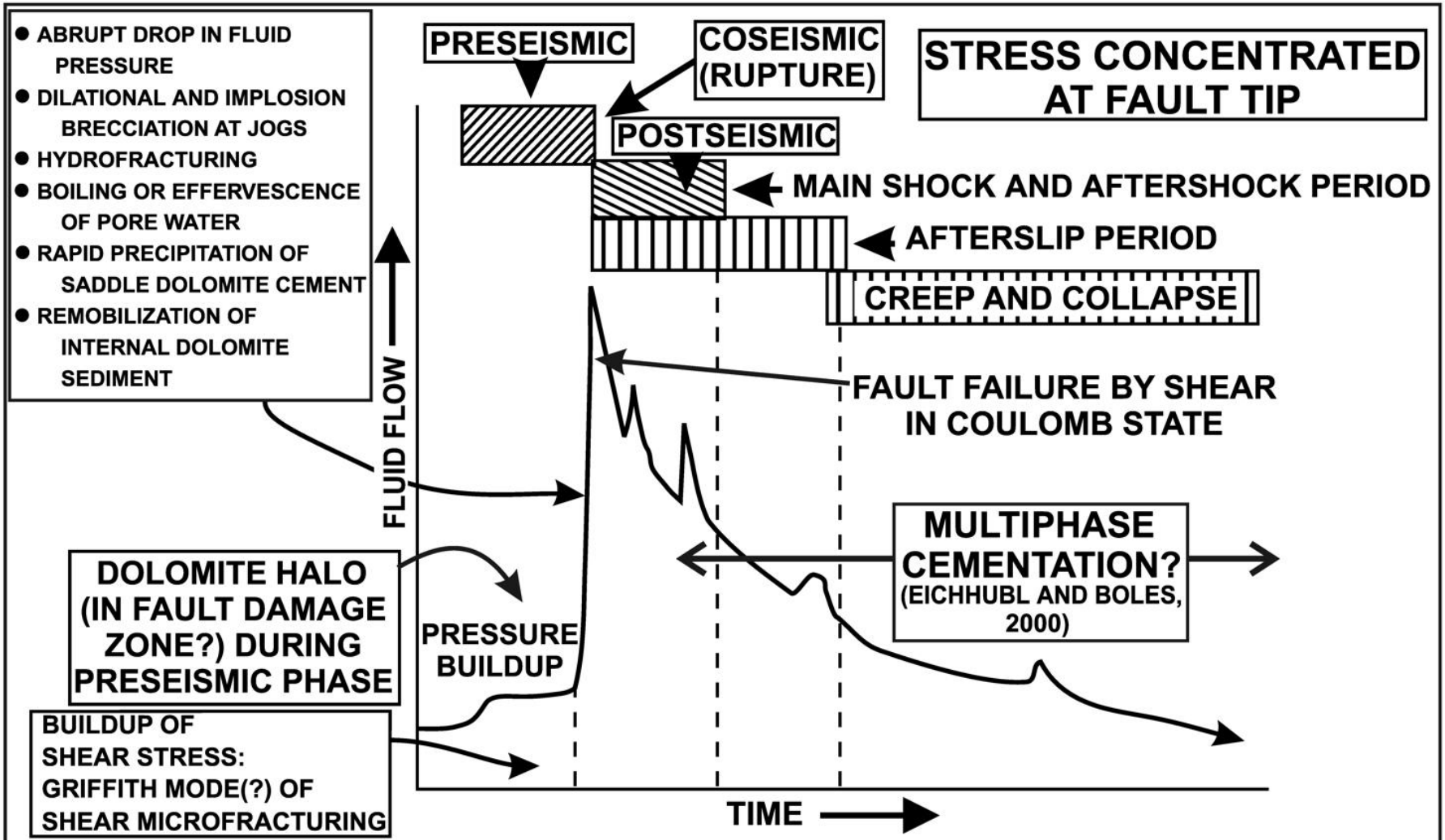
Earth Sciences Sector



# What is this talk about?

- Are all HDTs formed during active faulting?  
Are HDTs formed only along faults?
- Can fluid volumes moved during active faulting be responsible for masses of HDTs?
- Can HDT fabrics be explained as consequence of abrupt fluid pressure changes during faulting?
- Are there other explanations for HDTs and their characteristic fabrics?

# Rationale for “Explosive” HDT (after Davies & Smith, 2006)



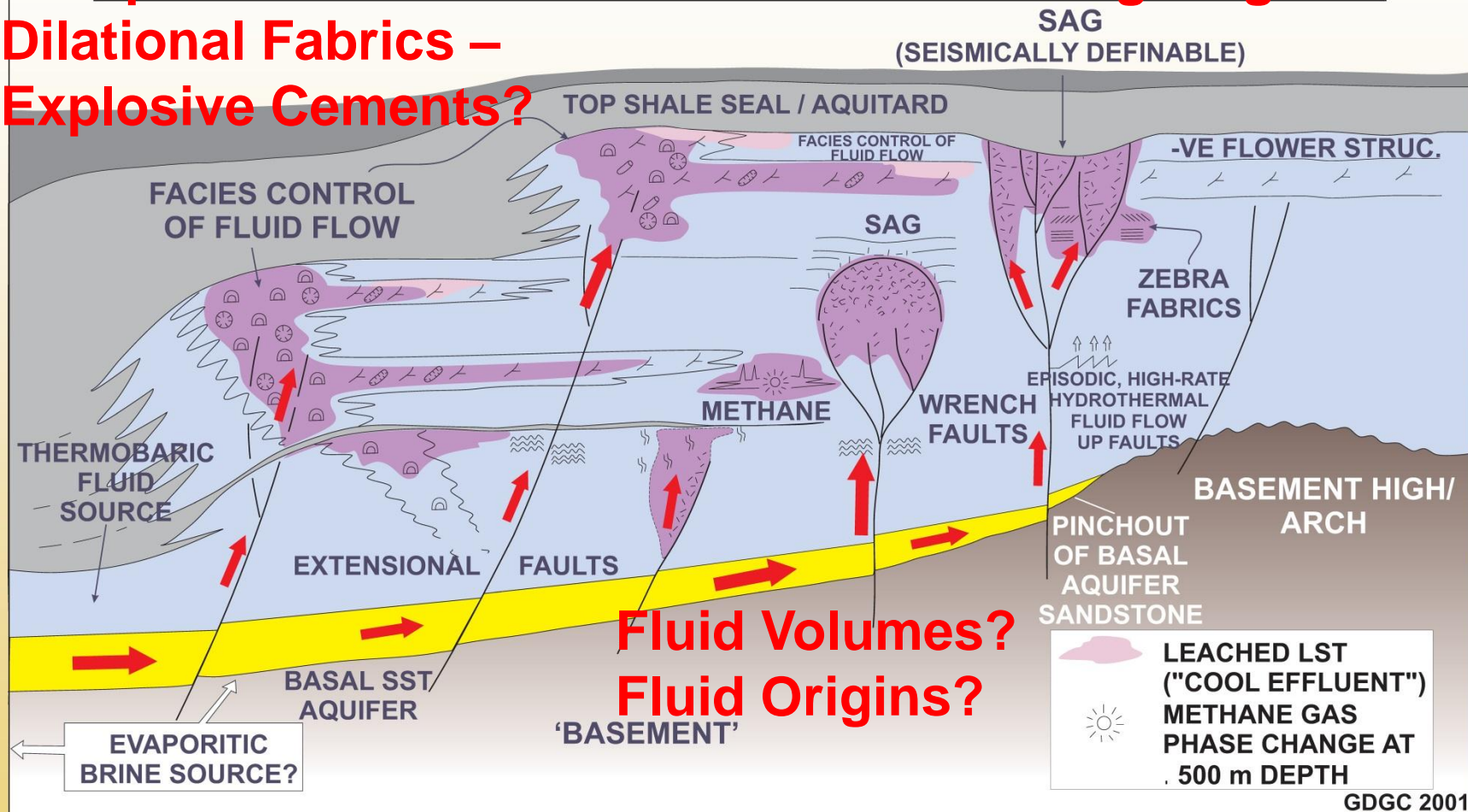
# THERMOBARIC DOLOMITE : EMPLACEMENT CONTROLS

Overpressured HDT

[DEVONIAN SETTING]

Sag Origin?

Dilational Fabrics –  
Explosive Cements?



GDGC 2001

SYPCDR01\_068

Graham Davies model for HTD in Devonian of Western Canada

# **Evidence cited for these assertions:**

- **HTDs exhibit close association with, and are localized along, extensional and transtensional faults and at their intersections. Possible temporal and spatial linkage of MVTs and basinal SEDEX deposits and associated faulting with inboard HDTs.**
- **Rock fabrics, such as rimmed microfractures, zebra fabrics, and dolospar (saddle dolomite) cemented breccias, are interpreted to be of structural origin related to, and approximately contemporaneous with, extensional, or transtensional faulting.**
- **Occasional association of HTDs with replacement sphalerite or other lead-zinc mineralization (galena).**

# Explosive dilational brecciation now preferred explanation for HDT Fabrics

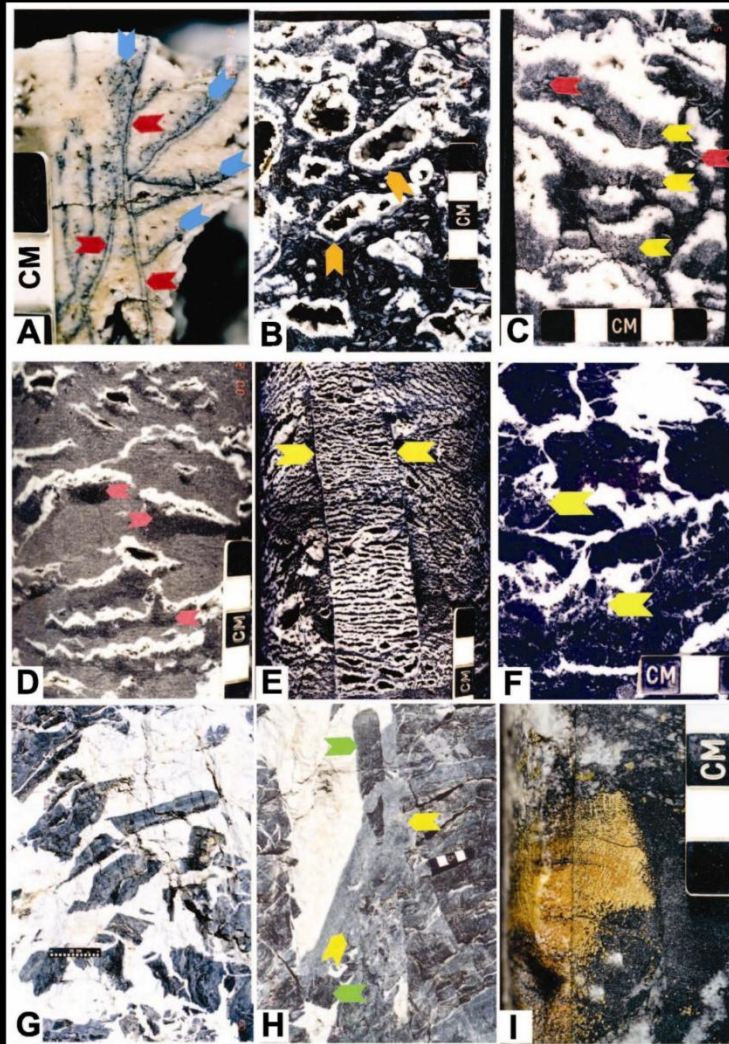


**“Zebra Fabric”  
- Saddle  
Dolomite Filling  
Horizontal  
Fractures and  
Voids**

**•Dolomitizing Fluids  
Injected under Pressure**



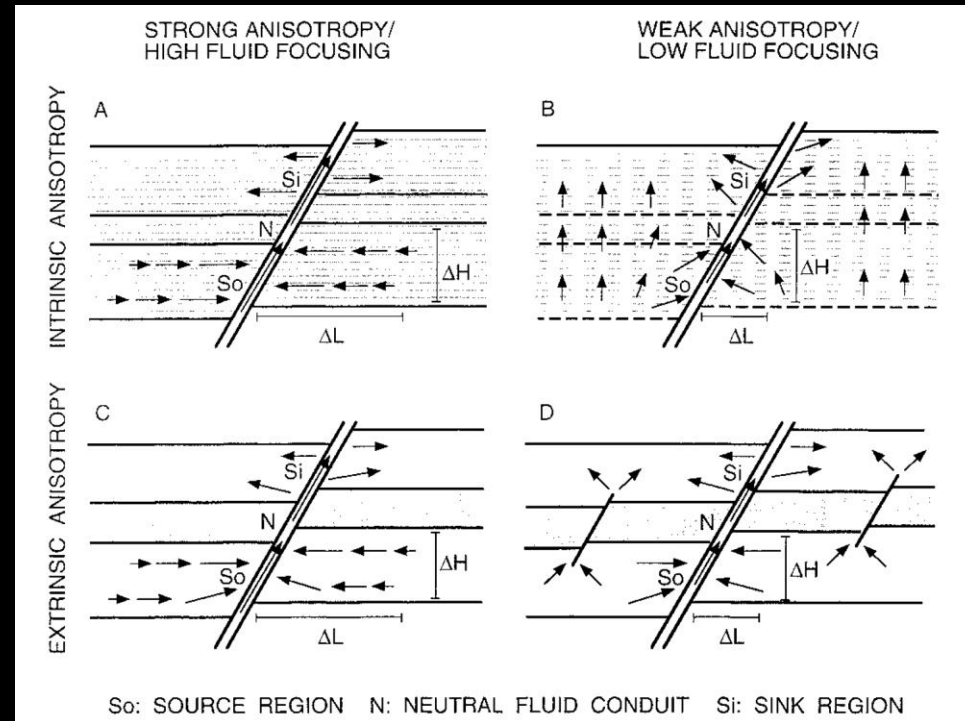
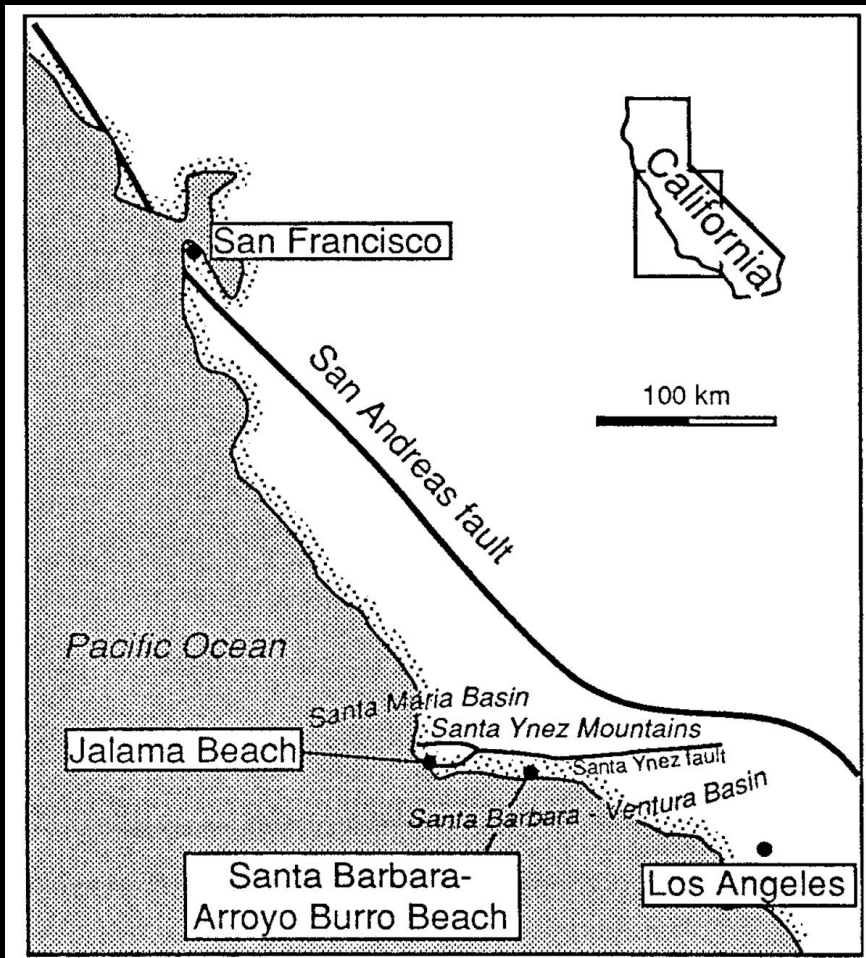
**After Gammer &  
Harrison, 20??**



**HDT in Petroleum Reservoirs w/ rimmed fractures, zebra fabric and “dilational” breccia (Davies & Smith, 2006).**

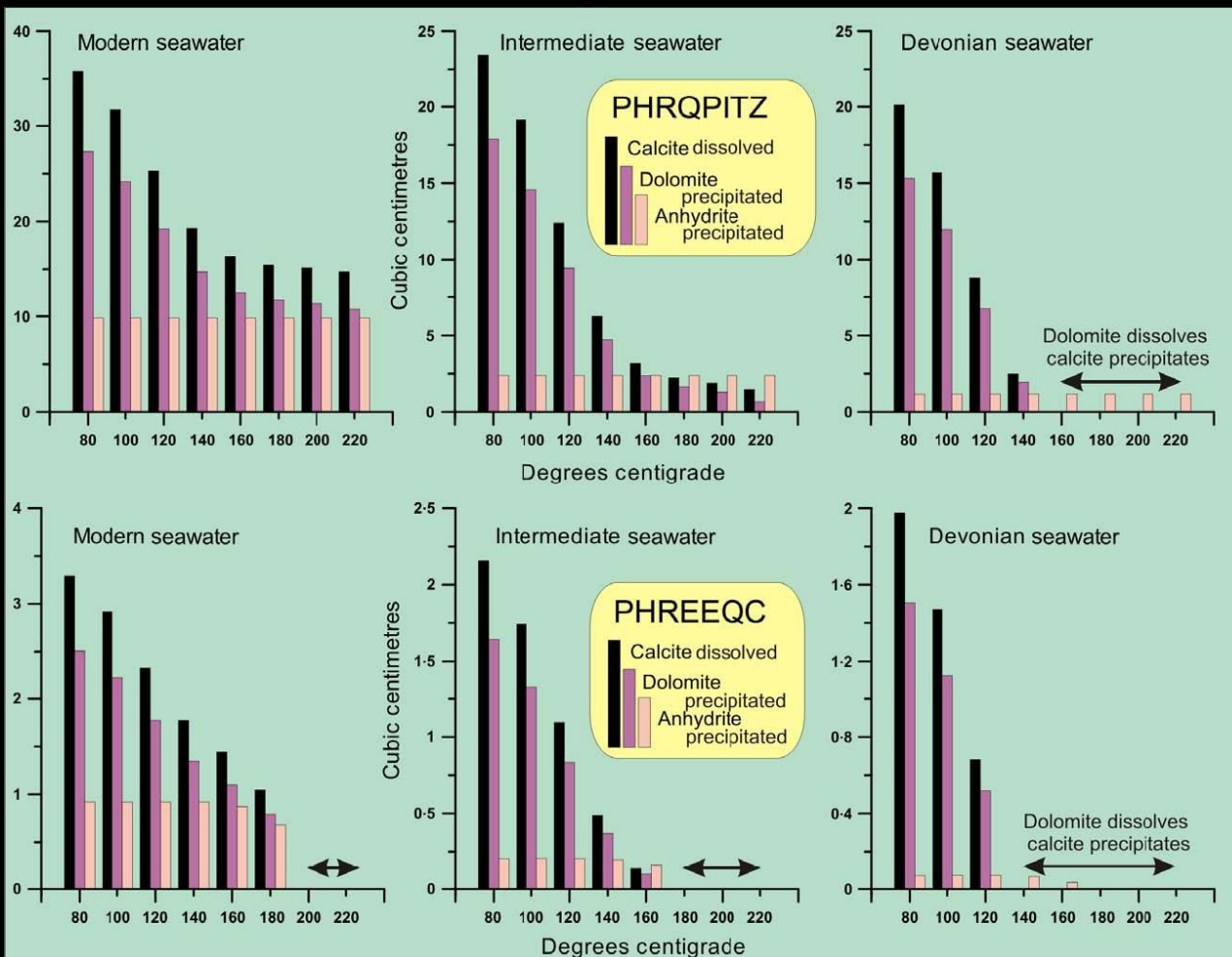
**Are these really structurally generated through abrupt changes in pressure?**

Presenter's notes: A variety of textures interpreted by Davies and Smith as Dilational breccias, and fault fracturing-generated textures, particularly the interesting Zebra Texture in the centre. Geopetal sediment in voids now cemented with Dolospar.



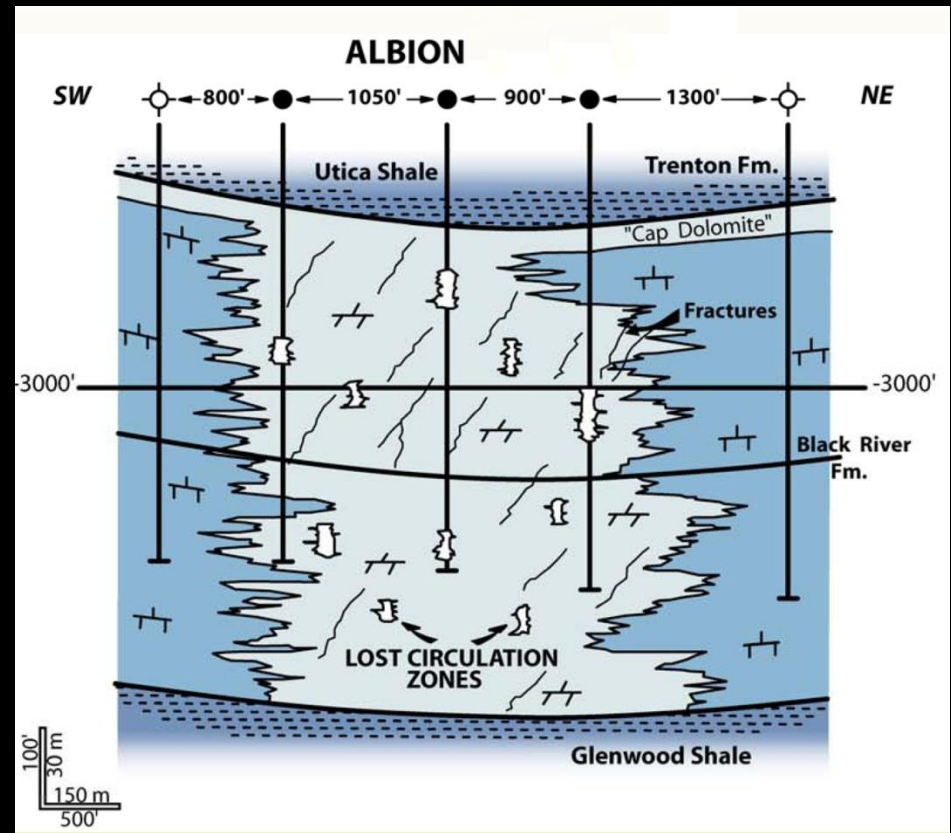
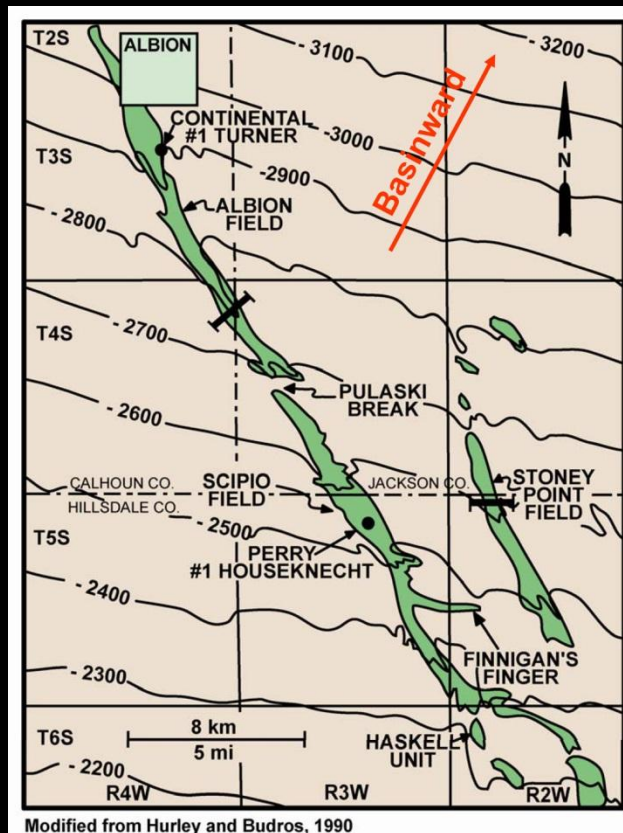
## Fluid movement during faulting

Eichuble and Boles (2000) estimated fluid volume  $12 \times 10^9 \text{ m}^3$  or  $12 \text{ km}^3$  based on dolomite cement. The corresponding radius of radial fluid drainage with intrinsic permeability is 12 km over a 400 meter long fault exposure.



**High temp  
dissolution of  
limestone  
causes  
dolomite  
oversaturation  
and HDT  
dolomitization.**

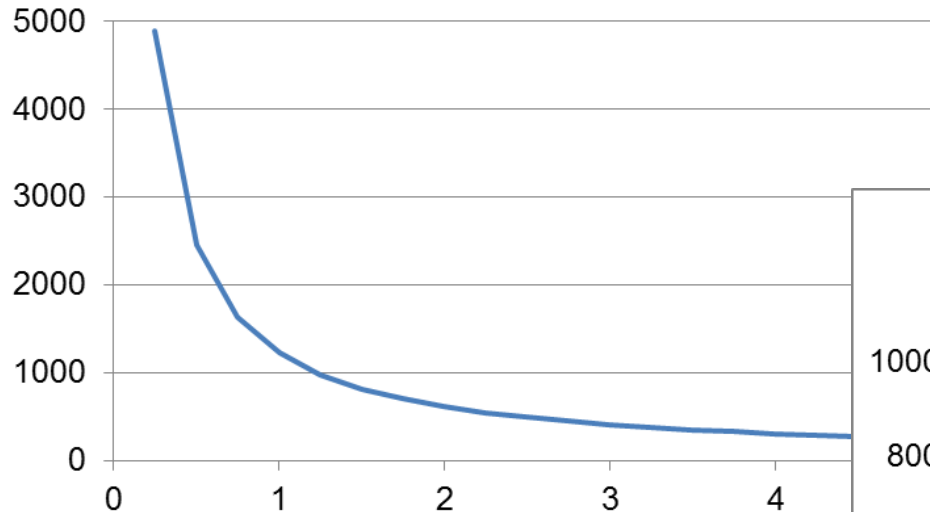
**Buoyant circulation of heated, dolomite-saturated, but calcite undersaturated, subsurface brines can cause limestone dissolution in the shallow subsurface. This can give estimate of fluid volumes needed for HDT masses.**



**Fluid volume (at  $0.5 \text{ cm}^3/\text{L}$ ) for Albion HDT  $\sim 2,500 \text{ km}^3$ , or  $60 \text{ km}^3$  per 400 m of fault length, 5 times the San Andreas fault splay fluid volume. An in-situ total fluid source rock volume (at 5%  $\Phi$ ) of  $\sim 50,000 \text{ km}^3$ , precludes an in-situ fault seismic-generated fluid source for Albion HDT.**

# Brine volume and rock volume to source fluids required for Albion dolomitization

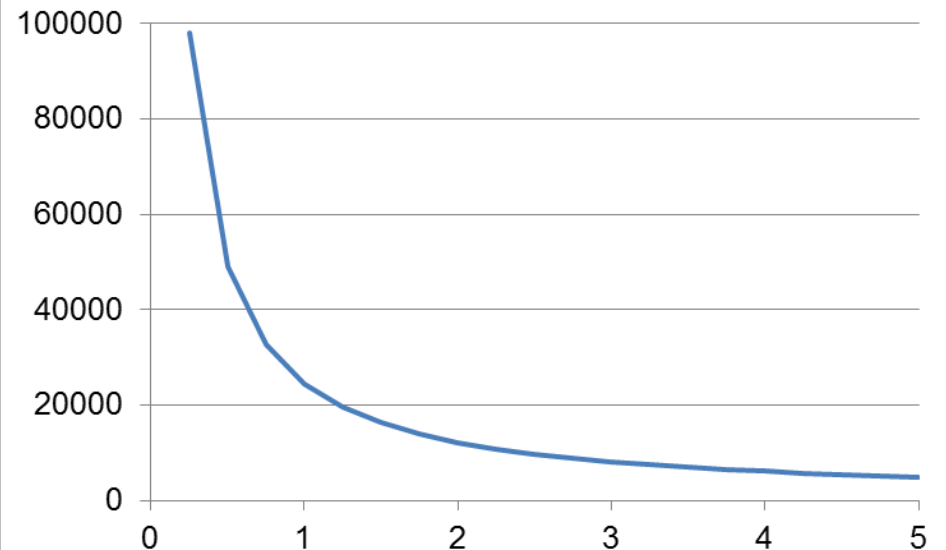
Brine volume (km<sup>3</sup>) for dolomitization

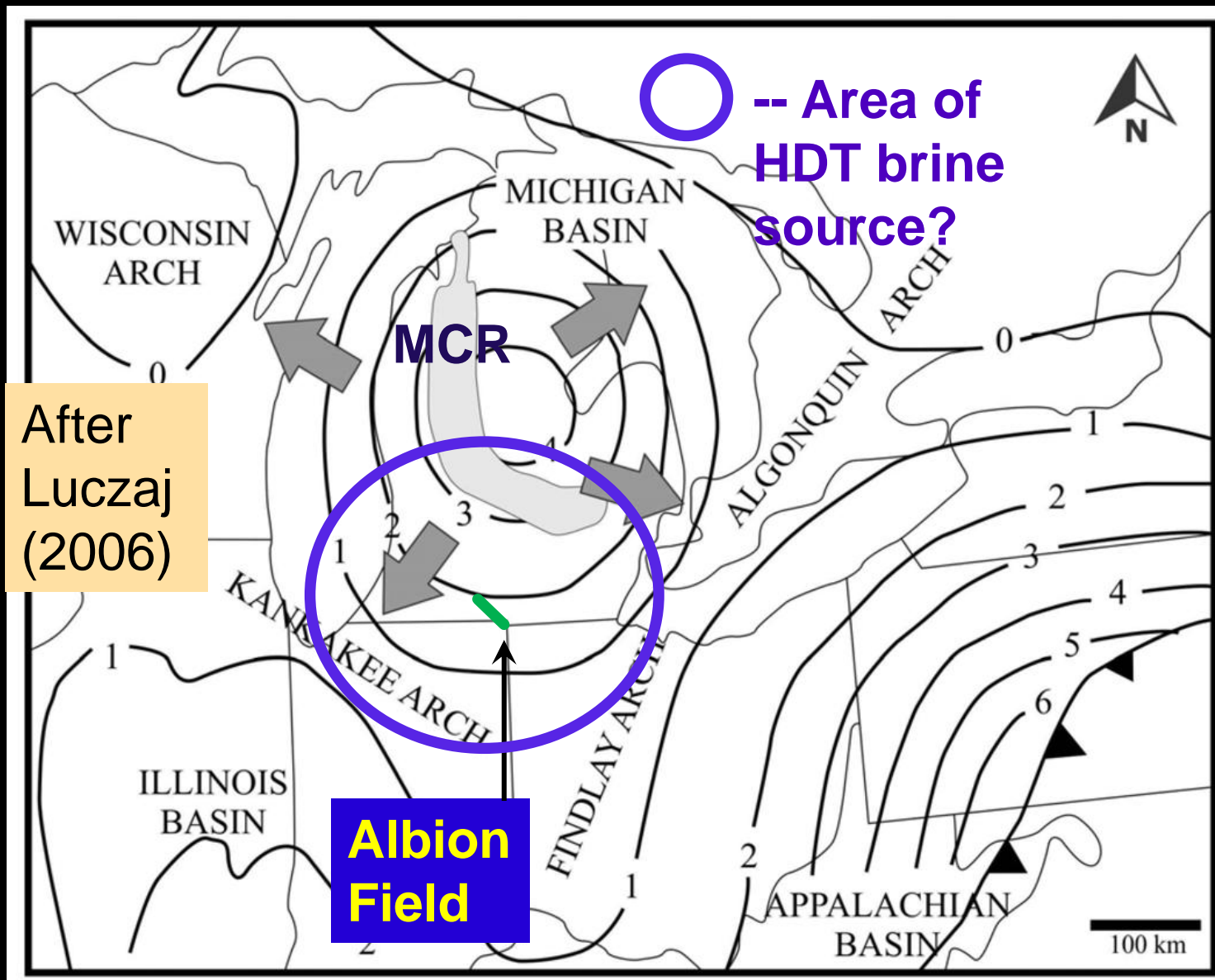


X axis is cm<sup>3</sup> of HDT dolomite formed per liter of brine

Brine from 50,000 km<sup>3</sup> of strata needed to form Albion HDT at 0.5 cm<sup>3</sup> dolomite per liter of brine

Rock volume (km<sup>3</sup>) at 5% porosity to supply brine





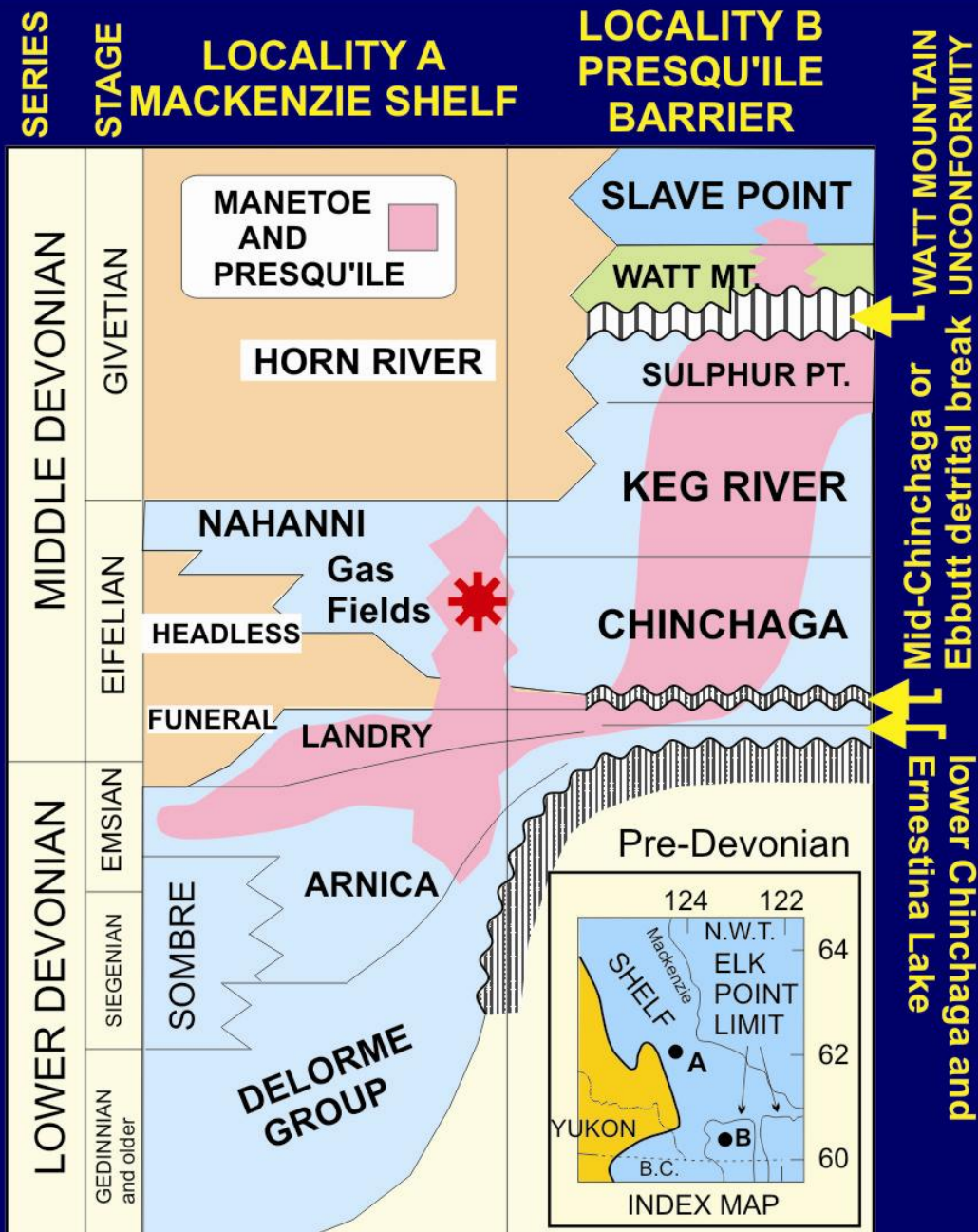
**Intrinsic  
brine  
source  
for  
50,000  
km<sup>3</sup> has  
130 km  
radius  
for 1.0  
km of  
host  
strata**

**Stoney Point, Scipio HDT have overlapping requirements!**

# Origin of Michigan Basin HTDs

**Not surprisingly, Haeri-Ardakani (2012) and Luczaj (2006) concluded that Devonian marine brines infiltrated deeper parts of the Paleozoic section of Michigan Basin. Dense descending brines warmed during Late Devonian-Mississippian reactivation of the MCR which provided an additional heat source for thermally-driven convection cells that caused radial outward flow through faults and fractures, forming HTDs along basement faults in the basin.**

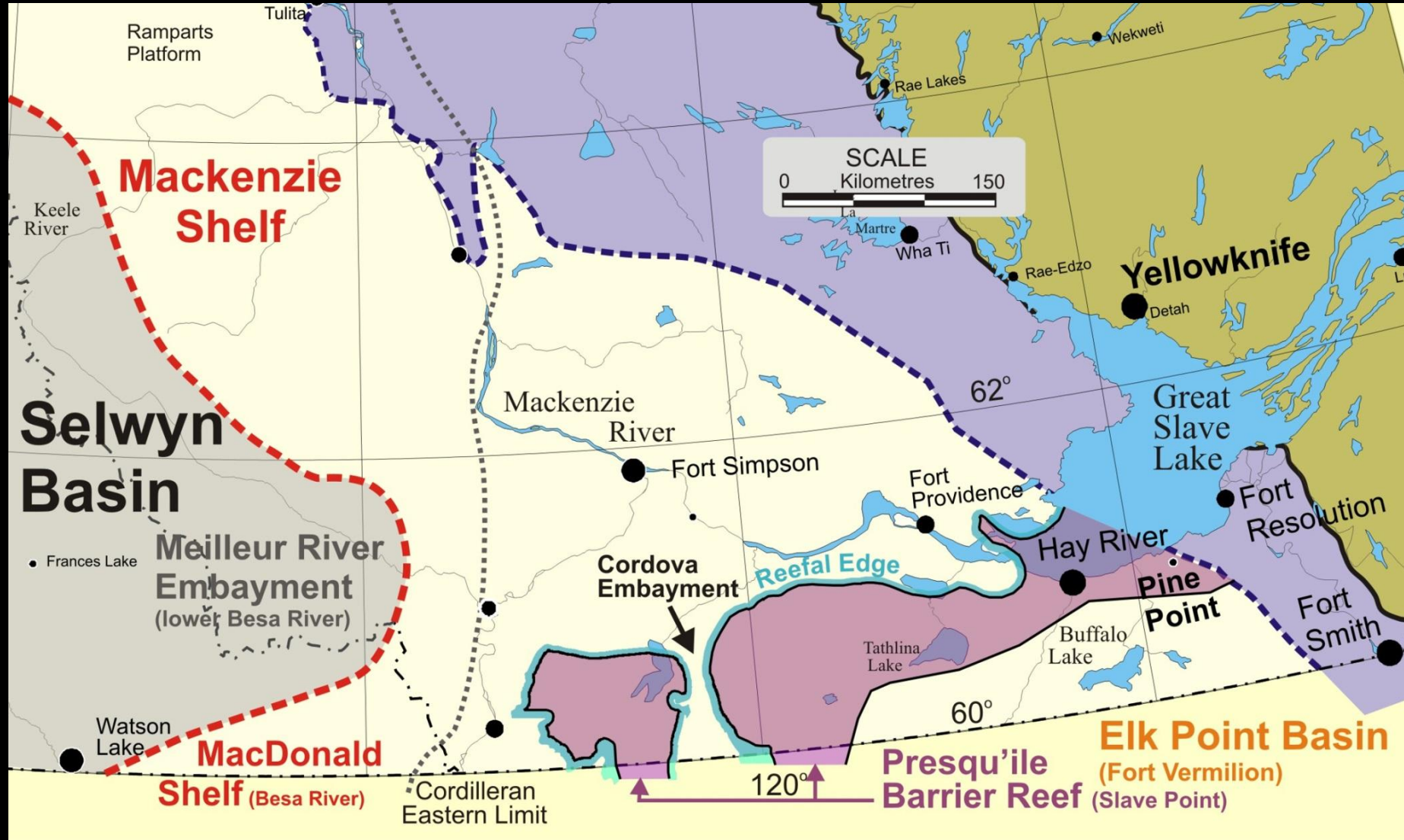
**They implicitly recognized that intrinsic fluid movements relying on episodic seismicity are inadequate, as indicated here by estimates for volumes of in-situ fluids required for the Albion HTD field alone.**



**Stratigraphic Setting of Manetoe-hosted Liard Gas Fields – regional HDT largely confined beneath Headless shale**

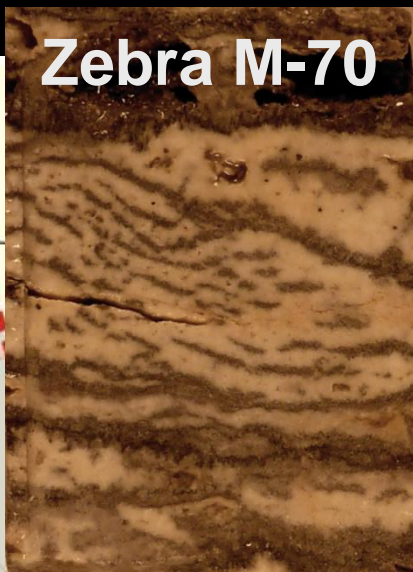
**Presqu'ile Dolomite passes downdip to Manetoe Dolomite. HC migration downward from Horn River shale.**

# Mid to Late Devonian N60 - Elk Point Evaporites behind Presqu'ile Barrier



# Manetoe in wells N60

Zebra M-70



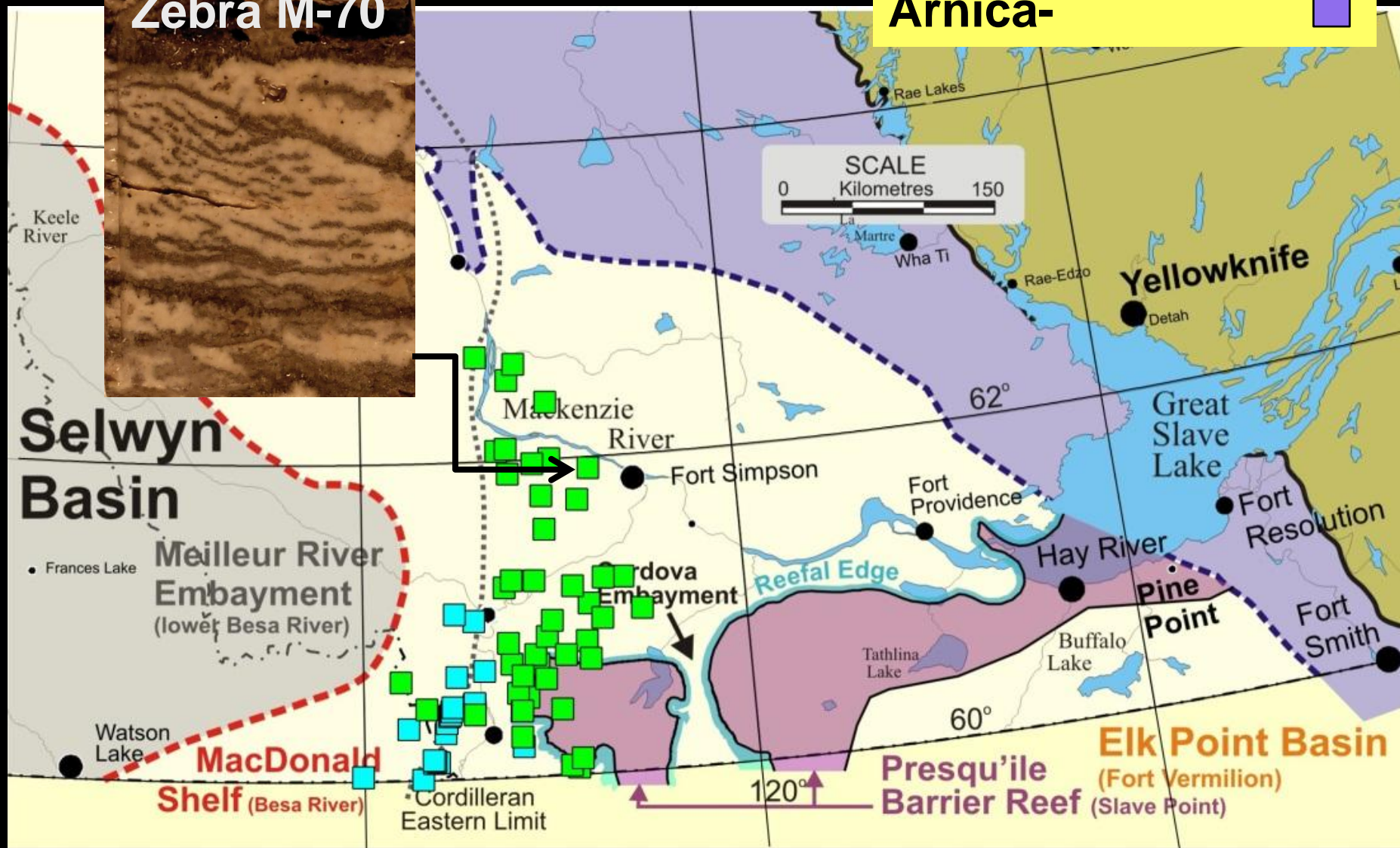
Nahanni-



Headless/Landry-

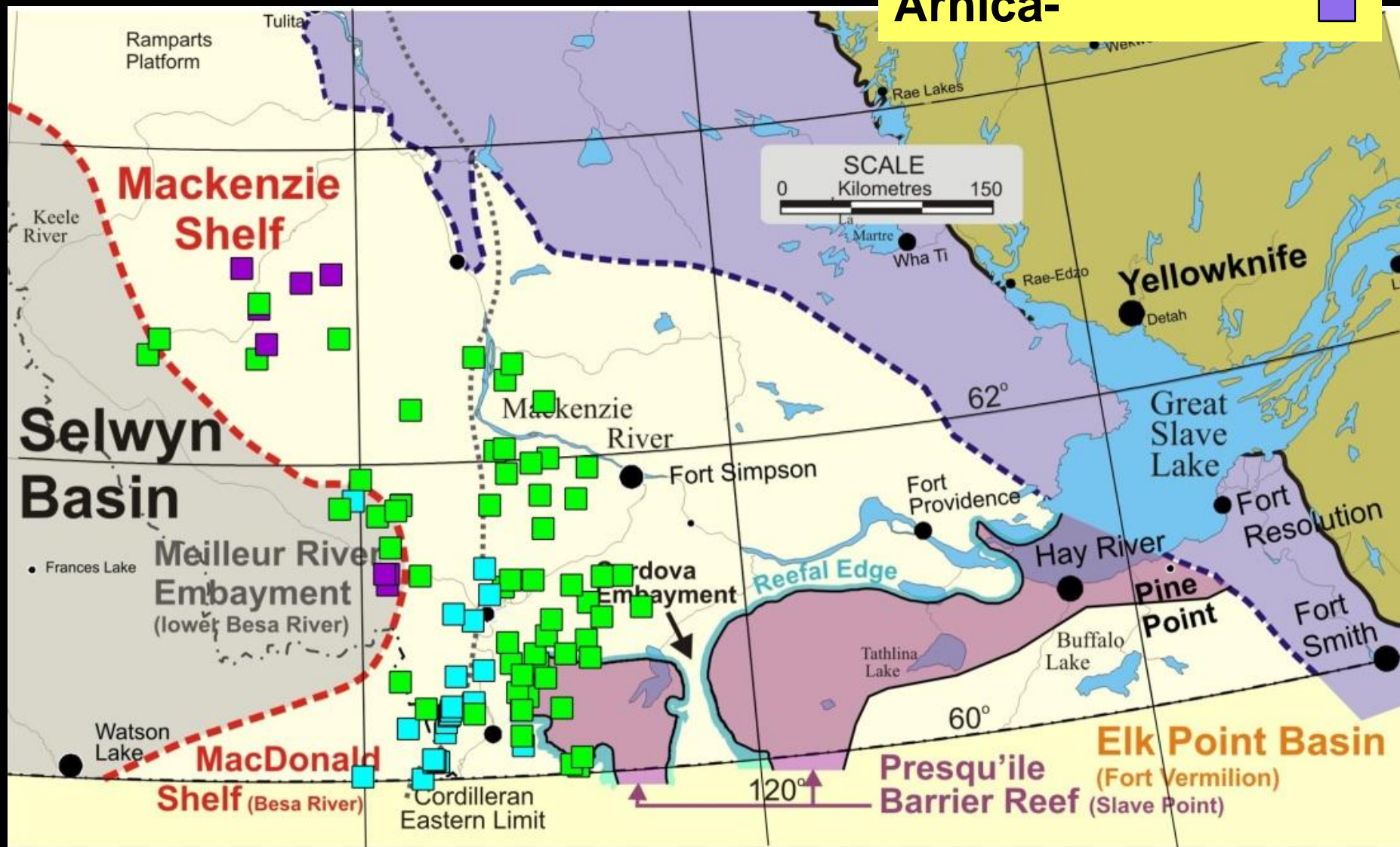


Arnica-

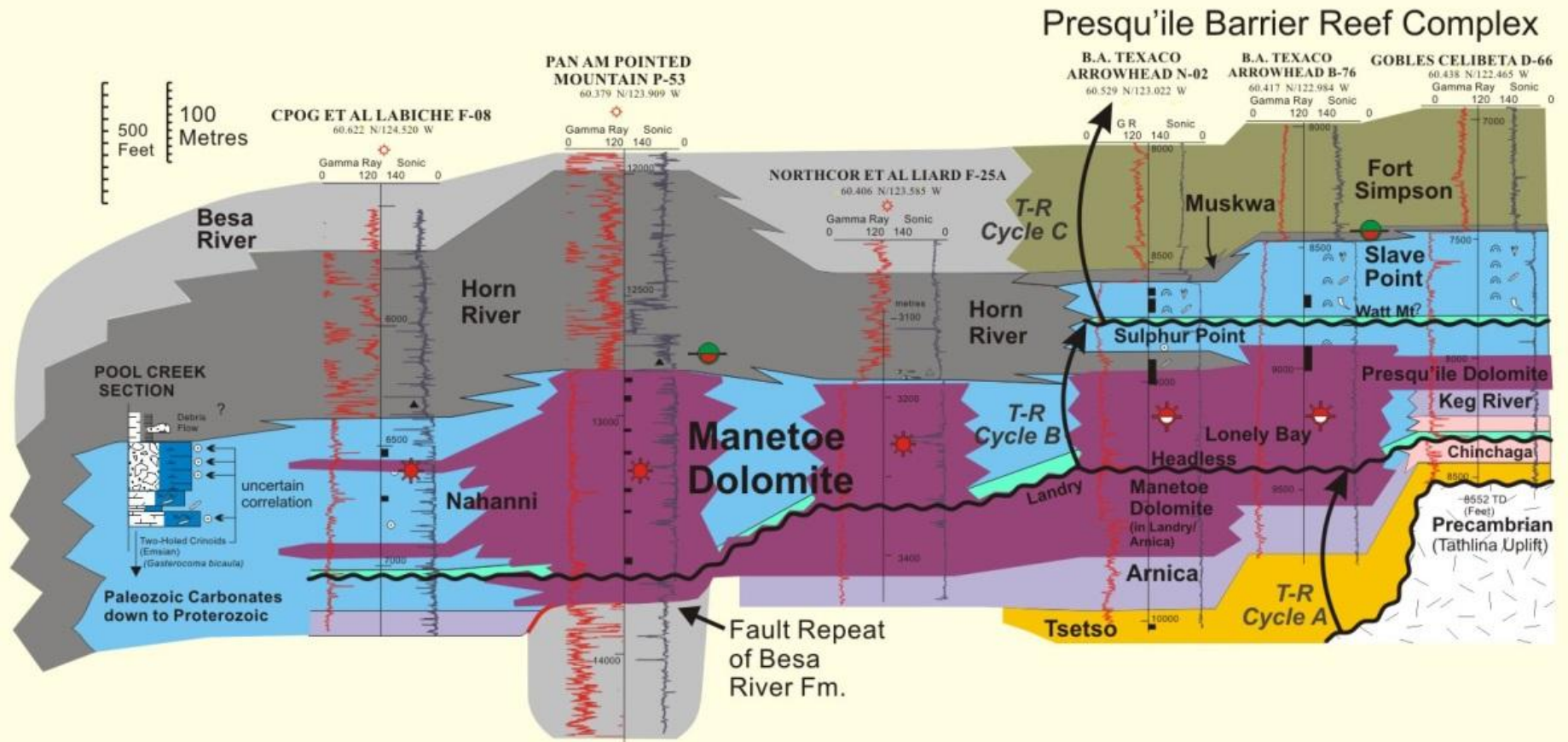


# Outcrop and wells – distal sections in Arnica

Nahanni-  
Headless/Landry-  
Arnica-

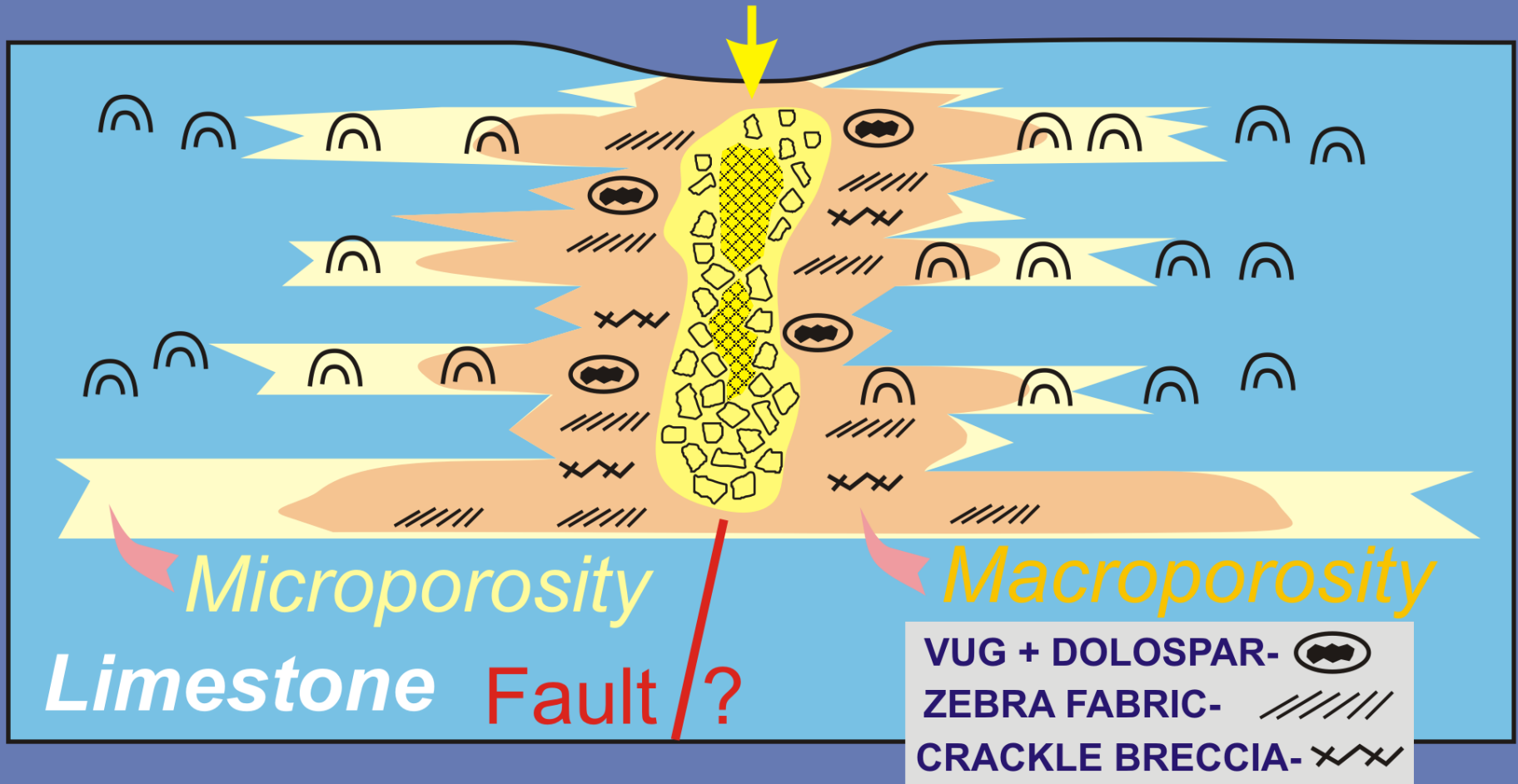


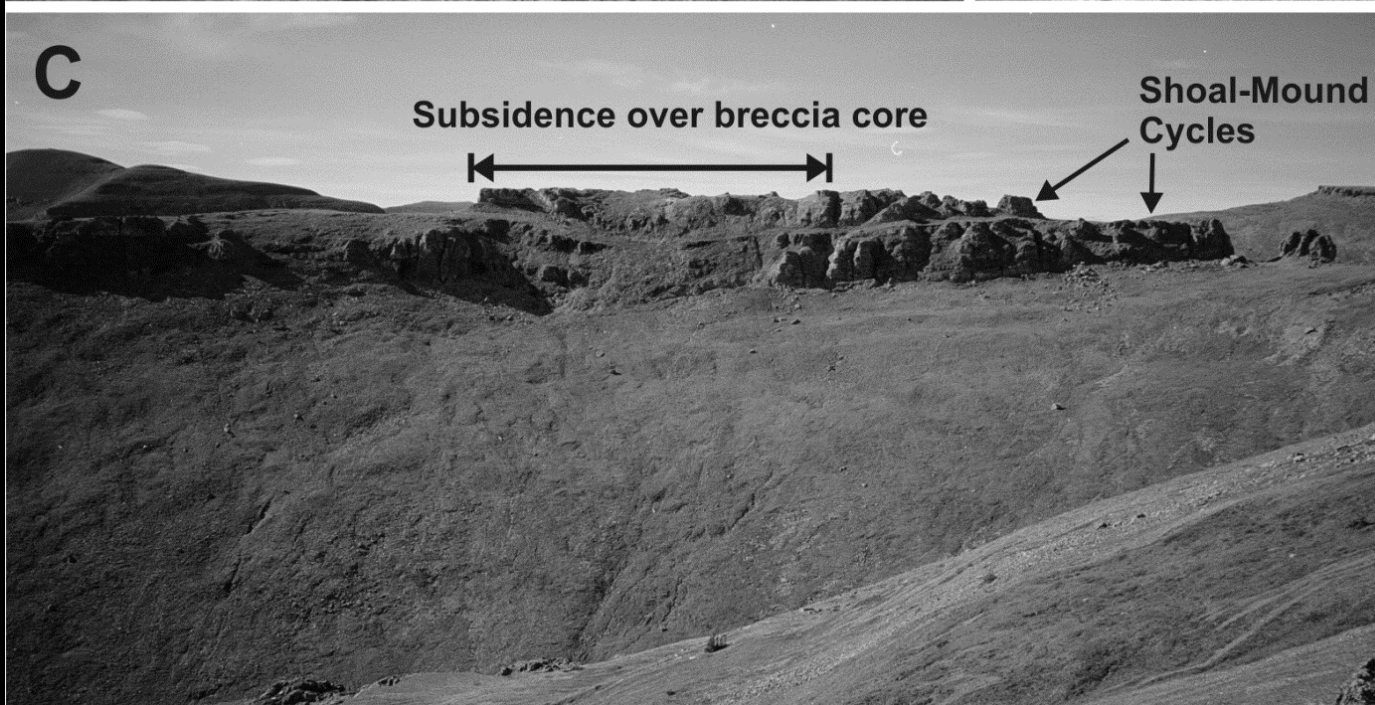
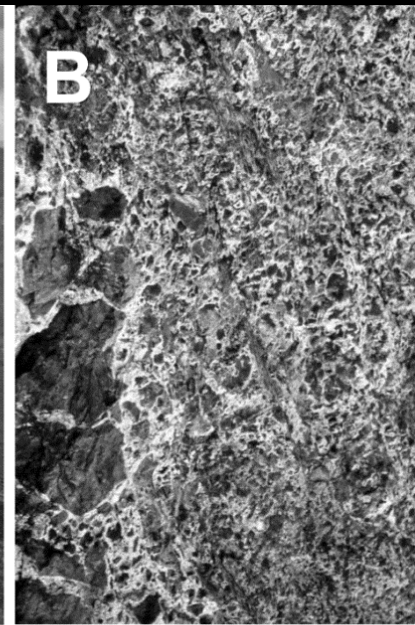
# Manetoe HDT extends basinward from Presqu'ile Barrier through Landry Fm and up through Nahanni at Liard Gas Fields



# HDT fabrics seen more completely in outcrop

Brecciated Core Zone





**Dolospar  
cemented  
Mosaic  
breccia**

**Subsidence  
over core  
zone an  
exploration  
guide, but  
not located  
over a fault  
system**

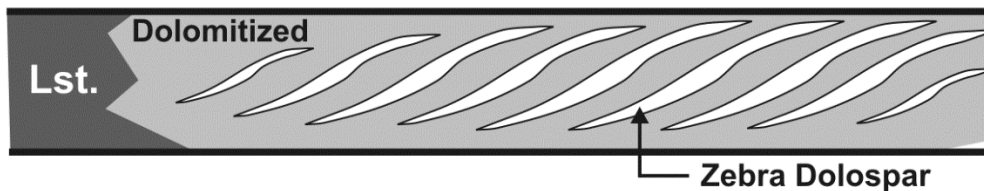
## Zebra and Boxwork Fabric Genesis

Process for Creation  
of Pore Space

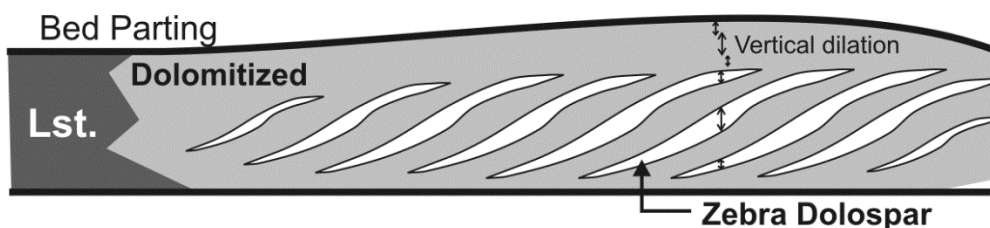
Emplacement of  
White Dolospar

Open fractures (visible porosity)	Cementation and replacement adjacent to fractures
Dissolution (visible porosity)	Cementation and replacement adjacent to macropores
Displacive vein growth (no visible porosity)	Displacive growth of dolospar forms veins without Macropores

No bed expansion during dissolution and cementation

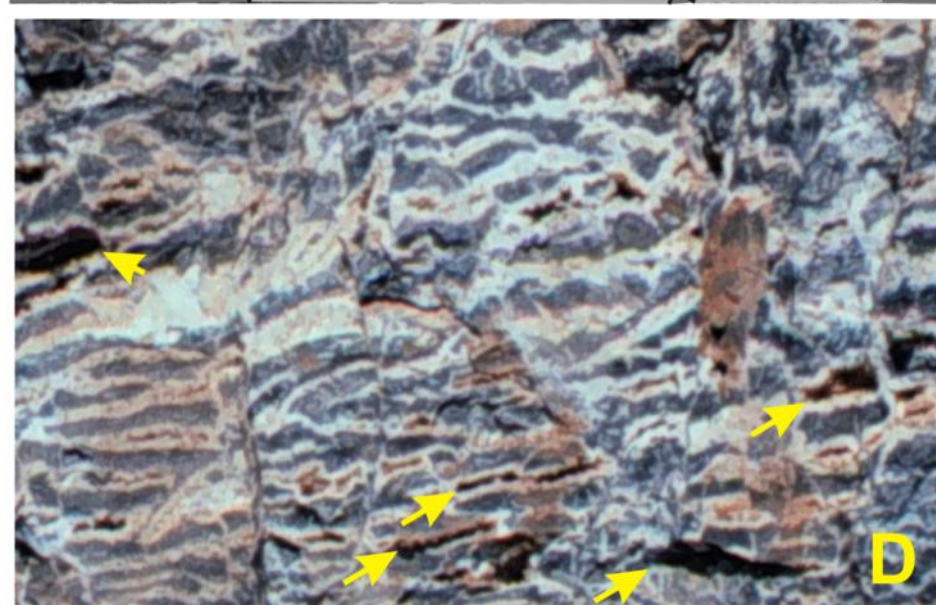
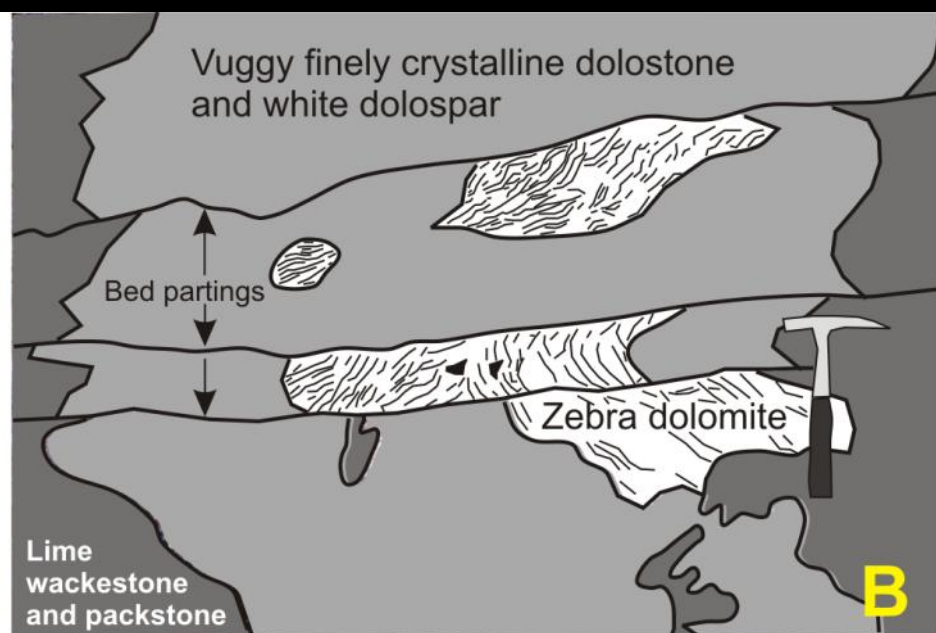


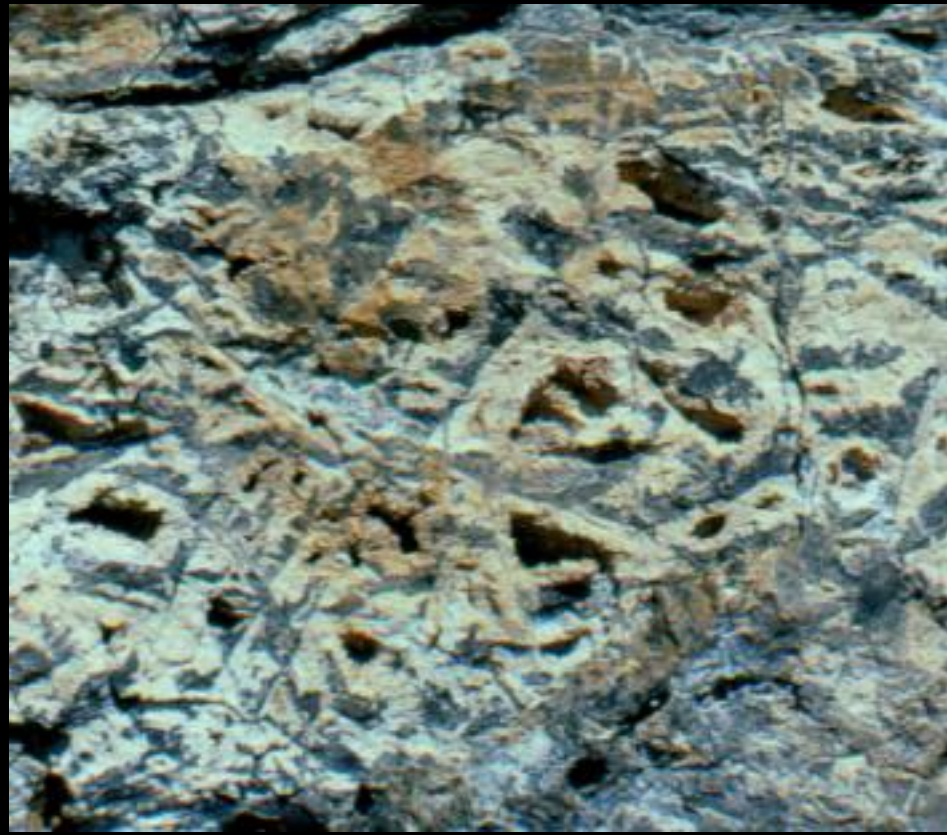
Expansion of bedding by dilational fracturing



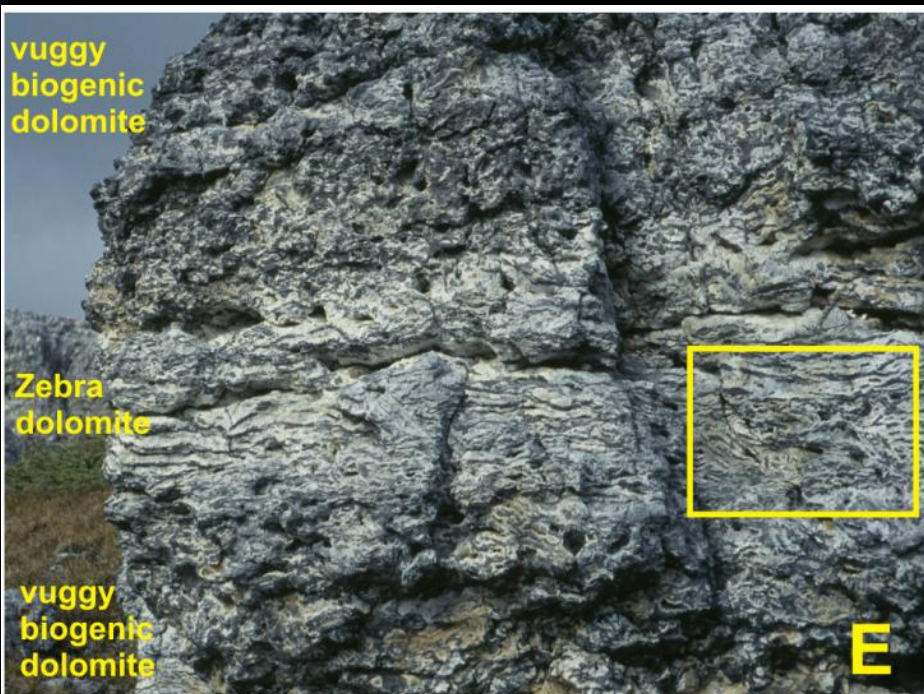
**Three Possible  
Origins for  
Zebra and  
Boxworks  
–  
Dilational  
Fracturing  
during  
Explosive  
pressurization?**

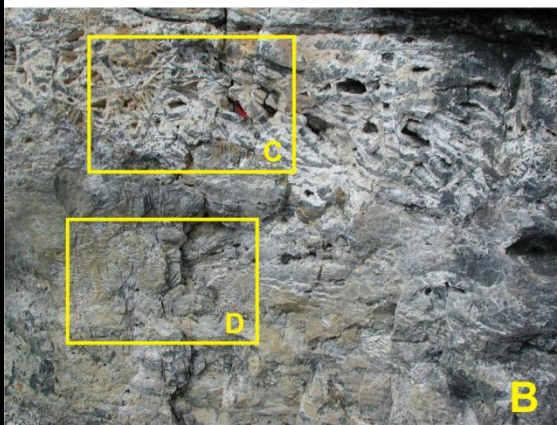
# Bed thickness constant across zebras





**Boxwork or  
Chevron Zebra?**



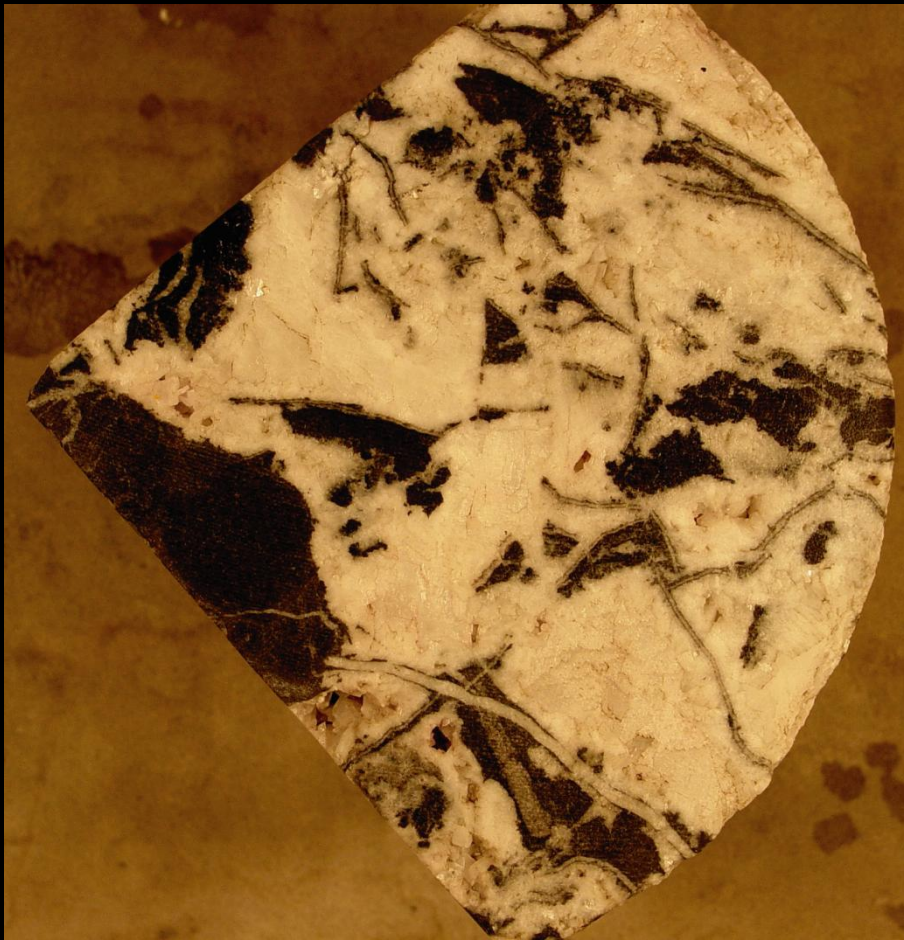


**Over-  
cemented &  
Imbricated  
Zebra Chips?**

**Boxworks-  
Linear and  
Solution-  
rounded –  
Pervasive  
small zebra**

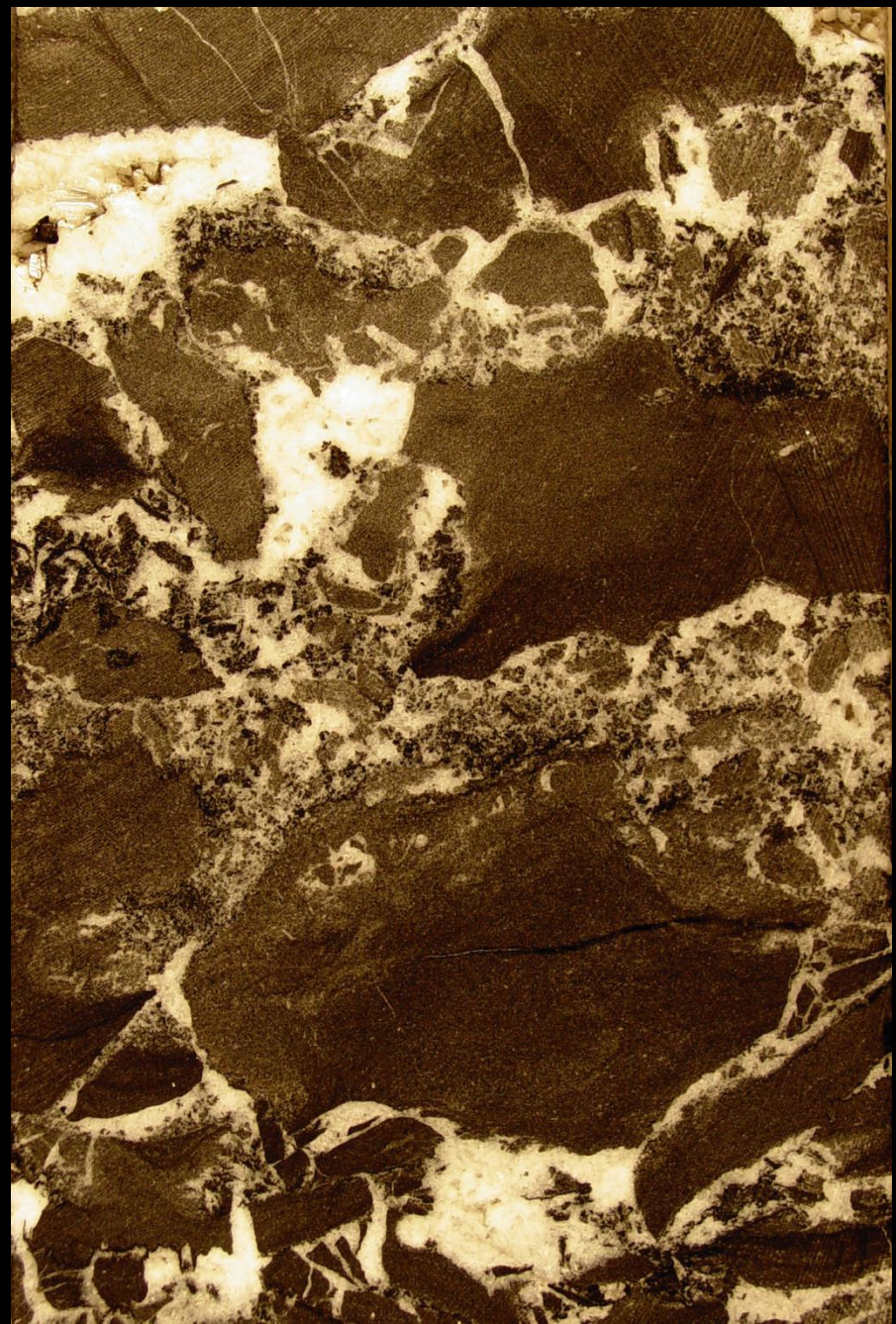
# Ladder & Chevron fabric, rimmed Fracs?



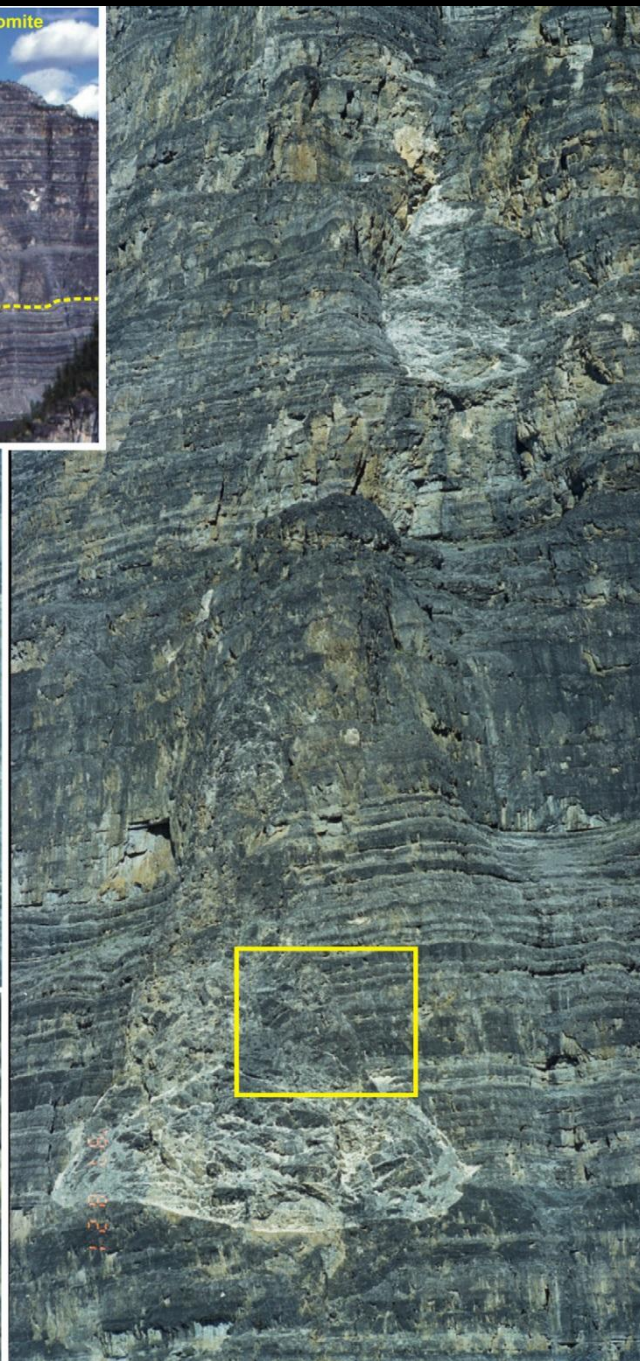
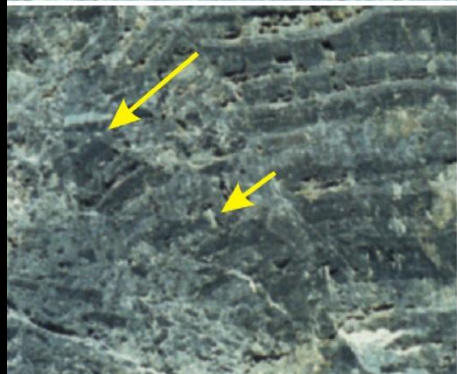
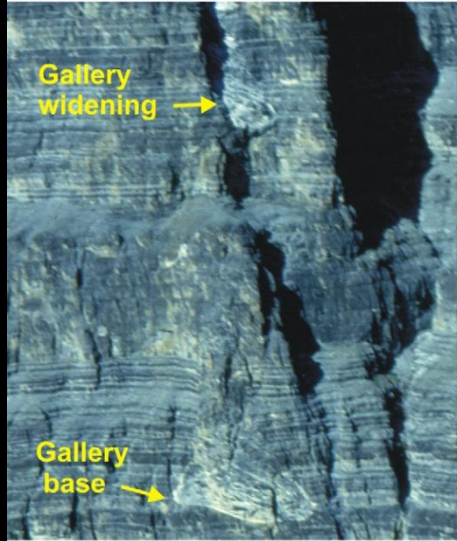
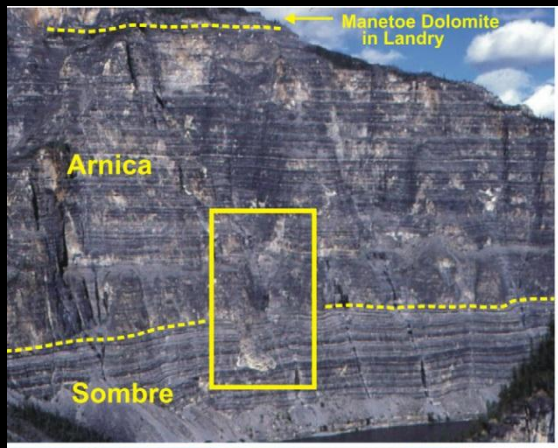


**Rimmed fractures appear to be edges of breccia fragments? Unorganized and not related to any deformational stress field?!**





**“Floating” breccia HDT  
replaces matrix fines?  
Explosions not required!**

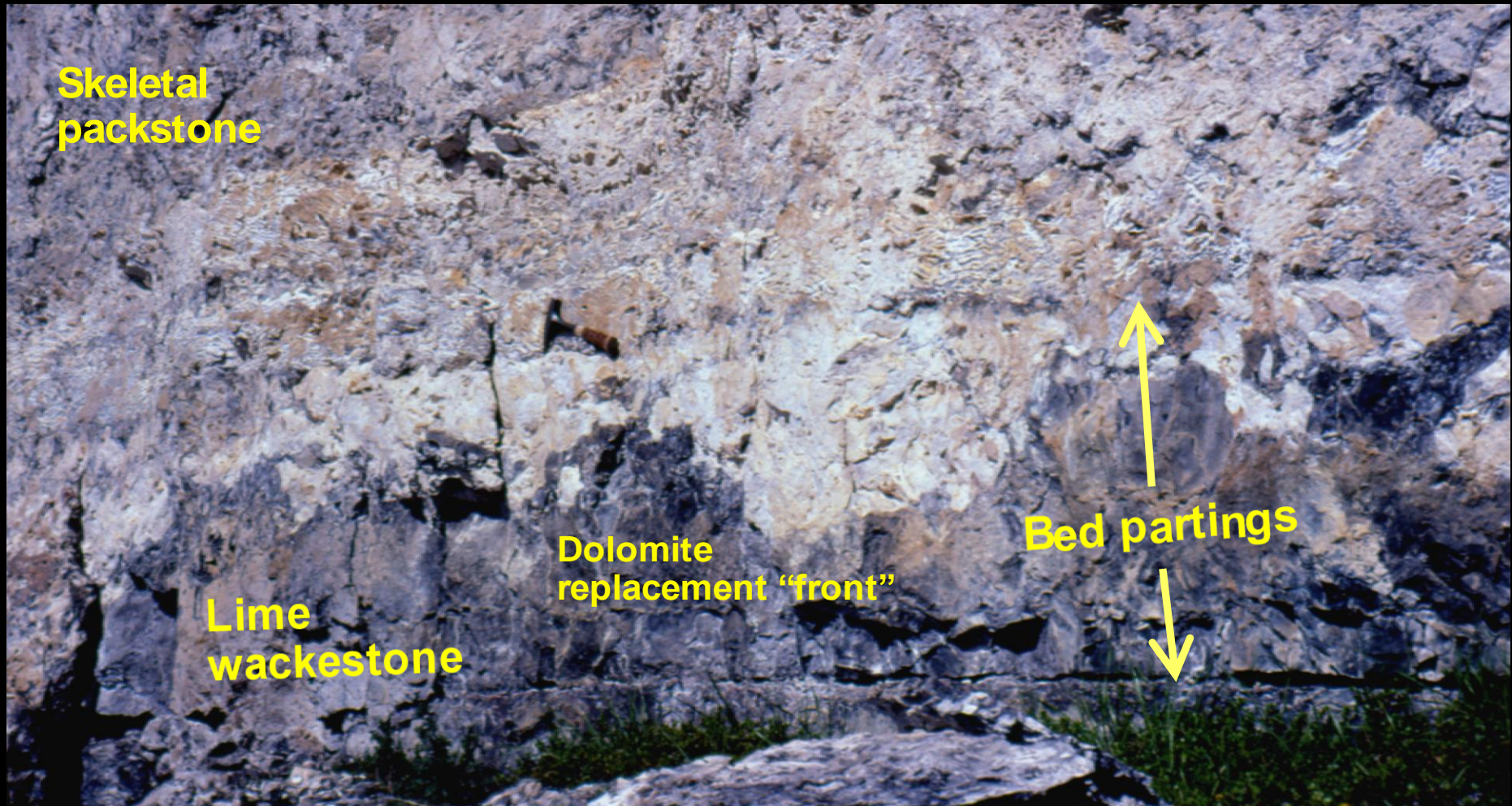


**Collapse,  
rather than  
dilation, a  
clear choice  
to explain  
Manetoe  
breccia fabric  
of solution  
gallery at  
First Canyon!**



**Base of Gallery  
>10 meters broad**

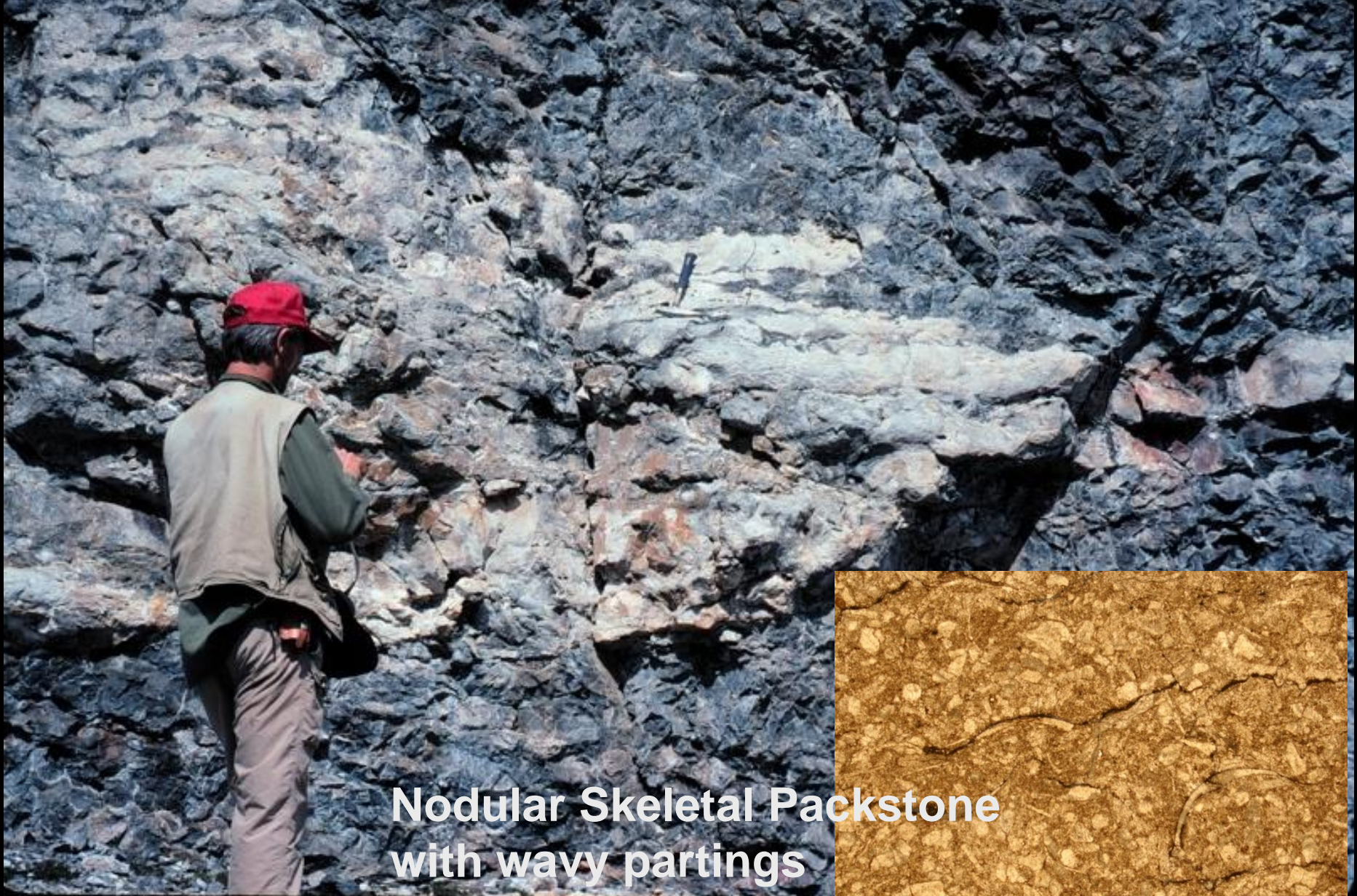
# Dolomite replacement adjacent to zebra beds – flow focused through porous zebra



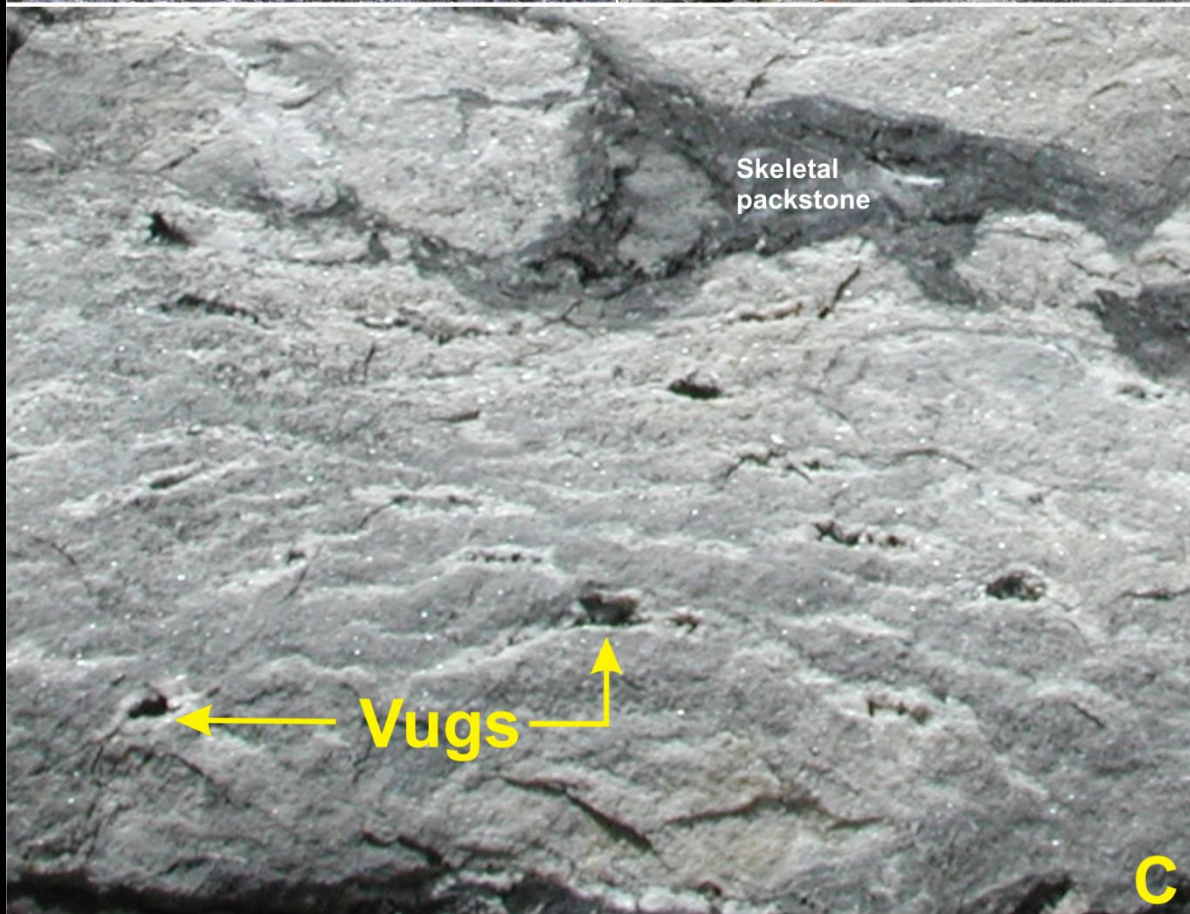
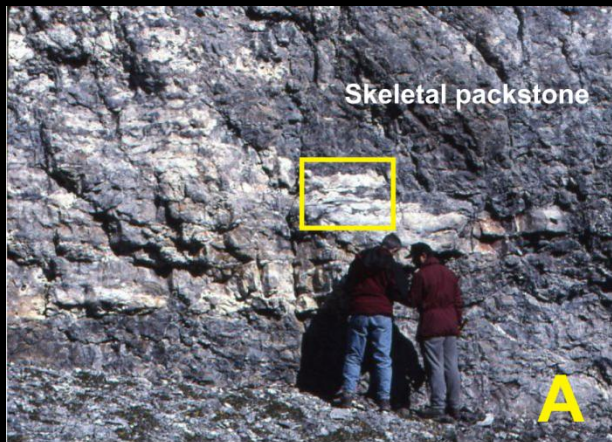
# HDT leak into Strom mound flank beds



# ***Mesoporosity and porous Zebra in HDT***

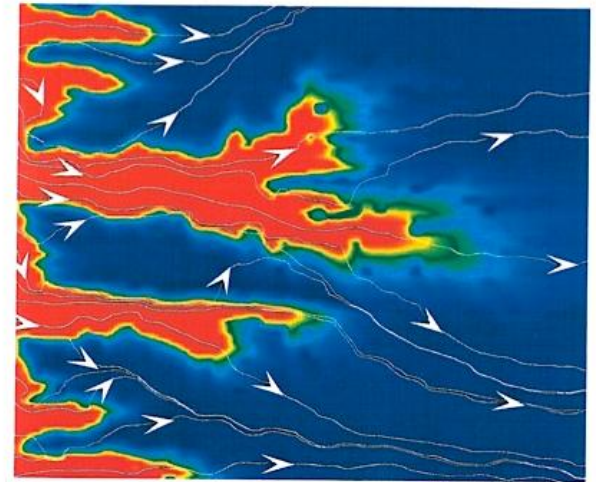


**Nodular Skeletal Packstone  
with wavy partings**

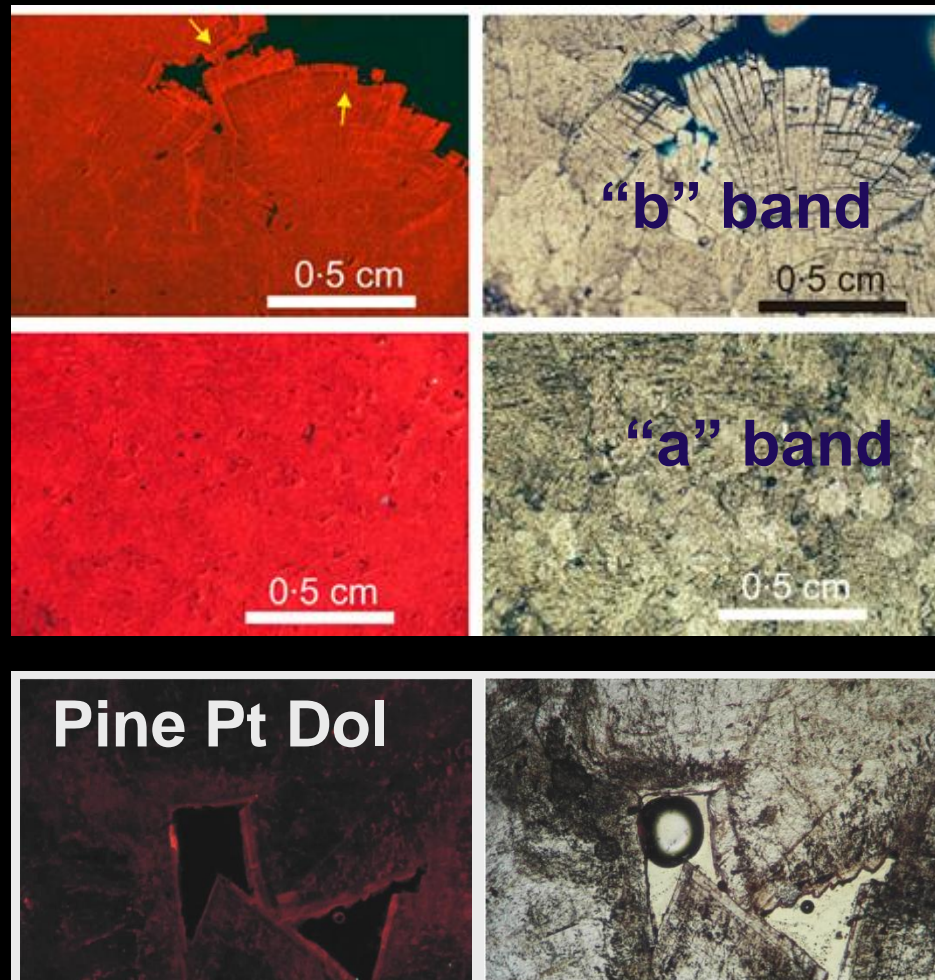
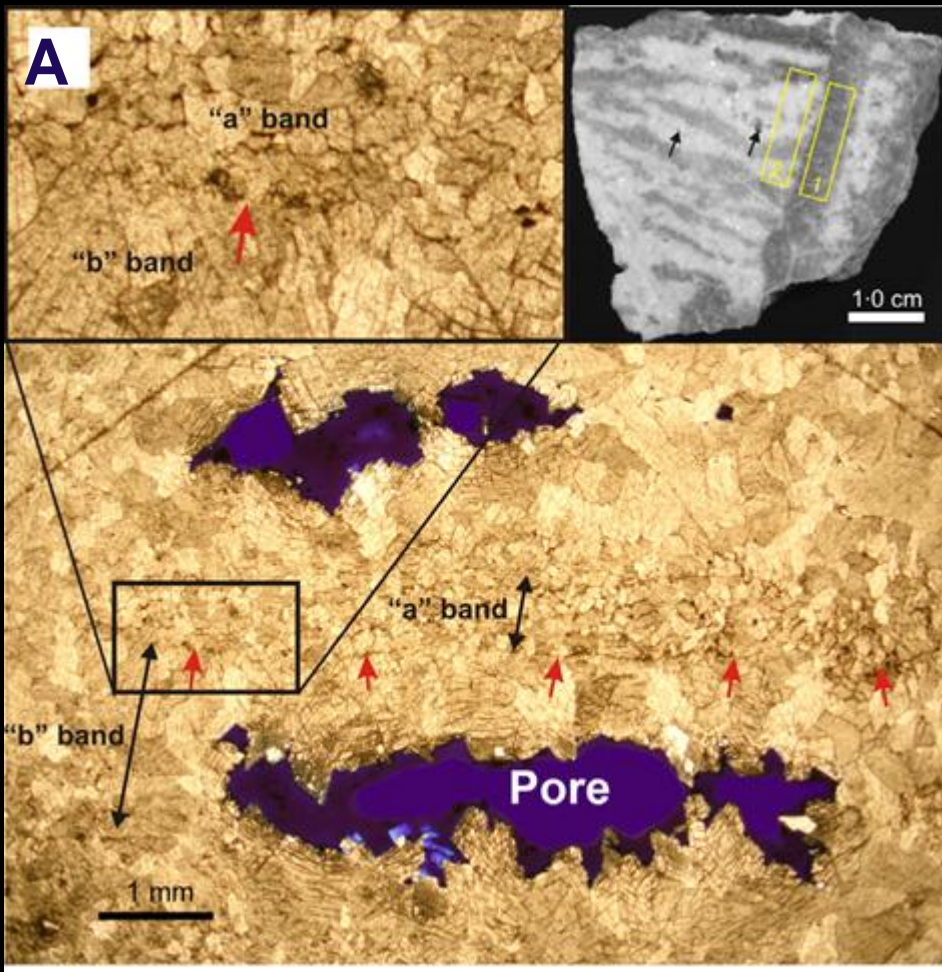


# REACTIVE TRANSPORT IN POROUS MEDIA

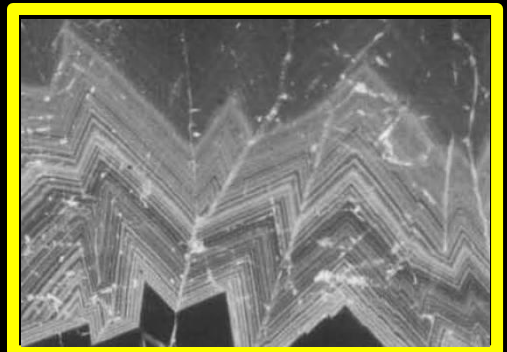
P.C. LICHTNER, C.I. STEEFEL  
& E.H. OELKERS, *Editors*



**Dissolution  
porosity  
developed  
during reactive  
transport**



**Monterey fault dolospar highly CL zoned, in contrast to unzoned Manetoe/Presqu'ile CL apart from final bright zone as seen above.**

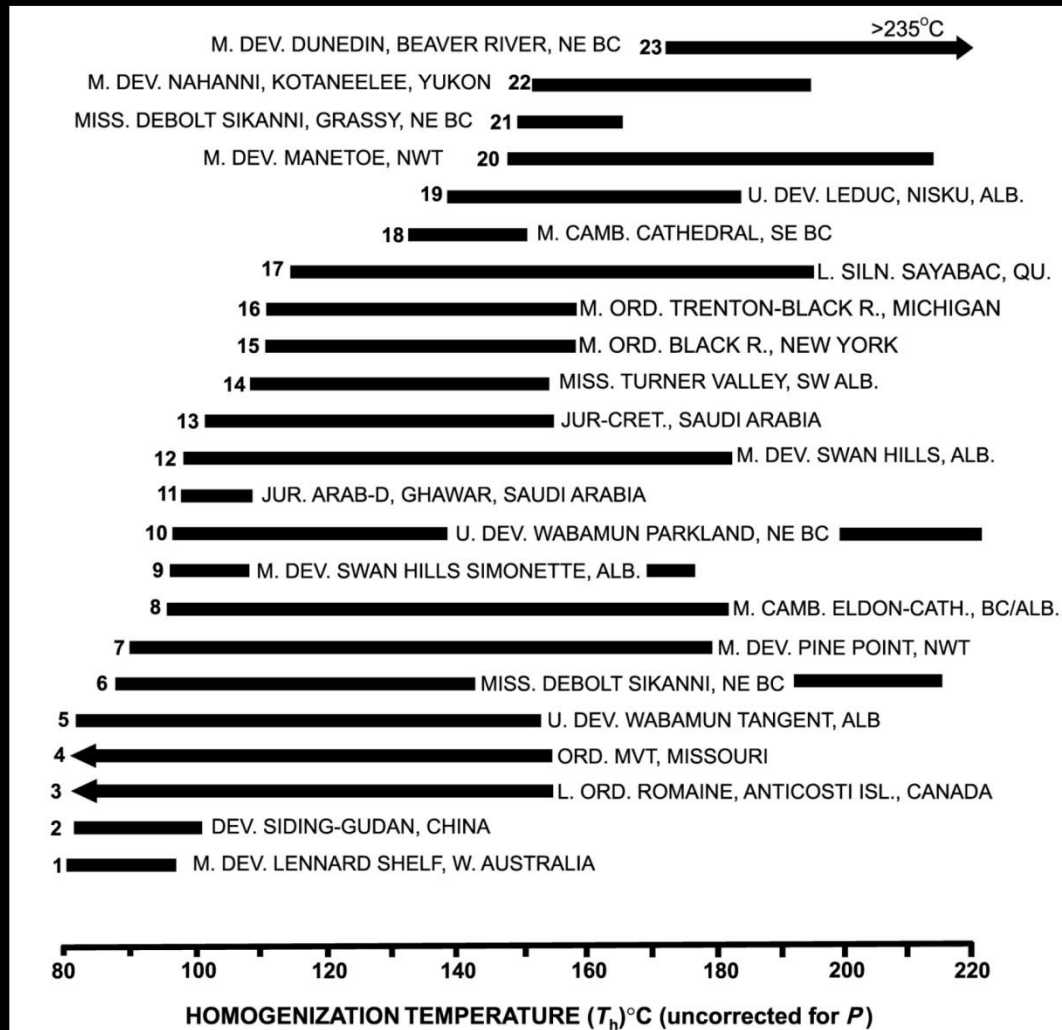


**Table 1.** Fluid inclusion analyses of dolospar in two thin sections from hand sample MTA-97-1.

$T_h$ aq (°C)	$T_e$ aq (°C)	$T_m$ aq (°C)	NaCl eq. wt%
Site 1 analyses of primary aqueous fluid inclusions in grey band			
140 to 145 (4)*	-27.0 to -33.0	-15.0 to -18.0	18.6 to 21.0 <sup>†</sup>
145 to 150 (2)	-39.0 to -45.0	-8.0 to -12.0	11.7 to 16.0
145 to 150 (2)	-48.0	-18.0	21.0
169 (1)	-31.0 to -33.0	-13.0 to -15.0	16.9 to 18.6
169 to 174 (2)	-27.0 to -33.0	-15.0 to -18.0	18.6 to 21.0
170 (1)	-50.0 to -57.0	-17.0 to -20.0	20.2 to 22.4
172 to 177 (4)	-50.0 to -57.0	-17.0 to -20.0	20.2 to 22.4
172 to 177 (2)	-31.0 to -33.0	-13.0 to -15.0	16.9 to 18.6
180 to 185 (3)	-31.0 to -33.0	-13.0 to -15.0	16.9 to 18.6
189 to 193 (2)	-50.0 to -57.0	-17.0 to -20.0	20.2 to 22.4
Site 2 analyses of primary aqueous fluid inclusions in white saddle dolomite			
153 (1)	-55.0 to -57.0	-25.0 to -27.0	25.8 to 27.2
165 to 170 (3)	-52.0 to -57.0	-19.0 to -25.0	21.7 to 25.8
173 to 175 (1)	-55.0 to -57.0	-19.0 to -24.0	21.7 to 25.1
175 to 180 (3)	-52.0 to -57.0	-19.0 to -25.0	21.7 to 25.8
180 (1)	-55.0 to -57.0	-19.0 to -24.0	21.7 to 25.1
180 (1)	-55.0 to -57.0	-25.0 to -27.0	25.8 to 27.2
187 (1)	-55.0 to -57.0	-25.0 to -27.0	25.8 to 27.2
189 to 193 (1)	-55.0 to -57.0	-19.0 to -24.0	21.7 to 25.1
195 to 200 (3)	-55.0 to -57.0	-19.0 to -24.0	21.7 to 25.1
201 (1)	-55.0 to -57.0	-25.0 to -27.0	25.8 to 27.2
201 to 205 (1)	-52.0 to -57.0	-19.0 to -25.0	21.7 to 25.8

\*

**Saddle - Th of 183°C, Average salinity ~23 wt%**  
**Grey - Th of 167°C, Average salinity ~18 wt%**

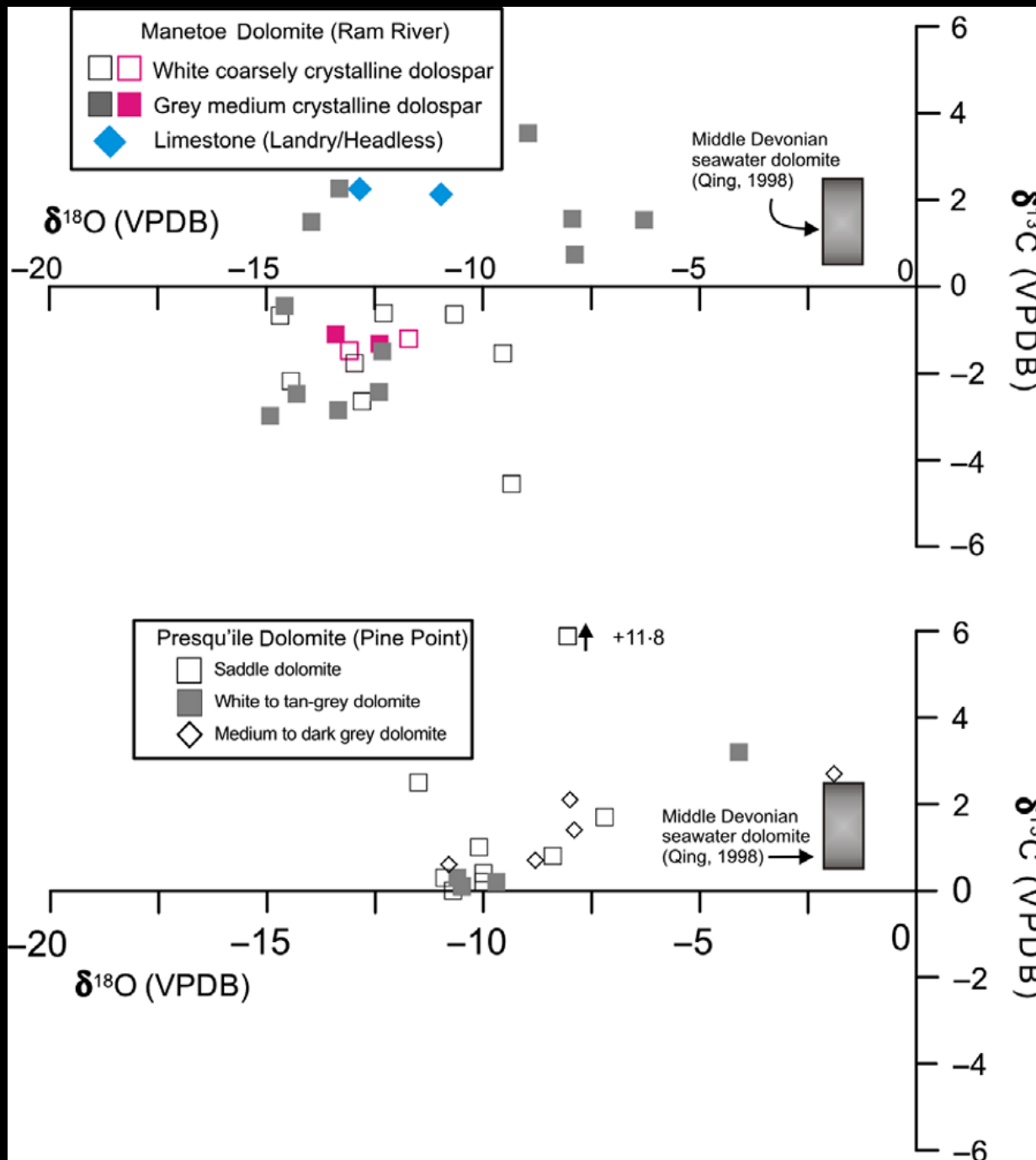


**The vast  
(all?)  
majority of  
HDT  
dolomite  
have normal  
primary  
inclusions  
with  
equilibrium  
vapor  
bubbles  
(from  
Davies and  
Smith, 2006)**

Presenter's notes: "Very few HDT saddle dolomites have any fluid inclusions with pressurized gas vacuoles indicative of boiling or effervescence. Hydrocarbons virtually non-existent in most HDT dolomites.

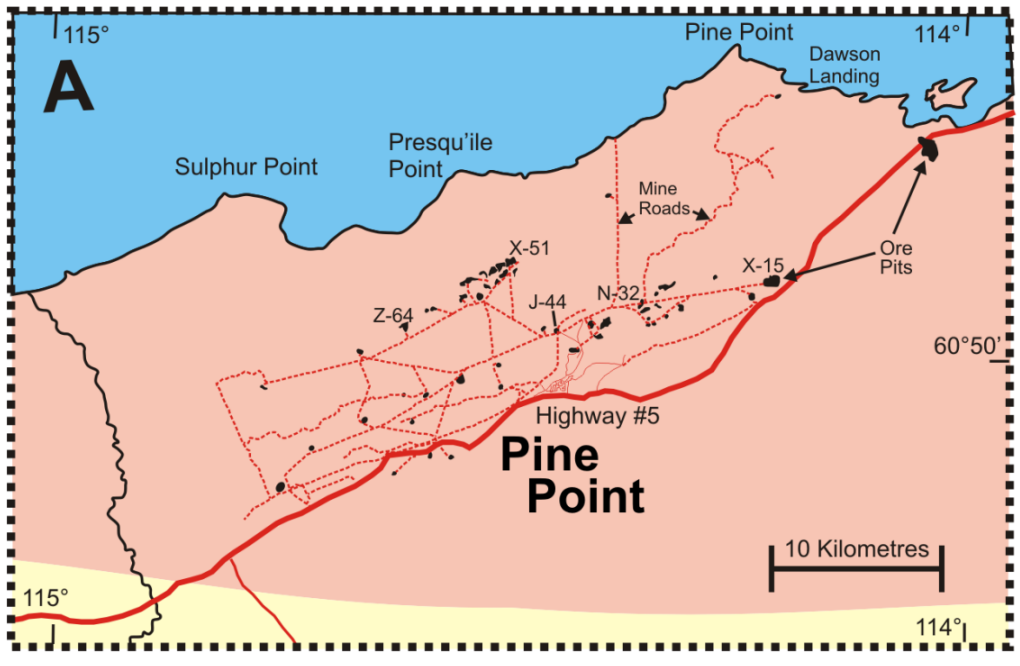
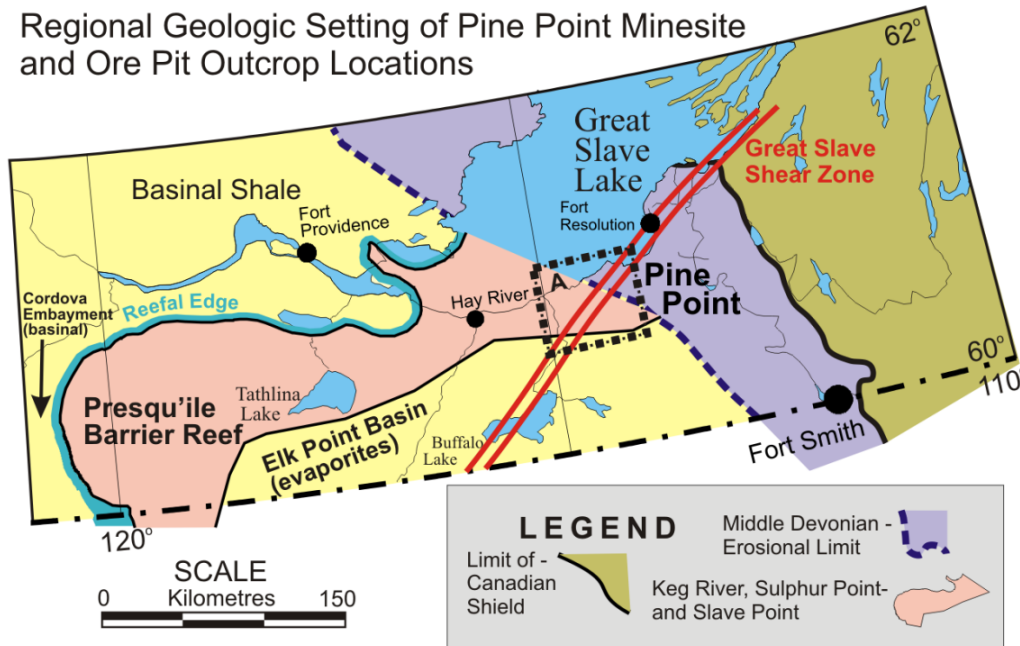
# **HDT Fluid inclusions – 99.9% primary marine brines with eq. vapor bubble**

- **Only small or no hydrocarbons, usually only trace amounts in Fls**
- **Very few with pressurized vapour bubbles, so CO<sub>2</sub> effervescence or boiling not factors**
- **Almost all HDT Fls slightly to somewhat modified evaporated marine brines with requisite iodine, bromine and boron where analysed (Ed Roedder (1968) first noted this)**
- **Manetoe/Presqu'île HDTs typical in these respects**

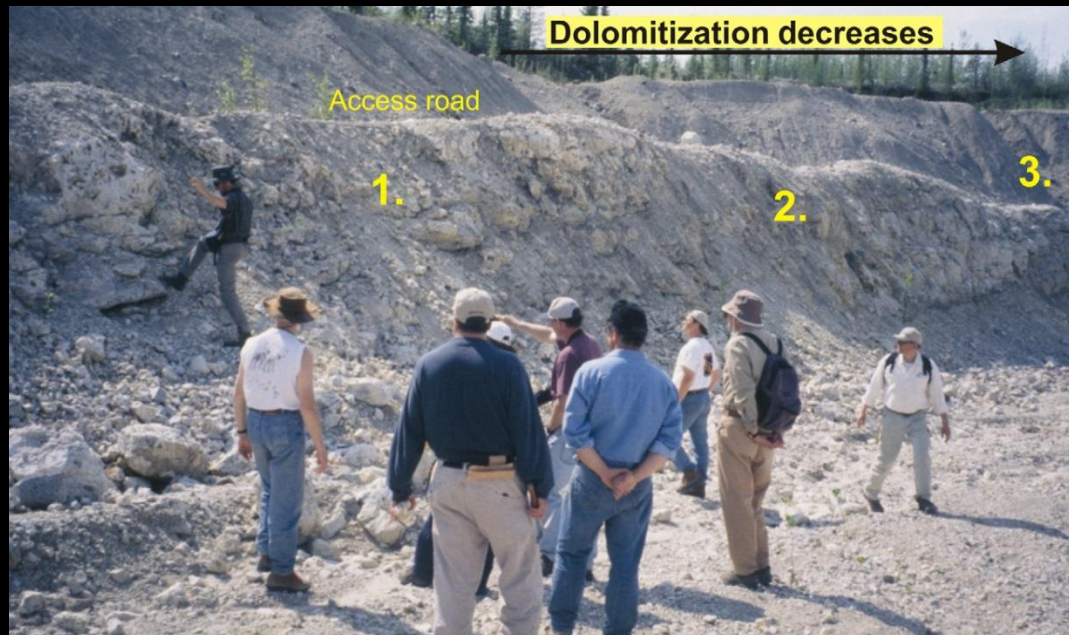


**Grey "a" band  
type dolomite  
retains more  
of host Lst  
isotopic  
character than  
does "b" band  
white dolospar**

# Regional Geologic Setting of Pine Point Minesite and Ore Pit Outcrop Locations



**Presqu'ile  
Dolomite at  
Pine Point  
Minesite-  
Similar to  
Manetoe in  
outcrop**



**Boxworks and Zebras at Pine Point – Isolated dolospar boxwork with rimmed fractures has not expanded bedding in planar bedded limestone**

# Bedding unaffected by Zebra and Boxwork

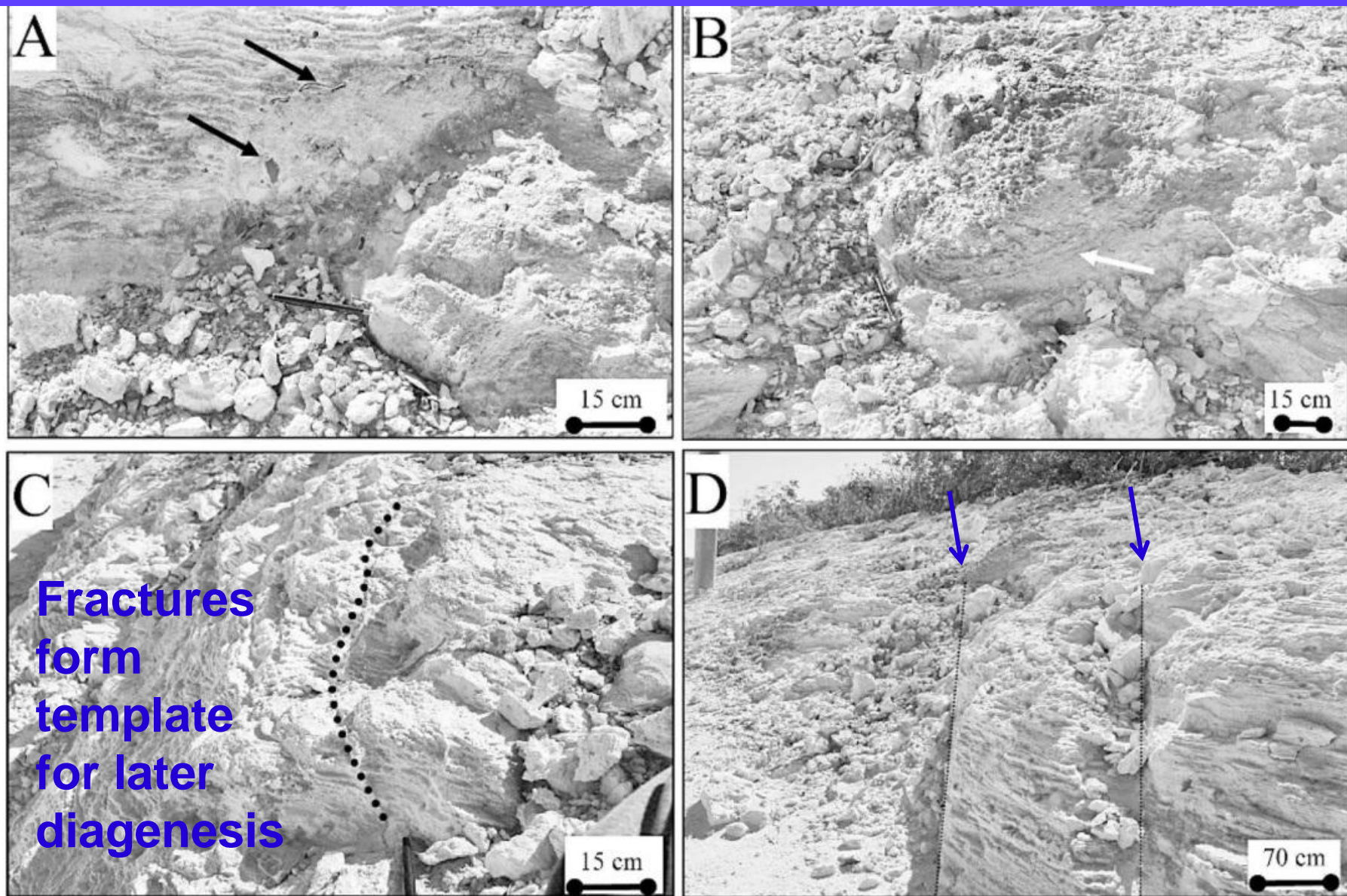


**OC maturation rims  
around boxwork cells**



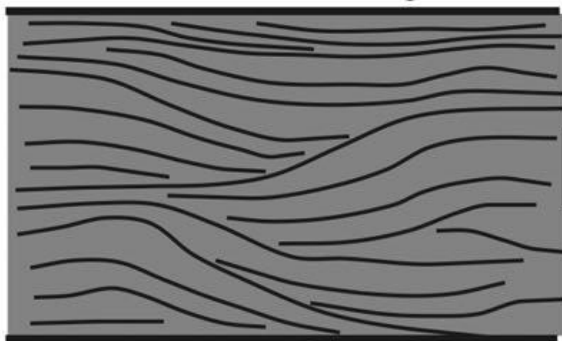
**Tan, ringing-hard pelletal lime packstone**

# Pre-burial fracture networks common in Quaternary Caribbean limestones (Guidry et al., 2007 Turks and Caicos)

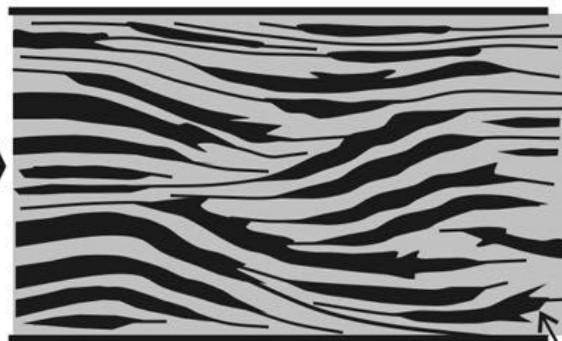


## Progression of hydrothermal dolomitization at Ram River - Zebra Fabric

Planar to wavy thick bedded skeletal lime packstone with Wavy to Cross-bedded Intrabed Partings

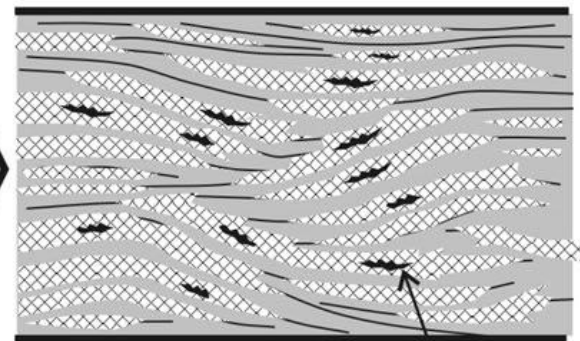


Partly dolomitized skeletal packstone with macropores Along intrabed partings



Macropores

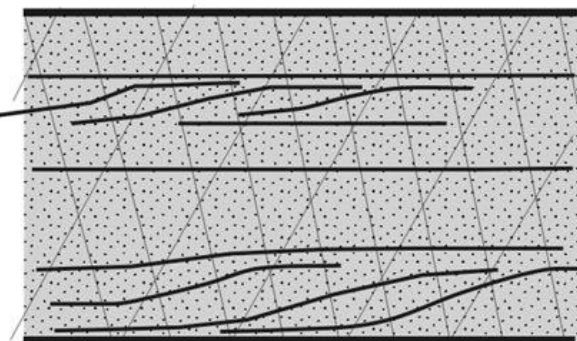
Dolomitized packstone. macropores largely filled with white dolospar (Zebra fabric)



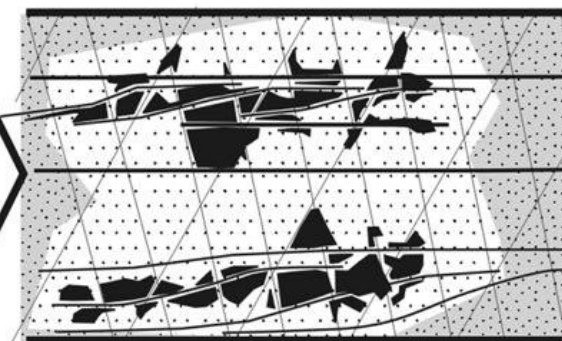
Meso- and micropores

## Progression of hydrothermal dolomitization at Pine Point - Zebra and Boxwork Fabrics

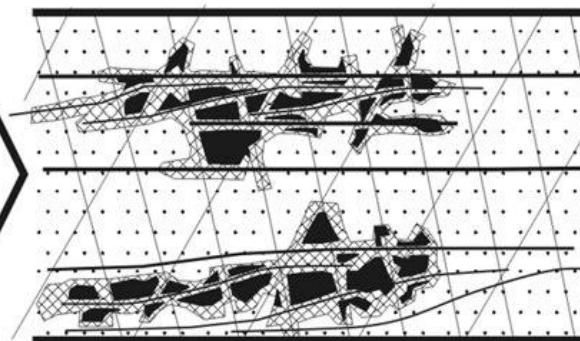
Planar thick bedded pelletal lime packstone with cross-bedded intervals and faint fracture sets



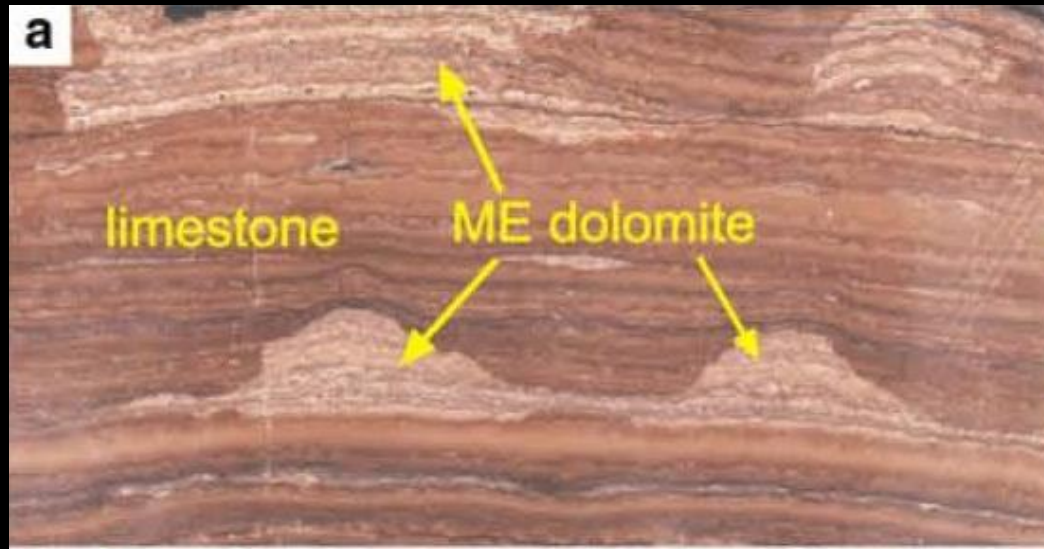
Partly dolomitized packstone with macropores between intrabed partings and thin fractures



Dolomitized packstone. White dolospar partly to largely fills macropores (Boxwork with zebra)

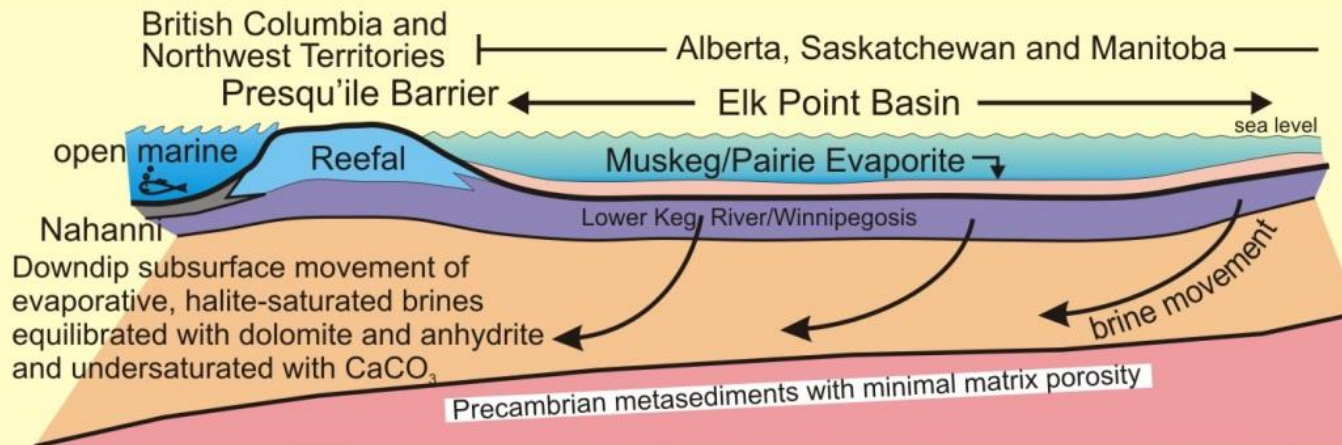


# Ratner- 2000 km south of Pine Point (Fu & Qing, 2011)



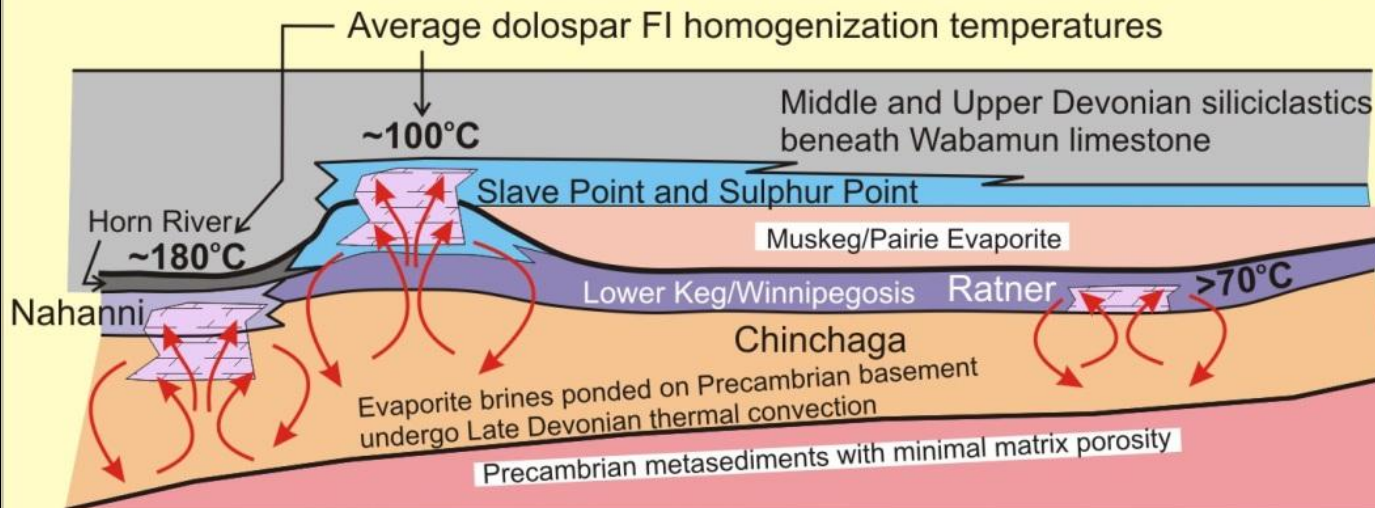
**Manetoe and  
Ratner - vugs in  
dolomite only**





1. Dense evaporated seawater brines in equilibrium with dolomite, but undersaturated with calcite, sink to base of Phanerozoic strata and move northwestward downdip along the top of impermeable Precambrian metasediments.

A

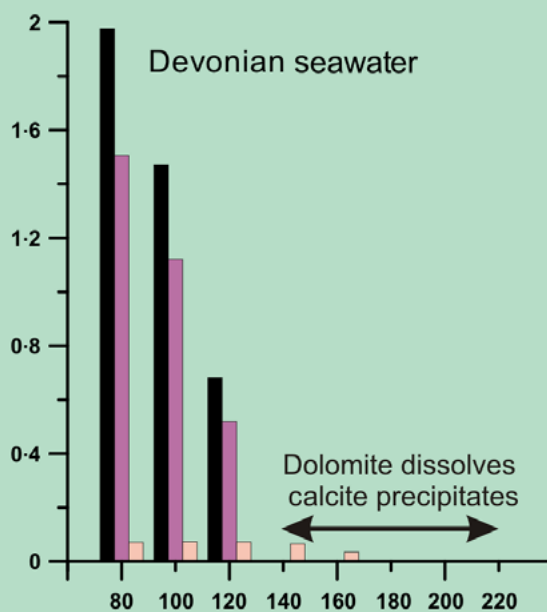
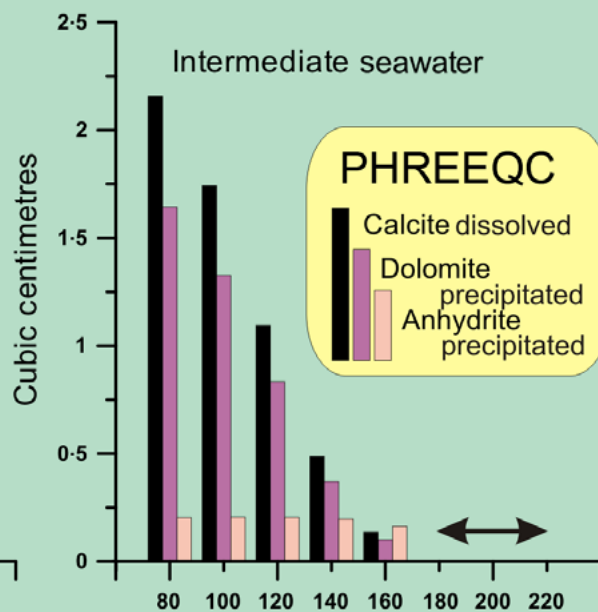
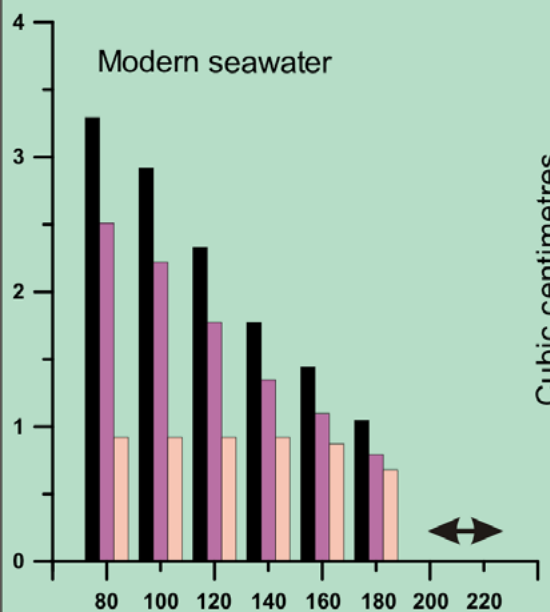
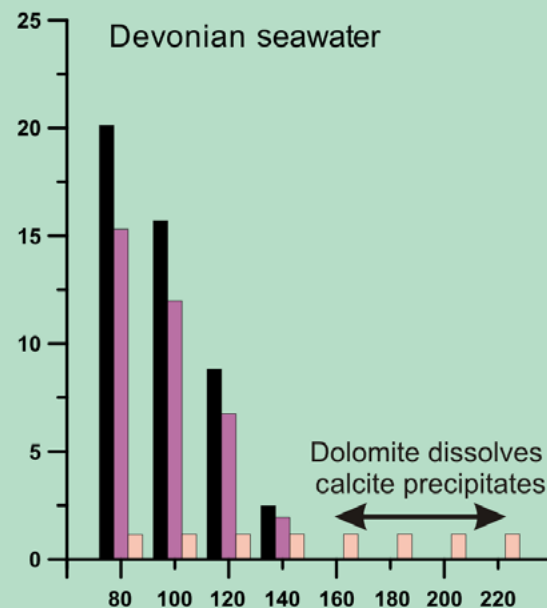
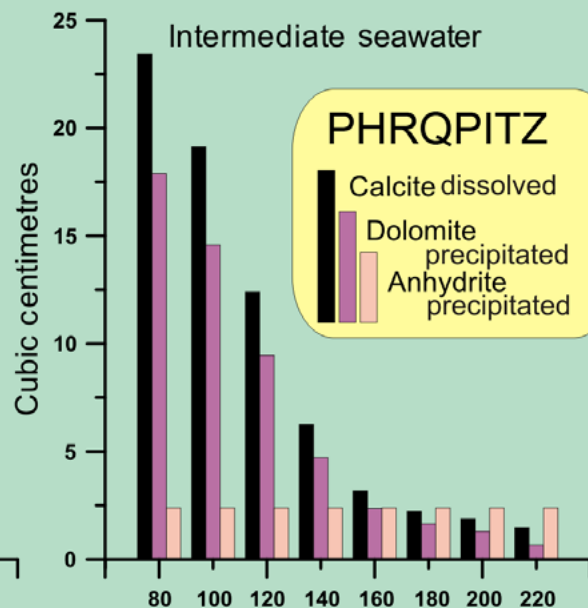
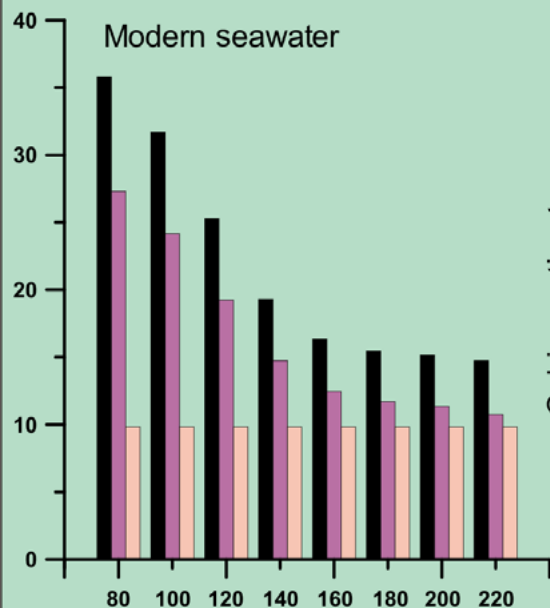


2. Brines ponded on top of Precambrian are heated and undergo accelerated thermal convection during Late Devonian Antler Orogeny. These brines dissolve Nahanni, Sulphur Point, Slave Point and Ratner limestones. The resultant oversaturation of dolomite causes precipitation of hydrothermal white dolospar to form the Manetoe and Presqu'ile dolomites and dolospar in the Ratner limestone.

B

**HDT by  
Geo-  
thermal  
Brines.**

**Fluid  
inclusion  
Th's  
reflect  
depth to  
basement**



PHRQPITZ

Calcite dissolved  
Dolomite precipitated  
Anhydrite precipitated

PHREEQC

Calcite dissolved  
Dolomite precipitated  
Anhydrite precipitated

# Salton Sea geothermal system – partial model for marine brine convection



# **So what can be concluded?**

- 1. There are HDT masses which bear little relation to past or present faults.**
- 2. The requirements for brine volumes to form fault-related HDTs is unreasonably large for in-situ formation fluid sources during fault episodes.**
- 3. HDT fabrics are not the product of explosive rock dilation during faulting. Solution-excavation, collapse and HDT replacement of fines explains Zebra, Boxworks, and “floating” breccias in HDTs.**
- 4. Regional subsurface convection is the driver for regionally developed HDT's including along faults.**
- 5. Exploration could proceed between fault zones in favourable facies or in areas remote from faults using enhanced seismic techniques.**

# Acknowledgements

Thanks are due  
to many  
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Ron Spencer,  
Kathy Aulstead,  
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(deceased),  
Graham Davies  
and many field  
trip participants.

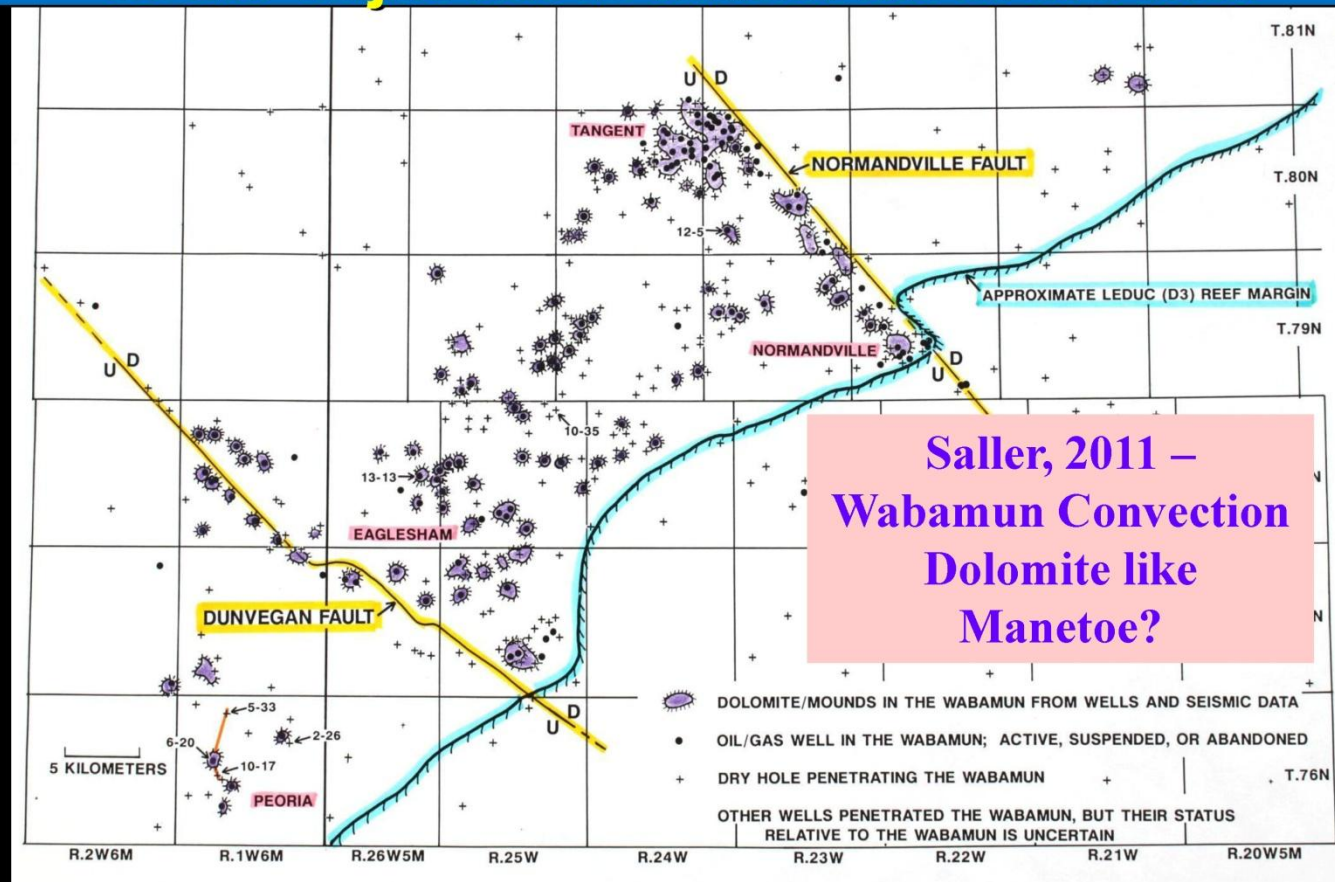


Where are facts when  
you need them?

54 8 24

# Porous reservoir dolomites in tight limestone

## Some adjacent to faults. Most are not!



Presenter's notes: Prolific HDT reservoirs in the Wabamun platform limestone of Alberta, Canada are only weakly associated with faults. Many are not. This implies that HDT fluids moved through the Wabamun horizontally between faults. This is most easily explained as caused by thermal convection of HDT brines.