Structurally-controlled hydrothermal diagenesis of Mississippian reservoir rocks exposed in the Big Snowy Arch, central Montana

Sarah Jeffrey

Montana State University

Department of Earth Sciences

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Applications for CO_2 Sequestration Technologies

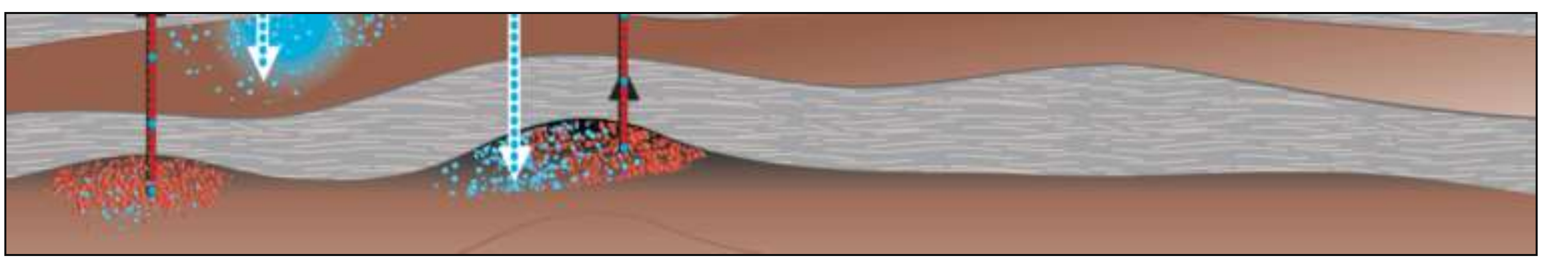
Importance of Carbon Sequestration Projects

Carbon Dioxide Emissions

- CO_2 accounts for 64% of emissions contributing to the greenhouse effect
- Since industrialization, atmospheric CO_2 levels have risen from 280 ppm to 360 ppm
  - The combustion of coal comprises 50% of energy generation in the United States, and 25% globally

Carbon Capture and Storage

- Techniques:
  - Collect CO_2 from point sources
  - Transport it as a supercritical fluid to an injection site
  - Pump fluid into geologic storage reservoirs
- Research:
  - Characterize the reservoir for structures that act as a barrier or conduit to subsurface fluid flow

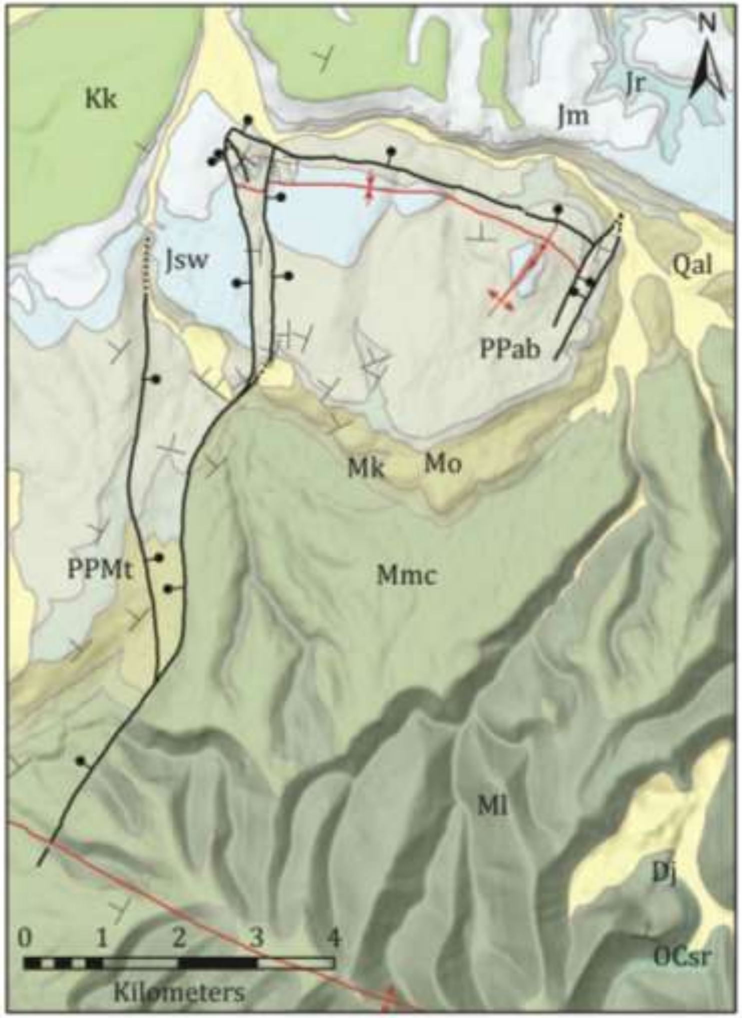


(modified from IPCC, 2005)

Statement of Problem and Research Objectives

Research Objectives

- What structures within the Big Snowy Mountains serve as an analog to other carbon sequestration sites, and at what scales of observation?
- What is the stratigraphic distribution of hydrothermal structures, such as breccia pipes?
- How does brittle (tectonic) deformation affect reservoir properties for CO_2 sequestration applications? To what extent does hydrothermal diagenesis affect porosity and permeability?
- Do hydrothermal breccia pipes serve as a conduit or as a barrier to fluid flow in the subsurface?



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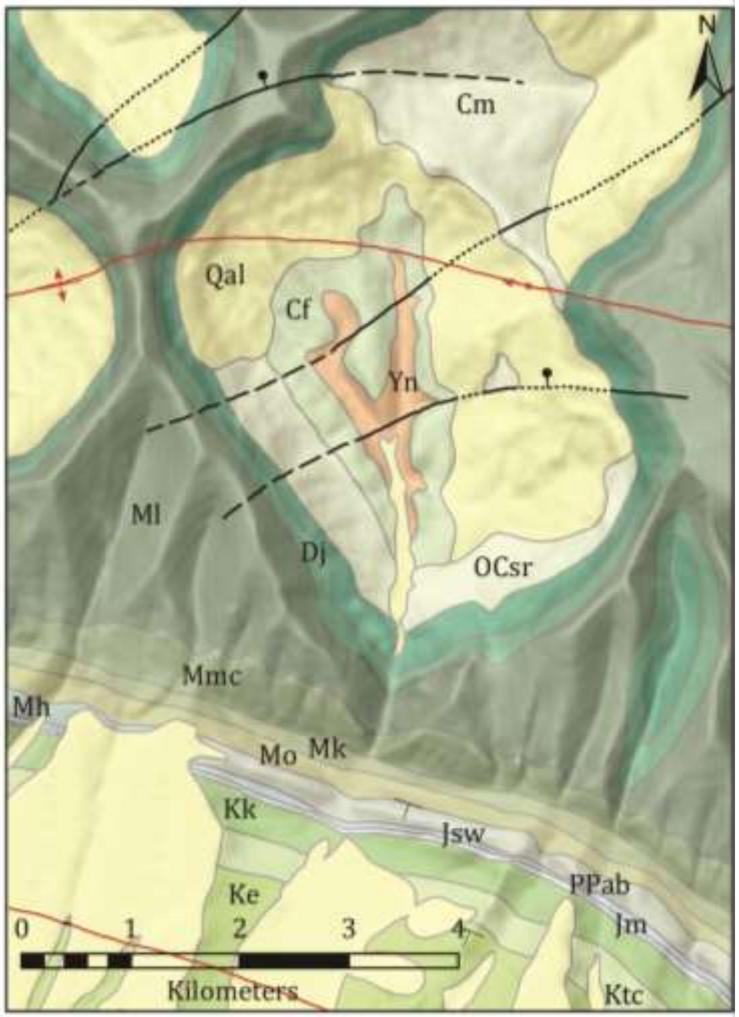

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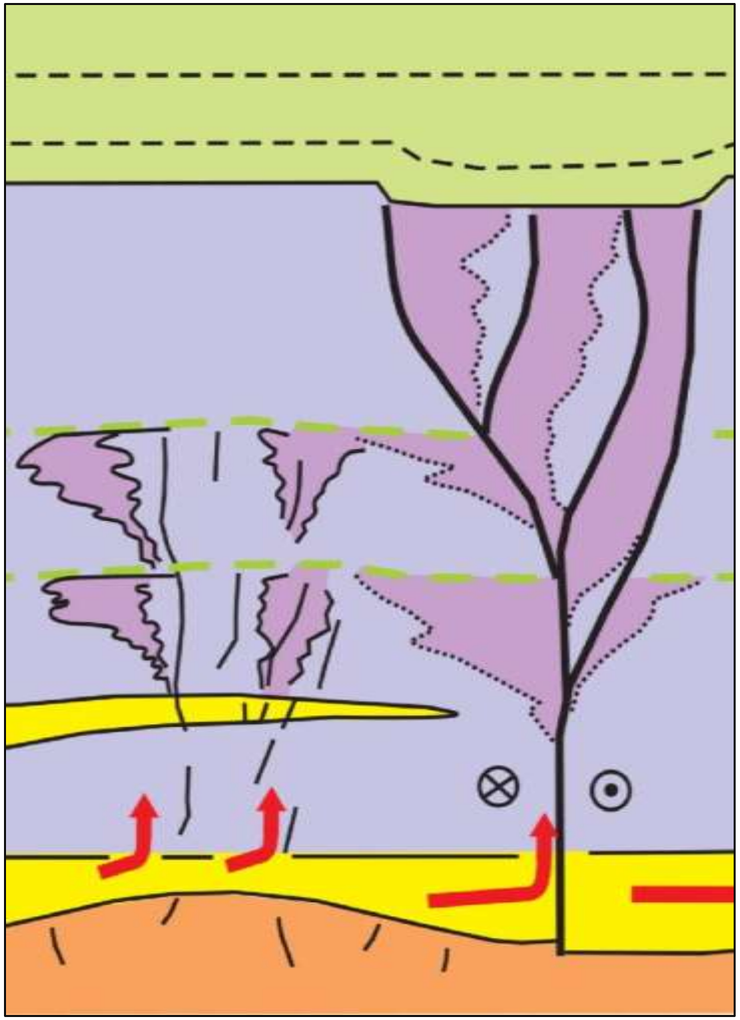

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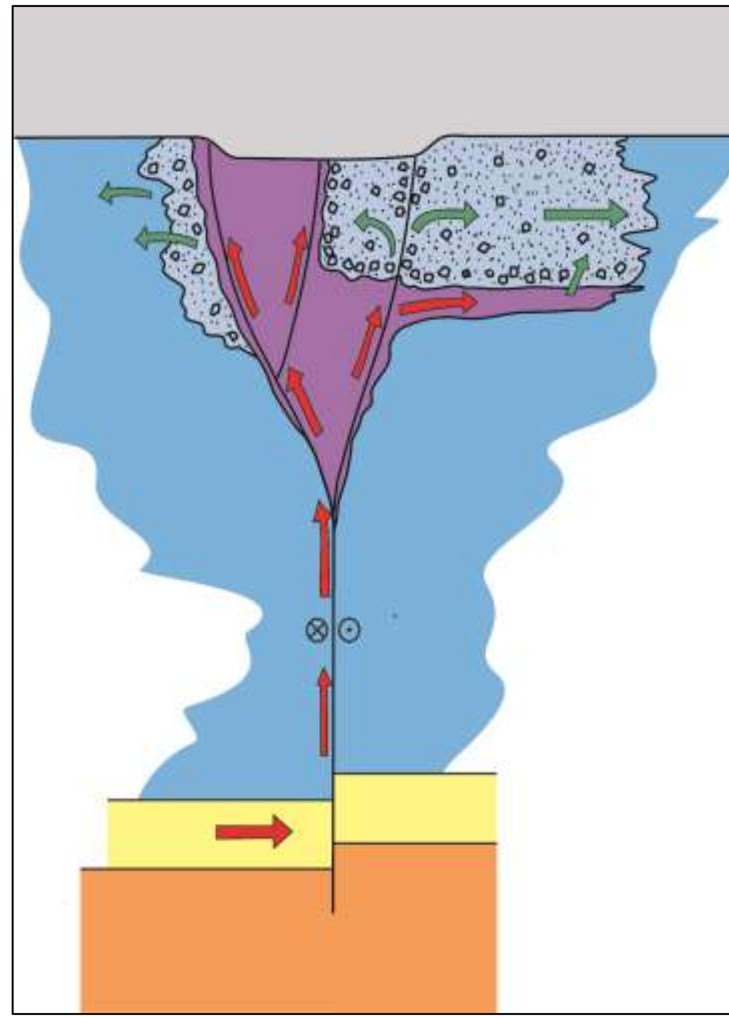

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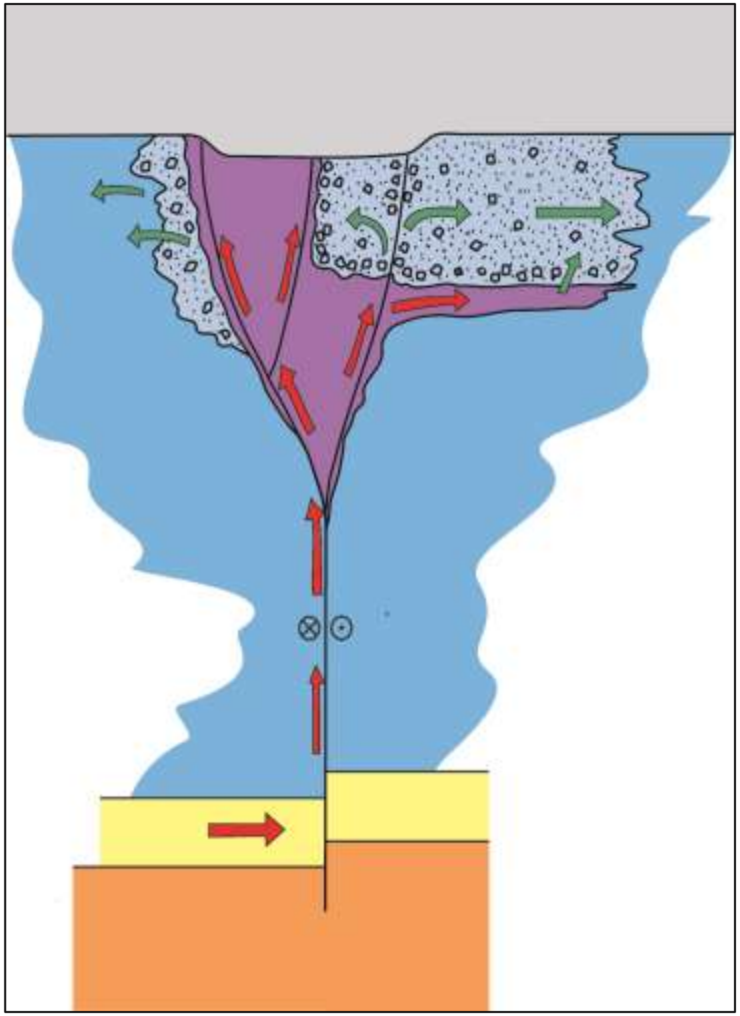

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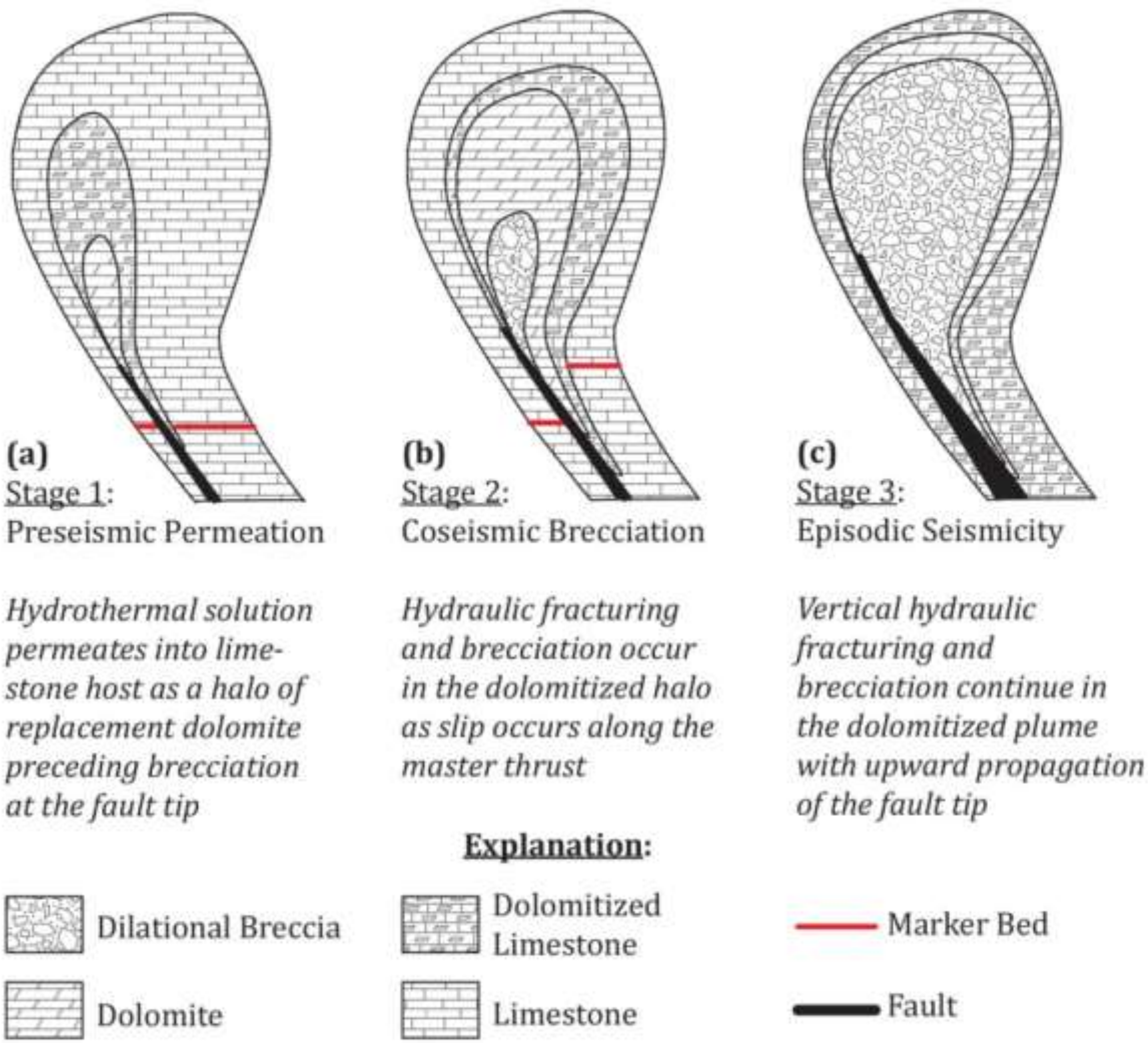
Hydrothermal Fluid Migration and Brecciation Mechanisms

Formation of a Hydrothermal Breccia Pipe



- Hydrothermal:
  - Aqueous solutions that are warmer to hotter relative to the ambient environment
- Reasons for variations in fluid properties:
  - Rapid introduction of fluids to the host rock prior to re-equilibration to ambient conditions

- (modified from Phillips, 1972; Davies and Smith, 2006)

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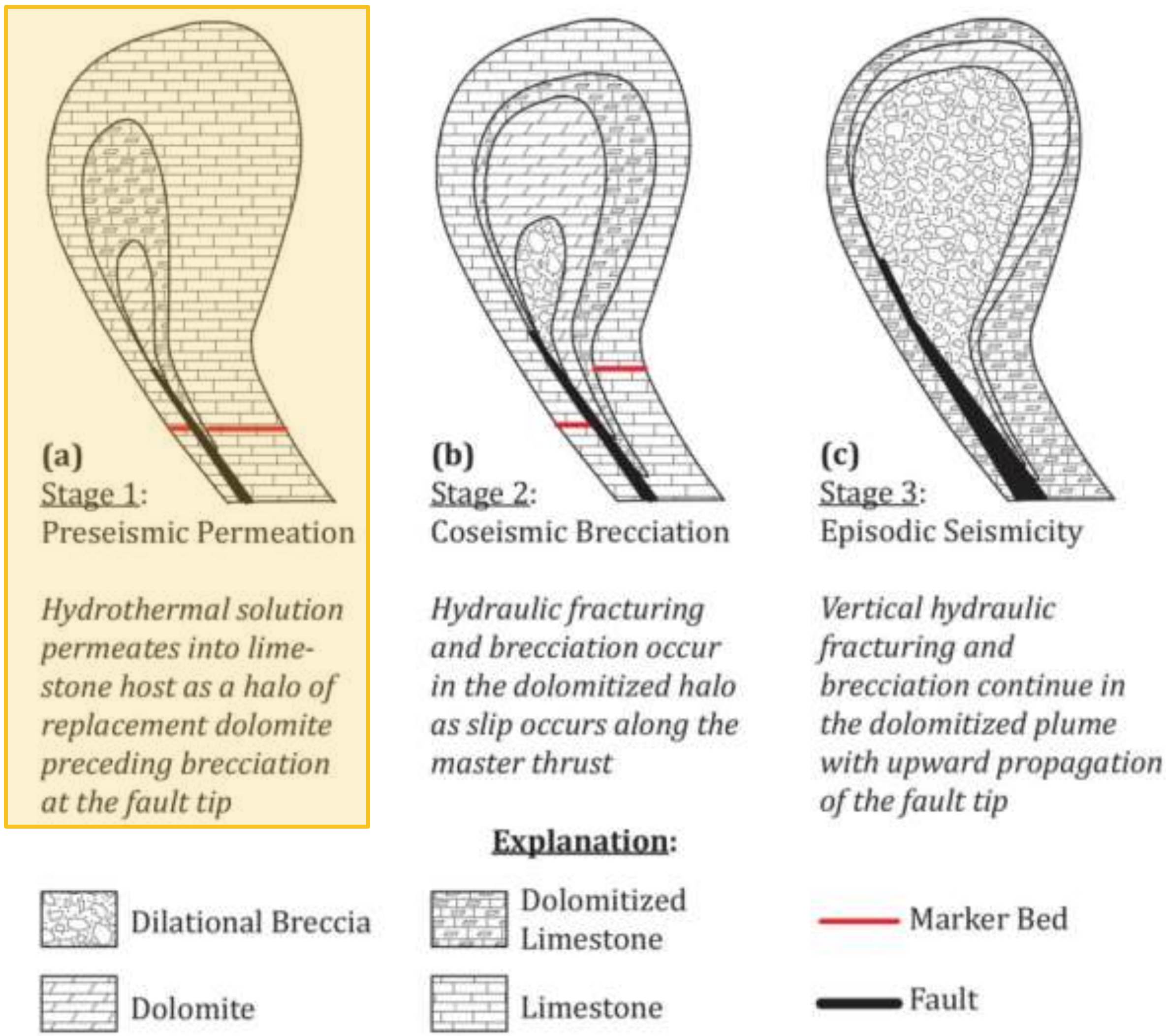

- Stage 1:
  - Fluids progressively permeate into the fault tip
  - Pore space of rocks peripheral to the fault is preferentially filled with fluid
  - Results in a zone of matrix dolomitization or mineralization

- (modified from Phillips, 1972; Davies and Smith, 2006)

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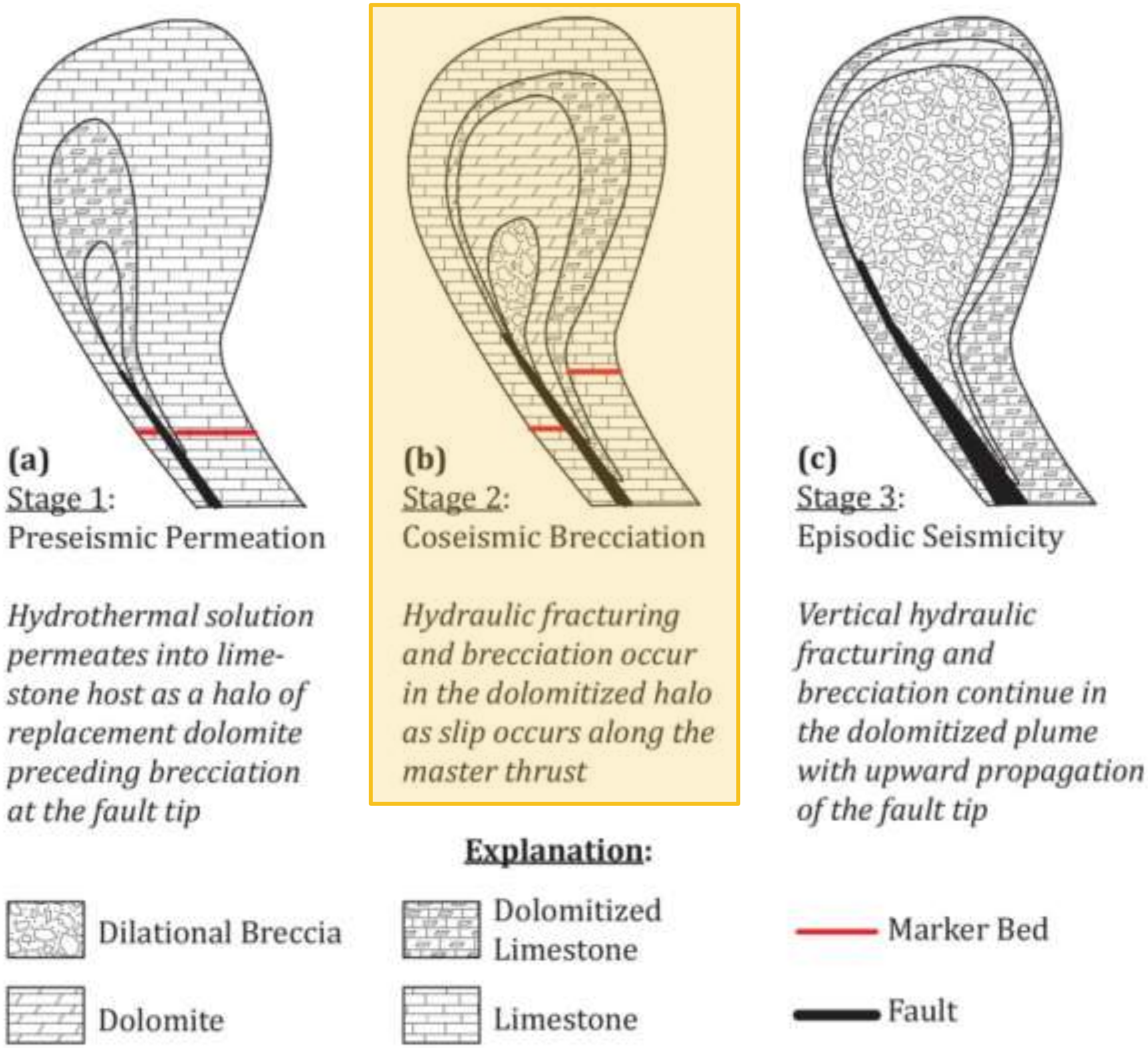

- Stage 2:
  - Fault failure results in an abrupt drop in pressure and loss of CO_2 by effervescence
  - Brecciation occurs along with the precipitation of coarser saddle dolomite, overprinting the earlier matrix dolomitization

- (modified from Phillips, 1972; Davies and Smith, 2006)

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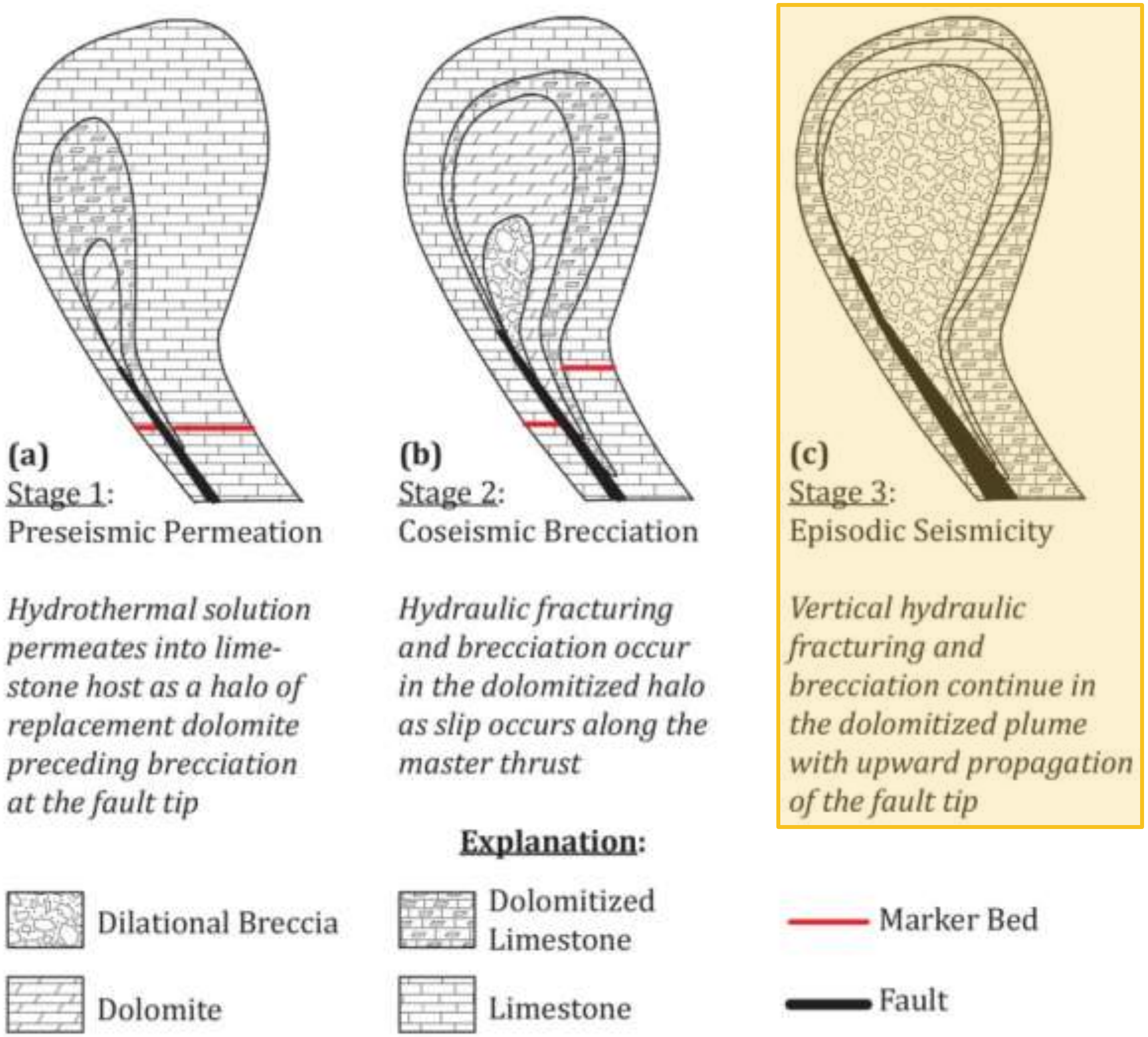
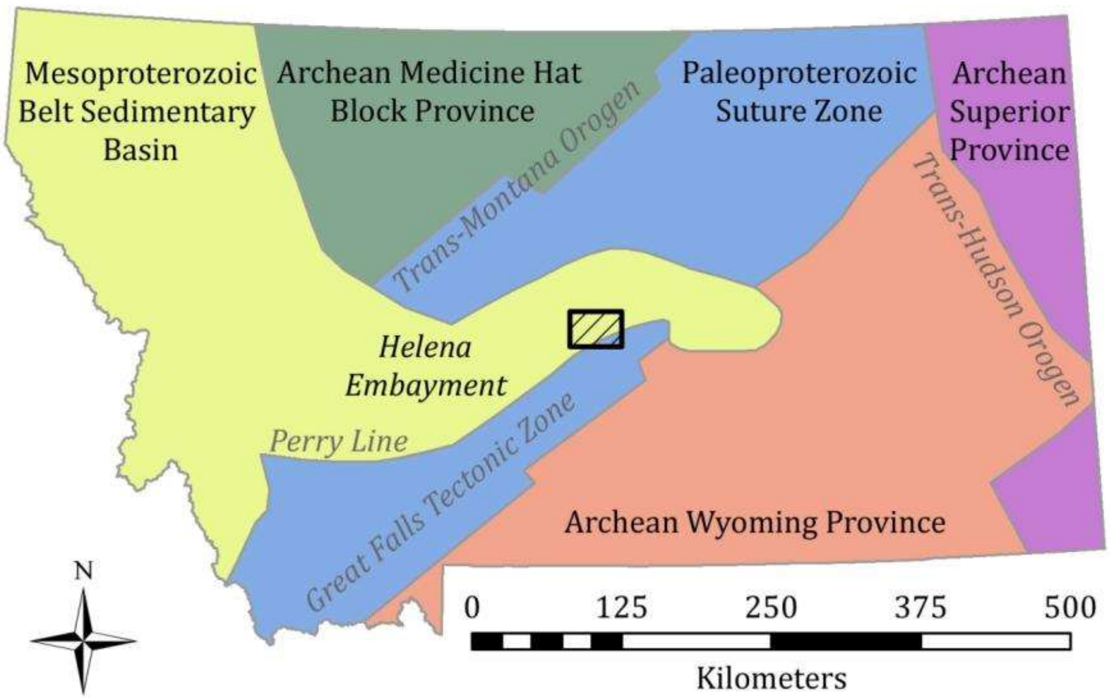


- Stage 3:
  - Cycle repeats itself as episodic fault reactivation continues, resulting in a halo of replacive dolomite surrounding the fault
  - Fault tip continues to propagate up-section

- (modified from Phillips, 1972; Davies and Smith, 2006)

Tectonic and Stratigraphic Settings of Central Montana

Big Snowy Mountains Field Area

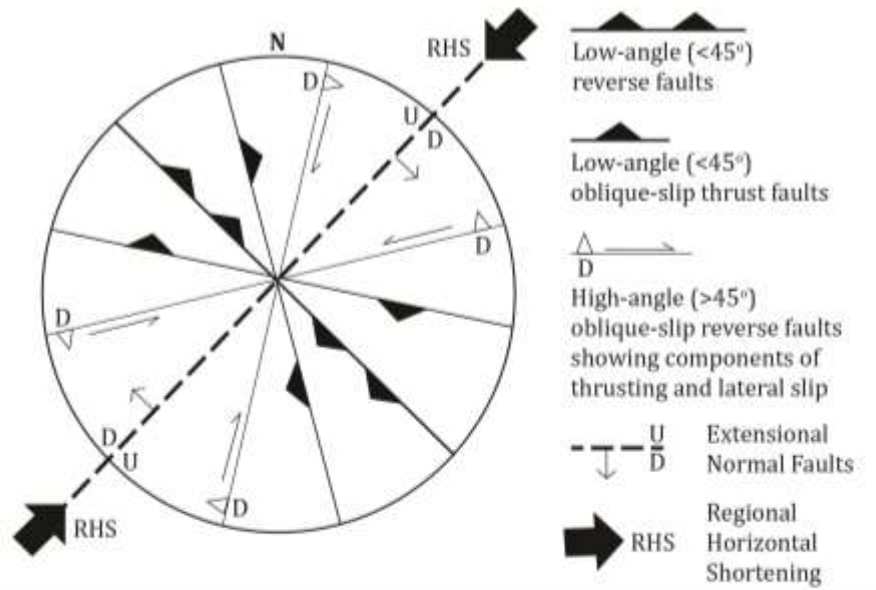


- The BSM lie within the Central MT Trough, a Mesoproterozoic rift basin that formed c. 1.4 Ga
- Fault zones associated with the rift have been reactivated by adjustment along basement faults

- WY Province (Basement): Late Archean fine-grained schists and gneisses that exhibit a strong foliation
  - Foliations strike W-NW and dip steeply
  - Basement inherited this structural grain, which later influenced middle to late Proterozoic fracture orientations
- Paleoproterozoic Suture Zone:
  - NE-trending suture zone of basement anomalies
  - Separates the Wyoming and Medicine Hat provinces

- (modified from Nelson, 1993)

Structural Setting of the Big Snowy Mountains

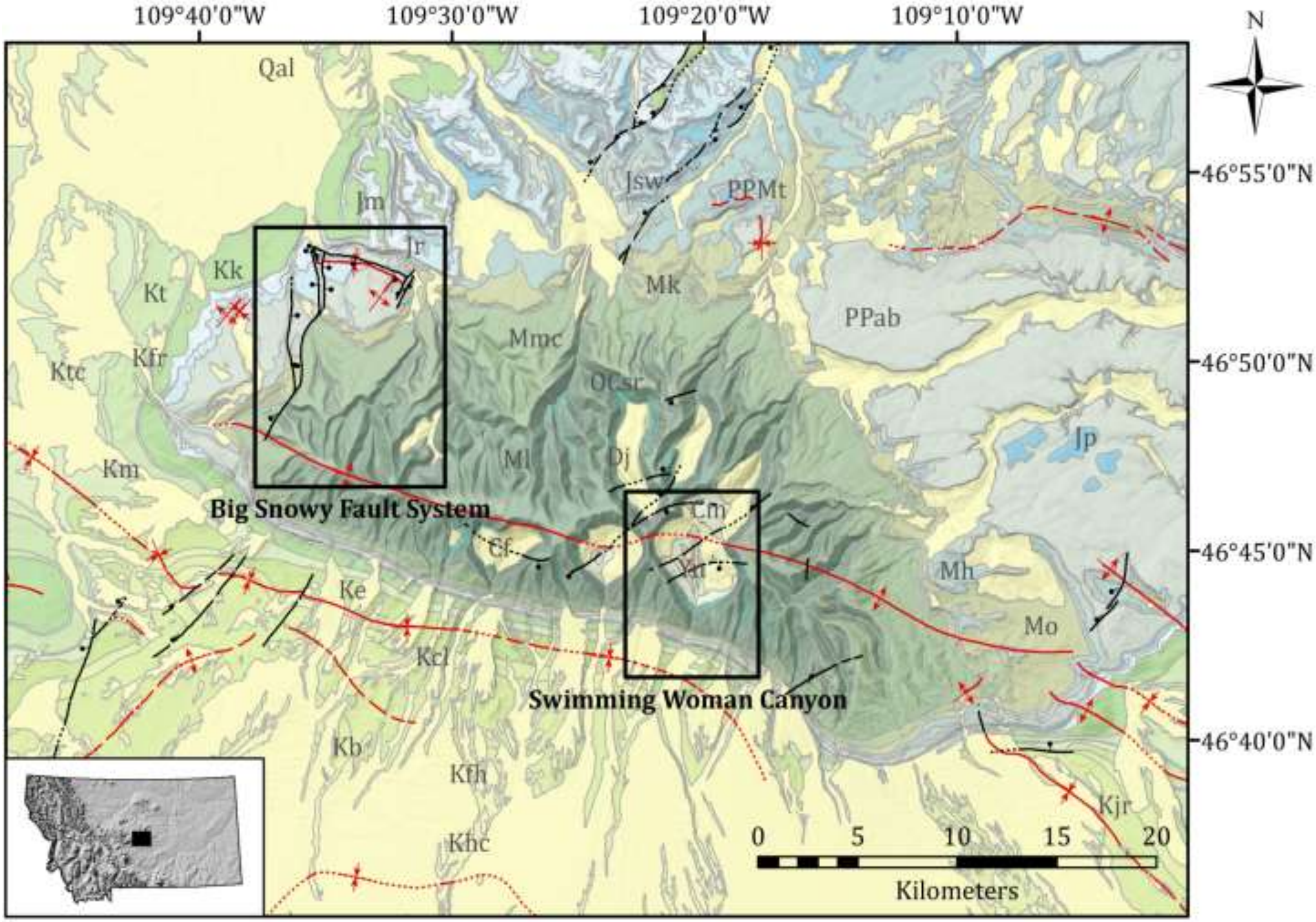


- The Laramide orogeny upwarped the Central MT Trough and structurally inverted topographic features

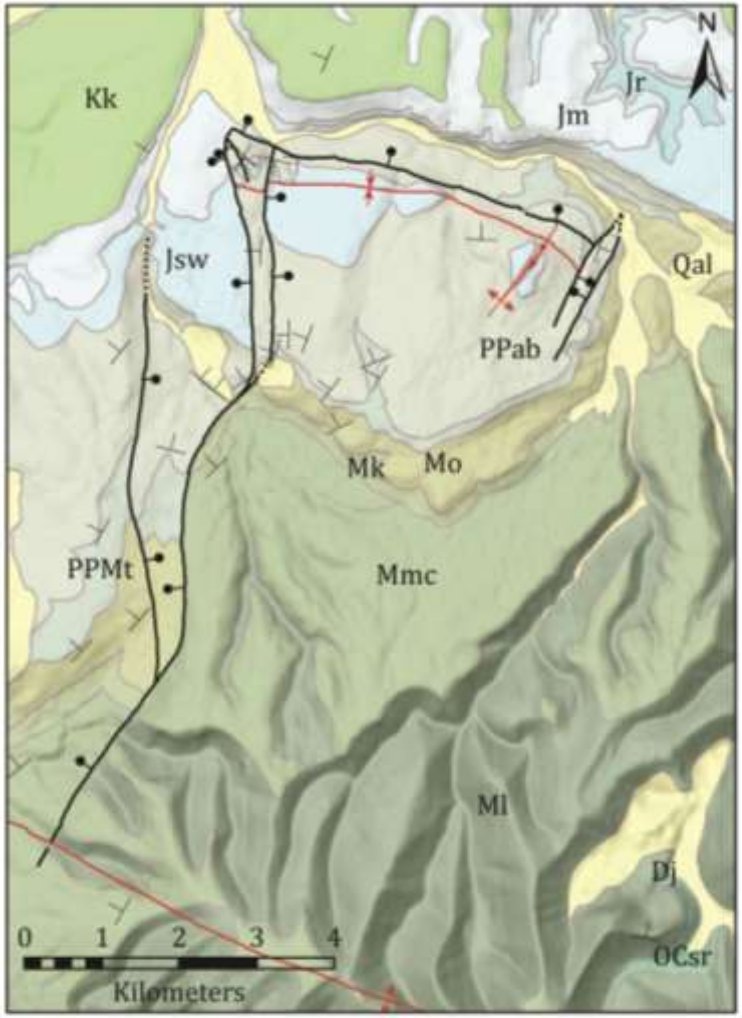
- N40°E to N50°E shortening
- Shortening accommodated by strike-slip displacement perpendicular to slip along major thrust faults
- Favorably reactivated basement structures
  - ENE, E, or ESE structures reactivated as left-lateral oblique-slip faults
  - SE, SSE, or NS structures reactivated as right-lateral low-angle dip-slip reverse faults

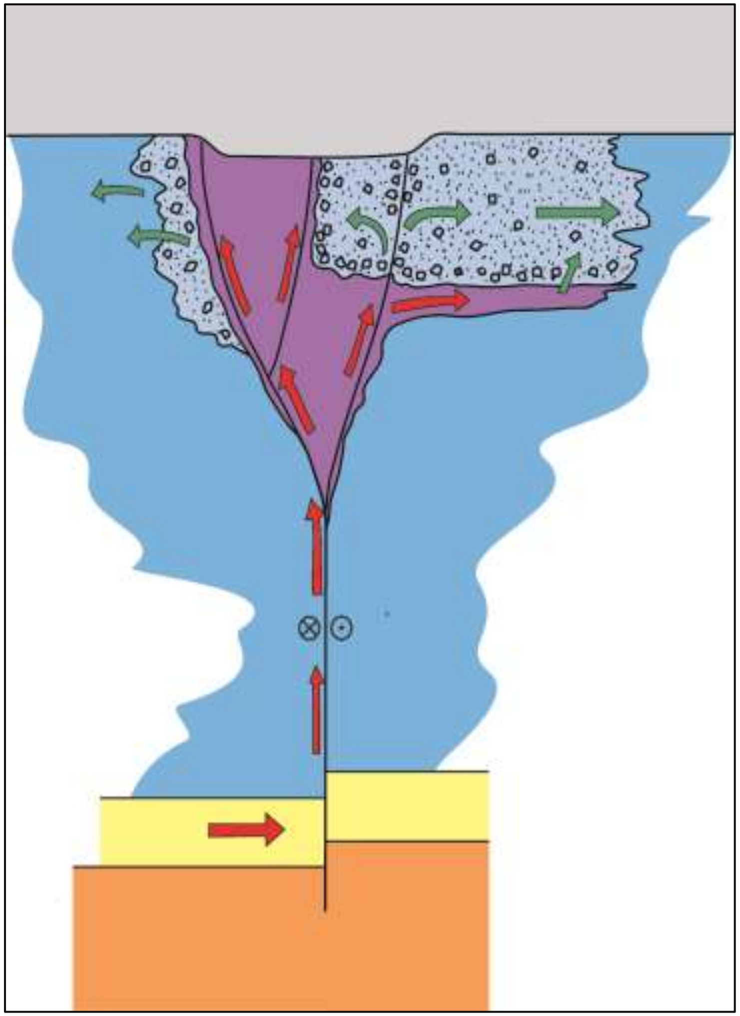
- (modified from Brown, 1993)

Big Snowy Mountains Field Area



Geologic Setting of Field Study Areas





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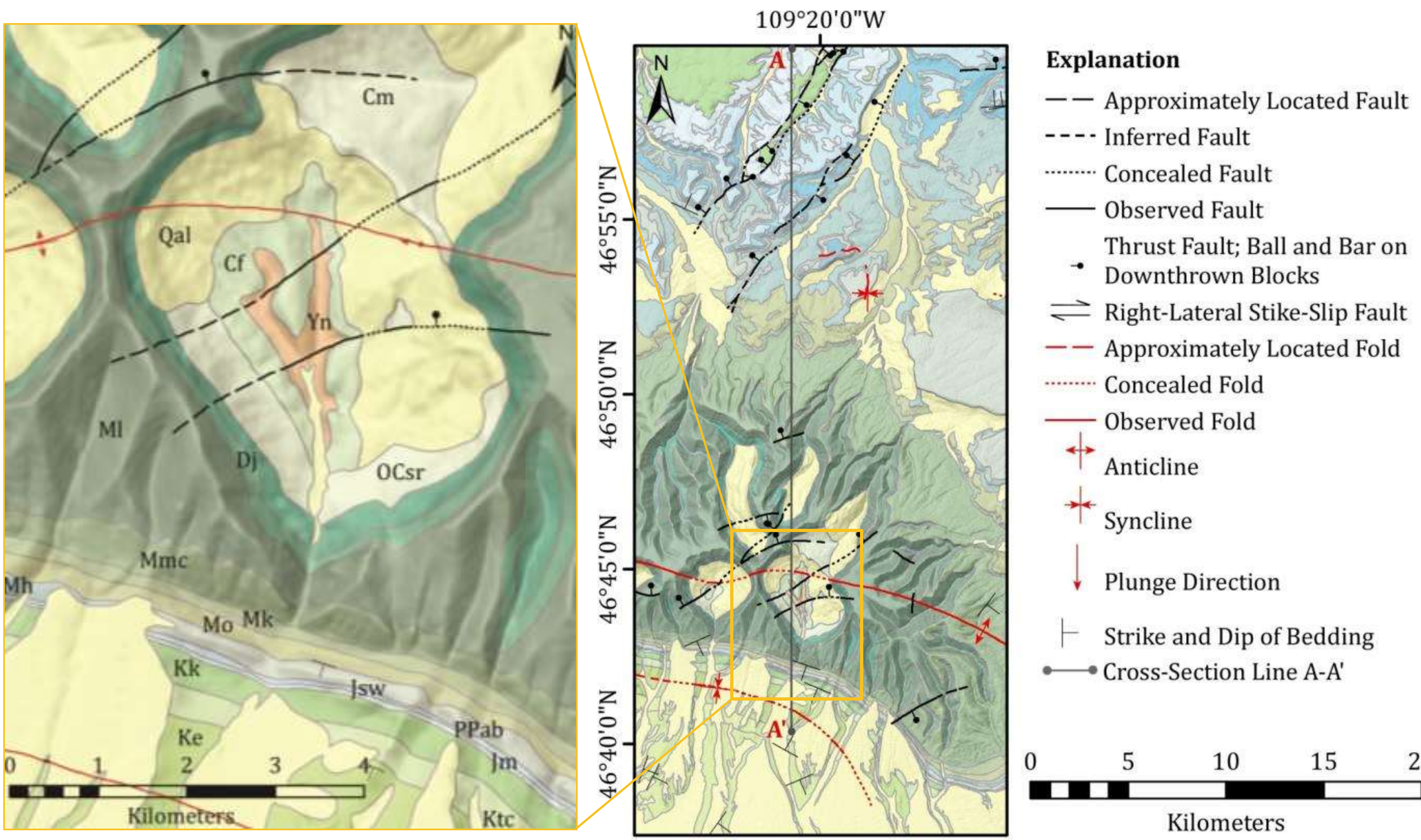

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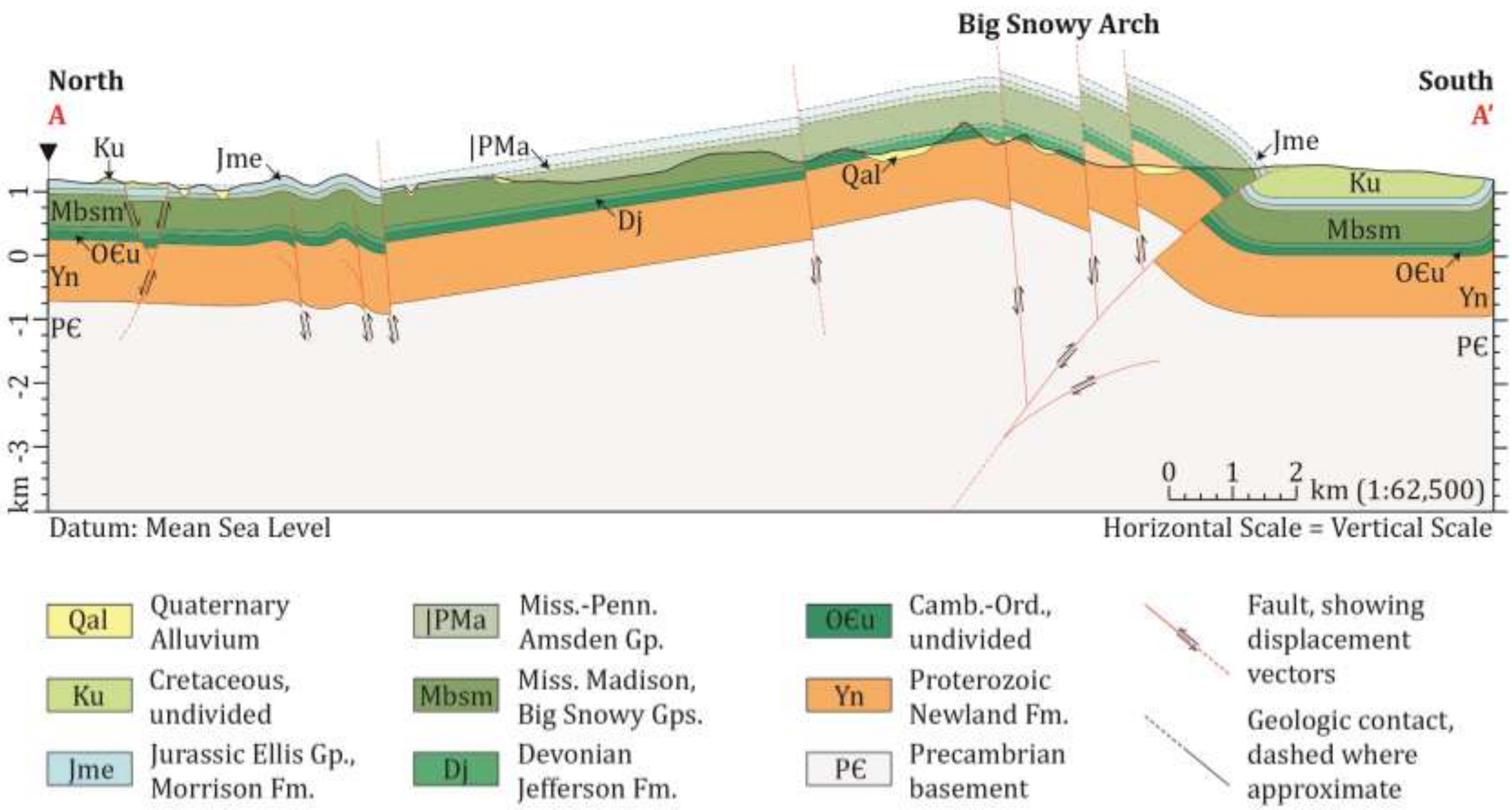
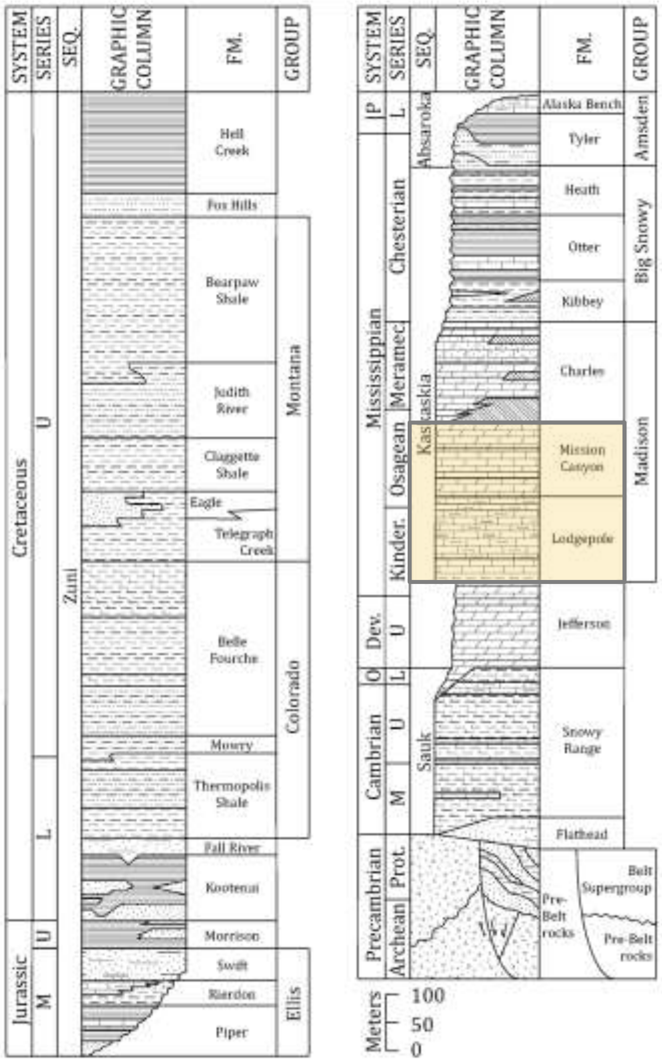


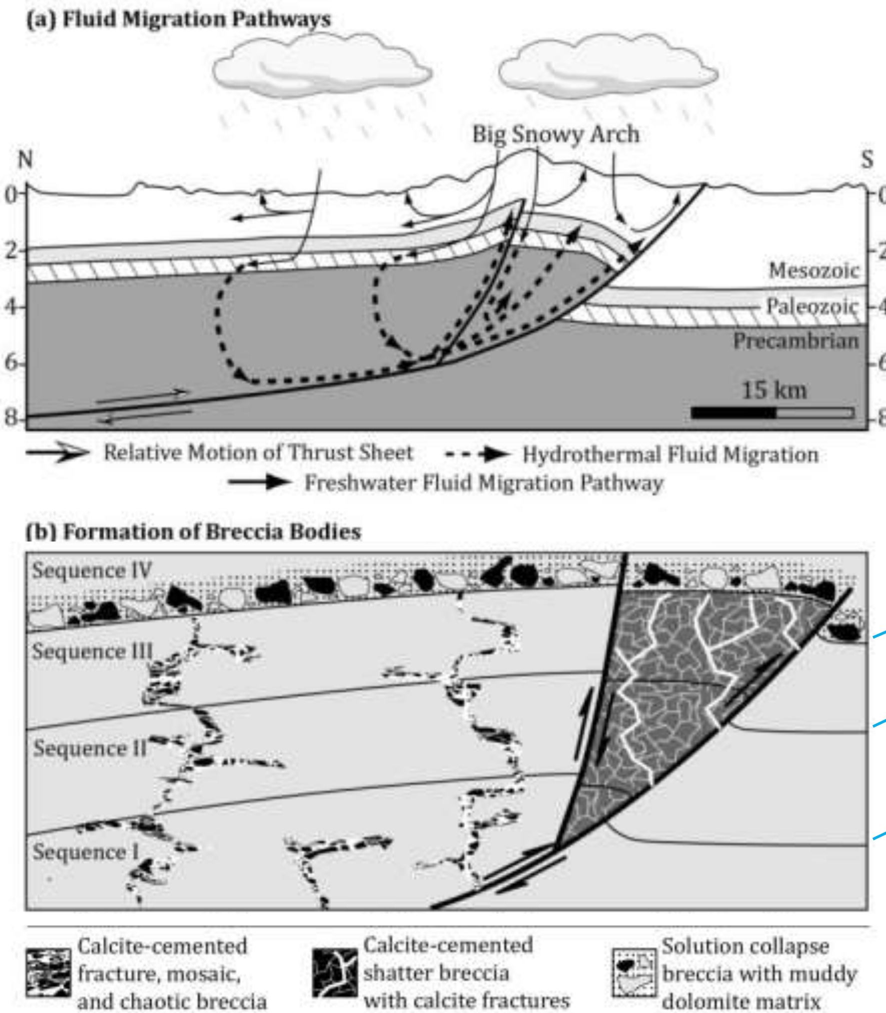
Sequence Stratigraphy of the Madison Group

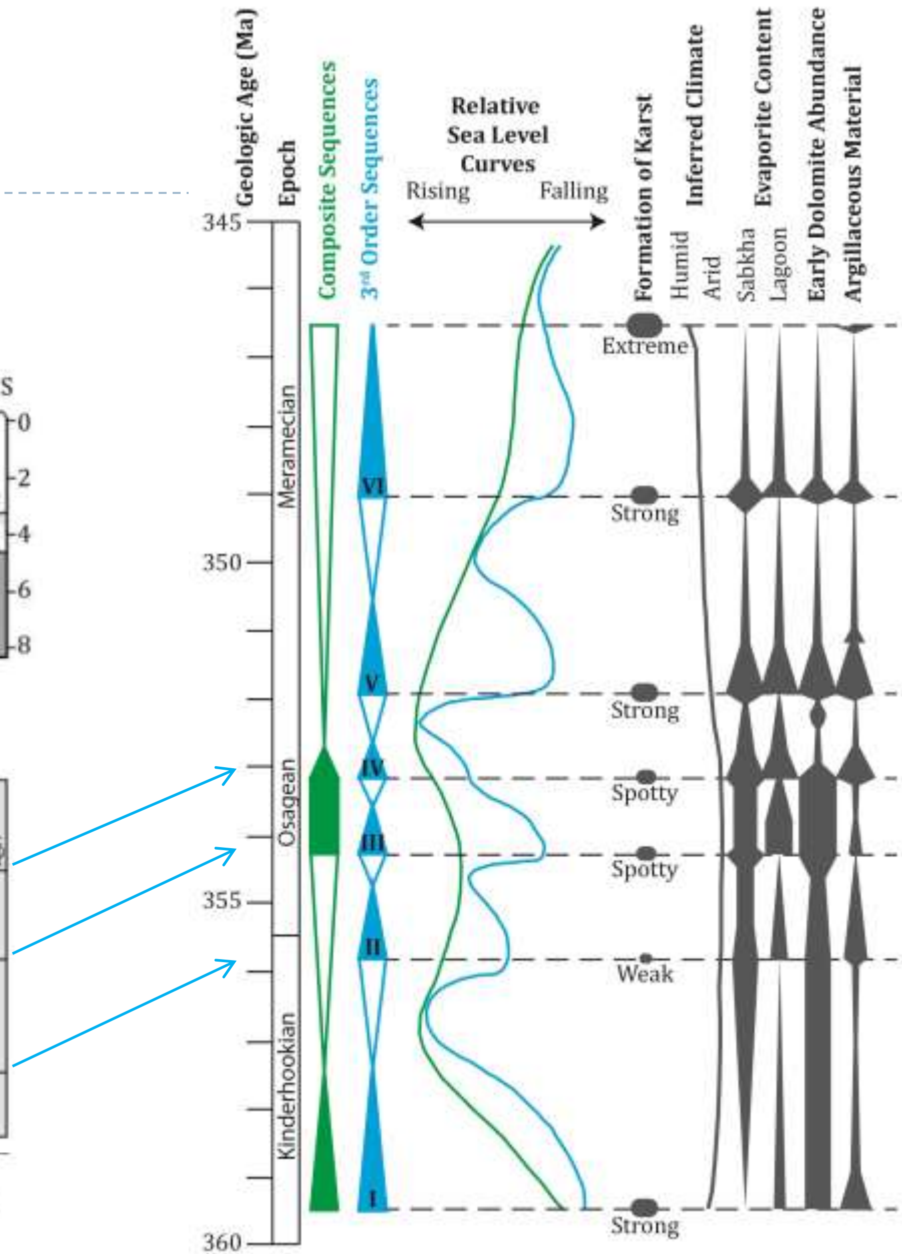


- Madison Group Limestones:
  - Deposited on a 400 km ramp
  - Thickest in the Central MT Trough due to high subsidence rates
  - Comprise a 2nd order supersequence spanning 12 m.y.
  - Capped by a regional unconformity
  - Composed of two composite sequences, six 3rd order sequences, and numerous higher frequency cycles

- (modified from Nelson, 1993)

Sequence Stratigraphy



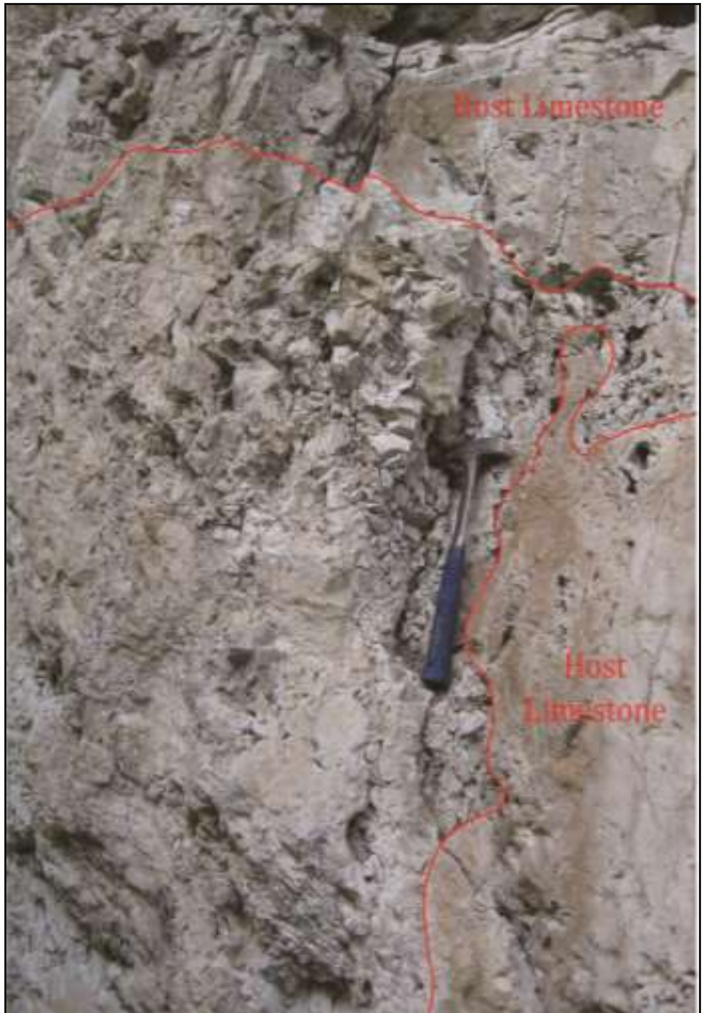


(modified from Katz et al., 2007)

(modified from Sonnenfeld, 1996)

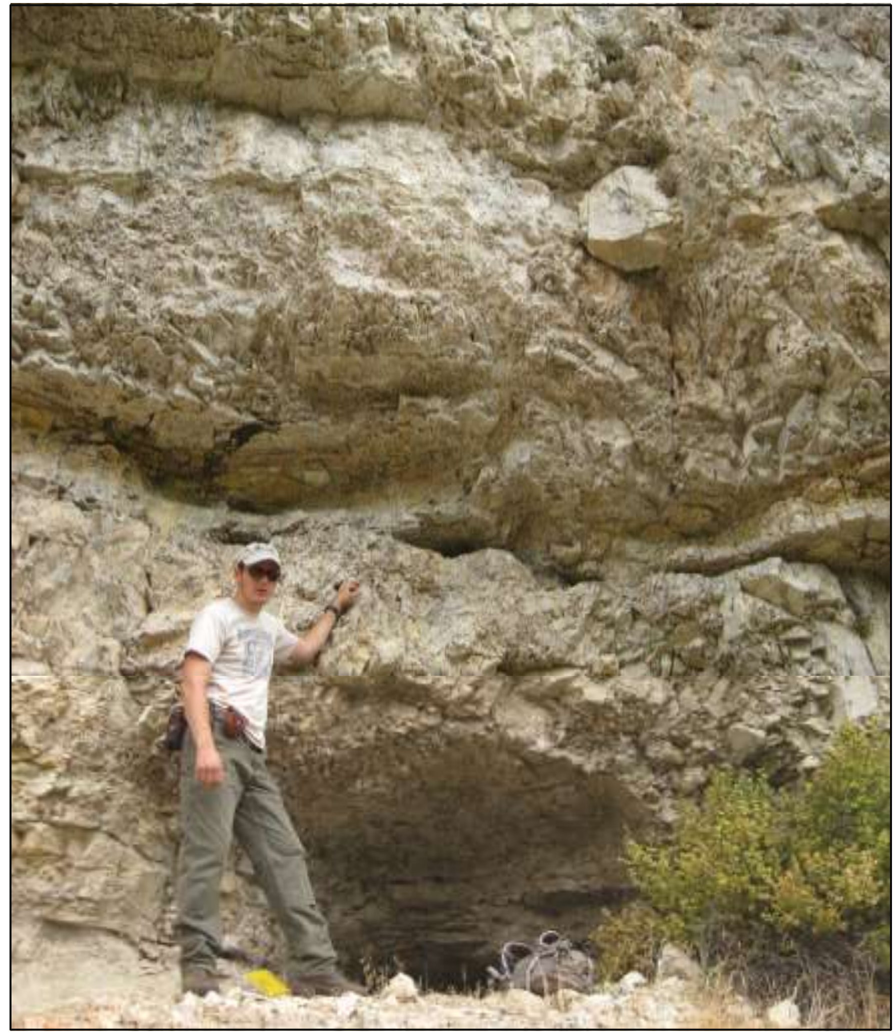
Breccia Pipe Properties and Heterogeneities

Properties of Hydrothermal Breccia Pipes



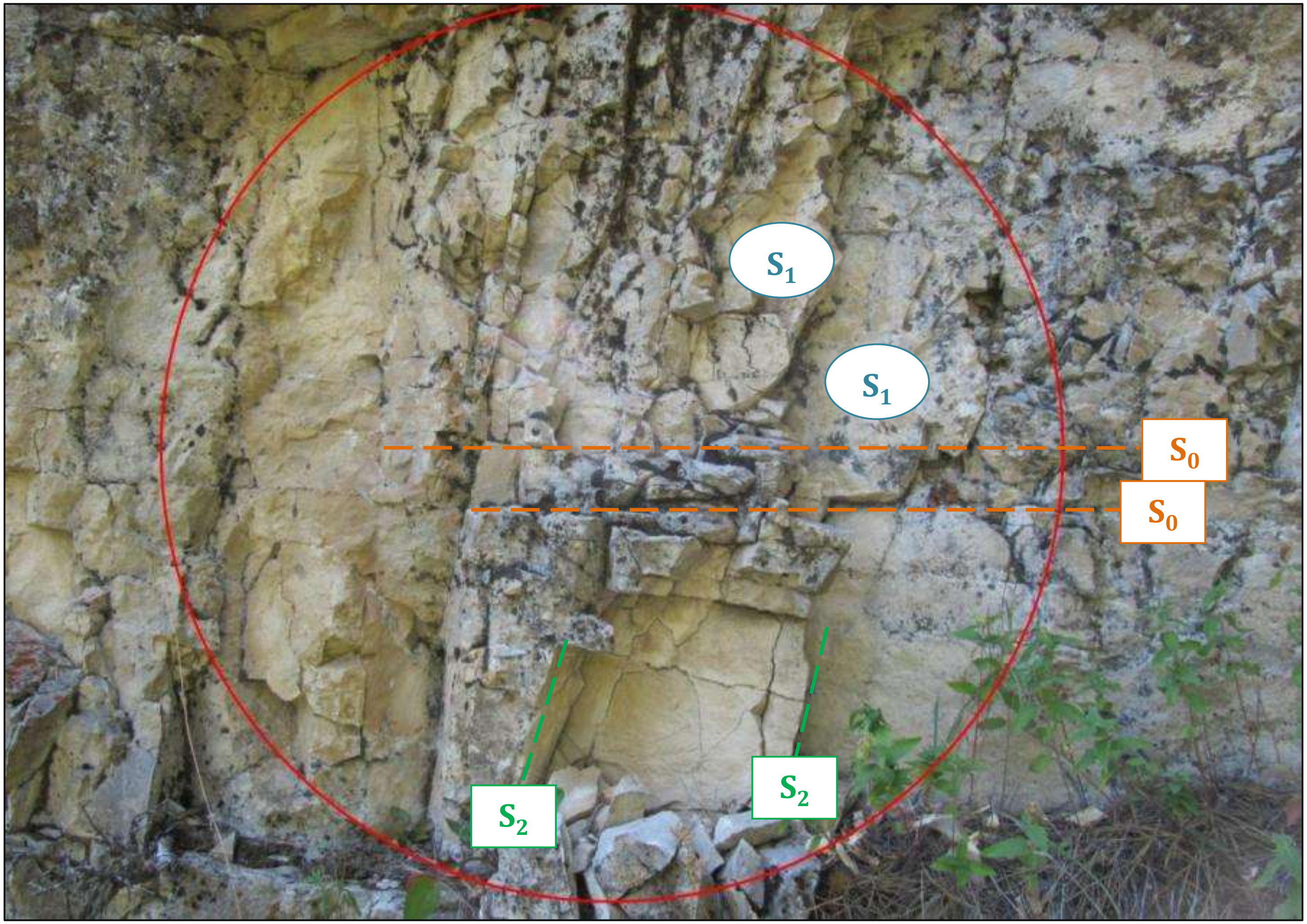
- Outcrops are characterized by:
  - Hydrocarbon bleaching
  - Minimal fracturing of the host rock
  - Iron- and manganese-oxide crusts and veins
  - Undisturbed bedding
- Breccia pipes display:
  - Crushed and rotated clasts
  - Zonation of alteration and mechanical differences

Types of Hydrothermal Breccia Pipes



Relation of Linear Discontinuities to Breccia Pipe Distribution

Field Fracture Station Measurements



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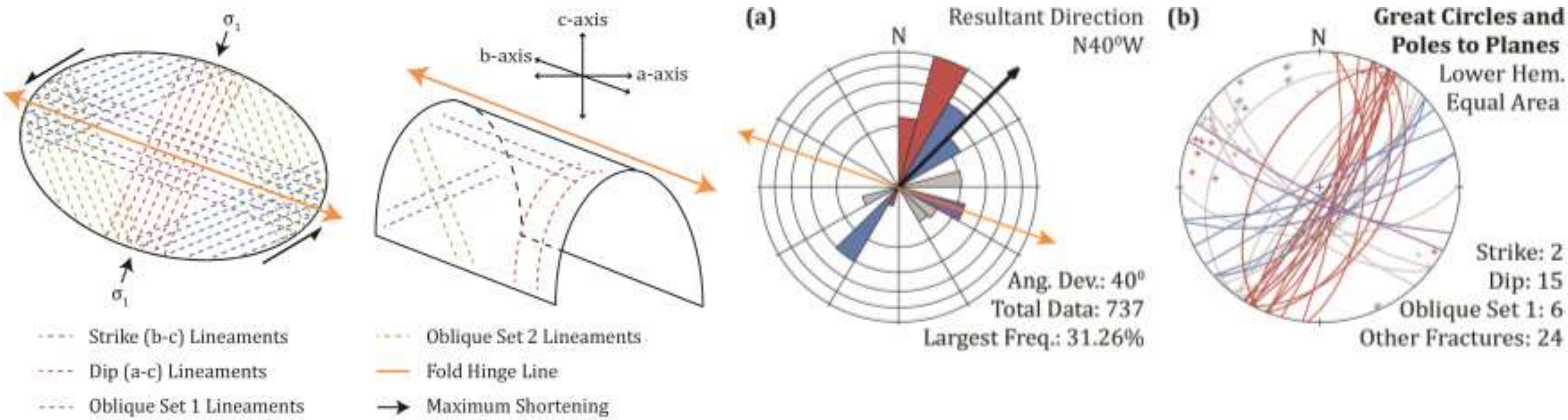
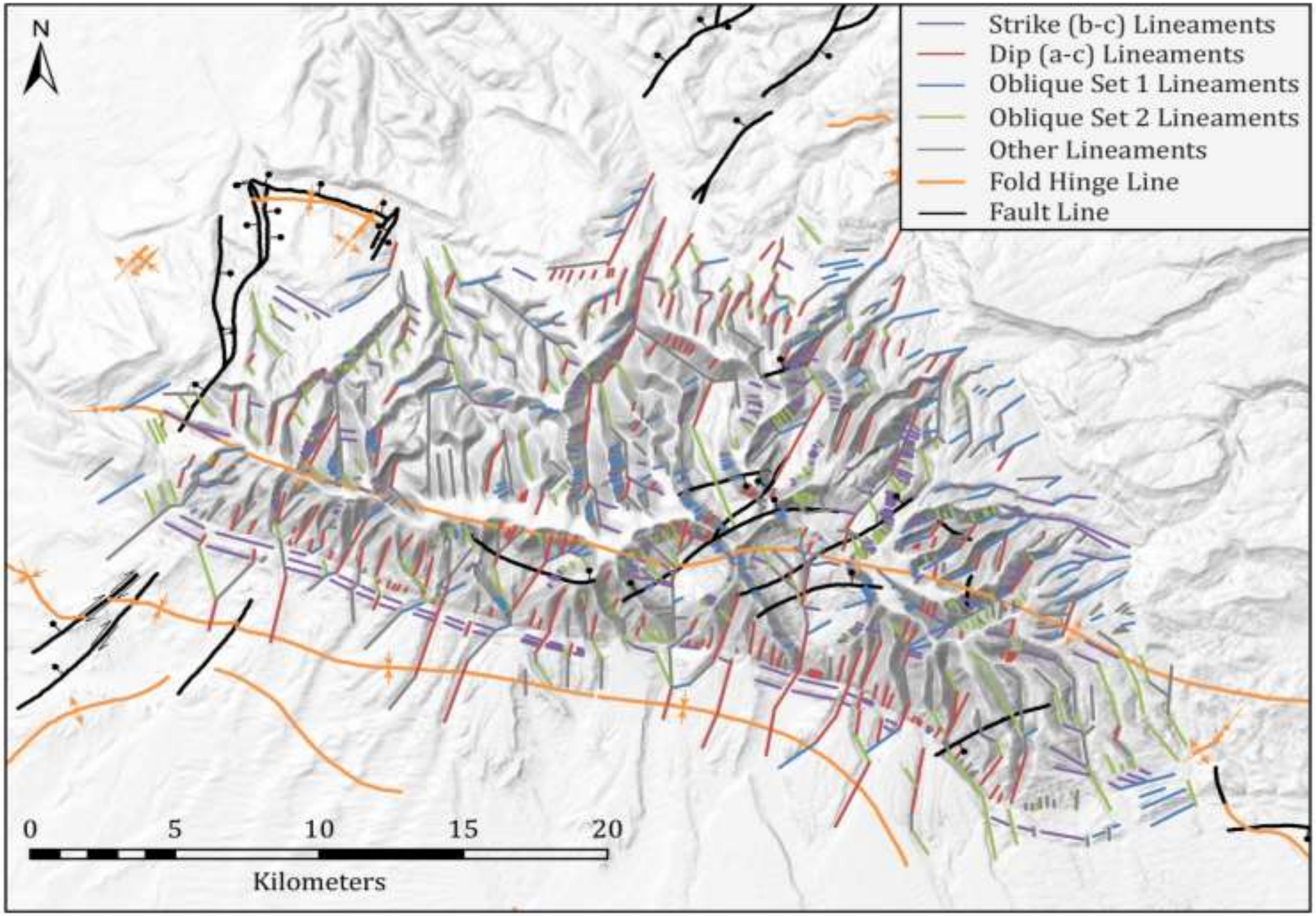


- "Strike" (b-c) lineaments:
  - ±15° of the fold hinge (109)
  - Azimuth of 094 -124
- "Dip" (a-c) lineaments:
  - ±15° orthogonal to the fold hinge (199)
  - Azimuth of 184-214
- "Oblique" lineaments:
  - Set 1 (NE-SW): Azimuth of 049-079
  - Set 2 (NW-SE): Azimuth of 139-169
- "Other" lineaments

- "Strike" (b-c) lineaments:
  - Hinge-parallel Mode I extensional joints
  - Formed in relation to outer-arc extension of a bed during flexural slip
- "Dip" (a-c) lineaments:
  - Hinge-perpendicular Mode I extensional joints
  - Formed in relation to plunge-parallel extension
- "Oblique" lineaments:
  - Shear array of conjugate joints

(modified from Lageson et al., 2012)

Satellite Image Lineament Analysis



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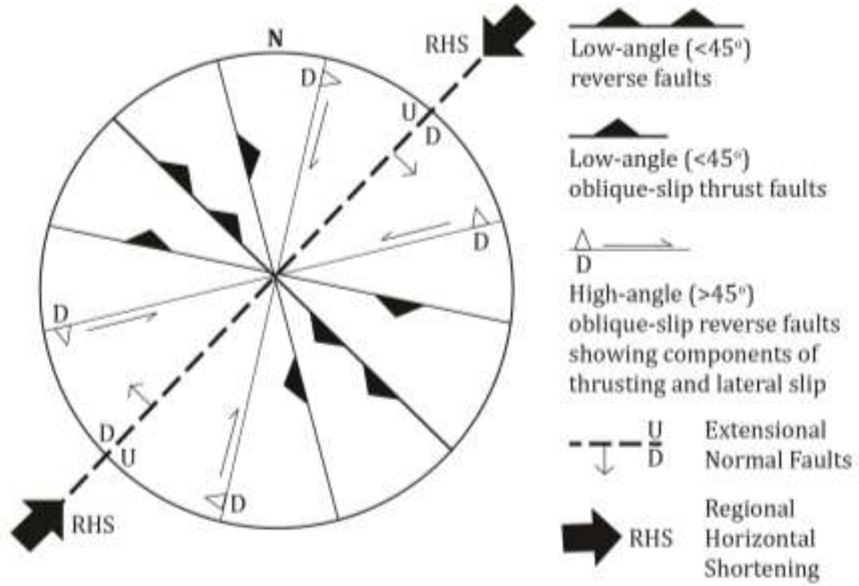
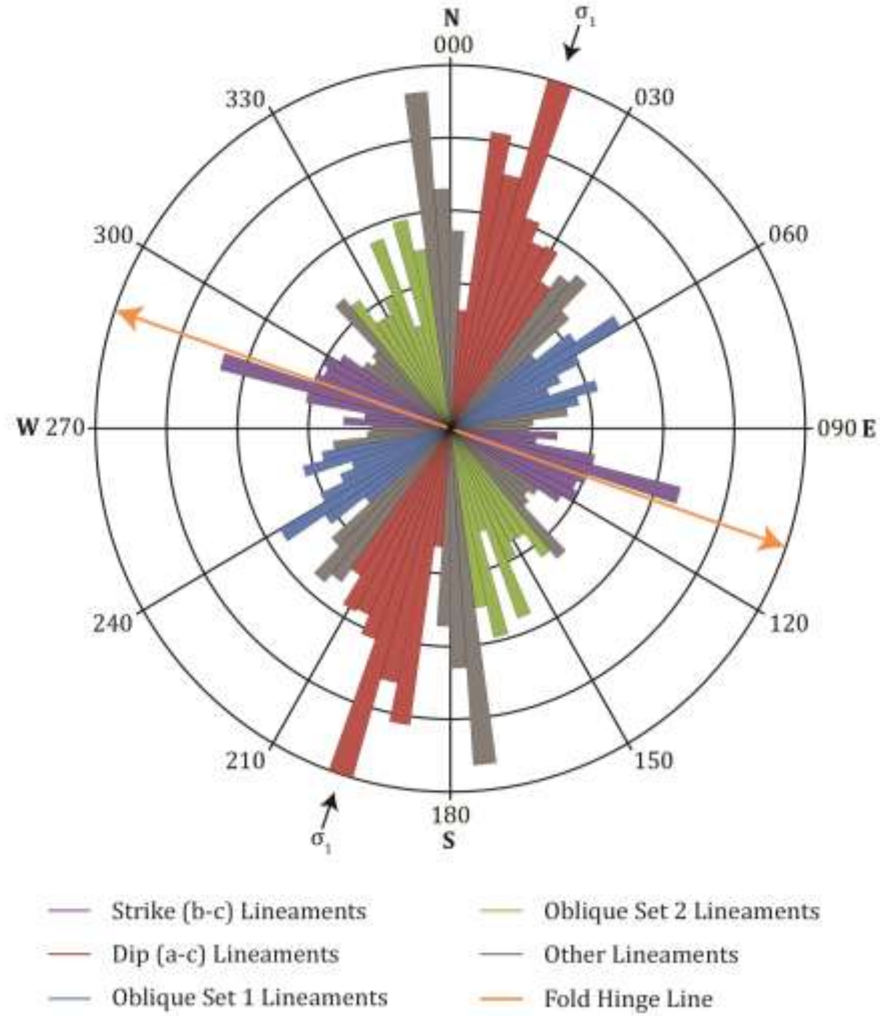


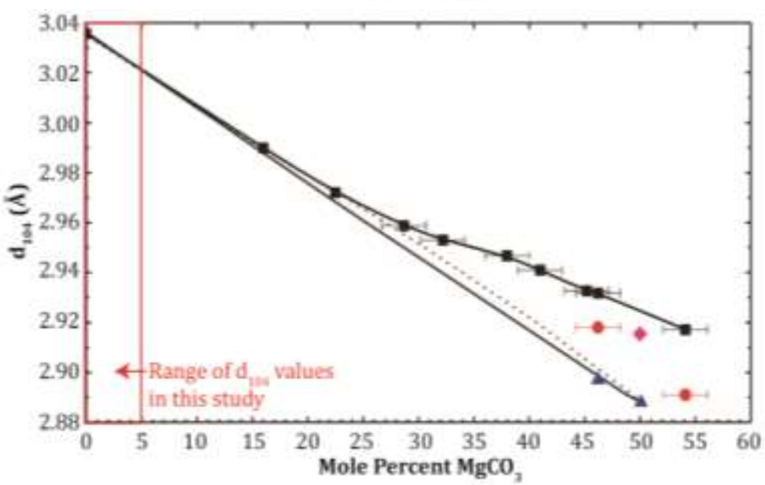
- σ_1 of 018 suggests a possible structural control by pre-existing planes of weakness, possibly by an array of Belt-age faults
- Overprinting of transpressive and rotational zones of shear



- (modified from Brown, 1993)

Effects of Secondary Mineralization on Porosity and Permeability

Chemical Compositions of Breccia Samples

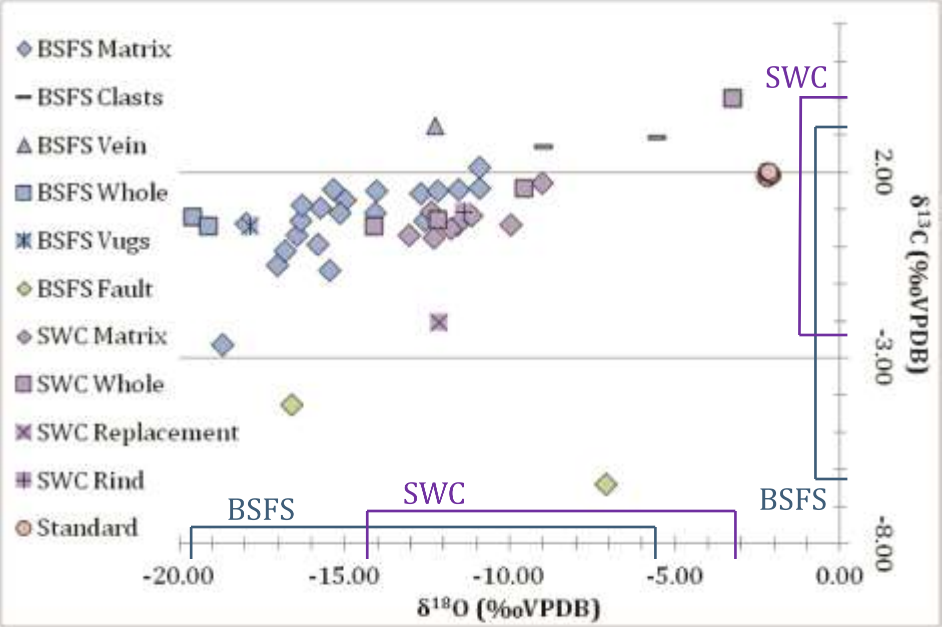


- XRD bulk mineral phase identification
  - Carbonate content determined from published empirical curves relating calcite and dolomite
    - Relates the differences in ionic sizes by the interplanar d-spacing
  - Dolomite reaches a maximum value of 5%
    - Distribution does not appear to be related to the sample type or region
  - Quartz more common in SWC samples
    - Only present in whole rock samples from the BSFS

- (modified from Zhang et al., 2010)

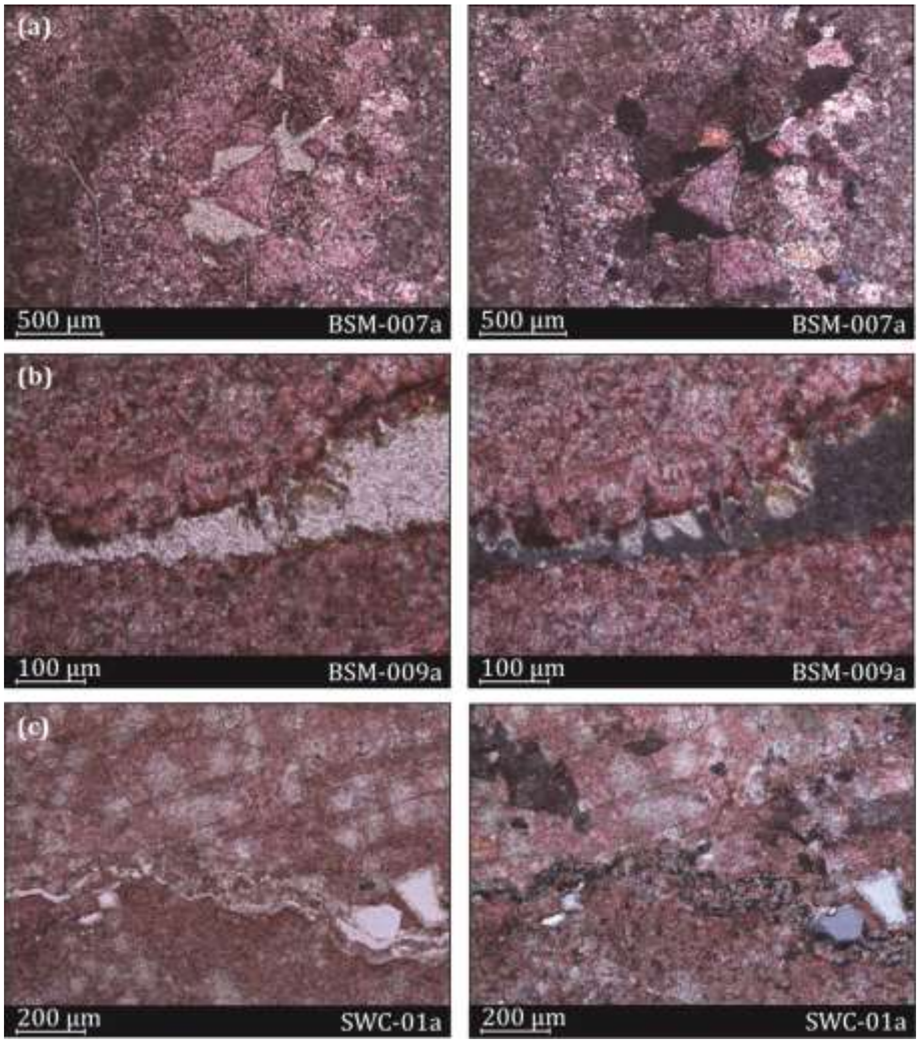
Chemical Compositions of Breccia Samples

- The isotopic signature of marine water is governed by the $\delta^{18}O$, $\delta^{13}C$, and ambient temperature of the fluid
- Strongly depleted $\delta^{18}O$ content:
  - Increased temperatures
  - Presence of non-marine fluids
  - Multiple episodes of hydrothermal fluid migration
  - Later stage cementation events
- Slightly positive average $\delta^{13}C$ content:
  - Marine origin
  - Little biogenic input



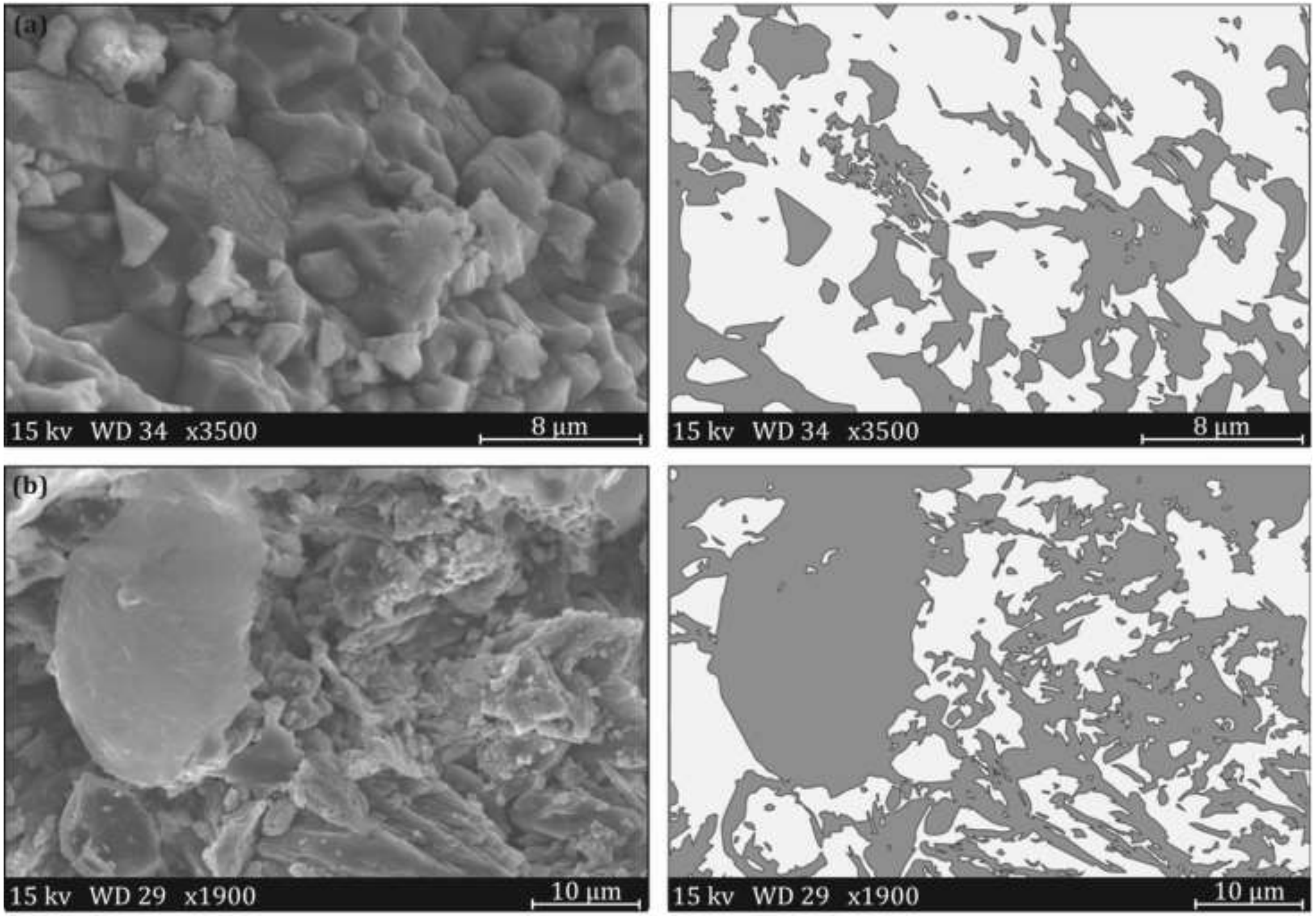
- $\delta^{18}O$ compositions:
  - BSFS: -5.56‰ to -19.62‰
  - SWC: -3.28‰ to -14.12‰
- $\delta^{13}C$ compositions:
  - BSFS: -6.38‰ to 3.27
  - SWC: -2.04‰ to 4.01‰

Secondary Porosity and Permeability



- Paragenetic Sequence:
  - Early compaction, cementation, and suturing of grains
  - Secondary in-situ dissolution and matrix dolomitization concurrent with extensive solution collapse brecciation along sequence boundaries
  - Faulting, fracturing, and hydrothermal brecciation
  - Late-stage tectonic stylolitization
  - Cementation of previously open fractures

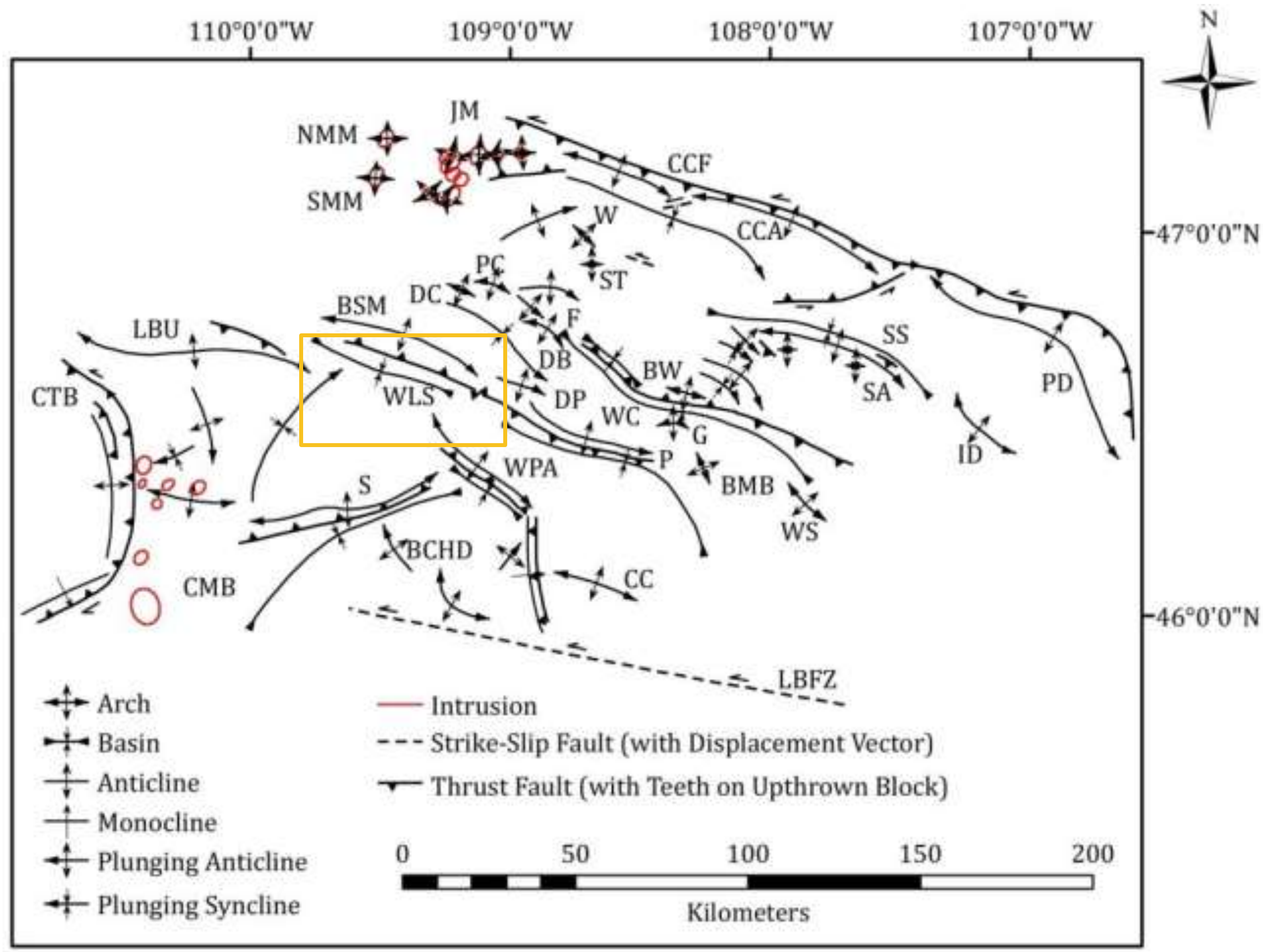
Secondary Porosity and Permeability



Discussion of Research Questions and Hypotheses

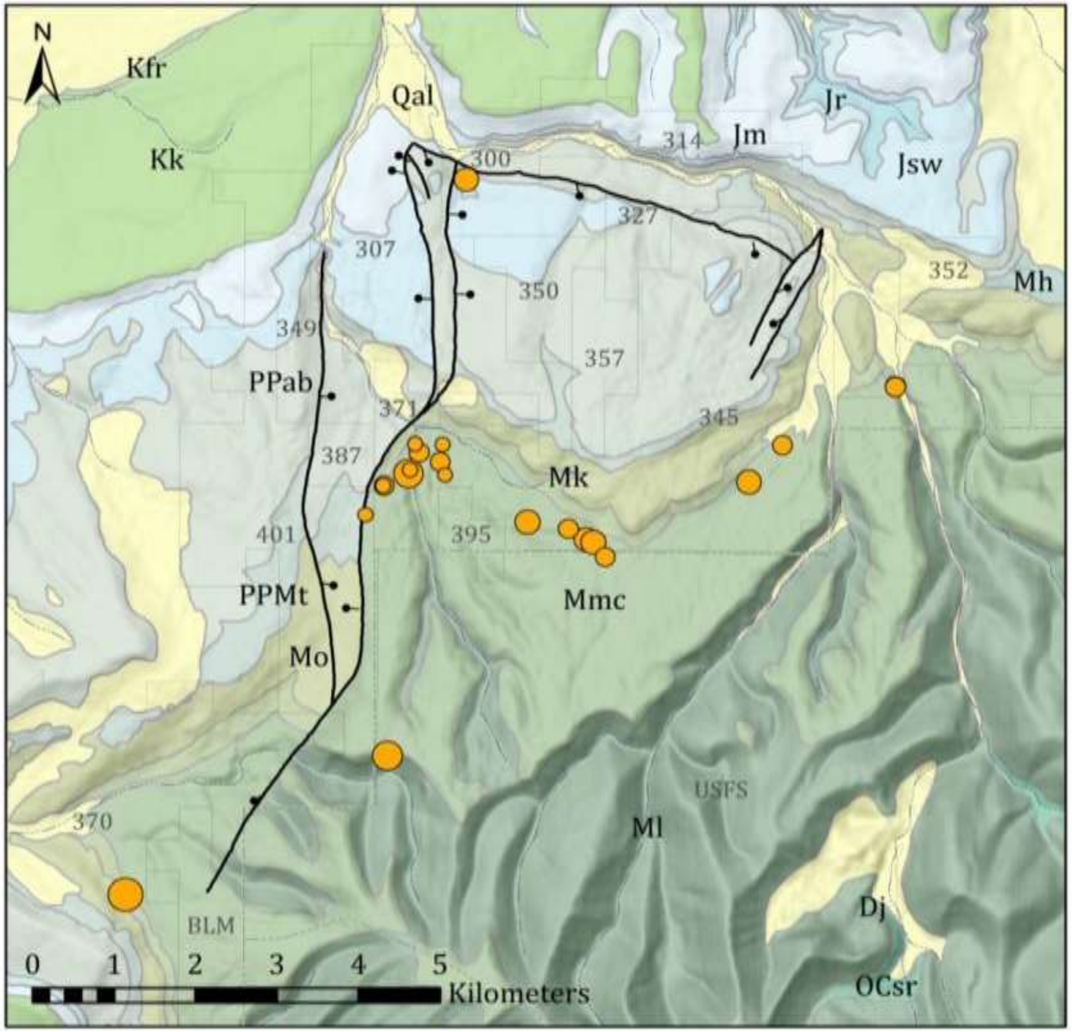
Structure and Lineament Mapping

- Outcrop fracture measurements
  - Dip and a set of oblique joints control breccia pipe emplacement
- Regional lineament mapping
  - Dip joints are most prevalent
  - Strike and oblique joints formed in association with tectonic uplift
  - Evidence of pre-existing structural grain



(modified from Woodward, 1997)

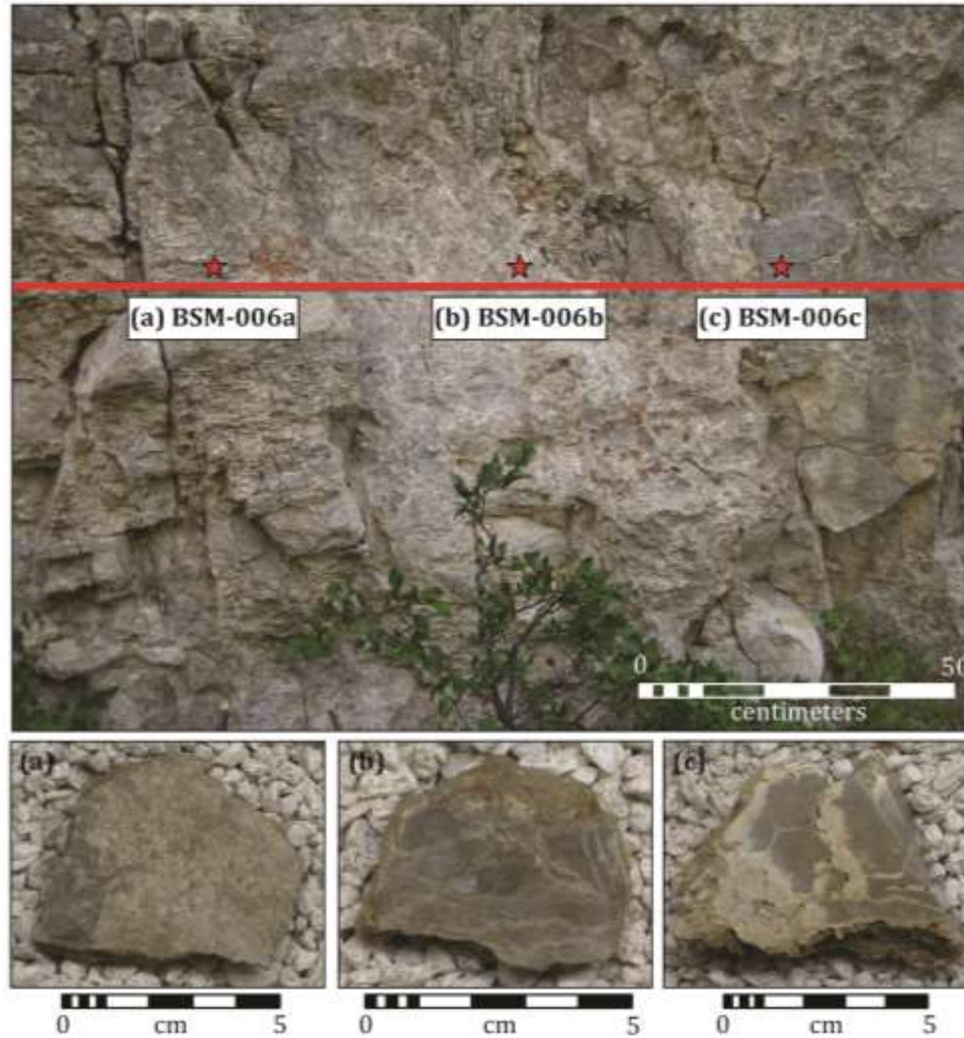
Stratigraphic Distribution of Breccia Pipes



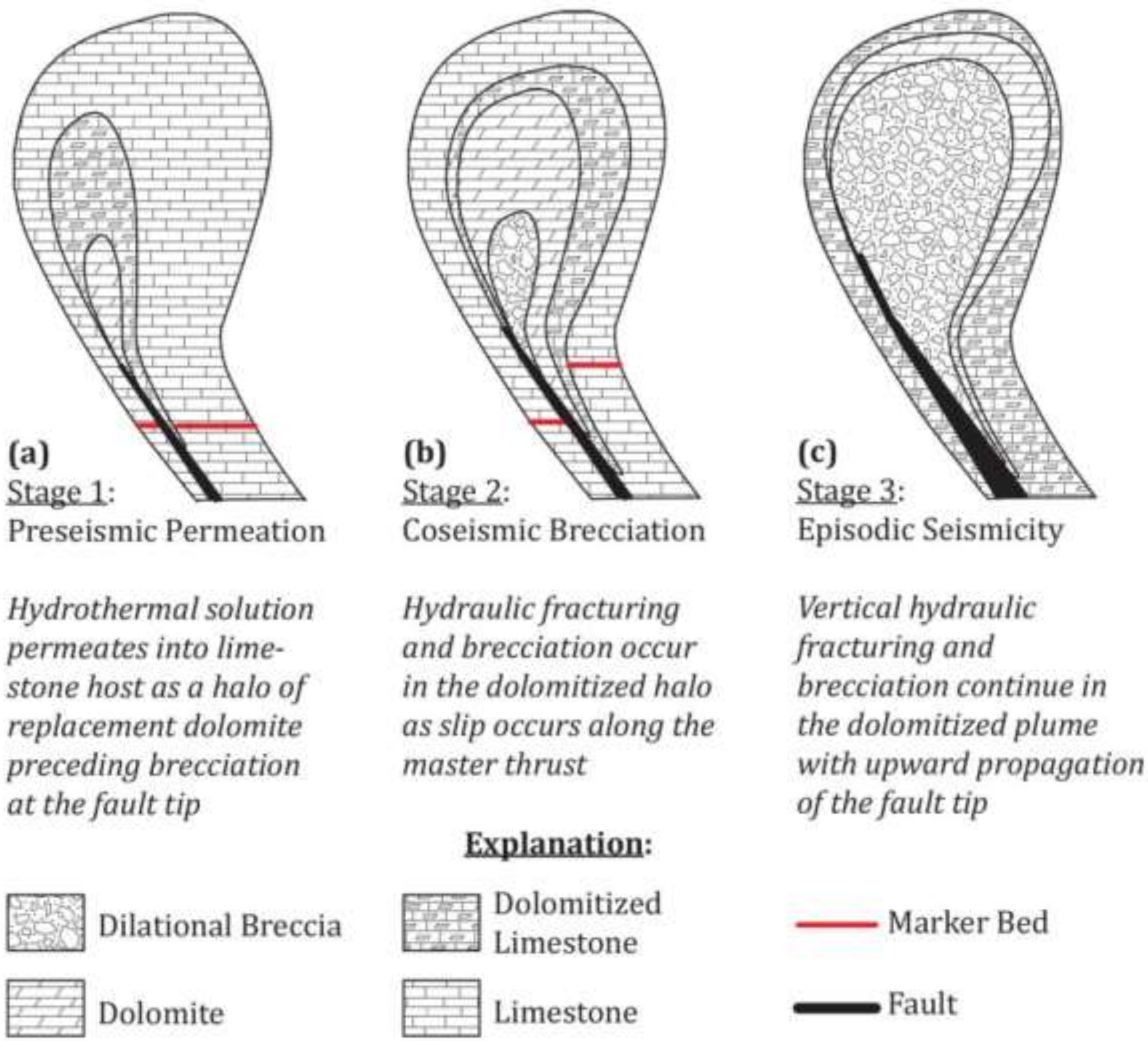
- The proximity to major fault zones did not influence the size and distribution of hydrothermal breccia pipes
- All breccia pipes measured along the BSFS and SWC lie along stratigraphic contacts
- Brecciation preferentially parallels bedding planes along major lithologic contacts
  - Bedding planes are weaknesses along which fluids may favorably migrate
  - The Mission Canyon Limestone acts as a more structurally competent unit within the region

Hydrothermal Diagenesis

- Hydrocarbon bleaching
- Selective dissolution and hydrothermal cementation of the host rock
- Strong depletion of $\delta^{18}O$
- Secondary mineral precipitates
- Increase in area porosity



Fluid Flow Parameters



- Hydrothermal breccia pipes form a combined conduit-barrier system
- Early dissolution and dolomitization likely increased porosity and permeability in the subsurface
- Late-stage precipitates such as calcite, quartz, and iron may have occluded porosity
- Compartmentalization by the formation of horizontal flow barriers along sequence boundaries
- Vertical migration as a concentrated pipe localized along structural features

- (modified from Phillips, 1972; Davies and Smith, 2006)

Acknowledgements

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