A Possible Origin of Hydraulically Significant Bed Parallel Macropore Networks in Siliciclastic Bedrock

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ABSTRACT

Bed parallel macropores (BPMs), commonly referred to as bedding plane fractures, are key pathways for groundwater flow in sedimentary bedrock. Long recognized in carbonate rock, they are now recognized as common in siliciclastic strata. Despite increased recognition of BPMs as integral parts of hydrogeologic systems, their origin remains poorly understood.

Our research combines borehole and outcrop observations in an effort to understand the genesis of BPMs in Lower Paleozoic siliciclastic bedrock of the North American cratonic interior. In Minnesota and Wisconsin, BPMs are common in sandstone, siltstone and shale, to depths exceeding 200 meters. They are densely clustered along discrete (<2m) stratigraphic intervals.

Individual macropores in two dimensions are elongate along bedding, with an irregular "pinch and swell" geometry. They can be traced laterally up to a few meters, and have an aperture height of less than 5 cm. Limited 3-dimensional exposure of BPMs, as well as hydraulic properties measured in boreholes and springs, are indicative of a larger scale geometry that includes connectivity as a network of channels along bedding.

BPMs are commonly associated with interbedded sandstone and mudstone displaying stratabound brittle to ductile deformation features that include breccia, boudin, contortions, flame structures, and mm- to cm-scale pipes, sills and clastic dikes. Aperture geometry of individual BPMs commonly mimics adjacent contorted beds. Deformation included significant lateral redistribution of sediment, typically most pronounced along thin beds of mud that were compacted and squeezed laterally into thick pods.

We propose an origin of BPMs via shallow stratabound redistribution of water and variably lithified sediment during deformation early in burial history. Water expelled by sediment compaction collected in macropore-scale voids connected in an anastomosing network. The macropores may be analogous to water voids produced in laboratory experiments simulating sedimentary deformation. Such voids are regarded as transient in experiments, but the presence of partially lithified and possibly thixotropic sediment, and the apparent confinement of deformation to discrete stratal intervals, may have caused the voids in our ancient examples to persist until further lithification.

BACKGROUND: BED PARALLEL MACROPORES ARE A KEY PART OF THE LOWER PALEOZOIC HYDROGEOLOGIC SYSTEM

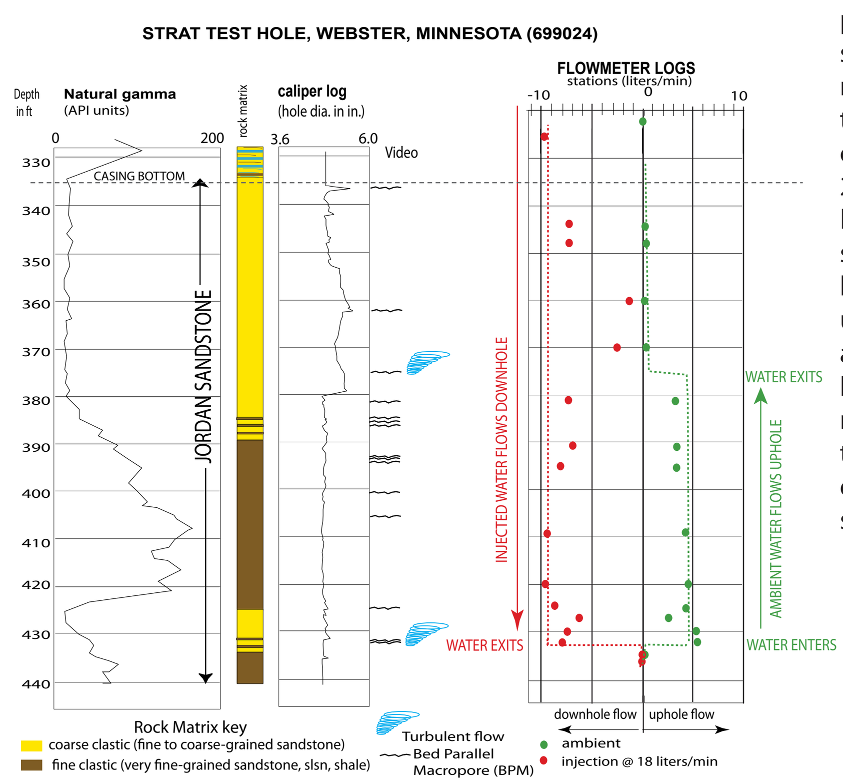
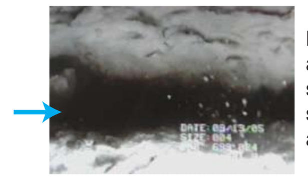


Figure 1.

Bed parallel macropores (BPMs), commonly referred to as bedding plane fractures, are key pathways for groundwater flow in sedimentary bedrock. Long recognized in carbonate rock, they are now recognized as common in siliciclastic strata. This includes their presence in the Lower Paleozoic siliciclastic strata of the central midcontinent (e.g. Swanson et al., 2006; , Runkel et al., 2006).

Figure 1 illustrates typical borehole conditions in Cambrian siliciclastic strata of this region. Borehole video and geophysical logs show ambient flow conditions dominated by relatively strong upflow from a BPM near the bottom of the hole, exiting at a BPM about 55 ft higher in the hole. Water injected at a rate of about 10 liters/minute exits at the BPM near the hole bottom. BPMs dominate hydraulics even in strata that includes material with extremely high matrix permeability, such as the coarse clastic strata of the Jordan Sandstone in this borehole. Based on injection results, Kh of this BPM near hole bottom exceeds 10,000 ft/day.



Bed parallel macropore (blue arrow) in fine- to medium-grained sandstone. Light dots are quartz sand grains held in suspension by ambient turbulent flow

HYROSTRATIGRAPHY OF PALEOZOIC BEDROCK, TWIN-CITIES METRO AREA, MINNESOTA -Fractures and bed parallel macropores dominate flow

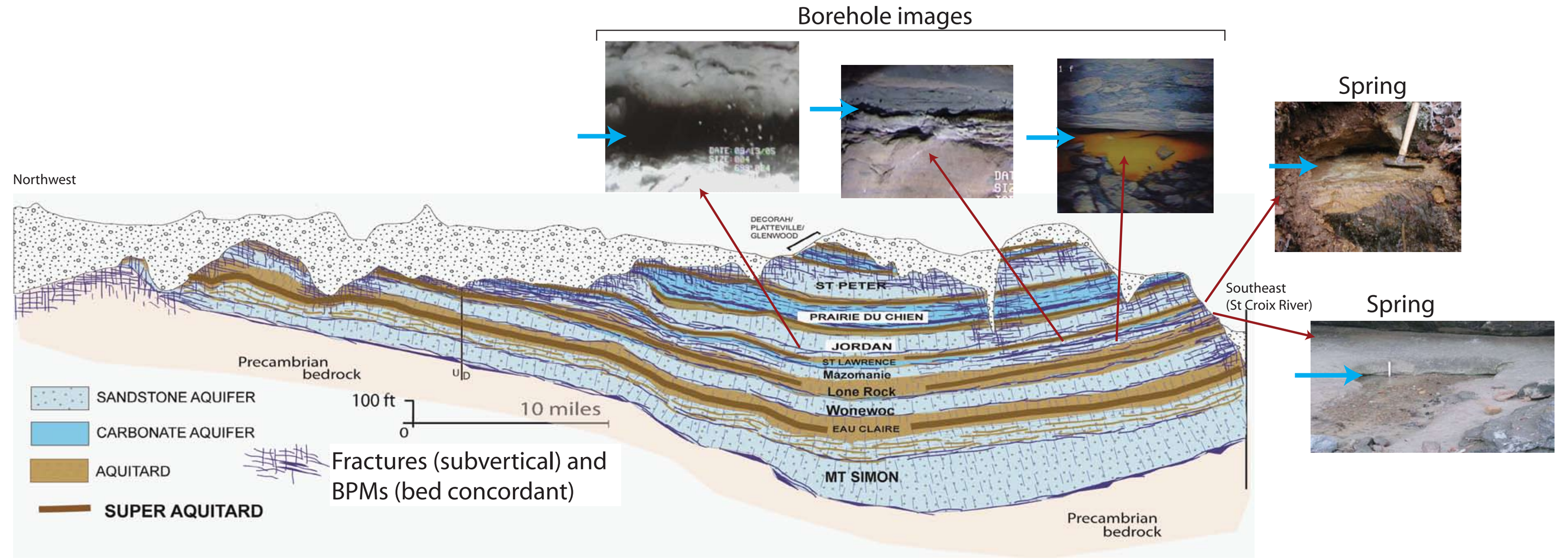
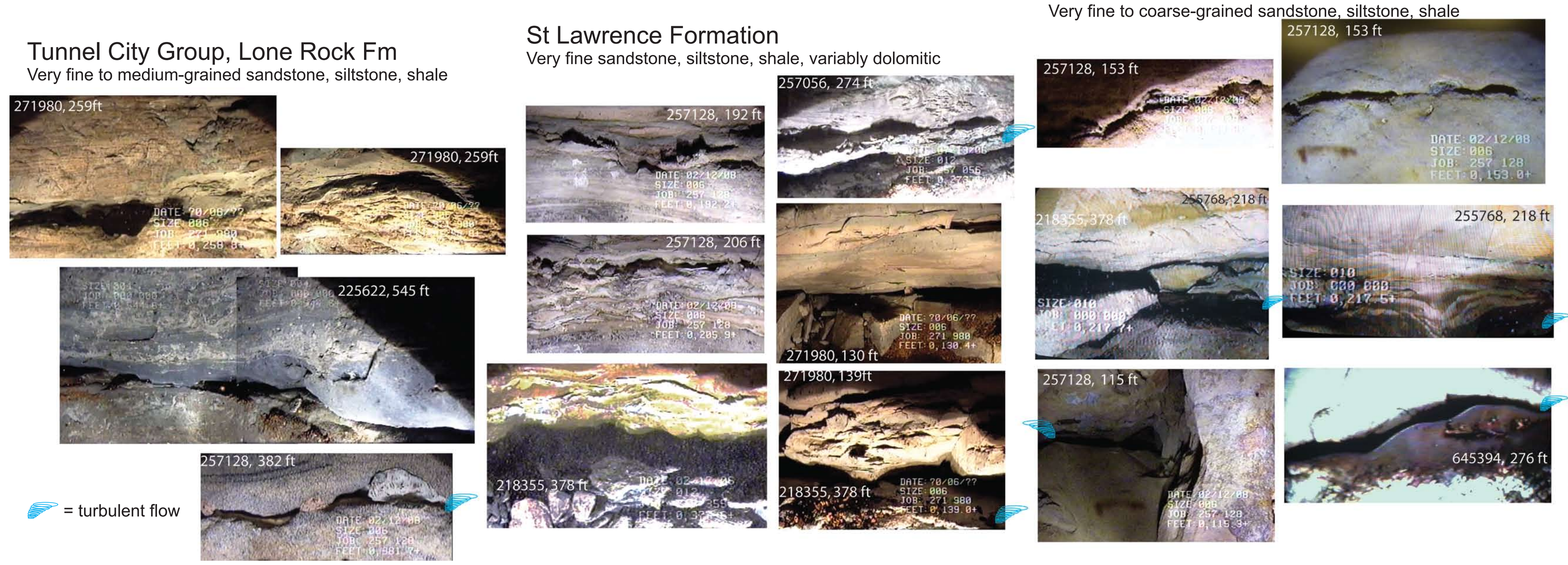


Figure 2. The conditions described in Figure 1, in which BPMs dominate flow, are common in the Lower Paleozoic siliciclastics of this region. Nearly two decades of borehole geophysical and video logging (including flowmeter), field observations at springs, and dye tracing (e.g. Runkel et al., 2006, 2014; Swanson et al., 2006; Green et al., 2012) has demonstrated that BPMs are regionally common, and appear to be particularly abundant in discrete stratigraphic intervals.

BED PARALLEL MACROPORES AND ASSOCIATED SEDIMENT DEFORMATION IN BOREHOLES AND CORE

Borehole video images, southeast Minnesota



Core, St Paul, Minnesota

St Lawrence Formation

KEY BOREHOLE AND CORE OBSERVATIONS

Macropores appear inconsistent with origin as "unloading fractures":
- Pores have irregular, convoluted margins
- Individual pores are commonly limited laterally to only several cm in extent

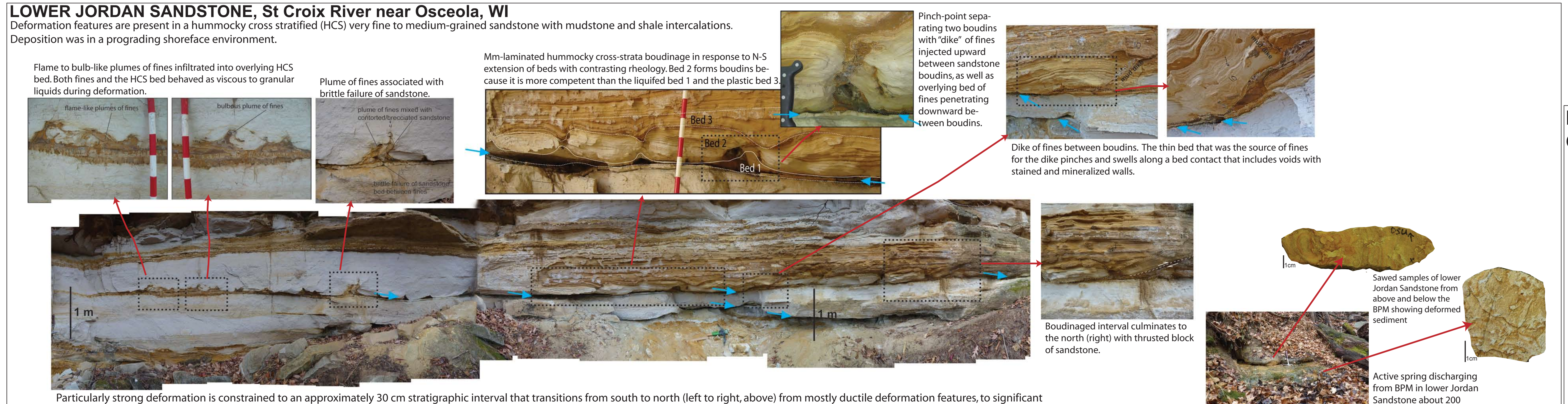
Macropores inconsistent with origin as solution features:
- Pores are limited in aperture height to a few cm (in contrast to ranging upward to far greater sizes in karst, e.g.)
- Pores are not preferentially selective to carbonate-rich sediment.
- No evidence for enhanced solution of siliciclastic sediment along aperture walls

Macropores appear to correspond to presence of early substratal deformation
- Pores are associated with deformed sediment that includes brittle and ductile features
- Pores commonly have aperture shapes mimicking deformed wall strata

OUTCROPS WITH BED PARALLEL MACROPORES ASSOCIATED WITH INTERVALS OF DEFORMED SEDIMENT

LOWER JORDAN SANDSTONE, St Croix River near Osceola, WI

Deformation features are present in a hummocky cross stratified (HCS) very fine to medium-grained sandstone with mudstone and shale intercalations. Deposition was in a prograding shoreface environment.



Flame to bulb-like plumes of fines infiltrated into overlying HCS bed. Both fines and the HCS bed behaved as viscous to granular liquids during deformation.

Plume of fines associated with brittle failure of sandstone.

Mm-laminated hummocky cross-strata boudinage in response to N-S extension of beds with contrasting rheology. Bed 2 forms boudins because it is more competent than the liquifed bed 1 and the plastic bed 3.

Pinch-point separating two boudins with "dike" of fines injected upward between sandstone boudins, as well as overlying bed of fines penetrating downward between boudins.

Dike of fines between boudins. The thin bed that was the source of fines for the dike pinches and swells along a bed contact that includes voids with stained and mineralized walls.

Boudinaged interval culminates to the north (right) with thrusted block of sandstone.

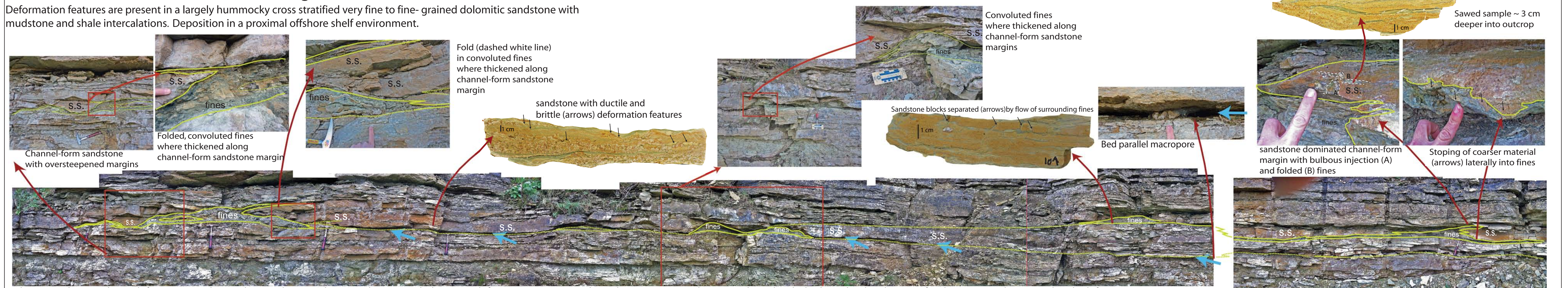
Sawed samples of lower Jordan Sandstone from above and below the BPM showing deformed sediment

Active spring discharging from BPM in lower Jordan Sandstone about 200 meters from the outcrop shown at left

Particularly strong deformation is constrained to an approximately 30 cm stratigraphic interval that transitions from south to north (left to right, above) from mostly ductile deformation features, to significant brittle as well as ductile. Blue arrows indicate stratigraphic position of lenticular BPMs. ("fines" refers to variable proportions of clay to very fine sand. "S.S." refers to material dominated by very fine to fine-grained sand)

ST LAWRENCE FORMATION, Red Wing, Minnesota

Deformation features are present in a largely hummocky cross stratified very fine to fine- grained dolomitic sandstone with mudstone and shale intercalations. Deposition in a proximal offshore shelf environment.



Channel-form sandstone with oversteepened margins

Folded, convoluted fines where thickened along channel-form sandstone margin

Fold (dashed white line) in convoluted fines where thickened along channel-form sandstone margin

sandstone with ductile and brittle (arrows) deformation features

Convoluted fines where thickened along channel-form sandstone margins

Bed parallel macropore

Sawed sample ~ 3 cm deeper into outcrop

sandstone dominated channel-form margin with bulbous injection (A) and folded (B) fines

Stoping of coarser material (arrows) laterally into fines

This example is similar to deformation in the Jordan Sandstone (above) in that particularly strong deformation is present along discrete stratigraphic intervals, and includes lateral redistribution of sediment. Here, however, ductile deformation is dominant, and the largest scale, visible redistribution of sediment is in the form of thin layers of mud (and intercalated very fine sand) squeezed laterally into thick pods alongside channel-form sandstone bodies.

Blue arrows indicate stratigraphic position of lenticular BPMs. ("fines" refers to variable proportions of clay to very fine sand. "S.S." refers to material dominated by very fine to fine-grained sand)

KEY OUTCROP OBSERVATIONS

Deformation includes features indicative of both brittle and ductile behavior (variable lithification/cohesion)

Particularly strong deformation along discrete, stratabound intervals

Significant lateral redistribution of materials

Small-scale deformation features similar to those associated with macropores in boreholes and core

MACROPORES IN LAB EXPERIMENTS

Sediment deformation produced in laboratory experiments commonly includes formation of "water voids". Such voids, in cohesionless material used in experiments, are transient, typically infilling with sediment after rupture of the void ceiling.

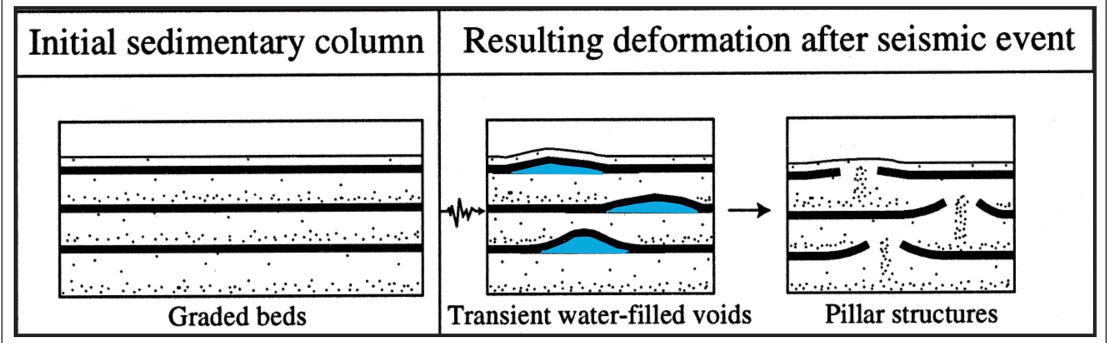
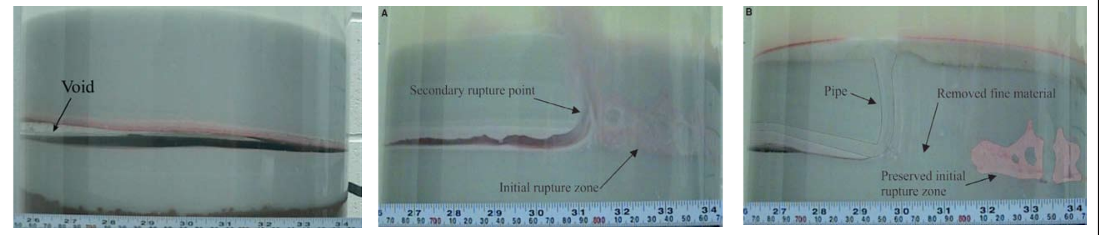
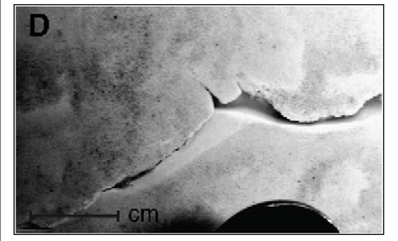


Illustration of sediment deformation structures formed by fluidization/liquifaction triggered by a shaking table simulating a seismic event. Water-filled voids formed beneath lower permeability beds (dark lines) prior to rupture. From Moretti and others, (1998).



Video stills showing structural evolution of features during fluidization of bedded, cohesionless sediment. Water-filled voids formed beneath fine sediment (pink) prior to rupture and persist for a short time (10's seconds) after rupture. From Ross and others (2011).



Macropore formed during piping experiment to simulate from fluid venting through unconsolidated, but cohesive sediment. From Morz and others, (2007)

A POSSIBLE ORIGIN OF BPMS

We suggest that bed parallel macropores may form via shallow stratabound redistribution of water and variably lithified sediment during deformation early in burial history. Water expelled by sediment compaction collected in macopore-scale voids, perhaps analogous to water voids produced in laboratory experiments simulating sedimentary deformation. The presence of partially lithified and possibly thixotropic sediment, and the apparent confinement of deformation to discrete stratal intervals, may have cause the voids in our ancient examples to persist until further lithification.

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