Persistence under pressure: the textural record of composite clay aggregate grains in Upper Cretaceous strata of the Western Canada Foreland Basin

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Summary
A systematic study of the petrology of Upper Cretaceous Colorado Group mudrocks across a range of coeval depositional environments, from lacustrine through nearshore to distal shelf, reveals a mutually exclusive distribution of different forms of clay aggregate grains. Detrital mudrock lithoclasts, identified on the basis of high backscatter coefficient and brittle deformation, are distinct from intraclastic aggregates which have openwork fabric, low backscatter coefficient and show evidence of varying degrees of ductile deformation. Lithoclasts are confined to coastal plain freshwater settings where intraclastic aggregates have not been observed. Conversely, lithoclasts are rare in offshore mudrocks where intraclastic aggregates are common. This suggests that the two grain types do not share a common origin, and that intraclasts may have been locally derived by erosion and resedimentation of syndepositionally consolidated shelf mud.

Introduction
Sedimentological analysis of siliciclastic mudrock has undergone a renaissance over the past decade. In large part, this is due to the realignment of the North American upstream oil and gas industry to pursue self-sourcing “shale gas” and “tight oil” plays. Prediction of storage and flow capacity, as well as geomechanical properties of organic-rich mudrocks necessitated a re-evaluation of many of the enduring paradigms related to these rocks. We have learned that the superficial monotony of mudrock disguises an underlying spectrum of heterogenous microfabrics and diverse grain types. These properties, in turn, determine essential source and reservoir properties (e.g.: organic matter sequestration, porosity preservation, matrix permeability, and elastic moduli).
Ultimately, the sedimentary fabric of mudrock is influenced by the response of particulate matter (suspended sediment and bedload) to bottom currents at the site of deposition. It is imperative, therefore, to develop a complete appreciation of the petrology of mudrocks if one is to predict the distribution of reservoir characteristics based on a sedimentological model. Petrographic studies of the Upper Cretaceous Colorado Group mudrocks of the Western Canada Foreland Basin (WCFB) have documented abundant silt-sized aggregate grains as one of the major components of many of the alloformations. The generation of these grains is the subject of ongoing debate, with opinions divided between an origin as reworked grains derived from deeply-buried and compacted mudrock (Schieber 2015, 2016; Schieber and Pedersen 2016) and locally-formed, and very shallowly-buried water-rich intraclastic aggregates (Plint et al. 2012; Plint and Cheadle 2015). This presentation offers visual evidence of both lithic and intraclast aggregate grains from a range of depositional settings and ages and offers a hypothesis to explain their relative distribution in the WCFB.

**Theory and/or Method**

The traditional model of mudrock deposition via settling of clay and fine silt from suspension in a relatively still water column has been challenged over the past decade. Experimental data (Schieber et al. 2007; Nishida et al. 2013) and observations from modern and ancient sediments (Macquaker et al. 2010; Plint et al. 2012; Plint 2014) demonstrate that mud is commonly transported as bedload of various types of aggregate grains by relatively energetic bottom currents (i.e.: velocities sufficient to transport fine-grained sand).

Silt-sized intraclastic aggregate (IA) grains, consisting of closely-packed clay flocs in edge-face and, more commonly, face-face packing, present a conundrum. The IA grains are typically rounded and relatively equant, and the component clay flakes are commonly randomly oriented. This suggests that the grains have not undergone significant compaction despite maximum burial depths in excess of 4000 metres (Cheadle 2014). Schieber (2015, 2016) argues that these grains are “shale lithics”, derived from erosion of previously consolidated mudrocks exposed in the hinterland or coastal plain. Plint (2014), on the contrary, contends that IA grains are the product of seabed erosion and transport of shelf mud that had undergone early consolidation. Schieber’s hypothesis implies that fluvial and nearshore mudrocks associated with forced regression shorelines and paleovalleys are enriched in lithoclasts, and that this provenance should be evident in a continuum of grain composition and fabric in nearshore to distal offshore shelf mudrocks.

The hypothesis is being tested using mudrock samples that have been collected from core and outcrop locations in various Colorado Group alloformations as part of ongoing research into the tectonstratigraphic evolution of the basin. This presentation is illustrated with samples from the Belle Fourche (Cenomanian), Dunvegan (Cenomanian), Second White Specks (Turonian), Kaskapau (Turonian) and Puskwaskau (Santonian) alloformations. Sample sites represent a range of depositional settings from proximal fluvial-lacustrine to distal offshore shelf with varied provenance due to punctuated tectonic loading of the orogenic margin (Plint et al. 2012).

Outcrop sampling and polished thin section preparation followed the technique described by Plint (2014). Core samples were prepared as polished thin sections (normal and parallel to bedding), or fresh broken chips mounted on scanning electron microscopy (SEM) stubs for Ga-ion sputter milling on a LEO (Zeiss) 1540XB FIB/SEM at the Western Nanofabrication Facility. The polished thin sections were examined using both optical petrographic microscopy and, subsequently, SEM. SEM images were captured as companion sets in secondary electron (SE) and backscatter electron (BSE) modes; the BSE mode is particularly effective for resolving clay floc fabrics and elemental differences related to cementation.

**Observations**

To date, petrographic analyses have confirmed the common occurrence of previously-consolidated mudrock lithoclasts in lacustrine deposits of the Dunvegan and Kaskapau alloformations. The lithoclast grains are silt to very fine sand-sized, varied in textural maturity, and composed of poorly-sorted mixtures of
randomly-oriented clay flocs, quartz and feldspar silt and pore-filling calcite and siderite cement. The cement gives the grains a distinctive, high backscatter coefficient. Organic matter, with the exception of rare phytoclasts, is absent from lithoclasts. Notably, the mudrock lithoclasts are the only form of clay aggregate grain evident in the terrestrial mudrocks; the matrix is dominated by individual clay flakes and small, face-face clay domains.

Conversely, the same form of cemented mudrock lithoclast rarely occurs in nearshore shelf mudrock deposits and, to date, has not been observed in distal shelf mudrocks. Clay aggregate grains are common, however, but have characteristics that distinguish them from the terrestrial grains. Backscatter coefficients are generally low (similar to quartz), an openwork fabric preserves intraparticle porosity and disseminated amorphous organic matter is relatively common as a grain component. A range of compactional effects are evident in these grains, from minor to severe ductile strain with rotation of the internal clay fabric.

Conclusions

Petrographic characteristics of clay aggregate grains in mudstones from coeval terrestrial and marine settings provide evidence of two distinct and mutually exclusive classes of grain. The absence of carbonate-cemented mudrock lithoclasts from open shelf mudrocks suggests these grains were not transported beyond the nearshore zone, but this hypothesis requires further study. The clay intraclastic aggregate grains that are a common component of open shelf mudrocks do not occur in the coeval terrestrial deposits examined to date, indicating that their origin lies elsewhere. Although it is possible that the shelf aggregate grains may have been eroded from units other than the coeval lacustrine deposits, no such source area has been identified. Furthermore, the preservation of intrinsic porosity and amorphous organic matter points to a different early diagenetic history than the cemented lithoclasts, suggesting that the two grain types do not share a common origin.

While the origin of the putative intraclastic aggregates continues to present a conundrum, particularly with respect to the early consolidation mechanism that allowed some of the grains to resist compactional strain, a renewed emphasis on conducting petrographic analyses of mudrocks promises to provide the textual evidence to resolve the question. It is premature to reject any plausible hypotheses regarding the origin of the fundamental components of mudrocks, pending systematic studies of the lateral distribution of grain types in coeval strata spanning source to sink.

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References


