Mud transport processes on a Cretaceous prodelta

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GeoConvention 2012:Vision

Summary

Various processes can transport mud offshore from river mouths. In shallow water, storm wave-re-suspension and geostrophic flows are important. Where a significant slope exists, river flood-generated hyperpycnal flows can operate; wave-enhanced sediment gravity flows may transport mud over lower slopes. To test the relevance of these processes to an ancient delta succession, large thin sections of prodelta mudstone were made from mudstones that form allomember G of the Cretaceous Dunvegan Formation. Four mud facies were recognized: wave-rippled or massive clean silt, and silt-streaked mud record turbulent wave and current activity beneath a wave-enhanced sediment gravity flow. Upward gradation into structureless silty mud and clay-rich mud is interpreted to record deposition from post-storm settling of fluid mud. Upward-coarsening successions from mud to silt-streaked mud and silt may record waxing hyperpycnal flows linked to rising river floods. Micro-ripples in the more distal muds indicate paleoflow down the prodelta to the SE. Very fine sand beds in more proximal facies indicate winds from the NE and geostrophic and combined flows to the S and SE. A combination of storm-driven geostrophic flows and gravity-influenced density flows seem to have operated in conjunction to move mud up to ~120 km from the delta front.

Introduction

It has been pointed out (e.g. Dalrymple & Cummings, 2005) that clay particles delivered by rivers to the ocean are rapidly packaged (by various physical and biological processes) into silt-sized aggregates that are then deposited within about 50 km of shore because mud plumes are deflected shore-parallel by Coriolis' effect. Notwithstanding the truth of this observation, it is clear from stratigraphic studies,- in this case the Cretaceous rocks of the Western Canada Foreland Basin,- that muddy sediment was transported seaward from river mouths for well over 500 km. The question is: How did the mud move?

Cretaceous shelf seas in Canada were mostly shallow and storm-influenced, and hence it is likely that storm-generated combined flows would have played an important role in re-suspending and transporting mud, both along and obliquely across-shelf. This mechanism was inferred by Varban & Plint (2008) to explain the extensive mud blanket represented by the Cenomanian-Turonian Kaskapau Formation in northern Alberta and BC. Provided that the sea floor remained above storm wave base, (i.e. sedimentation rate > accommodation rate), mud would have been gradually driven offshore by storms. Storm-wave suspension of mud has also been recognized as a mechanism to generate dense, near-bed suspensions that respond to gravity and flow down the local bathymetric slope (e.g. Traykovski et al. 2000; Friedrichs and Scully, 2007). Such 'wave-enhanced sediment gravity flows' deposit mud beds with a distinctive tripartite composition, comprising homogeneous or rippled, parallel-laminated and bioturbated layers (Macquaker et al. 2010). A third transport process likely to have been important in a deltaic setting is that of hyperpycnal flow, whereby dense suspensions of flood-borne sediment emerge from river mouths and sink beneath seawater to flow down the prodelta slope. Bhattacharya & MacEachern (2009), recently interpreted such 'hyperpycnites' from the prodelta region of the Upper Cretaceous Dunvegan Formation of Alberta.

Although wave-enhanced sediment gravity flows and hyperpycnal river outflows are readily recognized on modern shelves, and the direction of flow can be measured by instruments, it is difficult to prove flow direction from ancient muddy sediments. The study by Bhattacharya and MacEachern (2009) relied on un-oriented core from the Dunvegan Formation, and the ancient examples of wave-enhanced sediment gravity flows described by Macquaker et al. (2010) also lacked paleogeographic orientation.

In order to determine both the mechanism and direction of transport of mud in ancient rocks, it is necessary to study a unit for which the stratigraphy and paleogeography are well-known, and from which oriented samples can be obtained at outcrop. The Cenomanian Dunvegan Formation offers such an opportunity to combine a detailed allostratigraphic framework that extends to outcrop, with paleogeographic maps of the delta-plain and prodelta area, and isopach maps that reveal the strike of the prodelta slope, and the seaward lap-out limit of mud (Plint, 2000; 2003).

Rationale and Method

Allomember G of the Dunvegan Formation was selected for study. A well-exposed section on the Smoky River near Grande Cache grades up over 45 m from distal prodelta mudstone into heterolithic thin-bedded very fine sandstone and mudstone. This section has been correlated in detail to well logs located in the un-deformed part of the basin to the East (Plint, 2000). Isopach maps based on subsurface data showed that the strike of the prodelta was NE-SW, and there is no evidence that this trend does not continue into the outcrop belt. Therefore, the paleo dip-direction of the prodelta surface was to the SE. Using well-log cross-sections, individual parasequences could be traced up-dip to the contemporaneous delta-front sandstone, and hence distance from shore could be estimated for each part of the succession, which ranged from 10 to 120 km from shore.

In the upper ~ 20 m of the section, cm-scale sandstone beds are common and paleoflow data were measured for all well-exposed and accessible rippled sandstone beds. Mudstone in the Smoky River outcrop section is heavily weathered and frost-shattered, and it was necessary to excavate 50-70 cm into the surface to access less damaged material. Representative samples were taken about every 5 m throughout the 45 m studied section. Steel electrical junction boxes were hammered into a cleaned face to obtain a suite of 11 block samples that were oriented and bound with tape after removal. In the laboratory, samples were thoroughly dried, after which the open face of each box was flooded with liquid resin. The containing steel box was gradually sawn off with a diamond saw running dry to prevent expansion of clays. As each face was revealed, it was impregnated with resin to eventually yield a solid billet of stabilized mud about 5 x 5 x 8 cm. Each billet was sawn into slabs in the N-S, E-W and NW-SE planes from which over-size thin-sections were prepared. Each thin section was scanned at 800 dpi, using back-lighting, and the resulting image was printed in colour on 11 x 17' paper to produce a greatly enlarged 'map' of the thin section. For each thin section, a stratigraphic section was drafted using the enlarged prints as a basis, supplemented by binocular microscope observation of the thin section to obtain the fine details of mud stratification. A facies scheme for mud was developed, and various distinctive facies successions were recognized. For each thin section, bed thickness was measured, as was the relative proportion of each mud facies. The only real difference between this analysis and standard outcrop logging was that of scale: most mud beds were 1-5 mm thick and 'logging' required a microscope!

Results

<u>Facies</u>: Four distinct mud facies were recognized.

1. Structureless clay-rich mudstone is the least abundant facies, and appears to consist of 10-20µ clay aggregates. Beds range from 0.2 to 3.5 mm thick and the proportion of the facies diminishes upward from ~20 to ~20% up section. The lack of stratification suggests deposition from settling of a dense fluid mud.

2. Structureless mud with dispersed silt forms beds typically ~2 mm thick, ranging up to 5 mm. Clay minerals also appear to be packaged in aggregate grains 10-20µ and siliceous silt grains are dispersed through the matrix of clay aggregates. The proportion of this facies diminishes upward from ~60 to ~15%. The dispersal of silt grains amongst a matrix of clay aggregates and lack of stratification suggests deposition from a relatively dense fluid mud in which turbulence may have been suppressed.

3. Silt-streaked mud is volumetrically the most abundant facies and forms beds typically 1-3 mm, but up to 10 mm thick. Parallel, planar or occasionally wavy laminae of siliceous silt and clay mineral aggregates alternate on a sub-mm scale. The proportion of this facies increases upward from ~30 to 50%. Segregation of siliceous silt and clay aggregate grains is interpreted to have taken place in the boundary layer of a decelerating flow as a result of wave- and current-induced shearing and mixing (cf. Schieber, 1994; Macquaker et al. 2010).

4. Silt beds lack clay aggregates and form sharp-based, locally scoured beds 0.1 to 2.5 mm thick. Silt beds commonly form ripples, and a symmetrical external form is more common up-section. Internal cross-lamination is commonly uni-directional. Silt beds increase in abundance upward from ~10 to ~30% of the total section. Near the bottom of the section, cross-lamination dips mainly to the SE (i.e. down paleoslope), whereas up-section, dip is both up- and down-slope.

Bioturbation is on a mm-scale. The proportion (thickness) of the samples that is bioturbated increases upward from 0% at the base to 20-30% near the top.

<u>Facies Successions</u> Two main facies successions are recognized.

Upward-fining successions usually start with sharp-based silt, and grade up through silt-streaked mud to structureless silty mud. In some instances, clay-rich mud may cap, or replace the silty mud facies. Other variants of the succession may lack the basal silt unit, or the silt may be tabular rather than rippled. Silt-streaked mud may form the base of the succession, sharply overlying underlying structureless silty mud. Upward-fining successions are provisionally interpreted as waning flows. Because ripples tend to have a symmetrical form, the primary source of energy is interpreted to have been waves, and hence these waning-flow successions are interpreted as wave-enhanced sediment gravity flows. Down-slope (SE) directed ripple cross-lamination supports a gravity-influenced flow. The up-section increase in up-slope directed cross-lamination may reflect the effect of shoaling wave and the development of orbital asymmetry.

Upward-coarsening successions are less common. They typically consist of a sharp-based package of silt-streaked mud in which siliceous silt laminae thicken upward, and the succession may be capped by a sharp-based, lenticular bed, or beds of clean silt, << 1 mm thick. Such silt beds may be subtly bioturbated. There as an abrupt transition to silty mud or clay-rich mud at the top of the succession. Several such upward-coarsening successions may be stacked. A variant involves an upward-coarsening, followed by an upward-fining. Upward-coarsening successions are interpreted to record waxing flows. They might be interpreted as a record of rising river floods that generated hyperpycnal flows down the delta front. Symmetrical coarsening-fining successions may record rising and falling stages of river floods. Bhattacharya & MacEachern (2009) made a similar interpretation of much thicker facies successions from Dunvegan core.

In the upper 20 m of the section, cm-scale beds of very fine sandstone show wave ripple crests that trend NW-SE (i.e. shore perpendicular) and combined-flow ripples are directed between South and SW. This pattern indicates dominant winds blowing along-shore from the NE, generating geostrophic flows directed obliquely across the prodelta to the S and SW – as predicted by theory.

Conclusions

The prodelta area of Dunvegan allomember G extended up to 120 km from shore and sloped to the SE. Mud beds on the prodelta are of millimeter scale and comprise four facies:1. clay-rich mud; 2. structureless silty mud; 3. silt-streaked mud and 4. mud-free silt, sometimes with wave ripples and cross-lamination. Clay minerals appear to be packaged in 10-20µ aggregates. Facies are most commonly organized in upward-fining successions with facies 4 overlying a scoured surface, grading up through facies 3 to facies 2 or even 1. The succession is interpreted to record a waning, wave-enhanced sediment gravity flow where facies 3 and 4 reflect active sorting and grain segregation beneath a turbulent flow whereas facies 1 and 2 reflect settling of fluid mud after flow ceased. Less common are upward-coarsening successions from facies 2 or 3 that may culminate in facies 4; an upward-fining cap may also be present. These successions record waxing flows possibly attributable to rising river floods that produced hyperpycnal flows across the prodelta. Micro-ripple cross-lamination supports the idea of down-slope, gravity-influenced flow on the distal prodelta. Closer to shore (i.e. up-section), combined flow ripples in sand beds indicate winds from the NE and resulting geostrophic flows to the S and SW.

Acknowledgements

I am grateful to The Natural Sciences and Engineering Research Council of Canada for supporting my research on Cretaceous shelf systems for over 25 years.

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