Tectonic and eustatic controls on the distribution of sandstone and hot mudstone: the Goodrich-Shaftesbury transition, Upper Albian and Lower Cenomanian, NE British Columbia

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Introduction

Well-exposed sections in the B.C. Foothills, coupled with a large well-log database in the adjacent Deep Basin makes this proximal part of the foreland basin a natural laboratory in which to investigate the relationship between facies stacking patterns, stratal geometry, and possible tectonic and eustatic controls (Fig. 1). At a basin scale, the detailed relationship between the lithostratigraphic units of northeastern British Columbia (the Hasler, Goodrich and Cruiser formations; Fig. 2) and their equivalents in Alberta (the Shaftesbury Formation; Fig. 2) have remained enigmatic since the pioneer work of Wickenden and Shaw (1943) and Stott (1968). Lithostratigraphy worked well for outcrop mapping in British Columbia, but on a regional scale, the lithostratigraphic divisions cannot be extended far to the east because of both facies diachroneity and lateral variability. Therefore, new allostratigraphic correlations, based on tracing allostratigraphic discontinuities (mostly flooding surfaces) is necessary. The allostratigraphic approach of Roca et al. (2008; Fig. 3) illustrated how time markers cross different lithostratigraphic units from the Canada - USA border to the Alberta - British Columbia border. In this presentation, we now extend this correlation to the proximal foredeep (Fig. 4) in order to illustrate the lateral relationship between relatively sand-rich proximal facies (Hasler, Goodrich, Cruiser fms.) and more mud-rich distal facies (Shaftesbury Formation).

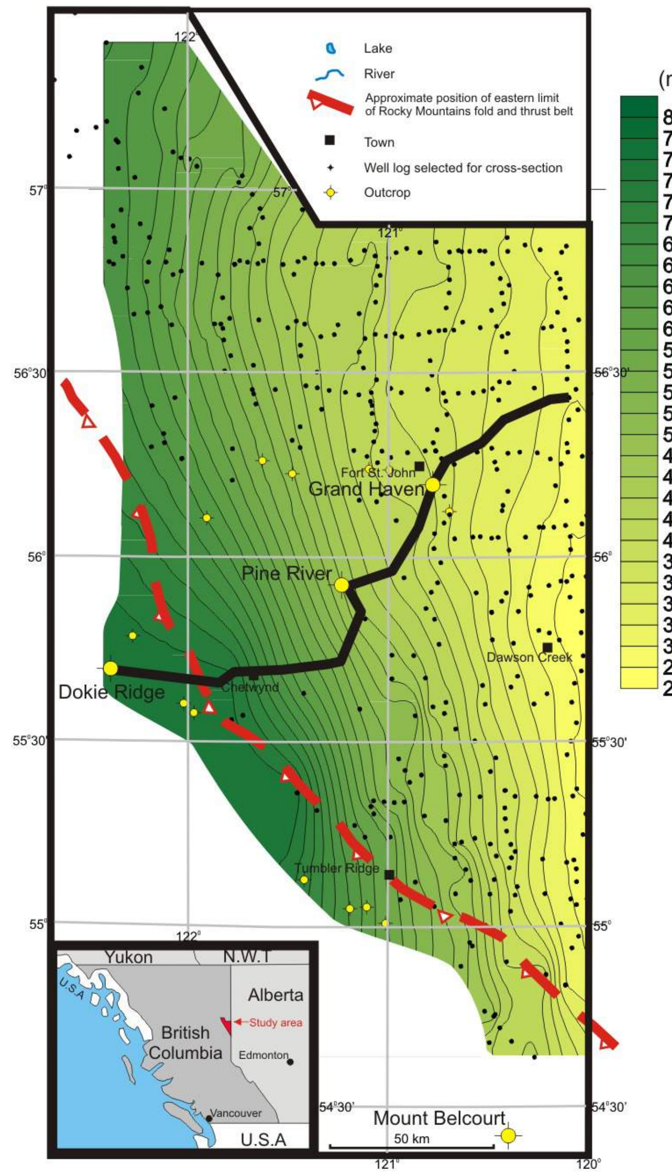


Fig. 1 Isopach map of the total thickness of Viking allomember VD, plus the Westgate and Fish Scales alloformations (~equivalents of the Shaftesbury Formation) in northeastern British Columbia showing location of cross-section in Figure 4.

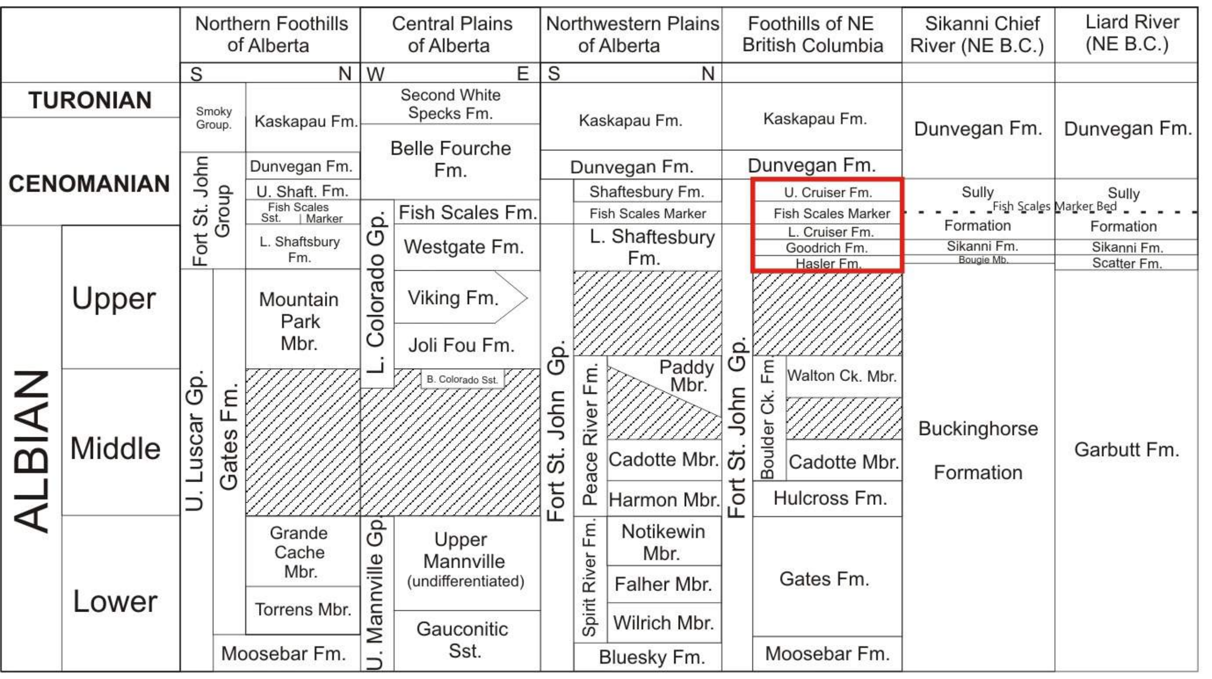


Fig. 2
Table summarizing lithostratigraphic terminology of Albian and Cenomanian rocks in different portions of the Rocky Mountain Foothills and adjacent Plains of Alberta and British Columbia. Modified from Roca et al. (2008) and Schröder-Adams and Pedersen (2003). Lithostratigraphy of the Lower Colorado Group and Peace River Formations based on Bloch et al. (1993) and Leckie et al. (1994); summary of the Mannville Group and equivalent rocks based on Hayes et al. (1994). Lithostratigraphy of Sikanni Chief and Liard River basins based on Stott (1982), Koke and Stelck (1987), and Leckie and Potocki (1998).

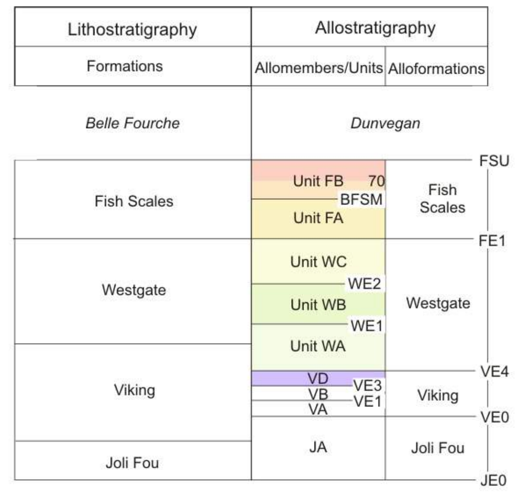


Fig. 3
Diagram to show the relationship between the lithostratigraphic divisions of the Lower Colorado Group and allostratigraphic divisions of the Lower Colorado allogroup. Modified from Roca et al. (2008).

Theory and Method

The rocks in the studied interval are characterized by strongly cyclical, sandier-upward transgressive-regressive successions, typically 5-20 m thick. The flooding surfaces that bound these successions are readily traceable in subsurface, sometimes for > 400 km, and can be considered to approximate time lines. This proxy chronostratigraphy provides a basis for facies and paleogeographic mapping. Isopach maps constructed for allostratigraphic units (effectively time slice maps of subsidence) allowed reconstruction of the subsidence history in three dimensions, on small time-steps. Paleogeographic maps for each time slice makes it possible to trace, with high resolution, changes in facies distribution in response to subsidence and eustasy.

For this study, gamma ray and/or resistivity logs from 435 wells were used to construct a grid of 20 cross sections with a spacing of ~20 km. These wells formed the basis for an allostratigraphic correlation grid over an area of about 50,000 km^2 (Fig. 1). Twenty one outcrop sections totalling 4090 m have been investigated.

Results (1)
Overall geometry

Allomembers show no clinoform geometry, nor do they lap out onto a single discrete surface (Fig. 4). Instead, each allomember fines and gradually thins eastward away from the foredeep. The sedimentological and stratigraphic evidence indicates that the proximal foredeep was a shallow, low-gradient, storm-dominated ramp. Sand was transported, primarily by combined flows, for up to 70 km offshore (Figs 4 and 6). The more distal part of the ramp accumulated mud. There is no evidence for the development of deep water (i.e. > ~30-40 m), and therefore the accommodation:supply ratio appears to have been near balance throughout deposition of the succession.

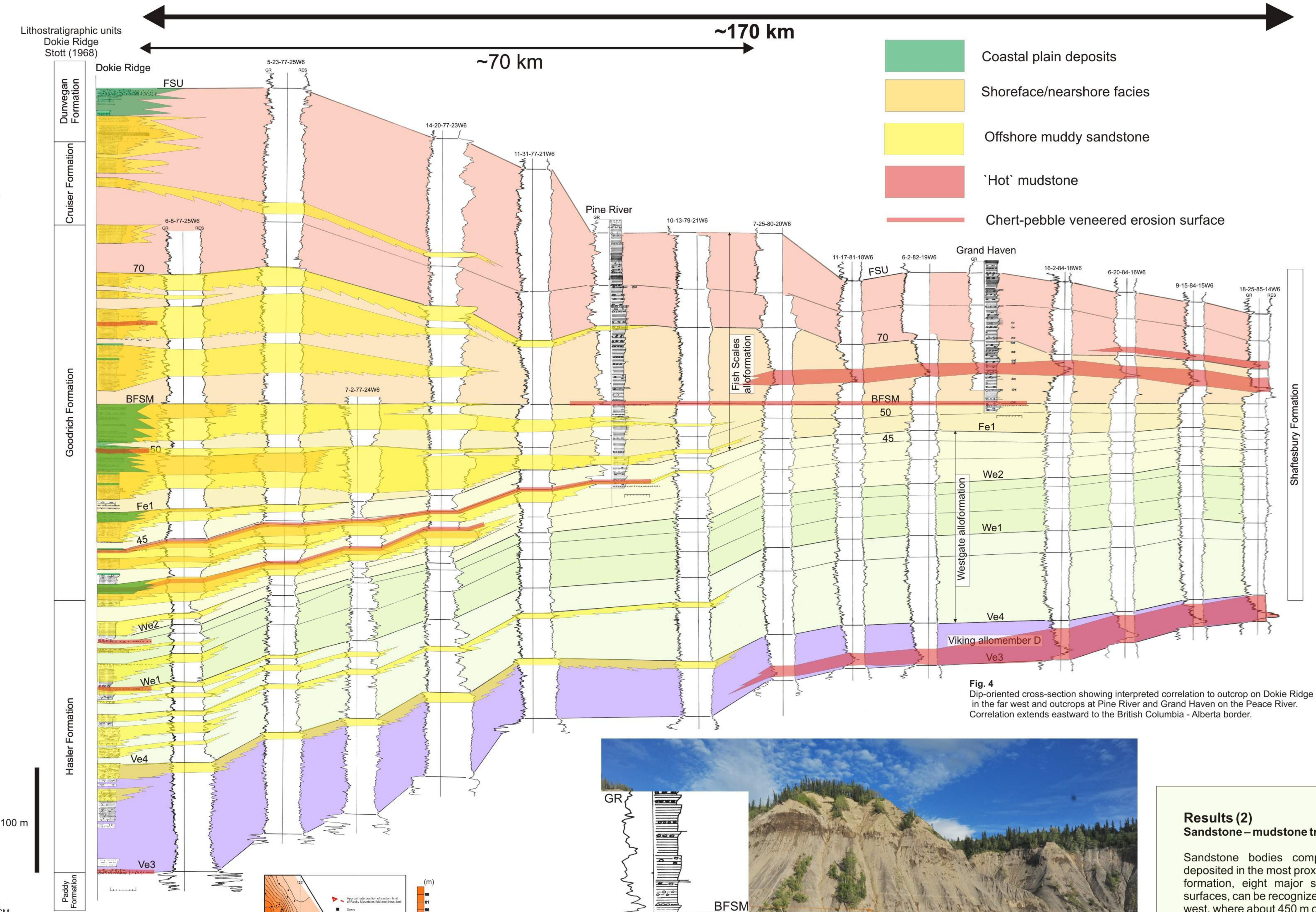
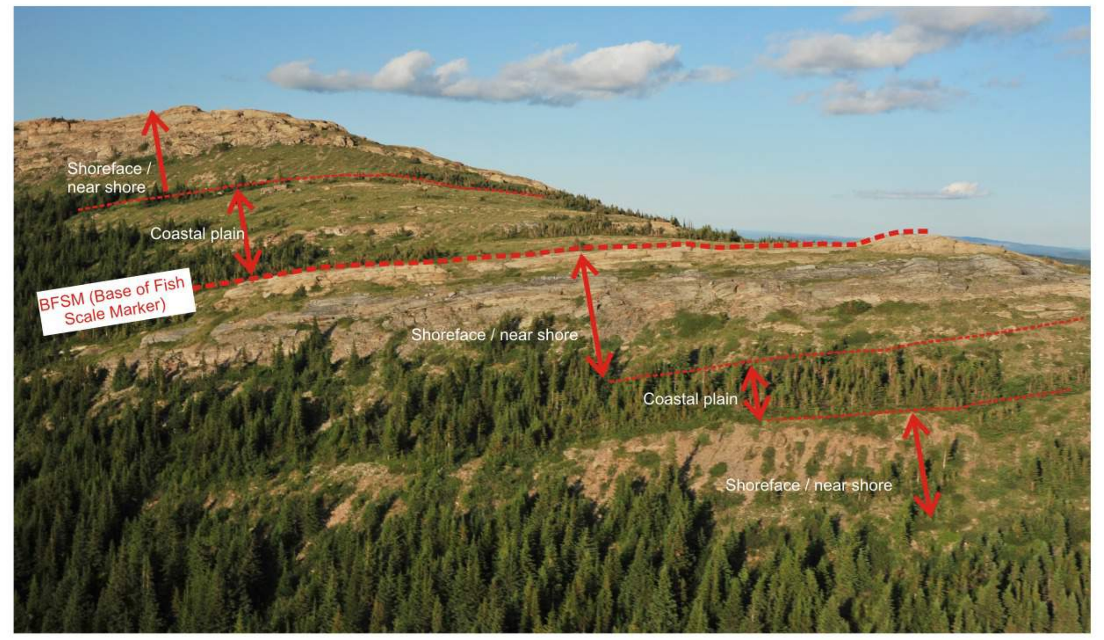


Fig. 4
Dip-oriented cross-section showing interpreted correlation to outcrop on Dokie Ridge in the far west and outcrops at Pine River and Grand Haven on the Peace River. Correlation extends eastward to the British Columbia - Alberta border.

Fig. 5 Aerial photograph of the Goodrich Formation at Dokie Ridge. Showing stack successions of shoreface sandstones and coastal plain deposits.Note that the BFSM is no longer a radioactive sandstone and is represented by a flooding surface.



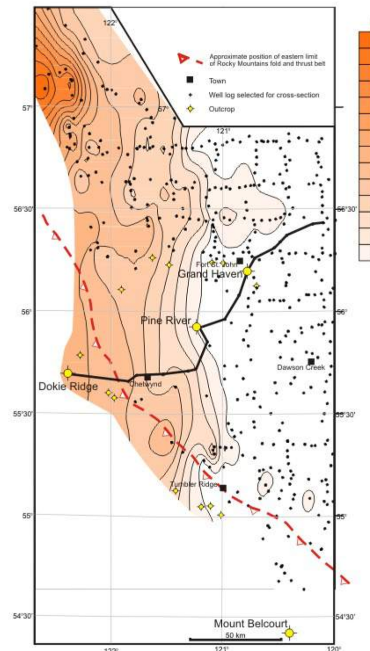


Fig. 6
Map of the total thickness of both clean nearshore and offshore muddy sandstone (<90 API) of the regressive package between markers Fe1 and 50 (within the Fish Scales alloformation). This package marks the most westward extent of the Goodrich sandstone.

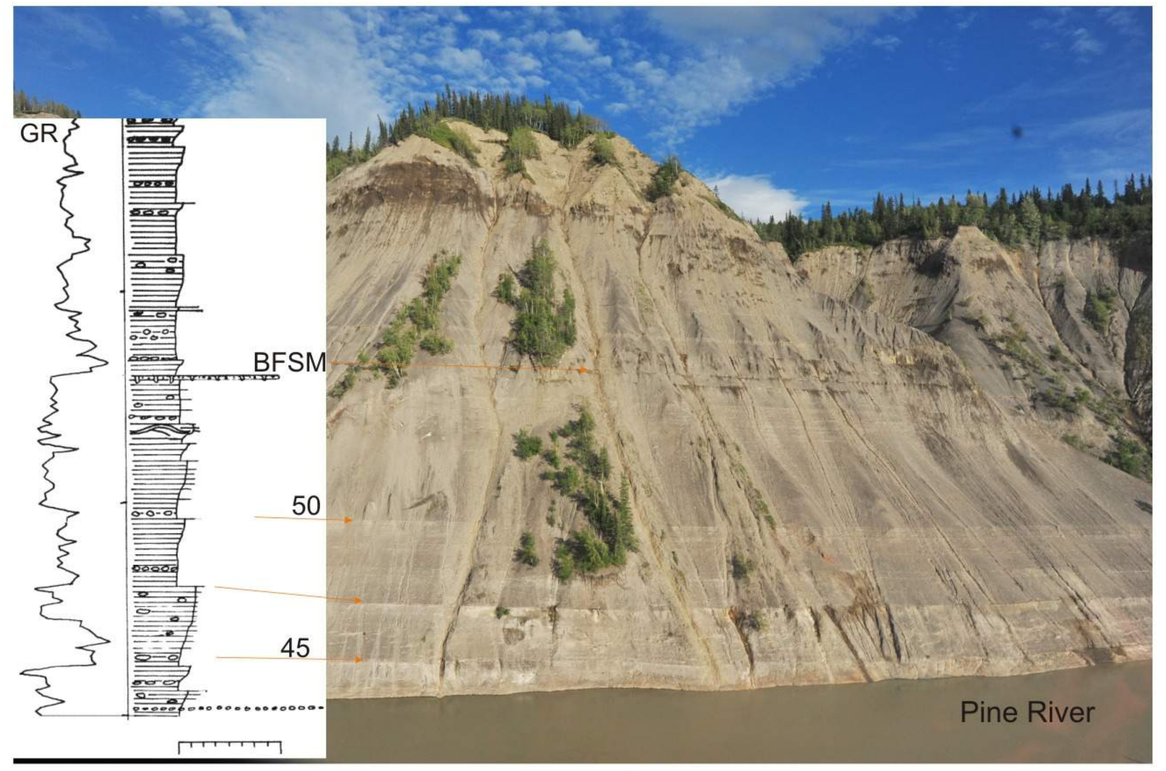


Fig. 7 Aerial photograph of the lower portion (~170 m thick) of the Pine River section with the outcrop log and Gamma Ray profile.

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Results (2)
Sandstone – mudstone transition

Sandstone bodies comprising the Goodrich Formation were deposited in the most proximal foredeep, over about 1 My. Within the formation, eight major sandstone tongues, capped by flooding surfaces, can be recognized. Sandstones are stacked vertically in the west, where about 450 m of nearshore and coastal plain deposits are observed (Figs. 4 and 5). An aggradational stacking pattern and a pronounced wedge-shaped geometry suggest that these units were deposited at a time of rapid subsidence and relative sea level rise. Lateral facies change is dramatic, and the progradational limit of inner-shelf sandstone (rippled heterolithic facies) never extends more than ~60-70 seaward of the paleoshoreline (Figs. 4 and 7). It is interpreted that each progradational sandstone tongue was deposited during a phase of slower relative sea level rise, perhaps linked to periods of eustatic fall. It is remarkable that the Goodrich Sandstones die out about 70 km from the paleoshoreline, east of which, the entire succession is represented by about 200 m of mudstone (the Shaftesbury Formation; Fig. 8).

Conclusions

The Hasler, Goodrich and Cruiser formations are relatively sandstone-rich, basin-margin facies that were deposited at a time of rapid tectonic subsidence and relative sea level rise. The high accommodation rate in the western, proximal foredeep trapped coarser sediment and caused sandy, nearshore facies to aggrade vertically. A high resolution allostratigraphic approach permitted recognition of changes in strata geometry. It appears that, at times of somewhat lower subsidence rate, shorelines were able to prograde further seaward, building more tabular-shaped rock bodies. Nevertheless, sand appears to have been transported only ~60-70 km seaward. An elevated radioactivity level is observed only above a pebble-veneered, formerly-subaerial unconformity that underlies the Base of Fish Scale Marker. This unconformity is blanketed by highly radioactive organic mudstone that was deposited following a major sea level rise. This rise is interpreted to have allowed connection between the Boreal and Tethyan water masses, leading to density stratification, bottom-water anoxia, and preservation of organic matter.
This study provides clear confirmation of theoretical foreland basin models (e.g. Jordan and Flemings, 1991) that predict nearshore trapping of coarse clastics during times of rapid flexural subsidence, and the domination of the offshore portion of the basin by mud. Some of the offshore mudstone units are organic-rich, and have the potential to source hydrocarbons and host shale gas. Therefore, it is important to understand the tectonic and oceanographic conditions under which organic-rich mudstone may be deposited, and to understand the dispersal processes and facies variability within mud-rich facies across a shallow, low-gradient shelf.

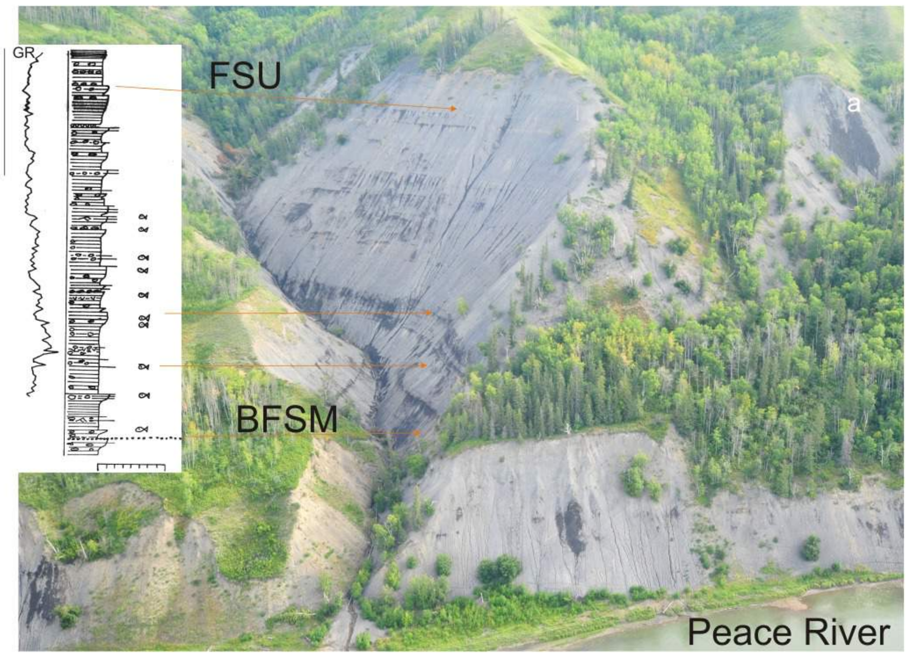
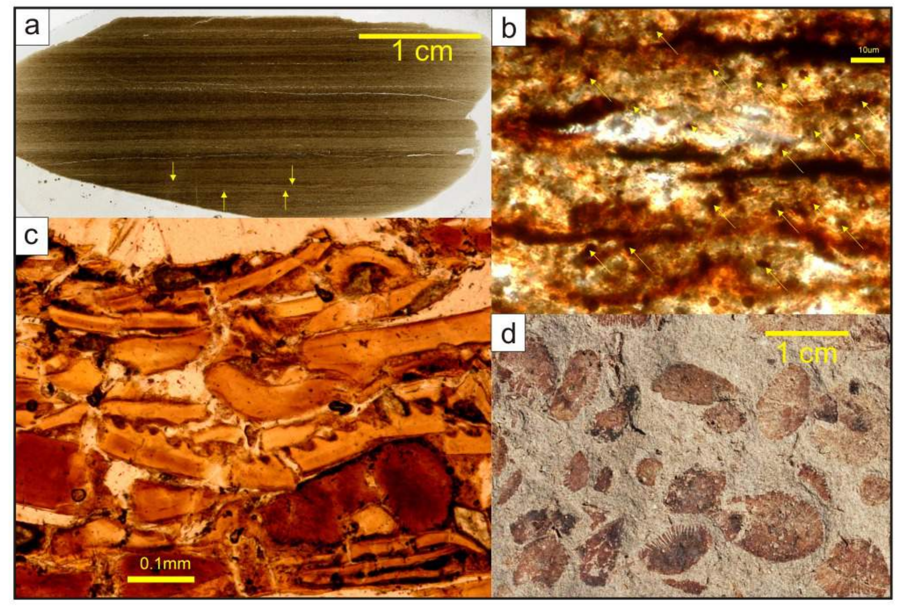


Fig. 8 Aerial photograph of mudstone-dominated Grand Haven section on the Peace River, with outcrop log and Gamma Ray profile.



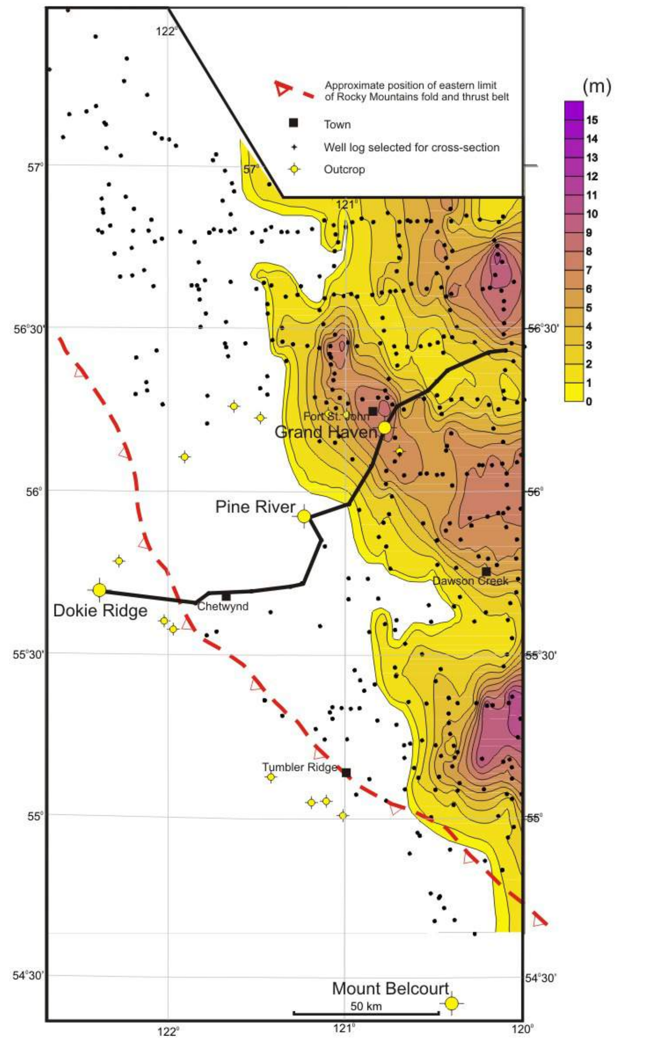


Fig. 8
Map of thickness of `hot` mudstone (>150 API) overlying the Base of Fish Scales Marker (BFSM).

Fig. 9
Detailed views of `hot` mudstone from the Fish Scales horizon.
a) Back lit scan of thin section of laminated, nonbioturbated `hot` mudstone, note a compacted mud ripple (arrows);
b) close-up of (a), note dark laminae of organic matter (o) and fine silt-sized aggregates of clay minerals (arrows);
c) Thin section of a phosphatic bed with abundant fish bones and fish scales; d) mudstone contaning abundant fish scales.

Results (3)
The Base of Fish Scales Marker and the origin of hot mudstones

The Base of Fish Scale Marker (BFSM) has a very prominent 'hot' signature in gamma ray logs, and is a basin-wide log marker (Fig. 4). Towards the northwest, in British Columbia, the radioactive signature of the BFSM gradually fades (Fig. 8). A chert-pebble veneered erosion surface underlies the BFSM and represents the most prominent sea level fall in the Goodrich time interval. The distribution of pebbles indicates that relative sea level fall caused the shoreline to move at least 130 km to the east. The overlying transgressive mudstone (Fig. 9) has a very high radioactivity (>150 API). It is notable that hot mudstone is not present below the BFSM surface whereas above, there are two horizons with elevated radioactivity. In the upper horizon, the lateral transition from shelf sandstone into radioactive mudstone takes place over a distance of only about 50 km. It is interpreted that deposition of hot mudstone was linked to the major transgression that connected the Boreal and Tethyan Ocean and which caused bottom-water anoxia, due to density or salinity stratification (Schröder-Adams et al. 1996).

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