Sedimentation Patterns and Reservoir Distribution in a Siliciclastic, Tectonically Active Slope Environment, Bowser Basin, Northwestern British Columbia (NTS 104B/01)

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Introduction

Deepwater submarine channels constitute important potential hydrocarbon reservoirs in offshore petroleum exploration. The spatial distribution and thickness of those sandstone bodies are highly unpredictable because they tend to be localized and interbedded with mass-transport complexes. Looking at well-preserved analogues in the rock record assists in understanding the behaviour of sedimentation processes in such environments. Sedimentary rocks mapped as Lower to Middle Jurassic Hazelton Group and exposed at Mount Dilworth, north of Stewart in British Columbia represent an excellent analogue of slope processes in deep-marine siliciclastic-dominated depositional systems (Figures 1, 2). Furthermore, the reservoir units associated with this stratigraphic interval are potentially charged with hydrocarbons in laterally equivalent units farther northeast in the Bowser Basin, where thermal maturation levels are favourable (Evenchick et al., 2002; Stasiuk et al., 2005). The relationships between the different sedimentary facies identified in a tectonically active slope environment described in this report assist in understanding the distribution of reservoir units and assessing the petroleum potential of this stratigraphic interval.

Geological Setting

Early to Middle Jurassic sedimentary rocks assigned to the upper Hazelton Group are widespread in northwestern BC. They mainly outcrop along the edge of the Bowser Basin and constitute the lowermost stratigraphic unit of the Bowser succession (Waldron et al., 2006). Siliciclastic sedimentary rocks of the upper Hazelton Group were deposited above the volcanic arc rocks of the Stikine Terrane during an episode of back-arc extension followed by thermal subsidence (Thorkelson et al., 1995). In the study area north of Stewart, upper Hazelton Group sedimentary rocks were previously assigned to the Salmon River Formation by Grove (1986). Regionally, sedimentary rocks of the Salmon River Formation were deposited above the dacitic tuff breccia of the Mount Dilworth Formation (Anderson and Thorkelson, 1990). However, geological mapping conducted by the authors in the summer of 2008 suggests that these sedimentary rocks might be correlative with the Todagin assemblage of the Bowser Lake Group (Evenchick et al., 2006). Uranium-lead zircon work is currently being conducted at the University of Alberta and should provide new constraints on the minimum depositional age and provenance of these units. The current report uses the previous stratigraphic framework established by Grove (1986).

Description of Depositional Units

Fine-Grained Turbidity Flows

Normally graded siltstone-mudstone and sandstone-mudstone couplets are widely exposed in the sedimentary succession (Figure 3). They usually occur in thin to medium beds and form laterally extensive sheet-like units. The presence of partial Bouma (1962) sequences $T_{a\text{-}e}$ is attributed to waning energy in turbidity flows. Abundant T_{cd} and T_{abd} sequences contain asymmetric current ripples and groove casts, which suggests that the predominant paleocurrent flowed towards the southwest. Loading features such as ball-and-pillow structures and flame structures are also common. These sedimentary structures are indicative of relatively high sedimentation rates, which led to density contrasts in water-saturated sediments shortly after deposition. In some cases, rapid deposition also produced pore pressure that exceeded the hydrostatic equilibrium and led to partial liquefaction of the sediments; this phenomenon is represented in the turbidite facies by abundant convolute laminations.

Keywords: *submarine channels, turbidites, debris flows, Bowser Basin, petroleum exploration, Hazelton Group*

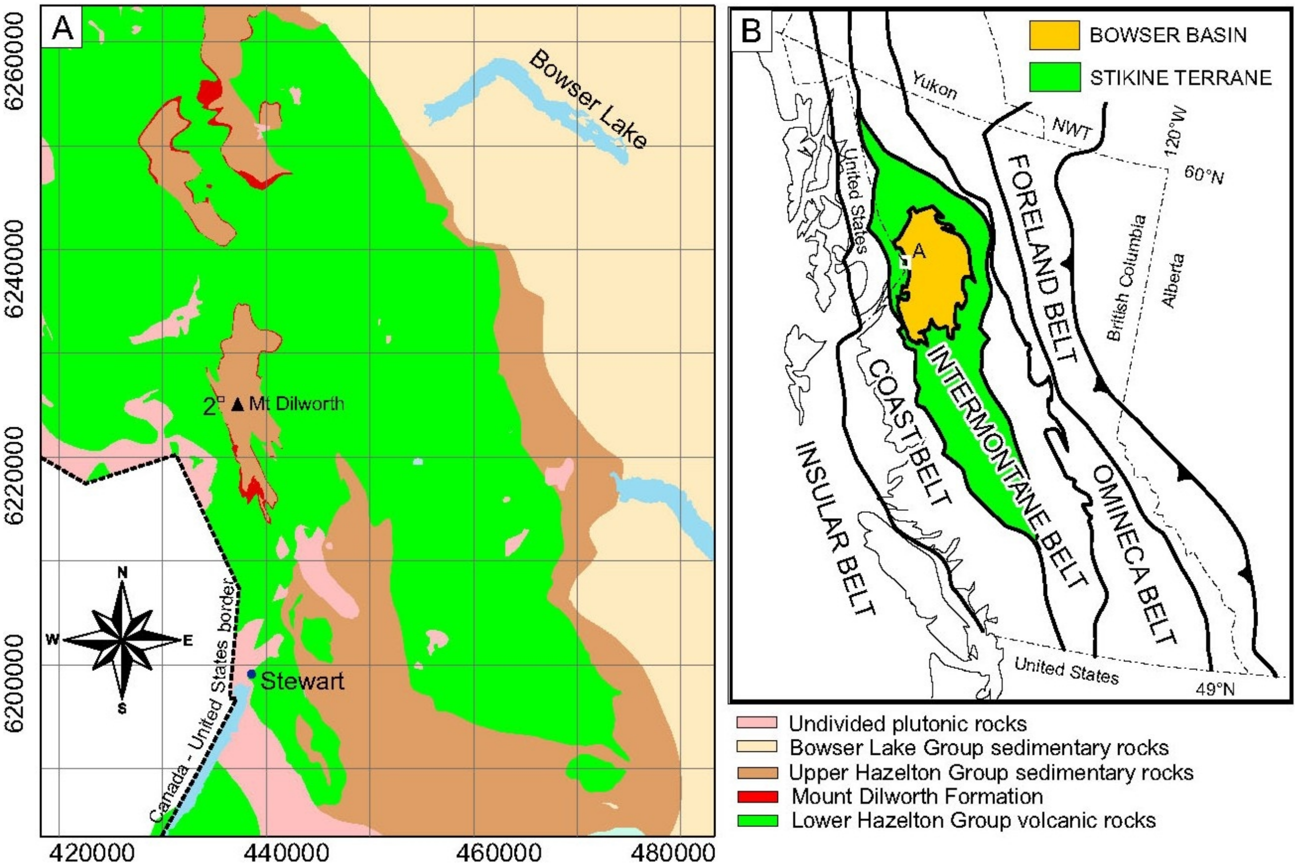

Figure 1. Simplified geology of the study area: **a)** location of the sedimentary succession presented in Figure 2 (projection in UTM NAD 83); **b)** location of the Bowser Basin in relation to principal tectonic belts of the Canadian Cordillera; white square delineates the extent of the geology described in (a). *Modified from* Grove (1986), Evenchick and Thorkelson (2005).

Some metre-thick intervals of thinly bedded fine-grained turbidites show evidence of biogenic reworking. The ichnological suite observed is dominated by two distinctive ichnogenera: *Phycosiphon* and *Helminthopsis*. These traces are horizontal to gently inclined, irregular, meandering burrows filled by organic-rich mud (Figure 4). Both these traces are generally interpreted as grazing trails of vermiform organisms (Pemberton et al., 2001) and typically occur near the sediment-water interface; this suggests that food resources were introduced mostly by suspension in a low-energy depositional environment, outside the principal sediment pathway. In terms of petroleum prospectivity, this unit has rather low reservoir potential due to its fine-grained nature. On the other hand, as it is situated above a thick sandstone package, it would constitute an excellent seal rock due to its impressive lateral extent and low permeability.

Submarine Channel Fills

The percentage of sandstone in turbidite deposits gradually increases upsection. The beds can consist of up to 90% of sand-dominated T_{abc} sequences, whereas the layers of laminated silt and hemipelagic mud T_{de} are centimetre-thick. This overall increase of sandstone is associated with a general thickening- and coarsening-upward trend at the outcrop scale (Figure 2). The vertical pattern is interpreted as a change from an off-axis area characterized by bioturbated silt and very fine sand to an axial zone of sandstone deposition. Around 85 m above the base of the section, turbidites are truncated by a series of very thick sandstone bodies (Figure 2). The beds typically consist of coarse- to very coarse grained sandstone with occasional pebbly sandstone lenses and *in situ* calcareous concretions (Figure 5). They range in thickness from 10 to 50 m and extend laterally up to 500 m. Thin-section observations indicate that the framework grains are mainly composed of chert, monocrystalline quartz, plagioclase and mud clasts. The grains are well to moderately sorted, with less than 5 % clay matrix.

In some cases, distinct sandstone beds become amalgamated along strike and form channellized lobe geometries. Figure 6 shows the spatial distribution of a channel system cutting down into a debris flow unit. The base of the channel is marked by a scoured surface above which a drape of thinly laminated mud and silt accumulated. The absence of coarse material immediately above the scoured surface suggests that important sediment bypass occurred prior to accumulation of the fine-grained sediments. The mud-

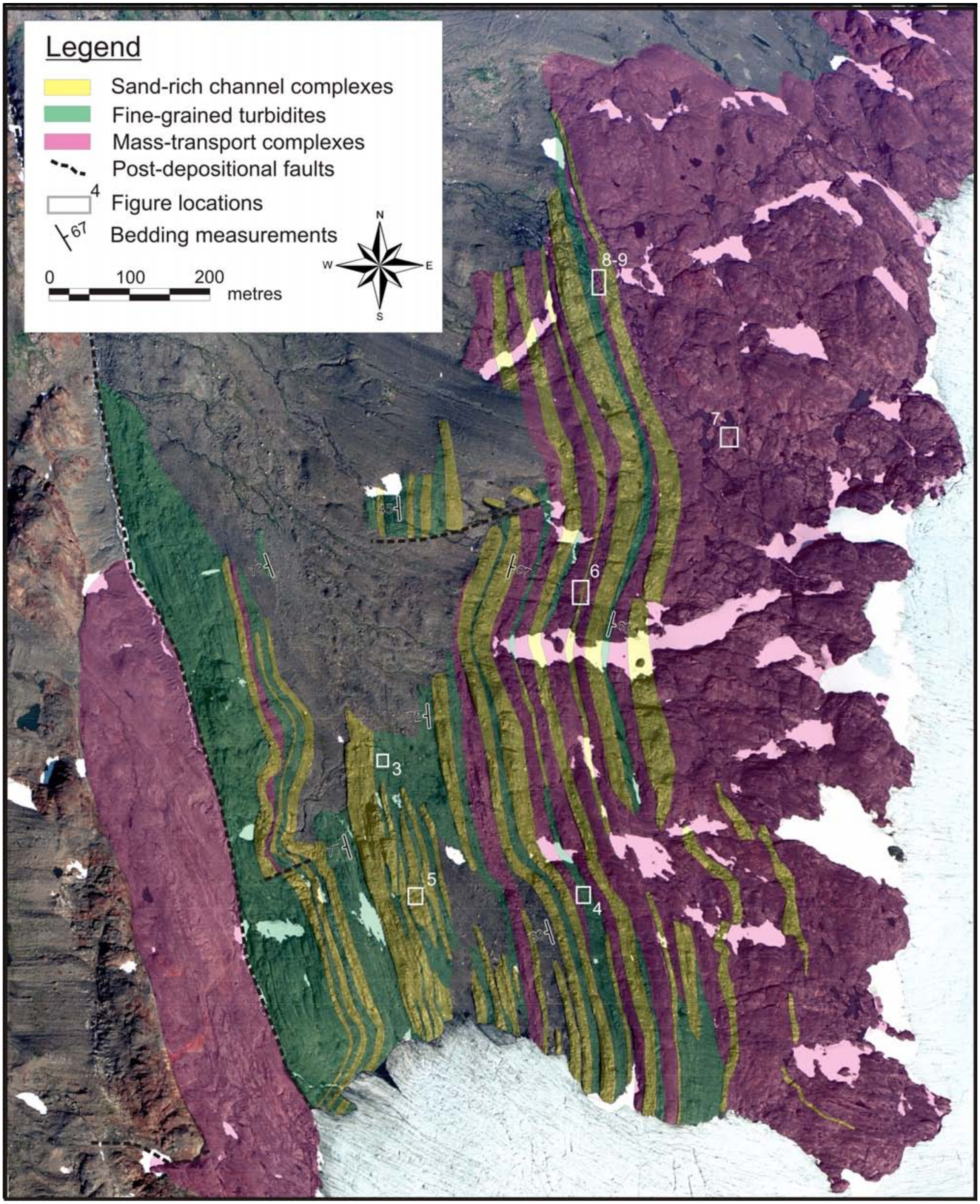

Figure 2. Annotated aerial photograph of the sedimentary succession, showing the main depositional units. Stratigraphic top is to the east.

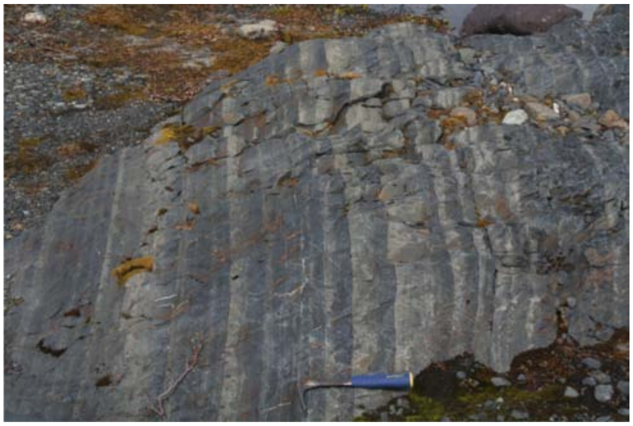

Figure 3. Thinly bedded succession of fine-grained turbidites with abundant partial Bouma sequences T_{a-e}. Stratigraphic top to the right. Hammer for scale is 30 cm in length.

Figure 4. *Helminthopsis* trace fossil in fine-grained turbidites. These traces are interpreted as grazing trails of worm-like organisms in a low-energy depositional environment. Lens cap is 6.5 cm in diameter.

Figure 5. Thickly bedded, very coarse sandstone of amalgamated channel complexes. Note the fining- and thinning- upward character of the beds. Stratigraphic top is to the left.

filled channel is truncated by an irregular erosional surface above which a unit of normally graded, clast-supported conglomerate was deposited. Upsection, the conglomerate gradually passes into moderately sorted medium- to coarse-grained sandstone containing abundant current-generated sedimentary structures. In each measured stratigraphic section, the channel sand is interbedded with laminated silt and very fine grained sand. These relatively thin, finer grained intervals are interpreted to be levée deposits associated with lateral migration of the channel axis.

The sand-rich submarine channels possess very good reservoir characteristics: they consist of homogeneous sandstone arranged in laterally extensive (~500 m) and very thick (~10 to 50 m) units (Figure 2). The coarse-grained nature of the sediments, combined with the relatively good sorting, is favourable for development of high initial intergranular porosity. Under the proper thermal maturation levels, these sand-rich channels could be charged with hydrocarbons and would constitute significant resources.

Mass-Transport Complexes

Debris flows and slump units are the most abundant units within the succession. These gravitational features, organized in mass-transport complexes (MTCs), consist of large dismembered calcareous concretionary blocks and layered rafts of sandstone and siltstone supported in a very poorly sorted fine-grained matrix (Figure 7). Soft-sediment deformation features, such as syndepositional folds and extensional faults, are ubiquitous in those units. Detailed mapping of a debris flow unit provided better understanding of the deformation mechanisms prevalent during slope failure. Sliding of a cohesive mass of sediments was initiated over a detachment surface underneath which the parallel beds remained undisturbed (Figure 8). Immediately above the décollement, fine-grained layers were gently folded during compression but retained their original thickness, whereas the softer sand-rich units were subject to more thorough ductile deformation. Pull-apart boudins of mud in a sandy matrix also indicate rheology contrasts between units of different grain size (Figure 9), the finer grained units behaving more competently. The slump unit becomes progressively more deformed near its top where disharmonic folding predominates. Eventually, most of the primary features are lost and the initial layering of the sediments becomes indistinguishable. As the matrix incorporated more fluids during transport, the slump unit evolved into an incoherent debris flow.

The uppermost stratigraphic unit exposed above the submarine channels consists of a very thick MTC (Figure 2). Conservative estimates made from aerial photograph interpretations suggest a minimal thickness of 400 m and a lateral extent over 1.4 km. The basal contact of the MTC on sandstone is variable along strike. At the northern end, the contact is erosional on granular sandstone; further south, the sandstone is cut by another debris flow, which shows that the MTC is a composite of several slumps. Internal deformation increases southward, where large blocks of the underlying sandstone become incorporated in the MTC. These rafts are organized in variable orientations and can reach up to 100 m in length. Even though no other mappable contacts were observed upsection, mostly due to extensive snow cover, the impressive thickness of the MTC probably results from multiple amalgamated debris flows with similar facies. In terms of petroleum prospectivity, MTCs do not represent good reservoirs due to their dominant fine-grained composition.

Implication for Petroleum Exploration

The basal sedimentary rocks of the succession exposed on the western side of the fault (Figure 2) consist of debris

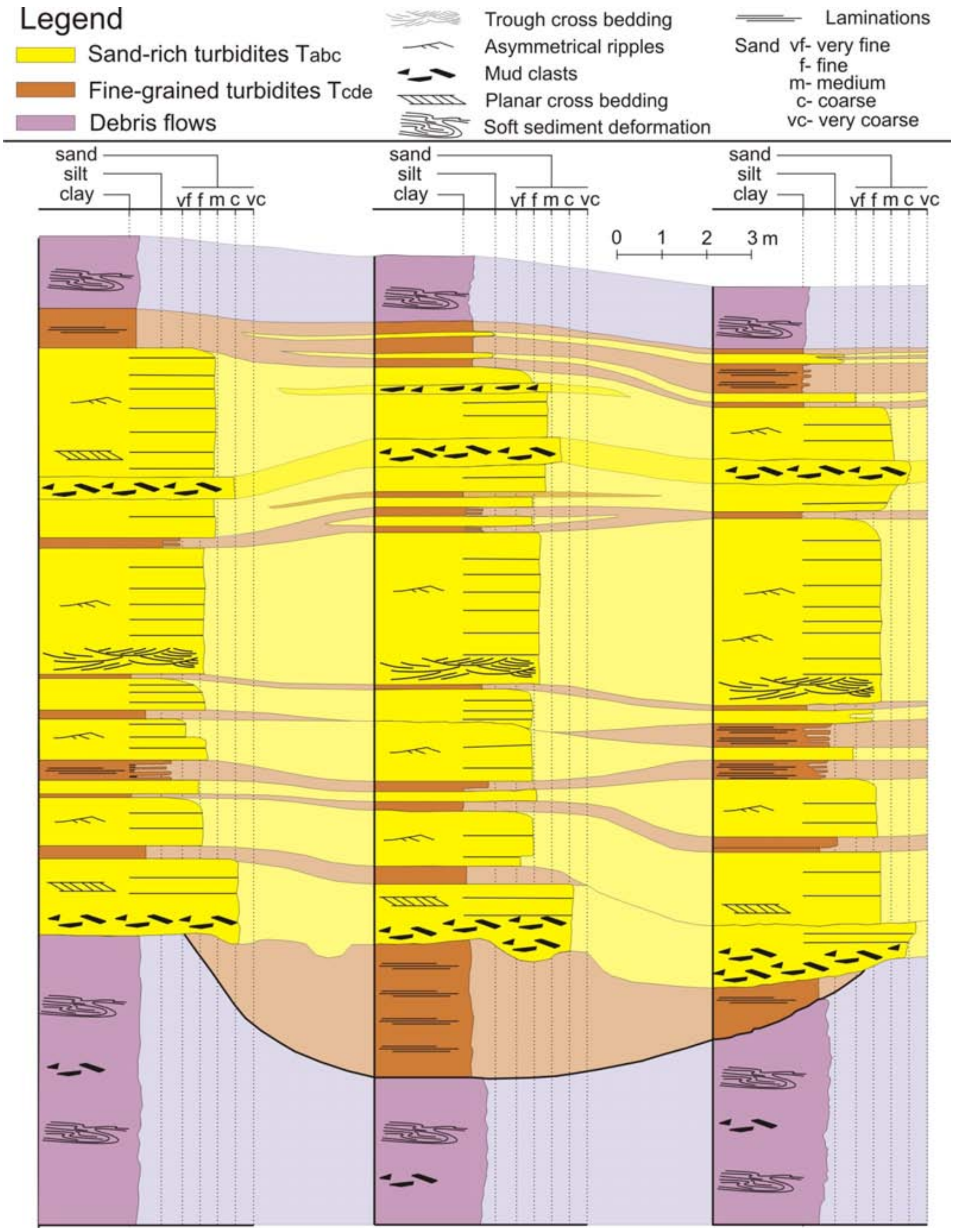

Figure 6. Stratigraphic cross-section of a mud-filled channel complex, showing the lateral variability of depositional units. No vertical exaggeration.

flows and slumps. Their fine-grained matrix and complexly folded laminated blocks suggest that they originally accumulated as fine-grained turbidites before being remobilized and deposited as cohesive gravity flows. Deposition probably took place in a slope environment, where gravitational collapses were more likely to occur. In contrast, younger sedimentary rocks located on the eastern side of the fault consist of unconfined thinly bedded turbidites and laterally extensive sandstone beds. Lobe geometry within those units suggests that repeated low- and high-density turbidity currents provided the bulk of the sediments to the submarine fan systems. The lack of MTCs in this interval suggests a return to more stable conditions. Upsection, scoured surfaces and mud-clast conglomerate found at the bases of the channel complexes are indicative of sediment bypass and incision (Figure 10). The sandstone beds are organized in channel-lobe geometries and show local incision into finer grained sedimentary rocks. These sand-filled channel complexes represent the best reservoirs of the succession. In addition to being relatively homogeneous and very thick, they are capped by intervening fine-grained deposits representing levée and overbank sediments, which constitute an adequate seal to prevent vertical fluid flow. These channellized flows are in gradational contact above the underlying unconfined frontal splays and lobes, and probably constitute a progradation of the slope over the basin floor.

The proportion of MTCs gradually increases near the top of the succession. Incoherent debris flows are interbedded with amalgamated sandstone beds, whereas fine-grained turbiditic intervals are generally absent. Even though the sandstone beds are laterally extensive along strike, reservoirs tend to be compartmentalized due to the abundant reworking by debris flows. This could inhibit permeability within the reservoir and represent an additional risk for petroleum exploration. Confined mud-filled channels deposited above irregular scoured surfaces indicate that incision and sediment bypass were still dominant processes in the slope environment.

Figure 7. Folded calcareous concretionary block in a chaotic debris flow unit. Brunton compass for scale is 8 cm in width.

Figure 8. Deformed slump unit located above a detachment surface. During slope failure, the underlying thinly bedded turbidites remained undisturbed, while the mass-transport complex was subject to compressional and extensional deformation. The letter A indicates the location of Figure 9. Hammer for scale is 30 cm long.

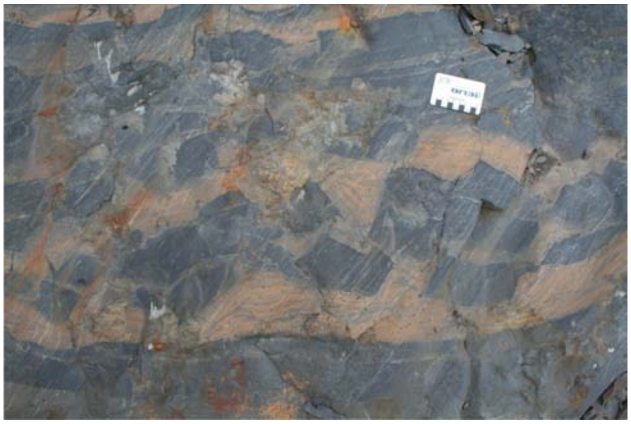

Figure 9. Synsedimentary deformation features formed by flattening during deposition of the slump. The more competent mud layers pulled apart into boudins, whereas the surrounding sandy layers flowed to fill the remaining available space. Scale card is 8 cm long.

Figure 10. Poorly sorted mud-clast conglomerate located above a scouring surface. These intervals are common at the bases of channel fills and are indicative of sediment bypass and incision. Hammer for scale is 30 cm in length.

Depositional elements of deepwater clastic systems are highly variable and include a wide range of gravity flows with different reservoir properties. They consist of cohesive debris flows and slumps (MTCs), channel complexes and fine-grained turbidity flows. The occurrence of one specific gravity flow over another is mainly a function of sediment supply to the deep portion of the basin. Variations in sedimentation rates can be related to base-level fluctuations above the shelf edge and/or tectonic activity. Two different scenarios are explored (base-level changes vs. tectonic activity) to explain the succession of gravity flows observed in the area.

During development of a typical passive-margin sequence, an early stage of forced regression is likely to trigger instability at the shelf edge and deposition of cohesive debris flows on the slope (Catuneanu, 2006). This could correspond to the lowermost debris flow unit observed on the western side of the fault. During late forced regression, the shelf becomes subaerially exposed and accumulation of sand in the deep part of the basin is optimal. This is represented by the progradation of the incised channel complexes above the submarine fans. As base-level rises, increasing accommodation space is made available on the shelf, which reduces the amount of coarse sediment delivered to the deep marine basin.

In the case of a tectonically active basin, re-adjustment of the slope angle may have profound impacts on the distribution of the gravity flows, independently of shoreline shifts. In this model, MTCs observed in the area would be related to repeated slope failure initiated by tectonic activity. Paucity of tectonic activity is inferred during deposition of the submarine fan/channel complexes, when normal progradation of the slope environment would have occurred over the basin floor. In contrast, sudden steepening of the slope in response to fault movement is likely to have triggered rapid incision and sediment bypass, as represented by confined mud-filled channels (Figure 6) and abundant MTCs in the higher portion of the succession.

Even though it is difficult to clearly separate the effects associated with shoreline shifts from those driven by tectonic processes in the rock record, sedimentary rocks of the upper Hazelton Group at Mount Dilworth attest to the strong influence of tectonic input during deepwater sedimentation. The MTCs are unusually thick (up to 500 m) and constitute more than 50% of the entire sedimentary succession. This is significantly higher than most well-studied deepwater passive-margin analogues such as the Isaac Formation of Western Canada (Gammon et al., 2007; Laurin et al., 2007; Navarro et al., 2007; Schwarz and Arnott, 2007), the West Crocker Formation of Borneo (Crevello et al., 2007) and the San Vicente Formation of Spain (Arbues et al., 2007). In addition, sediment bypass facies and repeated incision of channel complexes are too abundant to solely be driven by base-level fluctuations. Based on these observations, the authors conclude that synsedimentary faulting was a major component in determining the nature of the gravity flows. Thick MTCs were deposited during fault reactivation, which interrupted the overall regressive cycle responsible for progradation of the slope succession over the basin floor.

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