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ANATOMY AND EVOLUTION OF A SLOPE CHANNEL-COMPLEX SET (NEOPROTEROZOIC ISAAC FORMATION, WINDERMERE SUPERGROUP, SOUTHERN CANADIAN CORDILLERA): IMPLICATIONS FOR RESERVOIR CHARACTERIZATION

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ABSTRACT: A detailed architectural analysis was conducted in Isaac Unit 5 of the Isaac Formation in the Castle Creek area (east-central B.C., Canada). Isaac Unit 5 developed within a turbidite-dominated slope system on the Neoproterozoic passive margin of western North America where sediment gravity flows and mass movements were common.

Isaac Unit 5 crops out over a 3.5-km-long section oriented oblique to mean paleoflow direction and represents a long-lived pathway for transport and deposition that accumulated ~ 100 m of mostly sand in a deep-marine slope setting. It consists of three stacked, high net-to-gross channel-complex fills (8–30 m thick) that correspond to shorter-term flow conduits, which, in turn, are capped by mudstone-rich units. Fine-grained conglomerate and sandstone beds deposited from high-concentration sediment flows constitute most of channel-complex fills. In addition, muddy debrite and slump deposits occur, but although laterally extensive, are volumetrically minor. Laterally persistent, thin-bedded strata (4–20 m thick) composed mostly of Bouma Tc–e turbidites occur at the top of each channel complex and indicate episodes of local complex abandonment (interchannel complex deposition).

Different kinds of channel-fill elements were identified within Isaac Unit 5, each characterized by a unique combination of facies assemblage, internal geometry, and bounding surfaces. Most commonly, channel fills consist of amalgamated, thick-bedded, normally graded sandstone (Bouma Ta and Tab divisions) associated with backfilling processes. Poorly stratified mudstone-clast breccia, associated with Ta beds and dune cross-stratified sandstones occur in channel fills that exhibit aggradational and laterally migrating stacking patterns. Inner-bend levee deposits are associated with this type of channel fill. Channel fills with inclined sandstone- and mudstone-rich strata, on the other hand, relate to non-aggradational, high-sinuosity channel conditions that developed during gradual abandonment of the pathways for coarse-sediment transport. In contrast, sudden deactivation of these pathways, most probably related to abrupt updip channel avulsion, led to accumulation of structureless sandstone passively filling the deactivated thalweg.

In terms of hydrocarbon reservoir analogues, each of the five different channel-fill elements have unique reservoir attributes (connectivity and continuity), amalgamated and poorly stratified elements having the best (excellent to good) reservoir attributes. Due to high amalgamation at channel-fill scale, channel complexes would represent individual fluid-flow units where only laterally discontinuous permeability barriers (< 500 m long) are present. On the other hand, extensive thin-bedded elements and muddy debrites constitute kilometer-scale barrier-type facies that would effectively compartmentalize channel complexes within the channel-complex set. Strata of Isaac Unit 5 document the detailed stratigraphic complexity, evolution, and reservoir characterization that can be expected in turbidite-dominated slope channel systems developed on passive margins. Further, it is a potential analogue for similar systems developed in continent-margin basins that until now were known mostly from subsurface core and seismic data.

INTRODUCTION

Turbidite slope channels are among the most important deep-water hydrocarbon reservoirs currently being explored in continent-margin basins (e.g., offshore Brazil, Egypt, Gulf of Mexico, West Africa). In large part, many important advances in the understanding of these depositional systems have been recently made as a result of significant improvements in modern 3-D seismic imaging (see Posamentier and Kolla 2003 and references therein). These techniques illustrate the three-dimensional stratal complexity of most slope channel reservoirs in terms of reservoir distribution and sand connectivity (e.g., Mayall and Stewart 2000; Sikkema and Wojcik 2000; Abreu et al. 2003; Fonnesu 2003; Samuel et al. 2003). Lateral and vertical variability of reservoir properties appear to be associated with differences in the nature of channel fill and their stacking patterns, which commonly are at scales below the resolution of even high-frequency 3-D seismic, particularly in deeply buried strata (e.g., Kendrick 2000; Mayall and Stewart 2000).

Although generally 2D in nature, detailed architectural analysis of outcrops provides a powerful tool to study channel fills with different sand proportion and internal geometry, as well as different types of mudstone-rich overbank deposits (e.g., Elliot 2000; Martinsen et al. 2000; Abreu et al. 2003; Beaubouef 2004). Description and interpretation of these architectural elements can help to better understand the processes involved in the evolution of slope channels and, thereafter, provide insights that can be used for accurate characterization of deep-water reservoirs. Geometry, continuity, and distribution of reservoir facies at the scale of channel fills, as well as the lateral extent of fine-grained, impermeable units that form potential barriers and baffles to fluid flow, are among the more important characteristics that can be extrapolated from an outcrop-based architectural analysis (e.g., Elliot 2000; Martinsen et al. 2000; Abreu et al. 2003; Beaubouef 2004).

In the Castle Creek study area (east-central B.C., Canada) the Isaac Formation comprises six thick (generally > 50 m), laterally extensive sandstone-rich units surrounded on all sides by mudstone-rich strata. Stratigraphically upward, Isaac Unit 5 is the fifth unit and offers an excellent opportunity to explore from the small-scale anatomy to the large-scale stacking pattern of slope channels. Isaac Unit 5 occurs within a turbidite-dominated slope setting (Isaac Formation) that developed on the Neoproterozoic passive margin of western North America. Within Isaac Unit 5, five types of channel-fill elements have been recognized. Each consists of a different assemblage of facies, stratal patterns, and/or lateral dimensions, and as a consequence, each has unique reservoir characteristics. Thin-bedded, overbank elements and debris-flow deposits are also observed in Isaac Unit 5. They represent potentially important impediments to subsurface fluid flow.

The objectives of this contribution are threefold: (1) to document and interpret the depositional architecture of Isaac Unit 5, including different types of channel-fill, overbank and debris-flow/slump elements; (2) to present a generalized evolution of Isaac Unit 5; and (3) to discuss its implications for characterization of slope-channel reservoirs.

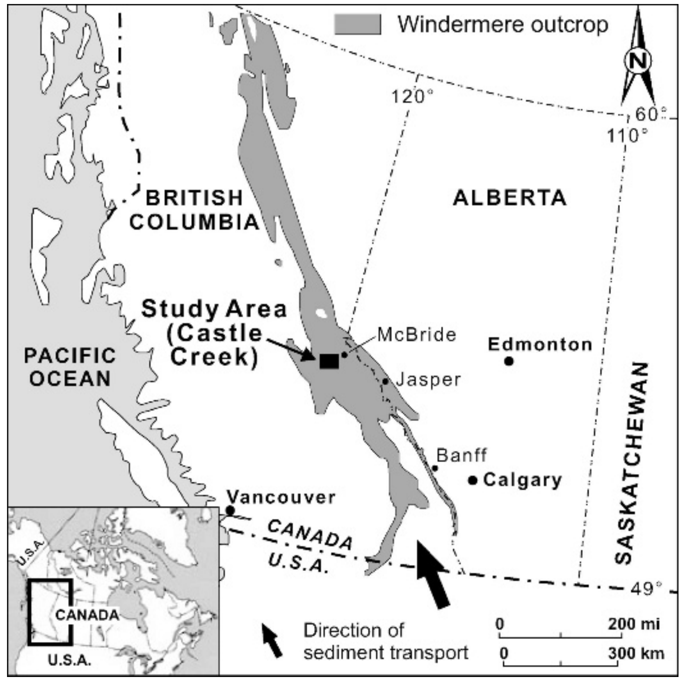

FIG. 1.— Location of the Castle Creek study area, Cariboo Mountains, east-central B.C., Canada. Distribution of Windermere strata is from Ross (1991). The inferred primary sediment source for the Kaza–Isaac turbidite system was located to the southeast (arrow).

GEOLOGIC AND STRATIGRAPHIC SETTING

The study area is located in the Cariboo Mountains, east-central British Columbia, Canada (Fig. 1). These mountains form part of the southern Canadian Cordillera, an extensive orogenic belt that borders the western margin of Canada and was built mainly during the Mesozoic (Ross et al. 1995). In the Cariboo Mountains, as well as many other places in the southern Canadian Cordillera, strata of the Windermere Supergroup crop out (Fig. 1) and record the Neoproterozoic evolution of western North America following the break up of the supercontinent Rodinia (Ross 1991). Initially the Windermere accumulated in fault-bounded basins related to an early phase of continental rifting. This was followed by a post-rift succession of deep-water sedimentary rocks (mainly Kaza Group and Isaac Formation) that locally shoal to platform carbonates (Cunningham Formation). This more than 7-km-thick succession represents the progradation of the passive continental margin of western North America into the proto Pacific Miogeocline to the west and northwest (Ross 1991; Ross et al. 1995).

The basal part of the Windermere turbidite system in the Cariboo Mountains comprises strata of the Kaza Group (2–3 km thick). It is composed of sheet-like sandstone-dominated units and subordinate mudstone packages that accumulated on the basin floor to toe of the slope (Ross et al. 1995; Meyer 2004). The Kaza Group, in turn, is overlain by the Isaac Formation, a mud-dominated unit over 2.5 km thick. The Isaac Formation consists principally of thin-bedded turbidites and lenticular, thick-bedded sandstone to conglomerate units (up to 100 m thick). In addition, debris-flow deposits and slide/slump complexes, some up to 100 m thick, are common and suggest deposition on an unstable slope. Deep-water carbonate intervals are also present in the Isaac Formation, indicating periods of relatively low clastic input interpreted to be associated with episodes of eustatic rise (Ross 2003). Provenance studies suggest that the principal sediment source for the Kaza–Isaac turbidite system was Archean rocks located to the southeast (Ross 2003). Inferred paleoflow data in the turbidite system also indicate that sediment transport was principally toward the north and northwest (Fig. 1).

Coeval shelf deposits of the Kaza–Isaac system are not preserved, mostly as a consequence of extensive erosion associated with uplift and rifting during latest Neoproterozoic–Early Cambrian throughout much of the southern Canadian Cordillera (Ross and Murphy 1988). However, shallow-water carbonate clasts (e.g., pisolitic–oolitic packstones, stromatolites, etc.) are common in several debris-flow deposits in the Isaac Formation, suggesting the occurrence of an adjacent shallow-water platform.

STUDY AREA AND METHODOLOGY

The Castle Creek study area constitutes a vertically dipping, recently deglaciated, superbly exposed section (Fig. 2). Strata of the Isaac Formation are about 1.4 km thick and comprise six major, laterally extensive (kilometer-scale), sandstone-rich units surrounded by thin-bedded, mudstone-rich strata and debris-flow/slide complexes. The sandstone-rich units are informally termed, stratigraphically upwards, Isaac Units 1 to 6 (Figs. 2, 3). Thin-bedded deposits comprise 63% of the total Isaac thickness, whereas sandstone-rich units made up 25%, and debris-flow/slide complexes about 12% of the total thickness. Low-grade metamorphism (primary sedimentary structures and textures are well preserved), relatively simple structure, extensive lateral continuity of strata, and periglacial conditions make this area an unparalleled region in which to examine the depositional architecture of deep-marine slope systems.

Isaac Unit 5 occurs about 1 km above the base of the Isaac Formation and forms part of a 3.5-km-long, SE–NW-trending section (Figs. 2, 3). The exposure was studied in four areas, which from SE to NW are: Cliff Section, Castle Creek South, Castle Creek North, and Hill Section (Fig. 2). The thickest succession occurs in the southeast end of the exposure, where it is 110 m thick. Thickness gradually decreases

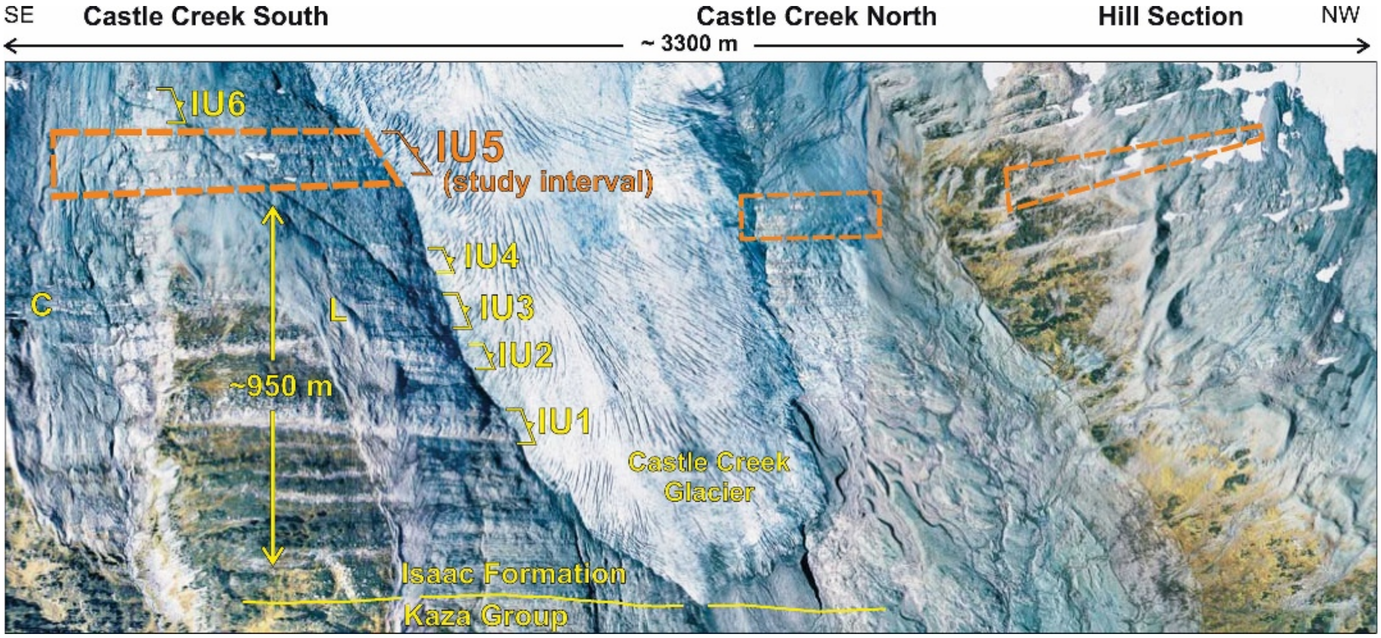

FIG. 2.—Aerial photomosaic of Castle Creek area showing the location of main (resistant-weathering) sandstone-rich units recognized in the Isaac Formation, which are informally termed Isaac Units 1 to 6 (IU1–IU6), and are surrounded by (more recessive) mudstone-rich strata. The study interval, Isaac Unit 5, was studied in four areas (indicated by dashed rectangles), but the detailed architecture characterization reported in this study was conducted in the Castle Creek South area (see Fig. 5). Toward the Cliff area (located immediately to the left of southwestern end of the photomosaic) Isaac Unit 5 thickens up to 110 m, but northwest of the Hill Section pinches out laterally into mudstone-rich strata. In the Castle Creek South area Isaac Unit 3 (IU3) is composed of channelized deposits (C) and laterally adjacent, genetically related levee and overbank deposits (L) (Navarro et al. in press). This figure is printed in color in the digital version.

northwestwards and is about 60 m thick in the Hill Section. Beyond the Hill Section (see Fig. 2) most of the sandstone-rich Isaac Unit 5 abruptly pinches out laterally into mudstone-rich strata. The unit has a locally scoured (up to 12 m deep) but regionally flat base, and a relatively sharp, transitional top. Isaac Unit 5 is capped by a mudstone-rich, thin-bedded interval more than 40 m thick (Fig. 3) that can be correlated between the four study areas.

Of the four study sites, the 700-m-long Castle Creek South study area is the most continuous and best exposed. Results presented herein are based mostly on observations made in this area. Major sedimentological sections were measured at decimeter-scale detail in the Castle Creek South area (Figs. 4, 5A). Lateral spacing between sections ranges from 100 to 200 m. Additional sections were measured to capture abrupt lateral facies changes. These sections are spaced laterally by a few tens of meters. This information was combined with field mapping using high-resolution aerial photos (1:250). In this way, all the significant surfaces could be identified and "walked out" laterally (see Fig. 5B). Outcrop gamma-ray logs were created using a hand-held scintillometer, and selected samples were analyzed in thin section.

GENERAL ORGANIZATION OF ISAAC UNIT 5

For most of the 3.5-km-long exposure, Isaac Unit 5 consists of three stacked sandstone-rich units (CC1, CC2, and CC3) that are separated by thin-bedded, fine-grained units. In Castle Creek South study area, Isaac Unit 5 thins northwestward from 100 to 75 m and is bounded above and below by > 25-m-thick, mudstone-rich units (T1 and T5 in Figs. 4, 5). T5 unit represents the fine-grained, thin-bedded interval that overlies Isaac Unit 5 across the 3.5-km-long outcrop.

In Castle Creek South, high-relief erosion surfaces, locally up to 12 m deep, are observed at the bases of two of the sandstone-rich units (Fig. 5B, C). Sandstone units range from 8 to 30 m thick and comprise multistory channel fills. These three stacked sandstone-rich units are considered herein as channel complexes and Isaac Unit 5 as a channel-complex set (*sensu* Campion et al. 2000, Fig. 6). One margin of the channel-complex set is observed northwest of the Hill Section study area (Fig. 2), where most of the unit abruptly pinches out into genetically related mudstone-rich deposits.

Thick-bedded, fine-grained conglomerate and sandstone beds deposited from high-concentration sediment flows constitute most of the channel-complex fill (Fig. 4). Fine-grained intervals are rare to absent within channel complexes, but where present they are truncated by the overlying channel fill (3C.t interval in Figs. 4, 5C). Paleocurrent directions were measured from cross-beds and flute marks within the sand-rich strata (Fig. 4) and suggest a general paleoflow toward the north (~ 350°). This indicates that the 3.5–km-long outcrop (SE–NW) provides a highly oblique cross section through the channel complexes, and as a consequence estimating channel width, and related width:depth ratio (aspect ratio), is highly subjective.

Debris-flow/slump units occur either within or at the base of channel complexes. A thin (< 1.5 m) debris-flow/slump unit is sandwiched between two channel fills in channel complex 2, and a thick (up to 7 m) debrite occurs at the base of channel complex 3 (D1 and D2, respectively in Figs. 4 and 5C). They are excellent stratigraphic markers within Isaac Unit 5 and can be correlated between the different study areas.

Laterally extensive, mudstone-rich units occur at the top of each channel complex. Mudstone-rich intervals capping channel complexes 1 and 2 range from 4 to 11 m thick and consist principally of thin-bedded upper-division turbidites (T3 and T4 in Figs. 4 and 5C). Similar deposits have been recognized immediately adjacent to channel complexes whose exposure represents an axis-normal cross section (IU3 in Fig. 2) (Navarro et al. in press). There, these thin-bedded deposits represent the muddier and thinner strata of a proximal-to-distal trend away from the channel complexes and were interpreted as distal levee deposits. Similarly, thin-bedded deposits (T3 and T4) in Isaac Unit 5 are interpreted to be overbank deposits related to out-of-the-plane channels.

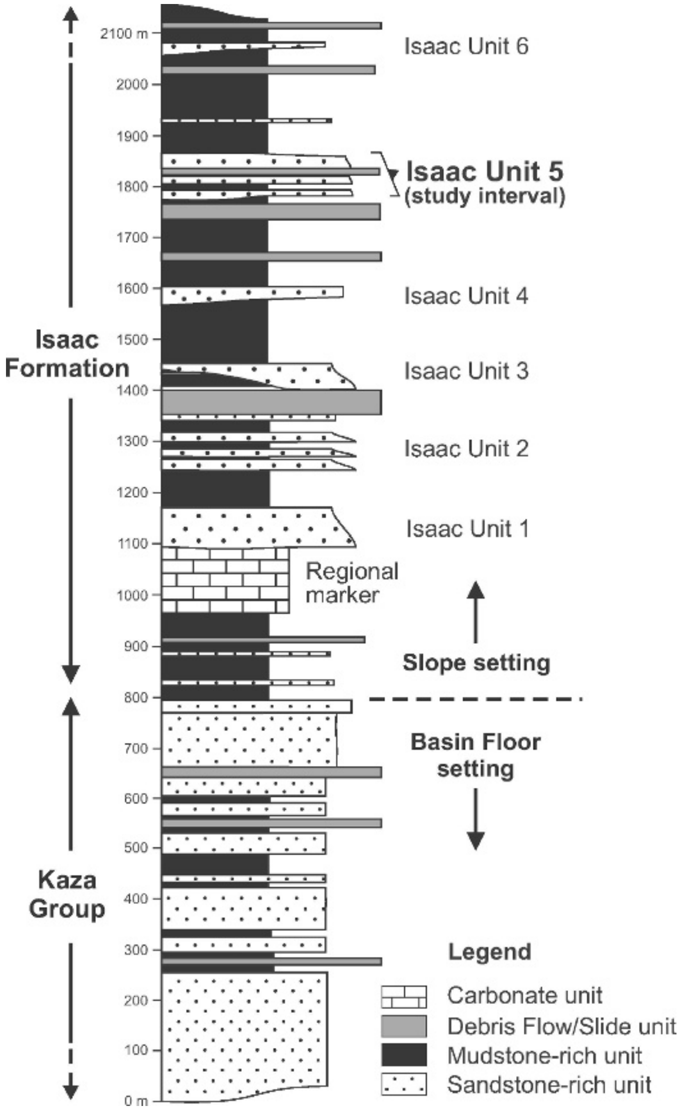

FIG. 3.— General stratigraphic section of Windermere strata in Castle Creek area and stratigraphic position of Isaac Unit 5.

Thin-bedded units also bound Isaac Unit 5 (T1 and T5 in Figs. 4 and 5C) but were not analyzed in detail in this study. Beneath Isaac Unit 5 the sheet-like strata (T1) decrease from 25 m to 13 m thick southeastward due to incision by channel complex 1 (Figs. 4, 5C). Unlike T3 and T4, T1 strata are composed of thin- to thick-bedded turbidites (up to 0.80 m thick, Fig. 4) that extend for at least another kilometer to the southeast of the Castle Creek South study area. Although these deposits are clearly unrelated to the overlying channel complex 1 (they are scoured by CC1), the genetic relationship between T1 and the channelized turbidite system represented by Unit Isaac 5 is presently poorly understood and is the subject of current research. The mudstone-rich element that overlies Isaac Unit 5 (T5) is similar but muddier than T3 and T4, and is more than 40 m thick. T5 is interpreted to represent background sedimentation following the deactivation, in space or time, of the entire channelized turbidite system.

DEPOSITIONAL ARCHITECTURE OF ISAAC UNIT 5

Channel-Fill Elements

The three stacked channel complexes are composed of several individual channel fills and are characterized by a high sand net-to-gross ratio (cumulative thickness of sandstone/conglomerate versus gross thickness, or simply N:G). Deeply scoured channel bases, although uncommon in the study area, are clearly recognizable in at least three places (Fig. 5B, C). The small number of deeply scoured bases is most probably an artifact of the subparallel orientation of the channels (mainly SE–NW) to the strike of the outcrop (N330°). Channel bases are more commonly approximately flat and are recognized by abrupt vertical changes in facies, for example sandstone (or coarser)-rich strata overlying fine-grained deposits (e.g., C3.1 channel fill) or slump deposits (e.g., C2.2 channel fill) (Fig. 4). Similarly, a sharp increase in grain size within a succession dominated by coarse-grained sediment is also inferred to represent the base of a channel fill (C3.2 overlying C3.1 in Fig. 4).

Channel fills range from 3 to 12 m thick and consist mostly of thick-bedded, Bouma Ta and Tab divisions, mudstone-clast breccia, and dune cross-stratified sandstone; Ta divisions are by far the most common lithofacies (Fig. 4). Finer-grained and thinner-bedded facies are uncommon. Vertical facies changes are normally associated with changes in internal geometry of the channel-fill strata. Internal geometry of the channel fills includes amalgamated, poorly stratified, non-amalgamated and inclined stratal successions.

The geometry of the channel fills (internal and external), in addition to facies assemblage, has resulted in the identification of five different channel-fill elements (Fig. 7). Their recognition is therefore based on descriptive and objective parameters (cf. Hickson and Lowe 2002).

Amalgamated Channel-Fill Element.—Amalgamated elements (C1.1, C2.1, C2.2, C3.1, and C3.2, in Figs. 4 and 5C) are the most common and contain the coarsest sediment in all three channel complexes. This channel-fill type consists almost entirely of thick-bedded, normally graded, pebble conglomerate or very coarse-grained sandstone that grade upward to medium-grained sandstone (Ta divisions, Fig. 4). Some beds show faint to well developed parallel lamination near the top (Tb division, Fig. 8A). Basal bedding surfaces are sharp, either flat or with shallow scours, and beds have fairly good lateral continuity (up to 300 m) (Fig. 8A). Fine-grained interbeds are rare to absent and as a result bed amalgamation is high (Fig. 7). At the bases of channel complexes, amalgamated channel fills commonly show erosional, concave-up bounding surfaces, increasing up to three times their thickness over distances of less than 100 m laterally (C2.1 in Fig. 5B, C; 100–200 m). Uncommon flute casts are observed associated with these basal bounding surfaces (Fig. 8B). C1.1 channel fill can be traced from the thickest section (axis) to the left channel margin (Figs. 5C, 9), a distance of ~ 400 m. Toward the channel margin, beds thin and onlap the basal surface of erosion. Grain size, however, decreases only slightly and amalgamation does not change from axis to margin (Fig. 9). Vertical changes in this type of channel fill were not obvious, but, in the case of

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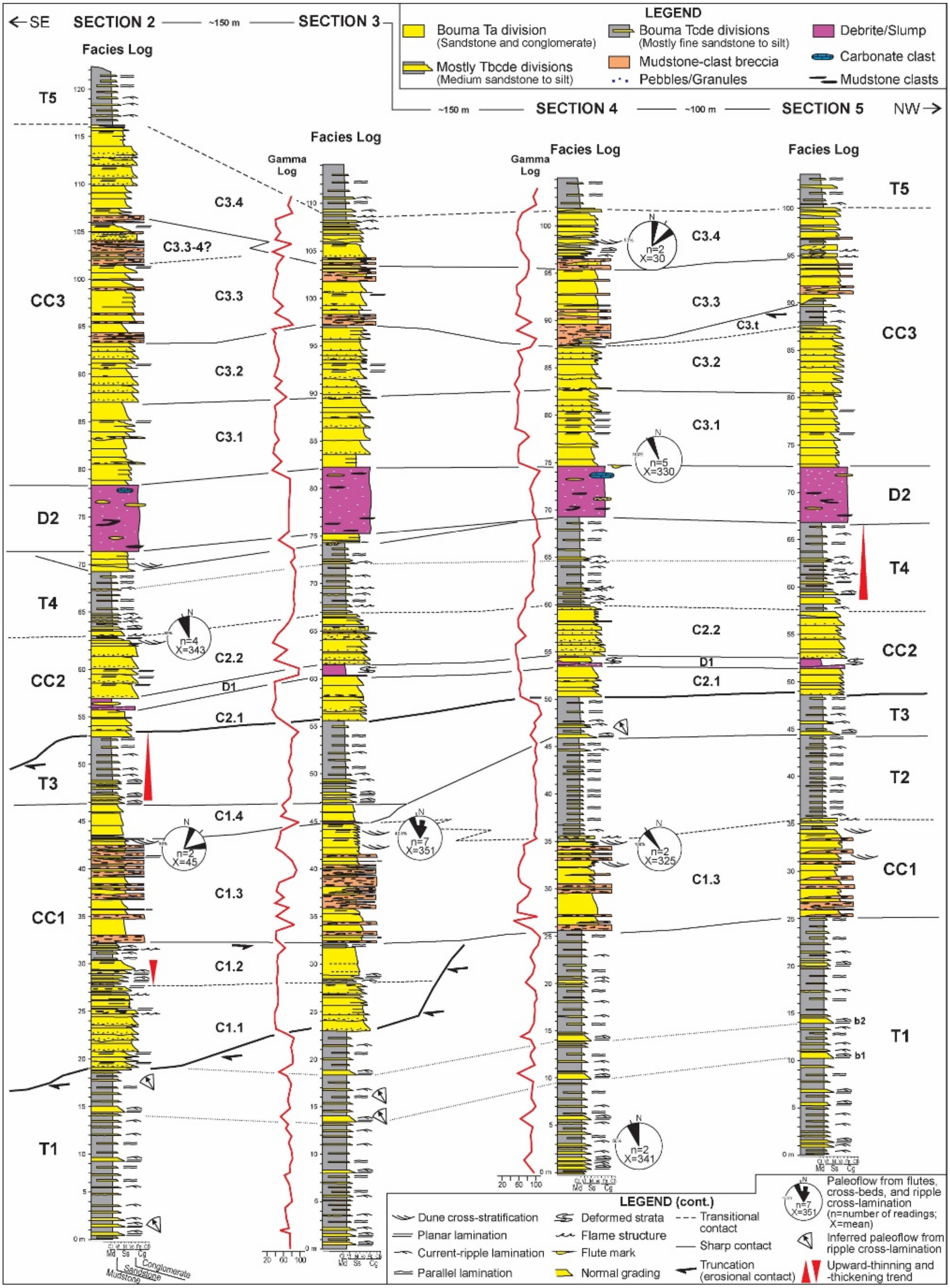
FIG. 4.—Selected bed-by-bed sedimentological sections measured in Isaac Unit 5 and general correlation between sedimentary units discussed in this study. The figure also shows correlation of two uncommonly thick (~ 0.80 m) beds that occur within unit T1 (labeled b1 and b2). This correlation suggests an erosive episode that formed an at least 12-m-deep scour prior to deposition of CC1. Location of sedimentological sections and detailed correlation is shown in Figure 5. This figure is printed in color in the digital version.


←SE
SECTION 2
~150 m
SECTION 3
~150 m
SECTION 4
~100 m
SECTION 5
NW→
Facies Log
Gamma Log
LEGEND
Bouma Ta division
(Sandstone and conglomerate)
Mostly Tbcde divisions
(Medium sandstone to silt)
Bouma Tcde divisions
(Mostly fine sandstone to silt)
Mudstone-clast breccia
Pebbles/Granules
Debrite/Slump
Carbonate clast
Mudstone clasts
T5
CC3
C3.4
C3.3-4?
C3.3
C3.2
C3.1
C3.t
D2
T4
CC2
C2.2
D1
C2.1
T3
T2
C1.4
C1.3
C1.2
C1.1
CC1
T1
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b2
n=4 X=343
n=2 X=45
n=7 X=351
n=2 X=30
n=5 X=330
n=2 X=325
n=2 X=341
Mudstone
Sandstone
Conglomerate
LEGEND (cont.)
Dune cross-stratification
Planar lamination
Current-ripple lamination
Parallel lamination
Deformed strata
Flame structure
Flute mark
Normal grading
Transitional contact
Sharp contact
Truncation (erosional contact)
Paleoflow from flutes, cross-beds, and ripple cross-lamination (n=number of readings; X=mean)
Inferred paleoflow from ripple cross-lamination
Upward-thinning and -thickening trend

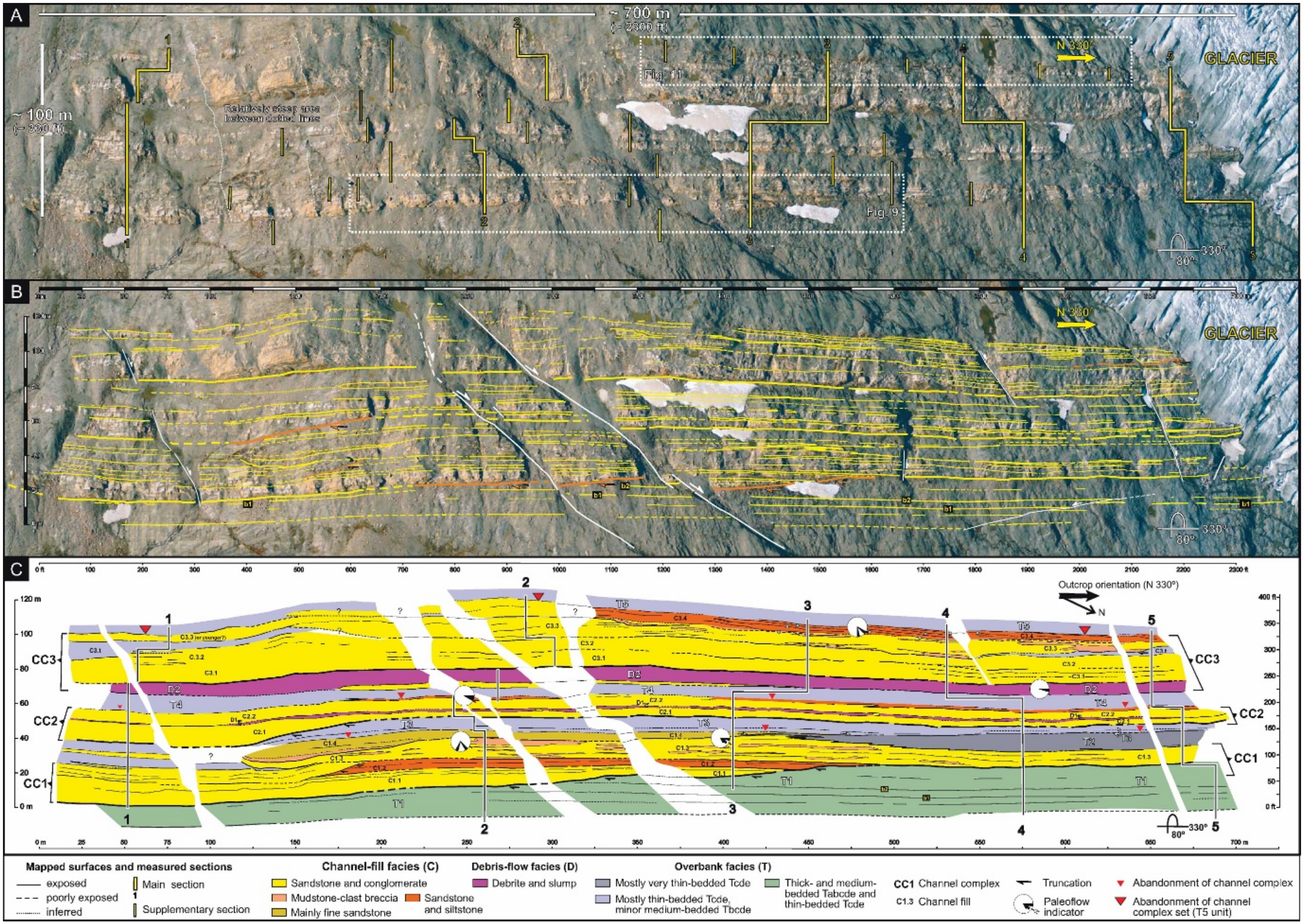


FIG. 5.—**A)** High-resolution aerial photograph (original scale 1:3800) of Isaac Unit 5 in Castle Creek South. Although covered locally with glacial debris, rocks of the study unit are commonly polished smooth with no lichen or soil cover because of rapid (< 100 years) deglaciation. Strata are overturned and ~ vertically dipping (75–85°) as part of the upright limb of a major anticline. Strike of strata and outcrop orientation is N150°–330°. **B)** Major surfaces mapped in Isaac Unit 5 and related units (all of them described and walked out in the field). Segments of surfaces where deep (> 5 m) incision was observed (interpreted as channel bases) are highlighted with orange lines. **C)** Fault-restored interpretation of Isaac Unit 5 showing main architectural elements: channel fills, channel complexes, thin-bedded units, and debris-flow/slump units. Rose diagrams (see Fig. 4 for statistic details) have been rotated to match north position in outcrop panel. Paleocurrent directions suggest a general paleoflow toward the north (~ 350°). This indicates that the outcrop provides a highly oblique cross section through the channel complexes, which may be responsible for the small number of deeply scoured channel bases. The stratigraphic stacking of three channel complexes vertically separated by thin-bedded deposits is considered to represent a channel-complex set (see Fig. 6). Larger version (11 × 17 in.) of Figure 5 is available in the digital version.

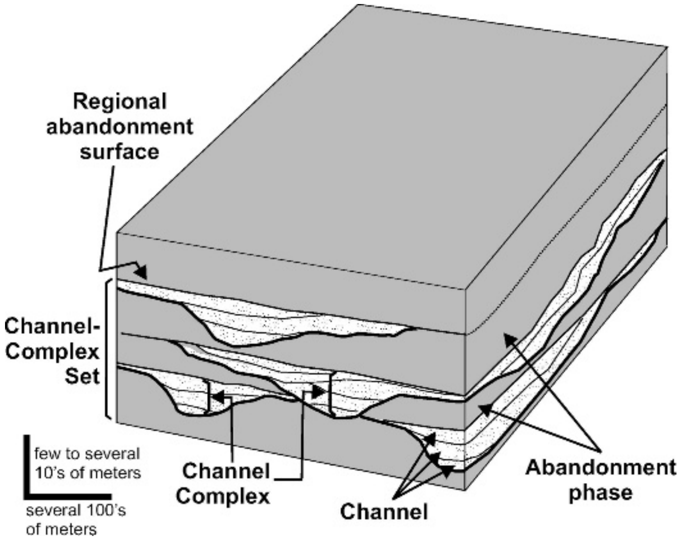


FIG. 6.— Schematic diagram showing stratigraphic hierarchy of deep-water channelized units (modified from Campion et al. 2000). Vertical or lateral stacking of channels form channel complexes, and channel complexes stack vertically to form channel-complex sets. The top of a channel-complex set is marked by a regional abandonment surface, whereas (less regionally extensive) abandonment phases cap channel complexes. The figure does not imply scale but channel complexes are typically approximately a few tens of meters thick and several hundreds of meters to few kilometers wide.

C1.1, strata become intercalated with siltstone-rich layers and are therefore less amalgamated toward the top (Fig. 9).

Amalgamated elements were deposited from sand-rich, high-concentration turbulent flows. Beds with basal shallow scours indicate an early erosional stage, succeeded by competence-driven suspension deposition, most probably because of waning flow speed (Camacho et al. 2002). This interpretation is supported by the common occurrence of Tb divisions at the top of the bed, indicating traction transport under conditions of reduced bed aggradation (Arnott and Hand 1989). Amalgamated and laterally continuous beds that gradually lap out onto the basal erosional surface (e.g., onlapping relationships in C1.1) are interpreted to represent broad, sheet-like deposits emplaced by oversized flows (i.e., wider than the width of the channel) that infilled most of the width of the active channel (cf. Sullivan et al. 2000). Similar amalgamated, sandy successions are common as turbidite channel fills in the ancient record (e.g., Mutti and Normark 1991; Clark and Pickering 1996; Beaubouef et al. 1999; Hickson and Lowe 2002; Camacho et al. 2002), and backfilling processes are typically invoked to explain these stratigraphic and architectural patterns (e.g., Clark and Pickering 1996). Sediment caliber and scale of amalgamated elements are also similar to high net-to-gross channel fills in Tertiary slope systems offshore West Africa (Mayall and Stewart 2000).

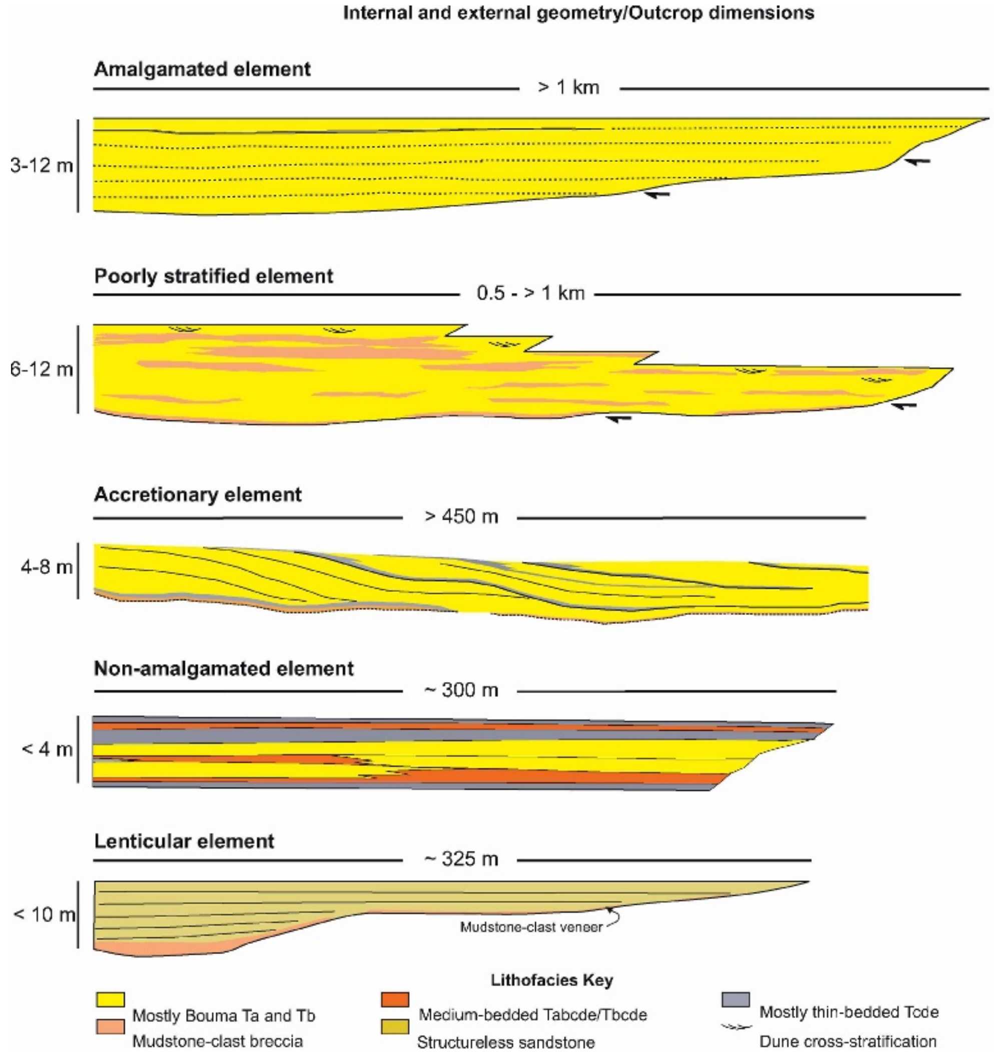
Poorly Stratified Channel-Fill Element.—Two channel fills are distinguished by abundant mudstone-clast breccia interbedded with sandstone (C1.3 and C3.3 in Figs. 4, 5C). Both units overlie an erosion surface, which in the case of C3.3 channel fill clearly incises thin-bedded deposits (C3.t in Figs. 4, 5C). Sandstone consists mostly of normally graded Ta turbidites (Fig. 7), but dune-cross-stratified beds become dominant toward the top of the C1.3 channel fill (Fig. 10A, E), where they interfinger with fine-grained deposits laterally (C1.3 interfingering with T2 unit in Fig. 5C). Mudstone-clast breccia typically represents less than 50% of the channel-fill thickness, but locally is up to 70%. Thin breccia with dispersed mudstone-flake clasts are associated with basal, concave-up surfaces, commonly overlain by sandstone beds (Fig. 10B). In contrast, many thick breccia layers (up to 2 m thick) typically show an irregular geometry (Fig. 5C), and amalgamate or bifurcate around sandstone layers over short distances (Fig. 10A). In these breccia layers, mudstone clasts are abundant and interconnected, displaying complex geometries (Fig. 10C). The matrix is not graded, and grain size is similar to the underlying and overlying strata. Millimeter-scale dikes protruding from underlying strata into the breccia layers are common (Fig. 10D), as well as mudstone clasts being incorporated into the underlying sandstone (rip-down clasts *sensu* Johansson and Stow 1995). Complete lateral transition from breccia layers to fine-grained laminated deposits has been observed locally.

Similar to the amalgamated elements, sand-rich flows are interpreted to have deposited normally graded sandstone beds in these channel fills. Scour by some of these sediment gravity flows, however, was more extensive and incorporated many silty clasts into the flow during the early erosional stage (possibly by erosion of updip overbank deposits). These clasts were probably transported in the lower, high-density part of the flow (e.g., Johansson and Stow 1995; Camacho et al. 2002), and were deposited soon thereafter, forming the thin breccia layers observed at the bases of some Ta beds. Thick, irregular breccia with interconnected (laterally continuous) mudstone clasts, sandstone dikes, and that grade sometimes abruptly laterally into fine-grained, laminated deposits are interpreted to be the result of postdepositional remobilization and injection of sand. Similar processes and related breccia layers have also been reported recently near the tops of deep-water channel fills in reservoirs of the North Sea (e.g., Duranti and Hurst 2004), where postdepositional brecciation is interpreted to be the product of catastrophic failure of mudstone-rich layers during hydraulic fracture (Hurst et al. 2003). Similarly, postdepositional brecciation modified the internal geometry of the poorly stratified channel-fill element (and reservoir connectivity), which originally was characterized by a relatively high number and/or thickness of intercalated mudstone-rich layers.

In channel fill C1.3, the postdepositional breccia zone grades upward into, but also is interbedded with, medium-bedded, cross-stratified sandstone. This suggests that dunes (bed-load transport) were originally interstratified with mudstone-rich layers and later were injected and brecciated. In addition, this association of breccia and dune cross-stratified beds in channel fill C1.3 thickens southeastward from section 4 to section 3, where it interfingers with thin-bedded deposits of T2 deposits (Figs. 4, 5C; 475–550 m). This succession is interpreted to be the result of simultaneous aggradation and lateral migration of an active thalweg that was oriented subparallel to the exposed section (see also interpretation of associated T2 thin-bedded deposits).

Accretionary Channel-Fill Element.—The uppermost channel fill of the Isaac Unit 5 is characterized by the presence of inclined strata (C3.4 in Figs. 4 and 5C). These inclined strata (4–8°) are up to 150 m wide and have a sigmoidal shape, converging updip and flattening downdip (Fig. 11). The basal surface of the channel fill is difficult to trace over the entire exposure but typically is overlain by a mudstone-clast breccia (Fig. 11). The channel fill comprises sandstone beds interbedded with fine-grained intervals forming packages up to 2.5 m thick. Packages are best defined by erosional surfaces, which are typically overlain by fine-grained intervals composed of very thin-bedded Bouma Tcde turbidites (Figs. 7, 11). Sandstone-rich portions of packages have a flattened lens shape and shale-out updip, as sandstone beds become less amalgamated (Figs. 11, 12A). Sandstone layers consist principally of Ta turbidites, but uncommon cross-stratified sandstone beds were also observed (Fig. 7). Average paleoflow direction (from trough axes of 3D cross stratification) is oriented at a high angle (mean toward 53°) to the inclined strata, which dip toward the northwest (Fig. 11).

Inclined strata are interpreted to represent lateral-accretion packages deposited on the inner bend of a laterally migrating, sinuous channel



Element	Grain size/ Facies/Basal bed surfaces	Bed-thickness range, average and lateral continuity (m)	Vertical/Lateral Trends	Interpretation
Amalgamated element	Pebbly conglomerate to fine sandstone Ta beds ~75% Tab beds ~25% Shallow scours (< 20 cm deep)	0.10 - 1.90 m 0.55 Fairly good (up to 300 m)	Amalgamation decreases slightly upward Decrease grain size and bed thickness from axis to magin	Backfilling of a thalweg; sheet-like deposits by sand-rich, high-concentration turbulent flows
Poorly stratified element	Pebbly sandstone to medium sandstone Ta beds <50% Tx beds[1] <20% Mudstone-clast breccias 30-70% Shallow scours	0.05 - 4 m N/A[2] Moderate to fairly poor (< 200 m)	Tx facies in upper 1/3 of element Postdepositional mudstone-clast breccias dominate in upper half of element	Aggradation and lateral migration of active thalweg; mostly high-concentration flows, but bedload transport common in upper parts
Accretionary element	Pebbly sandstone to mudstone Ta beds <80% Tx beds <5% Tc-e beds <20% Shallow scours	0.02 - 1.32 m 0.31 Fairly poor (< 150 m)	Sandstone packages shale-out updip Mudstone layers at base of packages, associated with erosion and truncation	Deposition on inner bend of sinuous, non-aggradational channel; bypass flows associated with thin-bedded intervals; gradual deactivation of sand-rich pathway
Non-amalgamated element	Pebbly sandstone to mudstone Ta-e beds <70% Tc-e beds >30% Flat, non-erosional	0.03 - 1.60 m 0.34 Moderate (< 200 m)	Upward-coarsening and -thickening cycles Mudstone intervals increase upward	Gradually waning flow and semi-confined deposition (lobes?) develop during terminal stage of channel filling
Lenticular element	Medium to very fine sandstone Structureless 65-95% Mud-clast breccias 5-35% Flat, non-erosional	0.01 - 1.80 m 0.57 Fairly good along the length of element (up to 300 m)	No trend observed	Passive filling after abrupt deactivation of thalweg (up-dip levee breaching and avulsion event?)

1. Tx beds: dune cross-stratified sandstone beds.

2. N/A: not available due to highly variable thickness of mud-clast breccias

FIG. 7.—Schematic representation, description, and interpretation of channel-fill elements recognized in Isaac Unit 5. This figure is printed in color in the digital version.

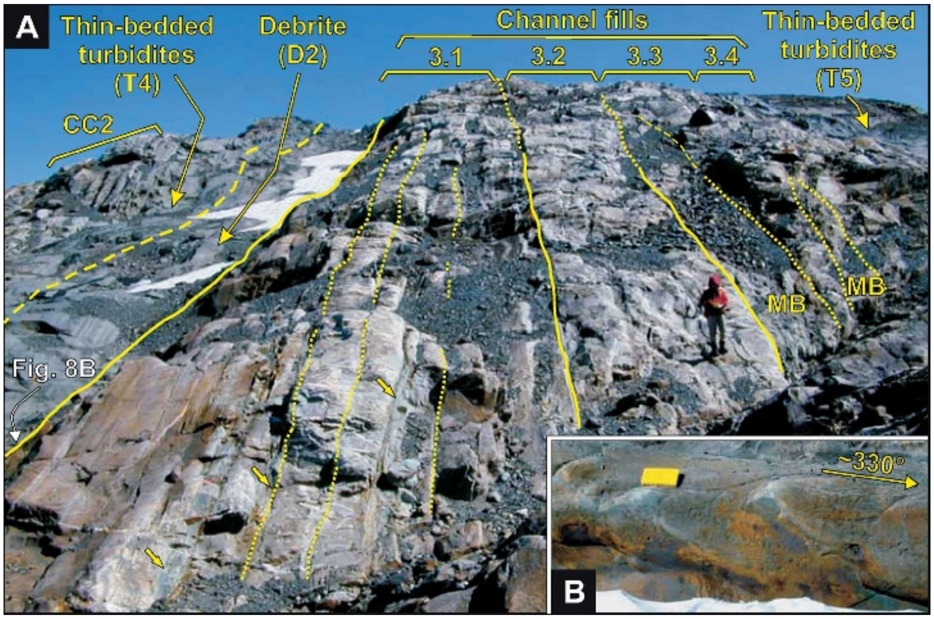


FIG. 8.—**A)** Main characteristics of amalgamated channel-fill elements as seen in C3.1 and C3.2 channel fills (near Section 4, view to SE). Beds are laterally continuous and tabular, but with occasional scoured surfaces. In some cases, normally graded Ta beds pass upwards to Tb divisions (thick arrows). This pattern is interrupted by mudstone-clast breccias (MB) of C3.3 channel-fill. Person for scale. **B)** Flute casts developed at the base of C3.1 channel fill. Notebook for scale. This figure is printed in color in the digital version.

(Elliot 2000; Abreu et al. 2003; Arnott in press a). Sandstone beds were mostly deposited from suspension from high-density turbidity currents. Thin-bedded turbidites associated with erosional basal surfaces, on the other hand, are most probably the result of deposition from the tails of bypass flows (Abreu et al. 2003). These high-energy flows were responsible for erosion of previous packages and were likely associated with discrete episodes of lateral migration of the channel (Kolla et al. 2001).

Non-Amalgamated Channel-Fill Element.—This element exhibits a general tabular geometry and gradationally overlies an amalgamated channel fill (C1.2 in Figs. 4, 5C). The 4.5-m-thick succession of C1.2 crops out over 350 m of length and is composed of a lower and upper interval (Figs. 9, 12B). The lower interval consists of thin-bedded Tcde turbidites grading upward to medium- and thick-bedded complete Bouma sequences, where basal, non-erosional surfaces predominate (Fig. 12B). Sandstone-rich tops of these upward-coarsening and -thickening successions thin and fine laterally (Fig. 9). This internal geometry suggests a compensational stacking pattern (*sensu* Mutti and Normark 1991). The upper interval is dominated by thin-bedded turbidites with subordinate medium-bedded Tbcde beds (Figs. 9, 12B). This upper section is truncated by an erosional surface associated with a younger channel fill (C1.3 in Fig. 9). Strata of C1.2 channel fill appear not to extend beyond an original, basal erosional surface in the northwestern margin (Fig. 9; 275–325 m). On the contrary, beds thin rapidly and lap out onto previous thin- and medium-bedded deposits of T1 unit (Figs. 4, 9).

Stratigraphic relationships suggest that the non-amalgamated element was deposited during the terminal stage of channel filling by underfit flows. Alternatively, it might represent the marginal area of a time-equivalent amalgamated channel-fill element. As described earlier, however, those kinds of channel fills show no significant change in sandstone amalgamation from axis to margin because of deposition from oversized flows, and therefore represent flows different from those suggested here. Complete Bouma sequences are considered to reflect deposition from weakly unconfined, moderate- to low-concentration flows, possibly undergoing rapid expansion. More dilute turbidity currents were responsible for the deposition of thin-bedded, upper-division turbidites. Facies, geometry, and upward-coarsening and -thickening packages in the lower interval could represent the development of depositional lobes (Mutti and Normak 1991). Gardner and Borer (2000) and Eschard et al. (2003) suggested that "spill-over" lobes may develop during the final stage of channel filling due to relatively unconfined flows. Similar flows are envisaged here, but in this case it appears that sedimentation occurred largely within the previous channelized relief with minor overspill. Dilute turbidity currents became dominant with time (upper interval), which in turn were terminated when the area became reactivated as a conduit for sand-rich flows (younger channel fill).

Lenticular Channel-Fill Element (with Structureless Sandstones).—This $>$ 300-m laterally extensive channel fill consists mostly of fine-grained sandstone beds and exhibits a concave-up, basal bounding surface (C1.4 in Figs. 4 and 5C). Sandstones are structureless to weakly normally graded, and beds are mostly thick-bedded (Fig. 12C). Millimeter-scale siltstone drapes between sandstones are uncommon, and hence bed amalgamation is high (Fig. 7). Toward the northwest the base of the element is covered by a mudstone veneer ($\sim$ 10 cm thick) overlain by sandstones that thin and onlap the basal surface (Fig. 12D). In contrast, along the southeastern margin, the basal 1/3 of the element is composed of an association of mudstone-clast breccia, grading upward to thin, planar-laminated sandstone and mudstone beds (Fig. 5C; 125–200 m). Despite the concave-up geometry of the basal bounding surface (Fig. 7), well developed erosion surfaces into underlying deposits were not observed.

Recently, Leclair and Arnott (2003, 2005) reported that deposition of structureless sandstones lacking evidence of traction and/or dewatering structures is the result of extremely high rates of sediment fallout and bed aggradation associated with a submerged hydraulic jump. Hydraulic jumps are the result of abrupt flow thickening and loss of flow competence and capacity in high-energy turbidity currents (Leclair and Arnott 2003), and are thought to be common in deep marine settings (e.g., Komar 1971). Similar facies have been interpreted to form part of a proximal crevasse splay in an interchannel area downflow of a breach in a channel-margin levee (Arnott in press b). In the case of Isaac Unit 5, structureless deposits infilled a channelized feature in which the basal bypass-related facies (mudstone-clast breccias and veneer) suggest an early stage of erosion and minor sedimentation (e.g., Eschard et al. 2003). It is not clear, however, whether all of the negative relief (up to 10 m) was

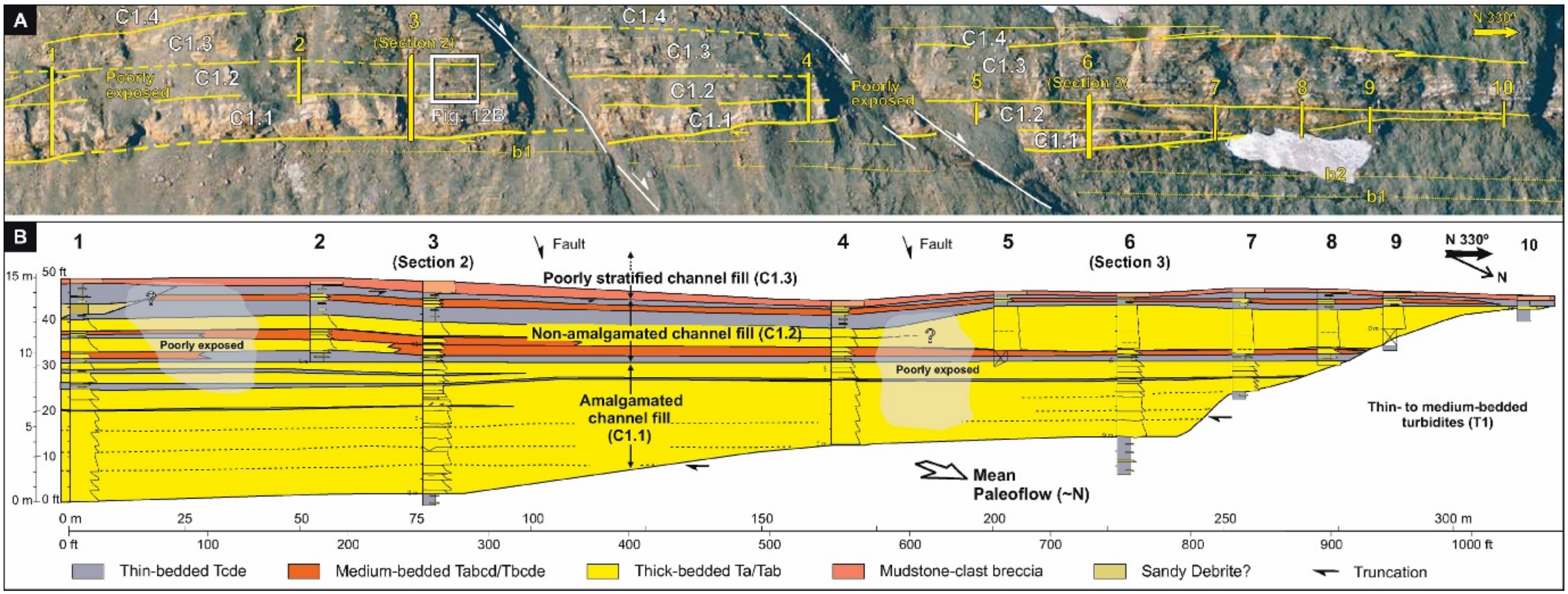


FIG. 9.—**A)** Aerial photograph of basal portion of Isaac Unit 5, showing channel complex 1 and its individual channel fills (C1.1 to C1.4), with location of measured sections. See Figure 5A for photograph location. **B)** Schematic (fault restored) cross section with sedimentary logs illustrating interpreted depositional architecture of amalgamated element (C1.1 channel fill), and non-amalgamated element (C1.2 channel fill). Note that in both cases beds lap onto an erosional basal surface scoured into thin- to thick-bedded turbidites of T1 (beds b1 and b2 as marker horizons in Fig. 9A). This figure is printed in color in the digital version.

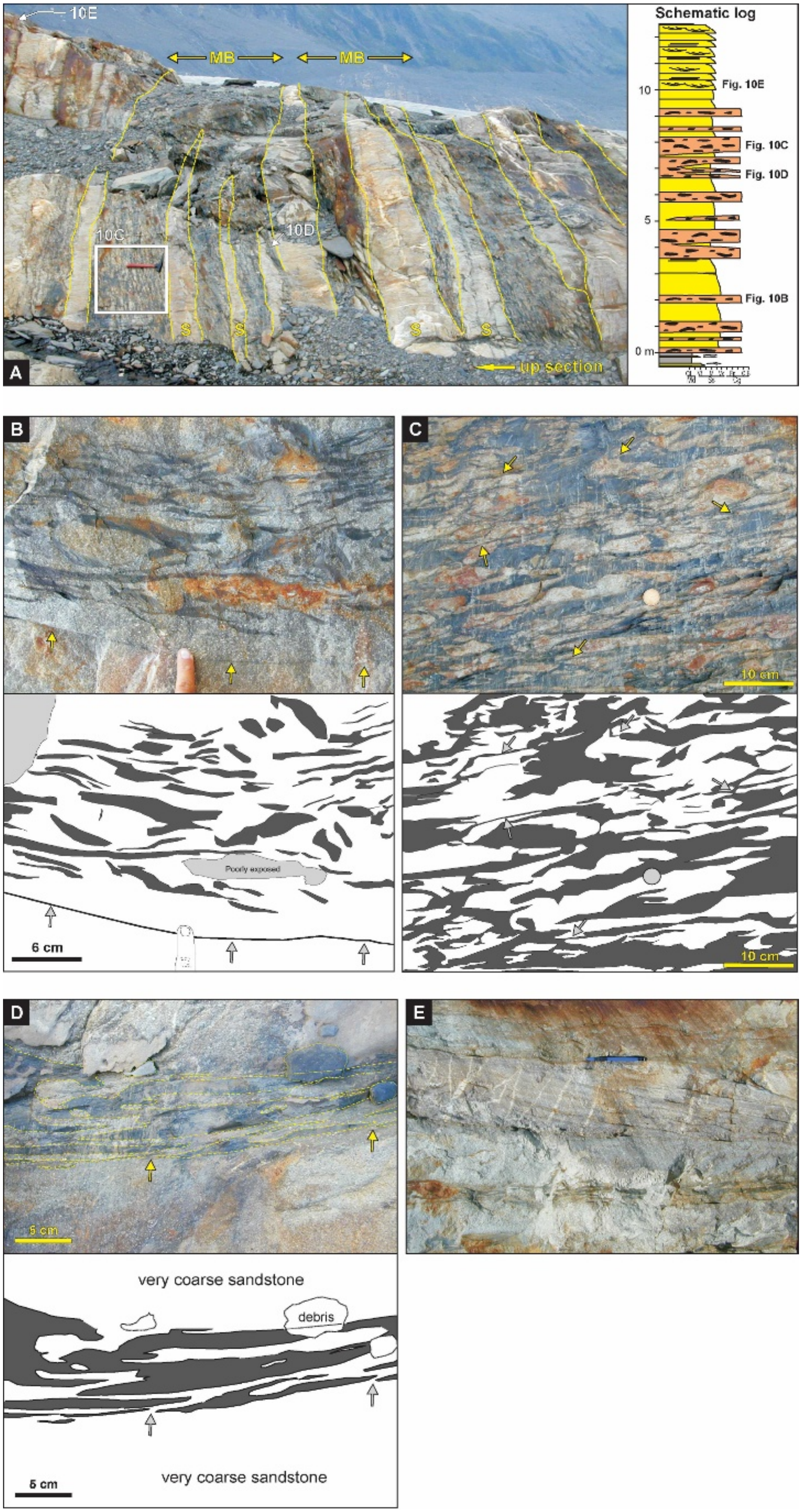


FIG. 10.—**A)** Detailed view of poorly stratified C1.3 channel fill and sedimentary log (legend as in Fig. 4). Note irregular bedding: several sandstones beds (S) pinch laterally into mudstone-clast breccia (MB). Hammer for scale. **B)** Photo and sketch of thin mudstone-clast breccia with low abundance of clasts and associated with a basal erosional bed surface (arrows). This breccia type is interpreted as a depositional feature. **C)** Photo and sketch of irregular clast-rich mudstone layer. Note the irregular lateral continuity of most clasts (arrows), in particular their rapid thinning and thickening and many delicate overhangs and protrusions (arrows). See location in Part A. **D)** Photo and sketch of mudstone-clast breccia that shows millimeter-scale dikes protruding from underlying sandstone (arrows). Note the ptygmatically "folded" (Z-shaped) shape of the sandstone dikes, which is the cumulative result of postdepositional compaction (Precambrian) and tectonic cleavage (Mesozoic) development. See location in Part A. Breccia layers in Parts C and D are interpreted to be the result of post-depositional (*in situ*) brecciation. **E)** Dune cross-stratified sandstone bed at the top of C1.3 channel fill; paleoflow direction is to the right. Pencil for scale. See location in Part A. This figure is printed in color in the digital version.

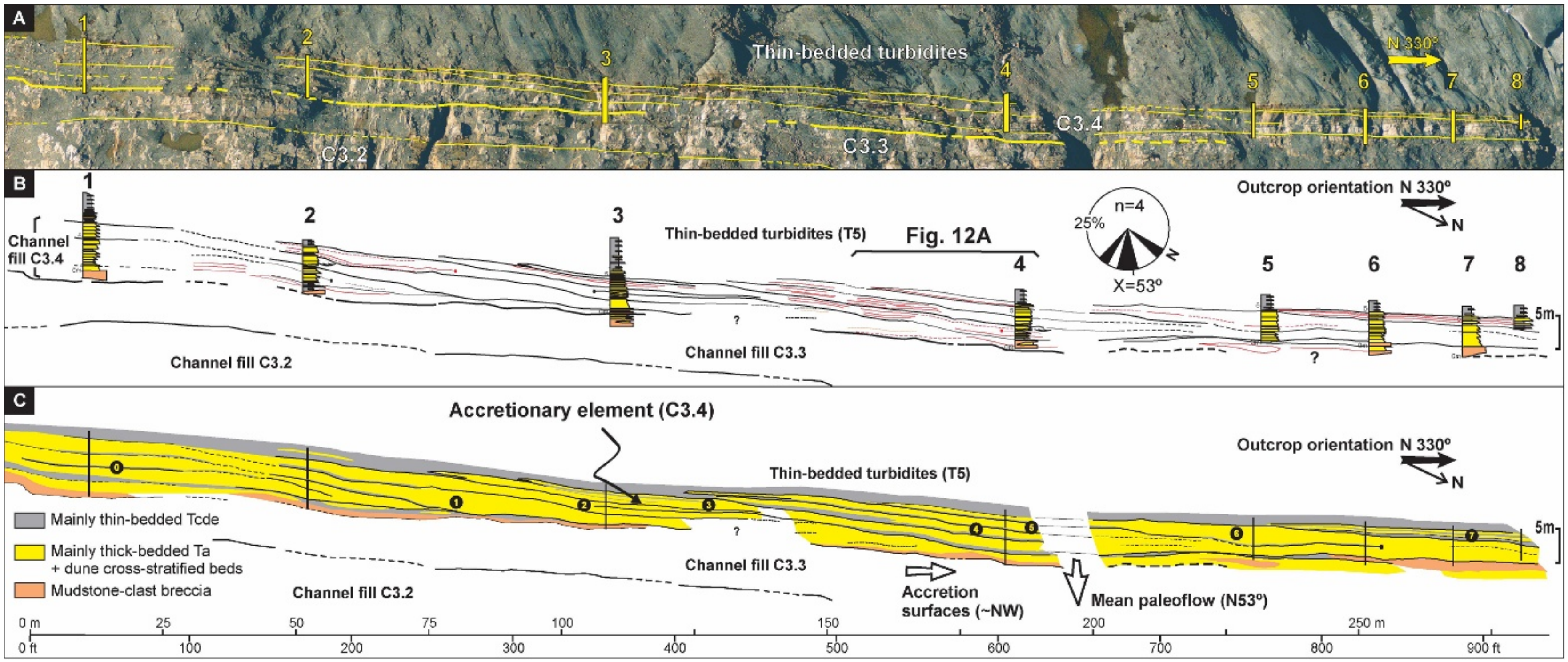


FIG. 11.—Accretionary channel-fill element (C3.4) developed in the uppermost part of Isaac Unit 5. **A)** Aerial photograph and principal mapped surfaces (see Fig. 5A for location). **B)** Sedimentary logs, paleoflow data, and all stratal surfaces mapped in the field and correlated between logs (black lines, boundaries between principal mapped stratal packages; red lines, secondary surfaces within packages). **C)** Facies distribution and internal architecture in this channel-fill element is interpreted to represent six major lateral-accretion packages (numbered 1 to 6), where sandstone-rich portions typically flatten downdip and shale-out updip. Inclined accretion surfaces dip 4–8° to NW, and mean paleoflow (N53°) is roughly perpendicular to accretion surfaces. This figure is printed in color in the digital version.

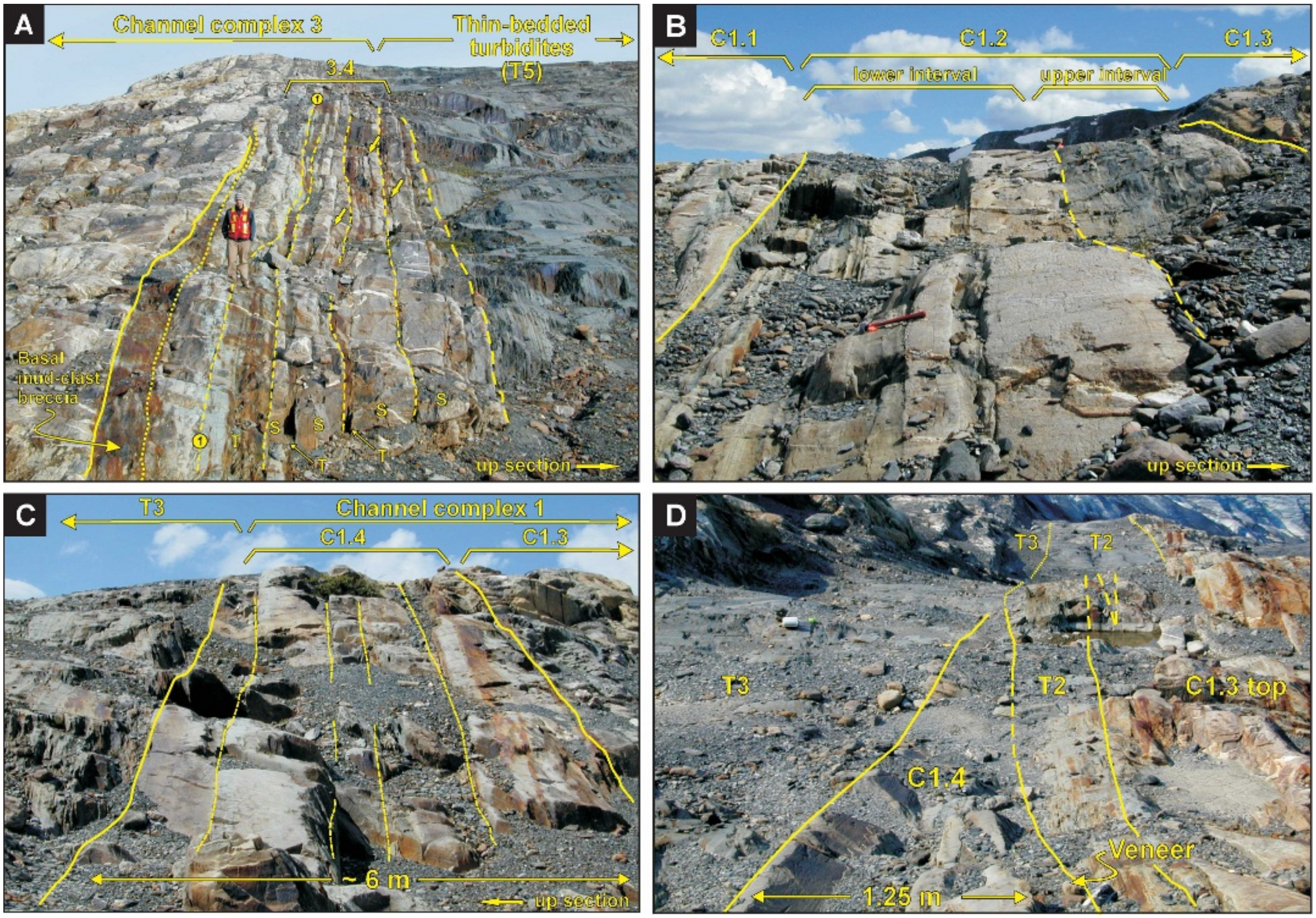


FIG. 12.—**A)** Accretionary channel fill (C3.4) showing inclined strata where sandstone beds (S) thin and mudstone-rich, thin-bedded intervals (T) thicken toward the updip section of lateral-accretion packages (arrows). Inclined strata are dipping to NW, and paleoflow is coming out from the outcrop (~ NE). View to southeast; see Figure 11B for location. Person for scale. **B)** Non-amalgamated element (C1.2) overlying an amalgamated channel fill (C1.1). C1.2 consists of a lower interval with upward-thickening and -coarsening trend, and an upper interval with muddier deposits (see Fig. 9A for location), hammer for scale. **C)** Lenticular channel-fill element with thick-bedded structureless sandstones (C1.4). Note massive aspect and amalgamation of beds, as well as sharp upper contact of the element with medium- to thin-bedded turbidites of T3 unit. **D)** Same channel fill in the northwestern (right) margin, where sandstone beds gradually thin and lap out onto a concave-upward basal surface (overlain by mudstone-clast veneer). This figure is printed in color in the digital version.

the result of excavation due to extensive erosion, or instead was preexisting topography. The lack of clear truncation of the underlying channel-fill element suggests that the second interpretation is more plausible. If this is true, it follows that the lenticular element represented the passive filling of an active, unfilled thalweg when, because of an updip avulsion event, it rapidly ceased to function as a pathway for coarse-sand-rich sediment gravity flows.

Overbank Elements

Thin-bedded sandstone and mudstone turbidites separate the three stacked channel complexes of Isaac Unit 5 (Figs. 4, 5C). Two kinds of overbank elements were identified: a very thin-bedded element (T2) that interfingers laterally with a channel-fill element (inner-bend levee), and medium- to thin-bedded deposits (T3 and T4) that overlie channel complexes 1 and 2 (abandonment phase). Channel complex 3 is also capped by a medium- to thin-bedded element (T5, Figs. 4, 5C, 12A), which is much thicker (> 40 m) than T3 and T4 and is interpreted to represent the abandonment phase, in space or time, of the channel-complex set.

Very Thin-Bedded Element (Inner-Bend Levee).—This element (T2 in Figs. 4 and 5C) consists largely of very thin-bedded turbidites (< 2 cm thick) where basal Tc divisions are up to fine sandstone with poorly developed ripple cross-lamination (Fig. 13A). These Tc divisions grade upward to laminated and/or massive siltstone or silty mudstone. The lower half of this very thin-bedded element interfingers laterally and vertically with the upper section of channel fill C1.3 (Fig. 14A; 300–375 m). Here, coarse-grained sandstone beds capped by ripple cross-lamination thin very rapidly away from the adjacent channel fill into the millimeters-thick turbidite beds (''fingers,'' Fig. 13B), suggesting a genetic link between the two elements.

Deposition of this overbank element is interpreted to be the result of aggradation by overspilling of very dilute flows from the adjacent channel, while it migrated and aggraded towards the SE (left in the outcrop face). Although the top of the mudstone-rich element and the channel fill crop out at the same level, a conservative decompacted cross section (Fig. 14B) shows that the top of T2 was at least 10 m higher than the channel floor (i.e., last deposited sandstone in channel fill C1.3). This relationship indicates that the overbank element did have a positive (levee) relief, making it analogous in lateral relationships and geometry to

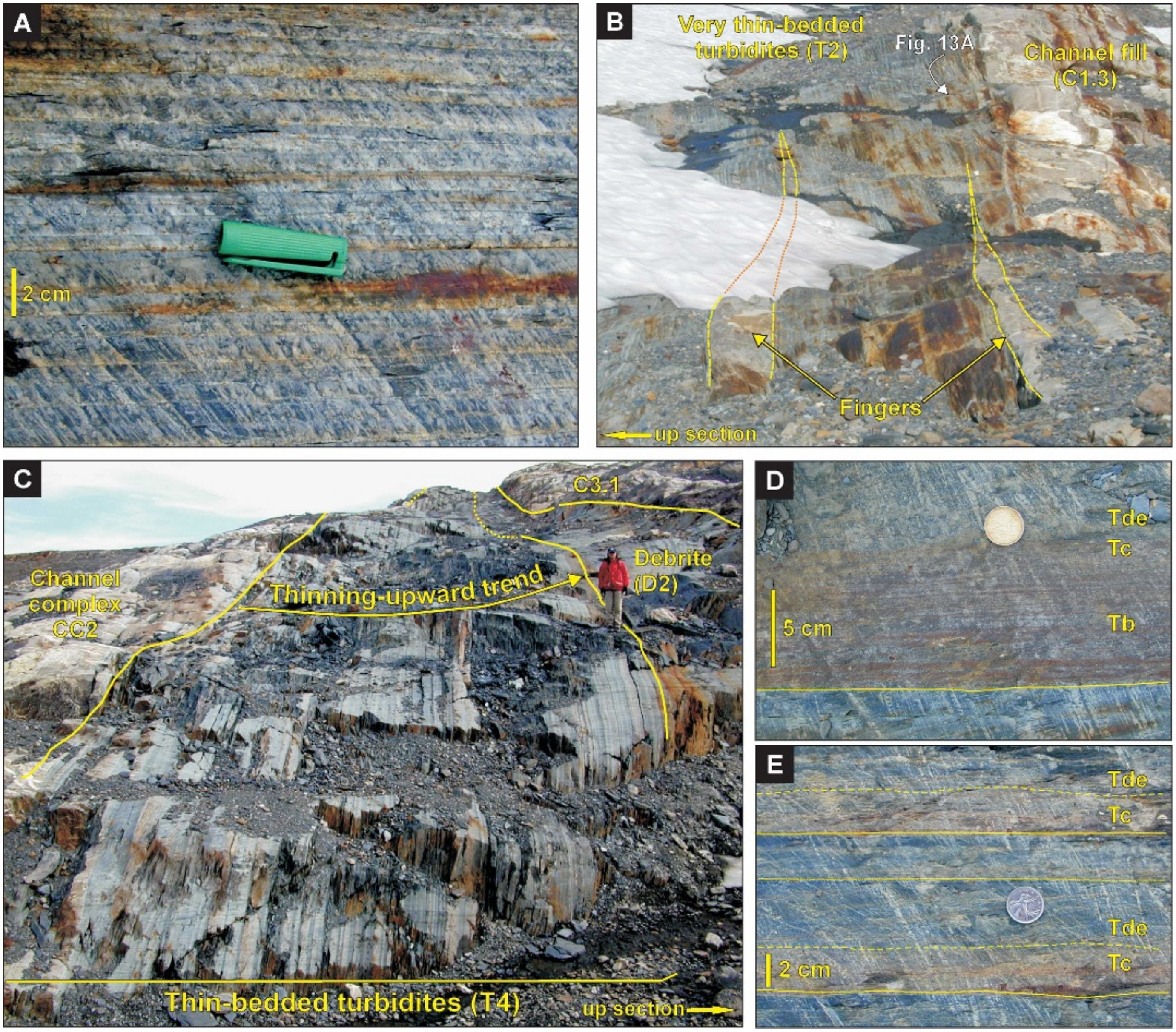


FIG. 13.—**A)** Detailed view of very thin-bedded turbidites that characterize the "inner-bend" levee element (unit T2). **B)** Sandstone beds in the upper part of C1.3 channel fill thin very rapidly ("fingers") into typical millimeter-thick turbidite beds of unit T2. See Figure 14A for location. **C)** Medium- to thin-bedded element (T4) formed as a result of local abandonment of the channel complex. Note overall upward-thinning trend. **D)** Medium-bedded sandstone bed (~ 15 cm thick) typical of lower interval in this element, with well-developed Tb division and diffuse wavy top, grading to silt-rich Tde divisions. **E)** Thin-bedded and very thin-bedded Tcde turbidites, typical of the upper intervals of T3 and T4 overbank elements. This figure is printed in color in the digital version.

a seismic element termed "inner levee" (*sensu* Deptuck et al. 2003; see discussion below).

Medium- to Thin-Bedded Element (Abandonment).—This type of overbank element occurs at two stratigraphic horizons in Isaac Unit 5 (T3 and T4 in Figs. 4 and 5C). Unit T3 sharply overlies the previous thin-bedded element (Fig. 14A) and the top of channel complex 1 (Fig. 12C), whereas unit T4 gradationally overlies channel complex 2 (Fig. 13C). These mudstone-rich units are up to 11 m thick and exhibit a fining- and thinning-upward trend (Fig. 13C). The lower third of the element consists commonly of Tbcde turbidites, 15–30 cm thick, interbedded with thin-bedded Tcde turbidites (Fig. 13D). Sandstone-to-mudstone ratio is on the order of 0.6, and loaded bases and flame structures are common. The upper two thirds is composed almost exclusively of thin-bedded Tcde turbidite beds, ranging in thickness from 2 to 15 cm (4 cm in average) (Fig. 13E). Tc divisions are typically less than 3 cm thick in these beds; cross-lamination is difficult to discern, but wavy tops are common (Fig. 13E). Tde divisions are composed largely of silty mudstone. Significantly, several beds in the upper interval can be traced laterally over a distance of at least 650 m (i.e., outcrop length) with only minor changes in thickness.

Turbidites of the medium- to thin-bedded element were deposited from moderate- to low-concentration turbidity flows that overspilled an adjacent, but not exposed, channel complex. They represent a phase of local channel-complex abandonment and areally extensive (kilometer-scale) middle to distal overbank deposition. The upward decrease in

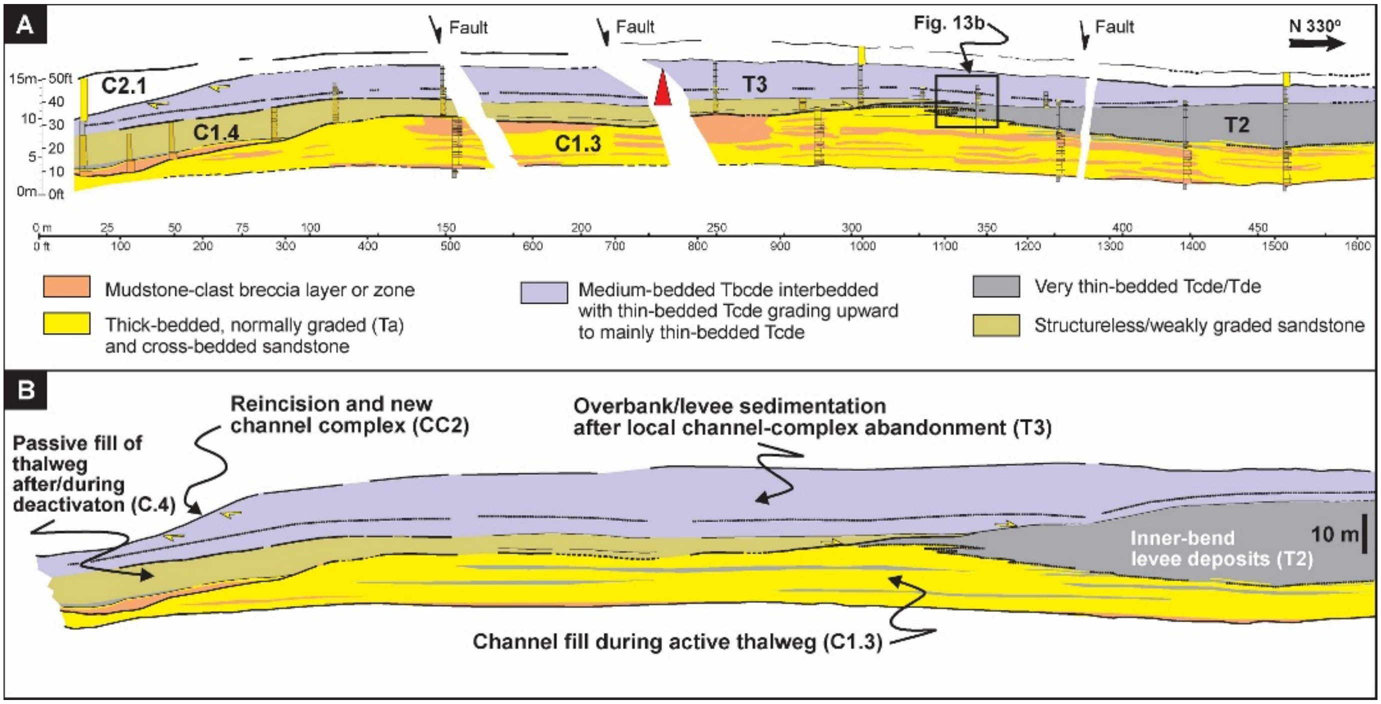


FIG. 14.—Detailed stratigraphy and architectural relationships between C1.3 and C1.4 channel fills, and T2 and T3 thin-bedded overbank units. See explanation in text. **A)** Normal cross section. **B)** Decompacted and interpreted cross section. Mudstone-rich intervals were decompacted by a factor of 2; mixed sandstone–mudstone intervals by a factor of 1.5; sandstone-rich intervals by a factor of 1. This figure is printed in color in the digital version.

sandstone proportion and bed thickness in this overbank element suggests that the genetically related channel complex gradually moved away from the outcrop face and/or become deactivated with time.

Debris-Flow/Slump Elements

Two unstratified units that are linked to cohesive sediment gravity flows and mass movement are observed in the study area (D1 and D2 in Figs. 4 and 5C). The lower unit (D1) is a laterally persistent horizon less than 1.5 m thick encased between amalgamated channel fills of channel complex 2 (Fig. 15A). At its base it comprises a laterally thinning and thickening (5–40 cm thick) layer where quartz grains (< 3 mm) are concentrated (Fig. 15B) and clasts of well-preserved thin-bedded turbidites are common. The top of this layer is diffuse and overlain by an interval composed mostly of tightly folded blocks of thin-bedded deposits (Fig. 15B) and sandstone rafts up to 2 m long (Fig. 15A). This unit is interpreted as being deposited by a debris flow that likely evolved rapidly from a mass movement (slump?) derived from collapse of the adjacent channel wall (e.g., Mayall and Stewart 2000; Eschard et al. 2003). This failure event could have resulted in rapid plugging and deactivation of the turbidite channel responsible for C2.1 channel fill.

The upper unit (D2) is 5–8 m thick and more than 3 km long (it pinches out in the Hill section, Fig. 2). For the most part it sharply overlies an overbank element (T4) and is slightly eroded at the top (Fig. 15C). D2 is a pebbly mudstone (debrite) composed of a massive, silty–muddy matrix with dispersed detrital pebbles (quartz and feldspars), large folded mudstone clasts, and cobble carbonate clasts (Fig. 15D). The occurrence of carbonate clasts suggests remobilization not only of deep-water deposits as in D1 but also of relatively shallower sediments. This unit most probably represents a cohesive sediment gravity flow that was related to gravitational instability up-system, likely near the shelf margin (e.g., Posamentier and Kolla 2003). Destabilization of a shelf margin that leads to frequent ignition of cohesive sediment gravity flows could be related to several causes, including: changes in relative sea level (e.g., Posamentier and Kolla 2003), tectonic pulses (e.g., Pickering and Corregidor 2005), a combination of the two, or seismicity. However, which one or a combination of these processes caused the instability cannot be assessed in this contribution. Nonetheless, the fact that D2 debris-flow deposition occurred after an episode of channel-complex deactivation (T4) and before dominant sand-rich flows filled a channel complex (CC3) suggest that this debrite is related to the early filling of the channel complex, and thereby be consistent with interpretations based on other outcrop (Campion et al. 2000; Beaubouef 2004) and subsurface (Sikkema and Wojcik 2000) studies.

DISCUSSION

Evolution of Channel Complexes in Isaac Unit 5

Isaac Unit 5 represents a long-lived slope depositional pathway that accumulated ~ 100 m of mostly sand and is bounded above and below by thick (> 20 m) fine-grained deposits (T1 and T5). The three stacked channel complexes-fills that make up Isaac Unit 5 (CC1, CC2, and CC3) correspond to shorter-term flow conduits capped by thin-bedded strata that represent intervening episodes of overbank sedimentation. An idealized evolution of each channel complex can be summarized as follows (Fig. 16):

a) Sediment bypass and incision (< 12 m deep), probably associated with very large, high-energy flows (cf. Kneller 2003). Cohesive gravity flows transporting shelf-derived carbonate boulders may occur during the final period of incision and early filling stage (e.g., D2 debrite).
b) Main filling of the channel by onlap onto the basal erosion surface (backfilling). Deposition, caused by loss of capacity and/or competence in high-concentration, sand-rich flows that locally? expanded across a large portion of the width of the channel

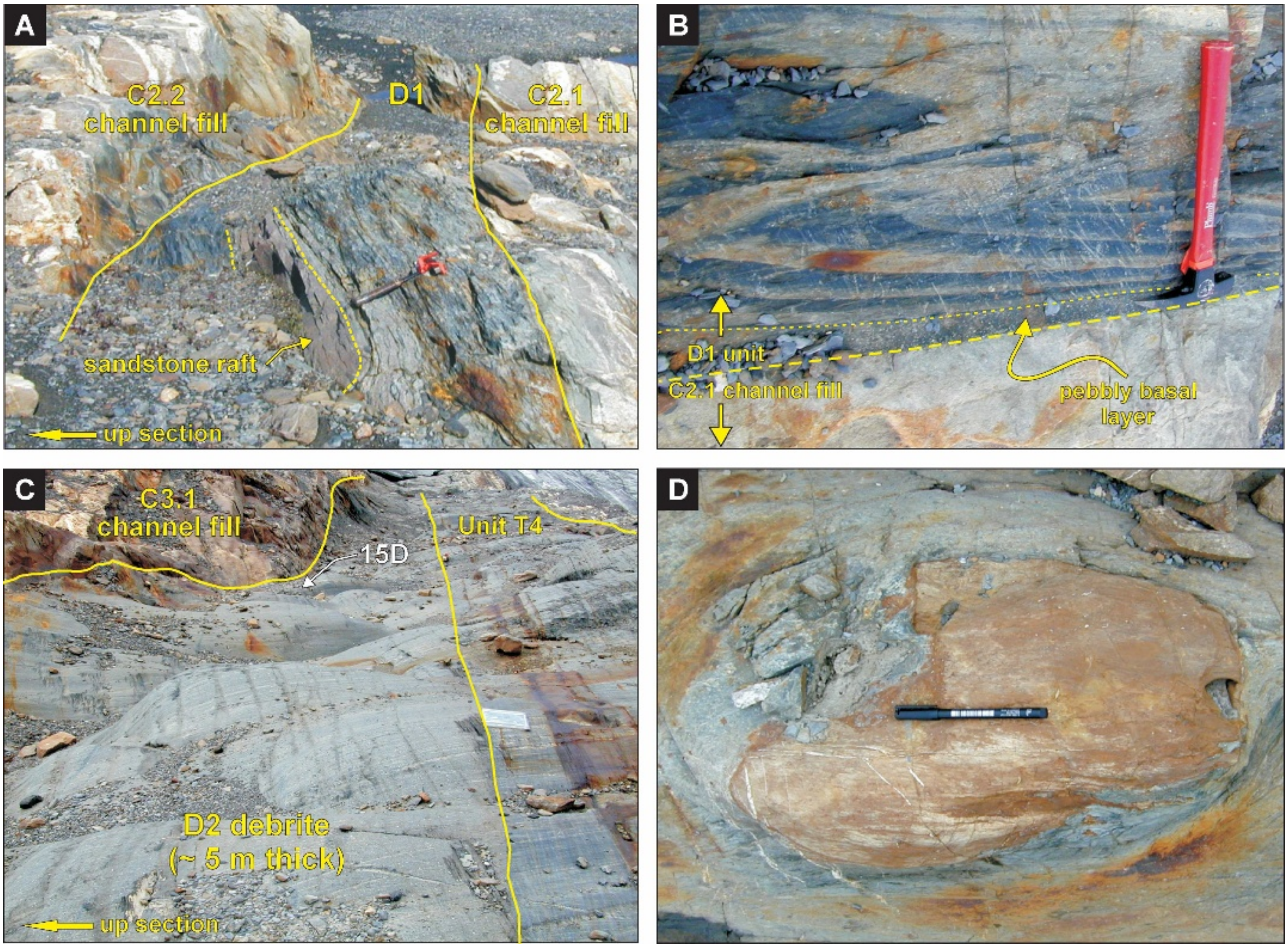


FIG. 15.—Debris-flow and slump deposits that occur in Isaac Unit 5. **A)** View of unit D1, which is sandwiched between two channel fills and is composed mostly of a thin-bedded interval with folded, disorganized blocks of turbidite beds and interbedded sandstone rafts. Hammer for scale. **B)** D1 basal layer characterized by quartz grains (white dots), overlain abruptly by tightly folded thin-bedded deposits with uncommon dispersed quartz grains. Deformation does not continue into the underlying or overlying strata. **C)** General view of unstratified, pebbly mudstone (D2 debrite), sharply overlying thin-bedded deposits of a channel-complex abandonment (Unit T4). **D)** Cobble of thinly-laminated carbonate clast in D2 debrite. Marker for scale (14 cm long). This figure is printed in color in the digital version.

(oversized flows, cf. Sullivan et al. 2000), formed amalgamated channel-fill elements composed mostly of sandstone beds with Bouma Ta/Tab divisions. The transition from sediment bypass to sediment deposition is probably triggered by a general reduction in flow energy (e.g., velocity or size) and/or an increase in the proportion of sand versus mud within the flow (cf. Kneller 2003). As channel filling proceeded, the energy of incoming flows waned, resulting in the superposition of the non-amalgamated channel-fill element with more complete Bouma sequences and thin-bedded Tcde turbidites (e.g., C1.2).

c) Reactivation and reincision within the channel complex is typically indicated by the abrupt, erosionally based mudstone-clast breccias of the poorly stratified channel-fill element, but where this element is absent, amalgamated elements are observed (Fig 16). These younger channels appear to have been narrower (e.g., both margins can be inferred in C3.3; Fig. 5) and, in some cases, they aggraded and simultaneously migrated laterally (e.g., C1.3). This aggradational stacking favored the development of adjacent low-energy, inner-bend levees (e.g., T2).

d) Rapid channel-complex deactivation, most probably associated with increased flow discharge that caused updip breaching and avulsion (e.g., Posamentier 2003), led to partial scour and rapid infilling of channelized relief (previous thalweg) with structureless sandstone (lenticular element C1.4, Fig. 16). Conversely, the accretionary channel-fill element (C3.4) most likely formed during more gradual channel-complex deactivation. Gradual deactivation is considered here as a general reduction in sediment caliber and sand content before complete abandonment of the system (C3.4 is the uppermost channel fill in Isaac Unit 5). The diminution of these parameters (prevailing over changes in flow size or density) likely caused a decrease in local gradient (cf. Kneller 2003) and a consequent change from aggradational to non-aggradational conditions (no vertical accommodation, *sensu* Samuel et al. 2003). Non-aggradational conditions favored the development of laterally accreting, highly sinuous channels (C3.4) that most probably were in equilibrium (at grade) with sediment transport conditions (cf. Kneller 2003). In many subsurface slope channelized systems (typically 50–200 m thick), the late stages of channel evolution are similarly characterized by laterally accreting, non-aggradational channelized bodies (Mayall and Stewart 2000; Abreu et al. 2003; Samuel et al. 2003).

e) Cessation of sand-rich sediment gravity flows (local channel-complex abandonment) results in accumulation of laterally extensive (> 2.5 km), thin-bedded units interpreted to reflect middle to distal overbank deposition (T3 and T4). Mudstone-dominated successions separating channel complexes have similarly been interpreted to indicate temporary abandonment of a main sediment-transport pathway (Campion et al. 2000; Elliot 2000).

f) Subsequent rejuvenation of the sediment-transport pathway led to initiation of a new channel complex.

The evolutionary stages described here are considered to reflect an idealized stratigraphic response to temporal and/or spatial changes in sediment flux and flow conditions. These parameters have a profound effect in creating or removing accommodation within a turbidite channelized system (Pirmez et al. 2000; Kneller 2003; Posamentier and Kolla 2003). Hence, these stages illustrate the stratigraphic complexity that can be expected within slope turbidite channels and is similar to examples reported previously from subsurface (Mayall and Stewart 2000; Sikkema and Wojcik 2000; Samuel et al. 2003) and outcrop (Campion et al. 2000; Beaubouef 2004) studies.

Inner-Bend Levee Analogue

Depositional elements termed "inner levees" have been reported from seismic studies and are situated adjacent to sandstone-rich channel-fill facies (Deptuck et al. 2003). These elements are best preserved in the inner bend of the channel (opposite the cut bank), and form as the channel axis migrates and aggrades laterally (Deptuck et al. 2003). Inner-levee elements have been reported from large muddy systems, for instance ancestral channel levee complexes of the Indus Fan (Deptuck et al. 2003 and references therein), but also from small sandy systems like the Hueneme Fan (Piper et al. 1999). Because core data from these modern inner levees is limited and these seismic features have not been identified unambiguously in outcrop, facies composition, sand proportion, and reservoir characteristics in these elements remain still unclear (Deptuck et al. 2003).

Fine-grained, overbank deposits that accumulated on the inner-bend levee of an aggrading and laterally migrating channel were identified in Isaac Unit 5 (T2, Figs. 13A, B, 14). This architectural element, although interfingering with the adjacent, coarse-grained channel-fill element, does not consist of sand-rich overbank deposits, nor does it exhibit a classical proximal (sand-rich) to distal (mud-rich) transition as commonly reported in the geological literature (e.g., DeVries and Lindholm 1994; Navarro et al. in press). Instead, inner-bend levee deposits of Isaac Unit 5 consist of < 1-cm-thick, up to fine-grained sandstone with poorly developed ripple cross-lamination interbedded with dominant siltstone (sandstone-to-mudstone ratio < 0.25), deposited by dilute turbulent flows (Fig. 13A, B). These observations are consistent with reports from modern and quasi-recent, moderately to highly sinuous, deep-water turbidite channels (e.g., Piper and Normark 1983; Posamentier 2003) and flume experiments (Keevil et al. 2005), which show more extensive overspill, including flow stripping, along the outer-bend levee. In contrast, the inner-bend levee and overbank area is the site of consistently low-energy flow, and accordingly, deposition of mostly silt and very fine sand. In terms of reservoir characterization, differentiating inner-bend from outer-bend levee strata is essential in order to better estimate reservoir volume and production performance in low-resistivity pay zones adjacent to turbidite channels.

Isaac Unit 5 Architecture: Implications for Deep-Water Reservoirs

The depositional architecture and stacking pattern reported in Isaac Unit 5 show superficial similarity with large-scale features reported from 3-D seismic surveys and borehole images of passive-margin deep-water systems, for example Mayall and Stewart (2000), Abreu et al. (2003) and Samuel et al. (2003), among others. High net-to-gross amalgamated elements that grade upward to more aggradational and laterally migrating channel fills with overbank related deposits, as well as the occurrence of laterally extensive debris-flow units at the bases of channel complexes (MTCs), have also been previously reported by these same authors. Although strata of Isaac Unit 5 have been affected by low-grade metamorphism and deformation, valuable analogies can be drawn between these deposits and subsurface slope systems in order to improve the understanding of distribution and connectivity of subsurface hydrocarbon reservoirs.

Channel-Fill Elements: Connectivity and Continuity.—As a consequence of their distinct sedimentologic and stratigraphic attributes, each of the different channel-fill elements recognized in this study (Fig. 7) have unique reservoir characteristics (Table 1). Reservoirs would be best developed in amalgamated channel fills, where a paucity of interbedded fine-grained layers result in good vertical and lateral connectivity (N:G > 0.9). These elements are 3–12 m thick, and considering their lateral continuity (> 1 km, Fig. 7) across the highly oblique outcrop, are at least of the order of several hundreds of meters wide. Furthermore, the amalgamated element is volumetrically the most significant, and unlike the other elements occurs in all channel complexes (Table 1). Similarly, Sikkema and Wojcik (2000) reported that the most common reservoir type in some Tertiary slope channel complexes offshore Angola is "amalgamated channel sands," although these Tertiary channel fills may be thicker than those described here.

Poorly stratified elements (C3.1 and C3.3) are up to 12 m thick, and channel fill C3.3 has an estimated maximum width of 600 m (both margins occur within Castle Creek South area, Fig. 5C). In these channel fills, sandstone beds are interstratified with abundant, thick mudstone-clast breccia layers that originally were laterally persistent mudstone-rich layers (Fig. 7). Postdepositional (*in situ*) brecciation has locally reduced or removed these permeability barriers by sand remobilization, and in doing so increased vertical permeability, albeit through a highly tortuous network of permeable conduits. However, while reservoir continuity is enhanced, total reservoir sandstone volume would be reduced because of abundant mudstone clasts. The challenge, therefore, is estimating the total volume of permeable sandstone in the now uncompartmentalized reservoir (cf. Lonergan et al. 2000).

The lenticular element (C1.4) consists largely of structureless sandstone that typically extends across the width of the channel fill (maximum ~ 325 m at the top; Fig. 7). Beds also have good vertical connectivity (N:G 0.8–1; Table 1). Despite the high sandstone content of these strata, their comparative thinness (average < 4 m) and small areal extent diminishes it as a volumetrically significant reservoir (Table 1). The accretionary element (C3.4) is 4–8 m thick and more than 450 m long (Fig. 7), and it consists of sandstone-dominated inclined strata (N:G 0.73–0.86; Table 1). The inclined strata typically consist of sandstone-rich packages (< 2 m) with significant amalgamation downdip but that pinch out rapidly into shale updip (Fig. 7). Sandstone-rich packages also have low lateral continuity (< 150 m) and are commonly separated by laterally extensive, thin-bedded intervals, forming local permeability barriers and hence diminishing vertical connectivity. Finally, the non-amalgamated element (C1.2) exhibits the poorest reservoir attributes. It consists of a < 4.5-m-thick, mixed sandstone/thin-bedded element with the lowest net-to-gross ratio (N:G 0.66–0.86, Table 1). In addition, laterally continuous siltstone-rich, thin-bedded intervals and flat, non-

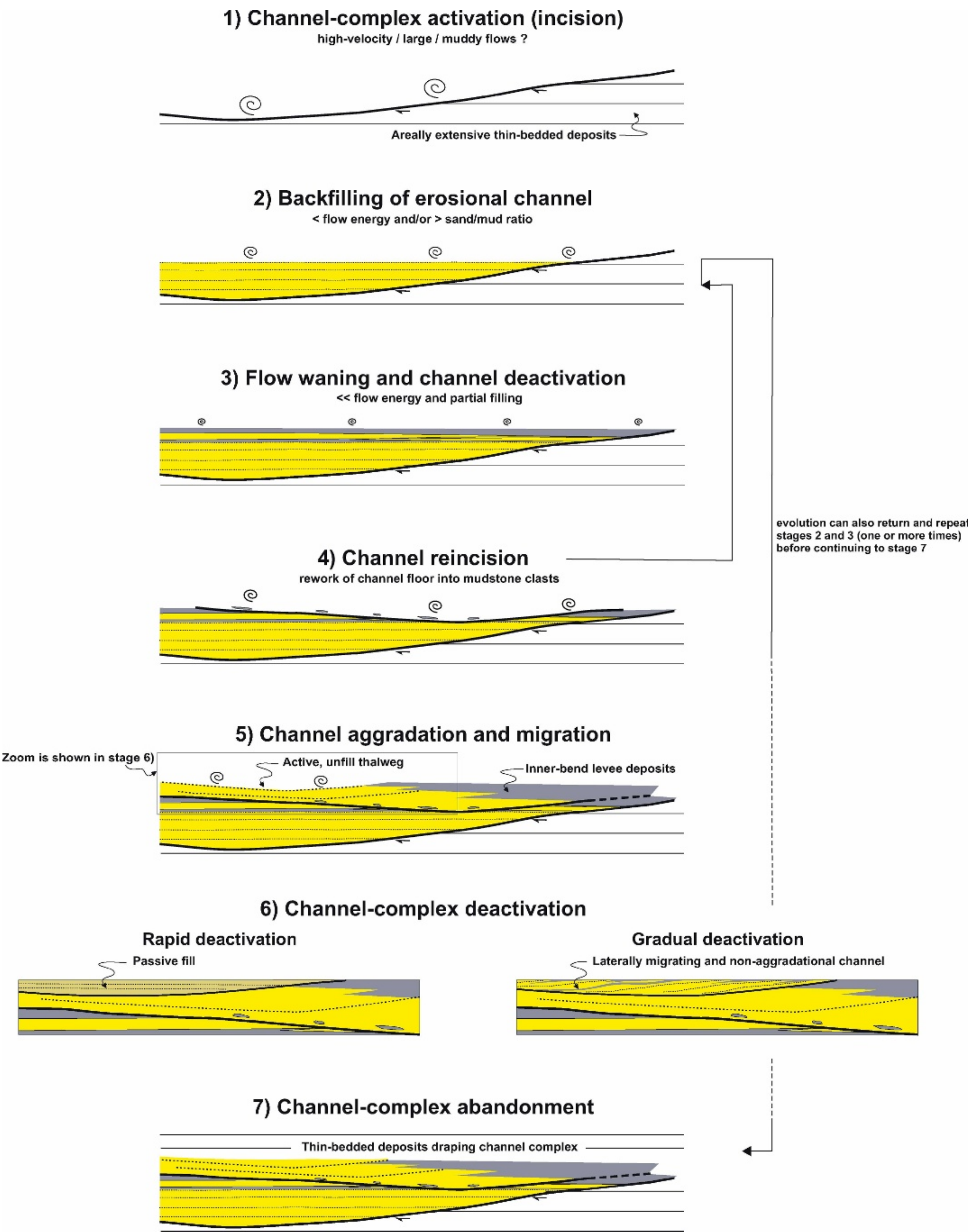


FIG. 16.—Conceptual model to illustrate evolution of channel complexes within Isaac Unit 5. This figure is printed in color in the digital version.

TABLE 1.—*Reservoir characteristics of the different channel-fill elements recognized in Isaac Unit 5 and their contribution to channel-complex gross thickness.*

Channel-fill element	Net-to-gross-ratio (N:G)[1]	Bed lateral continuity	Sandstone vertical and lateral connectivity	Element thickness (%) vs. total channel-complex thickness[2]
Amalgamated	0.9–1.0	Fairly good (> 300 m)	Paucity of fine-grained layers results in excellent to good connectivity	*C1.1*: 24–34% of CC1 *C2.1* + *C2.2*: 87–89% of CC2 *C3.1* + *C3.2*: 40–58% of CC3
Poorly stratified	0.9–1.0	Moderate to fairly poor (< 200 m)	Postdepositional brecciation locally reduces or removes mudstone layers by sand injection and increases vertical permeability (albeit through tortuous fluid pathways), which results in good to moderate connectivity	*C1.2*: 41–100% of CC1 *C3.3*: 25–37% of CC3
Accretionary	073–0.86	Fairly poor (< 150 m)	Lateral accretion packages with amalgamation downdip, but commonly separated by laterally extensive, thin-bedded intervals diminishing vertical connectivity	*C3.4*: 15–27% of CC3
Non- amalgamated	0.66–0.86	Moderate (< 200 m)	Interbeded nature of facies and non-erosional sandstone beds results in poor vertical connectivity	*C1.2*: 11–18% of CC1
Lenticular	0.8–1.0	Fairly good across the width of element (< 325 m)	Good vertical connectivity due to sandstone amalgamation but potential low permeability may reduce lateral connectivity	*C1.4*: 9–14% of CC1

[1] N:G—*Cumulative thickness of sandstone/conglomerate versus gross thickness measured in several sections.*
[2] *Range of numbers calculated for sedimentological sections 2 to 5 are indicated, except for non-amalgamated and lenticular elements, which are not present in sections 4 and 5. In each channel complex (CC1, CC2, and CC3), more than 73% of its total thickness is represented by amalgamated and/or poorly stratified elements.*

erosional sandstone bases typify this element (Fig. 7), which most assuredly would reduce vertical connectivity.

The three stacked channel complexes (CC1–CC3) are high net-to-gross units (N:G 0.85–1.0) and their cumulative thickness in each particular stratigraphic section totals 80 m to 46 m (thinning to the northwest). This cumulative thickness represents 80% to 60% of Isaac Unit 5 gross thickness (100 to 75 m thick from SE to NW). Amalgamated and poorly stratified elements, which show excellent to good reservoir connectivity, represent 73 to 100% of individual channel-complex gross sandstone (Table 1). This provides an overall good initial reservoir condition for individual channel complexes. Nonetheless, up to 25% of the gross sandstone is represented by elements with moderate to poor lateral and/or vertical connectivity (accretionary, non-amalgamated, and lenticular elements; Table 1). Because the identification of these elements is probably difficult at the reservoir scale, even with high-frequency 3-D seismic (e.g., Kendrick 2000; Mayall and Stewart 2000), their occurrence would have a major negative impact on the total interconnected sandstone volume in a deep marine slope channel-complex reservoir.

Barrier- and Baffle-Type Facies.—*Local* permeability baffles and barriers (up to several tens of meters long) are present *within channel-fill elements* (intrachannel), and consist of mudstone-clast breccia and siltstone-rich, thin-bedded turbidite intervals. Mudstone-clast breccias are common, particularly in the poorly stratified channel-fill element, where they seem to be randomly distributed (Fig. 7). Breccia layers are locally up to 3 m thick and have a sandstone or conglomerate matrix. These strata would likely only inhibit fluid flow, but more importantly, they reduce significantly local reservoir volume (e.g., up to 50%). Siltstone-rich intervals within channel-fill elements are typically less than 1 m thick and consist mainly of thin-bedded Tcde turbidites. They occur only in accretionary and non-amalgamated elements (Fig. 7), where they most probably represent local barriers to fluid migration.

More laterally persistent and thicker barrier-type facies are observed *within channel complexes* (interchannel). The siltstone-rich, debris-flow/slump unit (D1) is a laterally continuous horizon between two channel-fill elements across ~ 500 m of exposure (Fig. 5C). However, the two sandy channel fills do amalgamate at two places over the 700-m-long cross section (Fig. 5C; 75–125 m and 650–700 m). Thin-bedded intervals between channel fills are up to 5 m thick but are generally uncommon (Fig. 5C). Where present, they typically pinch out laterally because channel reactivation has locally eroded these deposits (C3.t in Fig. 5C). These more extensive and thicker barrier-type facies would affect connectivity and reservoir performance, but they most probably would not compartmentalize the channel fills in terms of cross-channel flow.

Regional (kilometer-scale), very effective barrier-type facies occur *between channel complexes*. A thick siltstone–mudstone-rich debris-flow deposit (D2) and thin-bedded, siltstone-rich overbank elements (T3 and T4) are as laterally persistent as the sandstone-rich parts of channel complexes and separate them completely, not only in the Castle Creek South area but across the full length of the Isaac Unit 5 outcrop (> 3 km). These mudstone-rich units constitute regional permeability barriers that would prevent channel-complex connectivity and pressure communication. These observations, therefore, contrast observations from the Upper Cretaceous Cerro Toro Formation, a deep-water turbidite system from the Andean foreland basin of southern Chile. In this example, reservoir continuity occurs at all scales beneath channel-complex set hierarchy (Beaubouef 2004; Beaubouef, personal communication 2006). For example, in contrast to Isaac Unit 5, the axes of individual complexes are locally in contact, and therefore suggest good, albeit local, vertical reservoir communication within the channel-complex set (Beaubouef 2004). Differences in the hierarchical level of connectivity between the passive-margin Isaac Unit 5 and the tectonically active foreland-basin Cerro Toro is currently unknown but might be a consequence of differences in important sedimentological parameters, including rates of subsidence versus rates of erosion/deposition.

CONCLUSIONS

Isaac Unit 5 represents a long-lived depositional pathway (channel-complex set) that accumulated ~ 100 m of mostly sand sediment in a deep-marine slope setting. It is composed of three vertically stacked, high net-to-gross channel complexes, thin-bedded elements and debris-flow/slump units.

Five types of channel-fill elements were identified within channel complexes. Each consists of a unique assemblage of facies, internal geometry, and bounding surfaces. Thick-bedded, Bouma Ta and Tab divisions, mudstone-clast breccia, and dune cross-stratified sandstone form most of the channel fills.

Two thin-bedded, overbank elements were recognized within Isaac Unit 5. Very thin-bedded deposits interfingering laterally with channel-fill facies are interpreted as inner-bend levee deposits. An analogue for the equivalent seismic element recognized in modern systems is provided for the first time. Medium- to thin-bedded deposits overlie channel complexes and represent their local abandonment.

An idealized evolution of a channel complex begins with a stage of incision and sediment bypass (+/− late debris-flow deposition), followed by backfilling of the channel relief with amalgamated and non-amalgamated elements. Following an episode of reincision, if aggradation permitted, new channels migrate obliquely upward (aggradation + migration, poorly stratified elements) and favor the development of inner-bend levees. Late stages of channel-complex filling can be represented by passive filling of a rapidly deactivated thalweg, likely due to updip breaching and avulsion (lenticular element), gradual waning of sand-rich flows (non-amalgamated element), or active filling by lateral accretion packages in highly sinuous channels developed under non-aggradational conditions and gradual (and regional?) deactivation of the channel complex (accretionary element). In all cases, however, final deactivation of the channel complex was followed by accumulation of laterally extensive, thin-bedded units interpreted to reflect distal overbank deposition associated with a distant channel complex not seen in outcrop.

Each of the five different channel-fill elements have unique reservoir attributes (connectivity and continuity). Amalgamated and poorly stratified elements have excellent to good reservoir attributes. They are the most common elements and represent 73–100% of the gross channel-complex sandstone. Different scales of permeability-barrier-type facies were identified in Isaac Unit 5. Channel complexes would represent individual fluid flow units where only non-areally extensive permeability barriers (< 500 m long) are present. Extensive thin-bedded elements developed during local channel complex abandonment and muddy debris-flow units, likely deposited during reoccupation of the pathway, constitute kilometer-scale barrier-type facies that would effectively compartmentalize channel complexes within the channel-complex set.

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