Hyperpycnal wave-modified turbidites of the Pennsylvanian Minturn Formation, north-central Colorado

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ABSTRACT

The Pennsylvanian Minturn Formation in north-central Colorado exhibits a complex stratigraphic architecture of fan-delta deposits that developed in association with high topographic relief in a tectonically active setting. The formation records a wide range of environments including alluvial fan, fluvial, deltaic, and open marine settings. This field trip will examine outcrops of a remarkable ~20 to 35-m-thick, unconformity-bound unit with turbidite-like beds that presumably developed within the lower reaches of incised valleys. This unit consists of dark green shale and graded sandstone beds with tool marks produced by abundant plant material. The sandstone event beds contain evidence for strong unidirectional flows and the variable influence of storm-generated waves. Proximal deposits contain beds with evidence for wave-dominated combined flows, including well developed, large-scale hummocky cross-stratification. Distal sections contain beds with reverse-to-normal grading and vertical successions of sedimentary structures that indicate long-lived waxing-to-waning unidirectional flows in conjunction with storm waves. We interpret these beds as a record of deposition from hyperpycnal flows, i.e., turbidity currents generated directly from highly concentrated river plumes, which waxed and waned in response to the rising and falling flood hydrograph. The focus of this trip will be the hydrodynamic interpretation of these different bed types, including their spatial and stratigraphic distribution.

Keywords: Hyperpycnal flow, Pennsylvanian, Minturn Formation, Colorado, Tempestites, Turbidites.

INTRODUCTION

Mechanisms for the seaward transport of sediment from shoreline sources have been debated for more than twenty-five years. Evidence from the geological record suggested to early workers that gravity-driven flows were common on ancient shelves (Hamblin and Walker, 1979; Wright and Walker, 1982; Dott and Bourgeois, 1982; Leckie and Walker, 1982; Walker, 1984). However, observations of modern shelves indicate that storms did not produce turbidity currents, but instead formed shore-parallel geostrophic flows (Swift et al., 1986). In addition, theoretical arguments suggested that turbidity currents could not maintain themselves over the low slopes typical of modern continental shelves (Pantin, 1979; Parker, 1982; Swift, 1985). Therefore, a major discrepancy exists between oceanographic and theoretical studies and those of ancient sedimentary successions that contain considerable evidence for cross-shelf sand transport (Leckie and Krystinik 1989). There is still no universal explanation for how sand is transported from shorelines across the shelf during storms. Although facies models exist for storm-dominated shelves, the basic mechanisms of transport and deposition for such models are unresolved. This is an astonishing gap in our knowledge of marine depositional systems.

Recently, sophisticated oceanographic measurements have shown that sediment-laden gravity driven flows are indeed important and a common occurrence on modern shelves that are associated with large-supply, fine-grained rivers. In these cases, the current is driven by “excess-weight forces” produced by the excess weight of entrained sediment. The discovery of dense, mobile bottom nepheloid layers (or fluid muds) on many margins around the globe (e.g., the Amazon: Trowbridge and Kineke, 1994; northern California: Traykovski et al., 2000; northern Papua New Guinea: Kineke et al., 2000) suggests that large sediment supply in combination with wave-orbital and tidal motions can lead to gravity-driven sediment-laden flows. Wave energy in particular is significant in that it may aid in the maintenance of high-density suspensions formed in bottom boundary layers near river mouths, and thus result in downslope transport. Studies of river plumes have shown that turbidity currents can be generated directly from a plunging river flow, and these are coined hyperpycnal flows (e.g., see review by Mulder et al., 2003). Hyperpycnal flows can occur in the ocean if the density of the sediment-laden river plume is greater than that of seawater. Under this constraint rivers would need to have greater than ~ 40 kg/m^3 of suspended sediment to plunge through seawater (using typical modern values of temperature and salinity (Mulder and Syvitski 1995). Using a rating curve technique, Mulder and Syvitski (1995) showed that 81 out of 147 modern rivers analyzed are capable of exceeding this threshold at least once per 100 years. Although, studies of modern environments have shown that mud is in cases transported across shelves by hyperpycnal flows, it is uncertain to what degree sandy event beds in the ancient may have formed from similar transport mechanisms.

Myrow and Southard (1996) sought to incorporate the various processes typically examined in modern oceanographic observations within the context of the geologic record. They proposed a continuum of sediment-transport processes governed by geostrophic flow, gravity-driven flow and wave motions. Depending on the contribution of each process, different styles of sedimentation would result. However, they did not address the degree to which various modes exist in nature, the degree to which they are common, and the quantitative limits of each component of flow that defines each type of transport process. Myrow et al. (2002) described ancient deposits that recorded the combined wave and gravity-flow subset of the Myrow and Southard (1996) continuum, coined the term “wave-modified turbidity currents”, and suggested that they might represent an important mechanism for deposition of tempestites in the rock record. Unfortunately, little experimental data exists to constrain the nature of such flows.

As Myrow and Southard (1996) point out, flow driven by excess-weight forces might arise from ‘equilibrium’ conditions in which a dense dispersion was produced solely by turbulence produced by ambient wave energy. They also point out that such flows could arise under ‘disequilibrium’ conditions in which sudden introduction of sediment into a wave-influenced body of water could occur from either sediment failure at a shoreline or by oceanic river flooding. Sediment failure might result from slope failure, which in shallow water could be caused by cyclic wave loading. Myrow et al. (2002) and others (e.g., Higgs, 1991; Myrow and Southard, 1996) have suggested that hyperpycnal flows produced by oceanic river floods might be responsible for tempestite beds in the rock record, although most ancient deposits do not have sufficient sedimentological evidence to directly link the storm beds to river floods. This field trip will examine event beds produced by hyperpycnal flows that contain evidence to directly link their grain size distributions and sequences of sedimentary structures to the flood hydrograph of the rivers that delivered their sediment. These beds also demonstrate the spatial and temporal distribution of the effects of waves upon these hyperpycnal flows. Finally, the depositional context of these strata helps define the nature of ancient depositional systems under which wave-modified turbidity currents originate.

GEOLOGIC SETTING

The Minturn Formation was deposited along the eastern margin of the Central Colorado Basin (CCB) during the Pennsylvanian, and sits on the western flank of the Gore Range (Fig. 1). In the Pennsylvanian, the basin was bounded by the Ancestral Front Range to the northwest and the Uncompahgre uplift to the southeast (Tweto, 1949). DeVoto et al. (1986) proposed that the Ancestral Sawatch uplift was also a positive feature. These areas of uplift supplied sediment to the basin. At this time the exposed rock was primarily Precambrian granite and Paleozoic sandstone units, and thus the sediment deposited in the CCB was largely arkosic (Tweto, 1949; Stevens, 1958). Deposition was controlled by eustatic changes related to glaciations on Gondwanaland (Crowell, 1978; Houck, 1993, 1997). The Minturn is coeval with the Eagle Valley Formation and Eagle Valley Evaporite, both of which were deposited in the central part of the basin (Schenk, 1986, 1989).

The study area is located 19 km west of the Gore fault zone (Figs. 1, 2), which was active during the Laramide Orogeny and in the Pennsylvanian (DeVoto et al., 1986). Dip-slip movement along the Gore fault was significant in the Pennsylvanian; DeVoto et al. (1986) estimated fault displacement of 1525-2135 m in the Desmoinesian stage alone. The amount of strike-slip movement (if any) in the Pennsylvanian is unknown (Houck, 1993).

The faults that form the eastern margin of the CCB are in an *en echelon* configuration. The study area is located 15 km south of an *en echelon* offset, where a transverse fault truncates both the Gore fault and an unnamed fault to the north (Fig. 1). The transverse and northern faults were inferred to be active in the Pennsylvanian (DeVoto et al., 1986), but because the Minturn Formation is covered to the north by Mesozoic rocks, Pennsylvanian movement on the northern fault cannot be documented (Houck, 1993).

PREVIOUS WORK

Tweto (1949) first described the Minturn Formation and designated a type section just east of the town of Minturn, Colorado. Stevens (1958) and Tweto and Lovering (1977) used fusulinid fossils to determine the age of the formation, which is late Atokan to Desmoinesian. Houck (1993, 1997) provided detailed stratigraphy of the middle Minturn Formation in the Bond/McCoy area. The Minturn Formation is composed primarily of conglomerate, sandstone, and shale (Fig. 3). These deposits are both marine and non-marine, and include fluvial, delta, prodelta, foreshore, and shallow marine facies. The formation contains a wide variety of preserved bedforms, trace fossils, and body fossils, and is coarser in character than the Eagle Valley Formation (Houck 1993, 1997). It is thus interpreted generally as a basin margin deposit, whereas the Eagle Valley Formation represents the inner basin. Schenk (1986) described turbidites in the Eagle Valley Evaporite, which he interpreted as having been deposited below storm wave base, based on a lack of HCS or other evidence of wave influence.

The turbidite unit examined in this study is Houck’s (1993) unit 5a (Fig. 3), which is early Desmoinesian in age. It occurs in the zone of the fusulinids *Beedina apachensis, B. cedarensis, B. leei*, and *Wedekindellina henbesti* (Houck, 1993), and is inferred to correspond to the Inola transgression in the US mid-continent, using the zones and sea level curve of Ross and Ross (1987). The turbidites are underlain by an unconformity at the Atokan-Desmoinesian boundary (Houck, 1993). This unconformity shows significant relief, and the turbidites are thought to have been deposited in two incised valleys located in the eastern and western parts of the study area (Fig. 4). They occur in roughly lobe-shaped bodies, and show paleocurrent directions to the south and southwest (Fig. 5). Houck (1991) showed that the orientation of fluvial paleocurrents and incised valleys in the study area is generally north-to-south; she inferred that stream drainages developed in the zone of fault offset to the north and supplied sediment to the study area. Lindsey et al. (1986) also described turbidites in the Minturn Formation from the southern part of the Central Colorado Basin. These authors interpreted the turbidites as prodelta deposits of fluvially-dominated fan-deltas. They found no evidence of extensive reworking, and inferred that the turbidites were deposited below storm wave base. Hoy and Ridgway (2002, 2003) also followed these interpretations.

TURBIDITE UNIT

The turbidite unit examined in this field trip crops out on the limbs of a large, south-plunging syncline. Stops 1, 2, and 3 are on the steeply dipping east limb, and Stop 4 is on the more gently dipping west limb. The turbidite unit range from 18.9 to 35.3 m thick at these stops. The unit consists of approximately 30% sandstone and 70% shale and the sandstone beds range from 2 cm to over a meter thick. Most beds are light tan-gray in color, although the coarsest beds are micaceous and darker gray to brown. Plant fossils including *Walchia* (conifer) Sphenopteris, Callipteris (ferns and seed ferns), and *Calamites* (horsetail) are common throughout the unit at all localities (Arnold, 1941; Donner, 1949).

STOP 1. Roadcut on Route 131 between the town of Bond and McCoy.

Proceed 1.2 mi northwest from road sign for Town of Bond that is just south of railroad tracks. Park vehicles on right (east) side of road adjacent to a thin to medium bedded green-gray weathering sandstone and shale unit.

The strata below and above the turbidite unit are well exposed at this locality and include coarse, red conglomerate and sandstone deposits. The turbidite unit at this stop is 18.9 m thick (Fig. 6). Sole marks are present on the bases of many beds and are prominent in float. These include grooves, prods, and chevron structures at various scales. Sole marks display very strong orientations towards the west and south (Fig. 7). Beds at Stop 1 are generally thinner than at the other more proximal stops. These very thin to medium sandstone beds are both normally graded and reverse-to-normal graded, the latter particularly abundant in the upper one-third of the unit. Internal sedimentary structures include graded divisions, massive bedding, parallel lamination, and ripple cross-stratification. The strata in this outcrop show a distinct lack of hummocky cross-stratification relative to the other outcrops of this unit. Preserved ripple forms and ripple cross-stratification are abundant in these deposits. They have unusual geometries relative to either typical current or wave ripples, namely rounded crests, near-symmetrical shape, and convex-up or sigmoidal foresets. Such features are characteristic of deposition under combined flows with both unidirectional and oscillatory components (Myrow and Southard, 1991; Yokokawa, 1995; Yokokawa et al., 1995; Myrow et al., 2003). The sigmoidal form of combined-flow ripples indicates that foresets were not formed by simple avalanching of sand grains, but by vortices formed in the troughs of the ripples. One of the intriguing aspects of the beds in this turbidite unit is that despite the abundant evidence for deposition under waves, particularly at Stops 2-4, there is a remarkable paucity of classic wave ripples with sharp, symmetrical, linear crests.

The event beds in this section contain a variety of vertical stratification sequences (Myrow and Southard 1991) and grain size trends that reflect temporal changes in depositional flows. Grain size successions recorded from various exposures of the turbidite unit include normal grading, reverse-to-normal grading, and no grading. Six different types of internal structures include massive sandstone, planar lamination, quasi-planar lamination, HCS, combined-flow ripple lamination, and grading. Figure 8 offers a graphical representation of all qualitatively different vertical stratification sequences within the event beds that are based on both grain size distributions and stratification styles. There are 29 separate successions preserved in these beds. Normally graded beds are about twice as abundant as those with other grain size patterns. Changes in grain size are generally closely associated with changes in sedimentary structure, and particular grain sizes are usually associated with specific sedimentary structures. Coarse and medium sandstone is commonly massive or planar laminated; fine sandstone is planar laminated, quasi-planar laminated, or hummocky cross-stratified; and very-fine sandstone is associated with combined-flow ripples (Fig. 8). Thus, reverse-to-normally graded beds commonly contain a succession that begins with combined-flow ripples, then planar lamination or massive sandstone, followed by combined-flow ripples on the top of the bed. Such beds, which are most abundant at Stop 1, clearly reflect waxing (temporally accelerating) and waning (temporally decelerating) flow conditions, and we refer to these as wax-wane beds. They are less common than beds with little or no grading and simpler sequences (numbers 1, 3-6, and 20 in Fig. 8).

We interpret the reverse-to-normal grading and wax-wane successions in the event beds as hyperpycnal flow deposits that are dynamically linked to the river system that fed the flows. In particular, these are thought to record the rising and falling limb of the hydrograph of the flooding river. A more detailed interpretation is given below in the Discussion section.

STOP 2. Outcrop on private land of Barry Simmers

Continue north beyond Stop 1 on road to McCoy for 0.4 mi and turn right (east) onto dirt driveway. Proceed uphill on driveway several hundred yards to house at top of hill. Drive down dirt path that forks to right across from house. Park at bottom of hill on the left. Walk a very short distance to base of section in gulley on right. If visiting alone please call landowner at 970-653-4334.

The turbidite unit at this stop is 19.7 m thick (Fig. 9). The lower 8 m of the turbidite unit at this outcrop contains abundant thin beds with excellent examples of small scale HCS, quasi-planar lamination, and combined-flow ripples. Sole marks are abundant in both outcrop and in float. Sole marks again display a very strong unidirectional orientation towards the south (Fig. 7). This stop contains more coarse- to medium-grained beds and numerous medium to thick beds of fine HCS sandstone. This is in stark contrast to Stop 1, which is directly south, and more distal based on the paleocurrent data.

A particularly important bed, exposed at 11.62 m, contains large-scale HCS at its base and combined-flow ripples on top. The geometry of the HCS indicates relatively symmetrical to slightly asymmetrical bedforms with spacing on the order of several meters. HCS forms as a result of complex oscillatory flow or combined flow (waves and current) associated with storms. The ripple cross-stratification in the 11.62 m bed is developed over a large-scale hummocky bedform surface and the ripple paleocurrents are oriented southward. On the southern (downstream) end of the HCS bedform a thick (up to 15 cm) succession of ripple cross-stratification is preserved. However, time-equivalent stratification on the northern (upstream) end of the bedform show only a few poorly developed ripples preserved within parallel lamination. These patterns are a clear response to deposition under waning combined flow. Waning flow is indicated by the transition from HCS to ripple lamination. Combined flow is recorded both in the distribution of the ripple stratification and in the geometry of the stratification itself. The ripples have rounded, convex-up geometries typical of deposition under combined-flows. The prevalence of parallel lamination on the upstream end of the HCS bedform reflects flow acceleration due to the reduction of flow depth caused by positive relief of the hummocky dune. In the lee of the dune, flow expansion led to a reduction in velocity and the production of ripple-scale bedforms. In contrast to the sole marks of the turbidite unit and the ripple stratification at the top of the bed, the large-scale HCS indicates strong oscillatory flow that dominated over a contemporaneous unidirectional flow.

Several other medium to thick beds of sandstone with prominent HCS and combined-flow ripples are exposed in the middle and upper parts of the section at Stop 2.

STOP 3. Outcrop a short distance off Copper Spur Road.

Drive back to main road from Stop 2 and take a right (north). Proceed 1.05 mi and turn right (east) onto Copper Spur Road. Proceed for 0.75 mi and park on right (south) side of road. Cross to the north side of road and walk to outcrop along flat area below gentle cliffs.

The turbidite unit at this stop is 35.3 m thick (Fig. 10). Numerous thin to medium beds with great examples of small scale HCS, combined-flow ripples, and various examples of different vertical stratification sequences are exposed between 2 and 6 m. Sandstone with large-scale HCS, parallel lamination and quasi-planar lamination is extremely abundant between 6 and 11 m.

Near the top of the section, at 31.8 m, is a prominent 38 cm thick sandstone bed with spectacular, large-scale sole marks, predominantly exposed in float. These markings include deep and wide groove marks, flutes, and gutter casts. Small grooves and prod marks cover much of the surface, including the surface of the gutter cast and large grooves. The lower division of the overlying bed consists of 10-15 cm of medium sandstone. The rest of the bed is parallel laminated with minor HCS and combined-flow ripples.

STOP 4. Outcrop on behind McCoy cemetery.

Drive back to main road from Stop 3 and turn right (northwest). Proceed 0.15 mi to a gravel road that forks right (north). Follow this gravel road to the cemetery. Continue north and east on the dirt road that goes along the edge of the cemetery. Walk east along the hill for 0.2 mi and drop into main drainage to the south. The base of the turbidite unit is exposed in the gulley. Examine these deposits, then walk up along dip slope of the lower part of the turbidite unit to cliffs at the top of the hill. Exposures occur along the base of small cliff and in hills to the east.

The basal 12 m of the turbidite unit at this outcrop are particularly well exposed (Fig. 11). The lower 2 m are mostly shale, and include a prominent shale marker bed at 1.43 m. This part of the unit is poorly exposed at Stops 2 and 3. Our recent work on outcrops exposed to the east and south of Bond (Fig. 2) indicates that the same interval includes several fine-grained debris flow and slump deposits. At Stop 4, minor slump blocks of sandstone are preserved within the 1.43 m marker bed. The lower 2 m of this unit is interpreted to record prominent marine transgression above the underlying unconformity at the Atokan-Desmoinesian boundary. At this proximal locality, a particularly thick (1.65 m) sandstone unit is developed at 1.97 m. This sandstone displays spectacular examples of small- and medium-scale HCS and combined-flow ripples. One example, near the large blocks that mark access to the small cliff-face, shows consistent offshore migration of rounded hummocks.

The upper part of the section is less well exposed, but contains several examples of small-scale ball-and-pillow structures, some of which are asymmetrical in shape. Myrow et al. (2002) used the asymmetric geometry of soft-sediment deformation features such as these, in combination with paleocurrent data, to demonstrate downslope direction and offshore-directed flow for wave-modified turbidites. Not enough orientation data has been taken on soft-sediment structures in the Minturn at this date to determine if these features preserve a consistent downslope orientation.

DISCUSSION

The turbidite beds of the Minturn Formation contain a remarkably wide variety of grain size grading patterns and vertical stratification sequences. Process-oriented sedimentological analysis reveals the influence of both strong unidirectional and oscillatory flow. Oscillatory flow is recorded by the presence of small- to large-scale HCS and quasi-planar lamination. HCS is well documented in both experimental work and field studies to result from long-period complex oscillatory flow or wave-dominated combined flow (Harms et al., 1975; Duke, 1990; Duke et al., 1991; Southard et al., 1990; Arnott and Southard, 1990). Quasi-planar lamination is the product of deposition near the boundary between hummocky bedforms and upper plane bed, presumably under combined flow conditions (Arnott, 1993). The asymmetric geometry of much of the HCS in this study, with steeper sides to the southeast (distal), and the presence of ripple cross-stratification with rounded, convex-up lamination, indicate that many of the beds were deposited under combined flows.

Powerful unidirectional currents, particularly during the early erosive stages of flow, is indicated by grooves, prods, gutter casts and flutes with distinct south and west flow orientations (Fig. 7). Myrow and Southard (1996) argue that flutes with classical v-shaped geometries and steep upstream snouts are not formed in oscillatory flows and are not likely to be formed in combined flows with even moderate velocities of the oscillatory flow component. Both direct and indirect evidence suggest that the unidirectional component of flow in these strata was driven by excess-weight forces. The sandstone beds in this unit contain classic features of turbidites, namely abundant sole markings, graded bedding and Bouma sequences. Such features have led numerous previous authors to interpret this unit, as well as similar deposits in time-equivalent formations, as turbidites (Schenk, 1986; Houck, 1993; Lindsey et al., 1986; Hoy and Ridgway, 2002, 2003).

Several lines of evidence link these excess-weight-driven flows with floods from an active river system. First, the abundance of plant fossils and sole marks made by large woody debris (grooves, chevron structures) implies that the flows were highly charged with plant matter. Woody debris that scraped the seafloor and made sole marks in some tens of meters of water must have been delivered in high-energy, bottom-hugging flow associated with storm-generated floods. Under calm conditions plant debris would either float or sink directly to the bottom. The association of large, well-oriented grooves and chevrons with current-generated features such as gutter casts, flute marks, and unimodally-oriented ripple cross-lamination clearly indicates deposition from a flow with at least a temporarily strong unidirectional component.

The second major line of evidence for a link between turbidite deposition and river flooding is the presence of reverse-to-normal graded beds and beds with vertical stratification sequences that indicate waxing-to-waning flow (e.g., ripple lamination followed by parallel lamination and then ripple lamination). Such successions within event beds are particularly unusual in the ancient record; in fact, to our knowledge they have never been described from outcrop. This might be because either waxing flow (accelerating in time) is uncommon in nature or because waxing flow is unlikely to be depositional. We interpret these beds as hyperpycnal flow deposits because this readily explains the origin of the waxing-to-waning sequences as the response to a fluvial flood hydrograph (which typically shows an increasing, followed by a decreasing, discharge over the course of a flood (Mulder et al. 2003)). This response could have been prolonged over many days, as rainfall made its way through watersheds to the river (Wheatcroft, 2000; Mulder and Syvitski, 1995). In addition, hyperpycnal flows are likely to be highly depletive (spatially decelerating), thus allowing their waxing phase to be depositional. This is due to a hyperpycnal flows loss of lateral confinement (i.e., channel) and reduction in driving stress (since seawater is much denser than air) when compared to its fluvial parent.

Hyperpycnal river plumes are more common in freshwater basins (i.e., lakes) since the concentration of sediment required to exceed the density of freshwater is much less than that of seawater. However, there is no evidence to suggest that the water body was fresh or brackish water at this time; in fact, well-developed limestone beds with standard Pennsylvanian open-marine fauna (brachiopods, bryozoans, echinoderms) occur within the lower part of the turbidite unit at several localities along the outcrop belt east of Bond and Copper Spur (Fig. 2). Although water temperature may have played a minor factor, the bulk of the negative buoyancy of these flows must have been produced by suspended sediment delivered to a river during runoff and entrained in the flood discharge. This part of the Minturn Formation was deposited in close proximity to range-bounding faults less than 20 km to the east and north, and these would have generated steep slopes and thus high suspended-sediment concentrations during runoff (Fig. 1).

The different successions of grain size and sedimentary structures can be understood with respect to variations in the temporal history of the hyperpycnal flows. Beds that display, for instance, very fine sandstone with ripple stratification overlain by fine sandstone with parallel lamination and then very fine ripple stratification are easily interpreted as having been deposited by waxing then waning flow. These changes might have been due either to temporal changes in sediment concentration or discharge of the associated river. The duration of these flows were probably on the order of many hours to days. Several beds, however, show jumps to coarser, massive divisions (Fig. 8a, #15–17), commonly across irregular erosion surfaces. These surfaces represent, in cases, the temporary denudation of the bed under accelerating flow that exceeded the threshold bed stress for erosion of the previously deposited, underlying division of the bed. The overlying massive division is interpreted to represent rapid deposition of coarser material from suspension and burial of the sediment without significant traction. In other words, such divisions represent Bouma T_a divisions. In cases, where stratification that might be expected for an accelerating flow is missing below this surface (e.g., parallel lamination in a case with ripple stratification overlain by massive sandstone) was either eroded prior to deposition of the massive division or never deposited because of acceleration of the flow. Some event beds of the Minturn also record multiple grain size and sedimentary structure transitions within one bed (Fig. 8, #2,17–19,23,25,28). These likely record pulses in the hyperpycnal flow that may reflect episodic changes in the discharge of the river.

Spatial Patterns

The spatial distribution of sedimentary structures, bed thicknesses and grain sizes are important for understanding the depositional dynamics of the event beds. A few of these aspects are summarized in Table 1, which lists the outcrops from most proximal (Stop 4) to most proximal (Stop 1). Covered intervals in the upper parts of Stops 2 and 3 (sections 86-1 and 84-33 of Houck) skew some of the data in that these preferentially occur in shale-rich, thin-bedded zones. Despite this, it is evident that thicker event beds are more abundant in the proximal sections. These thicker beds are dominated by hummocky cross-stratification, a feature absent in the much thinner bedded, distal deposits of Stop 1. Although individual event beds cannot confidently be traced between sections, the spatial distribution of thicker sandstone beds (>15 cm) suggests that individual event beds likely decrease in thickness distally, similar to standard tempestite proximality trends. Such a bed thickness distribution may reflect the spatial distribution of velocities, namely that these flows were possibly entirely depletive (decelerating in space) as expected (see discussion above) from the time they entered the basin. This is separate from the temporal history of flow, whereby all locations may have experienced initial acceleration followed by deceleration in response to hydrographic changes (discharge) or sediment concentration.

	Proximal			Distal
	Stop 4*	**Stop 3**	**Stop 2**	**Stop 1**
Section thickness (m)	12.40	35.27	19.75	18.84
Percent sandstone	32	33	30	35
Total number of beds	23	80	38	58
Average bed thickness (cm)	17.57	14.45	19.43	11.03
Number of beds over 15 cm thick	9	28	6	11
Percent of beds over 15 cm thick	39	35	16	19
Number of RNG/WW[+] beds	1	5	10	17

*Only the lower part of this section was measured.

+RNG=reverse-to-normal graded; WW=acceleration-deceleration as preserved in sedimentary structures.

The spatial distribution of wave effects is also discernable based on the distribution of sedimentary structures between outcrops. The greater abundance of medium to thick HCS beds in more proximal localities (Stops 2-4), and the absence of HCS at Stop 1, indicate that the influence of waves decreased distally. However, the presence of combined-flow ripples at Stop 1 suggests that Stop 1 was above storm wave base.

There is also a distal increase in beds that show reverse-to-normal grading (RNG) and/or waxing–waning (WW) as recorded in vertical sequences of sedimentary structures. The nature of flow in the more proximal sections, the timing and nature of deposition of thick HCS beds, and their relationship to RNG/WW beds are somewhat difficult to reconstruct. This requires careful consideration of the possible ways that waves and the hyperpycnal flow interacted. Several hypotheses are outlined below.

Hypothesis 1: Reworking: Hyperpycnal flow and waves, and the sedimentary structures that they generated, may have been largely separated in time and are thus unrelated. One could imagine that in a river with a large catchment, the river could flood and create a hyperpycnal flow without a local storm on the shelf. In this hypothesis, a standard turbidite would have been deposited and then later reworked by waves. We reject this hypothesis on a variety of grounds.

First, combined-flow ripples indicate the concomitant action of both unidirectional flow and waves. The sandstone bed at 11.62 m in Stop 2 with the asymmetric development of combined-flow ripples along a large hummock indicates that hyperpycnal flow continued throughout the course of the deposition of a large 3d hummocky bedform. In addition, the RNG/WW beds commonly have combined flow ripples at their base and top, again suggesting wave influence throughout deposition.

Hypothesis 2. Stratification: Event beds in the Minturn contain flutes, prods, grooves, and chevron marks on the bases, including well-developed deeply scoured flutes, grooves, and gutter casts on the sole of the 38 cm-thick sandstone bed near the top of Stop 3 (at 31.8 m). We argue that such structures are indicative of powerful unidirectional flow during the initial stages of the storm event. Powerful oscillatory flow is also indicated by the presence of large-scale HCS beds in Stops 2–4. If the bottom of the water-column was highly stratified with a dense hyperpycnal flow at its base, it might have suppressed wave oscillations at the bed and allowed unidirectional sole marks to form without a reduction of wave energy. In such a case, the top of the stratified layer might have served as a basal no-slip surface on which the wave boundary layer formed, rather than the bed. We are unsure of the degree of stratification that is needed to significantly reduce wave oscillations near the bed. Some insight is gained by the wave duct experiments by Lamb and Parsons (in review), in which a dense brine (1.1 g/cc) overlain by fresh tap water (1.0 g/cc) was not sufficient in reducing modest wave oscillations (U_o ~ 30 cm/s) within the brine. This is equivalent to a sediment concentration of ~ 200 g/l for a freshwater plume traveling through seawater (using a density of seawater of typical of the modern ocean ~ 1.025 g/cc). Sediment concentrations greater than 200 g/l seem unrealistic because this exceeds the criteria for viscous dominated flow (Ross and Mehta 1989) and approaches measurements of sediment concentration (porosity) of the seabed (Wheatcroft et al., 1996). However, additional experimental studies are needed to confirm the qualitative observations of Lamb and Parsons (in review). Even if stratification was important in limiting oscillatory motions, it must have been limited to the initial erosive stage of these flows since HCS and combined-flow ripples indicate the combined effects of waves and currents.

Hypothesis 3. Temporary and spatially restricted destruction of stratification: This hypothesis is largely the antithesis of Hypothesis 2, the latter of which requires that the hyperpycnal flow was maintained across the entire onshore-offshore profile. Instead, it may have been temporarily destroyed within the region of maximum wave energy by upward advection of suspended sediment into the water column. In this hypothesis, the gravity driven flow would have passed through a zone of high wave-generated turbulence where the flow was temporarily destroyed and where strongly wave-influenced deposits — thick HCS beds — accumulated. This hypothesis requires that the downstream margin of this zone would have been a region in which gravitational settling would have led to re-formation of a flow driven by excess-weight forces. This zone of destruction of the hyperpycnal flow would have had to vary in space and/or time to allow deposition of the sandstone bed at Stop 2 with asymmetric development of combined-flow ripples across a large hummock.

Hypothesis 4: Reversing and/or pulsating current flow: In this preferred hypothesis, currents and waves were active simultaneously during the bulk of deposition of these event beds. In this case, the superposition of waves onto a hyperpycnal flow helped to maintain high suspended-sediment concentrations and thus aided in the offshore transport of sediment (see Myrow and Southard, 1996 and Myrow et al., 2002). Two possible scenarios exist for the nature of water motions that would have resulted under such a combined flow, and both may have occurred at different times and places across the onshore-offshore profile. In one case, maximum orbital velocity of the oscillatory flow exceeds the velocity of the unidirectional hyperpycnal flow ($U_o > U_c$), and the flow actually reverses direction during each half-wave cycle. Such oscillatory-dominant combined, or reversing current, flow is consistent with the deposition of large-scale HCS and combined-flow ripples, but not with the unimodally-oriented prod marks, flute marks, gutter casts and large grooves.

In the second case, the hyperpycnal flow velocity exceeds the maximum orbital velocity of the oscillatory current ($U_o < U_c$) and the current is pulsating. There is little or no experimental or observational data on such flows, and so nothing is unknown about the nature of sole markings or bedforms produced by such flows. Unimodally-oriented sole marks are more likely in pulsating flows than in reversing current flows. These would have formed during times of peak hyperpycnal flow velocity (associated with the waxing-to-waning nature of these flows), when the unidirectional velocity component would have greatly exceeded the orbital velocity. The reversing current flows likely dominated during deposition and led to HCS and combined-flow ripples.

EPILOGUE

It is quite likely that the flows that deposited these event beds varied in character both in time and space. The event beds of this study were deposited under wave-modified turbidity currents. In this case, the density flows were not slump-generated surge-type turbidity currents but hyperpycnal flows. Beds with reverse-to-normal grading and wax-wane sequence indicate changes in flow velocity in the ocean that were associated with the temporal evolution of a flooding river. Differences between outcrops in grain sizes, vertical stratification sequences, and bed thicknesses are attributed to the spatial distribution of wave effects, the time-history of hyperpycnal flow, and the interaction of these processes. The latter is difficult to discern and was likely highly variable, but the bulk of evidence favors deposition under reversing and pulsating combined flows (Hypothesis 4 above).

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FIGURE CAPTIONS

Fig. 1. Pennsylvanian paleogeographic map of Colorado, showing uplifted areas and sedimentary basins. The location of the study area and the offset of the en echelon bounding faults on the eastern margin of the Central Colorado Basin are also shown. After Mallory (1972) and DeVoto (1980). [Locatinmap.tif]

Fig. 2. Locality map of Bond–McCoy region of Colorado [LocalitymapEPS2]

Fig. 3. Columnar section showing the Minturn Formation as it occurs around McCoy, Colorado. The 19 units were delineated by Chronic and Stevens (1958). The position of the study interval is also shown. [StratcolEPS.tif]

Fig. 4. Isopach map of Houck's units 3b, 3c, and 4 of Minturn Formation showing effect of erosional incision by fluvial channels on top of unit 4. [SobcropEPS.tif]

Fig. 5. Distribution of turbidity current deposits in unit 5a. [Turbfacies.tif]

Fig. 6. Stratigraphic Section for Stop 1. [BondHi-res.tif]

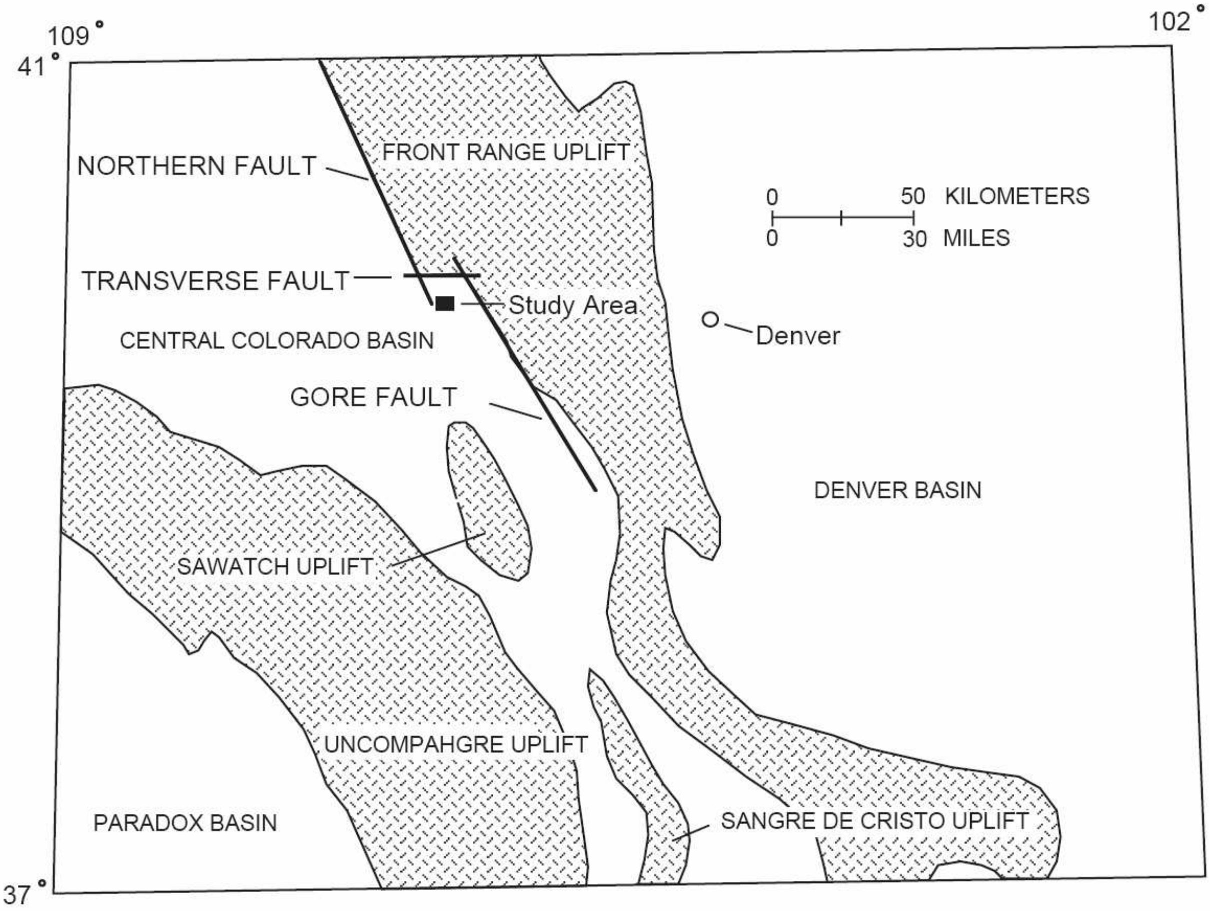
Fig. 7. Paleocurrent rose diagrams for Stops 1-4.

Fig. 8. Vertical Stratification Sequences: Organized According to Grading – #4 and #6 are most abundant. #13-19, 21-23, 25, and 28 record accelerating and decelerating flow. [Page1 and Page2.tif]

Fig. 9. Stratigraphic Section for Stop 2. [86-1]

Fig. 10. Stratigraphic Section for Stop 3. []

Fig. 11. Stratigraphic Section for Stop 4. []



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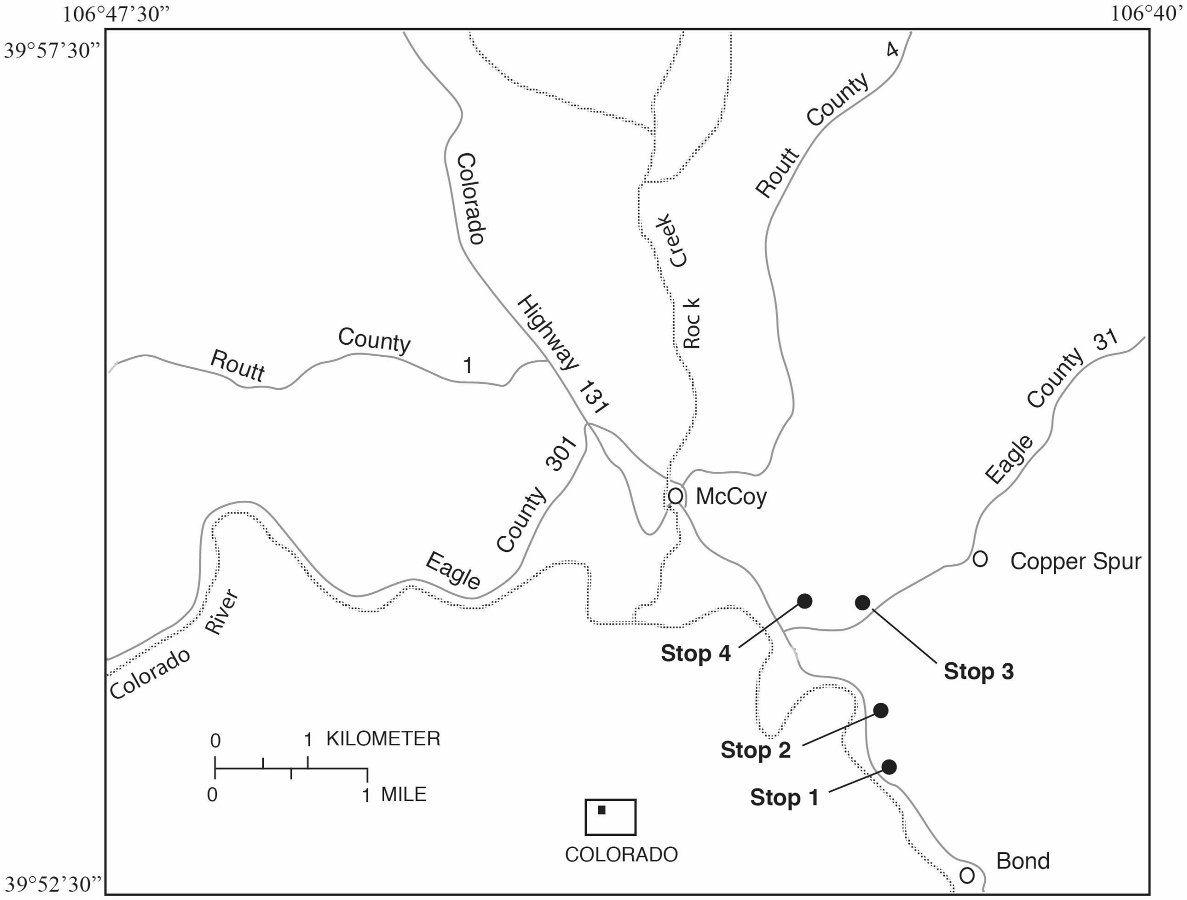

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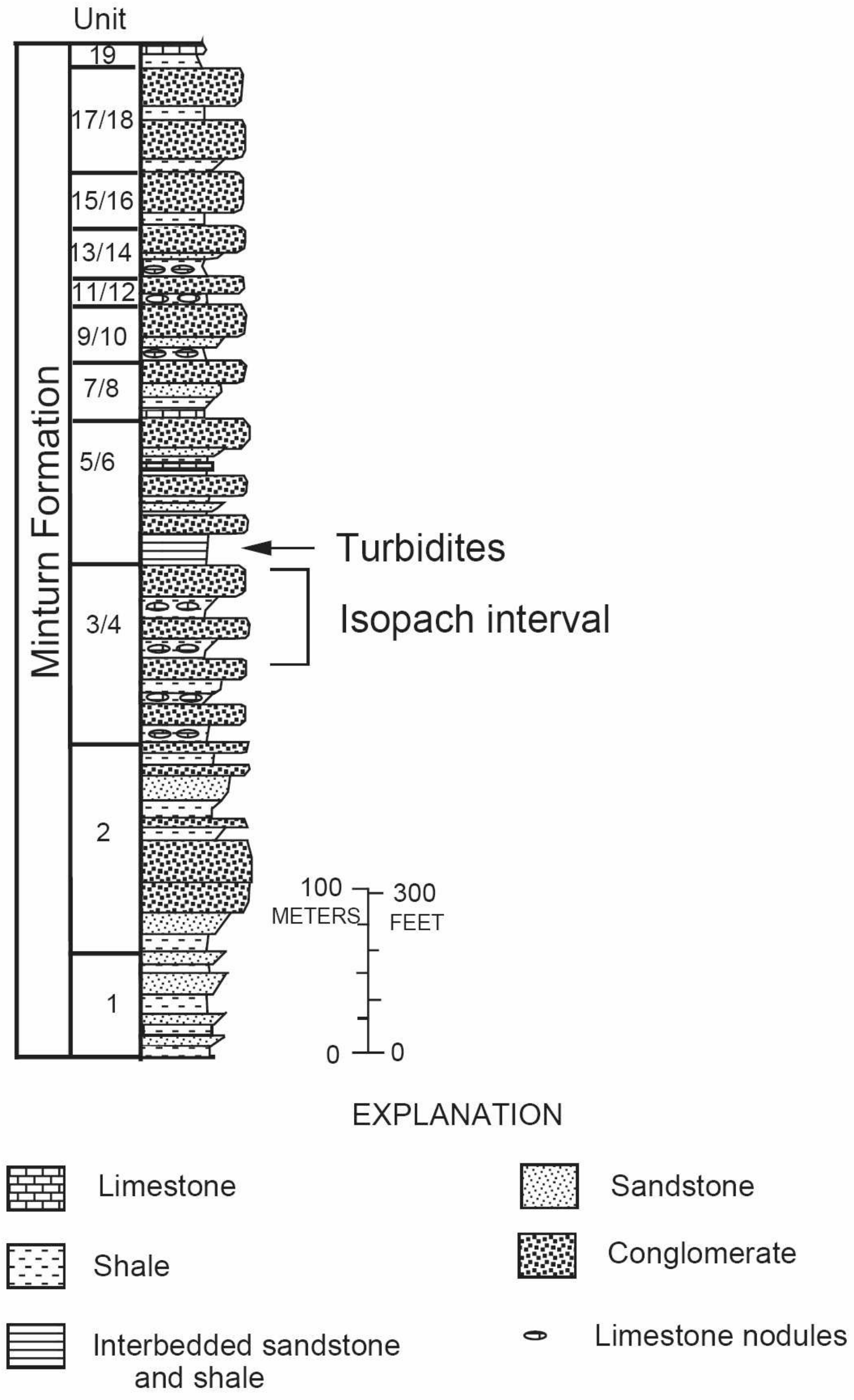

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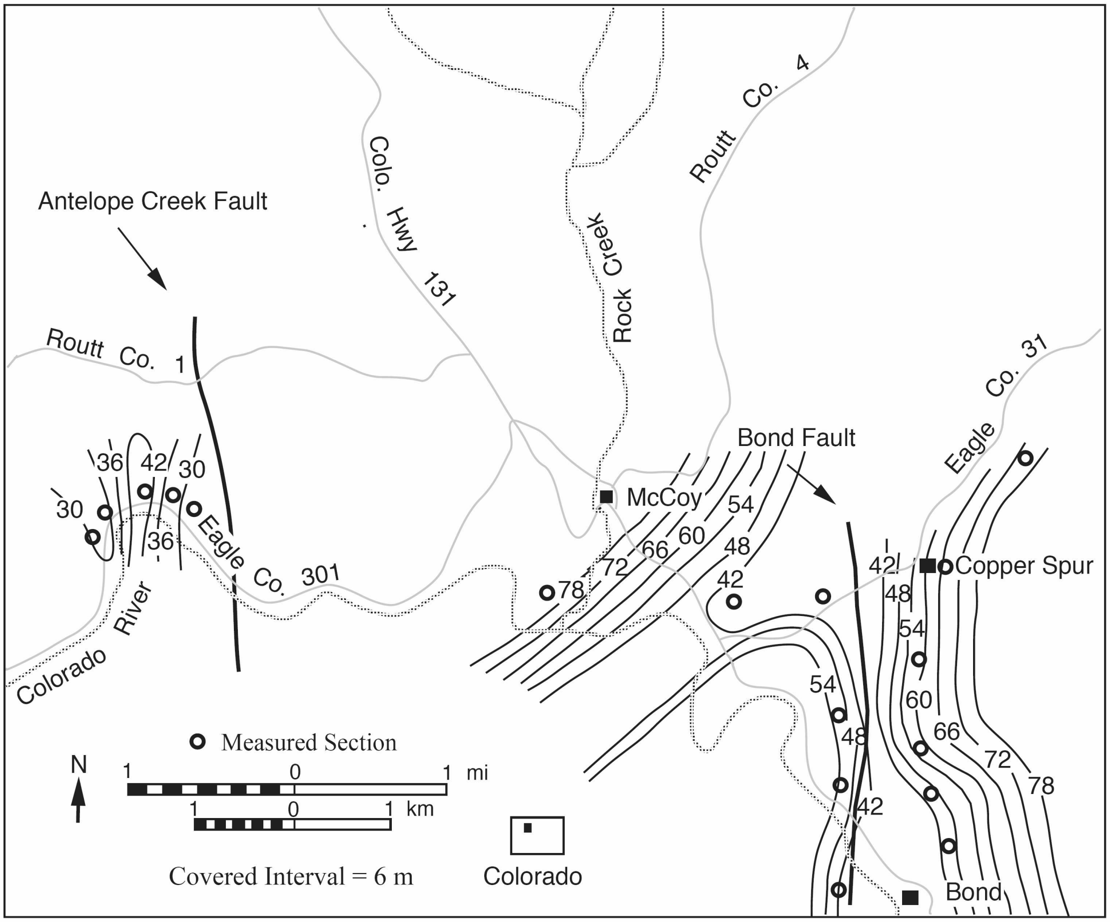

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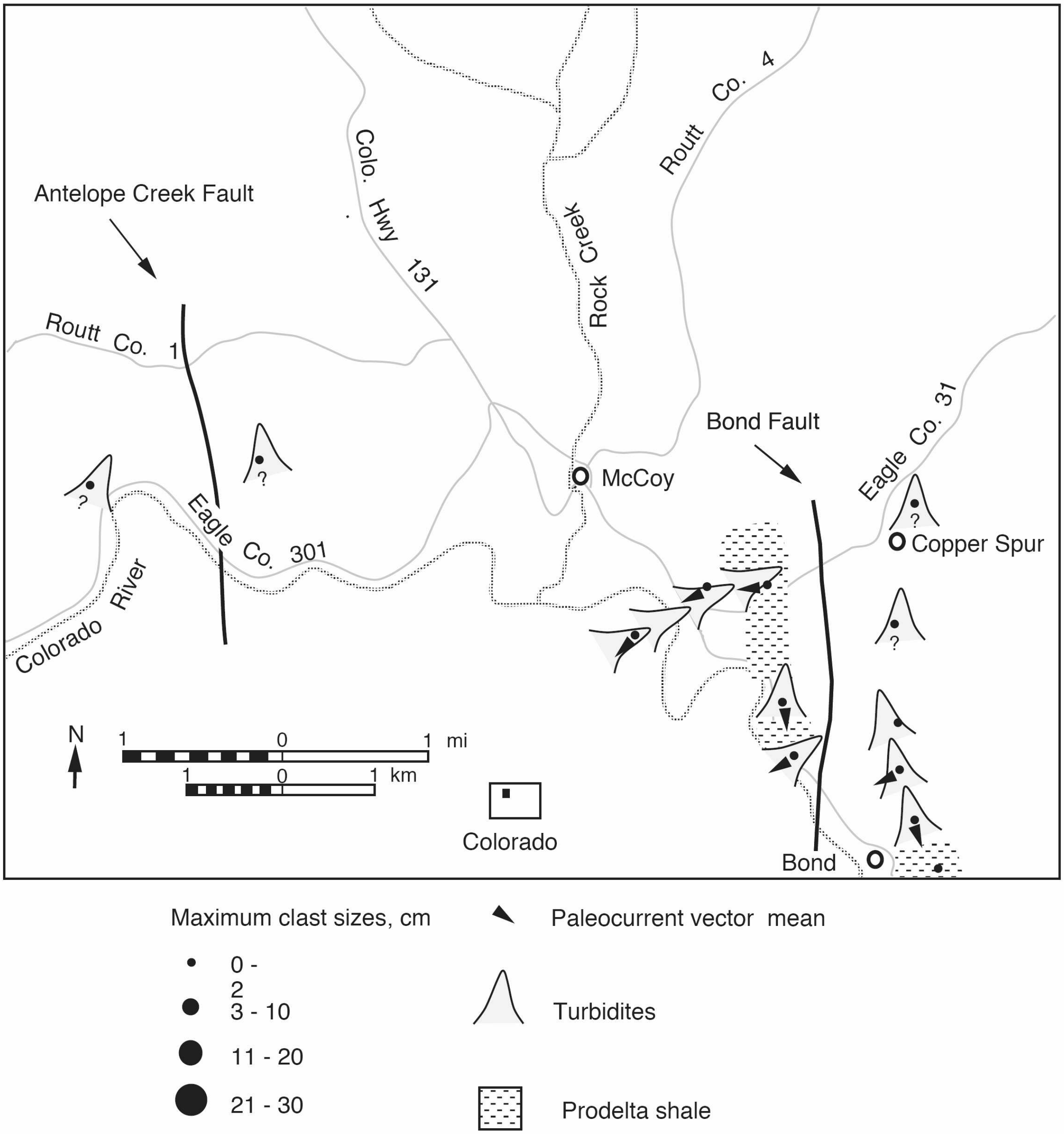

Fig. 5. Distribution of turbidity current deposits in unit 5a.

Figure 8