Submarine mass failure within the deltaic Domengine Formation (Eocene), California (USA)

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ABSTRACT

Outcrops within the Eocene Domengine Formation (central California) provide an exceptional opportunity to observe the relationship between depositional facies and submarine mass failure. The Domengine Formation is interpreted as an assemblage of heterolithic, shallow- to marginal-marine deposits that record progradation and aggradation prior to regional flooding and local collapse of the shelf. Structural analysis of soft-sediment folds and reverse faults within the informally named New Idria mass-transport deposit (MTD) suggests transport toward the west to southwest, which is consistent with paleoflow measurements from cross bedding within the MTD. Depositional facies have a strong influence on the character of soft-sediment deformation (e.g., style and scale of folding and faulting), and major layer-parallel detachment surfaces within and below the New Idria MTD occur where mudstone-dominated or heterolithic units underlie sandstone-dominated units. Conditions favorable to gravitational instability and eventual collapse of the shelf include (1) high sedimentation rates within a rapidly aggrading system; (2) loading of under-compacted, mechanically weak, fine-grained layers by overlying, denser sand bodies; and (3) earthquake seismicity and/or over-steepening of slopes within a tectonically active, convergent margin setting. This study provides a rare detailed glimpse into the collapse of a deltaic stratigraphic sequence, yielding insight into the linkage between marginal marine facies and depositional architecture and the propensity for submarine mass failure of continental shelves.

INTRODUCTION

Deltas that form near the shelf-slope break (i.e., shelf-edge deltas) constitute an important staging area for sediment delivery to the deep sea and are a dominant mechanism of continental margin progradation (Porebski and Steel, 2003; Covault et al., 2009; Sylvester et al., 2012; Schwartz and Graham, 2015). One mechanism of sediment transfer into deep-water slope and basin-floor settings is mass failure of shelf stratigraphy that can produce large, destructive submarine landslides, or mass-transport deposits (MTDs) (Anthony and Julian, 1997; Moscardelli and Wood, 2008). Mass-transport deposits that emanate from the edges of continental shelves have been termed “shelf-attached” and represent a globally significant variety of submarine landslide (Moscardelli and Wood, 2008). Shelf-edge instability is promoted by several factors: (1) juxtaposition of large sediment volumes adjacent to an increase in bathymetric slope at the shelf edge; (2) high sedimentation rates that can result in excess pore-water pressure; and (3) fluctuations in relative sea level (Coleman and Prior, 1988; Garziglia et al., 2008; Dalla Valle et al., 2013). Shelfal successions that form in tectonically active settings are subject to additional factors that may promote submarine landsliding, including narrow shelves, steep bathymetric slopes, and frequent earthquake shaking.

Despite the ubiquity of shelf-edge collapse along continental margins, outcrops of collapsed shelfal or deltaic deposits are relatively uncommon, with some exceptions (e.g., Nemec et al., 1988; Odonne et al., 2010). Submarine mass movement associated with shelf-edge deltas has been more commonly documented in historic examples (e.g., Anthony and Julian, 1997) and by seismic-reflection imaging of the shallow subsurface (e.g., Garziglia et al., 2008; Perov and Bhattacharya, 2011). Although these remote-sensing-based approaches (e.g., seismic-reflection data) have their advantages, they are unable to capture the detail of internal architecture and lithology that is possible through outcrop study.

This work aims to improve understanding of the influence of depositional facies, depositional architecture, and the resulting mechanically heterogeneous stratigraphy on submarine mass failure within a well-exposed outcrop example of collapsed deltaic facies in the Middle Eocene Domengine Formation. This is accomplished through detailed characterization of a MTD that is exposed for more than 6 km within the Coast Ranges of central California (Fig. 1). The informally named “New Idria MTD” records downslope translation and internal deformation of a shallow- and marginal-marine facies succession...
Figure 1. Overview of the study area. (A) Geographic context of central California showing the location of the Vallecitos syncline. Faults modified from Dickinson et al. (2005). (B) Generalized geologic map of the Vallecitos syncline modified from Anderson, 1998, and Dibblee, 1974). (C) Schematic cross section along the northern limb of the Vallecitos syncline showing the erosional truncation of progressively older stratigraphic units toward the west-northwest modified from Schulein, 1993). Datum is the contact between the Domengine Formation and the Kreyenhagen Formation. Abbreviations: CA—California; Ck.—Creek; Fm.—Formation; Mt.—Mountain; NV—Nevada; Sh.—Shale; Ss.—Sandstone; VS—Vallecitos syncline.
following rapid sea-level transgression (Milam, 1984). Although some shelf-attached MTDs result in disaggregation of sediments during downslope translation (e.g., Moscardelli and Wood, 2008), much of the original stratigraphic architecture is preserved within the New Idria MTD, providing insight into the relationship between depositional facies, architecture, and soft-sediment deformation style. Lateral discontinuity of the New Idria MTD in outcrop suggests that shelf failure was not regionally extensive but was focused in a narrow zone that was predisposed to failure.

We demonstrate that the structural style of soft-sediment deformation was preconditioned by the original depositional heterogeneity within this sedimentary sequence. Specifically, lithologically distinct units within the Domengine Formation display different styles of soft-sediment deformation (e.g., size and character of folding and faulting) and are inferred to control the location of layer-parallel detachment within the MTD. Investigation of depositional facies and deformatonal styles in the New Idria MTD improves understanding of the linkage between deltaic facies and the factors that contribute to gravitational instability. Additionally, study of both the depositional and structural history of the Domengine Formation provides much-needed context for the paleo-geographic and tectonic setting of the central San Joaquin basin, a region that has been sparsely studied despite preserving a rich history of convergent margin tectonism along the western United States.

## STUDY AREA AND GEOLOGIC BACKGROUND

The study area is located within the New Idria quadrangle on the south-eastern margin of the Vallecitos syncline, a structural and depositional trough within the Diablo Range of central California, ~50 km north of the town of Coalinga (Fig. 1). Structurally underpinned and bounded on the north and south by uplifted exposures of Franciscan subduction complex, the Vallecitos syncline preserves a thick succession of Upper Cretaceous–Miocene strata that accumulated within the extensive forearc basin that formed during Mesozoic–Paleogene subduction of the Farallon plate beneath North America (Dickinson and Seely, 1979) (Fig. 1). Remnants of this arc-trench system are preserved today as the Sierra Nevada batholith (mid-Cretaceous volcanic arc), Great Valley forearc basin, and Franciscan subduction complex (Dickinson, 1995).

Uppermost Cretaceous (Maastrichtian) to Eocene strata in the Vallecitos syncline record a complex history of depositional settings and bathymetry that reflects tectonic reorganization of the forearc basin (Fig. 2). Bathyal water depths (200–2000 m) persisted in the forearc basin for much of Late Cretaceous time (e.g., Panoche Group, Fig. 1; Ingersoll, 1979). However, structural exhumation and subaerial emergence of the underlying Franciscan Complex occurred during latest Cretaceous–Paleocene time, based on an episode of basin shoaling and the presence of Franciscan-derived detritus within the Moreno Formation (McGuire, 1986; Mitchell et al., 2010) (Fig. 2). Overlying the Moreno Formation, the Upper Paleocene to Lower Eocene Lodo Formation records a return to bathyal water depths, which is represented by shale and sand-rich turbidite deposits such as the Lower Eocene Cantua Sandstone Member (Graham and Berry, 1979; Anderson, 1998). Although the present-day structural configuration of the Vallecitos syncline developed during Neogene time, isopach maps of the Cantua Sandstone Member suggest that a bathymetric low, or mini-basin, existed in the area as an Early Eocene predecessor to the syncline (Schulein, 1993). The Early Eocene Vallecitos mini-basin was likely flanked to the north and south by uplifted subduction complex (Anderson, 1998), forming a trench-slope mini-basin perched atop the Franciscan subduction wedge. Throughout Lodo Formation deposition, sediment was routed to the Vallecitos mini-basin by a submarine canyon incised into the shelf-slope break to the east of the study area (Graham and Berry, 1979). The mini-basin shoaled by Middle Eocene time, resulting in deposition of shallow-marine facies of the Domengine Formation (Fig. 2).

The Domengine Formation is a regionally extensive, sandstone-dominated unit that crops out from north of San Francisco Bay southward to Coalinga, California (Figs. 1 and 2) (White, 1940; Dibblee and Nilsen, 1974; Schulein, 1993; Sullivan and Sullivan, 2012). The Domengine Formation is also widespread in the subsurface of the San Joaquin basin and is locally a petroleum reservoir (e.g., Vallecitos Oil Field) (CDOGGR, 1998; Scheirer and Magoon, 2007). Within the study area, the Domengine Formation thickens toward the center of the Vallecitos syncline, signaling continued subsidence and growth of the basin through Middle Eocene time. Similar to the underlying Cantua Sandstone, Domengine Formation sandstone exposed in the eastern half of the Vallecitos syncline was derived from the Sierra Nevada magmatic arc to the east, based on paleocurrent measurements, sandstone and conglomerate clast compositions, and detrital zircon U-Pb ages (Slagle, 1979; Schulein, 1993; Sharman et al., 2015a). However, Domengine Formation sandstone exposed from Griswold Canyon and Lopez Canyon through the western part of the syncline contains rounded pebbles of red radiolarian chert derived from the Franciscan Complex (Schulein, 1993) (Fig. 1). This indicates that, at least locally, the thick Mesozoic Great Valley Group forearc basin sequence had been uplifted and eroded prior to Domengine Formation deposition, exposing the underlying Franciscan subduction complex. Evidence for early uplift and subaerial exposure of the ancestral Coast Ranges to the west of the Vallecitos syncline also exists as a sub-Domengine unconformity where progressively older stratigraphic units are truncated toward the west-northwest (Dibblee and Nilsen, 1974) (Fig. 1C). Deposition of the Domengine Formation ceased following abrupt subsidence and basin-wide transgression that resulted in widespread deposition of the Middle Eocene Kreyenhagen Formation and a return to low-energy, deep-marine conditions over much of the Great Valley forearc (Milam, 1984) (Fig. 2).

## METHODOLOGY

Our analysis of the New Idria MTD includes a variety of complementary approaches that document the stratigraphic and structural character of the deposit.
(1) Approximately 300 m of section were measured from four locations along the outcrop belt to document depositional facies and architecture (Fig. 3). Measured section locations were chosen to encapsulate lateral variation in depositional facies and to avoid structurally complex portions within the New Idria MTD that obscure primary depositional architecture. We adopt the stratigraphic partitioning of Slagle (1979) and divide the Domengine Formation within the study area into five stratigraphic units (Units 1 through 5) to describe the vertical and lateral variability within the formation. The four measured sections include, from west to east, sections from the San Carlos Creek area (Units 1–3), the Large Folds SW area (Units 1–5), the Amphitheater area (Units 1–5), and the Large Folds NE area (Units 1–5) (Figs. 3 and 4). Ultimately, new data are compared to and selectively combined with previous work (e.g., Slagle, 1979; Schulein, 1993) in order to capture the variability in sedimentary architecture that is typical of shallow- and marginal-marine deposits.

(2) We collected a structural database of 24 orientations from large folds within the New Idria MTD for use in characterizing its deformational style and kinematic history (Table 1). Bedding measurements were collected from each...
limb and hinge of the fold, where possible, and fold orientations were calculated stereographically following Davis et al. (2012). Fold axes are approximated as the x-axis, and the axial plane is assumed to bisect the fold limbs. For asymmetric folds, vergence is taken as 90° from the x-axis, in the up-dip direction of the fold axial plane. All fold orientations have been restored to account for regional tilting associated with the development of the Vallecitos syncline (Fig. 1). We first removed the regional plunge (26°/12°) of the Vallecitos syncline, as estimated stereographically using bedding measurements from the 1:24,000-scale geologic maps of Dibblee (2007a, 2007b). We then restored bedding to horizontal, using the top of Unit 1 as a reference surface (Fig. 3). Kinematic analysis of the fold orientations was used to reconstruct the direction of MTD translation and the paleoslope orientation, following the methods outlined in Strachan and Alsop (2006) and Sharman et al. (2015b).

3) We compiled a digital database of surface-, drone-, and airplane-based photographs to document both stratigraphic and structural relationships along the 6-km extent of the New Idria MTD. A three-dimensional (3D) model
of the outcrop was created using the photogrammetry software, Agisoft PhotoScan Professional®, using a total of 235 photographs from five overhead passes from a fixed-wing airplane (Fig. 3). Ground control points were collected using a differential GPS unit and were used to georeference the outcrop model, and a georeferenced orthophoto was generated as a base for geologic mapping (Fig. 3). A composite aerial photomontage was draped on a textured 3D model of the outcrop and used to generate a synthetic cross section of the New Idria MTD (Fig. 5). The model was rotated such that the view is aligned parallel to the dip of bedding (~30° toward the north-northwest). An orthographic projection was applied to eliminate perspective effects and to ensure that vertical distances in the foreground and background are scaled similarly. A high-resolution image was exported and used as a basis for line-drawing interpretation (Fig. 5). Because the image was generated looking along bedding with an orthographic projection, the resulting line-drawing interpretation is a close approximation for a depositional cross section through the New Idria MTD (Fig. 5).
### RESULTS

#### Overview of the New Idria Mass-Transport Deposit

The New Idria mass-transport deposit (MTD) is exposed for at least 6 km along the southeastern hinge of the Vallecitos syncline (Fig. 1). The northern boundary of the MTD is not well constrained but likely is positioned near the axis of the Vallecitos syncline based on aerial reconnaissance and the presence of un-deformed Domengine Formation in the vicinity of Silver Creek (Fig. 1) (Schulein, 1993). Similarly, the western extent of the MTD is uncertain but cannot extend more than 9 km west of the study area (Lopez Canyon; Fig. 1), where the Domengine Formation consists of ~45 m of alluvial fan and braided fluvial deposits (Schulein, 1993). The Domengine Formation has been eroded south of the study area (Fig. 1), and thus the southern extent of the MTD is not constrained.

The New Idria MTD has characteristics of both a submarine slump and translational slide, in that original bedding is largely intact despite local deformation (Martinsen, 1994; Posamentier and Martinsen, 2011). Deformation structures are exclusively contractional (i.e., folds and reverse faults), suggesting that outcrop exposures are within the down-dip, contractual portion of the MTD. The basal surface of the MTD lies within a poorly defined detachment zone within the Domengine Formation, at or near the contact between Units 1 and 2 (Figs. 5 and 6E). Although the total stratigraphic thickness of the Domengine Formation (Units 1–5) at San Carlos Creek is ~250 m, the maximum thickness of the MTD (comprising Units 2–5) is greater (~280 m) due to local structural thickening. The upper surface of the MTD is well exposed and commonly displays significant relief (up to 80 m) that coincides with the crests of large anticlines in the uppermost parts of the MTD (Figs. 5 and 6A). The overlying Kreyenhagen Formation consists of poorly exposed mudrock, but where bedding planes are visible, it appears to passively fill synclinal troughs on the upper surface of the MTD (Fig. 6A).

#### Stratigraphy and Depositional Facies

The stratigraphy associated with the New Idria MTD is interpreted as an assemblage of shallow- to marginal-marine shoreline, estuarine, and deltaic deposits that record marked relative sea-level fluctuations during Middle Eocene time (Slagle, 1979; Schulein, 1993). Although previous studies broadly agree on depositional history, there is still uncertainty regarding some of the...
specific depositional environments represented in the formation. Interpretation of these specific environments is required to understand the relationship between the primary mechanical heterogeneity controlled by depositional environment and its subsequent effect on the deformational history of the MTD.

**Unit 1: Prograding Estuary-Mouth Bar Complex**

**Description**

The basal unit of the New Idria MTD is a tabular, 25–28-m-thick assemblage of medium- to coarse-grained, well-sorted, bright tan sandstone with minor mudstone that is continuous across the entire outcrop area (Figs. 4 and 5). Unit 1 abruptly overlies the Arroyo Hondo Shale, but the contact is largely obscured by vegetation (Slagle, 1979). The basal 20 m of sandstone in Unit 1 is heavily amalgamated and contains the following vertical succession of sedimentary structures: The lower part of the basal unit is pervasively bioturbated and structureless (Fig. 7A). In some areas, this bioturbated zone is greenish and glauconitic and contains abundant *Ophiomorpha* burrows. The structureless sandstone interval is overlain by 3.5–5.5 m of tan sandstone that contains normally graded sets of planar and low-angle lamination with intermittent zones of pervasive bioturbation (including *Ophiomorpha* and *Thalassinoides*) (Figs. 4 and 7A). Poorly developed hummocky and swaley cross stratification (HCS and SCS, respectively) were also identified by previous workers in this interval (Slagle, 1979; Schulein, 1993) but were not observed in this study.
Figure 6. Examples of slump folds and faults within the New Idria mass-transport deposit (MTD). (A) A series of large folds within the upper portion of the New Idria MTD. Black line marks the approximate boundary between Units 4 and 5. Note the topographic relief on the contact with overlying shale of the Kreyenhagen Formation. (B) Anticlinal folding within interbedded sandstone and mudstone (Unit 3). Black lines highlight bedding surfaces, and red lines show the location of slump-related faults. White outline of a person for scale. (C) A series of asymmetrical folds within a sandstone-dominated (light-colored) interval within Unit 2. The base of the sand bed is shown as a black line. Note that these folds detach downwards into a mudstone-dominated zone within Unit 2, and the underlying sandstone bed (black arrow) is not deformed despite the overlying shortening. (D) Two low-angle reverse faults (red lines) displace a sandstone bed in Unit 2. (E) Recumbent, isoclinal fold within a mudstone-dominated interval within the base of Unit 2. Note a post-MTD tectonic fault (brown line) crosscuts the northeastern side of the fold. White outline of a person for scale.
Figure 7. Example photos of depositional features within the New Idria mass-transport deposit (MTD). (A) Progradational tidal bar succession preserved by Unit 1. Note soft-sediment deformation of large-scale trough cross strata in the upper part of the succession. (B) Heavy-mineral placers (blue-gray sandstone) in cut-and-fill facies of Unit 1. Heavy-mineral accumulations are found in planar-laminated and trough cross-stratified intervals. Arrows depict cm-scale soft-sediment deformation within the facies. (C) Macaronichnus (Mac) assemblage highlighted by heavy-mineral sands in Unit 1. (D) Lenticular sandstone unit encased in varicolored mudstone of Unit 2, overlain by a zone of Thalassinoides (Th) burrows. Yellow line traces the base of the sandstone lens and displays meter-scale offset by a small thrust fault associated with development of the MTD; person for scale. (E) Large-scale tangential cross stratification lined by black and blue quartz pebbles in Unit 3; person for scale. (F) Heterolithic deposits within Unit 4 in the Amphitheater. White triangles denote partially amalgamated splays or channel sands at the base of Unit 4. Yellow arrows delineate erosional surface through upward-finining, tidal-flat successions near the top of Unit 4. (G) Sub-meter-scale, muddy channel fill within an upward-fining tidal-flat succession at the top of Unit 4. Note that mudstone beds form down-lapping drapes over the channel-bottom geometry. (H) Climbing ripples within Unit 4. (I) Bidirectional, gravely, tabular foresets in tidal channel fill of Unit 5; scale is 3 cm. (J) Close-up of channel-bottom deposits including ripples and mudstone drapes. Arrows indicate presence of double mud drapes over ripple bedforms; scale is 3 cm.
The planar laminated zone is overlain by a 2–6-m-thick interval dominated by cut-and-fill features with abundant trough and tangential cross stratification (“festoons” cross stratification of Slagle, 1979). Cross sets range from 10 to 80 cm in amplitude and are over-steepened and convolute in some areas (Figs. 7A–7B). Rare, blue-gray lenses of heavy-mineral accumulations, which highlight the presence of Macaronichnus and other Skolithos ichnofacies burrows (Figs. 7B–7C), are also present in this interval.

The basal amalgamated sandstone unit is variably capped by laminated mudstone, peat, and broadly lenticular, structureless to faintly structured sandstone bodies. In the San Carlos Creek area, the thick, basal sandstone unit is directly overlain by a 0.5-m-thick layer of peat, which grades directly into thick, varicolored mudstones of Unit 2 (Fig. 4). To the east, in the Large Folds SW and Amphitheater areas, the basal sandstone is overlain by ~0.5 m of laminated, sandy mudstone and ~2 m of structureless to faintly bedded sandstone (Figs. 4 and 7A). In the Large Folds NE area, the basal sandstone is capped by a 7-m succession of interlaminated organic mudstone and peat that grades into sandstone (Fig. 4). The lower 3 m of the succession is burrowed by Thalassinoides, and sandy intervals include Teredolites-bored wood fragments. The Thalassinoides interval is overlain by ~1.5 m of coarse sandstone with faint medium-scale trough cross lamination. The cross-laminated interval is capped by a ~1.5-m-thick bedset of tabular, normally graded beds of medium- to fine-grained sandstone. Faint planar lamination is present at the base of each bed, and each grades into structureless sandstone that is cemented by iron oxide. Finally, this bedset is overlain by 1.3 m of pervasively bioturbated, structureless sandstone and 0.7 m of peat.

**Depositional Environment**

We recognize two possible environmental interpretations for Unit 1, which include (1) a progradational sandy shoreline (after Slagle, 1979; Schulein, 1993) or (2) a progradational tidal bar complex (Fig. 8). In both scenarios, the consistent thickness and lateral continuity of Unit 1 support deposition along a broad, shallowly dipping shoreline profile. From its base above the Arroyo Hondo Shale to the top of the first thick, amalgamated sandstone in the unit, sedimentary architecture reveals progressive shoaling of marine environments. The heavily burrowed and glauconitic sandstone at the base of Unit 1 represents lower-energy, deeper environments, whereas overlying cross-stratified sandstone represents higher-energy, shallower environments. The presence of Skolithos ichnofacies trace fossils throughout the succession supports deposition in a high-energy, open-marine environment with clean, shifting substrate (MacEachern et al., 2010).

Slagle (1979) and Schulein (1993) interpreted Unit 1 to represent a wave-dominated beach shoreline due to the presence of HCS- and/or SCS-bearing sandstone intervals. In this scenario, the presence of HCS and/or SCS would represent storm deposition in middle to upper shoreline environments. Planar-laminated intervals would represent initial, high-energy conditions dominated by offshore-directed storm currents, whereas HCS and/or SCS intervals would represent subsequent combined flow conditions associated with waning storm energy (combined unidirectional and oscillatory currents; Reading and Collinson, 1996). The amalgamation of planar-laminated units and limited preservation of HCS and/or SCS indicates deposition relatively close to shore where successive storm-generated currents were strong enough to significantly erode the upper portions of previous storm deposits (Schwartz and Birkemeier, 2004). Overlying the HCS- and/or SCS-bearing intervals, mixed planar-laminated and trough cross-stratified intervals containing heavy-mineral accumulations represent upper shoreface to foreshore environments that include the longshore trough and swash zone (e.g., Clifton, 1969; Schwartz and Birkemeier, 2004; Clifton, 2006; Plint, 2010).

Although most of our field observations are similar to those of Slagle (1979) and Schulein (1993), we interpret the thick basal sandstone of Unit 1 as a complex of shoaling tidal bars. We prefer this model over a storm-dominated shoreline because (1) no storm-generated HCS/SCS was observed in outcrop; (2) a tide-influenced channel-and-bar environment is more consistent with overlying facies (this study); and (3) a tide-influenced environment is consistent with interpretations of other Domengine Formation deposits (e.g., Sullivan and Sullivan, 2012). In this scenario, the upward-coarsening succession observed in the basal 20 m of Unit 1 represents progradation and shoaling of estuary-mouth tidal bars (or compound dunes; after Dalrymple and Rhodes, 1995). In such bars and/or dunes, topsets are typically coarser grained than foresets and bottomsets due to higher current speeds acting on their crests (Dalrymple, 2010). Foresets and bottomsets commonly contain significant mud and are intensely bioturbated (Dalrymple, 2010). Ultimately, lateral migration of such features results in upward-coarsening successions of strata. Internally, cut-and-fill features, planar and low-angle lamination, and trough cross stratification represent stacked channel and bar deposits with superimposed, smaller-scale dunes (Dalrymple, 2010).

The mudstone, peat, and sandstone intervals that directly overlie the thick, basal tidal bar unit are interpreted as estuarine and/or tidal-flat environments that are located in a more landward position than the estuary-mouth bar complex. Rooted, laminated mudstone with peat intervals indicates deposition in quiet, low-energy environments where abundant organic material accumulated and was undisturbed by current energy, such as vegetated tidal flats or marshes. The presence of Thalassinoides and Teredolites indicates brackish-water conditions (MacEachern et al., 2010) and, therefore, limited connectivity with open marine environments. The tabular, normally graded units that are present in the eastern part of the outcrop indicate deposition by periodic waning currents. Iron-oxide cement at the top of each bed may indicate subaerial exposure (Slagle, 1979). In the context of bounding sedimentary facies, the normally graded beds likely represent sandy tidal-flat deposits (after Slagle, 1979; e.g., Flemming, 2012) where each bed represents shoaling from subtidal to intertidal or supratidal parts of the tidal flat. Alternatively, these beds may represent wash-over fan-like deposits that were deposited during extreme storm events (e.g., Schwartz, 1975; 1982).
• **Mass-Transport Deposit (MTD)–Related Deformation**

Unit 1 does not appear to be involved in MTD-associated soft-sediment deformation. Unit 1 is tabular and continuous across the study area and is only offset and broadly folded by tectonic faults and folds, respectively (e.g., Fig. 5). Internally, Unit 1 does contain minor convolute lamination near the top of the thick, basal sand (e.g., Fig. 7A), but it is possible that these sands were liquefied and deformed in situ in response to bar failure or paleoseismic activity.

**Unit 2: Inner to Middle Estuary Mud-Flat Complex with Tidal Channels**

• **Description**

Unit 2 overlies Unit 1 along the entire outcrop belt (Figs. 4 and 5) and is marked by an abrupt transition from sandstone-dominated to mudstone-dominated facies (e.g., Figs. 4 and 7A). Unit 2 consists of poorly exposed, varicolored (commonly reddish-brown) shale and siltstone, including thin (<10 cm) zones of lignite. Mudstone beds are well defined, intermittently bioturbated, and contain horizons of root casts beneath coal horizons.

Unit 2 also contains intermittent, lenticular, whitish-tan sandstone bodies up to 4 m thick that pinch out laterally over 10–20 m (Fig. 7D). The lenses are thicker, wider, and more abundant toward the east (e.g., the Amphitheater and Large Folds NE areas; Fig. 4). Sandstone lenses typically fine upward from coarse- to fine-grained sandstone with rare black quartz pebbles. Internally, the lenses commonly appear structureless but in some places display faint convolute lamination near the tops of lenses. Horizons of *Thalassinoides* also occur at the tops of some sandstone intervals (Fig. 7D).

• **Depositional Environment**

Unit 2 has been variably interpreted to represent mud-flat or intertidal-flat environments on a subsiding delta plain (Slagle, 1979) and prodelta bar environments (Schulein, 1993). Microfossils identified from within some of the...
mudstone intervals support a depositional environment that was, at least peri-
odically, fully marine (Schulein, 1993). However, the presence of thin lignite
intervals overlying rooted muds indicates depth and salinity conditions that
were suitable for vegetation, in contrast to seaward flushing of disseminated
organic material into prodelta regions (cf. Schulein, 1993). In addition, a low-
diversity but high-density trace fossil assemblage including zones of Thalassi-
noides burrows indicates periodic brackish-water conditions (MacEachern et al., 2010). As such, we interpret Unit 2 to represent intertidal mud-flat en-
vironments that were intermittently dissected by tidal and/or estuarine chan-
nels. Therefore, the abrupt lithologic transition from Unit 1 to Unit 2 indicates
continued progradation of the lower Domengine estuarine complex (Fig. 8).

Thick, interlaminated mudstone and peat intervals that dominate Unit 2
indicate ambient low-energy conditions. Sedimentation was dominated by
suspension deposition of mud and organic debris from the water column
and intermittent in situ accumulation of vegetation on estuary-margin tidal
flats. Most of the small, white to tan sandstone lenses that occur within Unit
2 likely represent small, shallow tidal channels that intermittently dissected
the low-energy environment. The presence of gray quartz pebbles within Unit
2 sandstone is consistent with provenance trends documented by Schulein
(1993), in which erosion of the Sierra Nevada magmatic arc is represented by
the presence of such pebbles. According to this interpretation, it is reasonable
that this lithic sediment was delivered to the estuary system by far-reaching
river systems and likely indicates the presence of a nearby bayhead delta. Nor-
mal grading and convolute lamination in such lenses indicates relatively rapid
deposition during waning flow conditions, such as would be associated with
riverine floods. Overall, the dominantly structureless appearance of sandstone
beds within Unit 2 is likely a result of pervasive bioturbation.

• MTD-Related Deformation

Within Unit 2, there are multiple mudstone-dominated horizons that record
soft-sediment shear and deformation (Figs. 6C–6E and 7D). Mudstone inter-
vals are sheared and deformed with locally developed isoclinal, recumbent
folds (Fig. 6E). In some areas, sandstone lenses are involved in this deforma-
tion, displaying meter-scale offset along small thrust faults and development
of continuous fold trains (e.g., Figs. 6C–6D and 7D). Smaller-scale convolute
lamination at the top of individual sandstone lenses is interpreted to be related
to primary depositional processes and unassociated with the development of
the MTD. Ultimately, we interpret the basal detachment zone of the New Idria
MTD to occur in the mudstone unit(s) near the base of Unit 2.

Unit 3: Bayhead Delta Complex

• Description

Unit 3 has a gradational contact with Unit 2 and is also heterolithic but is
differentiated based on the presence of unique, bright white sandstone lenses
with abundant blue and black quartz pebbles (Fig. 4). In the San Carlos Creek
area, the white, pebbly sandstone lenses are up to 6 m thick and are encased in
varicolored mudstone. The sandstone bodies fine upward, with quartz pebbles
concentrated at their bases. Most lenses appear to be structureless, but some
contain convolute ripple cross lamination.

In the central to eastern exposures of Unit 3, white sandstone lenses are
commonly amalgamated into more laterally continuous but lenticular units
up to 15 m thick. The lenses are dominated by granular to coarse-grained
sandstone with black and blue quartz pebbles that line cut-and-fill features and
large-scale trough and/or tangential cross strata (Fig. 7E). In many areas, cross
strata are over-steepened and convolute, but paleocurrent measurements
from undeformed strata reveal a net northwestward paleodispersal direction
(Fig. 8) (after Schulein, 1993). Amalgamated sandstone units also contain mud
rip-up clasts and log casts (generally oriented east-west to northeast-south-
west) along erosional surfaces. In addition, zones of intense bioturbation (most
commonly including Thalassinoides) were observed along horizons within the
thick, amalgamated sandstone successions, as well as at their tops.

• Depositional Environment

In context of the underlying estuarine facies represented by Unit 2, as well
as the overlying facies of Unit 4, we interpret Unit 3 to represent an assem-
blage of bayhead distributary channel fill and distributary mouth bar depos-
its encased in estuarine mudstone. Compared to sandstone lenses in Unit 2,
the increased abundance of quartz pebbles within Unit 3 indicates increased
proximity to a fluvial source. An overall increase in sediment caliber, degree
of amalgamation, and occurrence and size of internal sedimentary structures
indicates higher-energy, unidirectional flow conditions that deposited and
re-worked the sediment. The lateral, west-to-east increase in sandstone unit
size and internal structure likely represent a facies transition from dominantly
mouth bar deposits in the west (Schulein, 1993) to distributary channel depos-
its in the east (Slagle, 1979; this study). Zones of convolute meter-scale tangen-
tial cross sets support rapid deposition and founding of bar forms within or
at the terminus of distributary channels (e.g., Porebski and Steel, 2003; Olariu
and Bhattacharya, 2006). Intermittent horizons of intense bioturbation within
sandstone units indicate cyclic sediment delivery to the delta region, with bio-
turbation of sands occurring between riverine flood events. In addition, the
presence of a low-diversity trace fossil assemblage including Thalassinoides
reveals deposition in brackish to restricted environments (MacEachern et al.,
2010). Overall, the vertical transition from Unit 2 to Unit 3 records continued
progradation of the marginal marine facies complex (Fig. 8).

• Mass-Transport Deposit (MTD)–Related Deformation

Mass-transport deposit–associated soft-sediment deformation is evident
within the mudstone and sandstone intervals of Unit 3. Similar to Unit 2, mud-
stone intervals are sheared and internally deformed. In addition, the white,
pebbly sandstones of Unit 3 are variably folded and faulted across the study
area (e.g., Fig. 6B). In the NE Large Folds area, thick sandstone units are incorporated into tight, large-scale (>5-m amplitude) recumbent folds and fold trains and are locally repeated along westward-vergent thrust faults (e.g., Fig. 5). Focused soft-sediment deformation within individual sandstone units (e.g., convolute cross sets) is interpreted to be related to primary depositional processes such as dewatering and/or foundering during rapid sedimentation, and is possibly unassociated with the formation of the MTD.

Unit 4: Muddy Estuary-Margin Deposits with Tidal Channels

**Description**

Unit 4 gradationally overlies Unit 3 across most of the study area but is absent in the western San Carlos Creek area (Fig. 4) and the easternmost edge of the MTD exposure (east of the Large Folds NE area; Fig. 5). In the Large Folds SW area, Unit 4 is dominated by varicolored mudstone with discontinuous horizons of sandy fossil hash up to 25 cm thick; these horizons contain oyster, gastropod, and pelecypod fragments (Slagle, 1979; Schulein, 1993; this study). In addition, this area hosts tabular beds of medium-to very fine-grained sandstone up to ~1 m thick. Some exposures display crudely developed ripple cross lamination with abundant reactivation surfaces (Fig. 7H) (Schulein, 1993; this study). Some sandstone beds are pervasively bioturbated, with burrows including *Ophiomorpha*.

To the east, at the Amphitheater section, Unit 4 is heterolithic. In this area, the bright white, pebbly distributary channel sandstones of Unit 3 are overlain by a series of at least four, thin, broadly lenticular sandstone beds (Figs. 4 and 7F). The sandstone beds are sharp based and fine upward into mudstone, forming sandstone-mudstone successions up to ~1 m thick. Some exposures display crudely developed ripple cross lamination with muddy partings. In the western part of the Amphitheater, the sandstone lenses are partially amalgamated but thin and de-amalgamate to the east (e.g., Fig. 7F).

The basal sandstone bodies in the Amphitheater are overlain by a series of tabular successions of sandstone and mudstone that are variably incised by shallow, broadly nested, concave-up erosional surfaces filled with laminated sandstone and mudstone (Fig. 4). The tabular, upward-fining successions range from 1 to 2 m thick and grade from sandstone to mudstone (Fig. 7G). The sandstone-mudstone successions commonly appear structureless, likely due to pervasive bioturbation. Channel forms that crosscut these successions decrease in size upward in the section, from 10 to 20 m wide and ~32 m deep near the base of Unit 4, to <5 m wide and <1 m deep at the top of Unit 4. Erosional surfaces commonly contain a thin (<10-cm), sandy, shell hash–bearing lag at their bases. Larger erosional surfaces are commonly draped by mudstone with thin (<10-cm-thick) sandstone interbeds, whereas smaller erosional surfaces are draped by laminated mudstone. Mudstone-dominated channel fills also host gently inclined, muddy cross strata that parallel the margin of the underlying erosional surface (e.g., Fig. 7G). Small, fossilized oyster reefs are located at the margins of some of the smaller erosional surfaces.

**Depositional Environment**

In the Large Folds SW area, Schulein (1993) interpreted Unit 4 as estuarine, interdistributary bay and/or lagoonal deposits. Mixed salinity invertebrate fossils (including oysters, gastropods, and pelecypods) and low-diversity trace fossil assemblages support deposition in brackish-water environments (Slagle, 1979; Schulein, 1993; MacEachern et al., 2010), and horizons of fossil hash support intermittent transport and/or deposition by storms or flood events within such an environment (Schulein, 1993). Similarly, tabular sandstone bedsets containing convolute ripple laminae support periodic, rapid deposition of sand into an otherwise low-energy environment as splay, distributary mouth bar-like features, and/or tidal bars (Schulein, 1993; this study). Thicker successions of beds containing ripple cross lamination with mudstone partings and abundant reactivation surfaces support a tidal influence on the environment (after Collinson et al., 2006).

Immediately to the east, we interpret the vertical succession of Unit 4 facies in the Amphitheater area to represent laterally accreting estuary-margin deposits that were likely deposited in central to upper, mixed-energy sectors of an estuary (after Dalrymple et al., 1992; Dalrymple et al., 2012). Oyster reefs support deposition in brackish-water environments throughout the succession. The sharp-based lenticular sandstone bodies at the base of Unit 4 are interpreted as the fill of a broad tidal channel (e.g., Clifton, 1982) or possibly crevasse splay deposits that emigrated from an adjacent channel (e.g., Elliott, 1974). In either case, amalgamated units were deposited in the highest energy part of the channel or splay, such as a tidal channel thalweg or along the axis of a splay complex. Similar to filled fluvial channels, normal grading in estuarine tidal channels is common (Clifton, 1982). Normal grading in splay deposits reflects deposition of progressively smaller grain sizes during waning flow conditions associated with each splay event (Elliott, 1974). Ripple cross lamination is common in both environments, and muddy partings within the ripple lamination supports tidal influence (Clifton, 1982).

The overlying assemblage of upward-fining successions that are crosscut by small erosional surfaces is interpreted as a mixed-lithology tidal-flat flat succession incised by tidal channels. The tabular, upward-fining successions of sandstone and mudstone represent tidal-flat successions deposited on the margins of the estuary complex. The lower, sandy portions represent lower tidal-flat (sand-flat) environments affected by higher current energy, whereas upper, muddy portions represent lower-energy upper tidal-flat (mud-flat) environments (e.g., Reinick and Wunderlich, 1968; Weimer et al., 1982; Flemming, 2012). The structureless appearance in both the sandstone and mudstone likely reflects intense bioturbation (e.g., Gingras et al., 2012). Channel forms were incised by tidal channels that migrated laterally across the tidal flats (after Clifton, 1982; Weimer et al., 1982), indicating an intertidal depositional setting. The upward decrease in channel size likely reflects lateral accretion of the estuary-margin tidal flats through time, where narrower, shallower, muddy channel fills from higher on the tidal flats are stacked on top of broader, deeper, heterolithic channel fills closer to the main estuary basin (after Flemming, 2012). Similar to the tabular tidal-flat facies, this
association further supports the vertical stacking of lower-energy, upper tidal-flat channels on top of higher-energy, lower tidal-flat channels. Sandy, shell-hash lags are common in both types of channels (Clifton, 1982). Interbedded sandstone and mudstone in larger channels represents mixed current energy near the main estuary basin, likely associated with the time-velocity asymmetry of daily or monthly tidal cycles (such as recorded in inclined heterolithic strata; Thomas et al., 1987). In mudstone-dominated channels, gently inclined mudstone units (e.g., Fig. 7G) represent accretionary channel-bank deposits (Clifton, 1982). Oyster reefs formed on the margins of muddy tidal channels.

As a whole, Unit 4 represents the central to headward part of a tidally influenced estuary (e.g., Dalrymple et al., 2012, their figure 5.3). Unfortunately, exposures of Unit 4 are poor between the two outcrop areas, making precise stratigraphic correlations difficult. However, the west-to-east transition from mudstone-dominated lithofacies in the Large Folds SW area to heterolithic lithofacies with erosional channels in the Amphitheater area (e.g., Fig. 4) indicates an eastward increase in depositional energy, possibly associated with eastward shoaling of specific estuarine sub-environments. Importantly, the vertical transition from Unit 3 bayhead delta deposits to Unit 4 estuary deposits records the onset of significant sea-level transgression (Fig. 8).

**Mass-Transport Deposit (MTD)-Related Deformation**

Sandstone and mudstone of Unit 4 form the cores of the largest folds in the upper part of the New Irdia MTD in the central part of the outcrop belt, but the unit is absent in westernmost and easternmost sections (Fig. 5). Sandstone units define tight to broad, large-scale folds that are faulted in their cores (Figs. 5 and 6A). Mudstone intervals are mostly vegetated but do show signs of internal shear and deformation where large-scale folding is intense. The base of Unit 4 also provides a significant, internal zone of detachment within the New Irdia MTD, above which there is an abrupt increase in fold size and amplitude. This is most clearly observed in the Large Folds SW area where ~80-m-amplitude folds in Units 4 and 5 are detached from Unit 3, which is relatively undeformed in this location (Fig. 5). Detachment along this horizon may also explain the absence of Unit 4 (and Unit 5) stratigraphy to the east of the study area (e.g., Fig. 5). If translation along the detachment was sufficient to displace Units 4 and 5 facies from their up-dip equivalents, a structural “gap” in the stratigraphy would result. This inference is supported by the presence of Kreyenhagen Formation mudstone directly overlying Unit 3 strata (Fig. 5), without evidence of an intervening erosional surface.

**Unit 5: Outer Estuary Sand Flats and Channels**

**Description**

Similar to Unit 4, Unit 5 is only exposed between the Large Folds SW and Large Folds NE areas of the MTD exposure (Figs. 3 and 5). The transition from Unit 4 to Unit 5 is abrupt in most places and is marked by the transition from mudstone-dominated and/or heterolithic lithofacies to a thick assemblage of amalgamated sandstone (Fig. 4). In the Large Folds SW section, Unit 5 is a ~40-m-thick succession of amalgamated, coarse- to medium-grained, tan sandstone. Much of the unit is intensely bioturbated, including *Ophiomorpha* and *Thalassinoides* burrows, which obscure primary depositional architecture (Fig. 4). However, relict amalgamation surfaces are commonly marked by oyster hash lags, and some sandstone units contain large-scale, low-angle cross laminations that is lined by disseminated organic debris. In addition, rare sandstone beds display flaser bedding and sets of ripple cross lamination with reactivation surfaces, as well as rare, thin horizons of cm-scale flame structures and dish structures.

To the east, in the Amphitheater area, Unit 5 is an ~20-m-thick succession of amalgamated, very well-sorted, fine- to very fine-grained tan sandstone that appears massive due to pervasive, subvertical fracturing (Fig. 4). Basal exposures contain faint ripple cross lamination and oyster hash lags.

In the Large Folds NE area, Unit 5 is severely deformed, and depositional relationships are difficult to ascertain. Fossilized oyster reefs are scattered throughout the Unit 5 interval. In this area, resistant sandstone assemblages appear reddish, rather than tan. One well-exposed sandstone unit consists of pebbly, coarse-grained sandstone to pebble conglomerate and contains black quartz pebbles similar to those in Unit 3. This unit contains bidirectional, tabular, upward-coarsening foreset units that range from 5 to 15 cm in amplitude (Fig. 7I). Foreset units are in some places separated by thin (~5-cm-thick) beds of interlaminated, white claystone and very fine-grained sandstone (Fig. 7I). The very fine-grained sandstone forms asymmetrical ripple bedforms with internal ripple cross lamination (Fig. 7J). In well-preserved examples, ripples are oriented in the same direction as overlying gravelly foreset units. The ripple bedforms are draped by up to ~1 cm of white claystone. In some areas, the claystone drapes are bisected by a single lamination of sandstone (Fig. 7J), revealing the presence of double mud drapes in the interlamellated intervals.

**Depositional Environment**

Previous workers interpreted Unit 5 to represent sandy barrier island deposits formed by the reworking of deltaic sediments (Slagle, 1979) and/or intertidal sand flats (Schulein, 1993). New data presented here support deposition in sandy, tidally influenced environments, likely in estuarine sand flats and high-energy tidal channels.

In the Large Folds SW and Amphitheater sections, the significant thickness (~15 m) and internal amalgamation of the sandstone in Unit 5 indicate deposition in an area with relatively high ambient current energy that precluded preservation of significant mudstone, such as on lower tidal flats (sand flats) or in tidal bar assemblages similar to those in Unit 1 (e.g., Dalrymple et al., 2012; Fan, 2012; Flemming, 2012). Oyster fragments support continued deposition in (or derivation from) brackish-water environments, and the presence of *Skolithos* ichnofacies trace fossils indicates that ambient current energy was relatively high and that substrates were relatively clean (MacEachern et al., 2010). Flaser bedding and larger-scale cross lamination lined by disseminated
organic debris support deposition in a tidally influenced setting (Reineck and Wunderlich, 1968; Collinson et al., 2006).

The red-colored, pebbly sandstone unit in the Large Folds NE area (e.g., Fig. 7I) is interpreted as a high-energy subtidal channel deposit. Similar to Unit 3, the presence of quartz pebbles indicates fluvial delivery of sediment to marginal marine areas. However, the strong presence of bidirectional, upward-coarsening tabular foresets (Fig. 7I) reveals reworking of the sediment by reversing tidal currents. Each upward-coarsening foreset unit within a bundle likely represents the deposit of one flood or ebb cycle. Smaller foreset units in thinner bundles represent similar migration of smaller dunes under the influence of the subordinate tide (i.e., time-velocity asymmetry of Eisma, 1998; Wang, 2012). Vertical stacking of the opposing foreset bundles is interpreted to be the result of lateral separation of flow within the tidal channel through time, rather than daily variation in flow direction associated with tidal cyclicity (cf. herringbone cross stratification). The tabular, interlaminated claystone and very fine-grained sandstone beds that separate foreset bundles (Fig. 7J) are interpreted to have been deposited by suspension settling (?) in channel-bottom areas during lower-energy (e.g., neap tide) conditions. Small-scale (3–10-cm) stacking patterns record time-velocity asymmetry associated with tidal cyclicity (Fig. 7I). Asymmetric ripple bedforms and their internal cross lamination represent deposition during the dominant (higher-energy) stage of the tidal cycle, whereas claystone drapes represent suspension deposition of mud particles during slack-water periods of the tidal cycle (e.g., Visser, 1980; Dalrymple, 2010) or fluid muds that were deposited along the channel bottom as current energy waned (e.g., Longhitano et al., 2012). Where demonstrable double mud drapes are present (e.g., Fig. 7I), the first drape represents suspension deposition of mud during the first slack-water period, immediately following the dominant current stage. The single sandstone lamination is the deposit of the subordinate current, and is overlain by mud deposited during the second slack-water period in the tidal cycle (after Dalrymple, 2010). The structureless (non-laminated) appearance of thicker, bottom-most drapes may reflect deposition of fluid muds (after Schwartz and Graham, 2015), indicating deposition in turbidity maximum areas of the tidal channel (Longhitano et al., 2012).

Together, the lateral association of sand flat and/or tidal bar deposits and coarse-grained tidal channel deposits indicates deposition in tidal maximum areas of the estuary, where tidal current energy is high and sediment is mostly sand and gravel (after Dalrymple et al., 2012). The transition from mudstone-dominated estuarine facies of Unit 4 to sandstone-dominated estuarine facies of Unit 5 records continued sea-level transgression and back-stepping (landward migration) of estuarine environments (Fig. 8).

**Mass-Transport Deposit (MTD)–Related Deformation**

Similar to Unit 4, Unit 5 is absent in the easternmost exposures of the MTD (Fig. 5); these exposures likely reflect downslope translation of the unit. The thick sandstone assemblage of Unit 5 is incorporated into large (80-m-amplitude) folds that are cored by Unit 4 lithofacies. Sandstone beds define tight, large-scale folds that are upright to overturned (Fig. 8A). The folds are directly overlain by the Kreyenhagen Formation, which infills the rugose deformational topography at the top of the MTD complex. Internally, some thick sandstone assemblages are pervasively fractured (e.g., in the Amphitheater area), but it is unclear whether the fracturing is related to soft-sediment deformation or is a product of later tectonic deformation.

**Composite Depositional History of the Domengine Formation**

The five informal stratigraphic units described in the Domengine Formation record a period of early Middle Eocene shoreline progradation and aggradation that preceded a regional marine transgression event and shelf failure (Fig. 8). Units 1–3 record westward progradation of a tide-dominated shoreline (Fig. 8). As the shoreline advanced northwestward, sandstone-dominated estuary-mouth bar deposits of Unit 1 were progressively buried by mudstone-dominated estuarine deposits of Unit 2, followed by heterolithic bayhead delta deposits of Unit 3 (Fig. 8). Together, these deposits illustrate the existence of an irregular, embayed shoreline characterized by deposition in estuaries. Similar estuarine depositional facies have been interpreted for the Domengine Formation ~200 km to the north-northwest, along depositional strike (Sullivan and Sullivan, 2012). Sandstone provenance of these deposits indicates that the estuaries (embayments) were fed by rivers with headwaters draining the Sierra Nevada arc. Although estuaries commonly form along transgressive coastlines where seaward migration of such environments is uncommon (Dalrymple et al., 1992; Dalrymple, 2010), the vertical progression of environments reveals shoaling and progradation of the estuary system (Fig. 8). We posit that, although local sea level was high throughout deposition of the Domengine Formation, the apparent shoaling of the estuarine complex during Middle Eocene time was sustained by high sediment loads that were derived from the Sierra Nevada arc.

Units 4 and 5 of the Domengine Formation record a transition to sea-level transgression that caused back-stepping of the Middle Eocene shoreline (Fig. 8). Bayhead delta deposits of Unit 3 are progressively overlain by estuary-margin tidal-flat deposits (Unit 4) and outer estuary sand-flat deposits (Unit 5). This vertical progression of environments illustrates retrogradation of the estuarine complex related to relative sea-level rise. As transgression occurred, continued denudation of the remnant Sierran arc resulted in continued delivery of coarse-grained sediment to the drowned shoreline, where sedimentation remained focused along drowned paleovalley tracts (Fig. 8).

**Summary of Mass-Transport Deposit (MTD)–Related Deformation Structures**

**Slump Folds**

Although soft-sediment deformation was accommodated by a variety of ductile and brittle deformation mechanisms, slump-related folds are the most prominent expressions of submarine mass wasting within the New Idria MTD
Figs. 5 and 6). Fold height, or peak-to-trough amplitude, appears to vary between different depositional units. For instance, the largest folds (35–80 m height) occur within the uppermost Units 4 and 5 of the Domengine Formation, whereas the folds within Units 2 and 3 are typically less than 20 m in height (Figs. 5 and 6A–6C). Following structural restoration of the regional Vallecitos syncline deformation, fold attitudes are gently inclined to upright (20° to 90° dip) with interlimb angles that range from 30° to 160°. Fold axes plunge shallowly (typically <12°) toward either the north (325° to 26°) or south-southeast (184° to 139°) with a mean fold axis trend of 168°/348° (Fig. 9). The tendency of slump fold axes to fan about a horizontal plane is a characteristic of submarine slumps in general (Woodcock, 1979), supporting the validity of our structural restoration.

Most folds are asymmetric and verge consistently toward the west-northwest to southwest (229° to 296°) with a mean vergence direction of 258.5° ± 3.7° (1 s.e.) (Figs. 9 and 6A–6C). The trend of the outcrop belt is approximately northeast-southwest (55°–235°), and thus most folds verge parallel to or slightly oblique to the outcrop face (Fig. 3). When plotted by location, fold vergence shows a modest change in orientation of ~20°; folds in the northeastern portion of the outcrop have a mean vergence direction toward the west-southwest (252°), whereas folds in the central and southwest portions of the outcrop tend to verge in a more westerly direction (mean of 260° to 273°) (Fig. 10).
Slump Faults

Two general fault types are present in the Domengine Formation at New Idria: (1) slump-related reverse faults that are confined to within the New Idria MTD and (2) faults that postdate MTD emplacement and are interpreted to have a tectonic origin. The second group of faults can be readily distinguished because they crosscut the entire Domengine Formation and extend into underlying and overlying stratigraphic units; they tend to strike N-S or NNE-SSW, and they commonly contain fault gouge, mineralization, and slickenlines (Fig. 3).

Slump-related faults that accommodated brittle deformation during emplacement of the New Idria MTD are distinct from the younger group of tectonic faults: they (1) are confined to within the New Idria MTD; (2) tend to displace sandstone beds and sole out in finer-grained units; (3) often form within the hinges or limbs of slump folds; and (4) lack evidence for mineralization, fracturing, or slickenlines on their surfaces (Fig. 6D). Slump faults consistently verge toward the western quadrant (e.g., Figs. 5 and 6D), consistent with the direction of fold vergence.

Transport Direction of the New Idria MTD

Slump deformation structures (e.g., slump folds and faults) can provide a useful proxy for MTD transport direction (Hahn, 1913; Jones, 1939). However, kinematic analysis of MTD deformation structures is complicated by the observation that slump folds and faults can be variably oriented (parallel, perpendicular, or oblique) with respect to the trend of the paleoslope (Hansen, 1971; Woodcock, 1979; Farrell and Eaton, 1987). Oblique- or downslope-oriented deformation structures may form by (1) shortening perpendicular or parallel to the width of the slump sheet, (2) downslope rotation of folds during progressive deformation, and/or (3) layer-normal or layer-parallel shear within the deforming MTD (Alsop and Marco, 2013; Sharman et al., 2015b). For this reason, a number of methods of “paleoslope analysis” have been proposed, and each method has unique assumptions and limitations (see review in Sharman et al., 2015b). Slump folds within the New Idria MTD display little overall variation in fold axis orientation, and all observed folds and slump faults verge toward the western quadrant (Fig. 9). In order to estimate the transport direction of the New Idria MTD, we apply nine separate slump-fold-based paleoslope methods as outlined in Sharman et al. (2015b) (Table 2). Of these, seven methods are applicable, and all yield a consistent range of predicted MTD transport directions that vary from 256° to 288°. Methods based on fold axis orientations (mean axis method and separation arc method) are in good agreement with those based on fold axial surfaces (axial planar method and axial planar intersection method) (Fig. 9; Table 2). Relationships between fold orientation and degree of tightness (i.e., interlimb angle) or fold attitude (i.e., axial surface dip) show little evidence for progressive modification of fold orientations (e.g., downslope rotation) during progressive simple shear (Fig. 11). Thus, the fold and fault measurements from within the New Idria MTD convey a straightforward interpretation of overall WSW-directed transport, even though there may have been a slight change to more westerly transport in the downslope portion of the MTD (Fig. 10). WSW-directed transport of the New Idria MTD is consistent with the above-described facies relationships (landward to the east) and paleocurrent measurements with a mean flow direction toward the west-northwest (Fig. 8) (after Schulein, 1993).

Table 2. Summary of Paleoslope Analysis Results

| Method                                      | Applicable | Predicted transport direction |
|---------------------------------------------|------------|-------------------------------|
| Mean axis method (MAM)                      | Yes        | 258°                          |
| Separation arc method (SAM)                 | Yes (consistent fold axis orientation and vergence sense) | 262° |
| Dowslope average axis method (DAM)          | No (fold asymmetry senses do not oppose each other about a downslope average axis) | 256° |
| Axial planar method (APM)                   | Yes (mean axial planar intersection of Z- and S-folds is perpendicular to the downslope direction for layer-parallel shear) | 268° |
| Axial planar intersection method (APIM)     | Yes (folds do not display hinge rotation with progressive axial plane rotation) | 257° |
| Fold hinge azimuth and axial surface dip method (HIM) | Yes (folds do not display hinge rotation with progressive fold tightening) | 257° |
| Fold hinge azimuth and interlimb angle method (HAM) | Yes (folds do not display hinge rotation with progressive fold tightening) | 260° |
| Axial surface strike and interlimb angle method (ASIM) | Yes (folds do not display axial plane rotation with progressive fold tightening) | 257° |
| Axial surface dip and dip direction method (DDM) | No (no evidence for layer-normal shear or a position within the lateral to oblique portions of the mass-transport deposit) | – |

Note: See Sharman et al. (2015b) for references and an explanation of each paleoslope method.

Discussion

Middle Eocene Paleogeography of the Vallecitos Syncline

Integration of new results with those of Schulein (1993) indicates that early Middle Eocene time was characterized by a complex paleogeographic setting that developed within the forearc and accretionary prism (Fig. 12). Deposition of the Domengine Formation in the study area reflected both (1) Sierran-sourced shelfal-deltaic depocenters with generally west-directed
paleoflow and (2) estuarine, shelfal, and terrestrial depocenters sourced from uplifted Franciscan subduction complex and overlying Cretaceous–Paleogene forearc sequences (after Schulein, 1993) (Fig. 12). Our results suggest that the units comprising the New Idria MTD were sourced from the Sierra Nevada magmatic arc, based on sandstone composition and paleocurrent measurements from westward-prograding deltaic deposits in Unit 3 (Fig. 8). Additionally, the MTD was displaced toward the west-southwest, down bathymetric slope, into deeper water (Figs. 8 and 12). However, the presence of Franciscan-derived, non-marine Domengine Formation just 10 km to the west at Lopez Canyon (Fig. 1) (Schulein, 1993) suggests that the New Idria MTD may have been emplaced into a narrow trough with steep, ramp-like margins that separated Sierran- and Franciscan-derived portions of the Domengine Formation. Therefore, the New Idria MTD likely represents failure of a portion of the shelf into a local bathymetric low (Fig. 12).

Figure 11. Scatterplots of fold orientation data showing the relationship between fold tightness (interlimb angle) or attitude (axial plan dip) versus the orientation of the fold axis trend or axial plane strike (Table 1).

Depositional Controls on Deformation Style

Within the New Idria MTD, there is a distinct vertical trend in deformation style and magnitude (e.g., Fig. 5). At its base, the Domengine Formation shows little evidence of soft-sediment deformation in Unit 1. Upward in the section, in Units 2 through 5, deformation becomes increasingly apparent with a progressive up-section increase in the frequency and amplitude of folds (Fig. 5). Ultimately, this vertical trend in deformation style is related to the depositional history, including facies-dependent lithology and stratigraphic architecture, of the Domengine Formation at the New Idria locale.
Because Unit 1 shows no evidence for MTD-related deformation (Fig. 5), it is not considered to be part of the New Idria MTD. Because of the back-stepping nature of the upper Domengine shoreline (Units 3–5) through time, the sandstone-dominated estuarine deposits of Unit 1 were buried in an offshore location (relative to the Unit 5 shoreline) by at least 100 m of sediment. When mass failure occurred, Unit 1 deposits were already located in an offshore area.

Similar to Unit 1, Unit 2 was already buried in an offshore location during deposition of Unit 5. However, Unit 2 displays abundant evidence of shear in shale-dominated units, small-scale offset of thin sandstone assemblages, and occasional development of fold trains (Figs. 5 and 6C–6E), indicating that Unit 2 sediments were involved in mass failure. We interpret that the discrete lithologic transition between Unit 1 (sandstone-dominated) and Unit 2 (mudstone-dominated) resulted in juxtaposition of mechanically weak strata over mechanically strong strata and facilitated development of the MTD detachment zone at or near this lithologic contact (Fig. 13). Line tracing of continuous sandstone beds within Unit 2 suggests shortening of ~5% to 8% in the SW Large Folds area and ~20% in the NE Large Folds area (Fig. 6; Table 3). Shortening is primarily accommodated by small-scale folding and structural repetition along low-angle thrust faults (e.g., Figs. 5C and 5D), suggesting relatively minimal translation and foundering of the unit.

Unit 3 was also buried in an offshore location during deposition of Unit 5. However, Unit 3 contains the stratigraphically lowest large-scale folds with heights greater than a few tens of meters (Fig. 6B). Although Unit 3 is relatively undeformed in the SW Large Folds area, it has undergone ~50% shortening in the NE Large Folds area (Fig. 5; Table 3). Thus relative to Unit 2, this indicates an upward-increase in shortening and the magnitude of deformation within the MTD.

Above Unit 3, sandstone-dominated Units 4 and 5 form spectacular folds that are up to 80 m in amplitude (Figs. 5 and 6A). Shortening estimates indicate between 30% and 40% shortening of these units in the SW and NE Large Fold areas (Fig. 5; Table 3). The abrupt increase in fold size suggests that the mudstone-dominated transition zone between Units 3 and 4 likely hosted a second detachment zone that was internal to the MTD. Below this detachment, Unit 3 was translocated seaward but was not significantly displaced from its up-dip equivalents (Fig. 5). Above the detachment, Units 4 and 5 are tightly folded in the western part of the study area but are absent to the east (Fig. 5). Shortening and translation of Units 4 and 5 above the detachment may have been sufficient to fully displace the units from their up-dip equivalents.

In summary, the depositional history, including facies-dependent lithologic transitions, of the Domengine Formation dictated depositional style and magnitude within the MTD. At the time of mass failure, there was more accommodation and gravitational potential for upper units (e.g., Units 4 and 5) than lower, more deeply buried and offshore-located units (e.g., Units 1 and 2). The differential potential for mass failure resulted in an upward increase in the magnitude of deformation, size of deformation structures, and degree of shortening within and/or translation of each unit in the MTD.

**Depositional and Tectonic Controls on Shelf Instability and Collapse**

The New Idria MTD provides an excellent opportunity to interpret the conditions under which shelfal successions can become gravitationally unstable and collapse. A number of factors related to the depositional history of the Domengine Formation ultimately led to conditions favorable to gravitational instability. These include (1) sustained, high sedimentation rates into a rapidly deepening deltaic depocenter; (2) differential sediment loading of saturated, mechanically weak sediments; (3) tectonically induced sea-level change; and (4) seismicity along the active continental margin.

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**Figure 13. Schematic depiction of the evolution of the New Idria mass-transport deposit (MTD).** See text for explanation.
**Sedimentary and Paleogeographic Controls on Mass Failure**

The combination of abrupt deepening and sustained, high sedimentation rates may have promoted mass failure of the shelf and generation of the New Idria MTD. Uncompacted sedimentation rates for the Domengine Formation (~160 m/m.y.) are similar to those reported for other rapidly aggrading shelves such as the Cretaceous North Slope of Alaska, the Cretaceous Magallanes Basin, and the Eocene Gulf of Mexico (after Schwartz et al., 2016). The lateral discontinuity of the MTD in outcrop indicates that slumping was not regionally extensive, but rather, restricted to a relatively narrow zone of the shelf that was predisposed to failure (Fig. 1). The embayed shoreline that we interpret for the Domengine Formation not only focused deepening along drowned paleovalley tracts, but concentrated incoming sediment loads near their “point sources” at the heads of estuaries.

The focused fluvial input of sediment into the deposystem (Units 2–5; Fig. 8) likely resulted in under-compaction of fine-grained units within the Domengine Formation. These conditions would have favored high pore-fluid pressure within the mechanically weak, fine-grained units that ultimately facilitated detachment and downslope sliding (e.g., Coleman and Prior, 1988). Furthermore, both Units 2 and 4 are overlain by thick sand bodies within Units 3 and 5, respectively, that would have been denser than the underlying, uncompacted, fine-grained units at the time of deposition (Fig. 4). Ultimately, the loading of under-compacted, mechanically weak units by thick sand packages would have promoted gravitational instability (cf. Coleman and Prior, 1988). This is observed within the New Idria MTD where major layer-parallel detachment is focused at the base of Unit 2 and at the top of Unit 3 (Fig. 13).

Other documented examples of shelf and delta collapse also suggest that deposition of coarse-grained lithologies over mud-dominated lithologies can result in gravitational instability. For example, Nemec et al. (1988) document gravitational sliding of a delta front where distributary channel sands overlie prodelta shale and heterolithic units. Similarly, submarine mass failure in the Sobrarbe delta of the Spanish Pyrenees is preferentially focused at lithologic transitions (e.g., silt and sand overlying marl; Odonne et al., 2011). Our results confirm the importance of shelfal and deltaic stratigraphic packaging in pre-conditioning the position of both basal and internal detachment zones. This work also suggests that high sedimentation rates and accompanied rapid vertical aggradation of deltaic stratigraphic sequences may play a role in promoting eventual mass failure.

**Tectonic Controls on Mass Failure**

Submarine mass failure is also often associated with changes in relative sea level (Posamentier and Martinsen, 2011). Examples of collapsed deltaic successions have commonly been associated with lowstand conditions (e.g., Perov and Bhattacharya, 2011) or a decrease in relative sea level (e.g., Odonne et al., 2011). However, emplacement of the New Idria MTD occurred at the beginning of tectonically induced, regionally significant flooding event that marked the onset of Kreyenhagen Formation deposition (Figs. 2 and 8). Based on the presence of bathyal foraminifera within the basal Kreyenhagen Formation, the New Idria MTD may have been emplaced into water depths as great as 1450–2000 m (Schulein, 1993). Preservation of significant deformation-related relief atop the New Idria MTD (e.g., Fig. 6A) confirms that emplacement depths were sufficient (>80 m) to preclude wave reworking or current modification of the upper surface of the MTD. Pronounced, regional transgression prior to shelf collapse facilitated the preservation of bathymetric relief as the MTD was translated into deeper-water environments (Fig. 13).

This magnitude of deepening (up to 2000 m) cannot be explained by eustatic sea-level rise alone. Deepening was likely related to a pronounced episode of tectonically induced subsidence that broadly affected the Great Valley forearc (Moxon, 1990). As deepening occurred, accommodation was generated in offshore areas as the Eocene shoreline back-stepped to the east (Fig. 8). Although the triggering mechanism cannot be known unequivocally, large earthquakes would have been frequent along the Farallon subduction zone.

**TABLE 3. ESTIMATE OF PERCENT SHORTENING**

| Area               | Unit     | Undeformed length (m)* | Deformed length (m) | Shortening (%) |
|--------------------|----------|------------------------|---------------------|---------------|
| SW Large Folds     | 2 (middle) | 477.2                  | 500.6               | 4.9           |
| SW Large Folds     | 2 (upper) | 477.2                  | 515.0               | 7.9           |
| SW Large Folds     | 3 (middle)| 477.2                  | 480.1               | 0.6           |
| SW Large Folds     | 4 (middle)| 477.2                  | 620.2               | 30.0          |
| SW Large Folds     | 5 (base)  | 477.2                  | 612.5               | 28.3          |
| NE Large Folds     | 2 (middle)| 381.5                  | 457.5               | 19.9          |
| NE Large Folds     | 3 (base)  | 381.5                  | 578.3               | 51.6          |
| NE Large Folds     | 4 (middle)| 381.5                  | 535.3               | 40.3          |
| NE Large Folds     | 5 (base)  | 381.5                  | 536.3               | 40.6          |

*Made relative to the undeformed top of Unit 1.
during Middle Eocene time. Seismic shaking is commonly inferred to be an important trigger of large submarine mass-failure events (Wright and Rathje, 2003). Over-steepening of bathymetric slopes during tectonically induced subsidence may have also contributed to shelf instability (e.g., Coleman and Prior, 1988). Submarine mass-failure associated with tectonically controlled relative sea-level rise is also observed in the Talara forearc basin of northwest Peru (Fildani et al., 2008). Thus, the tectonic setting of the Vallecitos syncline likely played a role in facilitating shelf instability and eventual collapse by providing a triggering mechanism and sufficient accommodation. We thus speculate that the propensity for delta collapse is higher in tectonically active basin settings.

CONCLUSIONS

Outcrop exposures of the Domengine Formation within the Vallecitos syncline provide an exceptional opportunity to interpret submarine mass failure of a shallow marine sedimentary sequence, with implications for understanding the propensity for mass failure of continental shelves and deltas more generally. This study is the first to comprehensively document the informally named “New Idria MTD” that is mapped for a minimum of 6 km along strike. A combination of field and aerial measurements are used to characterize the MTD, including creation of a 3D outcrop model that provides a cross-sectional view of stratigraphic and structural relationships within the MTD.

The Domengine Formation is divided into five informal units (Units 1–5) that represent depositional environments consistent with shoreline progradation followed by a sea-level transgression event that caused back-stepping of the coastline. These environments include (1) prograding estuary-mouth bar complex, (2) inner-estuary tidal-flat complex, (3) bay-head delta complex, (4) estuary-margin tidal-flat complex, and (5) outer estuary sand-flat complex. Gravitational collapse of Units 2–5 occurred during or shortly after a regional transgression event that accompanied widespread deposition of the bathyal Kreyenhagen Formation.

Structural analysis of fold and fault orientations within the New Idria MTD demonstrates a probable transport direction toward the west or southwest, which is consistent with paleoflow measurements from within the MTD. These results, in conjunction with previous, regional studies of the Domengine Formation, suggest that the New Idria MTD represents a remobilized portion of an embayed shelf that was positioned between the denuded Sierran volcanic arc and the adjoining Franciscan subduction complex to the west.

The lateral discontinuity of the MTD in outcrop indicates that slumping was not regionally extensive but, rather, restricted to a relatively narrow zone of the shelf that was predisposed to failure. Several factors led to favorable conditions for gravitational instability and eventual collapse of the Sierran shelf and coastal plain: (1) high sedimentation rates that accompanied focused fluvial input into paleovalley tracts along a rapidly aggrading, embayed shoreline; (2) the presence of dense sand bodies overlying under-compacted, mechanically weak fine-grained units; and (3) an active tectonic setting that would have led to significant seismic shaking and possibly slope over-steepening. Our results thus suggest that both depositional architecture and tectonic setting play a critical role in influencing the propensity for submarine mass failure of continental shelves and deltas.

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