THE CHARACTER AND GENESIS OF SUBMARINE MASS-TRANSPORT DEPOSITS: INSIGHTS FROM OUTCROP AND 3D SEISMIC DATA

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Abstract: Extensive deep-water mass-transport deposits are observed both in slope and basin-floor settings. A detailed understanding of mass-transport deposits, in terms of emplacement processes, depositional products, and their stratigraphic and geographic distribution, is vital because they can constitute a significant portion of the stratigraphic section in deep-water settings. In addition, mass-transport deposits can play a significant role in hydrocarbon exploration, inasmuch as they can constitute seal, reservoir, and possibly source facies under the right circumstances.

Different data types bring to light different aspects of mass-transport deposits. This paper focuses on insights derived from seismic and outcrop data. Overall geometries and architecture of mass-transport deposits are readily observable in 3D seismic data; however, features below seismic resolution that are vital for process and lithologic understanding need to be observed in outcrop. Integrating observations across a broad range of scales by linking seismic and outcrop observations constitutes an effective way of improving our understanding of when and where mass-transport deposits are likely to form. In addition, this linkage sheds light on details of internal architecture that commonly characterizes these deposits.

Mass-transport deposits can comprise sheets, lobes, and channels fills, and reach 150 m or more in thickness. Greater thicknesses are observed where successive flows are amalgamated. This paper documents both internal architectural/stratigraphic as well as external geomorphic attributes of such deposits, as expressed in outcrop and imaged by 3D seismic data.

Recognition of mass-transport deposits in outcrop is based on identification of bedding deformed by synsedimentary processes, with deformation ranging from minimal redistribution of large slide blocks to complete disaggregation typical of debris-flow deposits. On seismic data, mass-transport deposits can be recognized by certain geomorphologic as well as stratigraphic distinguishing characteristics: basal linear grooved and scoured surfaces, hummocky relief at the top, and internal chaotic to transparent seismic facies, with internal thrust faulting common.

Key words: mass transport deposits, MTD, debris flow, seismic stratigraphy, seismic geomorphology

INTRODUCTION

Mass movements of sediments form kilometer-scale features (Fig. 1) that represent major subaerial and subaqueous geohazards, and can comprise significant depositional elements, characterizing marine slope and basin-floor systems. Catastrophic consequences of mass-transport processes such as tsunamis, avalanches, major rock falls, and mudslides are dramatic (e.g., Holmes, 1965; Bolt et al., 1977; Voight, 1978; Brunsden and Prior, 1984; Fisher and Smith, 1991; Martinsen 1994; Bondevik et al., 2003). In addition, mass movement of sediments can significantly affect stability of offshore installations (e.g., Prior and Coleman, 1982; Solheim et al., 2005).

Recently, these types of deposits have received increased attention because of petroleum exploration in deep-water settings, which are characterized by extensive mass-transport deposition. Posamentier and Walker (2006) have observed that in some deep-water settings, mass-transport deposits can comprise upwards of 50% of the stratigraphic section (Fig. 2). In some ancient outcrops, up to 75% of the stratigraphic succession has been deformed by mass-transport processes (Martinsen, 1989; 1994). Proliferation of 3D seismic coverage in deep-water settings and availability of high-quality shallow seismic and side-scan sonar data have provided striking evidence that mass-transport processes play an important role both on the surface and in the subsurface of marine slopes, as well as basin floors (Posamentier and Walker, 2006). A wealth of seismic-based examples of mass-transport deposits have been published (e.g., Piper et al., 1985; Piper et al., 1997; Piper et al., 1999; Weimer, 1990; Brami et al., 2000; Posamentier et al., 2000; Posamentier and Kolla, 2003; Tripsanas et al., 2004; Moscardelli et al., 2006; Posamentier and Walker, 2006; Sawyer et al., 2007). Integration of outcrop and 3D-seismic based analyses has yielded significant insights with regard to understanding mass-transport processes and temporal and spatial distribution of associated deposits (Damuth and Embly, 1981; Mutti, 1985; Martinsen et al., 2000; Martinsen et al., 2003; Posamentier and Kolla, 2003).

The objective of this paper is to discuss and review process sedimentology, stratigraphy, and geomorphology of mass-transport deposits as derived from outcrop and seismic data. Outcrop expression is useful primarily for viewing lithologic and kinematic details, stratigraphic context, and inferring small-scale emplacement processes. Interpretation of 3D seismic data provides paleogeographic setting, stratigraphic and system context, overall stratigraphic architecture, and morphological expression. Basin-wide sedimentary and rheological processes can be readily

Mass-Transport Deposits in Deepwater Settings
SEPM Special Publication No. 95, Copyright © 2010
SEPM (Society for Sedimentary Geology), ISBN 978-1-56576-287-9, p. xxx-xxx.

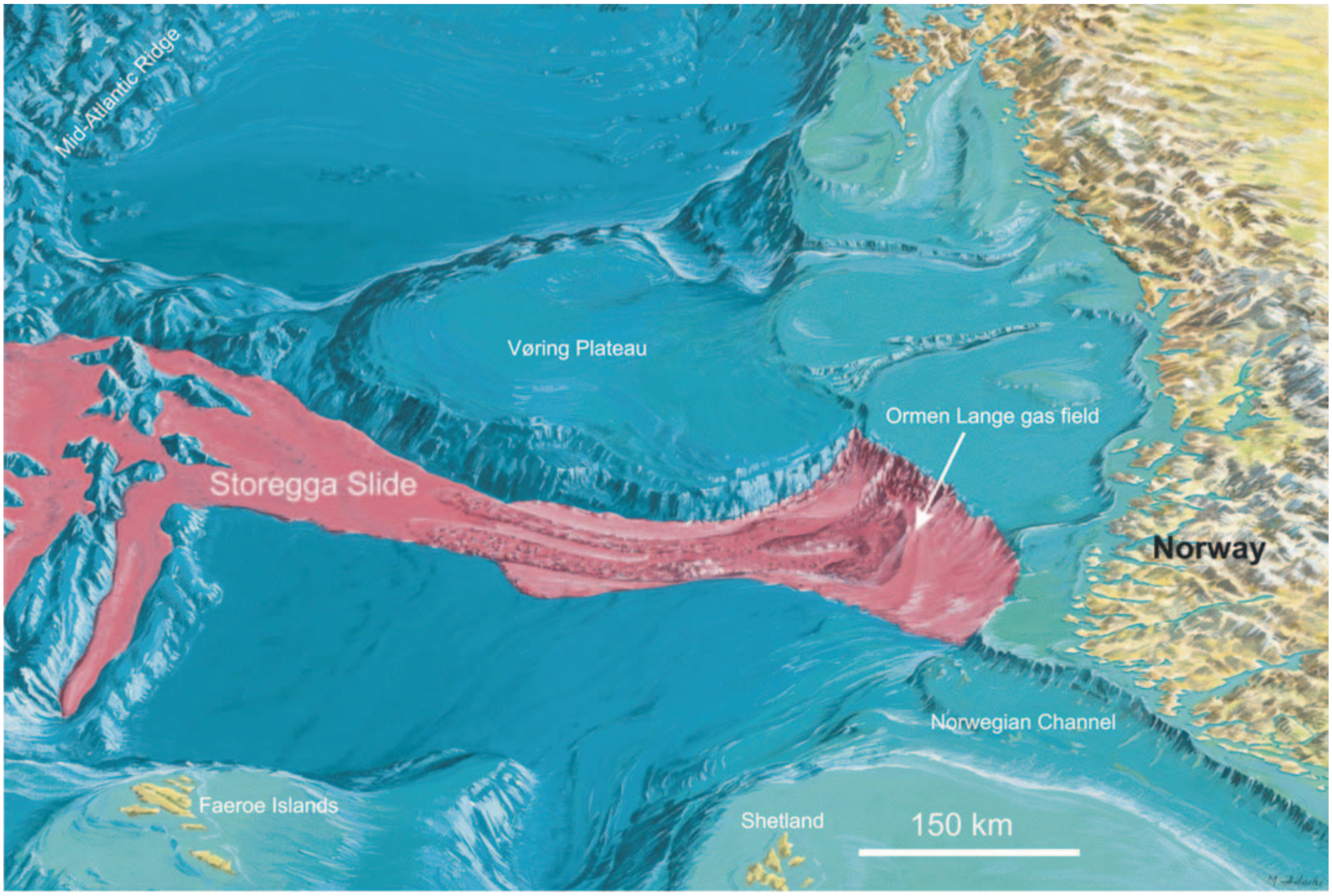


FIG. 1.—Painting of the Storegga slide, one of the world's largest surficial mass-transport deposits, offshore central Norway. The slide formed 8200 years BP, involved 3200 km^3 of sediments, and created a tsunami 4 m high in northern Scotland (Bondevik et al., 2003). MTDs of this scale are rare, but they show the importance of the process and the effects it can have on sedimentary environments, human life, and offshore installations. The giant Ormen Lange gas Field (14 Tcf) sits directly underneath the main mass-transport scar (arrow), and risk mitigation related to a potential future mass-transport event in the region has been a major task for the developers of the field.

inferred from such seismic data. In this paper, we first review existing classification schemes for mass-transport deposits and then move from detailed, relatively fine-scale outcrop-based observations to relatively broad-scale seismic-based observations. We will provide a comprehensive overview of stratigraphy and geomorphology at varying scales, as well as discuss processes associated with mass-transport deposition.

TERMINOLOGY AND CLASSIFICATION

The term *mass-transport deposit* (also known as MTD) encompasses several slope deformational processes (Fig. 3), including creep, slide, slump, and debris flow (cf. Jenner et al., 2007). These processes form a process continuum, and are intergradational. Many mass-transport deposits show evidence of several process mechanisms that were active at various points along their reach. Consequently, process-based classification should be exercised with caution in outcrop where only parts of mass-transport deposits are observed. Using seismic data, resolution issues associated with seismic data quality are crucial for process understanding and classification.

A unified and pragmatic process-based classification of mass-transport deposits is necessary for a full understanding of both their occurrence and significance, and for prediction in areas with little or low-resolution data. The term *mass-transport deposit* (commonly used synonymously in the literature with mass-transport complex, mass-movement complex, mass-gravity deposit, and a host of other terms) is a generic term that was used in studies by Peterson (1965) for pebbly mudstones in outcrop in California that were interpreted to represent debris-flow deposits. At that time, because understanding of mass movement mechanics was relatively poor, use of a general term was justified. Nonetheless, the term *mass-transport deposit* remains useful where data do not allow for interpretation of which specific slope processes operated (cf. Jenner et al., 2007).

Mass transport processes should *sensu stricto* include only those processes where sediments are moved *en masse* (i.e., grains do not move freely with respect to others). We prefer to use *mass movement* as a generic term for *en masse* slope deformational processes and *mass-transport deposits* as a generic term for their deposits. In mass-transport processes, the main grain support mechanism is not fluid turbulence. Thus, we exclude turbidity currents and

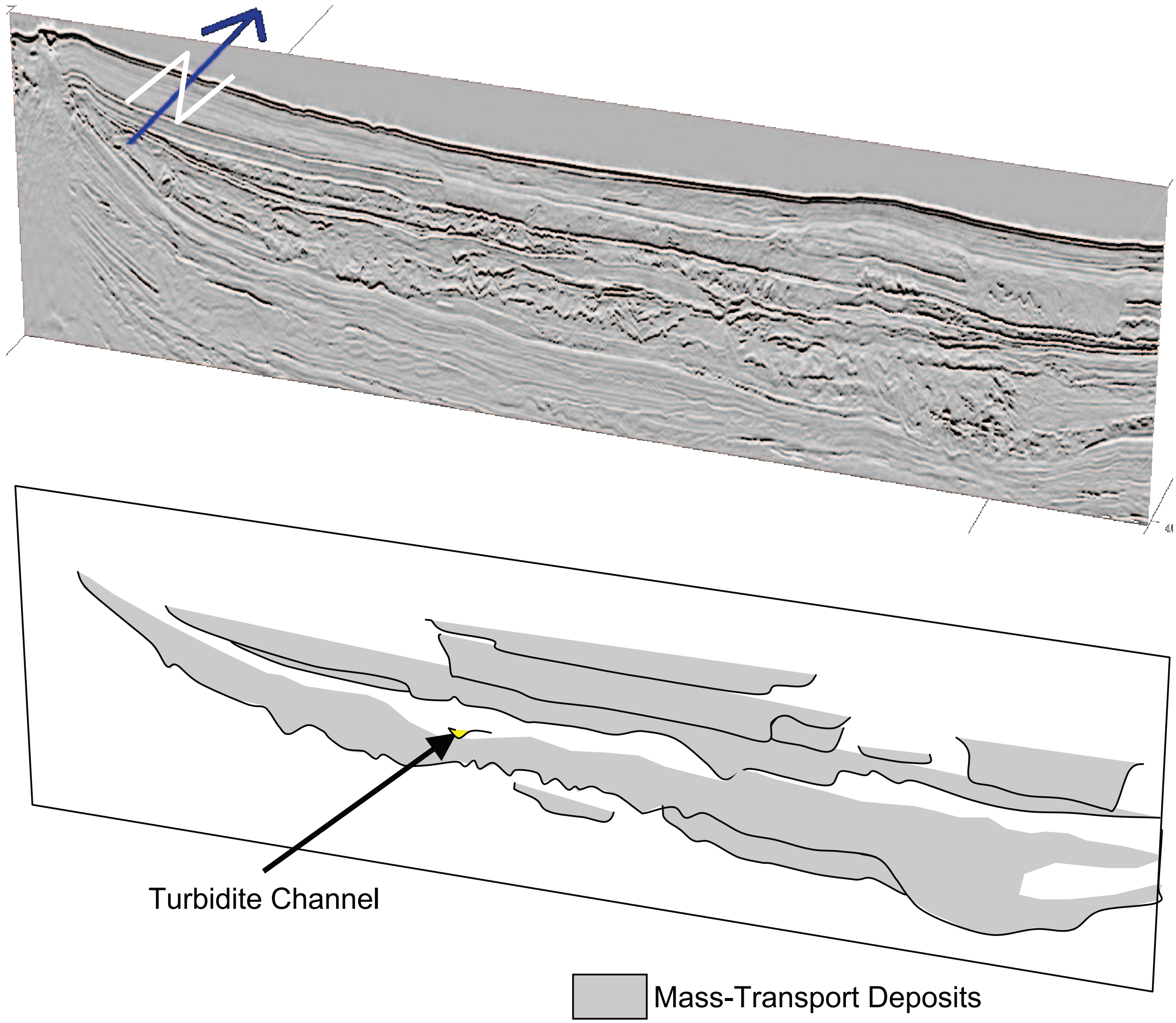


FIG. 2.—Seismic reflection profile from the northern deep Gulf of Mexico showing a deep-water stratigraphic section (at a water depth of approximately 3000 m), with mass-transport deposits constituting a significant portion of the strata. Note that the lateral margins of some of the mass-transport deposits are characterized by nearly vertical walls. Within this section, only one small turbidite channel is observed (seismic data courtesy of Western Geophysical).

their deposits from mass-transport deposits, although these processes and deposits can be transitional into mass- transport processes such as debris flows. The terms *slurry deposit* and *linked debrite* refer to those debrites (i.e., debris-flow deposits) that are genetically associated with turbidites. Slurry deposits form during the same depositional event and are associated with alternating laminar and turbulent flows (Lowe and Guy, 2000). Likewise, coupled debrites and turbidites comprising linked debrites are associated with a single depositional event. Consequently, although mass-transport deposits are considered here separate from turbidites, it should be recognized that a single depositional event can spawn both types of deposits, and as such both mass-transport deposits and turbidites are part of a continuum of depositional processes.

Mass-movement processes can be classified on the basis of process and rheology, product, climate, type of material moved, local geology, and triggering mechanisms (e.g., Ladd, 1935; Ward, 1945; Dott, 1963; Crozier, 1973; Middleton and Hampton, 1976; Nardin et al., 1979; Hansen, 1984; Pierson and Costa, 1987; Martinsen, 1994; Mulder and Cochonat, 1996). Many of these classification schemes are difficult to use, particularly in the field. Some schemes are concerned only with subaqueous gravity flows (e.g., Middleton and Hampton, 1973; Lowe, 1982), and do not include subaerial slope failures such as slides and slumps. Other schemes aim to classify all subaqueous processes whether they are gravity-driven or not (Pickering et al., 1986). Classification schemes should be simple, concentrate on descriptive and morphological factors, and direct the user towards genesis of a particular unit observed.

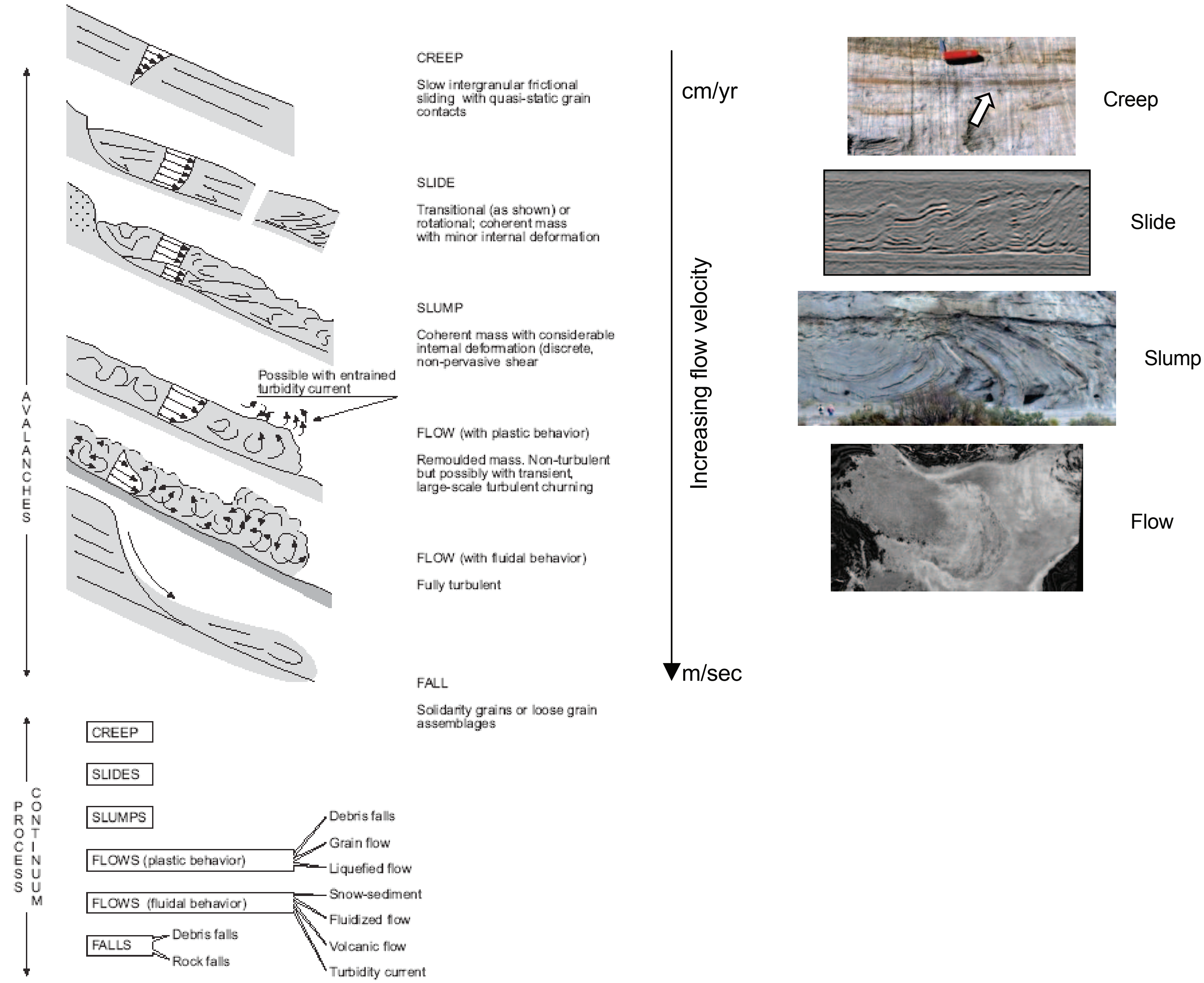


FIG. 3.—Schematic cross sections illustrating the spectrum of slope deformational processes, including those that form mass-transport processes and deposits. Note that these processes form a continuum from very slow-moving creep (cm/yr) to very fast-moving debris falls (m/s), where grains move fully independently of one another. The term mass-transport deposits should be limited to processes that involve *en masse*, gravitational sediment movement. The seismic and outcrop images illustrating creep (Fig. 16), slide (Fig. 10C), slump (Fig. 4), and flow (Fig. 33C) are discussed in greater detail below. (Redrawn and adapted from Nemec, 1991, and Martinsen, 1994).

Kruit et al. (1975), Rupke (1978), and Stow (1986) developed classification schemes where process and product are considered in a simplified way. The scheme, based on mass-movement rheology, was simplified by Nemec (1991), who grouped the processes into six categories (Fig. 3). This classification scheme is useful both for subaqueous and subaerial processes. This scheme shows a range from slow movement of coherent masses (creep), with little or no relative movement of individual grains ("quasi-static" grain contacts), through increasingly turbulent movements to rapid mass movement of grains, which move almost entirely independently of other grains (falls of debris). This scheme also shows that the processes are a part of a process continuum (Fig. 3). One process may evolve into another with time, or depositional effects of one process type may trigger other processes. This scheme is applicable both at outcrop and at seismic scale, and its use allows for easier comparison between various settings.

PROCESSES

Slopes, whether subaerial or subaqueous, are inherently unstable, because sediments deposited on them are subject to gravitational forces along an inclined surface. The resulting sediment deformation occurs on a broad range of temporal and spatial scales, yet for the most part the same structures or products are largely observed independently of scale. This is a basic premise for the comparison of outcrop and seismic examples, since scales of observation and resolution can differ significantly.

All types of mass movement behave in response to a range of factors, but failure and downslope movement depends on whether shear strength or shearing resistance of sediments is exceeded by the applied shear stress. Slopes vary in inclination from less than 0.1° (e.g., on modern delta fronts; cf. Prior and Coleman,1978a, 1978b, 1984) to vertical and overhanging, where rock falls may occur.

Terzaghi (1962) formulated the shearing resistance as

$$\tau = C + (\sigma_n - u) \tan \varphi$$

where is the shearing resistance of rock or sediment, *C* is the cohesion of sediments, σ_n is unit pressure at a point P on a potential slide surface, *u* is hydrostatic water pressure next to P, and φ is angle of shearing resistance or internal friction. Therefore, in more practical terms, the type of sediment, sedimentation rate, slope angle, heterogeneity of sediments (whether bedded or homogeneous), permeability, and to what extent pore water in sediments are drained, influence both the type and magnitude of mass transport. Consequently, mass-movement type can vary temporally and spatially along marine slopes, and a complete overview of the range of processes is necessary to analyze the depositional settings. The occurrence is to some degree predictable, inasmuch as the common factor of slope instability links all mass-movement deposits regardless of scale. However, caution is necessary particularly at outcrop scale, where commonly only 2D fragments of mass-transport deposits are observed. Seismic examples covering broad-scale examples of mass-transport deposits show that structural style, and thus classification, can vary greatly within the same units (e.g., Prior et al., 1984; Posamentier and Kolla, 2003; Posamentier and Walker, 2006).

Analysis of 3D seismic data allows a full spatial view of mass-transport deposits, particularly where they are located on or near the seafloor. The principal direction of movement can be readily interpreted from these data, though locally within the mass-transport deposits the direction of movement can vary considerably both as a result of local slopes (Prior and Coleman, 1979) and because of internal kinematics (Lewis, 1971; Martinsen, 1989, 1994). Based both on outcrop data and in deeper seismic data, the overall direction of movement, and consequently paleoslope, can be difficult to assess (Fig. 4; Woodcock, 1979; Martinsen and Collinson, 2002; Strachan and Alsop, 2006). In outcrop examples of mass-transport deposits, interpretations of paleoslope orientation must be made on measurements of all directional structures in as many mass-transport deposits as possible rather than on single observations (cf. Martinsen et al., 2000; Martinsen and Collinson, 2002; Martinsen et al., 2003). Core data can be useful to prove the presence of mass-transport deposits in deeply buried stratigraphy with poor seismic resolution, but direction of movement is usually impossible to attain, even with high-resolution dipmeter log data, due to the extensive deformation. Basal grooves observed on seismic data can be a direct indication of flow direction (Brami et al., 2000; Posamentier et al., 2000; Posamentier and Kolla, 2003; Posamentier and Walker, 2006). In the following sections, the most common processes that form mass-transport deposits are described to illustrate the main modes of gravitational sediment transport on subaqueous slopes.

Creep

Creep on subaqueous slopes is poorly studied and rarely identified compared to other

mass-transport processes, though exceptions include Carter and Lindqvist (1975), Hill et al. (1982), Silva and Booth (1984), Silva et al. (1989), and Lee and Chough (2001). The reason may be that creep is an extremely slow process (movements on the order of a few millimeters to centimeters a year), and that effects can be difficult to observe. In addition, Silva and Booth (1984) argued that creep mainly occurs on steep slopes (> 20°), and/or where thick sections (> 30 m) of sediments are deposited. These conditions give rise to creep and creep rupture, but as slope angles or thicknesses decrease, displacements are negligible. Creep can cause major displacement of surface sediment, and may precede other slope failures such as slumps and slides.

Subaqueous creep probably occurs where there is slow, intergranular frictional sliding of noncohesive sediment (Nemec, 1991). Strain rate must be low, preventing well-defined slip planes to develop. On steep, coarse-grained shorefaces or deltas where slope inclination may be up to 35°, creep can be important. In these settings, creep can probably stabilize slope successions as it reduces the slope gradient, so that more massive slope failures do not occur (W. Nemec, personal communication). Creep will be virtually unrecognizable on seismic data and will have subtle expression in outcrop, possibly in the form of stretched beds exhibiting boudinage structures in sandstone beds without associated significant bed deformation (Fig. 16) (W. Arnott, personal communication).

Slides

Slides involve mass movement of sediments with little or no internal deformation; the slide overlies a distinct shear surface

FIG. 4.—Photograph showing isoclinal recumbent folding in the complex middle Miocene Gordo megabed/mass-transport deposit in the Tabernas Basin, southern Spain (e.g., see also Kleverlaan,1987). Note the tripartite structure with a lower slumped unit, truncated by a middle graded sandstone (turbidite or debrite) and a mudcap, is an example of the linked nature of several processes within mass-transport deposits. General transport direction was from left to right. Note people in foreground for scale.

(*sensu* Stow, 1986; Martinsen, 1994) (Fig. 5). Original bedding can be slightly rotated along fault planes, such as in hanging-wall anticlines, but not deformed by simple shear or buckling. Near the terminus of some slides, compressional features such as imbricate thrusts can take up shortening of the section (Fig. 5). Slides include *rotational* slides and *translational* slides (cf. Allen, 1985) and encompass a range of marine slope instabilities, such as delta-front growth faults, shelf-edge faults (Fig. 6), failures on channel margins, submarine glide-blocks, and olistoliths.

Commonly, basal slide surfaces are spoon shaped in three dimensions with a tripartite morphology of upslope head region, middle "rigid" zone, and downslope toe zone (Fig. 7; Brunsden, 1984; Gawthorpe and Clemmey, 1985; Martinsen, 1989). In plan view, the upslope head region is concave downslope and dominated by extensional deformation. The middle region is mainly translational, and does not show any particular strain signature. The toe region is usually dominated by compressional deformation, and has a series of convex-downslope and characteristically lobate forms in plan view (Figs. 5, 8).

It is common in slides that a "family" of listric faults dominates the head region (cf. Crans et al., 1980) and sole out at a basal decollément. Such faults commonly are readily recognizable on high-resolution seismic data. In larger slides, the fault families can occur in a hierarchy so that one small family may be entirely enclosed in the hanging wall of a fault of a larger-order fault family. Antithetic listric or planar extensional faults occur (Fig. 9). These antithetic faults are dowthrown in the sense opposite to the master faults, and, as a consequence, can cause confusion in outcrop-based measurements of paleoslope (Martinsen, 1989).

The central region of the slide can be mostly undeformed. In both seismic data and in outcrops, slide recognition can be difficult in this zone. In outcrops, there may be evidence for internal slip between beds in the form of sheath folds or microfaults. Strike-slip deformation dominates at the lateral margins of slides (Fig. 5). Width variability of the slide in plan view determines whether deformation is transpressional or transtensional (Martinsen, 1994).

Compressional deformation dominates the toe region, and usually produces thrust faults. Thrusts form classic duplex and imbricate zone geometries (Lewis, 1971; Dingle, 1977; Martinsen and Bakken, 1990; Posamentier and Walker, 2006) (Figs. 10, 11, 12). Commonly, the plan-view expression is downslope lobate ridges, or "pressure ridges" that lie above blind thrusts (Roberts et al., 1980; Prior et al., 1984; Posamentier and Walker, 2006) (Figs. 8, 13).

Slumps

Slumps are characterized by significant internal distortion of bedding, above a basal shear surface (e.g., Stow, 1986; Martinsen, 1989; Martinsen and Bakken, 1990). Nevertheless, primary bedding should be recognizable. There is a continuous transition between slides, slumps, and plastic flows, and many mass-transport deposits may show characteristics of all three modes of transport (e.g., Bakken, 1987; see also below). Therefore, careful analysis is required to understand temporal and spatial behavior of the processes producing the mass-transport deposit and to satisfactorily categorize them.

Slumping is a common process where there is a significant involvement of clay-size sediments. Depth of the basal shear surface is determined by the pressure gradient within the sediment. Where pore pressure approaches or balances the normal stress of the overburden, slippage occurs along a basal shear surface. These relationships are given by the equations

$$\text{Shear strength } (\tau) = C + (\sigma - p) \tan \varphi \text{ (Hampton, 1979)}$$

and

$$\text{Shear stress } (S) = \rho\, g\, s\, Y \tan \alpha \text{ (Middleton and Southard, 1978)}$$

where C is sediment cohesion, σ is normal stress (or weight of overburden), p is pore pressure, φ is the angle of internal friction, ρ is sediment density, g is acceleration due to gravity, s is solidity (or the complement of porosity), Y is sediment thickness, and α is slope angle.

The shear surface propagates upslope in a radial fashion from a nucleation point (Williams and Chapman, 1983; Farrell, 1984), leading to the formation of a scoop-shaped, concave-downslope depression or failure scar, often with an irregular outline (Martinsen, 1989) (Figs. 14, 15). The shear surface is probably initiated as a slope-parallel feature, which can steepen at lithofacies boundaries or at sites of abrupt change in pore pressure where contrasts in material strength occur (Crans et al., 1980).

Idealized models of slumps (and slides) show the deformed units to have a well-defined upper extensional zone and a downslope contractional zone (Fig. 7; e.g., Lewis, 1971; Allen, 1985). Both extensional and contractional faults are common in slump deposits (Martinsen and Bakken, 1990; Strachan and Alsop, 2006). Seismic observations suggest that faults are common in many positions within slumps (Posamentier and Kolla, 2003; Frey-Martinez et al., 2006; Posamentier and Walker, 2006), such as laterally along slump margins, as well as distally in association with basal-shear surface ramps (Figs. 5, 10). Distinguishing between slumps and slides can be difficult because both are part of a continuum of mass-movement features. In outcrop, one distinguishing characteristic of slides is that internal to a slide block there is little or no deformation of beds. In contrast, within slump deposits original bedding integrity is maintained, while some deformation nonetheless characterizes bedding architecture.

A variety of other deformational structures such as folds, boudins, microfaults, internal shear surfaces, and faults are common in slumps (W. Arnott, personal communication; Fig. 16). The main fold style in slumps are sheath folds formed by simple shear (Martinsen, 1994), but buckle folds also occur (Woodcock, 1976). Martinsen (1994) argued that slumps experience a main phase of plastic/ductile deformation, wherein folds and boudins are formed. The ductile phase is followed by a late brittle phase, when faults form. It is common to see strain overprinting, where early-formed folds are truncated by late faults or where extensional structures are overprinted by contractional structures (Farrell, 1984; Martinsen, 1989; Martinsen and Bakken, 1990; Strachan and Alsop, 2007).

Slumps form on slopes as low as 0.1° or less (e.g., Prior and Coleman, 1978b) and can range in thickness from 0.5 m (e.g., Martinsen, 1987) to several hundreds of meters on continental margin slopes (e.g., Dingle, 1977; Jansen et al., 1987). On most modern delta slopes, slumps are generally less than 40 to 50 m in thickness (e.g., the Mississippi Delta, cf. Prior and Coleman, 1978a, 1978b), which correspond to the scale of mass-transport deposits in many ancient subsurface successions (Martinsen, 1994 and references therein).

Debris Flows

Debris flows are cohesive to noncohesive laminar flows that transport unsorted and disaggregated debris that can travel across extremely low-gradient slopes. Mud flows are analogous to debris flows but do not carry large volumes of disaggregated

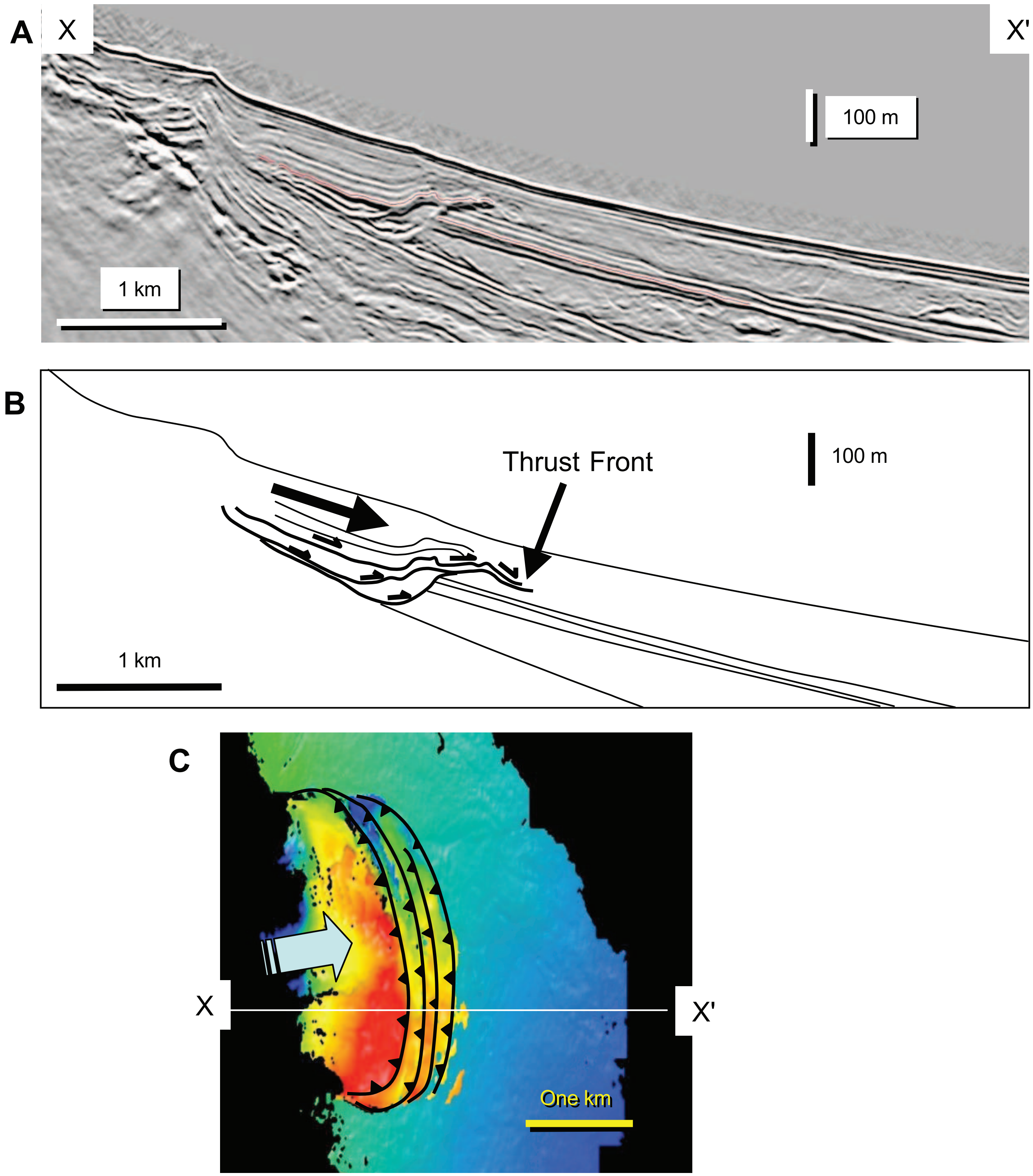


FIG. 5.—A slide deposit on the flank of a salt diapir in the northern deep Gulf of Mexico shown in **A)** seismic reflection profile; **B)** interpreted line drawing; and **C)** plan-view time structure map (colors indicate two-way travel time, with warm colors indicating bathymetric highs and cool colors bathymetric lows). Note in Part A the imbricate thrusts and the lack of disruption or internal deformation within the mass transported material. In Part C the imbricate thrusts in plan view are characterized by a lobate pattern; sides of this deposit are characterized by shearing. Large arrows in Parts B and C indicate direction of transport of slide. Location of seismic profile in is shown by white line in Part C (seismic data courtesy of Western Geophysical).

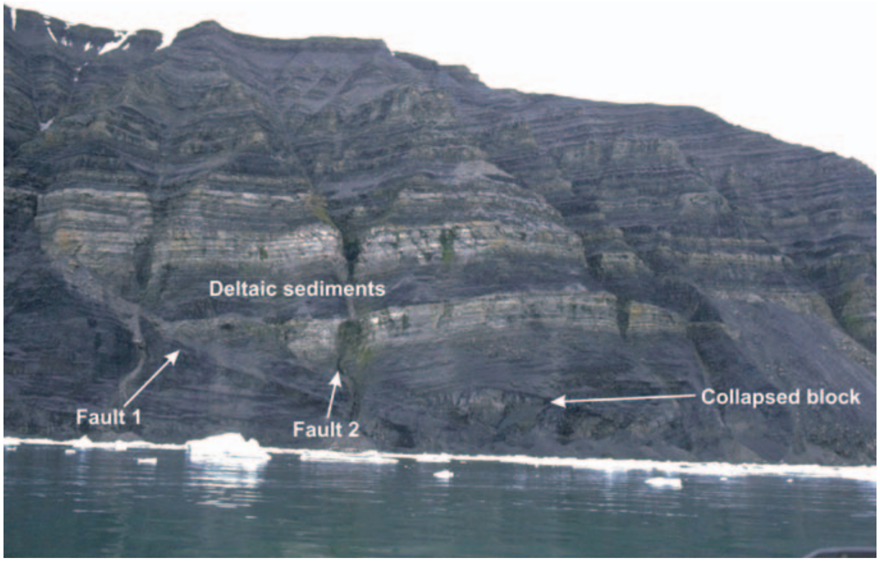


FIG. 6.—Photograph of a growth fault complex in shelf-edge megaslide head zone with two closely spaced faults (arrowed) in Triassic deltaic strata, Edgeøya, Svalbard. This slide cuts approximately 150 m of section, and the cliff is approximately 400 m high (Edwards, 1976). Note also the collapsed block at the base of the cliff above the upper fault. Similar growth-fault features are observed on many continental margins and are potential source and staging areas for major mass-transport deposits, if sediments are transported out of the upslope scar. In the current case, that did not happen, and these features are classified as classic growth faults.

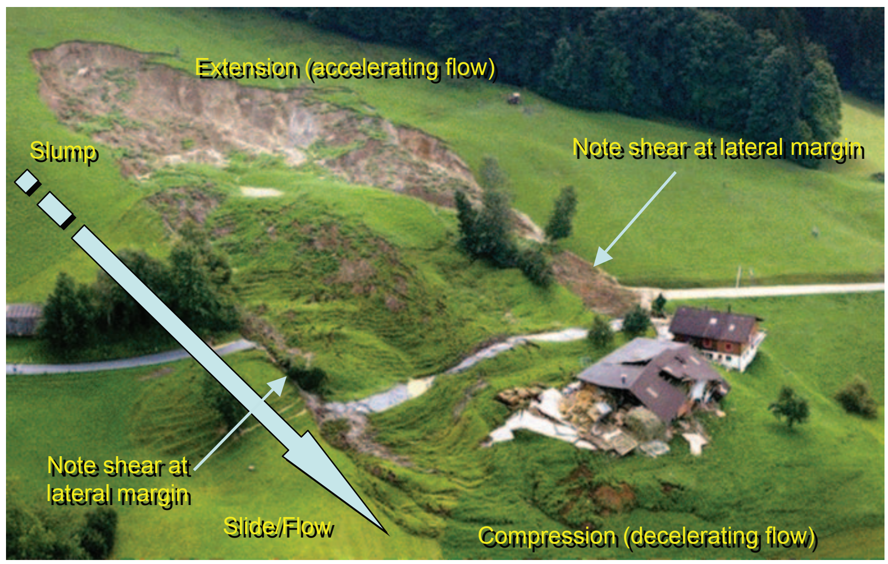


FIG. 7.—Modern subaerial mass-transport feature in the Austrian Alps. Note the extensional normal faults in the upslope area and the compressional thrust faults in the downslope area. Extension proximally implies accelerating flow, and compression distally implies decelerating flow at the time the event occurred. Note also shearing that characterizes lateral margins of the mass-transport deposit. Note farm house for scale.

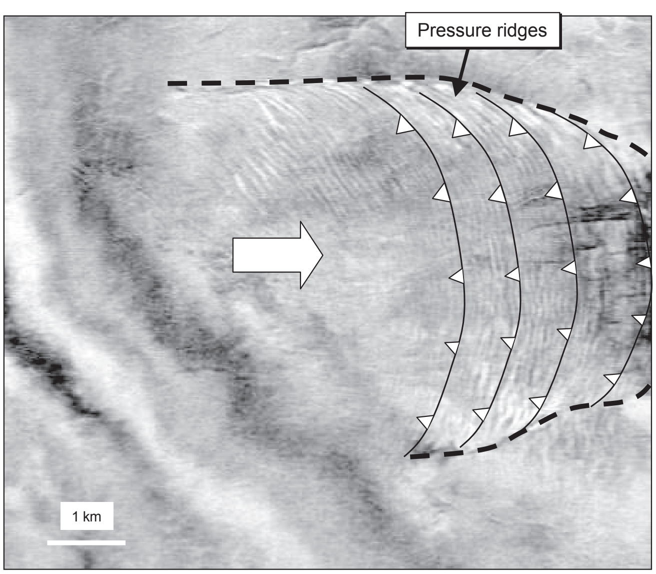


FIG. 8.—Seismic amplitude stratal slice in plan view displaying a deep-water (about 2500 m water depth) Miocene mass-transport deposit, characterized by compressional deformation (i.e., thrust faults) near its terminus. Note convex down-dip, lobate planform of these compressional features. Shearing characterizes lateral margins of this deposit (compare with Fig. 5).

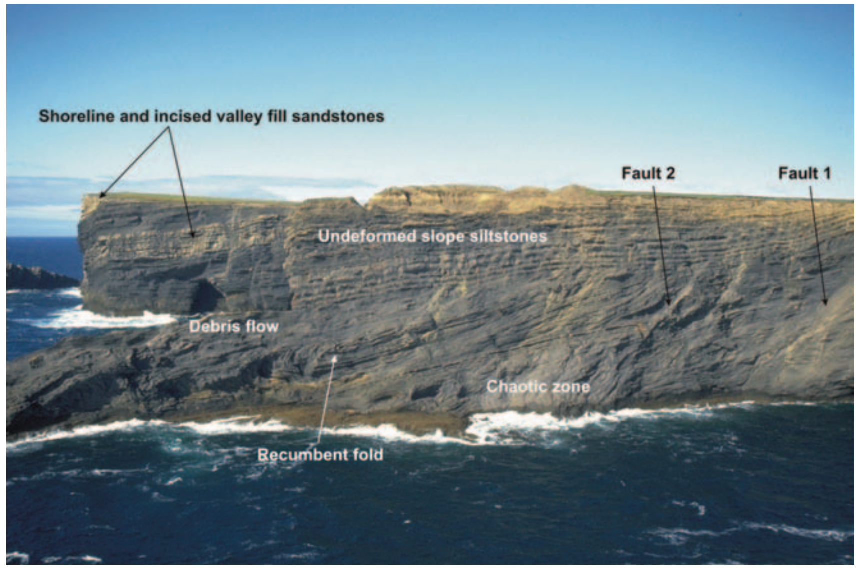


FIG. 9.— **A)** Photograph and **B)** complementary line diagram of the complex upper slope mass-transport deposits in the hanging wall of two extensional faults in the Upper Carboniferous Gull Island Formation, County Claire, western Ireland. Depositional setting was probably influenced by several types of mass movements (e.g., slides, slumps, and debris flows), which were trapped in the depression in front of extensional faults. Cliff orientation is strongly oblique to interpreted overall direction of movement, which was to the northeast (into the cliff to the right). The cliff is approximately 50 m high. See Martinsen and Bakken (1990) for a detailed description of the section.

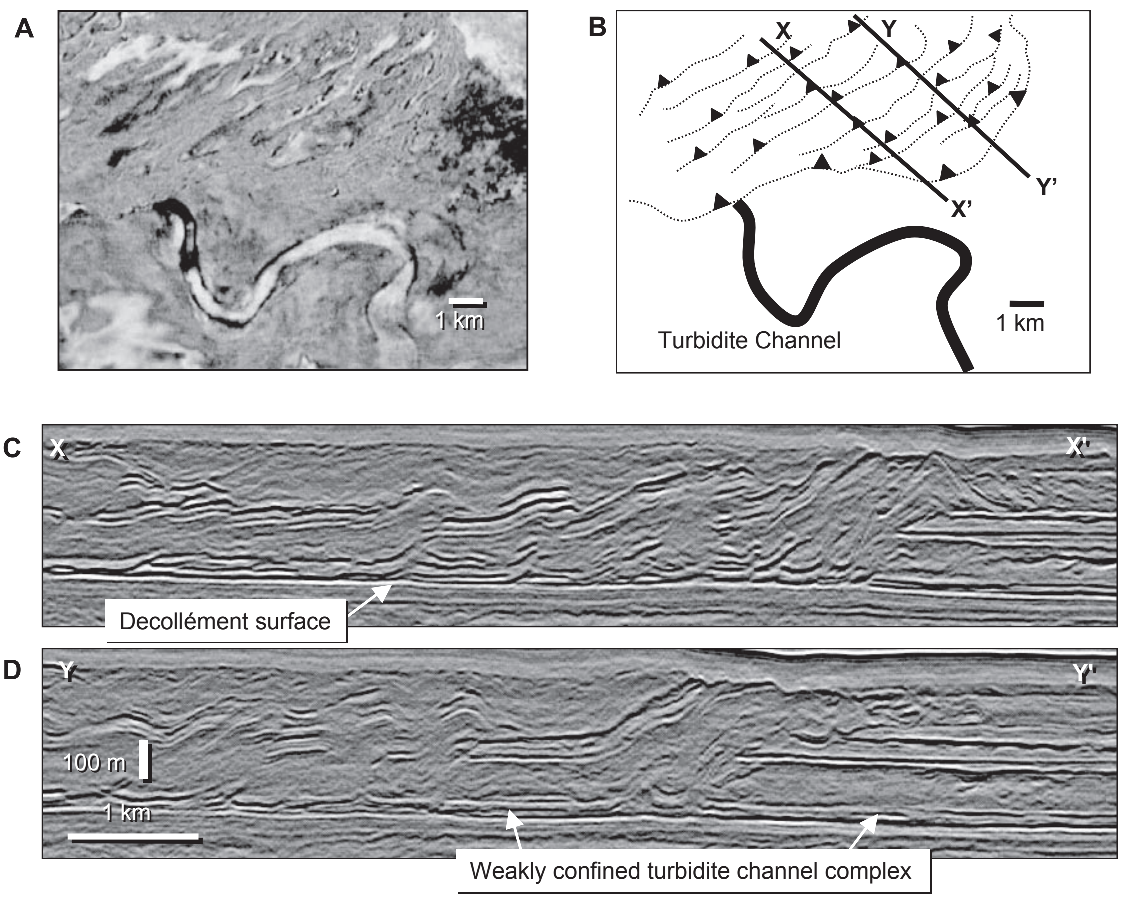


FIG. 10.—Mass-transport deposit in the deep-water northeastern Gulf of Mexico shown in plan view **A, B)**, as well as transverse view **C, D)**. The plan view shown in Part A is a strata slice through an amplitude volume. Note duplex imbricate thrusts and their arcuate planform. Decollément surface at base of the deposit likely is at a condensed section. Plan-view image (Part A) also illustrates how the mass-transport deposit has cannibalized turbidite channel-fill deposits. High-amplitude reflections within basal section of the mass-transport deposit, which are characterized by multiple thrusts, likely comprise turbidite sands incorporated into the mass-transport deposit. External to the mass-transport deposit and immediately adjacent to it, similar undeformed high-amplitude reflections at the same level are characterized by a complex of weakly confined channels as observed in plan-view images (from Posamentier and Walker, 2006).

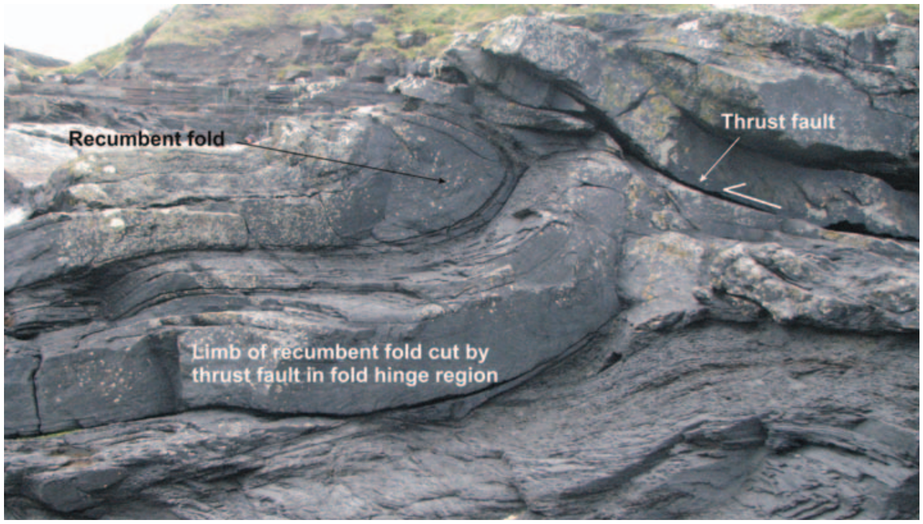


FIG. 11.—Outcrop photograph of a thrust fault overprinting a recumbent fold in the Upper Carboniferous Gull Island Formation, western Ireland. Strain overprinting like this example is common in mass-transport deposits and can occur at any scale in compressional zones (Farrell, 1984; Martinsen, 1989; see also Strachan and Alsop, 2006, for a detailed description of this slide). Such strain overprinting indicates that the mass-transport deposit stopped at its downslope margin first and that subsequent structures developed in an overstep fashion rather than in a piggy-back fashion (see Martinsen, 1989, 1994).

debris. Johnson and Rodine (1984) defined debris flows as "granular solids, in general only admixed by minor amounts of clay, entrained water and air, [which] move readily on low slopes".

During the last decade, detailed quantitative research in flumes has suggested that debris flows with sand and mud have significantly higher mobility than previously assumed (e.g., Mohrig et al., 1998). Observations of hydroplaning plastic flows in flumes, together with seismic stratigraphic observations, indicate that plastic flows may travel several hundred kilometers on low slopes. There has been considerable debate in recent years regarding the understanding of turbidity-current and debris-flow processes (e.g., Hampton, 1972; Middleton and Hampton, 1973, 1976; Shanmugam, 1996; Mohrig et al., 1998;

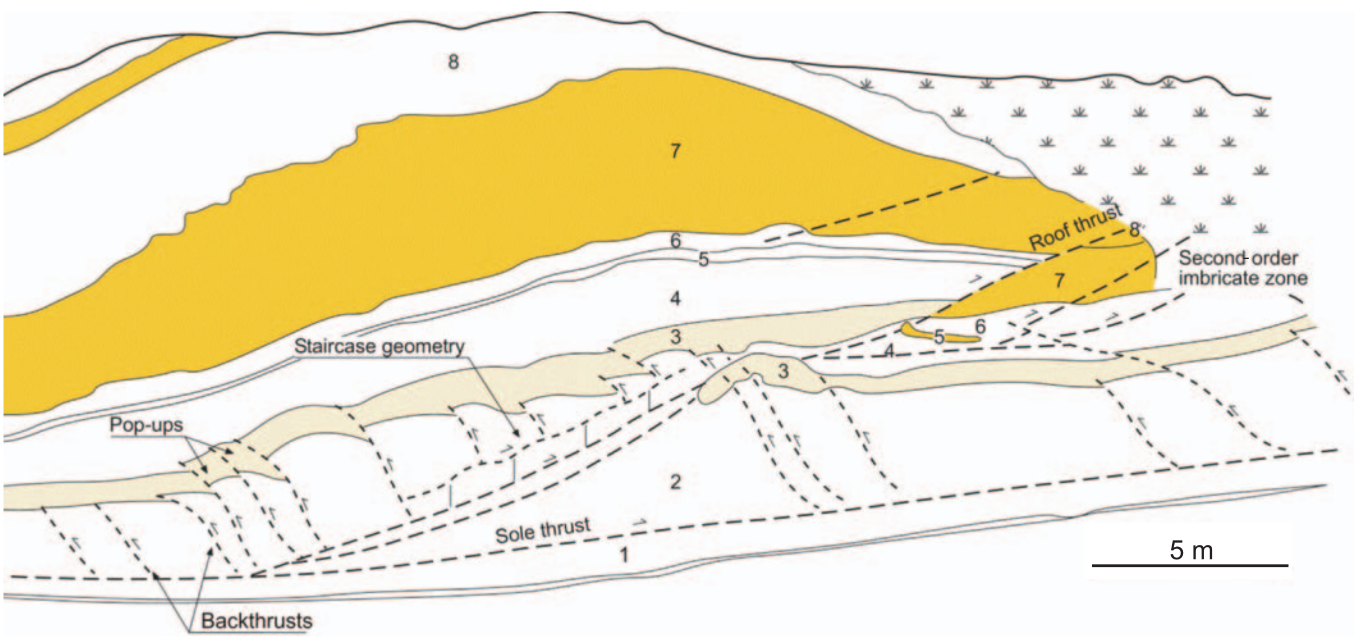


FIG. 12.—Line drawing of an imbricate thrust zone from Upper Carboniferous Gull Island Formation, County Clare, western Ireland. Note hierarchy of structures formed and offsetting of various mudstone and sandstone beds (in orange), annotated by numbers. This structural complexity is scale-independent and can be observed in much larger mass-transport deposits in seismic data (see e.g., Fig. 10).

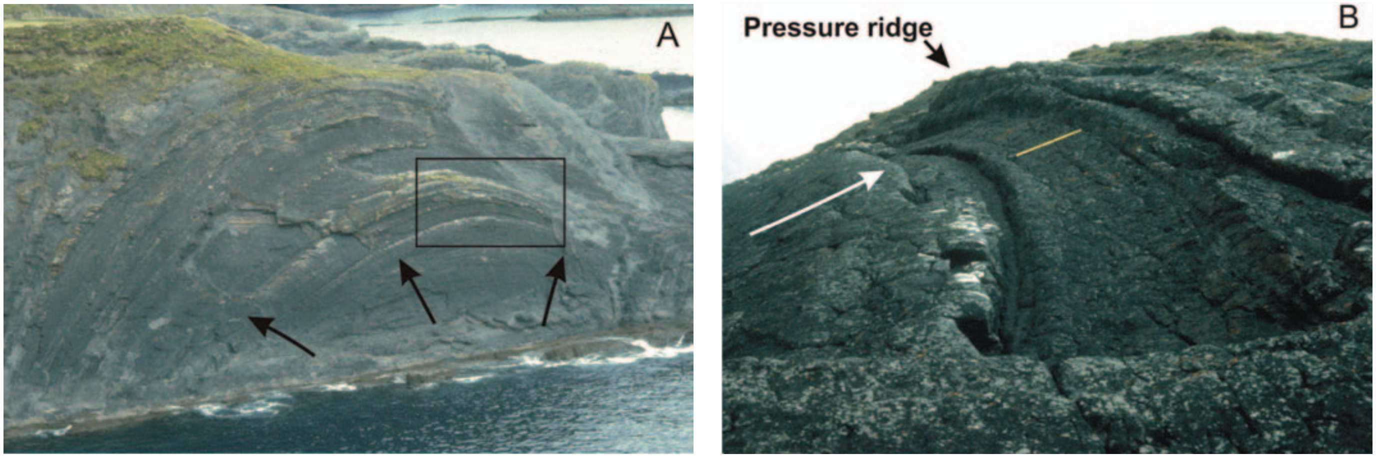


FIG. 13.—Outcrop photographs of the Upper Carboniferous Gull Island Formation, County Clare, western Ireland, illustrating pressure ridges associated with a deep-water slide deposit. See Martinsen and Bakken (1990) for detailed description. **A)** Plan-view expression of pressure ridges at the downslope end of minor slide. Beds dip steeply towards viewer, and the movement direction was probably towards top left of the picture as indicated by the arrows. Height of the cliff is approximately 25 m. **B)** Close-up of pressure ridges in Part A viewed obliquely upsection in from right to left in the rectangle shown in Part A. Ridges are clearly expressed and the depression immediately left of measuring tape in Part B is the surface expression of a thrust plane, separating the ridge on the left from the ridge on the right. Direction of thrusting was to the right as indicated by the arrow. Measuring tape is 1 m long. See also Figures 8 and 10 for similar subsurface examples on seismic data.

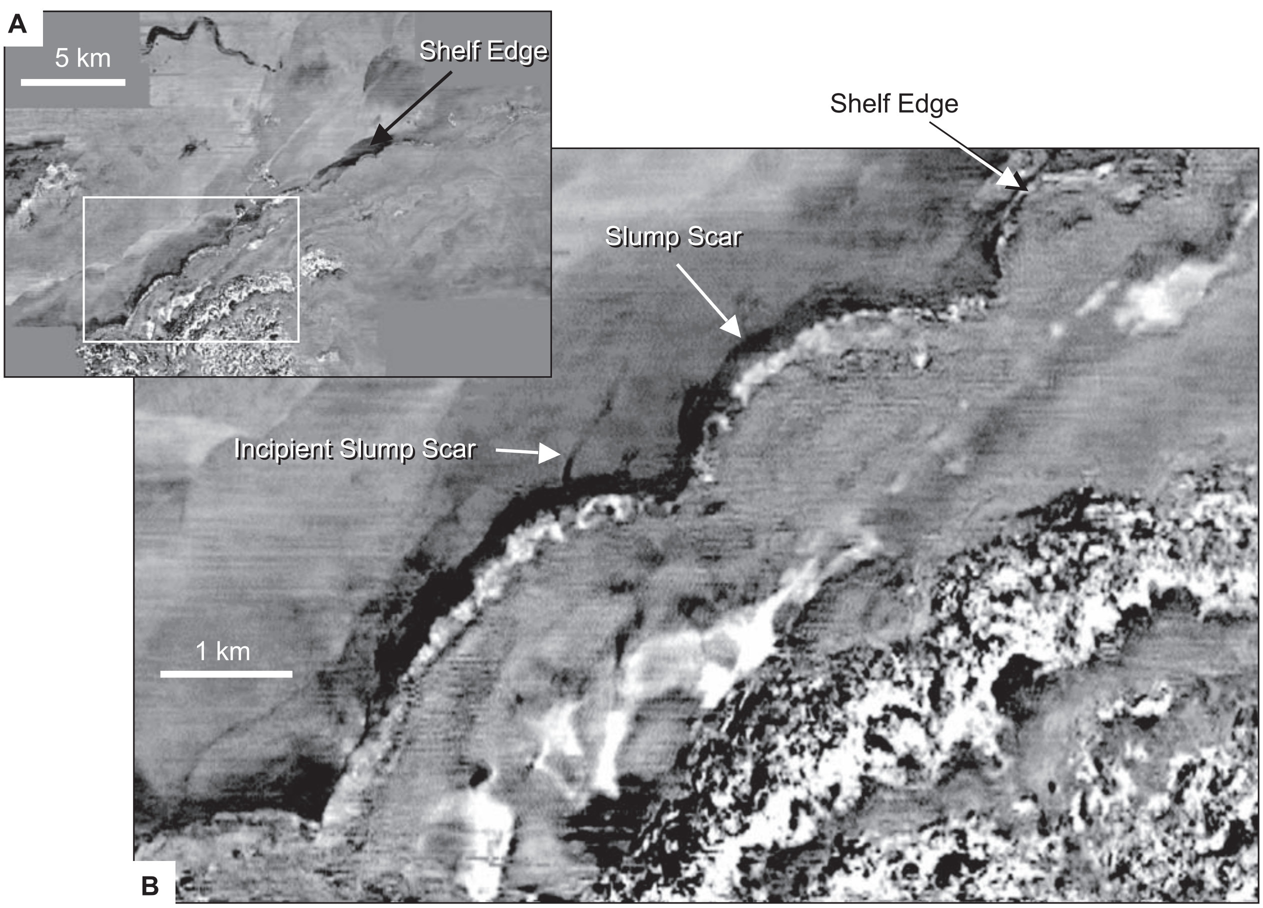


FIG. 14.—Amplitude time-slice, plan-view images of the shelf edge close to the modern sea floor, offshore Indonesia. **A)** Arcuate slump scars, with **B)** an enlargement of the shelf edge. Note incipient slump scar just inboard of the shelf margin (after Posamentier and Walker, 2006).

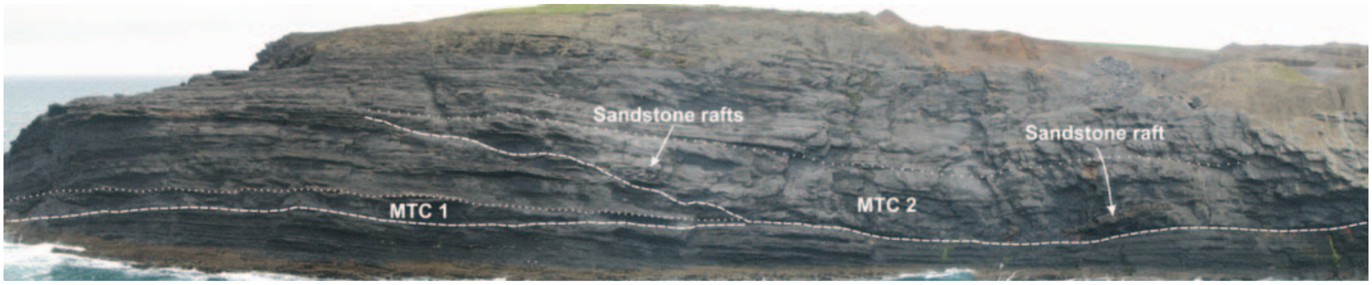


FIG. 15.—Outcrop photograph and interpretation of two upper-slope slump scars and fill of mass-transport deposits from the Upper Carboniferous Gull Island Formation, County Clare, western Ireland. Their lower boundaries are marked with dashed lines, and their upper boundaries by stippled lines. Note floating rafts of sandstone in the mass-transport deposit. Cliff is approximately 50 m high. Such scars dominate many upper-slope areas of modern slopes and are also commonly seen in seismic sections (see Fig. 14). These features can usually be differentiated from channels cut by turbidity currents by their lower aspect ratios (lower depth/width ratios) and by their fill, which usually is composed of mass-transport deposits or undeformed mudstones, if the mass-transport deposit is transported out of its scar.

Mulder and Cochonat, 1996; Mulder and Alexander, 2001; Elverhøi et al., 2005).

There is a critical thickness (T_c) for initiating or stopping debris flows, assuming Coulomb behavior of the debris (Johnson and Rodine, 1984):

$$T_c = (C / \gamma \sin \delta)/(1\text{-}\tan \varphi/\tan \delta)$$

where C is the cohesive strength, φ is the angle of internal friction, γ is the unit weight of the debris, and δ is slope angle of the surface (and base of debris flow). Thus, more cohesive debris flows can attain greater thicknesses, while greater slope angles will favor thinner flows. Subaqueous debris flows commonly may also be sheet-like, since entrainment and rapid mixing of sediment with water may cause lateral flow expansion and sheet development when flows occur outside channels.

Commonly, debrites are characterized by a matrix-supported texture with the largest clasts being positioned towards the top of the flows (i.e., "kinetic sieving"). This condition is driven by dispersive pressure between clasts in a buoyant matrix with some cohesive strength, causing the largest clasts to move preferentially towards the top of the flow. There commonly is a density difference between the debris and the dense matrix, also giving the largest clasts buoyancy (Rodine and Johnson, 1976). Hampton (1979) showed that debris-flow buoyancy is caused by two factors: (1) high density of the matrix, and (2) loading of pore fluid by clasts or matrix, causing overpressure within the debris flow, which keeps clasts in suspension. Hampton (1979) further showed that even in grain–matrix mixtures with up to 90% grains, the largest clasts could be supported. Rodine and Johnson (1976) further showed that in poorly sorted debris flows, mobility was sustained when matrix was as low as 5%.

Typically, debris flows sweep clean their pathway and entrain large clasts (Figs. 17, 18; Johnson and Rodine, 1984). The coarsest debris is generally carried in the snout of the flow, so that an upslope fining is commonly observed in the final deposit. Therefore, the finer and more fluid upslope debris sometimes remobilizes underlying coarser debris. Finer-grained debris flows commonly travel farther than coarser-grained flows, but because fine-grained and fluid flows readily incorporate coarser material, a simple coarse-to-fine gradation in a particular depositional setting (e.g., alluvial fans) should not always be expected (cf. Johnson and Rodine, 1984).

FIG. 16.—Sandstone boudins, marked by white arrow, from the slope facies of the Upper Proterozoic Windermere Group, British Columbia, Canada. Note the pinch and swell of the sandstone bed deformed by slow downslope gravity-driven movement—sediment creep. Lineaments transverse to bedding are modern glacial scours and striations. (W. Arnott, personal communication).

MASS-TRANSPORT DEPOSITS: OCCURRENCE AND MORPHOLOGY

Staging Areas for Mass-Transport Deposits

The *staging area* is defined as that location where mass-transport deposits originate. Staging areas can exist in any setting where slopes are unstable. Such instability can arise from a range of factors, including: (1) oversteepening of slopes due to rapid sedimentation associated with shelf-edge deltas (Whelan et al., 1976; Prior and Coleman, 1978b); (2) cyclic wave loading (Henkel, 1970; Suhayda et al., 1976); (3) sudden movement of the seafloor in response to seismic events (Seed, 1968; Leeder, 1987); (4) oversteepening of slopes due to erosional undercutting at the base of slope; (5) lowering of wave base in response to relative fall in sea level, leading to disequilibrium conditions at the seafloor; (6) oversteepening of slopes as a result of fault movement or diapiric movement associated with mud or salt; (7) overpressure associated with fluid expulsion and/or mud volcanism; and (8) dissociation of clathrates in the near-subsurface section (Carpenter, 1987; Maslin et al., 1998; Maslin et al., 2004).

The largest mass-transport events commonly originate in the mid to upper slope (Fig. 19). These events can cause volumes of sediments as large as hundreds of cubic kilometers to be set in motion. At the other end of the spectrum, small failures of channel–levee walls can be in the order of just a few cubic meters (Figs. 20, 21). Ultimately, the lithologic character of a mass-transport deposit reflects the lithology present in the staging area. Consequently, those mass-transport deposits that originate at the outer shelf or upper slope can have a mix of sand and mud, whereas those that originate in the mid-slope or beyond likely will be more mud prone. More locally derived mass-transport deposits, such as those associated with salt domes or mud volcanoes (Fig. 22), or those associated with oversteepened flanks of channel levees, are intrabasinal and commonly mud prone with locally derived material.

Commonly, the location where mass-transport deposits originate is characterized by arcuate scars. Such scars sometimes can be observed at the shelf–slope break (Fig. 14). Others can be seen in mid-slope settings (Fig. 19). Much smaller arcuate scars can be observed along inner channel–levee walls (Figs. 20, 21).

External Morphology

Seismic reflection data are better suited than outcrops for describing larger aspects of external as well as internal morphology of mass-transport deposits. Table 1 summarizes the seismic stratigraphic criteria for recognition of mass-transport deposits. These criteria are discussed below.

Mass-transport deposits can assume a variety of shapes and sizes ranging from lobate to sheet to channel-form (Posamentier et al., 2000; Posamentier and Kolla, 2003). Figure 23 illustrates several lobate-form, deep-water mass-transport deposit lobes. These lobes are characterized by relatively steep flanks (up to 20°), suggesting a flow mechanism that involved a relatively abrupt halt or *en masse* freezing of the flow. A similar, steep-flanked mass-transport deposit is illustrated on the left side of Figure 24. In contrast with these steep-sided debrites, a debrite lobe with tapered flanks is present on the right side of Figure 24, giving the appearance of a deflated lobe. The gradient that characterizes the margins of these deposits reflects their rheology.

Mass-transport deposits also can be channelized (Posamentier and Kolla, 2003) and leveed (Fig. 24). In some instances, channelized mass-transport deposits have opportunistically occupied an earlier-formed, basin-floor channel, likely formed by turbidity currents (Fig. 25). Most debris flows are characterized by a rugose external texture suggesting presence of large floating clasts (Figs. 26, 27). A cluster of large clasts within a mass-transport deposit is shown in Figure 17, with some clasts approaching ~ 500 m in diameter.

A hybrid type of channelized, large-scale mass-transport deposit is relatively common in basin-floor settings. In low-gradient settings immediately outboard of the base of slope, a common aspect of large mass-transport deposits is the tendency to plow deeply into the substrate. Apparent channels, such as that illustrated in Figure 28, are not erosional in the conventional sense. Such "channels" never existed as open conduits; rather they formed in a manner similar to how a trench is excavated by a snow shovel (Fig. 29). However, in contrast with the snow-shovel analogy, no open trench (behind the shovel) ever exists in the case of deepwater plowing. The role of the shovel is played by the mass of material that pushes the seafloor substrate, so that cut and fill of the trench occurs simultaneously. This plowing process results in significant "bulking

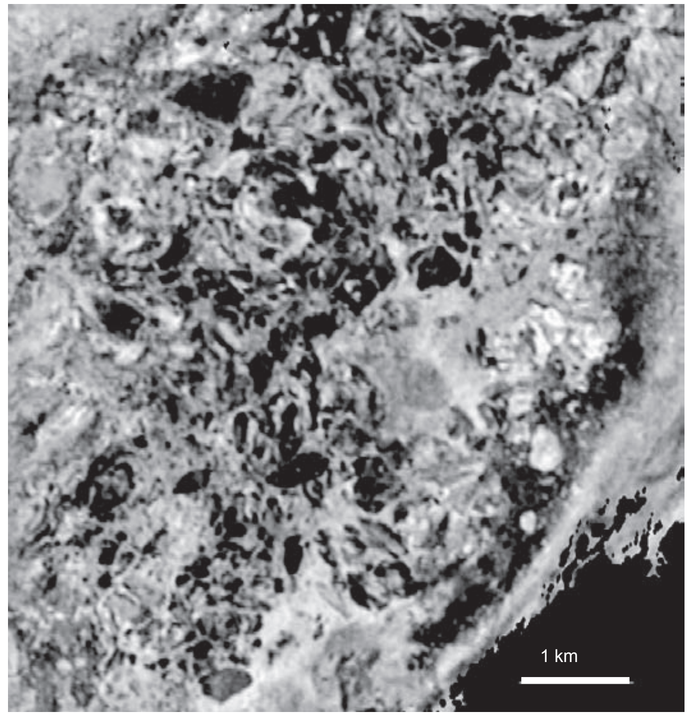


Fig. 17.—Seismic-amplitude image illustrating in plan view a stratal slice showing large clasts in a mass-transport deposit on the Gulf of Mexico basin floor. Note random orientation of these clasts, some of which exceed 800 m in diameter. The clasts stand out from the background gray matrix, indicating a marked impedance contrast between the clast and the surrounding sediments. This contrast could be caused by the effects on acoustic property of the greater degree of induration of the coherent clasts relative to the more poorly indurated matrix (seismic data courtesy of Western Geophysical).

Fig. 18.—Phototgraph of floating clasts in a thin debrite, Eocene slope strata of Sant Llorenc del Munt, northeastern Spain. Unit markings on the measureing stick are 10 cm long. The inverse grading and clasts observed in the upper bed are indicative of a flow with plastic behavior. Note the highly incisive base of the bed (arrowed), a feature also seen at much larger scales on continental margins. Many such features observed at outcrop scale are also seen at seismic scale, suggesting scale independence of formation processes.

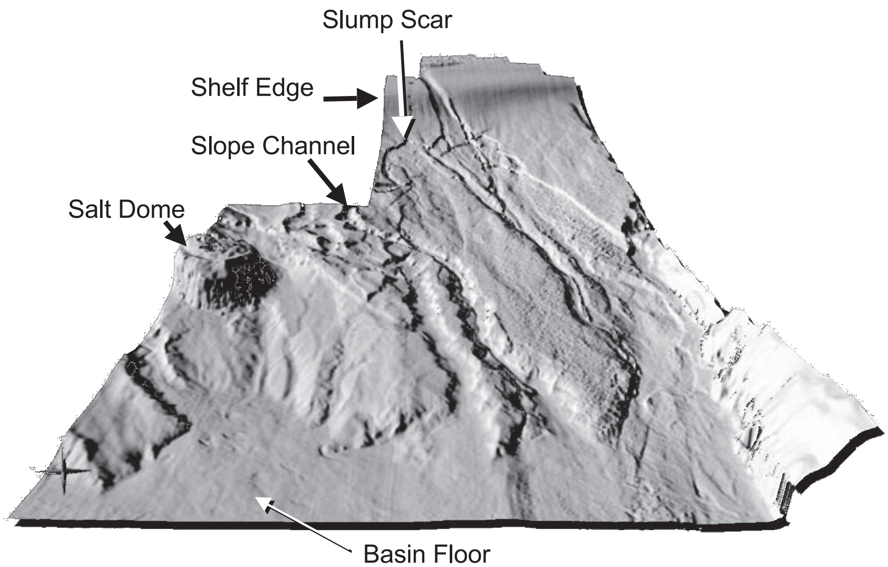


FIG. 19.—A 3D perspective dip azimuth image of the modern seafloor in the northeastern Gulf of Mexico showing slump scars indicative of past mass-transport events on the seafloor. Water depth ranges from approximately 200 m at the shelf edge to greater than 2000 m on the basin floor. Slump scars reach 45 m in height and are up to 17 km wide. The approximate volume of material excavated is estimated at 41.2 km^3 (after Posamentier and Walker, 2006).

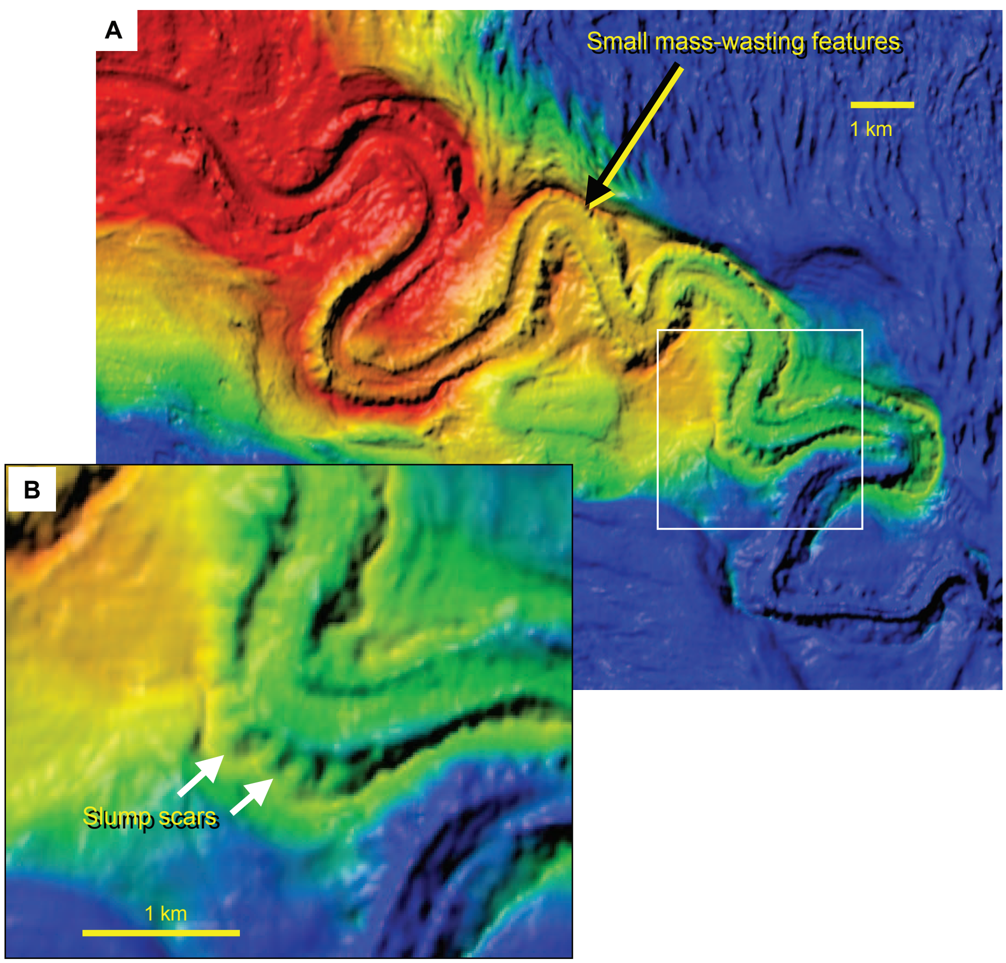


FIG. 20.—**A, B)** Plan view of small arcuate slump scars that characterize the inner face of levees bounding a Pleistocene deep-water channel in approximately 2000 m of water in the northeastern Gulf of Mexico. This channel lies approximately 80 m below the seafloor and was characterized by flows from right to left. Colors indicate time structure, with warm colors representing bathymetric highs and cool colors bathymetric lows. Note that channel fill is characterized by positive relief, associated with postdepositional differential compaction. The volume of materials excavated in association with these slumps likely was less than 100 m^3 (after Posamentier, 2003).

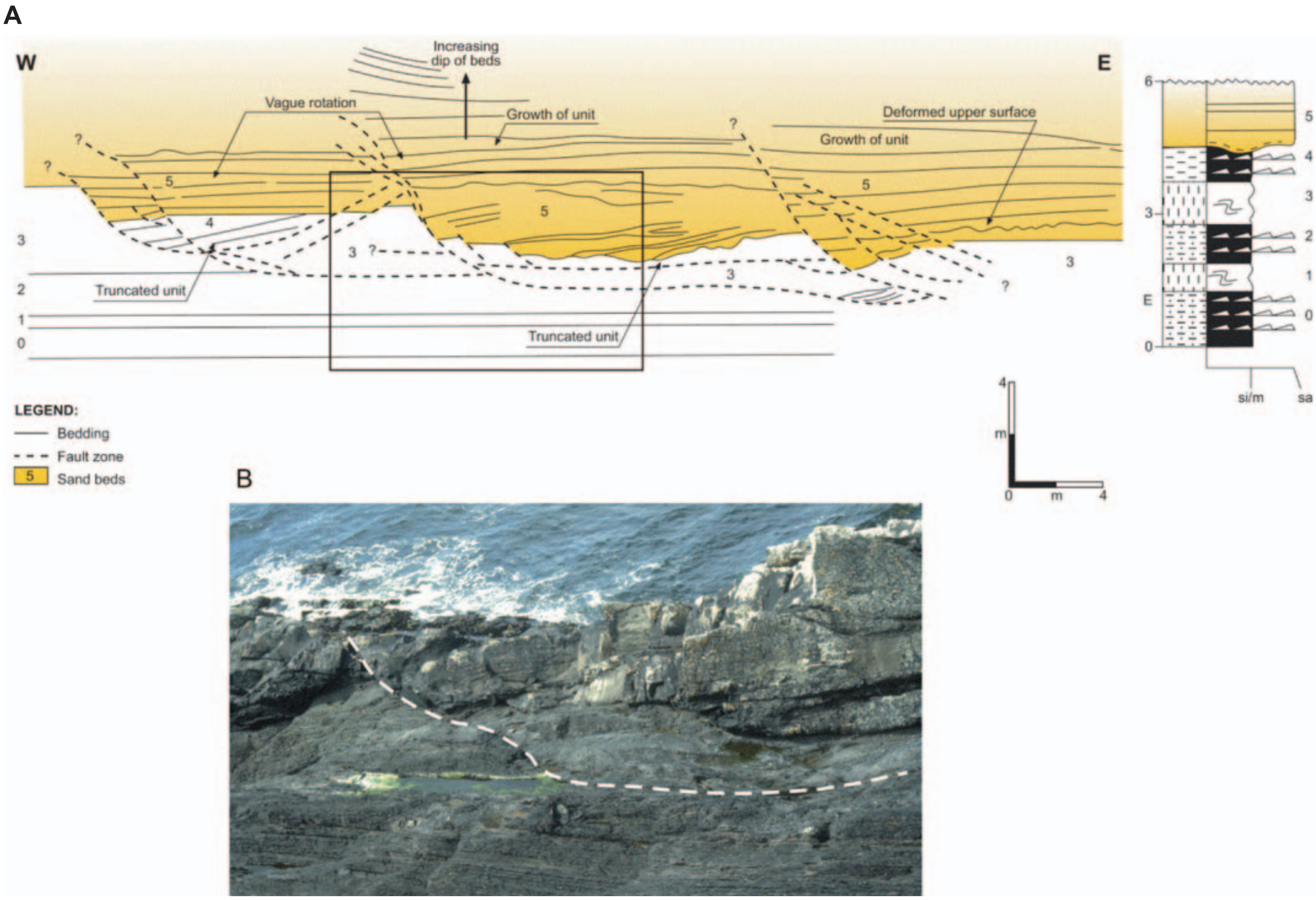


FIG. 21.—**A)** Line diagram of slumped channel margin in an upper-slope setting, Upper Carboniferous Gull Island Formation, County Clare, western Ireland. Note growth-faulted nature of deformation with increase of turbidite-bed thickness across faults, suggesting that these faults were active during deposition. **B)** Photograph of parts of the slumped channel margin. The position of the photograph is indicated by the rectangle in the line drawing. One of the listric faults is indicated by the dashed line. Similar features are seen on the seismic section in Figure 20.

up" of flow, as significant volumes of the basin-floor substrate are entrained into the flowing mass. Mass-transport trenches formed in this way commonly are flat-floored, suggesting shearing along a plane of weakness parallel to bedding, forming a basal decollément surface. Likewise, these trenches are steep-walled, with margins approaching slopes of 70 to 80°, suggesting that shearing at the margins is occurring as well. Such features commonly terminate as a "box canyon," with extensive, low-angle thrust faulting characterizing the mass-transport deposits near the terminus, as the flow comes in contact with and compresses against the terminal wall (Fig. 30). Sediments close to the terminal wall presumably have traveled a minimal distance. Palinspastic restoration suggests that for the feature shown in Figure 28, the materials located 40 km from the terminal wall (location Y in Fig. 28), traveled only about 6 km. In some instances, plowing by oversized clasts can produce giant grooves that can have the appearance of linear channels. Figure 31 illustrates such a giant groove or channel, which seems to have formed by a single large clast that has eroded through the substrate and come to rest at the terminus of the groove.

Seismic Stratigraphic Expression of Internal Architecture

The seismic stratigraphic expression of mass-transport deposits can vary from transparent to chaotic, and less commonly to convolute reflection architecture, in both transverse view and plan view (Fig. 32). This seismic stratigraphic response suggests a mass-flow rheology commonly characterized by little organized macrofabric, which is typical of debrite deposits. In transverse view, mass-transport deposits are characterized by transparent to chaotic seismic reflections. Mass-transport deposits commonly amalgamate, although surfaces between successive mass-transport deposits can be obscure and difficult to recognize, due to erosion and or similar superposed lithologies.

Internally, mass-transport deposits commonly are characterized by compressional structures near their termini as discussed above. Low-angle thrust faults (commonly dipping at ~ 15°), characterized by listric curvature, originate at the base and extend through to the top of the deposit and can be common features (Figs. 8, 10, 30, 33). These thrust faults are expressed near the upper surface of the deposit as arcuate fault traces, oriented

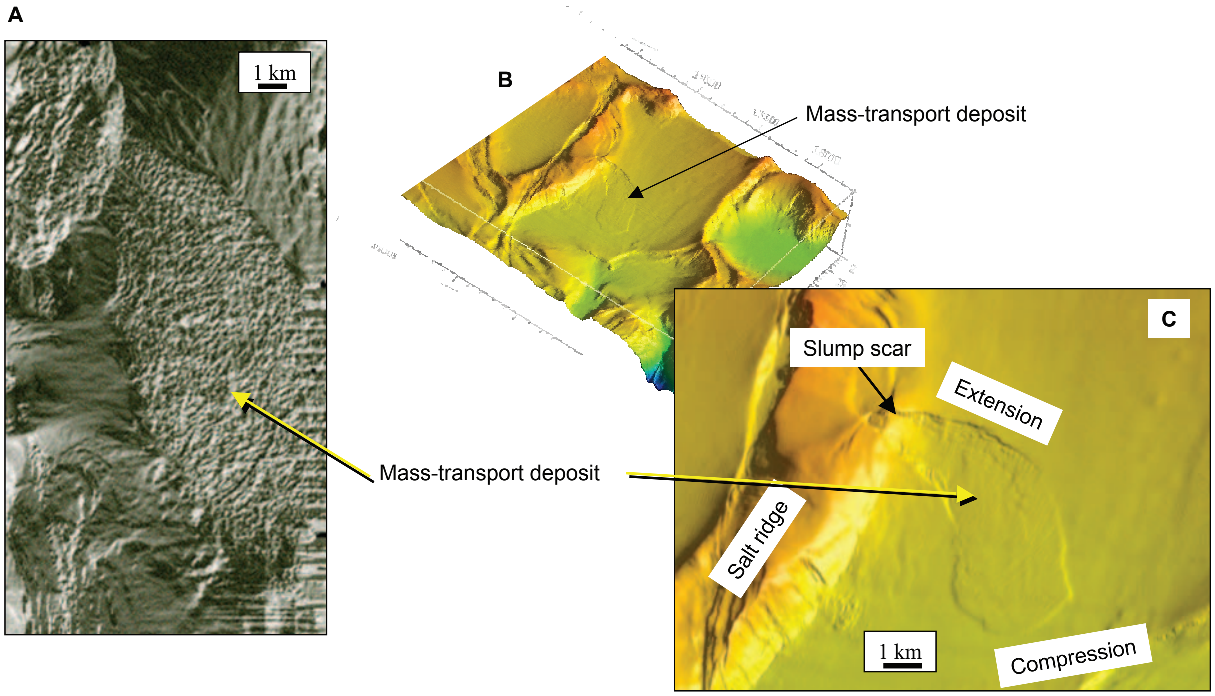


FIG. 22.—Intermediate-sized, intra-basinal, mass-transport deposits associated with **A)** a mud diapir, and **B**, **C)** a salt ridge. The water depth in Part A and in Parts B and C is approximately 1500 m. Part A is a dip azimuth map that illustrates pseudo bathymetry, and Parts B and C show shaded bathymetry and illuminated seafloor image (image courtesy of J.D. Stephenson).

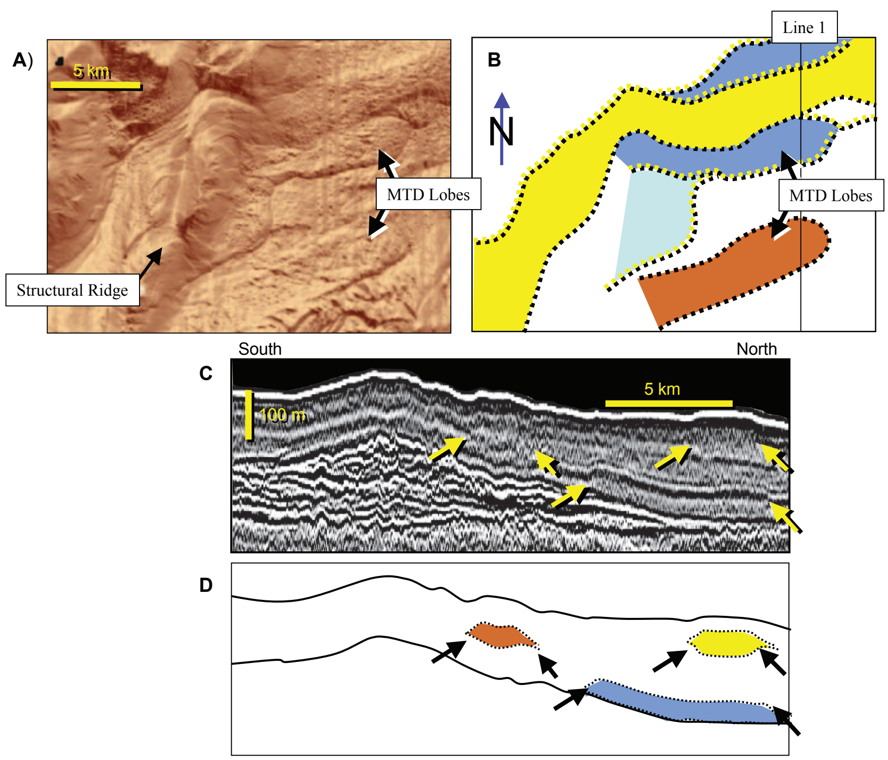
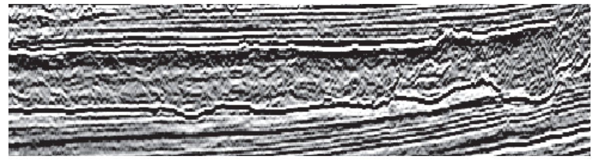
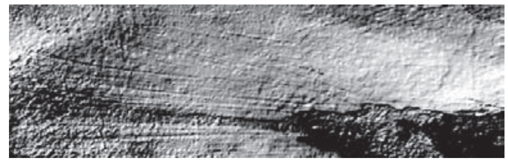
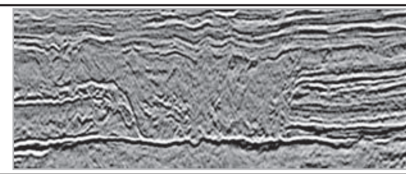
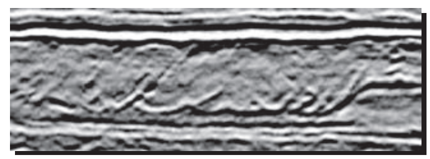
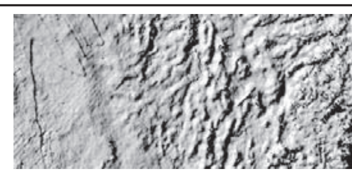
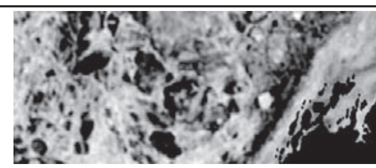


FIG. 23.— **A)** Dip azimuth display illustrating pseudo-bathymetry of the seafloor in the Makassar Strait, Indonesia, and **B)** complementary line diagram showing elongate mass-transport deposits. **C, D)** associated cross-sectional views of the deep-water, mass-transport deposits delineated with arrows in Part A. Water depth is approximately 1500 m. Mass-transport deposits lie at various levels in the substrate and are subsequently draped by hemipelagic and pelagic sediments, which preserve their positive relief. Note the relatively steepsided margins of these deposits (after Posamentier and Walker, 2006).

TABLE 1.—Seismic stratigraphic recognition criteria for mass-transport deposits

Internal chaotic to transparent seismic reflection character (see Figs. 32 and 33)	
Basal grooving and/or deep erosional scour (see Figs. 35-38)	
Plowing of sea-floor substrate resulting in nearly vertical erosional lateral margins (see Fig. 28)	
Presence of compressional thrust faulting (commonly ~ 15°) either near the flow terminus or lateral to the flow (see Figs. 5, 8, 10, 29, 30, 33 and 34)	
Irregular hummocks to featureless at upper boundary (see Figs. 22 and 26)	
Presence of discrete “clasts” within flow (see Figs. 17 and 31)	

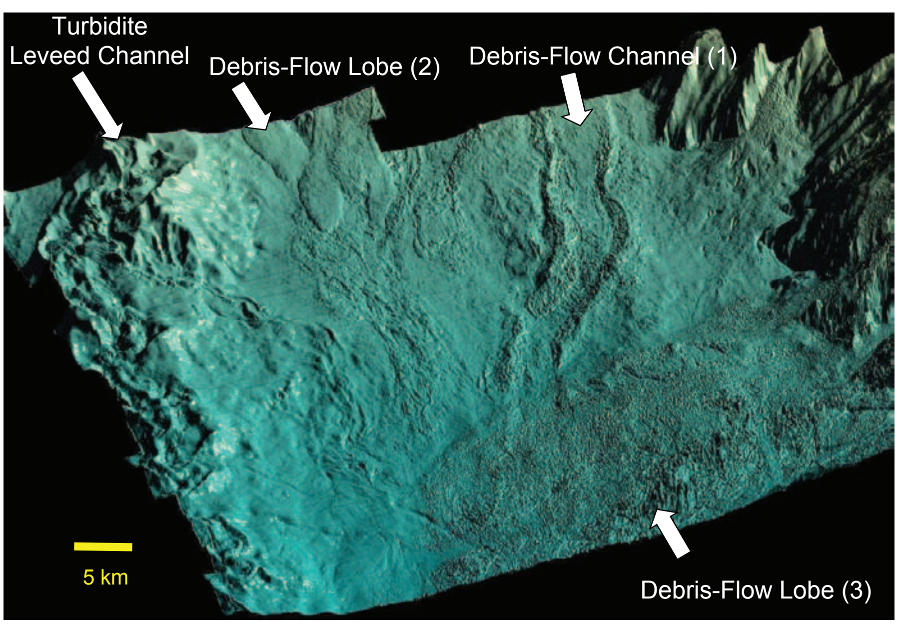


FIG. 24.—Seafloor physiography of the proximal basin floor in the northeastern deep Gulf of Mexico. Three types of mass-transport deposits are observed here: a debris-flow, leveed-channel deposit (1), a steepsided, mass-transport lobe (2), and a “deflated” mass-transport lobe (3), characterized by a gently tapering margin. Water depth is approximately 2000 m, and north is to the right (after Posamentier and Walker, 2006).

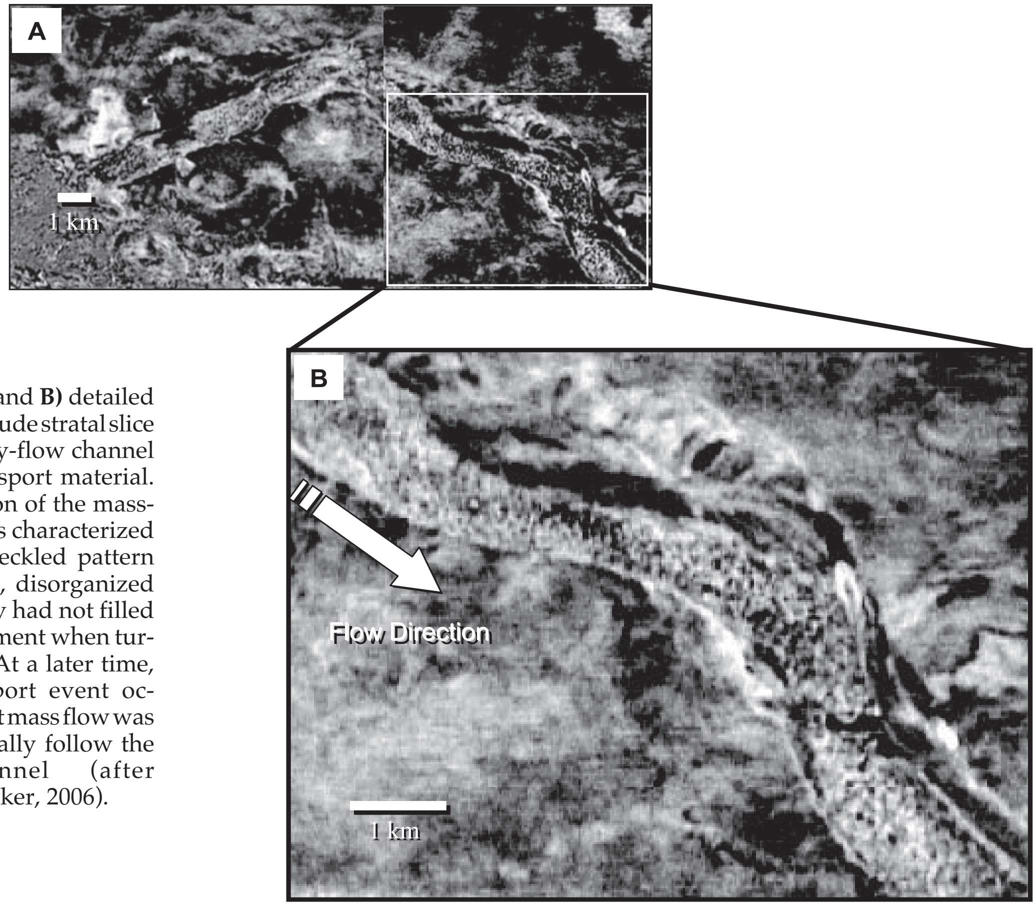


FIG. 25.—**A)** Broad-scale and **B)** detailed view of seismic amplitude stratal slice illustrating a turbidity-flow channel filled with mass-transport material. The seismic expression of the mass-transport sediments is characterized by a distinctively speckled pattern suggestive of chaotic, disorganized fill. The channel likely had not filled completely with sediment when turbidity flows ceased. At a later time, when a mass-transport event occurred, the subsequent mass flow was able to opportunistically follow the pre-existing channel (after Posamentier and Walker, 2006).

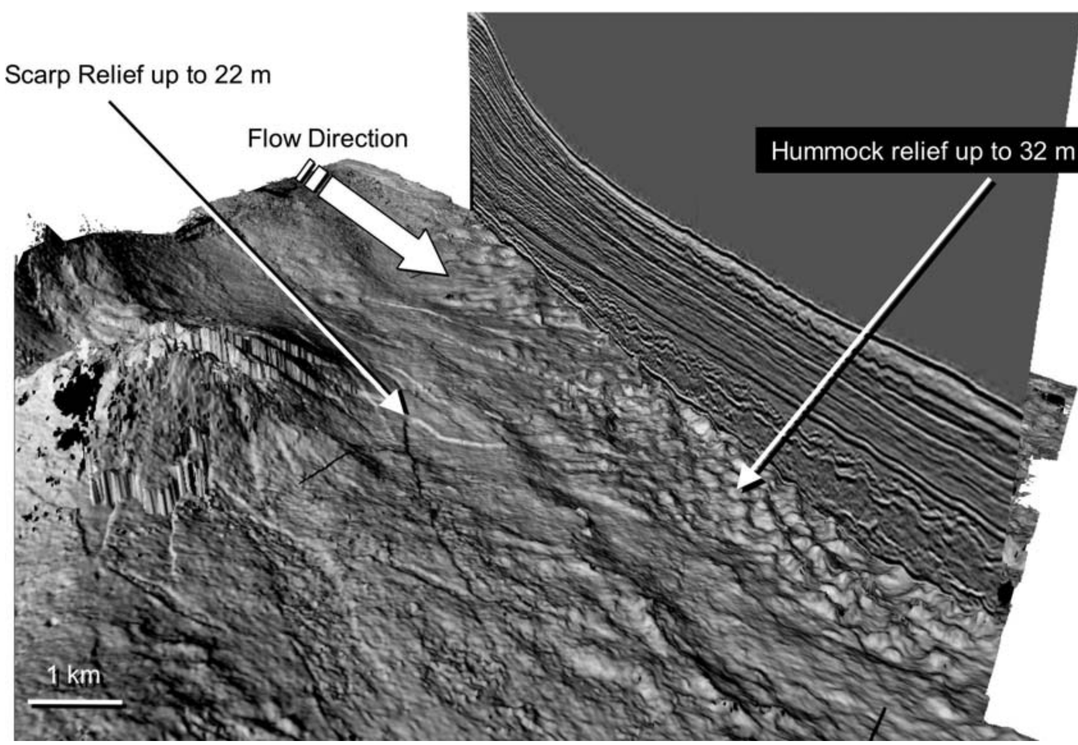


FIG. 26.—Seismic amplitude profile and extracted illuminated surface characterized by rugosity at top of a mass-transport deposit, northeastern Gulf of Mexico. The relief on these hummocks ranges up to 35 m. Note that the high degree of rugosity is somewhat localized and does not characterize the entire mass-transport deposit. It is unclear whether these deposits comprise a single mass-transport event or an amalgamation of multiple events (after Posamentier and Walker, 2006).

FIG. 27.—Outcrop photograph showing the rugose top of mass-transport deposits of the Ross Slide in Upper Carboniferous strata, County Clare, western Ireland. Note change in deformational style from near to far outcrop (lower left to upper right) of the mass-transport deposit where it appears as a debris-flow deposit (debrite) with extensive internal deformation in the near view and a slide in the back view with only little internal deformation. This rapid change of deformational style in mass-transport deposits is to be expected and shows that mass-transport deposits are part of a continuum of deposits formed by changing processes (see also Fig. 3), depending on internal strain and local factors. Person for scale in foreground.

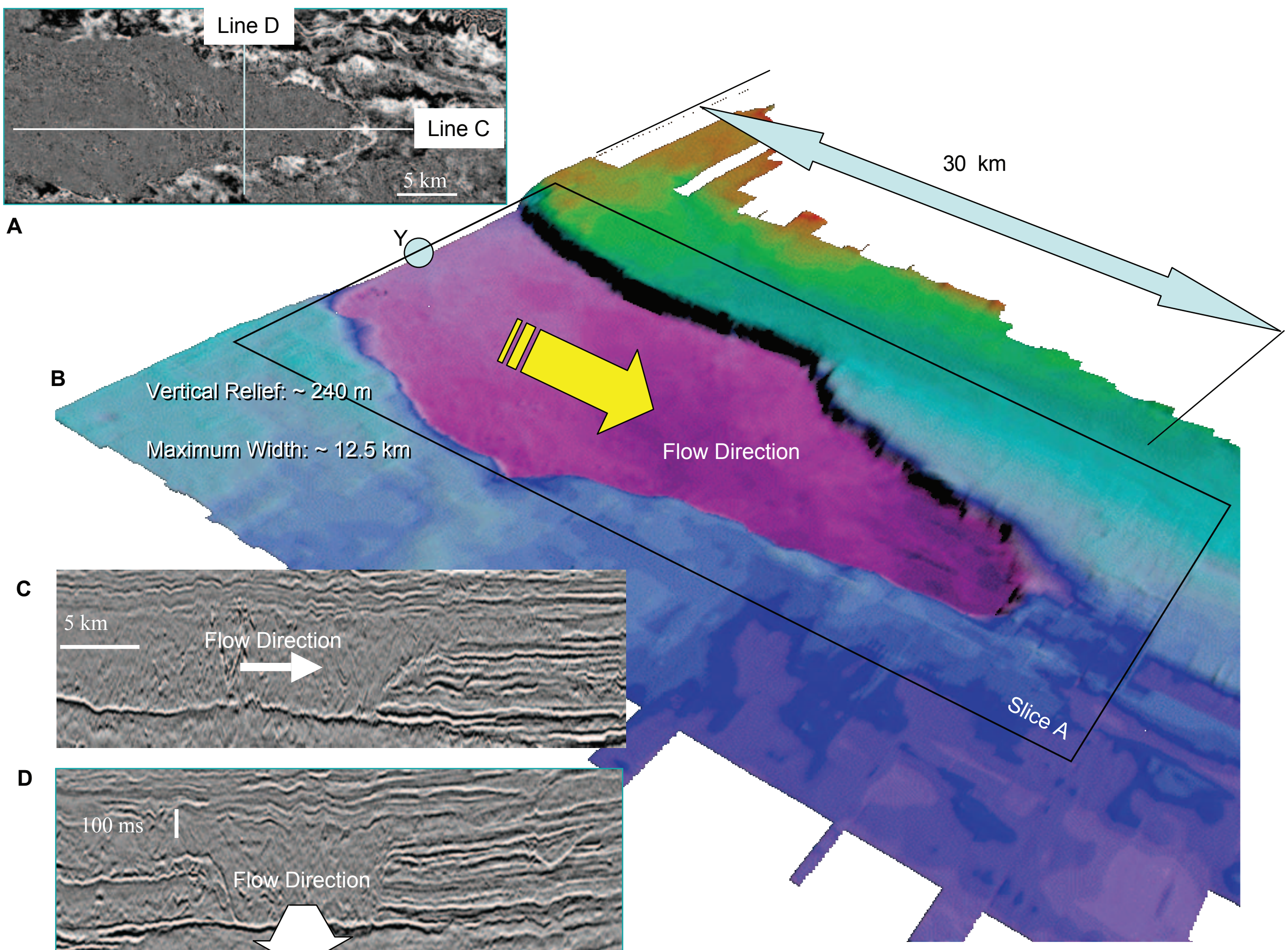


FIG. 28.—Four views of a mass-transport deposit filling a "trench", northeastern Gulf of Mexico. **A)** Seismic amplitude stratal slice illustrating lobe-like plan view. **B)** 3-D perspective view of base of mass-transport deposits and associated adjacent surface. C, D) Two seismic amplitude sections showing longitudinal **C)** and transverse **D)** sections. This trench and associated mass-transport fill terminate abruptly against a headwall or terminal wall at the distal end. The trench is characterized by nearly vertical walls approximately 240 m high, formed by shearing processes, associated with this mass-transport deposit. The location of this feature is on the basin floor approximately 100 km outboard of the base of slope (after Posamentier and Walker, 2006).

transverse to flow direction (Figs. 8, 10, 30, 33; Prior et al., 1984; Brami et al., 2000; Posamentier and Kolla, 2003). In some instances, successive flows can result in laterally directed compression as illustrated in Figure 34.

Erosion Associated with Mass-Transport Deposition

Erosional scour is a common characteristic of mass-transport deposits. Erosion can be expressed in the form of long linear grooves or striations at the base of a mass-transport deposit. The scale of such grooves can range up to 750 m wide and up to 50 m deep (Fig. 35) and can extend for tens of kilometers. Basal grooves can be observed at the bases of mass-transport lobes as well as channels (Fig. 36; Posamentier and Kolla, 2003). Occasionally, outrunner blocks with associated

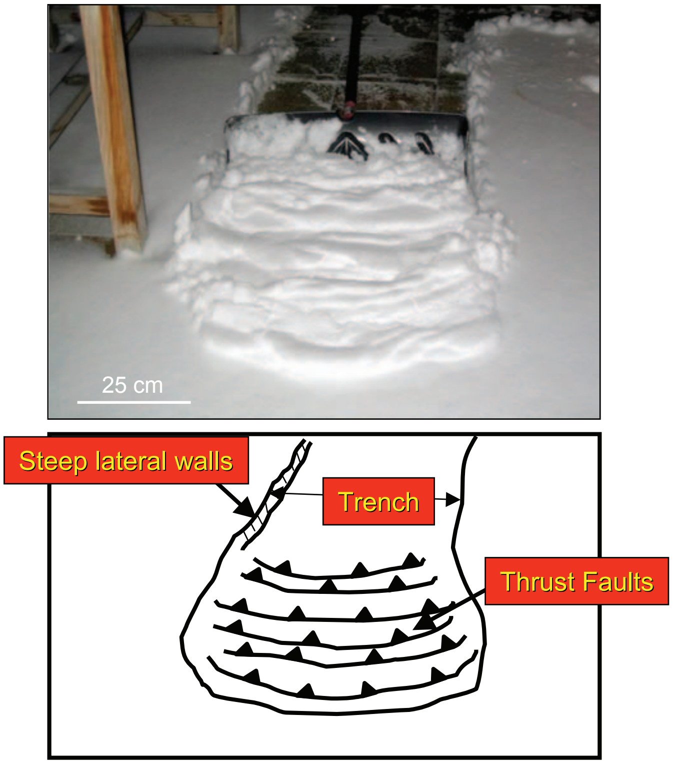


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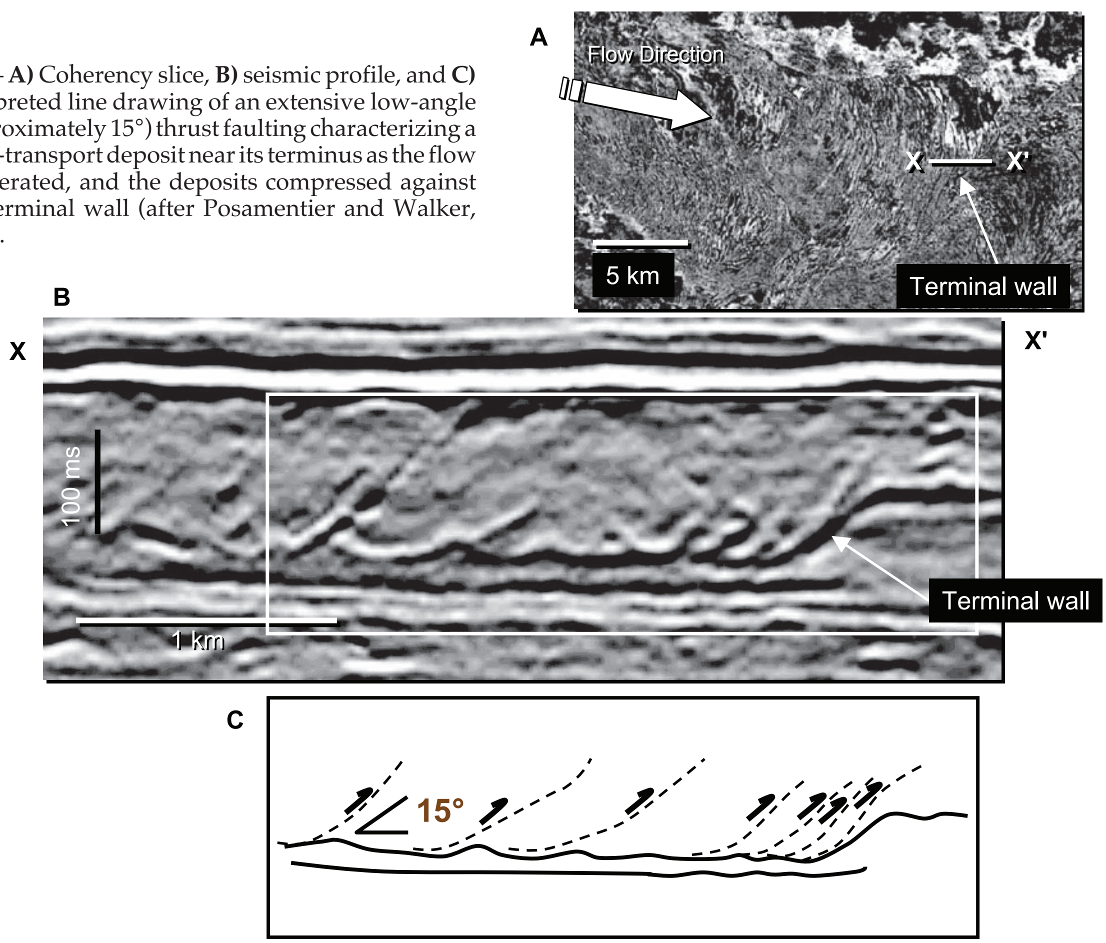
FIG. 29.—Small-scale analog for trench formation and associated deposition of mass-transport deposits in deepwater basinal settings. Snow shovel pushing a cohesive snow pack produces arcuate thrust faults at the snout and steep shear walls on either side, forming a trench. Note that in contrast with this example, where an open trench forms behind the shovel, in deep-water settings where trenching or plowing occurs, no open trench exists; rather, the role of the shovel is analogous to the mass of sediment that has moved from the slope inboard to this more distal location (after Posamentier and Walker, 2006).

FIG. 30.— **A)** Coherency slice, **B)** seismic profile, and **C)** interpreted line drawing of an extensive low-angle (approximately 15°) thrust faulting characterizing a mass-transport deposit near its terminus as the flow decelerated, and the deposits compressed against the terminal wall (after Posamentier and Walker, 2006).



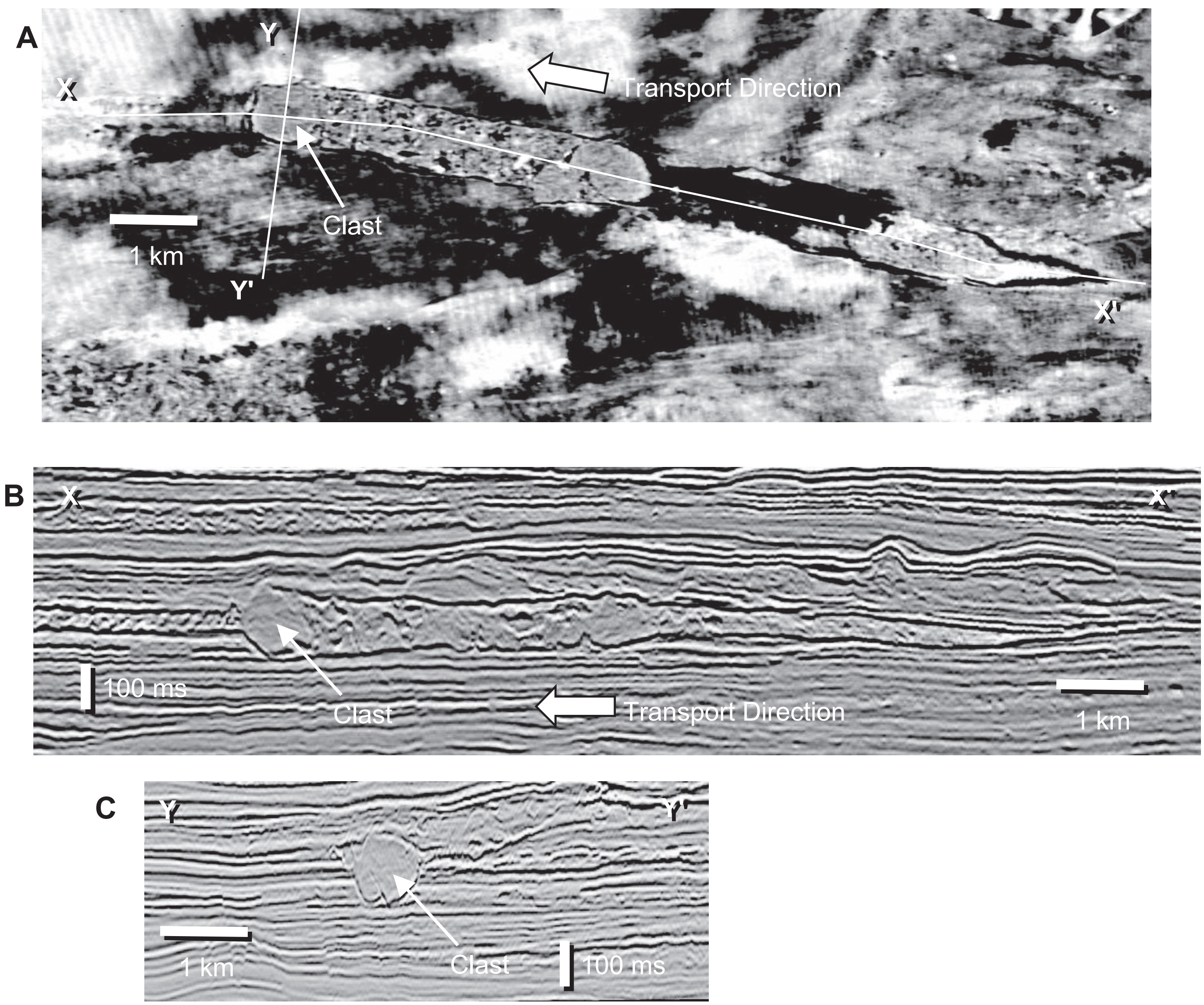
groove tracks occur, such as described by Prior et al. (1984) and Nissen et al. (1999) (Fig. 37).

The striking linearity of grooves that are commonly observed at the bases of mass-transport deposits form because of the laminar rather than turbulent flow that characterizes these flows. In the absence of turbulence, tools capable of scouring the substrate tend to have relatively long residence time at the bases of flows. Consequently, tools stay at the base and scour the substrate as the flow moves downslope, until such time as internal faulting carries them upwards into the flow or until they break up as a result of interactions with the substrate.

The erosive power of mass-transport events can be observed in Figures 32, 36, and 38, where erosion depth of as much as 80 m can be documented. The effectiveness of a mass-transport event to erode the substrate is a function of: (1) degree of substrate induration; (2) competency of intra-mass-transport clasts (i.e., erosive "tools") to withstand breaking apart during transport; (3) velocity of the flow; and (4) volume of the flow.

Slope to Basin-Floor Transition

The transition from slope to basin-floor settings in some instances can be characterized by a transition from erosion, characterized by deep grooves and scour, to deep plowing of the substrate (Fig. 39). The location of this transition seems to be where the rate of gradient change is maximum and nominally marks the basin-floor margin, near the base of slope. At this location, stress vectors are directed into the substrate at a higher angle than locations either on the marine slope or farther out on the basin floor. When this condition occurs, a decollément surface



IG. 31.— **A)** Coherency slice, and **B, C)** seismic profiles showing a deep groove in a deep-water slope setting. This groove was formed by erosion of the substrate by a massive clast measuring approximately 100 m high and 800 m wide. The clast itself came to rest at the end of the groove and can be observed in section view B, C) as well as plan view (A) (seismic data courtesy of Western Geophysical).

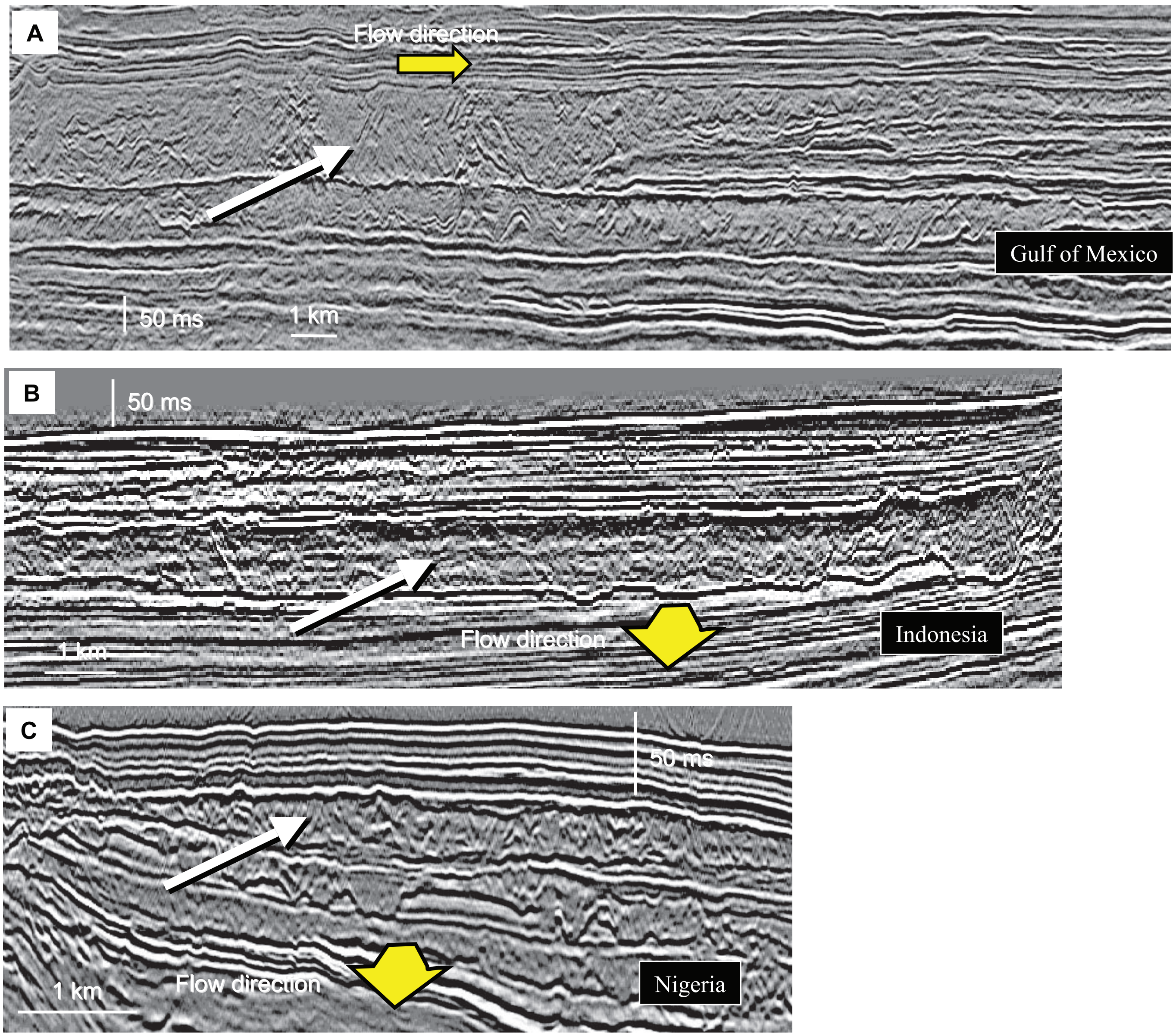


FIG. 32 (above and on facing page).—Internal seismic stratigraphic expression of mass-transport deposits (as indicated with white arrows) ranging from transparent **E)** and chaotic **A, B, C**, and **D)** to convolute **F)** as observed in both in transverse view (A, B, C) and plan view (D, E, F). Note the variable erosion that characterizes the base of these deposits in Parts A, B, and C) (after Posamentier and Walker, 2006).

can form in the substrate and result in formation of a trench or channel-form physiography (Figs. 28, 34, 39).

DISCUSSION

In many deep-water settings, mass-transport deposits comprise a significant percentage of the stratigraphic section. In outcropping sections, such as in the Gull Island Formation of western Ireland (Martinsen, 1987; Martinsen, et al., 2000; Martinsen et al., 2003), more than 75% of slope strata are affected by mass-movement processes. Posamentier and Walker (2006) estimate that within the Miocene to Recent of the eastern Gulf of Mexico mass-transport deposits constitute in excess of 50% of the entire section. Moreover, this estimate may be low, inasmuch as seismic resolution may be unable to detect finer-scale mass-movement processes. The staging area for much of this sediment is the mid- to upper slope, and as such contains significant amounts of mud, common to those physiographic settings. Presence of mud in the flow can provide cohesion to limit degree of transformation from laminar to turbulent flow. Routine presence of a mud matrix within such deposits in these settings suggests that these mass-transport deposits are excellent petroleum seals and poor reservoirs for hydrocarbon accumulations.

Mass-transport deposits can be observed at a variety of scales. These scales range from detailed outcrops, where millimeter- to centimeter-size features can be readily examined to regional seismic scales, where larger features greater than 100 m thick can be observed. Each type of data can image deposits and recognize

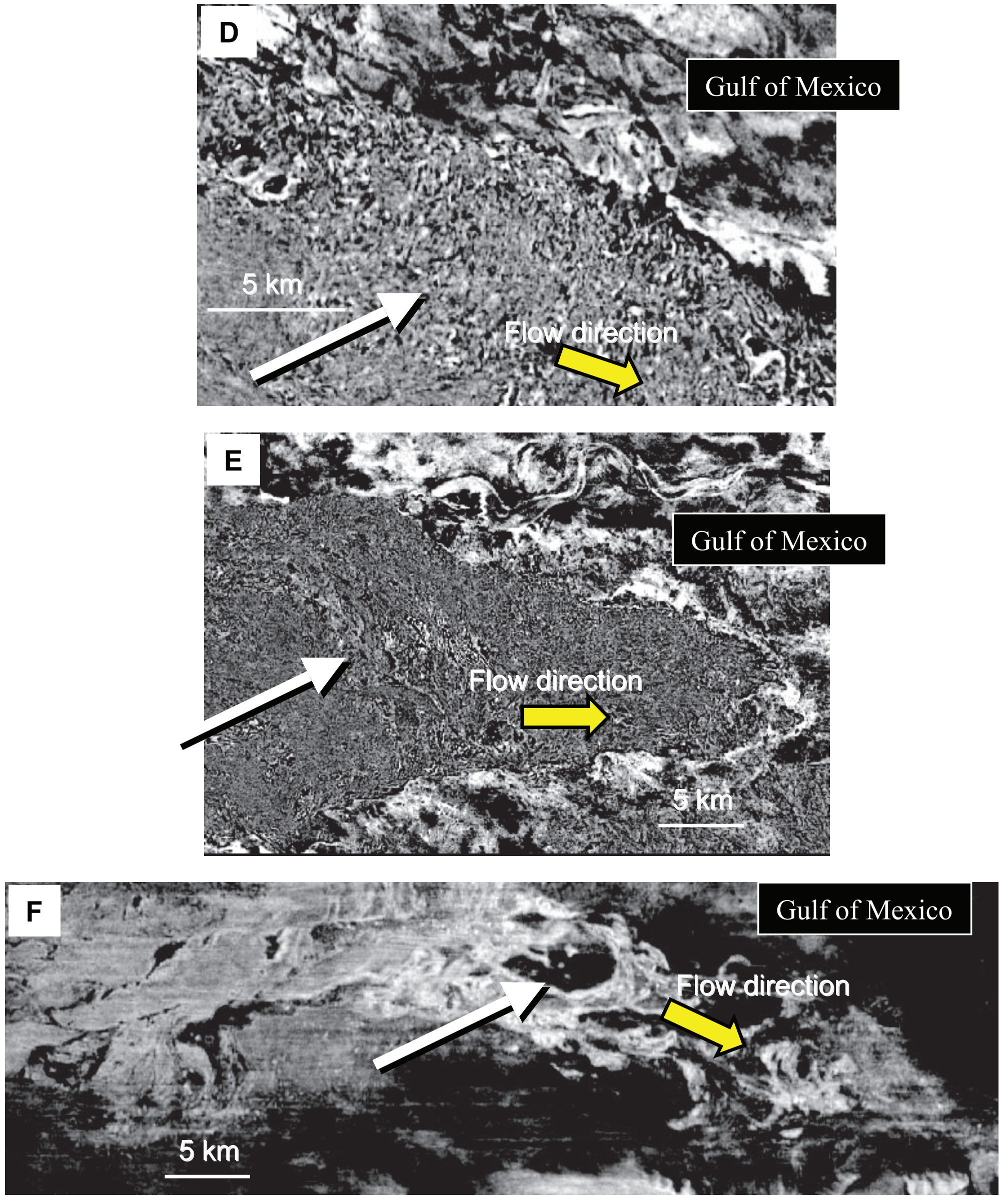


FIG. 32 (continued).—

processes at certain scales. Generally, outcrop data can yield different and more detailed analyses of mass-transport processes, which usually are not available on seismic data except in special settings. However, seismic data (especially 3D seismic data sets) can afford analysis of plan-view morphology as well as broad-scale stratigraphic architecture in ways that cannot be done with outcrop data, and therefore can complement inferences drawn from outcrop data. Broader-scale processes, such as erosion and internal structural deformation, can be more readily discerned using seismic data. Consequently, our understanding of both processes and products associated with mass transport is derived through integration of both outcrop-scale and seismic-scale observations.

Mass-transport processes are a response to slope instability, regardless of scale. In principle, instability can occur at any time; however, there are certain circumstances when instability is a more common occurrence. On a regional scale, instability of the shelf and slope generally tends to preferentially favor relative lowstands of sea level. This preference occurs for several reasons. When sea level falls, wave base is lowered and can directly impact the outer shelf and upper slope, two locations that commonly serve as the zone of initiation for many mass-transport deposits. Wave action has the affect of altering equilibrium conditions in those settings, resulting in potential for mass-transport events to occur. During relative lowstands of sea level, marginal marine depocenters shift towards the outer shelf in association with the process of forced regression (Posamentier et al., 1992). Rates of sedimentation at the outer shelf and upper slope are greatest, again potentially creating disequilibrium conditions and slope failure (associated with oversteepening and loading of the upper slope). Also during sea-level lowstands, dissociation of clathrates due to depressurization in the

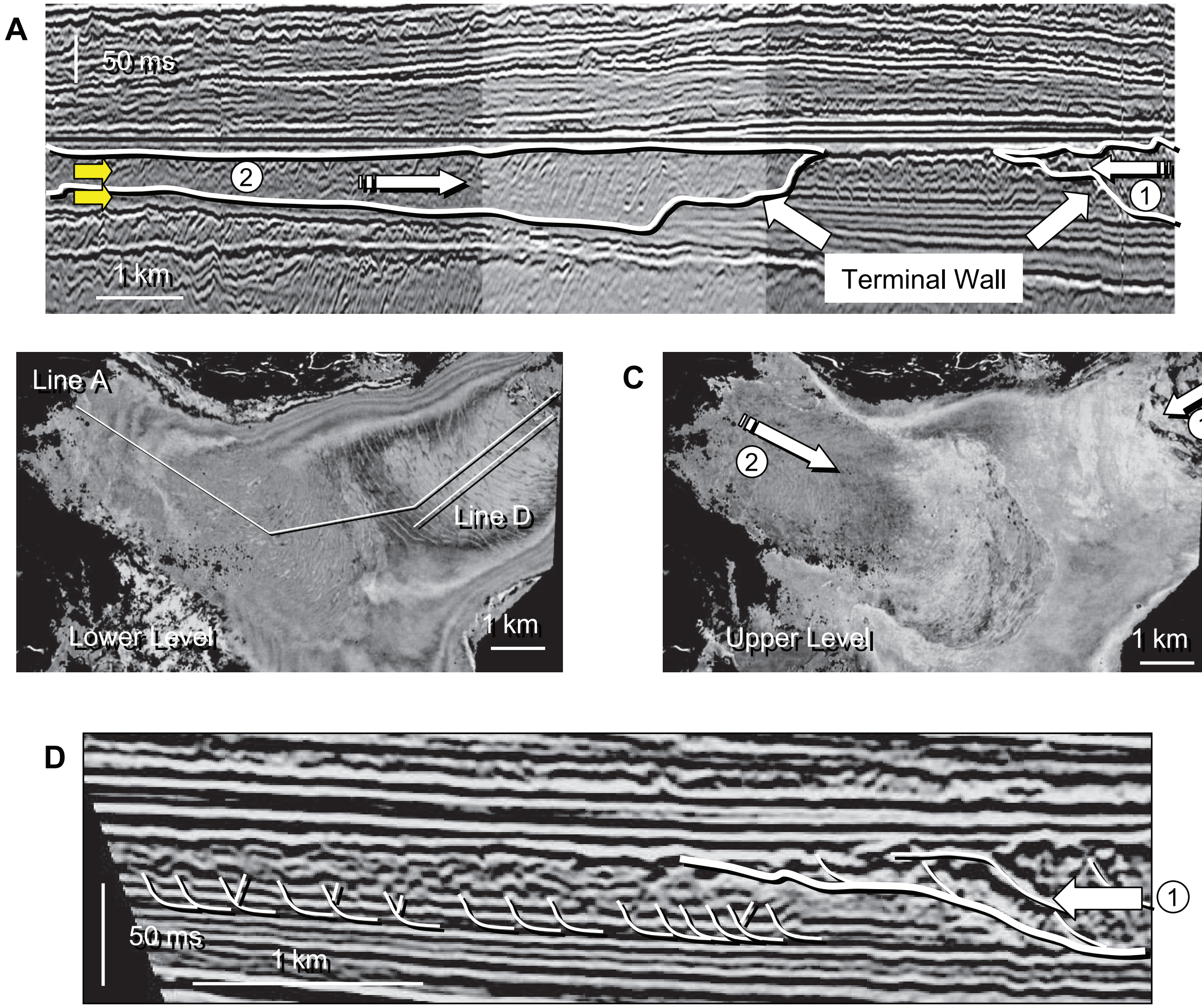


FIG. 33.—Transverse and strata slice seismic amplitude sections illustrating thrust faults in two mass-transport deposits feeding a small minibasin in the Gulf of Mexico. Note the trench-filling style of mass-movement deposits **A)**. Note also the thrust faults associated with underlying substrate **D)** distal to the snout of the mass-transport deposits coming from the northeast (i.e., mass-transport deposit labeled "1") in Parts **B and C**. This pattern suggests that the mass-flow event lost momentum before it could effectively increase in downslope underlying substrate (after Posamentier and Walker, 2006).

near-subsurface section has been tied to slope instability and hence slope failure (Carpenter, 1987; Maslin et al., 1998; Maslin et al., 2004).

From a petroleum-exploration perspective, mass-transport deposits can serve as seal, reservoir, or possibly even source rock under appropriate conditions. A variety of factors must be taken into consideration for the final grain size of the deposit and its potential as a reservoir, such as: (1) provenance or staging area of the mass-transport deposits; (2) lithology of the substrate over which the mass flow travels; (3) degree to which the mass flow plucks or plows through the substrate it is passing across; (4) degree to which the mass-transport deposits has disaggregated (i.e., debris flow vs. slide); and (5) degree to which the flow is characterized by coherent faults. Much depends on where the flow originated—i.e., the staging area. If the flow originated on the middle slope, commonly the site of predominantly mud deposition, then the resulting mass-transport deposit will likely be mud rich. As such, these mass-transport deposits would constitute excellent seals (Algar et al., this volume). If a mass-transport deposit originates at the shelf edge and is able to cannibalize previously deposited shelf-edge, sand-rich deposits, then the resulting mass-transport deposit may contain varying amounts of sand and may constitute a poor seal and may even be considered reservoir. The degree to which the original sand-rich deposits disaggregate or are deformed determines the continuity and hence reservoir quality of these deposits.

Under certain circumstances, mass movements that originate in mud-rich middle-slope settings can incorporate sand into the flowing mass as it travels. If a mud-rich flow passes over a sand-rich substrate, then the degree to which the flow can scour that substrate plays a role in determining the mass-transport deposit reservoir-versus-seal characteristics. In most

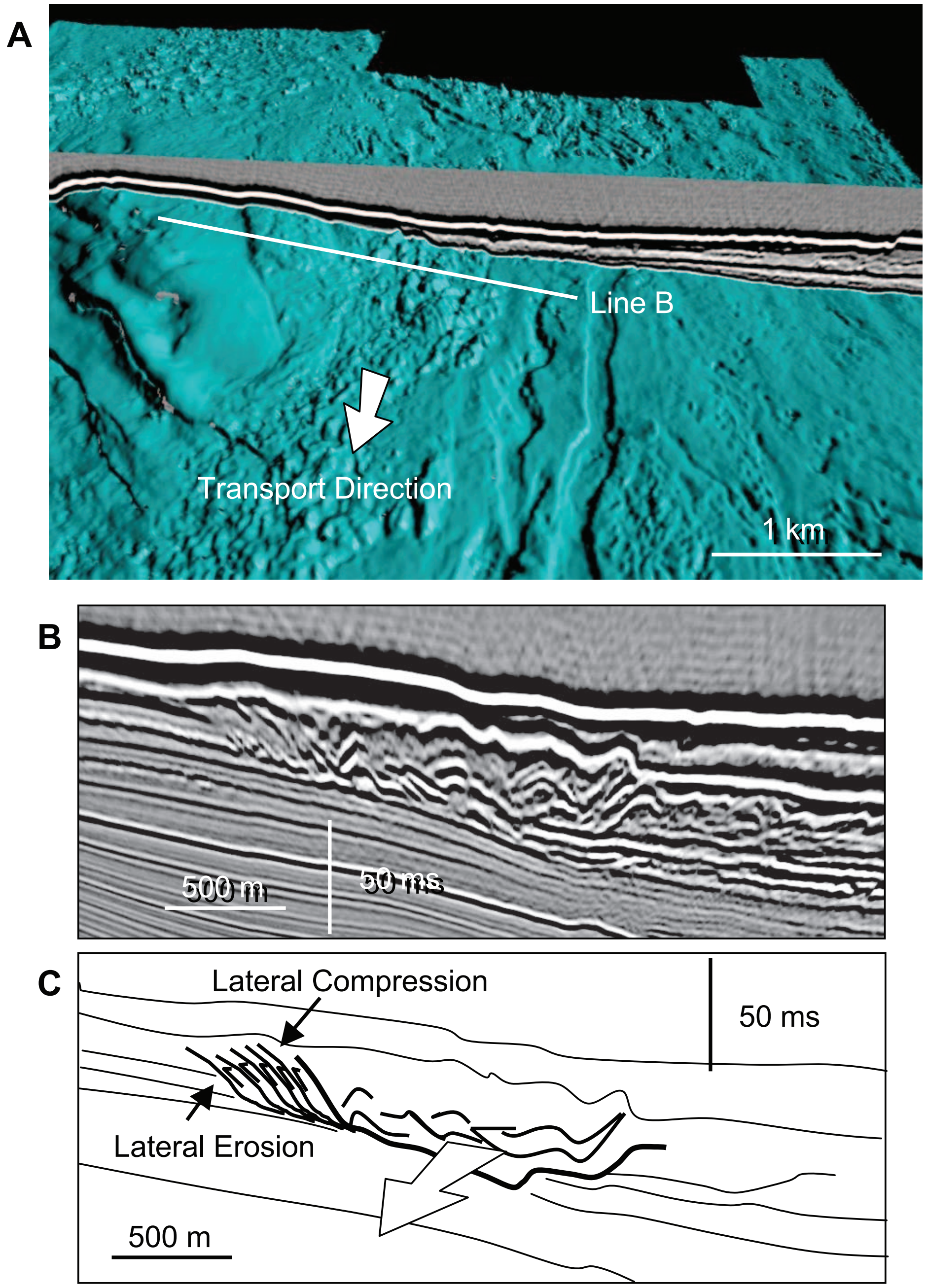


FIG. 34.—**A)** Illuminated horizon and **B)** transverse seismic amplitude section with **C)** complementary interpreted section, illustrating lateral compression in the form of low-angle thrust faults on the lateral margin of a mass-transport deposit. Flow is towards the front of the image. Note erosion that characterizes the margins of this mass-transport deposit (after Posamentier and Walker, 2006).

instances, even those mass-transport deposits that have incorporated substantial amounts of sand likely constitute poor reservoir because of the lack of stratigraphic continuity of these sand beds, a characteristic commonly associated with mass-transport deposits, and possible interspersed clay. Even slide deposits can lack significant stratigraphic continuity. Figure 10 illustrates a mass-transport deposit comprising a succession of thrusted, deep-water turbidite deposits that have largely remained intact. However, continuity is severely disrupted by multiple, low-angle thrust faults. From a seal perspective, such mass-transport deposits, characterized by poorly disaggregated sand deposits as well as through-going faults, would constitute relatively poor seals.

Future research into mass-transport deposits likely will focus on a variety of topics/questions, which include: (1) slurries and linked debrites—what do they tell us with regard to location within a mass-transport deposit and about the paleogeography of a mass-transport deposit; (2) role of mass-transport deposits in hydrocarbon exploration—under what circumstances can they comprise seal, reservoir, or source (i.e., what are the controlling

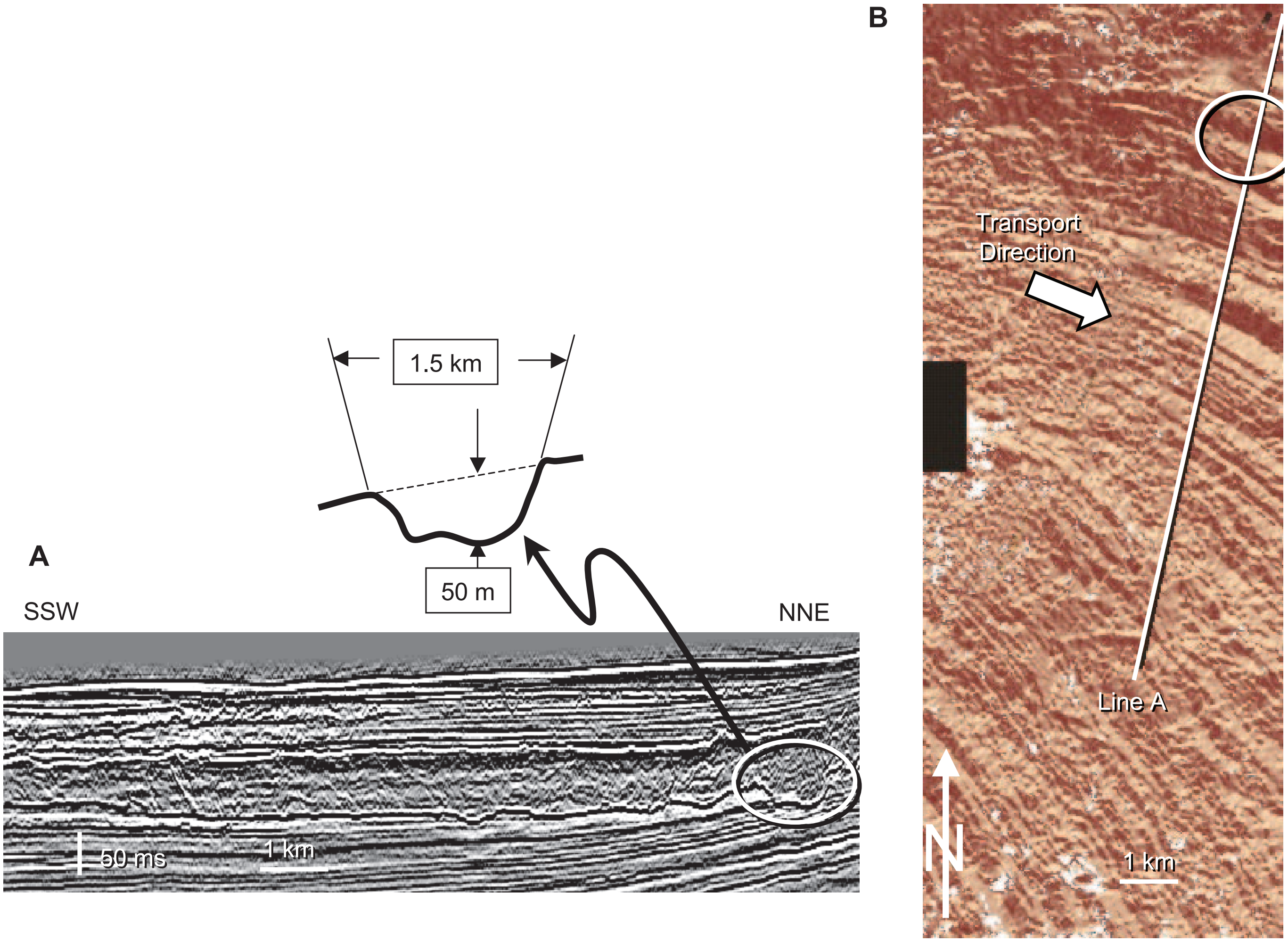


FIG. 35.—**A)** Transverse-view and **B)** plan-view expression of erosion at base of a mass-transport deposit. Note that numerous grooves cover the area and tend to diverge in the down-flow direction. These grooves range up to 1 km wide and up to 50 m deep. The image in Part B is a dip azimuth horizon attribute that yields a pseudo-relief map (after Posamentier and Walker, 2006).

parameters); (3) under what circumstances do mass flows plow versus hydroplane across underlying substrate; (4) under what circumstances does grooving of substrate occur; (5) what are the various triggers to mass-flow initiation (seismicity, upper-slope loading, presence of hydrates, etc.); (6) what physiographic setting favor mass-transport deposits; 6) linkage of borehole-scale to outcrop and seismic-scale characteristics of mass-transport deposits. In addition, future research will focus on documenting the broad variety of mass-transport deposits from the centimeter to the decimeter scale, using a variety of data types ranging from borehole logs to seismic data.

CONCLUSIONS

Mass-transport deposits are common features in deep-water environments. These deposits can be studied at a variety of scales, ranging from outcrop to reflection seismic data. The generic term *mass-transport deposit* includes a range of depositional processes, including creep, slide, slump, and debris flow, which form a continuum of deposits that is intergradational. Mass-transport deposits commonly are characterized by multiple process mechanisms at various points along their reach. Inferences regarding detailed mechanisms of flow are derived largely from outcrop studies, where analyses at the millimeter and centimeter scale are possible. Inferences regarding broader-scale processes and stratigraphic architecture and geomorphology are best analyzed using 3D seismic data.

The location where mass-transport deposits originate can be: (1) at or near the shelf edge; (2) the mid- to upper slope; and (3) locally, on the flanks of salt domes or mud volcanoes, or on the flanks of channel levees. Those flows that originate in the mid- to upper slope, in particular, are most likely to be mud prone, whereas those originating at the shelf edge may contain sand. However, even those deposits that originate at the shelf edge commonly have a mud matrix. From a petroleum-exploration perspective, mass-transport deposits commonly are characterized by poor reservoir quality, and hence constitute good to excellent seals.

The planform and internal stratigraphic architecture of mass-transport deposits can be quite variable. Internally, these deposits can range from completely disaggregated (i.e., debrites) to moderately deformed (i.e., slump deposits) to largely unde-

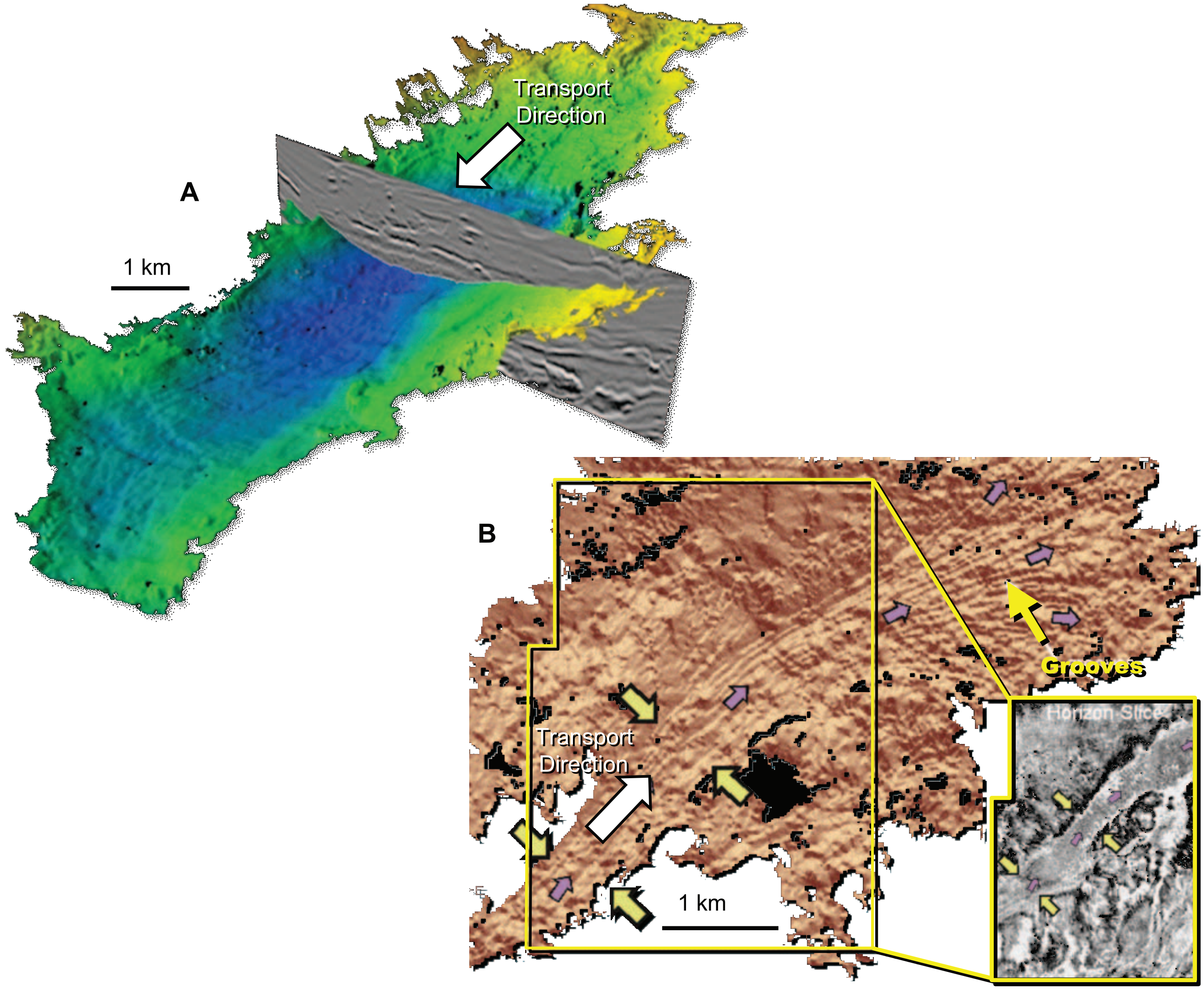


FIG. 36.— **A)** Illuminated horizon draped with time structure (warm colors denote bathymetric highs and cool colors bathymetric lows) and associated transverse seismic amplitude section illustrating basal grooves beneath mass-transport deposits within channels. **B)** Dip azimuth horizon attribute illustrating pseudo-relief illustrating basal grooves beneath a mass transport channel. Small inset represents a seismic amplitude stratal slice illustrating channelized morphology. Yellow arrows indicate margins of mass-transport channel; white and rose-colored arrows indicate transport direction (seismic data courtesy of Western Geophysical).

formed (i.e., slide or creep deposits). Extensional faulting commonly occurs in proximal updip areas, whereas compressional faulting commonly occurs in more distal downdip areas. Mass-transport deposits can occur as lobes, sheets, or channel fills. The external morphology of mass-transport deposits can range from rugose with relief in excess of 25 m to nearly featureless.

Another distinctive aspect of mass-transport deposits is the erosional scour that commonly can be observed at the basal contact. Long linear grooves can be formed through erosion by large clasts, or tools, occurring within the basal part of the flow. Such clasts remain in the basal part of the flow as a result of the laminar flow that characterizes these processes. A common aspect of large mass-transport deposits is the tendency to plow deep into the substrate just outboard of the base of slope. In those instances, these deposits take the form of the fill of large excavated trenches, characterized by detachment and shearing along the base and sides.

ACKNOWLEDGMENTS

The authors wish to acknowledge constructive reviews by David Hodgson, Mike Leibovitz, Craig Shipp, Mike Shultz, and Paul Weimer. These insightful reviews helped to bring clarity to this paper. We also acknowledge Chevron Energy Technology Company and StatoilNorskHydro for permission to publish this paper. Furthermore, we thank Ven Kolla, Morgan Sullivan, Andrea Fildani, Julian Clark, Bill Arnott, and Brian Romans for stimulating discussions from which we have greatly benefited.

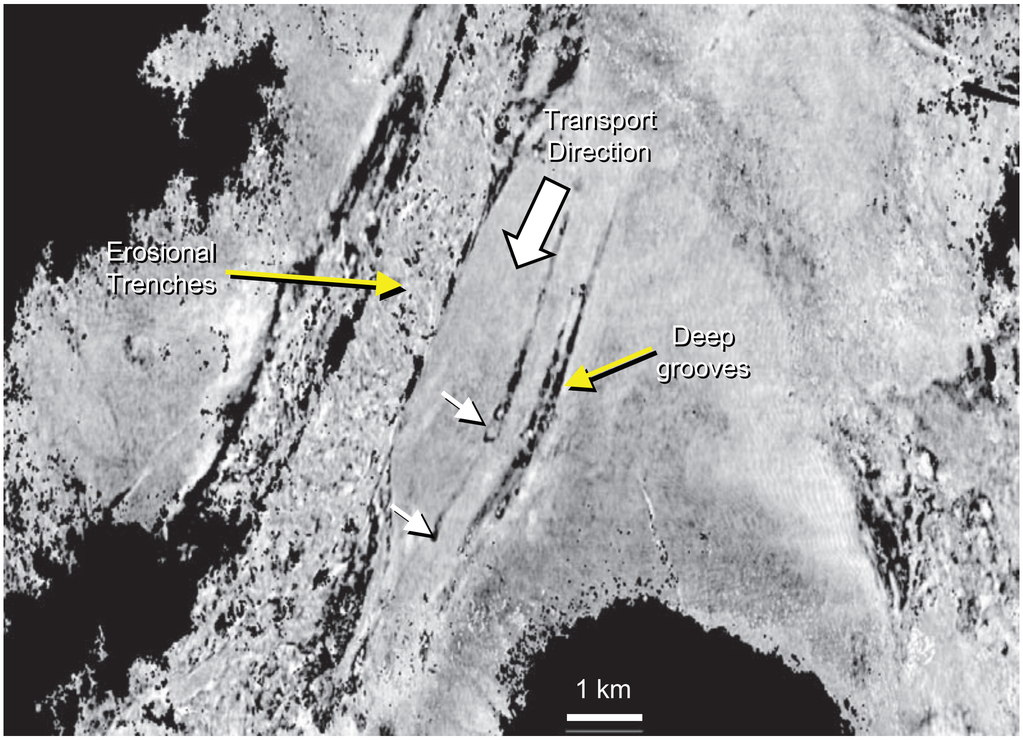


FIG. 37.—Seismic amplitude stratal slice illustrating outrunner blocks and associated grooves illustrated in plan view. Small white arrows indicate outrunner blocks; yellow arrows indicate erosional grooves and trenches (seismic data courtesy of Western Geophysical).

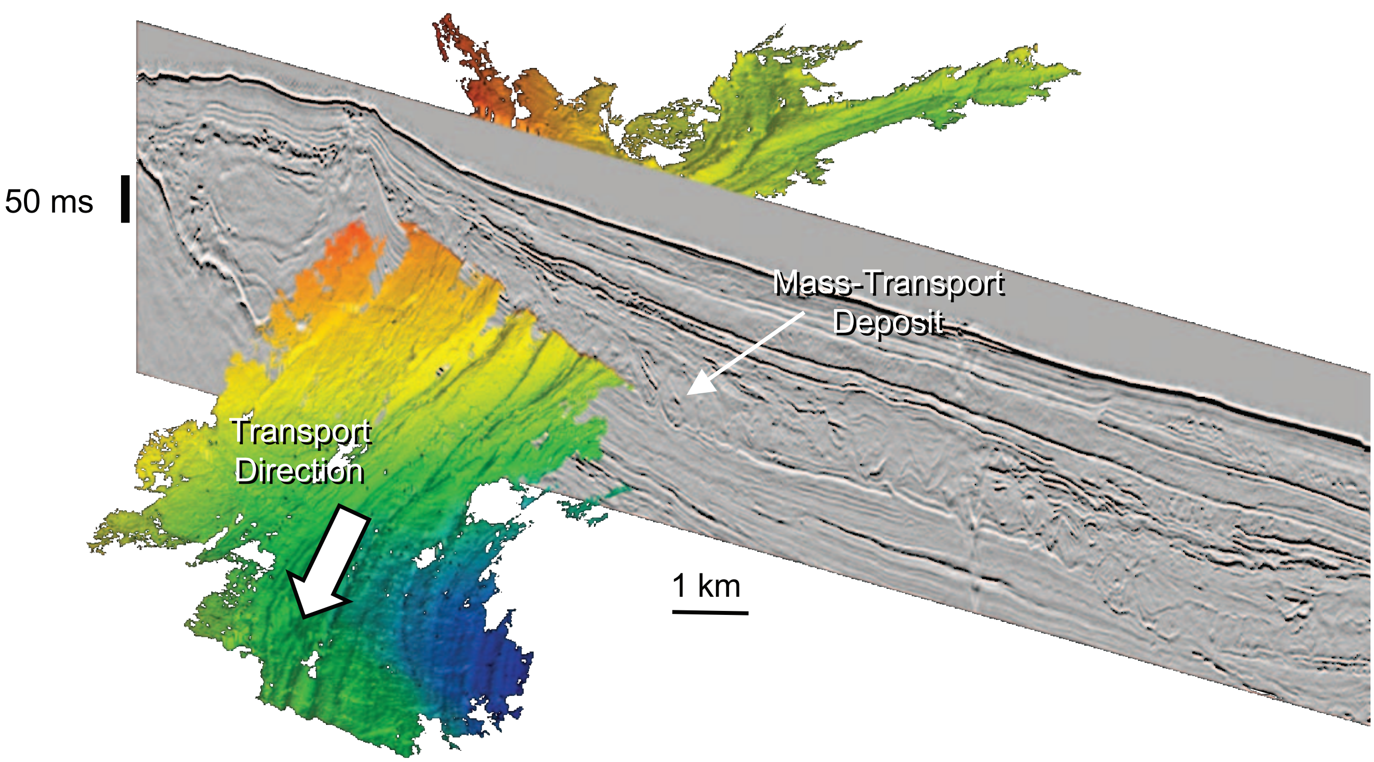


FIG. 38.—Illuminated horizon with time structure overlaid (warm colors indicate bathymetric highs and cool colors indicate bathymetric lows), with associated transverse seismic amplitude section, illustrating deep erosional scour at the base of a mass-transport deposit (seismic data are courtesy of Western Geophysical).

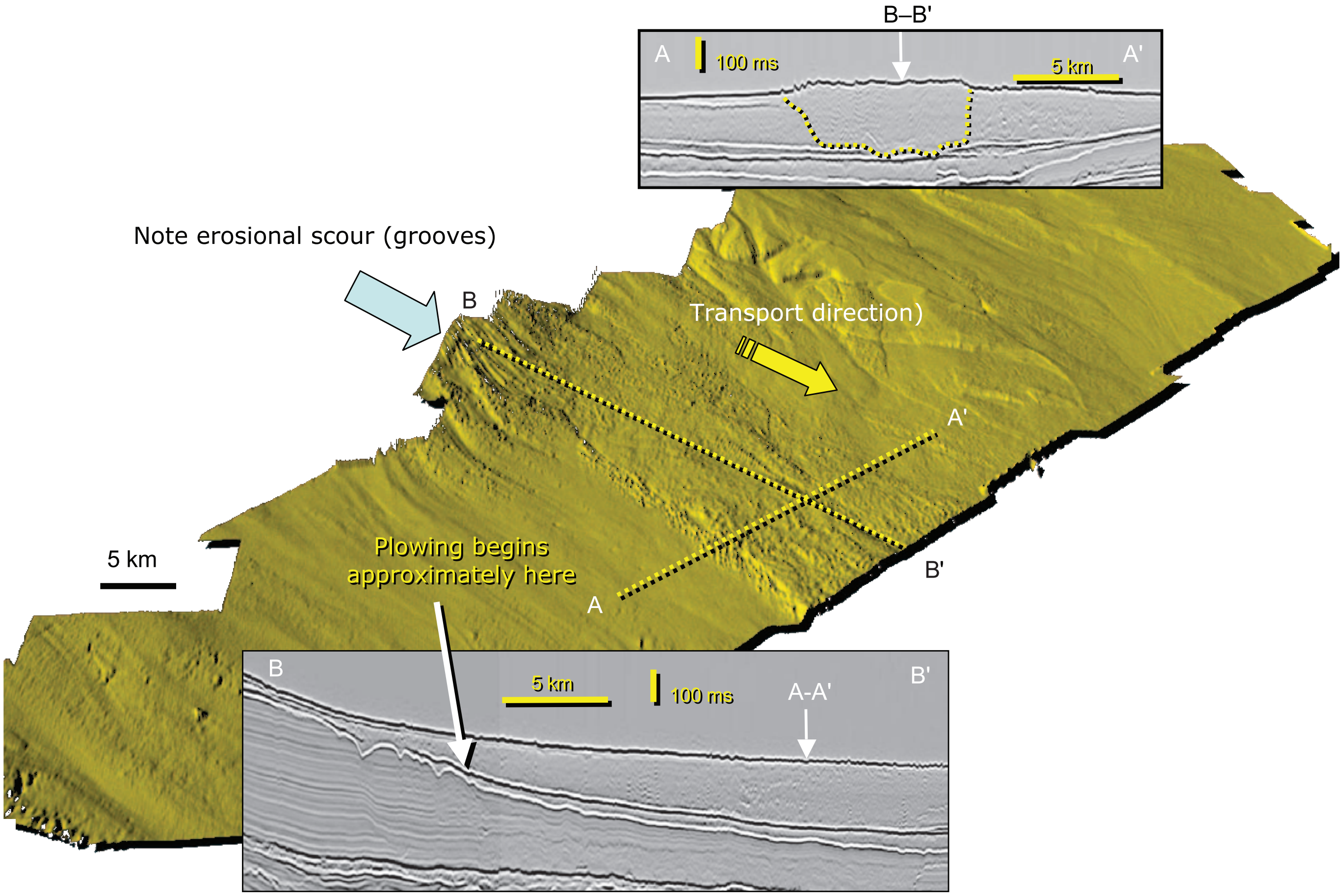


FIG. 39.—Illuminated horizon along with associated (A–A′) transverse and (B–B′) longitudinal seismic amplitude sections illustrating mass-transport deposits in a slope setting. The proximal part is characterized largely by bypass and erosional grooving, whereas the distal part by trenching and deposition (image courtesy of R. Lawrence).

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John Southard questions

Text:

(1) p. 1: Slashes used in this way are usually ambiguous in meaning: does it stand for *and*, *or*, *and/or*, *to*, or something else? The reader should not have to guess at your meaning. Try to reword this to eliminate the slash. (RTC I have highlighted other instances as well.)

(2) p. 6: Is this the same as the 2006 item in the list of references?

(3) p. 12: You don't need to use the future tense in a construction like this, because you are dealing with a "timeless" process. The present tense is better, stylistically. (But we are not insisting.)

(4) p. 13: I am not sure whether you mean *channel* to modify *levee* (the walls of a channel levee) or the walls of a combined feature that involves both a channel and its levees), in which case we would use an "en" (short) dash (–) to indicate that.

(5) p. 26: … *physiographic settings favor* … , or … *physiographic setting favors* … ?

(6) fig 4 caption: This "sentence" has two main verbs: *note* and *is*. It needs to be rewritten somehow. One way would be as … *Note that the* … , but that might not be what you mean.

(7) fig 39 caption: Bob: Use the "prime" symbol (′) rather than the apostrophe. (RTC, DONE)

References:

Bakken 1987; Fisher and Smith 1991; Kruit et al. 1975; Middleton and Southard 1978: Supply the number of pages.

Carpenter 1987: Supply the series number.

Pierson and Costa 1987: Shouldn't there be a volume number and a page range here?

Seed 1968: Check the name of the periodical (Journal of …). It doesn't look right.

Figures:

Minor editing on several of the figures. (RTC DONE)

1) Fig 39 – You had two A-A′ sections. I changed the one starting near the large blue arrow to B-B′.

2) Fig. 3. Do you have a better, (higher resolution) left part of figure 3? That part is low-res, and I guess scanned from somewhere else. The right side is OK!

Date: July 10, 2010

To: Authors of articles in SEPM SP 95 02 95 Henry and Ole

Revised letter to discuss return of your corrections by e-mail:

This letter covers a number of items for your article that will be in: SEPM Special Publication 95 (*Mass Transport Deposits in Deepwater Settings*).

1) **First page proof** of the publication. A low-res pdf first proof was sent to you in a separate e-mail. **Print the pdf proof.** This printed copy is the one you should mark your corrections and changes. Use a **RED** PEN. Write the changes clearly. If there are long passages you "need to change" (hopefully not too many of these), please supply the corrected text passages by e-mail with the changes you want. Also, mark on the printed page proof where the electronic text is supposed to be placed. **Review the entire proof carefully (text, figures, figure captions, title, running heads, references).** Double check the actual figures to insure that the electronic version that was placed into the page layout is exactly what you want. Remember, **MARK ALL CHANGES IN RED PEN ON THE PAGE PROOF COPY THAT YOU PRINTED. DO NOT MAKE ELECTRONIC CORRECTIONS IN THE PDF FILE.**

2) I have gone through the manuscript text that John Southard used for his copy edits and have highlighted the text about which he had questions for you to answer. These text passages now appear in red in the pdf page proof. This should make it easier for you because you do not have to hunt through your entire original manuscript to locate the questioned text. **You need to respond to ALL of these items. Please note your response directly on the page proof.** In addition, you may provide a separate list of responses if you feel the need to do so. Please address each question John has made. John does **not** need to see your answers at this time.

3) Color figures. **(SP 95 authors. Ignore this paragraph. SP 95 will be an electronic version and there are no additional color costs).** Your Editors for the volume probably have already discussed this item with authors who have color figures and want them printed in color. As I continue to complete proofs I will be able to more accurately calculate a cost for the color pages. We print in 16-page signatures and, in order to calculate a correct cost, I need an accurate count of pages from the front of the book to your article to figure color cost. I will provide this information as it becomes available.

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And finally

7) Please return your corrections and comments in 10-days to two weeks.

Thanks.

Bob Clarke (**rtclarke1@aol.com**).

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Date: July 10, 2010 02 95 Henry and Ole

To: Authors of articles in SEPM Special Publication 95 (*Mass Transport Deposits in Deepwater Settings*).

The SEPM Special Publication in which your article(s) appears will be sent to the printer in a few months. The Society appreciates the work your article represents and that you want it to be distributed at the lowest price possible so that it can reach the widest audience possible. One of the ways you can help us control costs is through making a voluntary page contribution toward printing your paper. Many of you and/or your co-authors have granting agencies or affiliations, which are able to assist you with funds for this purpose. You or your affiliation or granting agency will be acknowledged in the volume.

Please consider the number of pages in your paper and the cost of printing the volume. A good estimate of the costs would be $100 per page. However, your contribution ***in any amount*** will benefit our Society's publication efforts. Please check with your co-authors about the availability of funds and let us know if you are able to contribute. You may send your contribution at any time, but with sufficient advance time to place the acknowledgement of the contribution in the volume. As soon as you are able to arrange payment, please send your contribution to SEPM Headquarters. We will be happy to provide an invoice, if needed, and we do accept credit card payment.

Thank you again for the contribution you have already made by publishing your paper in this volume. Your monetary contribution will allow us to expand our program of publishing the best science to the widest audience at the lowest cost.

Sincerely,

Robert T. Clarke

Robert T. Clarke

Send reply to Michele Tomlinson
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Date: July 10, 2010 02 95 Henry and Ole

To: Authors of articles in SEPM Special Publication 95 (*Mass Transport Deposits in Deepwater Settings*).

Key words and Words for the Index … two separate items! * You sent "Key words" . I will also use these as Index words. Do you want additional words for the Index??**

We would like to receive a list of words from each first author to be used to build the Index in the SEPM Special Publication 95 volume. Many authors did provide keywords, and in some instances index words. However, many did not.

Key words are placed immediately below the Abstract and should be from 5 to 10 words that cover the most important items in your article. Check the proof to see if I have received your key words. If there are no words, please send them to me by e-mail.

Also, if you have not yet sent words for the Index, please submit a list of words from your article that you would like to have included in the Index. Perhaps a list of 15 to 30 words would be adequate from each author … maybe more, maybe less.

Also, an electronic file of the words would be most appreciated. The words do not need to be in alphabetical order … just separated by a comma, or as a list with a carriage return after each entry. Please send these to me by e-mail no later than the date you return the proofs of your article.

Thanks.

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