Journal of
Sedimentary
Research

Journal of Sedimentary Research, 2006, v. 76, 718–730
Perspectives
DOI: 10.2110/jsr.2006.073

# THE TSUNAMITE PROBLEM

G. SHANMUGAM[1]
[1]*Department of Earth and Environmental Sciences, The University of Texas at Arlington, P.O. Box 19049, Arlington, Texas 76019-0049, U.S.A.*
*e-mail: shanshanmugam@aol.com*

ABSTRACT: **The genetic term *tsunamite* is used for a potpourri of deposits formed from a wide range of processes (overwash surges, backwash flows, oscillatory flows, combined flows, soft-sediment deformation, slides, slumps, debris flows, and turbidity currents) related to tsunamis in lacustrine, coastal, shallow-marine, and deep-marine environments. Tsunamites exhibit enormous variability of features (e.g., normally graded sand, floating mudstone clasts, hummocky cross stratification, etc.). These sedimentary features may also be interpreted as deposits of turbidity currents (turbidites), debris flows (debrites), or storms (tempestites). However, sedimentary features play a passive role when these same deposits are reinterpreted as tsunamites on the basis of historical evidence for tsunamis and their triggering mechanisms (e.g., earthquakes, volcanic explosions, landslides, and meteorite impacts). This bipartite (sedimentological vs. historical) approach, which allows here classification of the same deposit as both turbidite and tsunamite, has blurred the distinction between shallow-marine and deep-marine facies. A solution to this problem is to classify deposits solely by a descriptive sedimentological approach. The notion that tsunami waves can directly deposit sediment in the deep sea is unrealistic because tsunami waves represent transfer of energy and they are sediment starved. During tsunamis and major storms, submarine canyons serve as the physical link between shallow-water and deep-water environments for sediment transport. Tsunami-related deposition involves four progressive steps: (1) triggering stage (offshore), (2) tsunami stage (incoming waves), (3) transformation stage (near the coast), and (4) depositional stage (outgoing sediment flows). In this progression, deep-water deposition can commence only after the demise of incoming tsunami waves due to their transformation into outgoing sediment flows. Deposits of these sediment flows already have established names (e.g., debrite and turbidite). Therefore, the term tsunamite for these deposits is obsolete.**

## INTRODUCTION

The term “tsunamite” has been formally adopted in thematic special volumes (Shiki et al. 2000), printed journal articles (Michalik 1997; Pratt 2002; Simms 2003), online Encyclopedia articles (Rodolfo 2003), and other publications (Aschoff et al. 2001; and Barnett and Ettensohn 2003). A “GeoRef” Database search has yielded Gong (1988) as the earliest reference for the usage of the term “tsunamite.” Yamazaki et al. (1989) used the term “tsunamite” for tractive-current-reworked conglomerates by tsunamis. Shiki and Yamazaki (1996, p. 177) defined tsunamites as follows: “We use the term tsunamites not only for sediments transported by the tsunami wave itself, but also for tsunami-induced current deposits. This usage is much the same as that of the term tempestites, which is used for storm-induced sediments.” Like the term “turbidite” for deposit of a turbidity current, it makes sense to label deposit of a tsunami as “tsunamite.” Unfortunately, this is where the simple logic ends on this matter.

The term tsunamite is not a self-defining expression of a single depositional process. Although the term appears to be a simple word with a straightforward meaning, a closer examination reveals a highly complex word with multiple and convoluted meanings. Furthermore, the meaning of the word changes drastically from one case to the next. The tsunamite problem is an amalgamation of issues at several levels. They are difficult to define precisely, but they can be described broadly.

### *Overlap in Nomenclature*

The crux of the problem is concerned with reinterpretation of deep-water turbidites (deposits of turbidity currents) and debrites (deposits of debris flows) as tsunamites. Unlike turbidites, which are interpreted on the basis of sedimentary features, tsunamites are interpreted on the basis of historical evidence. In interpreting deep-water muddy deposits as products of tsunamis using historical evidence, Cita and Aloisi (2000, p. 181) acknowledged that, “No sedimentological characteristics peculiar to tsunamites are observed in the deep-sea homogenite of the eastern Mediterranean.” The problem is that the term “homogenite” is used here as a synonym for “tsunamite.” The other problem is that the term “homogenite” actually represents “turbidite” (Cita and Aloisi 2000, their fig. 12). In other words: homogenite = tsunamite = turbidite. Similarly, debrite beds were reclassified as tsunamites (Barnett and Ettensohn 2003). The reason for this nomenclatural overlap is that tsunamis are oceanographic phenomena of local to global magnitude. As a phenomenon (extraordinary event), a tsunami can trigger a variety of processes, including turbidity currents and debris flows. Without realizing this,

1527-1404/06/076-718/$03.00

many turbidites and debrites have been reinterpreted as "tsunamites," causing nomenclatural congestion in the geologic literature.

### *Depositional Process versus Triggering Event*

When a deposit is interpreted as a turbidite, the emphasis is focused solely on the process of deposition (turbidity current). On the other hand, when the same deposit is reinterpreted as a tsunamite, the focus shifts from a depositional process (turbidity current) to a triggering event (tsunami). As a result, useful information on depositional process is being replaced by ambiguous information on tsunami. The ambiguity comes from a plethora of processes (overwash surges, backwash flows, oscillatory flows, combined flows, slides, slumps, debris flows, and turbidity currents) that can be generated by tsunamis in a range of environments (lacustrine, inland sea, coastal, bay, fjord, shallow-marine, and deep-marine). As a result, virtually any sedimentary deposit in the geologic record could be reinterpreted as a tsunamite, so long as there is historical evidence. Such a reinterpretation undermines sedimentological progress that has been made over the past fifty years to distinguish specific depositional facies (e.g., turbidites vs. debrites). Thus the basic premise behind reinterpreting a deposit as a tsunamite is flawed.

### *Deep-Water Deposition*

On a fundamental level, a prevailing notion is that deposition can occur directly from tsunami waves in deep-water environments (i.e., beyond the shelf edge or $>$ 200 m water depth). This is a conceptual problem. It may be attributed partly to a lack of synthesis of available data on the mechanics of sediment transport from shallow-water into deep-water environments during periods of tsunamis and violent storms.

The tsunamite problem is a blend of nomenclatural, interpretational, conceptual, and observational issues. Because of its immense magnitude, the problem cannot be addressed in isolation without a historical framework and a philosophical foundation. To cover this broad range of issues, I have organized this paper, somewhat unorthodoxly and disjointedly, in four parts:

- The first part is a philosophical retrospective on nomenclatural problems in geology.
- The second part is a critical analysis of case studies of tsunami-related deposits for demonstrating interpretational problems.
- The third part is a quantification of tsunami waves, storm waves, and sea waves for documenting sediment transport from shallow-water into deep-water environments.
- The fourth part is an attempt to introduce more clarity into our understanding of deep-water deposition from tsunami-induced sediment flows. The term "sediment flows" (e.g., debris flows and turbidity currents) is used in this paper as an abbreviated form of "sediment-gravity flows" (Middleton and Hampton 1973).

## A PHILOSOPHICAL RETROSPECTIVE

### *Genetic Nomenclature*

The tradition of genetic nomenclature in sedimentary geology began with the introduction of the term *turbidite* for a deposit of a turbidity current in deep-water environments (Kuenen 1957). Kuenen and Migliorini (1950, p. 99) and Kuenen (1967, p. 212) suggested that normal grading of a turbidite bed was a consequence of deposition from a single waning turbidity current. The AGI *Glossary of Geology* (Bates and Jackson 1980, p. 269) also explained the origin of normal grading by "deposition from a single short-lived turbidity current." The linkage between a turbidite bed and its origin by a single process is the foundation of genetic nomenclature. Although turbidity currents and their deposits have served as the impetus for the proliferation of genetic nomenclature, turbidites themselves have become the subject of controversy (Shanmugam 2002a). Nevertheless, flow behaviors of turbidity currents and debris flows have been reasonably well established (Sanders 1965; Hampton 1972).

In order for a genetic term to succeed: (1) it must be based on sound fluid dynamic *principles*; and (2) its *usage* must be accurate (relying on sedimentological description), precise (referring to a single process), and consistent (requiring a steady and a uniform application in time and space). Natural amalgamated deposits, however, are often the result of multiple processes. They exhibit a complex array of features. To maintain the integrity of a genetic term, researchers are often forced to de-emphasize features that are too "complex" to meet the requirements of a particular process-based genetic term. In discouraging the application of such rigid schemes (e.g., fluvial facies scheme) to the complex rock record, Leeder (1997, p. 374) cautioned, "The main philosophical reason is that it, and other schemes like it, are lazy intellectually and deny the great potential richness of the sedimentary record, full of possible variation not adequately tapped by rigid classification." If one chooses to classify a deposit using a genetic term, no matter how complex the deposit may be, the basic tenet (i.e., the built-in process interpretation) of the genetic term must be maintained. A prudent approach to classify complex deposits would be to follow principles of process sedimentology. *Process sedimentology* (aptly "depositional process sedimentology") is concerned with the detailed bed-by-bed description of siliciclastic sedimentary rocks for establishing the link between the deposit and the physics of the flow. Principles and procedures of process sedimentology are discussed elsewhere (Shanmugam 2006).

A constraint that all genetic nomenclatures must face is the change in scientific concepts with time. Science is not a steady, cumulative acquisition of knowledge as portrayed in the textbooks (Kuhn 1962). Instead, it is a series of peaceful interludes punctuated by intellectually violent revolutions. During these revolutions, one conceptual world view is replaced by another more complex view. In emphasizing the impact of these scientific revolutions, Kuhn (1996, p. 111) articulated "What were ducks in the scientist's world before the revolution are rabbits afterwards." Because geologic concepts and interpretations change with time, the definitive quality of genetic nomenclature encounters problems.

An attribute of genetic nomenclatures is that they usually end with "-ite" (Table 1). This practice is more cosmetic than scientific in purpose. There are terms that do not follow this practice. Examples are *flysch* for turbidites (see review by Hsü 1970) and *olistostrome* for debrites (Flores 1955).

### *Kinds of Problems*

Genetic nomenclatures have been used not only for sedimentary features but also for igneous, metamorphic, tectonic, and meteorite-impact features (Table 1). Problems related to genetic nomenclatures can be grouped into six kinds in geology:

1. Misrepresentation of Flow Behavior.—As a practice, a genetic term should directly reveal the nature of the flow behavior (e.g., turbidite for a deposit of a turbidity current). However, this is not the case in many instances. For example:

- The term *contourite* emphasizes current orientation with respect to bathymetric contours (Hollister 1967), not the flow behavior.
- The term *unifite* represents texture (i.e., ungraded mud) (Feldhausen et al. 1981), not the flow behavior.
- The term *eolianite* represents the god (i.e., Aeolius) (Bates and Jackson 1980), not the flow behavior. The term was introduced by Sayles (1931) to describe lithified rocks of eolian (wind) origin, regardless of the composition. Some authors use this term for

TABLE 1.—*Lexicon of selected genetic terms ending with "-ite".*

| Genetic terms | Comments (This study) | References* |
|---|---|---|
| Anastomosite | Implies river type, not flow behavior | Shanmugam (1984) |
| Atypical turbidite | Multiple processes (slumps, debris flow, and sand flow, not turbidity current) | Stanley et al. (1978) |
| Braidite | Implies river type, not flow behavior | Shanmugam (1984) |
| Contourite | Implies current orientation, not flow behavior | Hollister (1967) |
| Debrite | Plastic debris flow | Pluennekke (1976) |
| Densite | Implies multiple processes, not a single process | Gani (2004) |
| Diamictite | Pebbly mudstone; implies no genetic (glacial) connotation | Flint et al. (1960) |
| Eolianite | Represents the Aeolius (the god of the winds), not flow behavior | Sayles (1931) and Bates and Jackson (1980) |
| Fluxoturbidite | Complex origin (sand avalanche?), not turbidity current | Dzulynski et al. 1959) |
| Grainite | Implies grain constituents, not flow behavior | Khvorova (1978) |
| Gravitite | Implies sediment gravity, not flow behavior | Natland (1967) |
| Gravite | Implies multiple processes, not a single process | Gani (2004) |
| Hemipelagite | Hemipelagic settling | Arrhenius (1963) |
| Hemiturbidite | Muddy turbidity current | Stow et al. (1990) |
| High-concentration sandy turbidite | Implies sandy debris flow, not turbidity current | Abreu et al. (2003) |
| Homogenite | Implies grain size (ungraded mud), not flow behavior | Kastens and Cita (1981) |
| Hyperpycnite | Implies relative density of flow, not flow behavior | Mulder et al. (2002) |
| Impactite** | Impacts by meteorite, not flow behavior | Stöffler and Grieve (2003) |
| Injectite** | Injection in igneous, sedimentary, and metamorphic rocks, not flow behavior | Vivas et al. (1988) |
| Meanderite | Implies river type, not flow behavior | Shanmugam (1984) |
| Megaturbidite | Implies debris flow, not turbidity current | Labaume et al. (1987) |
| Pelagite | Pelagic settling | Arrhenius (1963) |
| Seismite** | Implies seismic shocks, not flow behavior | Seilacher (1969) and Iqbaluddin (1978) |
| Seismoturbidite | Implies mass flow, not turbidity current | Mutti et al. (1984) |
| Suspensite | Suspension settling | Lisitsyn (1986) |
| Tectonite | Tectonically deformed rocks | Turner and Weiss (1963) |
| Tempestite | Implies multiple processes, not a single process | Ager (1974) |
| Tidalite | Deposition from tidal currents | Klein (1971 and 1998) |
| Tillite | Pebbly mudstone; implies no genetic (glacial) connotation | Harland et al. (1966) |
| Tractionite | Traction deposition by bottom current | Natland (1967) |
| Tsunamite | Multiple processes, not a single process | Gong (1988) |
| Turbidite | Implies turbulent turbidity current | Kuenen (1957) |
| Undaturbidite | No discernible meaning | Rizzini and Passega (1964) |
| Unifite | Implies grain size (ungraded mud), not flow behavior | Feldhausen et al. (1981) and Stanley (1981) |
| Winnowite | Winnowing action of bottom current | Shanmugam and Moiola (1982) |

* References include those that introduced the term, used the term early, or considered appropriate.

** Unrelated to depositional processes.

carbonate-cemented eolian deposits, whereas others use it for deposits of Quaternary age.

- The term *meanderite* represents river sinuosity (Shanmugam 1984), not the flow behavior. In *meandering* channels, the sinuosity (i.e., the ratio of the length of the channel to the down-valley distance) must exceed 1.5.

2. Multiple Processes for a Single Term.—As a rule, a genetic term must represent a single process. Gani (2004), however, proposed the term *densite* for deposits of multiple processes (i.e., high-density turbidity current, sandy debris flow, slurry flow, concentrated density flow, liquefied flow, and fluidized flow).

   Natland (1967) originally coined the term *gravitite* for deposits of debris flows. Lisitsyn (1986), however, redefined the term *gravitite* for multiple processes and products that include submerged landslides, slumps, mud torrents, slurry flows, fluxoturbidites, dynamictites, single argillites, low and high density turbidity currents, and contourites. Surprisingly, Lisitsyn (1986) did not cite the reference of Natland (1967), who coined the term.

3. Two Genetic Terms for a Single Origin.—As a rule, a genetic term must represent a single origin. The term *tectonite* was first used for a tectonic origin of a rock with deformation features (Turner and Weiss 1963). Later, the term *seismite* was used for earthquake-induced deformation features (Einsele et al. 1996, p. 2). The distinction between tectonics and earthquakes is fallacious because earthquakes are integral parts of tectonic activity.

4. Misuse of Established Nomenclature.—As a rule, the term turbidite must be used only for deposits of turbidity currents (Sanders 1965). However, Nakajima and Kanai (2000, p. 3) misused the term *turbidite* for deposits of submarine slumps. Mutti et al. (1999, p. 19) misused the term *turbidite* for deposits of all sediment gravity flows, which include grain flows, debris flows, fluidized flows, and turbidity currents.

5. Nomenclature without Sound Principles.—The term *fluxoturbidite* was introduced by Dzulynski et al. (1959). The origin of these deposits is unclear. These deposits appear to represent sand avalanches, slumps, and other mass movements. Hsü (1989, p. 85), after investigating the meaning of the term fluxoturbidite, concluded that "…this is another case when a geologist wanted to hide his ignorance behind an exotic name."

   The term *undaturbidite* was introduced by Rizzini and Passega (1964, p. 71). This deposit was thought to be formed from a suspension induced by violent storms. It was considered to represent an intermediate type between *tempestite* and *turbidite*. The problem is that the concept of "tempestite" itself was ill-defined.

   The term *tempestite* (Latin word *tempestus* = storm) was first coined by Gilbert Kelling for storm-generated shelf sandstones

(Brenchley 1985), but the first published reference is by Ager (1974). Johnson and Baldwin (1996, p. 249) acknowledged that "The hydrodynamic interpretation of modern shelf storm deposits is difficult because it has never been possible to correlate precisely the physical processes accompanying major storms and processes acting on the sea bed. Processes proposed include: (i) storm waves; (ii) wind-driven currents; (iii) storm waves combined with ebbing tidal currents; (iv) storm-surge ebb currents; (v) rip currents; (vi) tsunamis; and (vii) density currents." This statement implies that tsunami is a storm-related process; however, storms and tsunamis are two genetically unrelated phenomena. Storms, for example, are caused by changes in meteorological (climate and weather) conditions, whereas tsunamis are caused by undersea seismic activity, volcanic explosions, landslides, and by extraterrestrial (meteorite) impacts on the sea surface. There is no geological reason for these two phenomena to occur concurrently. Furthermore, storm is not a single well-defined process. Therefore, the genetic term "tempestite" falters in principle.

5. In emphasizing the difficulties of interpreting storm deposits, Morton (1988, p. 8) stated, "The sedimentologic consequences of great storms are still debated because we almost always lack direct evidence linking the observed depositional features with extremely rare meteorologic events that have poorly defined characteristics other than the implied condition of equaling or exceeding storms of historical record."

5. Direct evidence for depositional mechanics of tsunamis is also lacking. Although the high velocities of tsunami waves allow them to transport sediment ranging in size from mud to boulders, the mechanics of tsunami waves and related sediment transport have never been adequately modeled (Dawson and Shi 2000). Attempts to simulate the movement of large boulders by tsunamis have encountered difficulties in simulating the effects of bottom friction on boulders of different shapes and densities (Noji et al. 1993).

5. Nott (2003) has used revised hydrodynamic wave transport equations along with numerical storm-surge and wave models to distinguish the type of wave (i.e., tsunami vs. storm) responsible for deposition of boulders in the Gulf of Carpentaria, northern Australia. Despite these attempts, our understanding of sediment entrainment and emplacement by tsunami waves is still lacking. This is perhaps because of our inability to observe directly the mechanics of deposition during periods of tsunamis. Without a clear process–product linkage, the genetic term "tsunamite" is meaningless for process interpretations.

6. Different Levels of Usage.—A lingering problem in geology has been the usage of a single word whose meaning would change depending upon the level (sense) in which it is being used. Examples are:

- The term *ophiolite* was introduced to denote serpentinized mafic and ultramafic rocks ranging from spilite and basalt to gabbro and periodotite (see review by Wood 1974). It was later used both as an *assemblage* term ("Steinmann Trinity") to emphasize its association with pillow lavas and radiolarian cherts (Hess 1955) and as a *tectonic* term to represent oceanic mantle and crust (Dewey and Bird 1970).
- The term *mélange* was introduced as a mappable rock unit by Greenly (1919). But it was later used as a genetic term to represent both *sedimentary mélange* or olistostrome (Hsü 1974, p. 325) and *tectonic mélange* (Raymond 1975, p. 8).
- The term *flysch* was introduced as an informal rock-stratigraphic unit, but it was later used not only as a descriptive term (*greywacke*) but also as an interpretive (turbidite) term (see review by Hsü 1970). In the 1960s, "flysch," "greywacke," and "turbidite" were used as synonymous terms.
- The term *greywacke* was first introduced as a descriptive term in 1789 (see Bates and Jackson 1980), but was later used as an interpretive (*turbidite*) term (Pettijohn 1957, p. 313). Traditionally, geologists have shown a remarkable tolerance for words with multiple meanings (e.g., flysch and greywacke) and for words with no discernible meanings (e.g., fluxoturbidite and undaturbidite). However, once in a while someone like R.L. Folk comes along and puts an end to this dialectal nonsense. Folk (1968, p. 125), following McBride (1962), abandoned the term "greywacke" by stating that he "…has discarded the term "greywacke" from any seat in a quantitative, mineralogically-oriented classification of sandstones." The term greywacke is seldom used now.
- The term *facies* is being used as: (1) a *descriptive* term (e.g., sandstone facies); (2) an *interpretive process–product* term (e.g., turbidite facies); and (3) an *interpretive environmental* term (e.g., fluvial facies). Reading (1986, p. 4) discouraged the usage of the term "fluvial facies" for implying "fluvial environment." He preferred to use the term facies only for the products of an environment, not for the environment (setting) itself.
- The term *tsunamite* is being used at two different interpretive levels (*sedimentological* vs. *historical*). Customarily, researchers tend to place more emphasis on historical data than on sedimentological data for classifying deposits as products of tsunamis (Cita and Aloisi 2000). This is troubling because the history can establish only the occurrence of a tsunami as a phenomenon; it cannot establish the physics of the flow. As a consequence, the term "tsunamite" is the only word in the lexicon of geology that can represent a multitude of deposits or rocks that include turbidite, debrite, tempestite, fluxoturbidite, undaturbidite, seismite, seismoturbidite, gravitite, gravite, densite, tractionite, hyperpycnite, tidalite, unifite, homogenite, and injectite. In a parody on genetic terms, Davies (1997, p. 22) coined the term *interpretite* that "…may be applied universally to any and all sedimentary structures in any depositional sequence!"

## INTERPRETATIONAL PROBLEMS

Tsunami-related deposits have been interpreted from lacustrine (Bondevik et al. 1997), coastal (Whelan and Keating 2004), shallow-marine (Bussert and Aberhan 2004), and deep-marine (Kastens and Cita 1981) environments. The problem is that a plethora of sedimentary features have been used for interpreting tsunami-related deposits (Table 2). These features suggest extreme variability in processes that include erosion, reworking, overwash surges, backwash flows, lower-flow-regime currents, upper-flow-regime currents, bidirectional tidal currents, oscillatory flows, storm-generated combined flows, liquefaction, fluidization, soft-sediment deformation, slides, slumps, freezing of boulders in debris flows, settling of sand from turbidity currents (waning flows), and settling of mud from hemipelagic suspension clouds. Selected case studies are discussed below to demonstrate interpretational problems associated with tsunamites.

### *Tempestite versus Tsunamite*

There are major challenges in distinguishing tempestites from tsunamites (Young and Bryant 1998; Einsele 1998). Cores of shoreface sediments off Fire Island, Long Island, New York, recovered normally graded fine sand 2 m thick. This graded sand was attributed to waning stages of a storm (Kumar and Sanders 1976). On the basis of historical data, this sand could be classified as a *tempestite*. However, normally graded beds can also be deposited during overwash surges triggered by storms (Leatherman and Williams 1977). The problem is that the term tempestite represents mainly *shoreface* storm deposits, but storm deposits also include *overwash*. This environmental distinction is necessary because tsunamis can also create overwash deposits.

TABLE 2.—*Examples of tsunami-related features in various environments.*

| Features | Environment | Reference |
|---|---|---|
| Chaotic bedding | Shallow to deep water | Coleman (1968) |
| Coconuts in "turbidites" | Deep water | Ballance et al. (1981) |
| Coarse-grained sandstone with mudstone clasts grades upward into wave-rippled sandstone | Shallow water (mid to outer shelf) | Bourgeois et al. (1988) |
| Inverse grading with basalt boulders (1.5 m diameter) and dune-like ridges in boulders (1 m high and 10 m apart) | Coastal uplands (at 375 m elevation) | Moore and Moore (1988) |
| Gravel clusters and imbrications | Deep water (200–400 m deep) | Yamazaki et al. (1989) |
| Antidune with chute- and pool-structure | Deep water (upper bathyal) | Shiki and Yamazaki (1996) |
| Erosional unconformity | Coastal lakes | Bondevik et al. (1997) |
| "Rope-ladder" texture (i.e., sigmoidal deformation) | Shallow water (carbonate ramp) | Michalik (1997) |
| Floating boulders in sandy matrix and sheet geometry | Coastal to shallow water | Dawson and Shi (2000) |
| Coarse fraction at the base of biogenic sandy unit (normal grading) | Deep water | Cita and Aloisi (2000) |
| Fine sandstone with swaly, trough, tabular, and hummocky cross stratification (HCS) | Shallow water (shoreface) | Rossetti et al. (2000) |
| Dune bedforms, imbricated boulder stacks, and cavitation features | Coastal to shallow water | Bryant (2001) |
| Earthquake-induced deformation structures, sporadic distribution of conglomerates, high degree of scouring, and angularity of intraclasts | Shallow water (intracratonic sea) | Pratt (2002) |
| Unit with HCS, which is underlain by seismites containing slump folds, microfaults, dikes, truncated top, etc. | Shallow water | Simms (2003) |
| Cobble-size clasts on sand dunes | Coastal dunes | Nichol et al. (2003) |
| Reworked shell fragments | Shallow water | van den Bergh et al. (2003) |
| Breccia with angular chert and dolostone clasts | Shallow water | Barnett and Ettensohn (2003) |
| Inverse to normal grading and opposing current directions | Shallow water | Bussert and Aberhan (2004) |
| Gravel-size corals mixed with man-made items | Coastal beaches | Whalen and Keating (2004) |
| Clast-supported textures, normally graded planar conglomerate-sandstone couplets, and upcurrent-dipping low-angle cross-laminae | Shallow water (shoreface to prodelta) | Lawton et al. (2005) |

In Papua New Guinea, deposits of the 1998 tsunami contain normally graded sand (Jaffe 2005). This graded unit, representing overwash deposition, could be classified as a *tsunamite*. Because both tsunamis and storms can generate sedimentologically identical overwash deposits, the same deposit could be classified either as a tsunamite or as a tempestite based on historical data. However, classification of ancient overwash deposits, for which there are no historical data, as tsunamites would be a challenge. An additional complication is the generation of freak waves (rogue waves) in some areas (e.g., Lavernov 1998). Deposits related to these unusual events have not been understood and they may be misclassified as tsunamites as well. Therefore, a clear link between a deposit and its emplacement mechanism is imperative in naming a deposit.

In explaining the origin of ancient hummocky cross stratification (HCS), Rossetti et al. (2000, p. 309) stated, "…combined flows responsible for the genesis of these structures were formed by tsunami waves enhanced by tsunami-induced ebb currents and/or tidal currents." HCS has traditionally been considered as evidence for storm deposition (Harms et al. 1975). The problem here is that HCS can be classified both as tsunamites and as tempestites, the two poorly defined genetic terms.

According to Michalik (1997, p. 221), "Tsunamites are [sic] special type of tempestites." This implies that tsunamis and storms are genetically related. As pointed out earlier, storms are meteorological phenomena, whereas tsunamis are not. However, both storms and tsunamis can develop identical deposits. Thus the separation of tempestites from tsunamites is mostly a semantic distinction without a sedimentologic difference.

### *Debrite versus Tsunamite*

An early usage of the term *debrite* for deposits of debris flows was by Pluenneke (1976) in an unpublished M. S. thesis, but a published reference is by Stow (1984). Sedimentological properties of debrites were discussed by Hampton (1972) and Middleton and Hampton (1973).

The Middle Devonian Duffin Bed of the New Albany Shale in south-central Kentucky was originally interpreted as a debrite, but it was later reinterpreted as a tsunamite (Barnett and Ettensohn 2003). Barnett and Ettensohn (2003, p. 602) acknowledged that, "Indisputable evidence for tsunamis is absent and will probably be difficult to identify in shallow-water, epicontinental settings, but an association of features and circumstances, especially evidence of coeval seismicity, can rule out more common alternatives and lend support for a tsunami model origin."

Michalik (1997, his figs. 4.2, 4.3, and 4.8) used sigmoidal deformation features (i.e., "rope-ladder texture") as the evidence for tsunami deposition in shallow-water carbonate platforms. These deformation features are analogous to imbricate slices deposited by sandy debris flows in flume experiments (see Shanmugam 2000, his fig. 18B) and to duplex-like structures formed by slumps in deep-water channels (Shanmugam et al. 1988). The problem is that soft-sediment deformation is not unique to tsunami deposition.

In their study of the Maastrichtian conglomerates in northeastern Mexico, Aschoff et al. (2001) concluded that field and petrographic analyses show evidence for both debrite and tsunamite origin. The problem is that debrites and tsunamites are one and the same. For example, Cantalamessa and Di Celma (2005) attributed deposition of backwash sandy debrites to tsunamis in northern Chile.

Moore and Moore (1988) explained the origin of gravel bedforms (cross bedding) on Hawaiian uplands by high-speed backwash flows related to tsunamis. Because tsunami backwash can induce both freezing (debrite) and traction (cross bedding) deposition, process-based nomenclature should always be the basis for classifying deposits of sedimentary environments.

### *Homogenite (Turbidite) versus Tsunamite*

The term *homogenite* was first coined for deep-sea tsunami deposits, composed of thick marly intervals with a normally graded sandy base, in the Mediterranean Sea (Kastens and Cita 1981; see also Cita et al. 1982). As pointed out earlier, the term *homogenite*, which was used as a synonym for *tsunamite*, actually represents a *turbidite*. Although the term homogenite implies a homogeneous nature of sediment, these sediments are not homogeneous in texture. Cita et al. (1996, p. 155) indeed acknowledged that, "We keep the term "homogenite" which we do know is not well accepted by several orthodox sedimentologists for consistency with our previous works. The quotations indicate that the term is not to be considered as strictly referring to the homogeneous characteristics of the sediments, which indeed are not always and not entirely homogeneous. "Homogenite" is the sedimentary expression of a unique event, with a definite stratigraphic position." The problem is that the term "homogenite" represents neither a homogeneous texture nor a direct deposition from tsunamis.

### *Seismite versus Tsunamite*

According to Einsele et al. (1996, p. 2), "In-situ earthquake structures may be termed as 'Seismites,' including sand dikes, sand blows, and mud volcanoes…" It is important to note that the origin of seismites does not involve sediment transport and deposition. The term seismite simply refers to deformation of existing sediment. Also, not all deformation structures in the rock record are induced by seismic shocks. Although deep-water turbidites could be deposited from turbidity currents triggered by earthquakes, such as the 1929 "Grand Banks" earthquake (Piper et al. 1988), earthquakes themselves are not depositional processes. Seilacher (1984) emphasized that although seismites may exhibit deformation structures, independent verification of the seismic origin is still needed in every case.

In the Triassic of the United Kingdom, a seismite unit is overlain by a "tsunamite" unit with hummocky cross-stratified and wave-ripped sandstone (Simms 2003). But for the underlying "seismite" unit, the overlying "tsunamite" unit with hummocky cross stratification would otherwise be interpreted as a "tempestite." The problem here is the use of a genetic term (seismite), which is already an interpretive term, as the basis for another interpretation (tsunamite). Associated facies may be useful for interpreting environment of deposition, but not the process of deposition. The depositional origin of each bed should be interpreted solely on the basis of its own inherent features, not on features of adjacent beds.

### *A Solution*

A solution is to use only descriptive sedimentary features as the basis of interpreting depositional processes and to label deposits on the basis of depositional processes. This descriptive approach is necessary because sedimentary features represent flow conditions that prevailed during the final stages of deposition (Middleton and Hampton 1973; Postma 1986). These depositional features, however, may not necessarily relate to the processes of transport (Shanmugam 1996). Similarly, depositional features are unrelated to triggering mechanisms of depositional processes (Einsele et al. 1996).

In classifying a deposit, it is irrelevant whether a given depositional process was triggered by tsunamis, earthquakes, landslides, meteorite impacts, or volcanic explosions. Otherwise, the same deposit would be classified differently by different researchers without regard for the physics of the depositing flow. First, for example, a deposit with inverse grading, floating mudstone clasts, and planar clast fabric would be interpreted as a *debrite* strictly on the basis of its sedimentary features that exhibit evidence for plastic fluid rheology, laminar flow state, and flow strength (Fisher 1971; Hampton 1972; Middleton and Hampton 1973; Shanmugam 1996). Second, the same deposit could be interpreted as a *tsunamite* if it can be documented that debris flows were generated by tsunamis based on historical and circumstantial evidence. Third, the same deposit could also be interpreted as a *seismite* if it can be established that tsunamis, which generated the debris flows, were initially triggered by seismic activity.

TABLE 3.—*Number of tsunamis and submarine earthquakes that occurred in the main tsunamigenic regions of the Pacific Ocean during 1901–2000. From Gusiakov (2005).*

| Regions | Number of tsunamis | Number of submarine earthquakes |
|---|---|---|
| Japan | 123 | 255 |
| South America | 102 | 122 |
| New Guinea–Solomon | 86 | 130 |
| Indonesia | 68 | 86 |
| Kuril–Kamchatka | 68 | 150 |
| Central America | 62 | 112 |
| New Zealand–Tonga | 62 | 162 |
| Philippines | 55 | 73 |
| Alaska–Aleutians | 49 | 108 |
| Hawaii | 13 | 3 |
| **All Pacific** | **688** | **1201** |

The question remains how to classify sedimentary deposits that may be related to tsunamis. A simple rule is to classify deposits as turbidites, debrites, or other types strictly on the basis of sedimentological criteria. Then, these deposits could be further characterized as "tsunami-related turbidites," or "tsunami-related debrites." Similarly, coastal deposits could be classified as "tsunami-related overwash" or "tsunami-related backwash debrites." Such a characterization would not only preserve the integrity of process interpretation, but also would recognize the role of tsunamis as a triggering event.

The current debate over historical (tsunamite) versus sedimentological (turbidite) interpretation of ancient strata is just more than an academic exercise. This has economic implications. Flume experiments, for example, have shown a clear contrast in sediment distribution between turbidites and debrites in plan view. Because of their Newtonian rheology, turbidity currents flow freely as they exit a channel and spread out laterally forming fans. Debris flows, on the other hand, when released from a flume channel form tongue-like patterns because of their plastic rheology (Shanmugam 2002b, his fig. 8). Thus lumping both debrites and turbidites under the term "tsunamites" would be detrimental for communicating reservoir distribution accurately in petroleum exploration.

Since the earliest interpretation of fluvial processes by the Greek philosopher Herodotus (born 484 B.C.; see Miall 1996), fluvial deposits have been interpreted successfully over the past two millennia without the need for genetic terms, such as *braidite, meanderite*, or *anastomosite* (see Table 1). Therefore, genetic (erudite) nomenclatures are not prerequisites for geologic interpretations.

## TSUNAMI WAVES, STORM WAVES, AND SEA WAVES

To resolve the conceptual component of the tsunamite problem, physical aspects of tsunami waves, storm waves, and sea waves must be quantified and compared, and the link between shallow-water processes and deep-water processes must be established.

### *Origin, Timing, and Frequency*

A tsunami is a water wave or series of waves, with long wavelengths and long periods, caused by an impulsive vertical displacement of the body of water by earthquakes (USGS 2005), landslides (Tappin 2004), volcanic explosions (van den Bergh et al. 2003), or extraterrestrial (meteorite) impacts (Bryant 2001). Colossal energy, released during a magnitude 9 Sumatra–Andaman Island earthquake (with landslides) along the Sunda Trench at 4,000 m water depth, was the source of the 2004 Indian Ocean tsunami (USGS 2005). Although tsunamis are

TABLE 4.—*Observational wave heights of landslide-generated tsunamis. Compiled from several sources (see Papadopoulos and Kortekaas 2003).*

| Location of tsunami (Year) | Wave height (m) | Possible cause |
|---|---|---|
| Hammerås (1963) | 1 | slides in loose deposits |
| Nice (1979) | 3 | aseismic submarine slide |
| Eikesdalsvann (1966) | 3 | aseismic subaerial rock fall |
| Izmit (1999) | 3 | seismic coastal slide |
| Songevann (1935) | 3 | slides in loose deposits |
| Nordset (1956) | > 3 | slides in loose deposits |
| Stegane (1948) | 3–5? | rock fall |
| Sokkelvik (1959) | 4 | slides in loose deposits |
| Trondheim (1888) | 4–5 | slides in loose deposits |
| Kitimat (1975) | 5 | slides in loose deposits |
| Aegion (1963) | 6 | aseismic coastal slide |
| Skagway (1994) | 9–11 | slides in loose deposits |
| Fatu Hiva (1999) | 10 | aseismic subaerial rockslide |
| Ravnefjell (1950) | 12–15 | rock fall |
| Papua New Guinea (1998) | 15 | seismic submarine slide |
| Tjelle (1756) | 38 | rock fall |
| Loenvann (1905) | 41 | aseismic subaerial rock fall |
| Ravnefjell (1936) | > 49 | rock fall |
| Tafjord (1934) | 62 | aseismic subaerial rockslide |
| Loenvann (1936) | 74 | aseismic subaerial rock fall |
| Rammerfjell (1731) | 77 | rock fall |
| Vaiont (1963) | 100 | rock fall |
| Lituya Bay (1958) | 524* | seismic subaerial rock fall |

* Represents maximum tsunami run-up height above mean sea level (Bryant 2001, p. 23).

commonly referred to as "tidal wave," this is a misnomer because tides represent the daily rise and fall of sea level under the extraterrestrial, gravitational influences of the moon and the sun on the rotating earth. Similarly, the term "seismic sea wave" for tsunamis is misleading because it restricts the origin of tsunamis to earthquakes alone. Thus the Japanese word "tsunami" (i.e., harbor wave) has been internationally adopted because it covers all forms of sea-wave generation (NOAA 2005a). Tsunamis are random, unpredictable, non-meteorological phenomena that can occur in major water bodies anywhere on the globe at any time. When they reach the coast or an estuary, tsunami waves may mimic a rising or falling tide, a series of breaking normal sea waves, or a bore. Tsunami waves, composed of (1) sinusoidal, (2) Stokes, (3) solitary, (4) N-simple, (5) N-double, and (6) Mach-Stem types, have played a key role in shaping many coastal regions of the world (Bryant 2001).

According to a recent survey (Gusiakov 2005), 688 tsunamis occurred in the tsunamigenic regions in the Pacific during 1901–2000 (Table 3). At this rate, nearly seven million tsunamis of varying magnitudes would occur per million years in the Pacific alone. Scheffers and Kelletat (2003) reported that at least 100 megatsunamis have occurred during the past 2000 years worldwide. Thus tsunami-related deposits should be volumetrically important in coastal, shallow-water, and deep-water environments.

Unlike tsunami waves, storm waves are meteorological phenomena. Necessary conditions for the development of tropical cyclones are (1) sea surface temperature (26.5°C), (2) atmospheric temperature, (3) atmospheric moisture, (4) weather disturbance, and (5) wind shear. Tropical cyclones (the broader category), which include storms and hurricanes (members), originate during summer months, and they travel from east to west (Gray 1968). The most frequent location where tropical cyclones form that affect North America is in the Atlantic Ocean, just west of Central Africa. Extratropical cyclones are mid- to high-latitude winter storms that travel from west to east. Tropical storms have a sustained wind speed of 39–73 mph (63–118 km/hr), whereas hurricanes (Atlantic) and typhoons (Pacific) have a wind speed of greater than 74 mph (119 km/hr). An estimated frequency of tropical cyclones striking the U.S. Atlantic coastline ranges from 14 to 85 per year (Simpson and Lawrence 1971). In 2005 (June–November), 13 hurricanes (including Katrina) formed in the Atlantic Ocean.

Wind-generated normal surface waves are called "sea waves," and they are complex (Komar 1976). Tsunami waves and large wind-generated waves share the same characteristic in "shallow water" where they both are considered "long" waves. Normal sea waves, however, differ from tsunami waves in some important respects. First, small parcels of water associated with normal sea waves move in circular orbits, whereas the orbits of water parcels of tsunami waves are elliptical. Second, sea-wave energy is focused near the sea surface, whereas tsunami-wave energy is concentrated below the sea surface. Although in both cases, the wave energy is carried in an indeterminate zone from the surface downward, the wind-generated waves may not carry their energy all the way to the deep ocean bottom. Third, unlike wind-generated sea waves, tsunamis with small wave amplitude and relatively long passage time are the reasons why sailors invariably fail to realize when a major tsunami wave passing under their ship. Fourth, no rapid withdrawal of sea water from the shoreline occurs before normal sea waves, whereas prior to a tsunami the sea water recedes rapidly exposing the sea floor. Fifth, normal sea waves come and go without flooding over higher coastal areas, whereas most tsunami waves and major storm waves invariably flood over land areas. Other differences are quantified below.

### *Wave Height*

There are a plethora of definitions of wave height ($H$) associated with tsunamis (Bryant 2001). They are $H$ at the source region, $H$ above mean water level (sinusoidal), $H$ at shore, and $H$ at run-up point above present sea level. Run-up wave heights can be thirty times greater than the wave height of the open-ocean tsunami approaching the shore (Bryant 2001, p. 98). Run-up heights should not be confused with sinusoidal types, which represent the vertical distance from the bottom of a trough to the top of a crest. As a tsunami wave leaves the point of origin (e.g., an earthquake epicenter) in the open ocean and approaches the coast, its velocity decreases and wave height increases. Tsunami waves have raised the water level up to 41 m (Johnson 1919). Papadopoulos and Kortekaas (2003) have compiled data on observed wave heights of landslide-generated tsunamis from published sources. These wave heights range from 1 to 524 m (Table 4). The 524 m value, observed at Lituya Bay in association with the 1958 Alaskan Earthquake (Miller 1960), represents tsunami run-up height (Bryant 2001). Wave heights of the 2004 Indian Ocean tsunami reached up to 15 m (Wikipedia, The Free Encyclopedia 2005). The coastline of Sumatra, near the fault boundary, received waves over 10 meters tall, while those of Sri Lanka and Thailand received waves over 4 meters (NOAA 2005b). On the other side of the Indian Ocean, Somalia and the Seychelles were struck by waves approaching 4 meters in height. Wave height measured from space, 2 hours after the earthquake, reached 60 cm near the east coast of India (NOAA 2005c). On 17 July 1998, a magnitude 7.0 earthquake generated a series of catastrophic tsunami waves that hit the north coast of Papua New Guinea (PNG). Maximum water level of the PNG tsunami reached up to 15 m near the Sissano Lagoon. Tappin et al. (2001) attributed the PNG tsunami to submarine slumps.

The Category 5 (i.e., hurricanes with sustained wind speed > 249 km/hr in the Saffir-Simpson Hurricane Scale) Hurricane Camille hit the Mississippi Gulf Coast on 17 and 18 August 1969. It had winds up to 94 m/s (338 km/hr), a maximum wave height of 22 m, and a diameter of about 650 km (Morton 1988). Swell, which represents smooth waves beyond the storm center, reaches wave height of 15 m (Shepard 1973). Supertyphoon Tip in the Pacific Ocean (October 1979) had a maximum wave height of 15 m and a peak wind velocity of 85 m/s (Dunnavan and Diercks 1980). One of the highest wind-generated surface waves recorded was 34 meters high (Komar 1976 p. 78).

Allen (1970, p. 159), on the basis of more than 40,000 observations, quantified that 45% of normal sea waves are less than 1.2 meters in height, 80% are less than 3.6 meters high, and 10% exceed a height of 6 meters. Allen (1984, p. 32), on the basis of published data, estimated that wave heights would increase with increasing wind speed as follows:

- At a mean wind speed of 0 m/s, wave height would be 0 m.
- At a mean wind speed of 7.5 m/s, wave height would be 1.0 m.
- At a mean wind speed of 16.7 m/s, wave height would be 5.5 m.
- At a mean wind speed of 21.7 m/s, wave height would be 9.0 m.
- At a mean wind speed of 26.8 m/s, wave height would be $>$ 14.0 m.

### *Wavelength*

The wavelengths of tsunamis are hundreds of kilometers long. The Chilean tsunami of 1960 had a wavelength of about 500–800 km (Takahasi and Hatori 1961). By contrast, wavelengths of storm waves vary from 15 to 75 m, and those of swells range from 300 to 900 m (Friedman and Sanders 1978). Normal sea waves hitting a California beach have a wavelength of about 150 m (University of Washington 2005).

### *Wave Period, Speed, and Duration*

A wave period is the time required for one wavelength to pass a fixed point. According to Bryant (2001, p. 27), tsunamis typically have wave periods of 100–2,000 seconds (1.6–33 minutes), and this range is called the "tsunami window." Tsunamis with longer wave periods of 40 to 80 minutes were reported (Takahasi and Hatori 1961; their table 4). In the Pacific Ocean, tsunamis had wave periods of 15–100 minutes (Apel 1987). In the U.S. Virgin Islands, wave periods associated with the 1989 Hurricane Hugo reached 13–16 seconds (Hubbard 1992). Normal swells have wave periods of 6 to 14 seconds, whereas normal sea waves have short wave periods of about 9 seconds (Friedman and Sanders 1978).

In the Pacific Ocean, typical wave speeds of tsunamis are 230 m/s (Apel 1987). Waves of the 2004 Indian Ocean tsunami traveled at up to 800 km/hr (222 m/s) in the open ocean (NOAA 2005a; USGS 2005). Travel times of this tsunami ranged from minutes in Sumatra (close to the epicenter) to 8 hours in Somalia, Africa (NOAA 2005b and NASA (2005).

The time a storm takes to cross the continental shelf is called "shelf duration" (Morton 1988). Shelf duration was 12 hours for the 1969 Hurricane Camille in the Gulf of Mexico and 48 hours for the March 1962 storm in the U.S. Atlantic coast (Cooperman and Rosendal 1962). The 1962 storm was particularly destructive because it lasted more than four spring high tides. In such cases, the potential for destruction increases considerably when the normal astronomical tide combines forces with abnormal meteorological storm events.

### *Sediment Transport on the Shelf*

Aspects of sediment transport by nearshore processes, such as longshore and rip currents, were discussed by Komar (1976). Snedden et al. (1988) concluded that during fair-weather periods winds cannot generate bottom-current flow sufficient in strength to transport fine sand beyond the shoreface region (i.e., water depths of 0–10 m). In an investigation of sediment transport on the San Pedro continental shelf off southern California, measurements showed significant bedload transport caused by surface sea waves (maximum wave speeds 10–30 cm/s) at 22 m of water, but no such bedload transport was observed at 67 m of water near the shelfbreak (Karl et al. 1983).

In contrast to sea waves, storm waves can erode and transport sediment in deeper shelf environments at depths of 200 m (Komar et al. 1972). This is because *combined flows*, a combination of unidirectional and oscillatory currents, are powerful storm-generated agents of sediment transport on the shelf (Swift et al. 1986). Butman et al. (1979), using long-term measurements, documented that storm-induced currents were the most significant process in sediment transport on the mid-Atlantic continental shelf.

Tropical Storm Delta (3 to 5 September 1973) in the Gulf of Mexico generated alongshore flows with velocities of 200 cm/s and offshore flows with velocities of 50–75 cm/s in 21 m of water (Forristall et al. 1977). A current meter located 100 km east of the eye of the Hurricane Camille (Mississippi Gulf Coast) in 10 m of water measured near-bottom current velocities up to 160 cm/s (Murray 1970). Major storms would create near-bottom velocities of about 500 cm/s in 20 m of water and 300 cm/s in 45 m of water (Morton 1988). At these high velocities, gravel-size material would be eroded, transported, and deposited.

The Category 5 Hurricane Ivan (September 2004) generated wave heights up to 27 m. In reporting current velocities, generated by Hurricane Ivan on the shelf and slope in the Gulf of Mexico, Mitchell et al. (2005) summarized that, "The Naval Research Laboratory has undertaken an intensive measurement program in the northeast Gulf of Mexico as part of its Slope to Shelf Energetics and Exchange Dynamics (SEED) project. To understand cross-shelf exchange processes, with the primary focus on currents just west of the DeSoto Canyon, 6 acoustic Doppler current profilers (ADCPs) were deployed on the shelf bottom at depths ranging from 60 to 90 m, and 8 Long Ranger ADCPs were deployed about 500 m below the surface on the slope at depths ranging from 500 to 1000 m. Additionally, the deep moorings contained a current meter located 100 m above the bottom. Fortuitously, the eye of Hurricane Ivan passed directly through the array without disrupting the instrumentation. For the first time, extreme storm induced currents spanning from just west of the eye to just east of the region of maximum wind stress were measured. Currents in excess of 2 m/s and 1.5 m/s were measured on the shelf and slope, respectively."

Direct measurements of storm-related erosion of the shelf floor range from 1 to 2 m (Blumberg 1964; Herbich 1977). There is little difference between large storms with long wave periods and the effects of tsunamis in terms of hydrodynamics on the shelf (Bryant 2001, p. 40). Both tsunamis (Einsele et al. 1996) and storms (Henkel 1970) can cause shelf-edge sediment failures that can trigger slumps and sediment flows into deep-water environments.

### *Sediment Transport via Submarine Canyons*

Submarine canyons serve as the physical link between shallow-water and deep-water environments for sediment transport. The origin of submarine canyons by tsunamis was first proposed by Bucher (1940). Chaotic sediments were attributed to deposition from tsunamis in submarine canyons (Bailey 1940). The possible role of tsunamis in generating deep-water turbidity currents was first suggested by Kuenen (1950) and later emphasized by Coleman (1968).

Tsunamis and storms influence sediment transport in submarine canyons associated with passive-margin and active-margin settings. Many submarine canyons in the U.S. Atlantic Margin commence at a depth of about 200 m near the shelf edge; but heads of California canyons in the U.S. Pacific Margin begin at an average depth of about 35 m (Shepard and Dill 1966). The Redondo Canyon, for example, commences at a depth of 10 m near the shoreline (Gardner et al. 2002). Such a scenario would allow a quick transfer of sediment from shallow-water into deep-water environments. In the San Pedro Sea Valley, large debris blocks have been recognized as submarine landslides. Lee et al. (2003) suggested that these landslides may have triggered local tsunamis. The significance of this relationship is that tsunamis can trigger submarine landslides, which in turn can trigger tsunamis. Such mutual-triggering mechanisms can result in frequent sediment failures in deep-water environments during periods of tsunamis. The problem is that tsunami-generated landslides would not

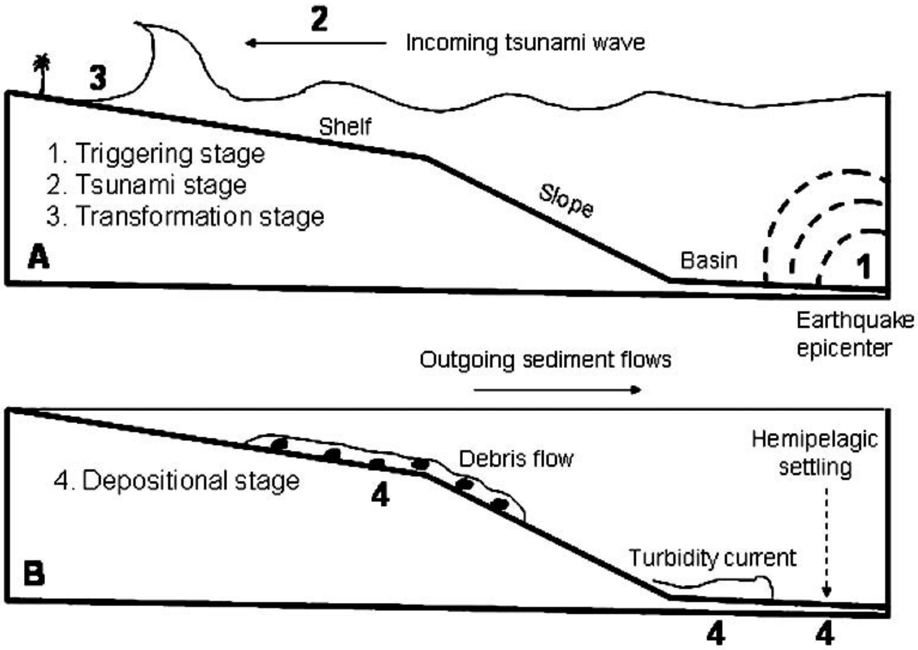

FIG. 1.—A conceptual depositional model showing the link between tsunamis and deep-water deposition in four stages. **A**) 1. *Triggering stage* in which earthquakes trigger tsunami waves. 2. *Tsunami stage* in which an incoming tsunami wave increases in wave height as it approaches the coast. 3. *Transformation stage* in which incoming tsunami waves erode and incorporate sediment, and transform into sediment flows. **B**) 4. *Depositional stage* in which outgoing sediment flows (i.e., debris flows and turbidity currents) deposit sediment in deep-water environments. Suspended mud created by tsunami-related events would be deposited via hemipelagic settling.

be any different from earthquake-generated landslides. So the volumetric significance of tsunamis-generated landslides may never be realized in the ancient rock record.

Inman et al. (1976) made simultaneous measurements of currents and pressure in the Scripps Submarine Canyon (La Jolla, California), and of winds, waves, and pressure over the adjacent shelf for several years. They measured the strongest down-canyon current at a speed of 190 cm/s at a depth of 44 m. This high-velocity sediment flow was recorded during the passage of a storm front on 24 November 1968 over La Jolla. During a fair-weather period, maximum down-canyon current velocity in the Scripps Canyon was 32 cm/s (Shepard et al. 1979). In the Scripps Canyon, a large slump mass of about $10^5$ $m^3$ in size was triggered by the May 1975 storm (Marshall 1978). Coarse sand and cobbles up to 15 cm in diameter in micaceous sands were moving down the head of the Scripps Canyon (Shepard et al. 1969). These sands could be interpreted as deposits of sandy debris flows. Shepard et al. (1969, p. 411) attributed this sediment movement to the intensity of winter storms, which moved sediment from the beaches into the heads of the canyons. In addition to these mass movements, submarine canyons are subjected to daily deep-marine tidal currents. Shepard et al. (1979) measured velocities of tidal currents in 25 submarine canyons worldwide that included the Scripps Canyon. Depths of these canyons ranged from 46 to 4,200 m. Maximum velocities of up-canyon and down-canyon tidal currents commonly ranged from 25 to 50 cm/s. Deposits of tidal currents and mass flows have been documented in both modern and ancient submarine canyons (Shanmugam 2003). Studies showed that internal waves also move up and down submarine canyons (Shepard et al. 1979).

The first quantitative analysis of sediment transport caused by Hurricane Hugo, which passed over St. Croix in the U.S. Virgin Islands on 17 September 1989, in a submarine canyon was made by Hubbard (1992). Hugo had generated winds in excess of 110 knots (204 km/h) and waves 6–7 m in height. In the Salt River submarine canyon (> 100 m deep), a current meter measured net downcanyon currents reaching velocities of 2 m/s and oscillatory flows up to 4 m/s. Hugo had caused erosion of 2 m of sand in the Salt River Canyon at a depth of about 30 m. A minimum of 2 million kg of sediment were flushed down the Salt River Canyon into deep water. The transport rate associated with Hurricane Hugo was 11 orders of magnitude greater than that measured during fair-weather period.

A tsunami with 7–9 m wave height reached St. Croix on 18 November 1867 (Bryant 2001, p. 16), but no quantitative data on sediment transport rate are available. In comparison to Hugo with 6–7 m wave height, it is reasonable to expect that the 1867 tsunami with 7–9 m wave height would have generated even higher transport rates in St. Croix. In the Salt River Canyon, much of the soft reef cover (e.g., sponges) had been eroded away by the power of the storm. Debris composed of palm fronds, trash, and pieces of boats found in the canyon were the evidence for storm-generated sediment flows (Hubbard 1992). Storm-induced sediment flows have also been reported in a submarine canyon off Bangladesh (Kudrass et al. 1998), in the Capbreton Canyon, Bay of Biscay in SW France (Mulder et al. 2001), and in the Eel Canyon, California (Puig et al. 2003), among others.

Sediment transfer can also occur outside of the canyons into the deep water. Tsutsui et al. (1987) attributed development of downslope sediment flows, based on cores containing coarse sands and gravels and displaced shallow benthic foraminifera, to the Hurricane Iwa in 1982, Hawaii.

In summary, tsunamis and storms are two genetically unrelated phenomena. Despite their differences in origin, both tsunamis and storms are remarkably similar in their physical power and in their ability to transport sediments across the shelf and to deliver them into deep-water environments via submarine canyons.

## A DEPOSITIONAL MODEL

A conceptual depositional model is proposed to illustrate that there are four progressive steps that eventually lead to tsunami-related deposition in deep-water environments: (1) triggering stage, (2) tsunami stage, (3) transformation stage, and (4) depositional stage (Fig. 1).

### *Triggering Stage*

Earthquakes (Fig. 1A), volcanic explosions, undersea landslides, and meteorite impacts can trigger displacement of the sea surface, causing tsunami waves. The site of triggering mechanisms (e.g., earthquake

FIG 2.—An aerial image showing sediment-rich backwash flows during the 2004 Indian Ocean tsunami. Note that position of shoreline has retreated seaward nearly 300 meters (arrow) during the tsunami. Also note the development of backwash fans along the position of former shoreline, Kalutara Beach (south of Colombo), southwestern Sri Lanka. Image collected on 26 December 2004. Courtesy of DigitalGlobe.

epicenter) is unrelated to the ultimate site of deep-water deposition (Fig. 1B). In the case of the 2004 Indian Ocean tsunami, for example, the site of tsunami origin was located in northern Sumatra, whereas the possible site of deep-water deposition would be on the continental slopes of the east coast of southern India. The tectonic setting of the east coast of India is analogous to the modern passive-margin setting of the U.S. Atlantic margin, with submarine canyons and gullies. Submarine canyons and feeder channels, common on the east coast of India (Bastia 2004, his fig. 7A), are potential conduits for transporting sediment by tsunami-triggered sediment flows into the deep sea. This stage involves neither sediment transport nor deposition.

### *Tsunami Stage*

Tsunami waves carry energy traveling through the water, but these waves do not move the water. During this transient stage, velocity, wavelength, and wave height of an incoming (run-up) tsunami wave change with time, depth, and proximity to the coast. The incoming wave is depleted in entrained sediment. A theoretical analysis indicates that tsunami waves are unlikely to entrain sediment coarser than fine sand and silt in water depths greater than 200 m (Pickering et al. 1991). This stage is one of energy transfer, and it does not involve sediment transport. Therefore, deposition of sediment cannot occur from tsunami waves directly in deep-water environments.

### *Transformation Stage*

As the tsunami wave approaches the coast, it tends to erode and incorporate sediment into the incoming wave. This sediment-entrainment process commences once there is significant frictional interaction with the sea bottom. This transformation occurs when waves of all kinds (i.e., tsunami waves, storm waves, or normal sea waves) approach the coast. It is called *shoaling transformations* (Friedman and Sanders 1978). The transformation is evident in numerous videos of the 2004 Indian Ocean tsunami. The incoming ocean waters are clearly blue in color (implying sediment free), but these waters transform into brown in color near the coast because of their incorporation of sediment. The transformation to brown color is the result of the wave breaking, and the wave will break in different water depths according to its wavelength and sea-floor irregularities. The transformation stage is evident in sediment-rich (brownish in color) backwash water during the 2004 Indian Ocean tsunami in Sri Lanka (Fig. 2). Bryant (2001, p. 102) suggested that tsunami-generated backwash flows "… can scour the seabed and deposit sand gravels considerable distances from the shelf edge." The outgoing sediment-rich waters invariably carry a large amount of sediment and assorted debris. Such a transformation of tsunami waves and storm waves into sediment-rich flows is somewhat analogous to gravity-flow transformation (Fisher 1983). The outgoing sediment flows should no longer be considered as tsunami *waves*, although they were triggered by tsunamis.

### *Depositional Stage*

The outgoing sediment flows would generate not only debris flows and turbidity currents, but also suspended clouds of mud resulting in hemipelagic settling (Fig. 1B). These sediment flows are the primary depositional processes in deep-water environments. In terms of depositional features, tsunami-generated debrites and turbidites would not be any different from earthquake- or slump-generated debrites and turbidites. Considering the high frequency of tsunamis (Gusiakov 2005), tsunami events can be important controlling factors of deep-water deposition similar to periods of falling sea levels (e.g., Shanmugam and Moiola 1982).

## A CRITICAL PERSPECTIVE

A popular myth is that tsunami waves can deposit sediment directly in deep-water environments. The reality is that tsunami-related deposition in the deep sea can commence only after the transformation of tsunami *waves* into sediment *flows*. These sediment flows already have established names (e.g., debris flow and turbidity current). Deposits of these processes are recognized on the basis of their sedimentary features. These deposits already have established names (e.g., debrite and turbidite). Thus the genetic term tsunamite is obsolete in process sedimentology. The endite!

## ACKNOWLEDGMENTS

My personal interest on tsunamis was accelerated by the 2004 Indian Ocean tsunami, which hit the coast of Tamil Nadu in southeastern India on 26 December. My hometown (Sirkali), which is located about 12 km from the tsunami-devastated coast, provided immediate shelter for tens of thousands of tsunami victims. Color videos of the tsunami, shown on BBC and CNN Television from 27 December 2004 to 5 January 2005, were used for inferring flow transformation near the coasts (offshore) of Thailand, India, and Sri Lanka. I am grateful to Brock Adam McCarty of DigitalGlobe for granting permission to use an aerial image of Kalutara Beach in Sri Lanka. I thank many local individuals who narrated their eye-witness accounts of tsunami waves and who helped in digging trenches along the coast of Tamil Nadu to study the effects of tsunami on coastal sedimentation. I dedicate this paper to all those who perished (over 265,000) in 15 countries in the 2004 Indian Ocean tsunami.

In an attempt to trace the source of the genetic term "tsunamite," I sought information from many colleagues worldwide. I would like to thank the following who responded promptly to my e-mail queries: G. Racki, J. Bourgeois, T. Shiki, M. Cita, B. Pratt, G. van den Bergh, K. Rodolfo, M. Simms, S. Barnett, J. Morrow, D. Stow, A. Hurst, D. Gorsline, and G. Klein. I thank the JSR reviewers from Australia (Ron Boyd and Brian Jones), New Zealand (Scott Nichol), and the editorial crew from Scotland (Colin North, Co-Editor), Canada (David Piper and Martin Gibling, Associate Editor), and the U.S. (John Southard and Melissa Lester) for their comments and help. Jean Shanmugam is thanked for general comments.

## REFERENCES

Abreu, V., Sullivan, M., Pirmez, C., and Mohrig, D., 2003, Lateral accretion packages (LAPs): an important reservoir element in deep water sinuous channels: Marine and Petroleum Geology, v. 20, p. 631–648.

Ager, D.V., 1974, Storm deposits in the Jurassic of the Moroccan High Atlas: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 15, p. 83–93.

Allen, J.R.L., 1970, Physical Processes of Sedimentation: New York, American Elsevier Publishing Company, 239 p.

Allen, J.R.L., 1984, Sedimentary Structures; Their Character and Physical Basis, unabridged one-volume edition: Amsterdam, Elsevier, 593 p.

Apel, J.R., 1987, Principles of Ocean Physics: New York, Academic Press, 631 p.

Arrhenius, G., 1963, Pelagic sediments: The Sea, v. 3, p. 655–727.

Aschoff, J.L., Giles, K.A., and Lawton, T.F., 2001, Origin of Upper Cretaceous (Latest Maastrichtian) massive, boulder–cobble conglomerates, Porterillos Formation, La Popa Basin, northeastern Mexico: incised valley-fill or mega-tsunamite?: Geological Society of America, Annual Meeting, Session no. 84, Booth #139.

Bailey, E.B., 1940, Submarine canyons: Nature, v. 146, p. 493.

Ballance, P.F., Gregory, M.R., and Gibson, G.W., 1981, Coconuts in Miocene turbidites in New Zealand: possible evidence for tsunami origin of some turbidity currents: Geology, v. 9, p. 592–595.

Barnett, S.F., and Ettensohn, F.R., 2003, A possible Middle Devonian tsunamite: Duffin Bed, New Albany Shale of south-central Kentucky (abstract): Geological Society of America, Abstracts with Programs, v. 35, p. 602.

Bastia, R., 2004, Depositional model and reservoir architecture of Tertiary deep-water sedimentation, Krishna–Godawari offshore basin, India: Geological Society of India, Journal, v. 64, p. 11–20.

Bates, R.L., and Jackson, J.A., 1980, Glossary of Geology, Second Edition: Alexandra, Virginia, American Geological Institute, 751 p.

Blumberg, R., 1964, Hurricane waves, winds, and currents test marine pipeline design: Pipeline Industry, v. 20, p. 43–72.

Bondevik, S., Svendsen, J-.I., and Mangerud, J., 1997, Tsunami sedimentary facies deposited by the Storegga tsunami in shallow marine basins and coastal lakes, western Norway: Sedimentology, v. 44, p. 1115–1131.

Bourgeois, J., Hansen, T.A., Wiberg, P.L., and Kauffman, E.G., 1988, A tsunami deposit at the Cretaceous–Tertiary boundary in Texas: Science, v. 241, p. 567–570.

Brenchley, P.J., 1985, Storm influenced sandstone beds: Modern Geology, v. 9, p. 369–396.

Bryant, E., 2001, Tsunami: The Underrated Hazard: Cambridge, U.K., Cambridge University Press, 320 p.

Bucher, W.H., 1940, Submarine valleys and related geologic problems of the North Atlantic: Geological Society of America, Bulletin, v. 51, p. 489–451.

Bussert, R., and Aberhan, M., 2004, Storms and tsunamis: evidence of event sedimentation in the Late Jurassic Tendaguru Beds of southeastern Tanzania: Journal of African Earth Sciences, v. 39, p. 549–555.

Butman, B., Noble, M., and Folger, D.W., 1979, Long-term observations of bottom current and bottom sediment movement on the mid-Atlantic continental shelf: Journal of Geophysical Research, v. 84, p. 1167–1205.

Cantalamessa, G., and Di Celma, C., 2005, Sedimentary features of tsunami backwash deposits in a shallow marine Miocene setting, Mejillones Peninsula, northern Chile: Sedimentary Geology, v. 178, p. 259–273.

Cita, M.B., and Aloisi, G., 2000, Deep-sea tsunami deposits triggered by the explosion of Santorini (3500 y BP), eastern Mediterranean: Sedimentary Geology, v. 135, p. 181–203.

Cita, M.B., Maccagni, A., and Pirovano, G., 1982, Tsunami as triggering mechanism of homogenites recorded in areas of the eastern Mediterranean characterized by the "Cobblestone Topography," *in* Saxov, S., and Neuwenhuis, J.K., eds., Marine Slides and Other Mass Movements: London, Plenum Press, p. 233–261.

Cita, M.B., Camerlenghi, A., and Rimoldi, B., 1996, Deep-sea tsunami deposits in the eastern Mediterranean: new evidence and depositional models: Sedimentary Geology, v. 104, p. 155–173.

Coleman, P.J., 1968, Tsunamis as geological agents: Geological Society of Australia, Journal, v. 15, p. 267–273.

Cooperman, A.I., and Rosendal, H.E., 1962, Great Atlantic Storm, 1962: Mariners Weather Log, v. 6, p. 79–85.

Davies, G.R., 1997, Interpretites: the new universal, non-genetic, non-descriptive classification of sedimentary products and environments: Canadian Society Petroleum Geologists, Reservoir, v. 24, no. 8, p. 22–23.

Dawson, A.G., and Shi, S., 2000, Tsunami deposits: Pure and Applied Geophysics, v. 157, p. 875–897.

Dewey, J.F., and Bird, J.M., 1970, Mountain belts and the new global tectonics: Journal of Geophysical Research, v. 75, p. 2625–2647.

Dunnavan, G.M., and Diercks, J.W., 1980, Supertyphoon Tip: Monthly Weather Review, v. 108, p. 1915–1923.

Dzulynski, S., Ksiazkiewicz, M., and Kuenen, P.H., 1959, Turbidites in flysch of the Polish Carpathian Mountains: Geological Society of America, Bulletin, v. 70, p. 1089–1118.

Einsele, G., 1998, Event stratigraphy: Recognition and interpretation of sedimentary event horizons, *in* Doyle, P., and Bennett, M.R., eds., Unlocking the Stratigraphic Record: Chichester, John Wiley & Sons, p. 145–193.

Einsele, G., Chough, S.K., and Shiki, T., 1996, Depositional events and their records—an introduction: Sedimentary Geology, v. 104, p. 1–9.

Feldhausen, P.H., Stanley, D.J., Knight, R.J., and Maldonado, A., 1981, Homogenization of gravity-emplaced muds and unifites: models from the Hellenic Trench, *in* Wezel, F.C., ed., Sedimentary Basins of Mediterranean Margins: Bologna, Tecnoprint, p. 203–226.

Fisher, R.V., 1971, Features of coarse-grained, high-concentration fluids and their deposits: Journal of Sedimentary Petrology, v. 41, p. 916–927.

Fisher, R.V., 1983, Flow transformations in sediment gravity flows: Geology, v. 11, p. 273–274.

Flint, R.F., Sanders, J.E., and Rodges, J., 1960, Diamictite: a substitute term for symmictite: Geological Society of America, Bulletin, v. 71, p. 1809–1810.

Flores, G., 1955, Discussion of a paper by F. Beneo: Les resultants des etudes pour la recherché pétrolifêre en Sicilie, 4 th World Petroleum Congress, Proceedings, Section 1, p. 121–122.

Folk, R.L., 1968, Petrology of Sedimentary Rocks: Austin, Texas, Hemphill, 170 p.

Forristall, G.Z., Hamilton, R.C., and Vardone, V.J., 1977, Continental shelf currents in Tropical Storm Delta: observations and theory: Journal of Physical Oceanography, v. 87, p. 532–546.

Friedman, G.M., and Sanders, J.E., 1978, Principles of Sedimentology: New York, John Wiley & Sons, 792 p.

Gani, R., 2004, From turbid to lucid: A straightforward approach to sediment gravity flows and their deposits: The Sedimentary Record, v. 3, p. 4–8.

Gardner, J.V., Dartnell, P., Christopher Stone, J., Mayer, L.A., and Hughes Clark, J.E., 2002, Bathymetry and selected perspective views offshore greater Los Angeles, California:U.S. Geological Survey, Water-Resources Investigations, Report 02-4126.

Gong, Y., 1988, Tempestite, seismite, and tsunamite: a discussion of several sedimentological terms: Geological Review, v. 34, p. 481–482 (in Chinese).

Gray, W.M., 1968, Global view of the origin of tropical disturbances and storms: Monthly Weather Review, v. 96, p. 669–700.

Greenly, E., 1919, The geology of Angelsey: Great Britain Geological Survey, Memoir, 980 p.

Gusiakov, V.K., 2005, Tsunami generation potential of different tsunamigenic regions in the Pacific: Marine Geology, v. 215, p. 3–9.

Hampton, M.A., 1972, The role of subaqueous debris flows in generating turbidity currents: Journal of Sedimentary Petrology, v. 42, p. 775–793.

Harland, W.B., Herod, K.N., and Krinsley, D.H., 1966, The definition and identification of tills and tillites: Earth-Science Reviews, v. 2, p. 225–256.

Harms, J.C., Southard, J.B., Spearing, D.R., and Walker, R.G., 1975, Depositional environments as interpreted from primary sedimentary structures and stratification sequences: SEPM, Short Course no. 2, 161 p.

Henkel, D.J., 1970, The role of waves in causing submarine landslides: Geotechnique, v. 20, p. 75–80.

Herbich, J.B., 1977, Wave-induced scour around offshore pipelines: Offshore Technology Conference, v. 4, p. 79–90.

Hess, H.H., 1955, Serpentines, progeny and epeirogeny, *in* Poldervaart, A., ed., The Crust of the Earth: Geological Society of America, Special Paper 62, p. 391–408.

Hollister, C.D., 1967, Sediment distribution and deep circulation in the western North Atlantic [Unpublished Ph.D. dissertation]: New York, Columbia University, 467 p.

Hsü, K.J., 1970, The meaning of the word Flysch—a short historical search, *in* Lajoie, J., ed., Flysch Sedimentology in North America: Geological Association of Canada, Special Paper 7, p. 1–11.

Hsü, K.J., 1974, Mélanges and their distinction from olistostromes, *in* Dott, R.H, Jr., and Shaver, R.H., eds., Modern and Ancient Geosynclinal Sedimentation: SEPM, Special Publication 19, p. 321–333.

Hsü, K.J., 1989, Physical Principles of Sedimentology: Berlin, Springer-Verlag, 233 p.

Hubbard, D.K., 1992, Hurricane-induced sediment transport in open shelf tropical systems—An example from St. Croix, U.S. Virgin Islands: Journal of Sedimentary Petrology, v. 62, p. 946–960.

Inman, D.L., Nordstrom, C.E., and Flick, R.E., 1976, Currents in submarine canyons: an air–sea–land interaction: Annual Review of Fluid Mechanics, v. 8, p. 275–310.

Iqbaluddin, G., 1978, Occurrence of seismite in the Precambrian rocks of Rajasthan, India: Current Science, v. 47, p. 230–231.

Jaffe, B., 2005, Preliminary analysis of sedimentary deposits from the 1998 Papua New Guinea (PNG) Tsunami, URL: http://walrus.wr.usgs.gov/tsunami/itst.html (accessed June 9, 2005).

Johnson, D.W., 1919, Shore Processes and Shoreline Development: New York, Wiley, 584 p.

Johnson, H.D., and Baldwin, C.T., 1996, Shallow clastic sea, *in* Reading, H.G., ed., Sedimentary Environments; Processes, Facies and Stratigraphy: Oxford, U.K., Blackwell Science, p. 232–280.

Karl, H.A., Carlson, P.R., and Cacchione, D.A., 1983, Factors that influence sediment transport at the shelf break, *in* Stanley, D.J., and Moore, G.T., eds., The Shelfbreak: Critical Interface on Continental Margins: SEPM, Special Publication 33, p. 219–231.

Kastens, K.A., and Cita, M.B., 1981, Tsunami induced sediment transport in the Abyssal Mediterranean Sea: Geological Society of America, Bulletin, v. 89, p. 591–604.

Khvorova, I.V., 1978, Terrigenous clastic formations of oceans and certain seas: Litologiya i Polenzye Iskopaemye, v. 3, p. 3–24.

Klein, G.D., 1971, A sedimentary model for determining paleotidal range: Geological Society of America, Bulletin, v. 82, p. 2585–2592.

Klein, G.D., 1998, Clastic tidalites—a partial retrospective view, *in* Alexander, C.R., Davis, R.A., and Henry, V.J., eds., Tidalites: Processes and Products: SEPM, Special Publication 61, p. 5–14.

Komar, P.D., 1976, Beach Processes and Sedimentation: Englewood Cliffs, New Jersey, Prentice-Hall, 429 p.

Komar, P.D., Neudeck, R.H., and Kulm, L.D., 1972, Origin and significance of deep-water oscillatory ripple marks on the Oregon continental shelf, *in* Swift, D.J.P., Duane, D.B., and Pilkey, O.H., eds., Shelf Sediment Transport Processes and Pattern: Stroudsburg, Pennsylvania, Dowden, Hutchinson, & Ross, p. 601–619.

Kudrass, H.R., Michels, K.H., and Wiedicke, M., 1998, Cyclones and tides as feeders of a submarine canyon off Bangladesh: Geology, v. 26, p. 715–718.

Kuenen, P.H., 1950, Marine Geology: New York, John Wiley & Sons, 568 p.

Kuenen, P.H., 1957, Sole markings of graded greywacke beds: Journal of Geology, v. 65, p. 231–258.

Kuenen, P.H., 1967, Emplacement of flysch-type sand beds: Sedimentology, v. 9, p. 203–243.

Kuenen, P.H., and Migliorini, C.I., 1950, Turbidity currents as a cause of graded bedding: Journal of Geology, v. 58, p. 91–127.

Kuhn, T.S., 1962, The Structure of Scientific Revolutions: Chicago, University of Chicago Press, 172 p.

Kuhn, T.S., 1996, The Structure of Scientific Revolutions, Third Edition: Chicago, The University of Chicago Press, 212 p.

Kumar, N., and Sanders, J.E., 1976, Characteristics of shoreface storm deposits: modern and ancient examples: Journal of Sedimentary Petrology, v. 46, p. 145–162.

Labaume, P., Mutti, E., and Seguret, M., 1987, Megaturbidites: A depositional model from the Eocene of the SW-Pyrenean foreland basin, Spain: Geo-Marine Letters, v. 7, p. 91–101.

Lavernov, I.V., 1998, The wave energy concentration at the Agulhas Current off South Africa: Natural Hazards, v. 17, p. 117–127.

Lawton, T.F., Shipley, K.W., Aschoff, J.L., Giles, K.A., and Vega, F.J., 2005, Basinward transport of Chicxulub ejecta by tsunami-induced backflow, La Popa basin, northeastern Mexico, and its implications for distribution of impact-related deposits flanking the Gulf of Mexico: Geology, v. 33, p. 81–84.

Leatherman, S.P., and Williams, A.T., 1977, Lateral textural grading in overwash sediments: Earth Surface Processes, v. 2, p. 333–341.

Lee, H.J., Kayen, R.E., Gardner, G.V., and Locat, J., 2003, Characteristics of several tsunamigenic submarine landslides, *in* Locat, J., and Mienert, J., eds., Submarine Mass Movements and Their Consequences: Dordrecht, The Netherlands, Kluwer Academic Publishers, p. 357–366.

Leeder, M.R., 1997, Book Reviews, "The Geology of Fluvial Deposits—Sedimentary Facies, Basin Analysis, and Petroleum Geology" by A.D. Miall: Journal of Sedimentary Research, v. 67, p. 374–375.

Lisitsyn, A.P., 1986, Avalanche sedimentation in seas and oceans. Part V: Special mechanisms of transport of sedimentary matter and formation of sedimentary bodies of the second global level. Gravitites, their classes and series: Litologiya i Polenzye Iskopaemye, v. 4, p. 3–28.

Marshall, N.F., 1978, Large storm-induced sediment slump reopens an unknown Scripps submarine canyon tributary, *in* Stanley, D.J., and Kelling, G., eds., Sedimentation in Submarine Canyons, Fans, and Trenches: Stroudsburg, Pennsylvania, Hutchinson & Ross, p. 73–84.

McBride, E.F., 1962, The term greywacke: Journal of Sedimentary Petrology, v. 32, p. 614–615.

Miall, A.D., 1996, The Geology of Fluvial Deposits: Berlin, Springer, 582 p.

Michalik, J., 1997, Tsunamites in a storm-dominated Anisian carbonate ramp (Vysoká Formation, Malé Karpaty Mts., western Carpathians): Geologica Carpathica, v. 48, p. 221–229.

Middleton, G.V., and Hampton, M.A., 1973, Sediment gravity flows: mechanics of flow and deposition, *in* Middleton, G.V., and Bouma, A.H., eds., Turbidites and Deep-Water Sedimentation: Los Angeles, California, SEPM, Pacific Section, Short Course, p. 1–38.

Miller, D.J., 1960, The Alaska earthquake of July 10, 1958: giant wave in Lituya Bay: Seismological Society of America, Bulletin, v. 50, p. 253–266.

Mitchell, D.A., Teague, W.A., Jarosz, E., Wang, D.W., and Hulbert, M.S., 2005, Current measurements under Hurricane Ivan, URL: http://www.agu.org/meetings/sm05/sm05-sessions/sm05_OS34A.html (accessed August 19, 2005).

Moore, G.W., and Moore, J.G., 1988, Large-scale bedforms in boulder gravel produced by giant waves in Hawaii, *in* Clifton, H.E., ed., Sedimentologic Consequences of Convulsive Geologic Events: Geological Society of America, Special Paper 229, p. 101–110.

Morton, R.A., 1988, Nearshore responses to great storms, *in* Clifton, H.E., ed., Sedimentologic Consequences of Convulsive Geologic Events: Geological Society of America, Special Paper 229, p. 7–22.

Mulder, T., Weber, O., Anschutz, P., Jorissen, F., and Jouanneau, J.-M., 2001, A few months-old storm-generated turbidite deposited in the Capbreton Canyon (Bay of Biscay, SW France): Geo-Marine Letters, v. 21, p. 149–156.

Mulder, T., Migeon, S., Savoye, B., and Faugeres, J.-C., 2002, Reply to discussion by Shanmugam on Mulder et al. (2001, Geo-Marine Letters 21: 86–93) Inversely graded turbidite sequences in the deep Mediterranean. A record of deposits from flood-generated turbidity currents?: Geo-Marine Letters, v. 22, p. 112–120.

Murray, S.P., 1970, Bottom currents near the coast during Hurricane Camille: Journal of Geophysical Research, v. 75, p. 4579–4582.

Mutti, E., Ricci Lucchi, F., Segure, T.M., and Zanzucchi, G., 1984, Seismoturbidites: a new group of resedimented deposits, *in* Cita, M.B., and RicciLucchi, F., eds., Seismicity and Sedimentation: Amsterdam, Elsevier Scientific Publications, p. 103–116.

Mutti, E., Tinterri, R., Remacha, E., Mavilla, N., Angella, S., and Fava, L., 1999, An introduction to the analysis of ancient turbidite basins from an outcrop perspective: American Association of Petroleum Geologists, Continuing Education, Course Note Series 39, 61 p.

Nakajima, T., and Kanai, Y., 2000, Sedimentary features of seismoturbidites triggered by the 1983 and older historical earthquakes in the eastern margin of the Japan Sea: Sedimentary Geology, v. 135, p. 1–19.

NASA (National Aeronautics and Space Administration), 2005, Earth Observatory and Natural Hazards, URL: http://earthobservatory.nasa.gov/NaturalHazards/natural_hazards_v2.php3?img_id=12645 (accessed June 15, 2005).

Natland, M.L., 1967, New classification of water-laid clastic sediments: American Association of Petroleum Geologists, Bulletin, v. 51, p. 476.

Nichol, S.L., Lian, O.B., and Carter, C.H., 2003, Sheet-gravel evidence for a late Holocene tsunami run-up on beach dunes, Great Barrier Island, New Zealand: Sedimentary Geology, v. 155, p. 129–145.

NOAA (National Oceanic and Atmospheric Administration), 2005a, International Tsunami Information Center, URL: http://www.prh.noaa.gov/itic/library/about_tsu/faqs.html (accessed January 15, 2005).

NOAA (National Oceanic and Atmospheric Administration), 2005b, Pacific Marine Environmental Laboratory, Tsunami Research Program, URL: http://www.pmel.noaa.gov/tsunami/indo_1204.html (accessed June 15, 2005).

NOAA (National Oceanic and Atmospheric Administration), 2005c, NOAA News Online, Story 2365, URL: http://www.noaanews.noaa.gov/stories2005/s2365.htm (accessed June 15, 2005).

Noji, M., Imamura, F., and Shuto, N., 1993, Numerical simulation of movement of large rocks transported by tsunamis, *in* Tsuchiya, Y., and Shuto, N., eds., Tsunami '93 Proceedings of the IUGG : IOC International Tsunami Symposium: Wakayama, Japan, August 23–27, 1993, p. 189–198.

Nott, J., 2003, Tsunami or Storm Waves?—Determining the origin of a spectacular field of wave emplaced boulders using numerical storm surge and wave models and hydrodynamic transport equations: Journal of Coastal Research, v. 19, p. 348–356.

Papadopoulos, G.A., and Kortekaas, S., 2003, Characteristics of landslide generated tsunamis from observational data, *in* Locat, J., and Mienert, J., eds., Submarine Mass Movements and Their Consequences: Dordrecht, The Netherlands, Kluwer Academic Publishers, p. 367–374.

Pettijohn, F.J., 1957, Sedimentary Rocks, 2nd Edition: New York, Harper, 718 p.

Pickering, K.T., Soh, W., and Taira, A., 1991, Scale of tsunami-generated sedimentary structures in deep water: Geological Society of London, Journal, v. 148, p. 211–214.

Piper, D.J.W., Shor, A.N., and Hughes Clark, J.E., 1988, The 1929 "Grand Banks" earthquake, slump, and turbidity current, *in* Clifton, H.E., ed., Sedimentologic Consequences of Convulsive Geologic Events: Geological Society of America, Special Paper 229, p. 77–92.

Pluenneke, J.L., 1976, Comparative analysis of debrites, turbidites, and contourites [M.S. thesis]: Texas A&M University, College Station: Texas, U.S.A., 93 p.

Postma, G., 1986, Classification of sediment gravity-flow deposits based on flow conditions during sedimentation: Geology, v. 14, p. 291–294.

Pratt, B.R., 2002, Storms versus tsunamis: Dynamic interplay of sedimentary, diagenetic, and tectonic processes in the Cambrian of Montana: Geology, v. 30, p. 423–426.

Puig, P., Ogston, A.S., Mullenbach, B.L., Nittrouer, C.A., and Sternberg, R.W., 2003, Shelf-to-canyon sediment-transport processes on the Eel continental margin (northern California): Marine Geology, v. 193, p. 129–149.

Raymond, L.A., 1975, Tectonite and mélange—a distinction: Geology, v. 3, p. 7–9.

Reading, H.G., 1986, Facies, *in* Reading, H.G., ed., Sedimentary Environments and Facies, 2nd Edition: Oxford, U.K. Blackwell Scientific Publications, p. 4–19.

Rizzini, A., and Passega, R., 1964, Évolution de la sédimentation et orogenèse, Vallée du Santerno, Apennin Septentrional, *in* Bouma, A.H., and Brouwer, A., eds., Turbidites: Amsterdam, Elsevier, Developments in Sedimentology 3, p. 65–74.

Rodolfo, K.S., 2003, Tsunamites and seismites: McGraw-Hill Encyclopedia of Science & Technology, AccessScience, on-line article, URL: http://www.accessscience.com/ResUpdates/2003/YB_030915_frameset.html?qq=&q=tsunamite || tsunamites (accessed January 21, 2005).

Rossetti, D.F., Góes, A.M., Truckenbrodt, W., and Anaisse, J, Jr., 2000, Tsunami-induced large-scale scour-and-fill structures in Late Albian to Cenomanian deposits of the Grajaú Basin, northern Brazil: Sedimentology, v. 47, p. 309–323.

Sanders, J.E., 1965, Primary sedimentary structures formed by turbidity currents and related resedimentation mechanisms, *in* Middleton, G.V., ed., Primary Sedimentary Structures and Their Hydrodynamic Interpretation: SEPM, Special Publication 12, p. 192–219.

Sayles, R.W., 1931, Bermuda during the Ice Age: American Academy of Arts and Sciences, Proceedings, v. 66, p. 382–467.

Scheffers, A., and Kelletat, D., 2003, Sedimentologic and geomorphologic tsunami imprints worldwide—a review: Earth-Science Reviews, v. 63, p. 83–92.

Seilacher, A., 1969, Fault graded beds interpreted as seismites: Sedimentology, v. 13, p. 155–159.

Seilacher, A., 1984, Sedimentary structures tentatively attributed to seismic events: Marine Geology, v. 55, p. 1–12.

Shanmugam, G., 1984, Rock names challenged: Geotimes, v. 29, June, p. 6.

Shanmugam, G., 1996, High-density turbidity currents: are they sandy debris flows?: Journal of Sedimentary Research, v. 66, p. 2–10.

Shanmugam, G., 2000, 50 years of the turbidite paradigm (1950s–1990s): deep-water processes and facies models—a critical perspective: Marine and Petroleum Geology, v. 17, p. 285–342.

Shanmugam, G., 2002a, Ten turbidite myths: Earth-Science Reviews, v. 58, p. 313–343.

Shanmugam, G., 2002b, Deep-water processes and turbidite facies models: a paradigm shift, *in* Swamy, S.N., and Kapoor, P.N., eds., Stratigraphic Challenges and Paradigm Shift in Hydrocarbon Exploration with Special References to Frontier Basins: Mussoorie, India, Proceedings of the 1st Association of Petroleum Geologists Conference and Exhibition, v. 1, p. 155–162.

Shanmugam, G., 2003, Deep-marine tidal bottom currents and their reworked sands in modern and ancient submarine canyons: Marine and Petroleum Geology, v. 20, p. 471–491.

Shanmugam, G., 2006, Deep-Water Processes and Facies Models: Implications for Sandstone Petroleum Reservoirs: Amsterdam, Elsevier, 476 p.

Shanmugam, G., and Moiola, R.J., 1982, Eustatic control of turbidites and winnowed turbidites: Geology, v. 10, p. 231–235.

Shanmugam, G., Moiola, R.J., and Sales, J.K., 1988, Duplex-like structures in submarine fan channels, Ouachita Mountains, Arkansas: Geology, v. 16, p. 229–232.

Shepard, F.P., 1973, Submarine Geology, Third Edition: New York, Harper & Row, 517 p.

Shepard, F.P., and Dill, R.F., 1966, Submarine Canyons and Other Sea Valleys: Chicago, Rand McNally, 381 p.

Shepard, F.P., Dill, R.F., and Von Rad, U., 1969, Physiography and sedimentary processes of La Jolla Submarine Fan and Fan-Valley, California: American Association of Petroleum Geologists, Bulletin, v. 53, p. 39–420.

Shepard, F.P., Marshall, N.F., McLoughlin, P.A., and Sullivan, G.G., 1979, Currents in submarine canyons and other sea valleys: American Association of Petroleum Geologists, Studies in Geology, no. 8, 173 p.

Shiki, T., and Yamazaki, T., 1996, Tsunami-induced conglomerates in Miocene upper bathyal deposits, Chita Peninsula, central Japan: Sedimentary Geology, v. 104, p. 175–188.

Shiki, T., Cita, M.B., and Gorsline, D.S., 2000, Sedimentary features of seismites, seismo-turbidites, and tsunamites—an introduction: Sedimentary Geology, v. 135, p. vii–ix.

Simms, M.J., 2003, Uniquely extensive seismite from the latest Triassic of the United Kingdom: Evidence for bolide impact?: Geology, v. 31, p. 557–560.

Simpson, R.H., and Lawrence, M.B., 1971, Atlantic hurricane frequencies along the U.S. coastline: National Oceanic and Atmospheric Administration, Memorandum NWS SR-58, 14 p.

Snedden, J.W., Nummedal, D., and Amos, A.F., 1988, Storm- and fair-weather combined flow on the Central Texas continental shelf: Journal of Sedimentary Petrology, v. 58, p. 580–595.

Stanley, D.J., 1981, Unifites: structureless muds of gravity flow origin in Mediterranean basins: Geo-Marine Letters, v. 1, p. 77–83.

Stanley, D.J., Palmer, H.D., and Dill, R.F., 1978, Coarse sediment transport by mass flow and turbidity current processes and downslope transformations in Annot Sandstone canyon-fan valley systems, *in* Stanley, D.J., and Kelling, G., eds., Sedimentation in Submarine Canyons, Fans, and Trenches: Stroudsburg, Pennsylvania, Hutchinson & Ross, p. 85–115.

Stöffler, D., and Grieve, R.A.F., 2003, Towards a unified nomenclature of metamorphic petrology: 11. Impactites. A proposal on behalf of the IUGS Subcommission on the Systematics of Metamorphic Rocks: Web version of April 30, 2003, URL: http://www.bgs.ac.uk/scmr/docs/paper_12/scmr_paper_12_1.pdf (accessed February 22, 2005).

Stow, D.A.V., 1984, Anatomy of debris-flow deposits, *in* Hay, W.W., and Sibuet, J.C., et al. (1984). Initial Reports, Deep Sea Drilling Project: Washington, D.C., U.S. Government Printing Office, v. 75, p. 801–807.

Stow, D.A.V., Amano, K., Batson, B.S., Brass, G.W., Corrigan, J., Raman, C.V., Tiercelin, J.-J., Townsend, M., and Wijayananda, N.P., 1990, 31. Sediment facies and processes on the distal Bengal Fan, Leg 116, *in* Cochran, J.R., Stow, D.A.V., et al. Proceedings of the Ocean Drilling Project, Leg 116, Scientific Results: College Station: Texas, Ocean Drilling Program, p. 377–396.

Swift, D.J.P., Han, G., and Vincent, C.E., 1986, Fluid processes and sea floor response on a modern storm-dominated shelf; middle Atlantic shelf of North America. Part 1: the storm-current regime, *in* Knight, R.J., and McLean, J.R., eds., Shelf Sands and Sandstones: Canadian Society of Petroleum Geologists, Memoir 11, p. 99–119.

Takahasi, R., and Hatori, T., 1961, A summary report of the Chilean tsunami of 1960, *in* Takahasi, R., ed., Report on the Chilean tsunami of May 24, 1960, as Observed along the Coast of Japan, Committee for field investigation of the Chilean tsunami of 1960: Tokyo, Maruzen Co., p. 23–34.

Tappin, D.R., 2004, Submarine slump-generated tsunamis: Marine Geology, v. 203, p. 199–200.

Tappin, D.R., Watts, P., McMurtry, G.M., Lafoy, Y., and Matsumoto, T., 2001, The Sissano, Papua New Guinea tsunami of July 1998—offshore evidence on the source mechanism: Marine Geology, v. 175, p. 1–23.

Tsutsui, B., Campbell, J.F., and Coulbourn, W.T., 1987, Storm-generated episodic movements off Kahe Point, Oahu, Hawaii: Marine Geology, v. 76, p. 281–289.

Turner, F.J., and Weiss, L.E., 1963, Structural Analysis of Metamorphic Tectonites: New York, McGraw-Hill, 545 p.

USGS (U.S. Geological Survey), 2005, Magnitude 9.0—Sumatra–Andaman Island earthquake, URL: http://earthquake.usgs.gov/eqinthenews/2004/usslav/ (accessed January 15, 2005).

University of Washington, 2005, Tsunami, URL: http://www.geophys.washington.edu/tsunami/general/physics/meaning.html (accessed January 4, 2005).

van den Bergh, G.D., Boer, W., de Haas, H., van Weering, T.C.E., and van Wijhe, R., 2003, Shallow marine tsunami deposits in Teluk Banten (NW Java, Indonesia), generated by the 1883 Krakatau eruption: Marine Geology, v. 197, p. 13–34.

Vivas, V., Macsotay, O., Furrer, M., and Alvarez, E., 1988, Injectitas clásticas asociadas a desplomes en sedimentitas batiales del Cretáceo Superior de Venezuela nor-oriental: Sociedad Venezolana de Geología, Boletín, v. 34, p. 3–33.

Whelan, F., and Keating, B., 2004, Tsunami deposits on the Island of Oahu, Hawaii: Coastline Reports, v. 1, p. 77–82.

Wikipedia, The Free Encyclopedia, 2005, 2004 Indian Ocean earthquake, URL: http://en.wikipedia.org/wiki/2004_Indian_Ocean_earthquake#Countries_affected (accessed January 28, 2005).

Wood, D.S., 1974, Ophiolites, mélanges, blueschists, and ignimbrites: Early Caledonian subduction in Wales, *in* Dott, R.H, Jr., and Shaver, R.H., eds., Modern and Ancient Geosynclinal Sedimentation: SEPM, Special Publication 19, p. 334–344.

Yamazaki, T., Yamaoka, M., and Shiki, T., 1989, Miocene offshore tractive current-worked conglomerates—Tsubutegaura, Chita Peninsula, central Japan, *in* Taira, A., and Masuda, F., eds., Sedimentary Features in the Active Plate Margin: Tokyo, Terra Scientific Publishing Company, p. 483–494.

Young, R.W., and Bryant, E.A., 1998, Morphology and Process on the Lateritic Coastline near Darwin, Northern Australia: Zeitschrift für Geomorphologie, v. 42, p. 97–107.

Received 5 July 2005; accepted 10 December 2005.