Journal of Palaeogeography, 2016, 5(4): 318—362 (00104)

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: http://www.journals.elsevier.com/journal-of-palaeogeography/

Multi-origin of soft-sediment deformation structures and seismites

The seismite problem

G. Shanmugam

Department of Earth and Environmental Sciences, The University of Texas at Arlington, Arlington, TX 76019, USA

Abstract During a period of 82 years (1931—2013), 39 genetic terms were introduced for various deposits. Of the 39 terms, only ten are meaningful in understanding the true depositional origin (*e.g.*, turbidites), the remaining 29 are just jargons (*e.g.*, seismites, tsunamites, *etc.*). The genetic term "seismites", introduced by Seilacher (1969) for recognizing palaeoearthquakes in the sedimentary record, is a misnomer. The term was introduced in haste, based on an examination of a single exposure of the Miocene Monterey Formation (10 m) in California, without a rigorous scientific analysis. The fundamental problem is that earthquake is a triggering mechanism, not a depositional process. Type of triggers cannot be recognized in the ancient sedimentary record because evidence for triggers is not preserved by nature. Soft-sediment deformation structures (SSDS), commonly used as the criteria for interpreting seismites, are a product of liquefaction. However, liquefaction can be induced by any one of 21 triggers, which include earthquakes, meteorite impacts, tsunamis, sediment loading, among others. Brecciated clasts, typically associated with earthquake-induced deposits in the Dead Sea Basin, are also common depositional products of debris flows (*i.e.*, synsedimentary product unrelated to earthquakes). Also, various types of SSDS, such as duplex-like structures and clastic injections, can be explained by synsedimentary processes unrelated to earthquakes. Case studies of sandstone petroleum reservoirs worldwide, which include Gulf of Mexico, North Sea, Norwegian Sea, Nigeria, Equatorial Guinea, Gabon, and Bay of Bengal, reveal that there is compelling empirical evidence for sediment loading being the primary cause of SSDS. The Krishna—Godavari Basin, located on the eastern continental margin of India, is ideal for sediment failures by multiple triggering mechanisms where overpressure and liquefaction have led to multi-origin SSDS. Because tsunamis and meteorite impacts are important phenomena in developing extensive deposits, lateral extent of SSDS cannot be used as a unique distinguishing attribute of earthquakes. For these reasons, the genetic term "seismites", which has no redeemable scientific value, is obsolete.

Keywords Soft-sediment deformation structures (SSDS), Seismites, Earthquakes, Meteorite impacts, Liquefaction, Clastic injections

Received 18 April 2016; accepted 1 June 2016; available online 16 August 2016

E-mail address: shanshanmugam@aol.com.

Peer review under responsibility of China University of Petroleum (Beijing).

http://dx.doi.org/10.1016/j.jop.2016.06.002

1. Introduction

Logan (1863) was one of the early workers who accurately sketched the complexity of soft-sediment deformation structures (SSDS), which include slump folds in Devonian limestones exposed in the Gaspé Peninsula of Quebec, Canada. The significance of his observation is that localized deformed beds occur within otherwise undeformed beds (Fig. 1). This sandwiched occurrence of folded layers between undeformed layers is the underpinning principle of SSDS. In a detailed study of slump folds in the Upper Ordovician flysch of Newfoundland Appalachians, Canada, Helwig (1970, p.172) attributed the origin of slump folds to early deformation, but cautions that "*A strict distinction between sedimentary and tectonic structures seems unrealistic because the close relationship of tectonics and sedimentation in mobile belts assures widespread prelithification deformation*". Perhaps for this reason, the origin of soft-sediment deformation has long been a point of contention (Maltman, 1984, 1994a, 1994b).

Kirkland and Anderson (1970) were the first to describe some spectacular microfolds in the anhydrite—calcite layers of the Castile Formation of Permian Age in the Delaware Basin, New Mexico and Texas. The significance of their study is that they utilized not only outcrops but also subsurface cores (Fig. 2), taken specifically for research purposes, funded by the National Science Foundation (USA). Kirkland and Anderson (1970) attributed the origin of microfolds to tectonism. The meter-scale folds on each side of the basin intermittently slumped. In the process, the millimeter-scale microfolds formed in the interior of the larger folds. As the folds formed there was a room problem in the center of the larger folds, which caused the microfolding to occur (Fig. 2). It is worth noting that anhydrite layers may behave differently than those of clastic rocks due to differences in their plasticity during deformation. In further explaining the origin of Castile microfolds, Alexander and Watkinson (1989, p. 750) state that "*In conclusion, we envisage the tectonic scenario for the Castile folds as multilayer buckling with stress concentrations in the hinge zones of the larger-scale folds causing increased strain rates and initiation of buckle-folded layers between stabilized layers, both thicker and thinner than the folded layers*". These authors dealt with the origin of microfolds strictly as a structural geology problem.

On the other hand, the Castile microfolds are attractive candidates for classifying them as "seismites" for two reasons. First, the Castile microfolds are sandwiched between undeformed layers (Fig. 2), which is a major criterion for recognizing seismites (Seilacher, 1969). Second, discrete units of Castile microfolds were correlated over a distance of 113 km (Kirkland and Anderson, 1970; Kirkland *et al.*, 2000), which is another criterion for recognizing seismites (Sims, 1975). The seismic origin, however, suffers because it is difficult to explain as to why seismic

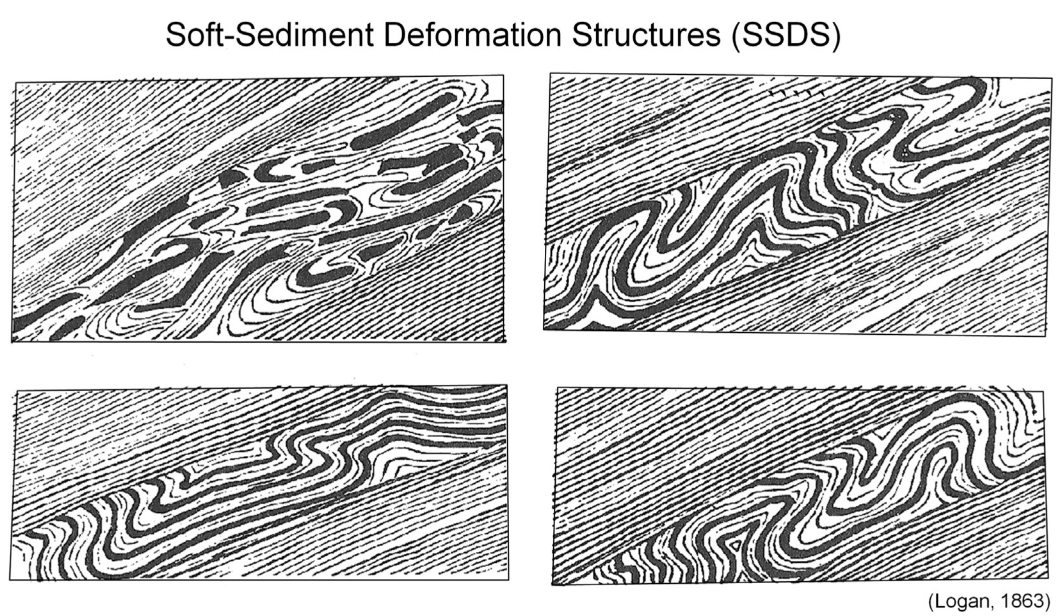

Fig. 1 Detailed sketches by Sir William Edmond Logan of localized deformed beds within otherwise undeformed Devonian limestones, Gaspé Peninsula, Quebec, Canada (Logan, 1863). Such deformed beds are commonly called "Soft-sediment deformation structures" (SSDS). Diagram reproduced from Maltman (1994a).

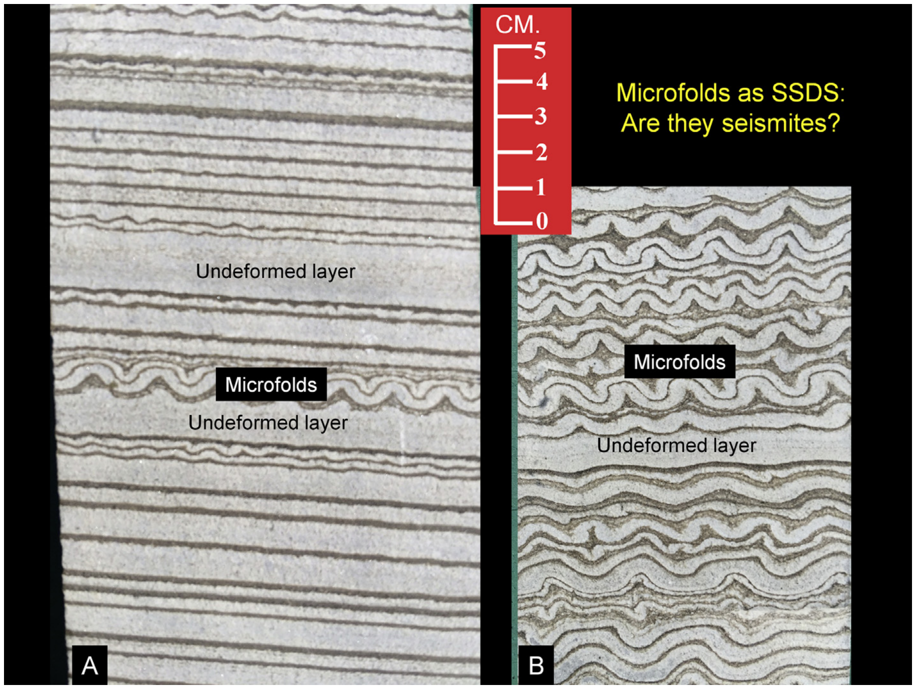

Fig. 2 Core photographs showing microfolds in anhydrite (white) layers with intervening undeformed anhydrite layers. Dark layers represent calcite with organic matter. A—Core slab dominated by undeformed layers with rare layers of microfolds; B—Core slab dominated by layers of microfolds with rare unreformed layers. These examples are classic SSDS because deformed layers are sandwiched between undeformed layers. SSDS = Soft-sediment deformation structures. Castile Formation, Permian, Delaware Basin, New Mexico. Samples courtesy of D. W. Kirkland. See Kirkland and Anderson (1970) for a detailed study of the Castile microfolds.

shocks affected only certain millimeter-thick anhydrite layers but not the adjacent anhydrite millimeter-thick layers (Fig. 2) that are located just millimeters apart. The tectonic origin of these microfolds faces the same challenge. This conundrum is not unique to the Castile microfolds. For example, Rodríguez-Pascua *et al.* (2000) and Rodríguez-Lopez *et al.* (2007) have interpreted SSDS that are sandwiched between undeformed layers as seismites. They occur at various scales. I have encountered this challenge in many of my subsurface studies worldwide. In fact, the very use of SSDS, with alternating deformed and undeformed layers, as a key criterion for interpreting seismites requires a close scrutiny at several fundamental levels.

1.1. The seismite problem

Seilacher (1969) first proposed the genetic term "seismites" to interpret earthquake-deformed beds composed of SSDS. There are inherent problems associated with the genetic terms in general (see Section 2), and "seismites" in particular. Selected examples are:

1) Seilacher (1969, pp. 155—158) proposed the genetic term "seismites" with the following characteristics: *"These units differ from ordinary marine slides by the soupy top layer and by lack of a basal slip surface (G. Einsele, personal communication, 1969). It seems more plausible to connect them with seismic shocks acting on gently dipping muds in which compaction gradually increased down from the water—sediment interface. In this case the sliding process may not have had time to develop fully so that the deformational structures became 'frozen' in an embryonic stage, without resulting in a major lateral transport. It should be realized that this would be only one type of earthquake beds, or* ***seismites*** *(genetic term, proposed herewith). Depending on mud consistency and paleoslope, as well as strength, duration and type of the shock, quite different structures may result. In perfectly horizontal mud layers, or under weaker shocks, for instance, nothing but the liquefied zone would form. Nevertheless gradational transition at the lower and sharp contact at the upper boundary would make the structure distinctive. Stronger shocks and paleoslope, on the other hand, may lead to regular slides or turbidity currents, the deposits of which would not be earmarked as seismites any more".*

2) The two important contributions of Seilacher (1969) are: ① The introduction of the genetic term "seismites"; ② The proposal of a standard vertical sequence for seismites composed of the following four divisions:
   a — Soupy zone (top);
   b — Rubble zone;
   c — Segmented zone;
   d — Undisturbed sediment (bottom).
3) Seilacher (1969) used the terms "earthquake-beds" and "seismites" synonymously, despite the differences in meanings between the two. For example, an earthquake refers to shaking of the surface of the Earth, whereas seismicity refers to frequency and size of earthquakes over a period of time. However, there are no objective criteria to distinguish deposits of seismicity, which has a time component, in the ancient sedimentary record.
4) Although the seismite problem is a complex sedimentological/structural/tectonic issue, the late Adolf Seilacher (1925—2014) was a paleontologist by training and the one who pioneered analyses of trace fossils (Briggs, 2014).
5) Clearly, the term "seismite" implies a triggering mechanism (*i.e.*, earthquake), not flow behavior of a specific depositional process that is the requirement for a genetic term (see Section 2). Furthermore, "soft-sediment deformation structures" (SSDS), which are used for recognizing seismites, are not depositional features that are unique to earthquakes (see Section 3). The moment a deformed bed is classified as a seismite, there is only one designated origin for that bed, which is earthquake. All other options are immediately excluded in interpreting the ancient sedimentary record. Such a rigid approach is detrimental to a pragmatic analysis of considering alternative possibilities.
6) The key problem with the standard vertical sequence (a, b, c, and d), proposed by Seilacher (1969) for seismites, is that it is based on a short field excursion to a single outcrop, without corroborations from multiple sites in California. For comparison, Bouma (1962) proposed a standard vertical sequence for an ideal turbidite bed with five internal divisions in ascending order (Ta, Tb, Tc, Td, and Te) based on his detailed outcrop studies covering 18 field locations in France, Switzerland, Germany, The Netherlands, and Italy (see Table 2).
7) According to Einsele *et al.* (1996, p. 2), "*In-situ earthquake structures may be termed to 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 other words, the term "seismites" is purely a cosmetic one.
8) 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). Except for the underlying 'seismite' unit, the overlying 'tsunamite' unit with hummocky cross stratification would 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).
9) Soft-sediment deformation structures (SSDS), composed of load casts, ball-and-pillows and pipes induced by liquidization (liquefaction and/or fluidization, in Upper Miocene sandy deposits of the eastern Betic Cordillera (SE Spain) were originally interpreted as a result of seismic shocks (*i.e.*, seismites) (Alfaro, 1995). However, Alfaro *et al.* (2002) reinterpreted the same deposits with SSDS as the product of storm waves (*i.e.*, tempestites). In other words, the observation has remained the same, but the interpretation has totally changed. Such cases demonstrate the lack of objective criteria for interpreting seismites.
10) Merriam and Neuhauser (2009) have published an article entitled "*Seismite Indicates Pleistocene Earthquake Activity in Ellis County, Kansas*". In this case, the authors have used an interpretive term "seismites" as "data" to justify their interpretation, which is circular reasoning.
11) Even in seismically active areas, such as the Northern San Andreas Fault, recognition of the influence of seismic activity on a deposit is challenging (see debate by Shanmugam, 2009).

Shanmugam (2006b) originally wrote a cautionary note on the dangers of applying genetic terms, such as tsunamites and seismites, to the rock record and suggested that these terms are sedimentologically obsolete for conveying their depositional origin. Without acknowledging this fundamental problem, Moretti and Van Loon (2014) wrote a cautionary note on the limitations of the seismite concept. Despite these warnings, researchers continue to apply the concept (see papers in this issue). The concept of seismites has been popular (Ettensohn *et al.*, 2002; Feng *et al.*, 2016; Gao *et al.*, 2010; Greb *et al.*, 2002; Jewell and Ettensohn, 2004; Mazumder *et al.*, 2006, 2016; Montenat *et al.*, 2007; Moretti and Sabato, 2007; Moretti and Van Loon, 2014; Obermeier, 1996; Rodríguez-Pascua *et al.*, 2000; Seilacher, 1984; Shao *et al.*, 2012; Sims, 1975; Tian *et al.*, 2015; Van Loon, 2009, 2014; Wheeler, 2002; Wizevich *et al.*, 2016; among others). The use of a wide range of SSDS as criteria to recognize seismites is common (Agnon *et al.*, 2006; Allen, 1986; Du, 2011; He and Qiao, 2015; Kale *et al.*, 2016; Martín-Chivelet *et al.*, 2011; Mazumder *et al.*, 2006; Mohindra and Bagati, 1996; Moretti, 2000; Pinto and Warme, 2008; Rodríguez-Pascua *et al.*, 2000; Roy and Banerjee, 2016; Su and Sun, 2012; Van Loon and Pisarska-Jamroży, 2014; Zhang *et al.*, 2007).

Song (1988) discovered "plate-spiny breccia structure" occurring in the seismic-tsunami sedimentary succession in the Proterozoic Wumishan Formation of the Ming Tombs area, Beijing. The sedimentologic significance of these SSDS was presented at the 30th IGC held in Beijing (Song and Einsele, 1996). Furthermore, Ettensohn *et al.* (2011) termed these structures as "accordion folds", and proposed that they be considered as the new seismogenic indicator. Paradoxically, the standard vertical sequence of seismites proposed by Seilacher (1969), with four internal divisions (a, b, c, and d), has not been reported universally. The prevailing disconnect between the flawed genetic term "seismites" and its continued application in geology is rather troubling. In this context, it is imperative to have a critical appraisal of this problem that has implications for process sedimentology, structural geology, seismology, soil mechanics, and petroleum geology.

1.2. Objectives

The primary objective of this review is to critically appraise the merits of the genetic term "seismites" and its applicability to the geologic record. Specific objectives are the following:

1) To understand the geologic details that served as the basis for proposing the genetic term "seismites" and the related vertical sequence.
2) To present the basic principles of genetic nomenclatures, their history, and statistics.
3) To document a myriad of subsurface SSDS in cores associated with sandstone petroleum reservoirs worldwide. The advantage of freshly slabbed subsurface cores is that they offer pristine surfaces that reveal immaculate details of sedimentary features (Figs. 2—15; and see Figs. 22, 23, 25C, 28B, 29C, 31C and 35 in below). There are only a few published examples of subsurface SSDS in cores (*e.g.*, Ezquerro *et al.*, 2015; Kirkland and Anderson, 1970; Zheng *et al.*, 2015).
4) To illustrate the challenges in establishing the seismic origin of SSDS in terms of trigger and liquefaction.
5) To demonstrate the challenges in distinguishing the lateral extent of SSDS by earthquakes from those by tsunamis and meteorite impacts.
6) To discuss the importance of SSDS for evaluating petroleum reservoirs.

This contribution, a follow-up to my earlier "*The tsunamite problem*" (Shanmugam, 2006b), is the sixth in a series of critical reviews that identify and document major problem areas in sedimentology, with emphasis on deep-water processes, deposits, and environments:

1) Turbidites (Shanmugam, 2000);
2) Tsunamites (Shanmugam, 2006b);
3) Landslides (Shanmugam, 2015);
4) Submarine fans (Shanmugam, 2016a);
5) Contourites (Shanmugam, 2016c);
6) Seismites (Shanmugam, this article).

This article covers 153 years of research (1863—2016) by citing 269 references. A companion paper discusses the multiple origins of earthquakes and their implications for interpreting SSDS with different types of breccias as seismites (Shanmugam, 2017).

1.3. Datasets

In compiling this review, I have relied not only on the traditional method of evaluating published articles on seismites, but also on my rock description of 35 case studies of deep-water systems, which comprise 32 petroleum-producing massive sands worldwide. Description of core and outcrop was carried out at a scale of 1:20 to 1:50, totaling 11,463 m, during 1974—2011, by G. Shanmugam as a Ph.D. student (1974—1978), as an employee of Mobil Oil Corporation (1978—2000), and as a consultant (2000 to present). Global studies include a total of 7832 m of conventional cores from 123 wells, representing 32 petroleum fields worldwide (Shanmugam, 2015, his Fig. 1 and his Table 2). These modern and ancient deep-water systems include both marine and lacustrine settings. Selected core and outcrop examples are used in this contribution. Specifically, I have utilized deep-water

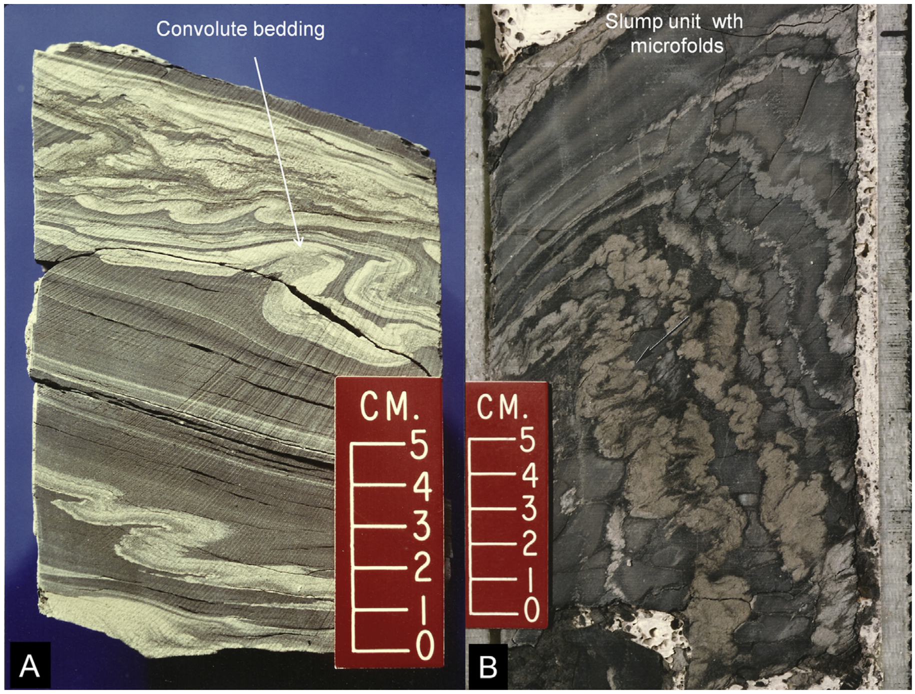

Fig. 3 A—Core photograph showing interbedded occurrence of deformed (convolute bedding) sandstone and siltstone (light gray) layers with undeformed claystone (dark gray) layers. Paleocene, U.K. North Sea. Figure from Shanmugam (2012a), with permission from Elsevier. Copyright Clearance Center's RightsLink: Licensee: G. Shanmugam. License Number: 3880791052847. License Date: June 2, 2016; B—Core photograph showing an asymmetrical slump fold in mudstone with internal microfolds, Edop Field, Pliocene, Offshore Nigeria. From Shanmugam (2006a), with permission from Elsevier.

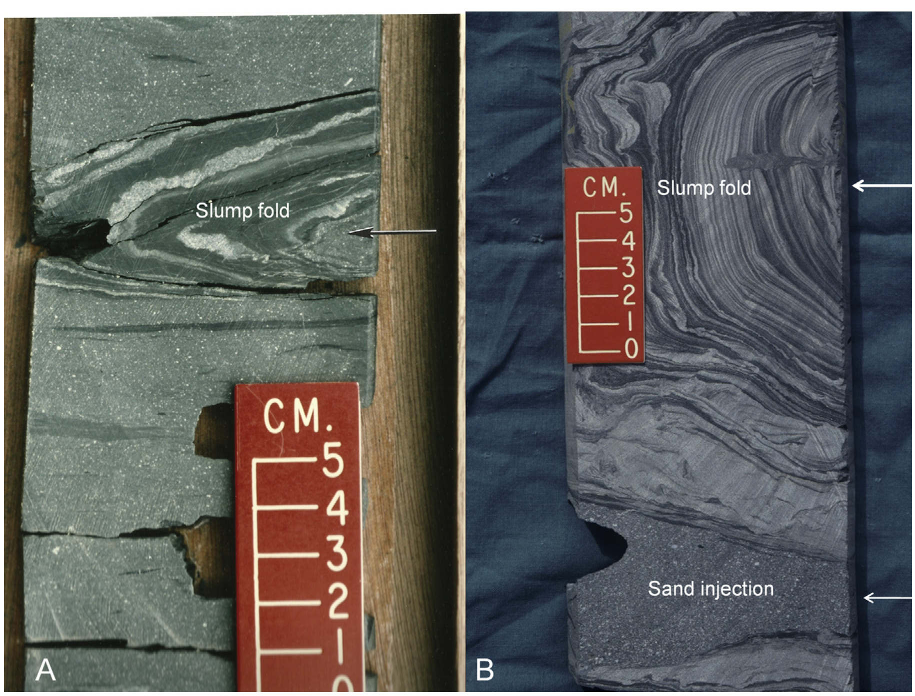

Fig. 4 A—Core photograph showing slump-fold axis (arrow) of a heterolithic facies unit in sandstone, Cretaceous, West Africa. Figure from Shanmugam (2012a), with permission from Elsevier. Copyright Clearance Center's RightsLink: Licensee: G. Shanmugam. License Number: 3880791052847. License Date: June 2, 2016; B—Core photograph showing slump-folded heterolithic (sand and mud) facies and associated sand injection, Paleocene, Faeroe Basin, U.K. Continental Margin. After Shanmugam *et al.* (1995), with permission from American Association of Petroleum Geologists (AAPG).

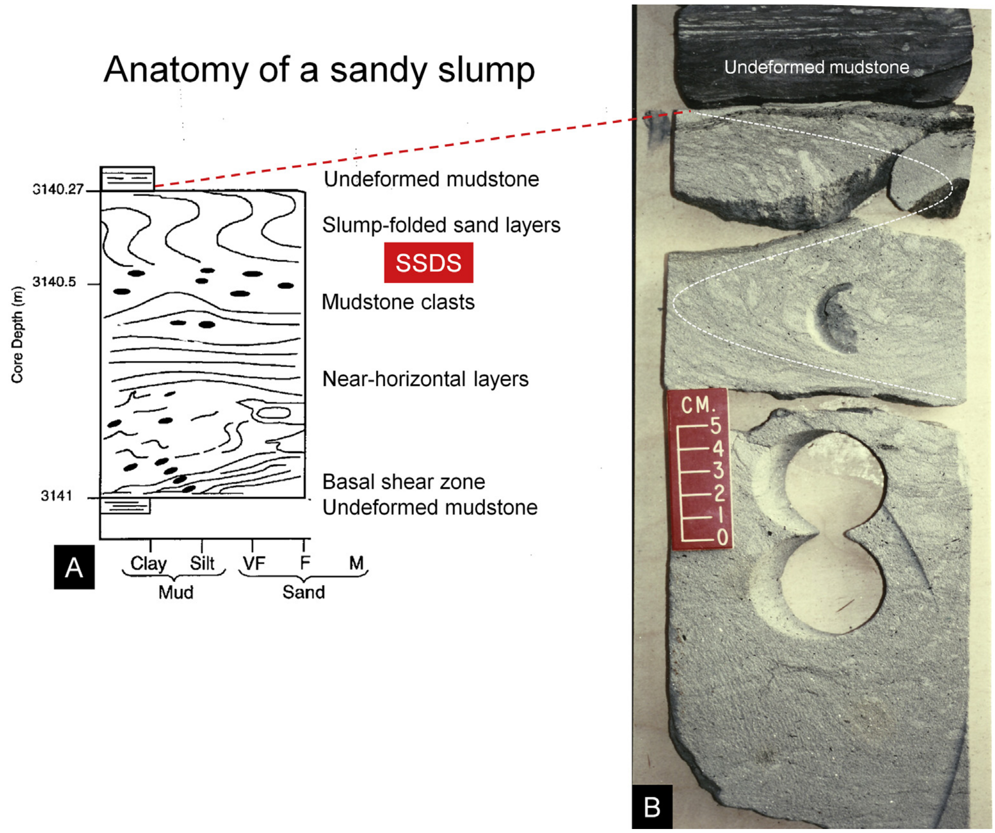

Fig. 5 A—Sedimentological log of the entire sandy slump unit that is sandwiched between undeformed mudstone units above and below. Note the basal shear zone; B—Core photograph showing slump-folded sand layers with overlying undeformed mudstone. SSDS = Soft-sediment deformation structures. Cretaceous, Lysing Formation, offshore Norway. After Shanmugam *et al.* (1994), with permission from American Association of Petroleum Geologists (AAPG).

case studies from the Gulf of Mexico, Norwegian Sea, North Sea, Offshore Nigeria, Offshore Equatorial Guinea, Offshore Gabon, and Bay of Bengal (Shanmugam, 2006a, 2012a, 2015, 2016a, 2016b).

2. Genetic nomenclatures

2.1. History

As noted earlier, Seilacher (1969) first introduced the genetic term "seismite". By decree, the term has a built-in origin (*i.e.*, earthquake induced). Therefore, other possibilities are disallowed. Given these constraints, it is worth reviewing the origin of genetic terms.

In science, words should have clear and consistent meanings. In geology, however, this has not always been the case (Shanmugam, 2006b). 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. For a genetic term in process sedimentology to be meaningful, 1) it must be based on sound principles of fluid dynamics; 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); and 3) it must imply a diagnostic flow behavior (Shanmugam, 2006a). Nonetheless, different authors have expanded the original meaning of the term "turbidite" to include deposits that are not turbidites. As a consequence, there is a plethora of turbidite nomenclature that include 1) atypical turbidites, 2) fluxoturbidites, 3) hemiturbidites, 4) high-concentration sandy turbidites, 5) megaturbidites, 6) problematica turbidites, 7) seismoturbidites, and 8) undaturbidites. And all these terms fail to reveal a clear flow behavior (Table 1). Van der Lingen (1969) was the first one to publish a paper entitled "*The turbidite problem*" by addressing fundamental issues associated with turbidites. Furthermore, some researchers misuse

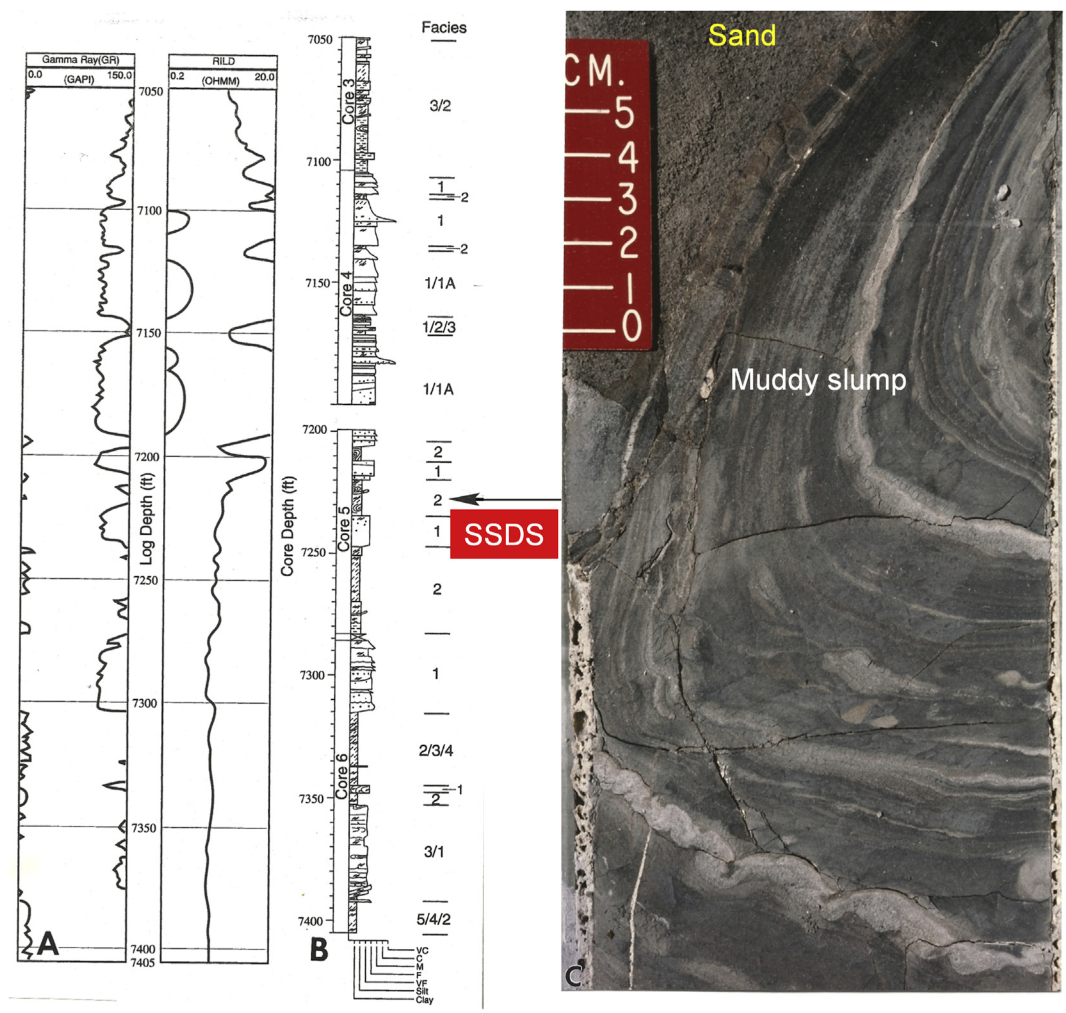

Fig. 6 A—Blocky wireline log motifs, IQI-3, Mobil 25C well, Edop Field, offshore Nigeria; B—Depth-tied sedimentological log; C—Core photograph showing an asymmetrical slump fold in mudstone. SSDS = Soft-sediment deformation structures. Arrow shows stratigraphic position of core photograph. Note undeformed sand above. After Shanmugam (2006a), with permission from Elsevier.

the concept of genetic nomenclature. Mutti *et al.* (1999), for example, used the term "turbidite" for "debrite". Stow *et al.* (2008) proposed the term "contourite" for "tidalite" (see review by Shanmugam, 2016c). The term "tsunamite" is sedimentologically meaningless (Shanmugam, 2006b). An extreme case is the use of the term "injectite" for clastic injections (Table 1) that are commonly post-depositional and in many cases tectonic in origin.

2.2. Statistics

A survey of genetic terms reveals that during a period of 82 years (1931—2013), geoscientists have manufactured and published at least 39 genetic terms (Table 1). On the average, a genetic term is being introduced every two years. Of the 39 terms listed in Table 1, only ten are meaningful in understanding the true depositional origin, the rest are just jargons and should be abandoned.

2.3. The genesis of the term "seismites"

In understanding the root-cause of the problem, it is worth evaluating the circumstances that led to the introduction of the genetic term "seismites". See Seilacher (1969) for details:

1) Prof. Adolf Seilacher was appointed to a position of a visiting professor at the University of California at Santa Cruz in the late 1960s. In that capacity, he had carried out research under the auspices of the

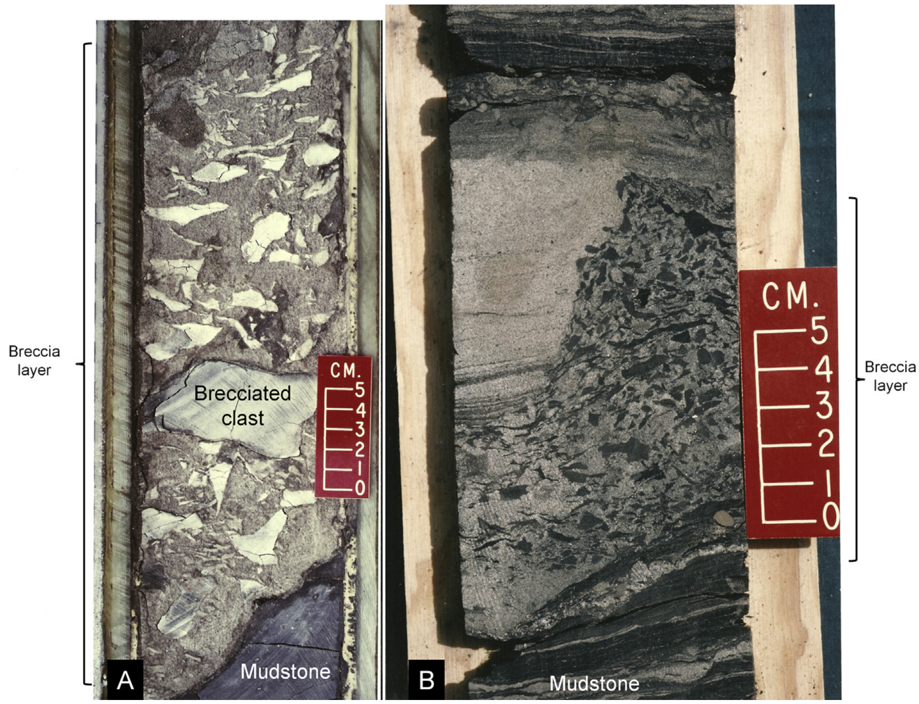

Fig. 7 A—Core photograph showing brecciated mudstone clasts (light gray) in fine-grained sand, Eocene, U.K. North Sea. Figure from Shanmugam (2012a), with permission from Elsevier. Copyright Clearance Center's RightsLink: Licensee: G. Shanmugam. License Number: 3880791052847. License Date: June 2, 2016; B—Core photograph showing brecciated mudstone clasts in sandy matrix. This could represent the incipient stage of sandy debris flow. Cretaceous, Agat Formation, offshore Norway. After Shanmugam *et al.* (1994), with permission from American Association of Petroleum Geologists (AAPG).

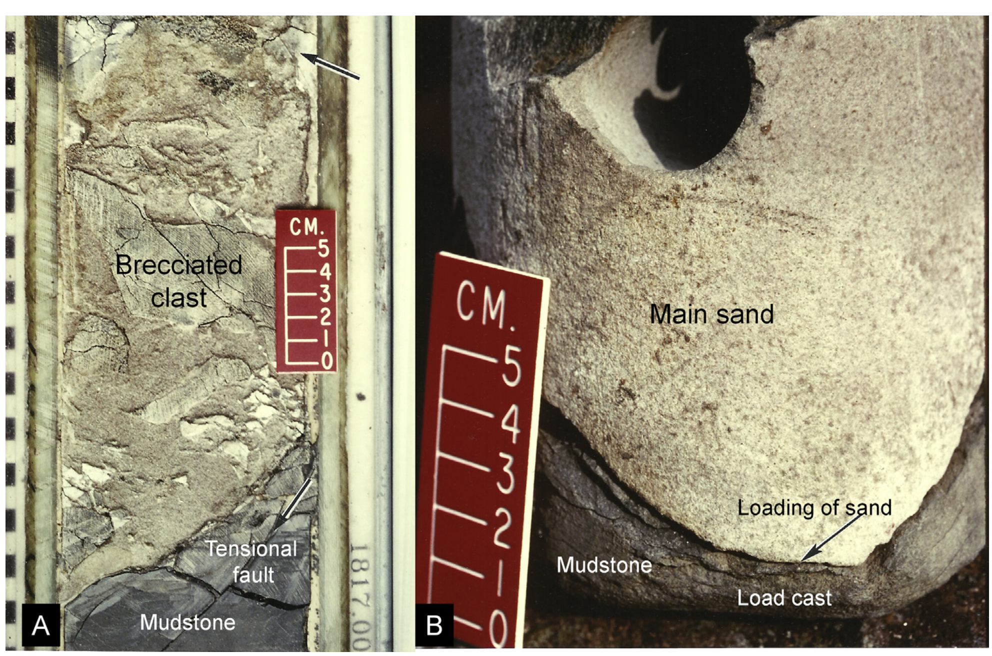

Fig. 8 A—Core photograph showing tensional fault in mudstone (lower arrow) and planes of weakness in the deformed sand (upper arrow). Middle Eocene, U.K. North Sea; B—Core photograph showing loading of the main sand into underlying mudstone (arrow). Note load cast in the underlying mudstone, Eocene, U.K. North Sea. Figures from Shanmugam (2012a), with permission from Elsevier. Copyright Clearance Center's RightsLink: Licensee: G. Shanmugam. License Number: 3880791052847. License Date: June 2, 2016.

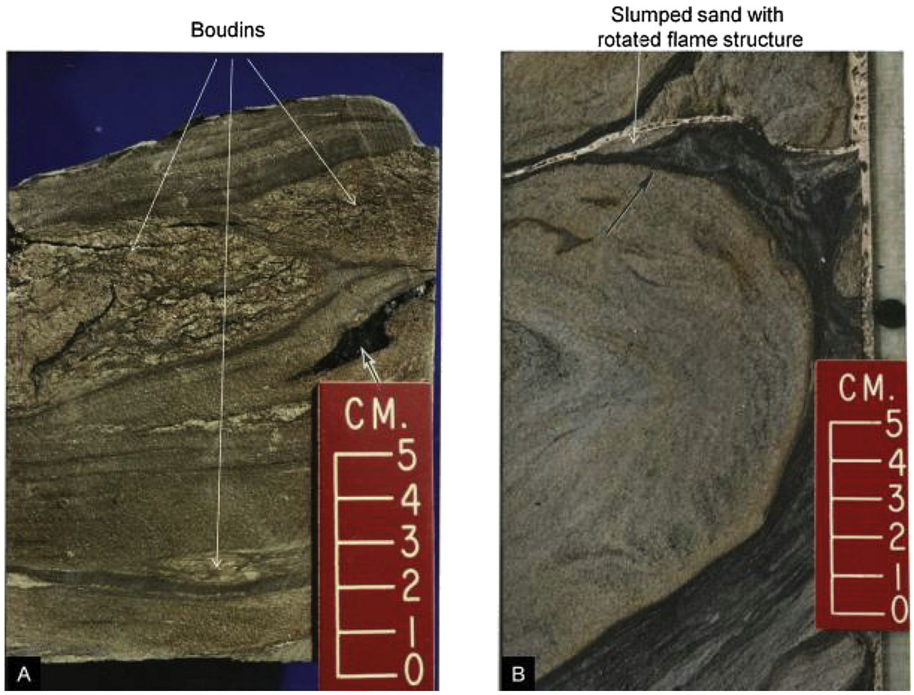

Fig. 9 A—Core photograph showing deformed sand with boudins (arrows) of heterolithic grains and carbonaceous (coal) fragments, Paleocene, U.K. North Sea; B—Core photograph showing rotated flame structure (arrow) in slumped sand, Pliocene, offshore Nigeria. Figures from Shanmugam (2012a), with permission from Elsevier. Copyright Clearance Center's RightsLink: Licensee: G. Shanmugam. License Number: 3880791052847. License Date: June 2, 2016.

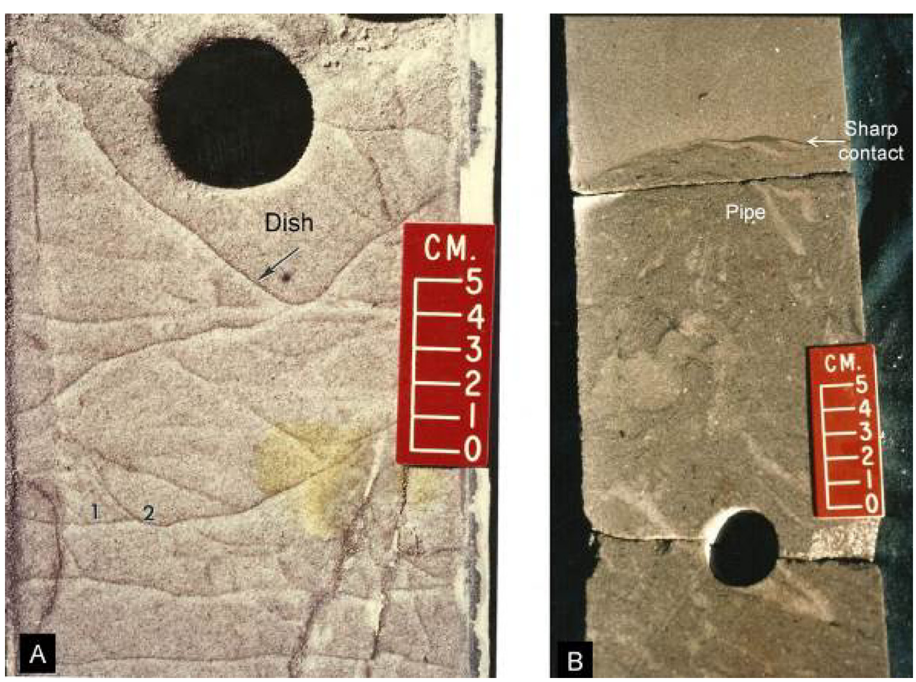

Fig. 10 A—Core photograph showing water-escape dish structures by liquidization in fine-grained, well-sorted sand. The arrow shows a concave-up (dish structure) color couplet with left wing dipping at 45° from the core horizontal due to deformation. Note cross-cutting relationship between two dish structures in which an earlier formed dish structure (1) has been terminated by a later one (2). Eocene, U.K. North Sea. From Shanmugam (2006a), with permission from Elsevier; B—Core photograph showing pipes (water-escape structures). Paleocene, U.K. Atlantic Margin. Figures from Shanmugam (2012a), with permission from Elsevier. Copyright Clearance Center's RightsLink: Licensee: G. Shanmugam. License Number: 3880791052847. License Date: June 2, 2016.

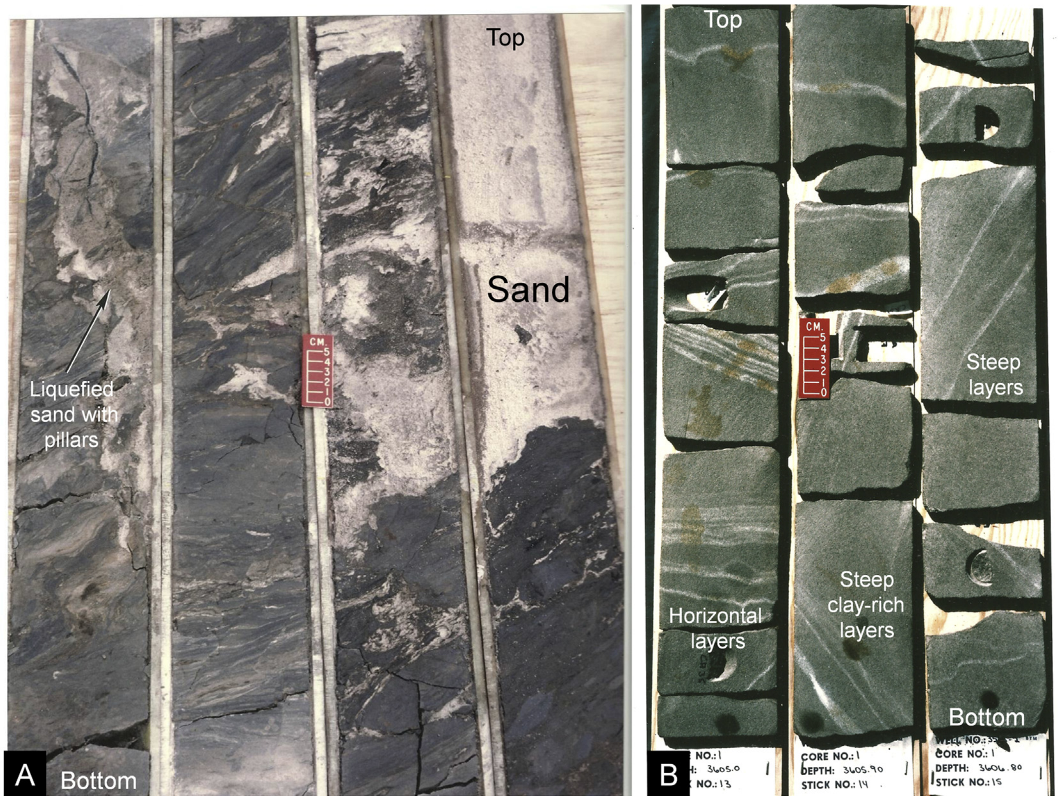

Fig. 11 A—Core photograph showing liquefied sand with a vertical pillar of sand (arrow) cutting across mudstone. Lower left is bottom and upper right is top. Pliocene, offshore Nigeria. Figure from Shanmugam (2012a), with permission from Elsevier. Copyright Clearance Center's RightsLink: Licensee: G. Shanmugam. License Number: 3880791279258. License Date: June 2, 2016; B—Core photograph showing steeply dipping clay-rich layers (white) adjacent to horizontal layers in sandstone. Cretaceous, Agat Formation, offshore Norway. After Shanmugam *et al.* (1994), reprinted by permission from American Association of Petroleum Geologists (AAPG).

university regents and of Dr. Aaron Waters, Head of the Geology Department. During this appointment, he took a short field excursion to study the steeply dipping beds of the Monterey Shales (Miocene) at a nearby Elwood Beach, north of Santa Barbara, California, USA. He described this excursion as follows (Seilacher, 1969, p. 155): "*When the observations were made during a short excursion (May 1968), only a narrow stretch of about 10 m remained free from sand. Nevertheless it was possible to observe three major and a few minor **fault-graded beds** as described in Plate I and Fig. 1. Each one retains the same aspect over the whole outcrop (about 50 m) and probably over a much larger area*".

2) Based on his brief study, he proposed the genetic term "seismites" in the journal *Sedimentology* (Seilacher, 1969). The publication was a "Short communication", not a regular research article (Table 2).
3) In this publication, there are no detailed descriptions or sedimentological logs of studied beds.
4) There is no stratigraphic or structural framework for the studied beds. This is critical because the Miocene Monterey Formation is composed of a lower calcareous facies, a middle transitional phosphatic facies, and a thick upper siliceous facies composed of diatomaceous rocks and their diagenetic equivalents (chert, porcelanite, *etc.*) (see Isaacs *et al.*, 1983).
5) Historically, the Monterey Formation has been one of the best studied and documented geological units in California because of its geological interest (Behl, 1999; Bramlette, 1946) and its petroleum potential (Crawford, 1971). Disappointingly, none of the five references included in the publication of Seilacher (1969) dealt with the Monterey Formation.
6) There is no independent evidence for earthquakes at the time of deposition of the Miocene Monterey beds.
7) There are no discussions of alternative hypotheses to earthquake to explain the deformation in the Monterey Formation.

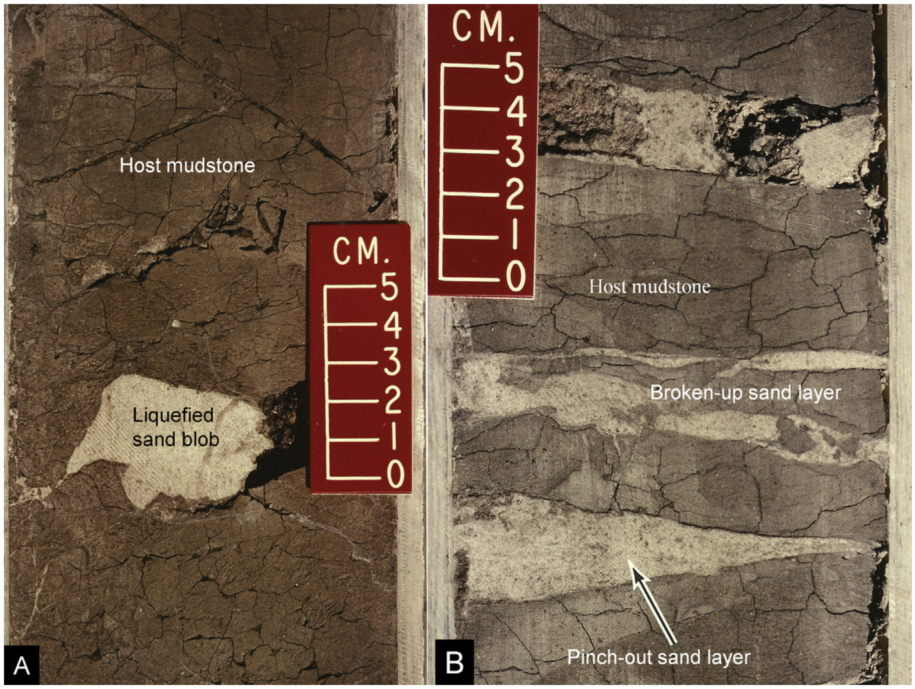

Fig. 12 A—Core photograph showing a sandstone blob injected into mudstone host. Such features may be interpreted to be injection of liquefied sand. Eocene, U.K. North Sea; B—Core photograph showing lateral pinch-out shape (arrow) of a sand injection. Eocene, U.K. North Sea. Figures from Shanmugam (2012a), with permission from Elsevier. Copyright Clearance Center's RightsLink: Licensee: G. Shanmugam. License Number: 3880791279258. License Date: June 2, 2016.

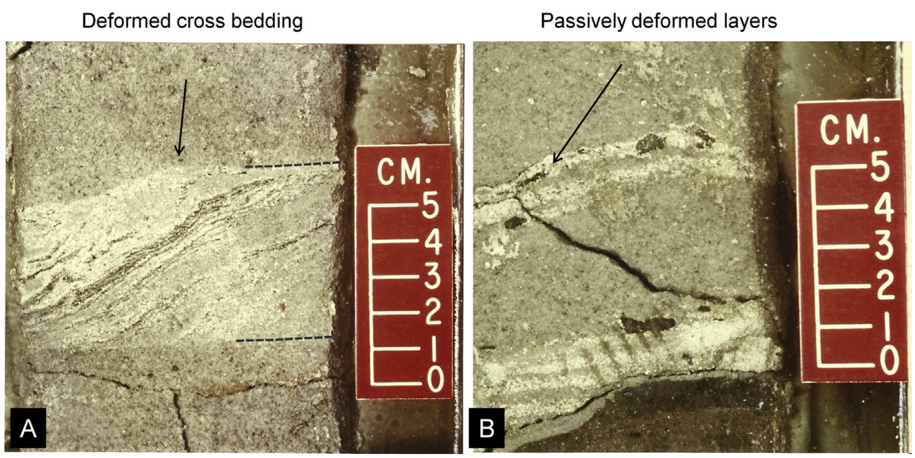

Fig. 13 A—Core photograph showing injection of cross-bedded sand (middle) into massive sand. Note distinct change in lithology revealed by a change in texture and coloration between the injected (cross bedded) and host (massive) sands. Dashed lines mark the upper and lower margins of the injected sand. Eocene, U.K. North Sea; B—Core photograph showing passively deformed internal clay-rich layers (arrow) with mudstone clasts. Eocene, U.K. North Sea. Figures from Shanmugam (2012a), with permission from Elsevier. Copyright Clearance Center's RightsLink: Licensee: G. Shanmugam. License Number: 3880791279258. License Date: June 2, 2016.

However, other researchers have proposed a different origin for SSDS in the Monterey Formation and in other deep-water sediments in California. Selected examples are:

1) The seminal document on the Monterey Formation in California was the U.S. Geological Survey Professional Paper 212 by Bramlette (1946), published some twenty three years earlier than the publication by Seilacher (1969). Bramlette (1946, his Plate 19B) shows a classic example of a folded unit sandwiched between undeformed layers (*i.e.*, SSDS) and the Plate 19B caption reads "*Intraformational deformation due to slumping during deposition*".

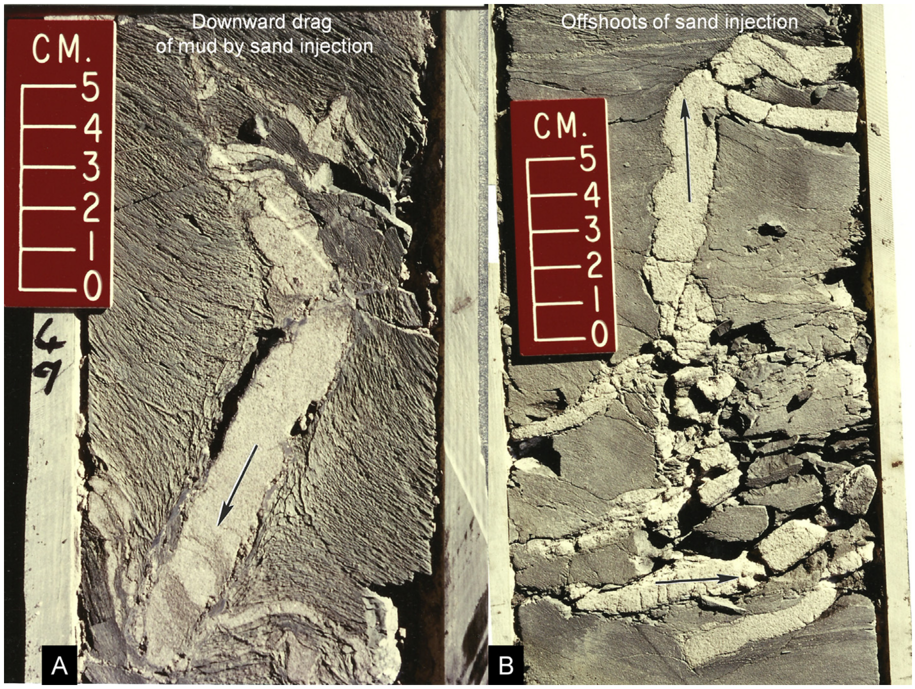

Fig. 14 A—Core photograph of a sandstone injection showing downward drag of mudstone in the direction of penetration (arrow). Eocene, U.K. North Sea; B—Core photograph showing curved branching of sand injection with offshoots in multiple directions. Note both dikes (vertical arrow) and sills (horizontal arrow). These injection features suggest that both host sediment and injecting sediment are in a soft state. Eocene, U.K. North Sea. Figures from Shanmugam (2012a), with permission from Elsevier. Copyright Clearance Center's RightsLink: Licensee: G. Shanmugam. License Number: 3880791279258. License Date: June 2, 2016.

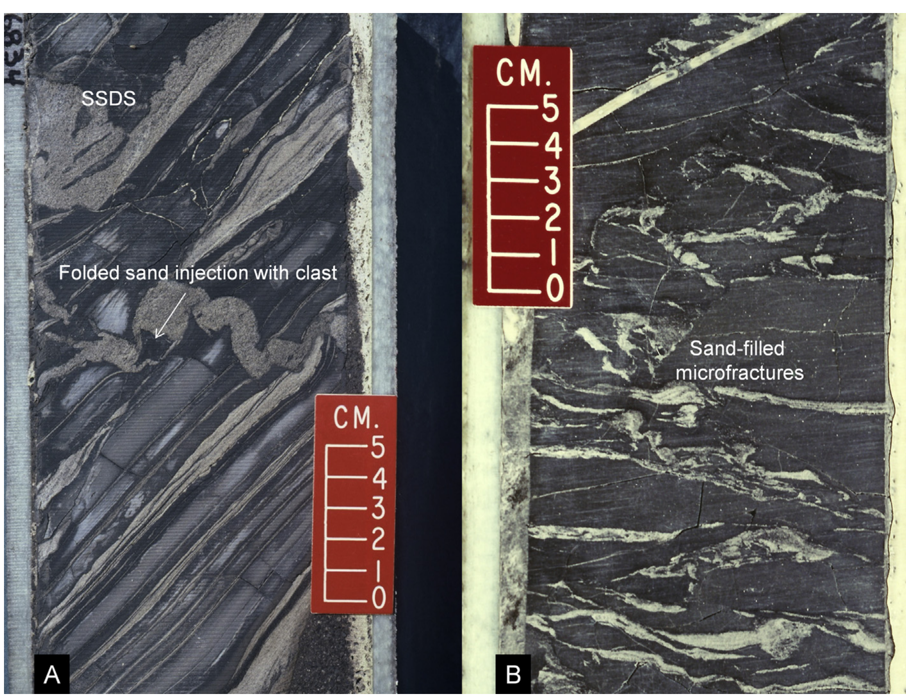

Fig. 15 A—Core photograph of a sandstone injection showing ptygmatic folding of a dike due to compaction (arrow). Pliocene, offshore Nigeria; B—Core photograph of small-scale injection features showing sand-filled microfractures in mudstone host. Note small-scale normal faults. Eocene, U.K. North Sea. Figures from Shanmugam (2012a), with permission from Elsevier. Copyright Clearance Center's RightsLink: Licensee: G. Shanmugam. License Number: 3880791279258. License Date: June 2, 2016.

Table 1 Lexicon of 39 genetic terms ending with "-ite" introduced during a period of 82 years (1931–2013). Updated after Shanmugam (2006b). Genetic terms in bold font are obsolete in process sedimentology, which include "seismite".

Genetic terms	Comments (This article)	References[a]
1. Aeolianite	Implies the Aeolius (the god of the winds), not flow behavior	Sayles (1931); Bates and Jackson (1980)
2. Anastomosite	Implies river type, not flow behavior	Shanmugam (1984)
3. Atypical turbidite	Implies slumps, debris flows, and sand flows, not turbidity current	Stanley *et al.* (1978)
4. Baroclinite	Implies baroclinic currents	Shanmugam (2013a,b)
5. Braidite	Implies river type, not flow behavior	Shanmugam (1984)
6. Cascadite	Implies driving force (cascading), not depositional process	Gaudin *et al.* (2006)
7. Contourite	Implies current orientation, not flow behavior	Hollister (1967)
8. Debrite	Implies plastic debris flow	Pluenneke (1976)
9. Densite	Implies hybrid processes, not a single process	Gani (2004)
10. Diamictite	Implies pebbly mudstone, not flow (glacial) behavior	Flint *et al.* (1960)
11. Fluxoturbidite	Implies no discernible meaning (see Hsü, 1989)	Dzulynski *et al.* (1959)
12. Grainite	Implies grains, not flow behavior	Khvorova (1978)
13. Gravitite	Implies sediment gravity, not flow behavior	Natland (1967)
14. Gravite	Implies multiple processes, not a single process	Gani (2004)
15. Hemipelagite	Implies hemipelagic settling	Arrhenius (1963)
16. Hemiturbidite	Implies muddy turbidity current	Stow *et al.* (1990)
17. High-concentration sandy turbidite	Implies sandy debris flow, not turbidity current (see Shanmugam, 1996)	Abreu *et al.* (2003)
18. Homogenite	Implies uniform grain size (ungraded mud), not flow behavior	Kastens and Cita (1981)
19. Hyperpycnite	Implies relative flow density, not flow behavior	Mulder *et al.* (2002)
20. Impactite[b]	Implies impact by meteorite, not flow behavior	Stöffler and Grieve (2003)
21. Injectite[b]	Implies injection, not flow behavior	Vivas *et al.* (1988)
22. Internalite	Implies internal waves and tides, not flow behavior of baroclinic currents (see Shanmugam, 2013b)	Pomar *et al.* (2012)
23. Interpretite	A spoof on genetic terms	Davies (1997)
24. Meanderite	Implies river type, not flow behavior	Shanmugam (1984)
25. Megaturbidite	Implies debris flow, not turbidity current	Labaume *et al.* (1987)
26. Pelagite	Implies pelagic settling	Arrhenius (1963)
27. Seismite[b]	Implies triggering mechanism (*i.e.*, seismic shocks), not flow behavior	Seilacher (1969)
28. Seismoturbidite	Implies mass flow (debris flow), not turbidity current	Mutti *et al.* (1984)
29. Suspensite	Implies suspension settling	Lisitsyn (1986)
30. Tectonite	Implies tectonic deformation, not flow behavior	Turner and Weiss (1963)
31. Tempestite	Implies multiple processes, not a single process	Ager (1974)
32. Tidalite	Implies deposition from tidal currents	Klein (1971, 1998)
33. Tillite	Implies pebbly mudstone, not flow (glacial) behavior	Harland *et al.* (1966)
34. Tractionite	Implies traction deposition by bottom current	Natland (1967)
35. Tsunamite	Implies multiple processes, not a single process (see Shanmugam, 2006b)	Gong (1988)
36. Turbidite	Implies turbulent turbidity current	Kuenen (1957)
37. Undaturbidite	Implies no discernible meaning	Rizzini and Passega (1964)
38. Unifite	Implies grain size (ungraded mud), not flow behavior	Feldhausen *et al.* (1981); Stanley (1981)
39. Winnowite	Implies winnowing action of bottom current	Shanmugam and Moiola (1982)

[a] References include those that introduced the term, used the term early, or considered appropriate.

[b] Unrelated to depositional processes. Note that transportational processes may be different from depositional processes of a deposit due to flow transformation (Fisher, 1983).

Seilacher (1969) did not cite this most relevant reference, which proposed an alternative synsedimentary origin, unrelated to earthquakes, for the deformed beds in the Miocene Monterey Formation.

2) Grimm and Orange (1997) attributed the occurrence of deformed beds sandwiched between undeformed beds in the Miocene Monterey Formation to a synsedimentary origin related to slope failure and mass movements.

3) Perhaps the most impressive documentation of a slump fold sandwiched between undeformed layers in the Monterey Formation was by Chang and Grimm (1999, their Fig. 11B). They classified it as a "speckled bed" and attributed it to a synsedimentary depositional origin, which is unrelated to earthquakes.

4) Surpless *et al.* (2009) studied the Miocene Monterey Formation, exposed at Gaviota Beach, about 50 km

Table 2 A comparison of studies on original concepts in sedimentology by Seilacher (1969) and by Bouma (1962).

Details	Seilacher (1969)	Bouma (1962)
Original concept	"Seismites" as a genetic term	Turbidite facies model (*i.e.*, The Bouma Sequence)
Geologic unit studied	Monterey Shales (Miocene, California)	Annot Sandstone (Eocene—Oligocene, French Maritime Alps)
Vertical sequence	a — Soupy zone (top) b — Rubble zone c — Segmented zone d — Undisturbed sediment (bottom)	Te — Pelitic interval (top) Td — Upper parallel laminae Tc — Current ripple laminae Tb — Lower parallel laminae Ta — Graded interval (bottom)
Origin	Earthquakes (Triggering mechanism)	Turbidity currents (Transporational and depositional process)
Concept	Sequence is related to a trigger that cannot be recognized from the depositional record	Sequence is related to a depositional process that can be inferred from the depositional record
Reliability of field study	Based on a short excursion to Elwood Beach, north of Santa Barbara, California, USA	Based on his Ph.D. study covering 18 field locations (see his Fig. 4) in France, Switzerland, Germany, The Netherlands, and Italy (spending several years)
Publication	Five-pages long "Short communication" in a journal	168-pages long book
Documentation	Number of figures: 1 Number of plates: 1	Number of figures: 31 Number of plates: 8 Number of tables: 17 Number of enclosures: 3
Number of cited references and their relevance	Total: 5 Only two are related to earthquakes (Barrett, 1966; Dill, 1969), but even those two are irrelevant to seismite sequence proposed. None of the five is related to geology of the Monterey Formation	Total: 322 Very comprehensive and totally relevant to the subject matter
Scientific analysis	Seilacher (1969) did not provide any independent evidence as to why the proposed "seismites" sequence is unique to earthquakes. Also he did not consider alternative hypothesis published at that time for SSDS in the Monterey Formation (see text)	Provided a detailed discussion of various aspects of turbidite deposition; although controversies still exist (see Shanmugam, 2016a)
Impact	Although the genetic term "seismites" is popular in some circles, the vertical seismic sequence with four divisions (a, b, c, and d) has failed to have a worldwide acceptance	The Bouma Sequence with five internal divisions has a worldwide acceptance

west of the Santa Barbara Beach where Seilacher carried out his study. Surpless *et al.* also observed SSDS in the Monterey Formation and they attributed the origin of SSDS to deposition as slope gully complexes in deep-marine environments.

5) Kennett and Fackler-Adams (2000) reported SSDS, identical to the ones described by Seilacher (1969), in the bathyal sediments of Upper Neogene of California. They ascribed the origin of SSDS to clathrate instability.

In summary, the origin of SSDS in the Monterey Formation is much more complex than by simple seismic activity. The genetic term "seismites" appears to have been introduced in haste without sufficient supporting field data and without the necessary stratigraphic, structural, lithologic, and literature information.

3. Soft-sediment deformation structures (SSDS)

3.1. *Deformation*

Allen (1984, II, p. 343) provided an accurate account of soft-sediment deformation in terms of physics. He states that "*Stratigraphical and sedimentological studies over many years have shown that soft sediments often become deformed non-tectonically. The structures induced take myriad forms and are increasingly called **soft-sediment deformations**. It is clear from field evidence, and consistent with experiment and theory, that they were formed either during deposition or shortly after burial started. Certainly most, possibly all, soft-sediment deformation is* *associated in time with the earliest stages of sediment consolidation, when the deposit is weakest and pore fluid is being expelled most rapidly. By interrupting the normally gradual processes of pore fluid expulsion, the actors causing soft-sediment deformation may also abruptly and significantly enhance that process, provided that pore fluid is mobilized. For this reason* Lowe (1975) *categorized most soft-sediment deformations as water-escape structures, aqueous environments being alluded to because it within these that soft-sediment deformations chiefly arise. At the same time, it should be clearly understood that the mobilization of pore fluid is generally a consequence of deformation and seldom the direct cause. Under the circumstances described, at or close to the sediment-fluid interface, the only forces available to cause soft-sediment deformation are weak in ordinary geological terms. Hence the deposits affected must at the time have been either liquid-like or solids of insignificant yield strength compared to sedimentary rocks...... and there are good reasons for believing that at least* ***liquefaction*** *is significant in the production of many kinds of soft-sediment deformation*".

Maltman (1984, p. 592) cautioned that "*The term 'soft-sediment deformation' includes a range of processes and resulting structures whose breadth is only now being recognized. The phrase is therefore often misleadingly loose and fails to convey the nature of the process or structure being reported. Various difficulties, especially the masking of the nature of the material at the time of deformation by later changes, preclude rigorous definitions, but more careful usage is urged. The kind of structure should be specified. The softness of the material is suggested to be equivalent to its cohesion, which in near-surface sediments might be judged from the form of the structure. Inclusion of words such as early or late would help clarify the timing. Of particular growing need is an indication of the generating force, which could derive from some local movement, from gravity, or from tectonism, all of which are now known to act on unlithified material*".

3.2. Liquefaction

Allen (1984) used a general process term "liquidization" to describe mechanisms involving a change of state from solid-like to liquid-like (*i.e.*, 'quick') in cohesionless grain mass. The two mechanisms of liquidization are 1) liquefaction and 2) fluidization. Liquefaction occurs when loosely packed, well-sorted, granular material collapses totally as a consequence of increased pore-fluid pressure. This *in situ* disruption of the grain fabric, commonly a consequence of seismic shock, sediment loading, *etc.*, results in reduction of shear strength to merely nothing. Liquefaction involves neither influx of external fluids into the grain mass nor volume change. Lowe (1979, p. 76) defined a type of sediment-gravity flow known as "liquefied flow" in which "...... *the sediment is not fully supported but is settling through its pore fluid, which is displaced upward*". Unlike other sediment flows (*e.g.*, debris flow and turbidity current), liquefied flow is an ineffective agent for transporting sediment downslope because it is primarily an *in situ* process. Thus liquefied flow is not considered here as a type of sediment-gravity flows. In deep-water slope and canyon environments, rapid deposition of well-sorted sand by sandy debris flows and slumps commonly results in syn- and post-depositional liquidization. Escape of fluids upward in rapidly deposited granular material tends to cause water-escape structures (Fig. 10A). The escaping fluids tend to remove clay from a lower zone and accumulate it in an upper zone when the fluids encounter a low-permeability layer (Fig. 10A). Such encounters redirect fluid movement from a vertical to a horizontal direction (Lowe and Lopiccolo, 1974). This redirection creates a color couplet with a light-colored (clay-depleted) lower layer and a dark-colored (clay-enriched) upper layer (Fig. 10A). The orientation of color couplets may be used to determine the amount of upward push or to determine the amount of deformation a horizontal layer has suffered. The color couplets may also be used to determine the relative timing of various layers based on cross-cutting relationships (Fig. 10A). Internal glide planes associated with slide deposits are potential candidates for forming color couplet flow. Fluidization occurs when a 'quick' condition is achieved by forcing a fluid upward through the grain mass, until the immersed weight of grains is balanced by the total fluid drag (Allen, 1984). Unlike liquefaction, fluidization requires influx of external fluid and its upward movement.

Despite the type of trigger, be it an earthquake or a sediment loading, the ultimate control on the origin of SSDS is liquefaction and deformation (Fig. 16). Under this scenario, the type of trigger is inconsequential for developing SSDS. Therefore, one cannot distinguish SSDS formed by earthquakes from those formed by sediment loading. Similarly, transportational and depositional processes are inconsequential in developing SSDS. For example, one cannot distinguish SSDS associated with slides from those associated with debris flows. For these reasons, SSDS cannot be used as a criterion to interpret layers associated with seismic activity (*i.e.*, seismites) in the ancient sedimentary record. In summary, the genetic term "seismites" is a misnomer.

3.3. Deformation structures

Maltman (1994a) discussed mechanical aspects of deformation in terms of 1) volume changes due to burial, 2) sediment strength, 3) sediment deformation, and 4) role of pore fluids. Deformation refers to a change in the bulk shape of the aggregate of sediment (Maltman, 1994a). Deformation is concerned with deformation early in the burial history. Physical processes involved are (Collinson, 1994): 1) Partial loss of strength and density inversion (*e.g.*, flame structures); 2) Progressive loading of cohesive sediment (*e.g.*, mud diapirs); 3) Partial loss of strength and applied shear (*e.g.*, slump folds); 4) Liquefaction-induced upward escape of pore water (*e.g.*, dish and pillar structures) and sediment—water mixture (*e.g.*, sand boil and sediment injection); 5) Synsedimentary faults (*e.g.*, extensional and contractional types); 6) Sediment shrinkage (*e.g.*, subaerial desiccation cracks and subaqueous synaeresis cracks); 7) Sediment wetting (*e.g.*, buckling on steep slopes of eolian dunes); 8) Compaction (*e.g.*, reduction in the inclination of dipping surfaces). A summary of SSDS by Allen (1984), by Collinson (1994), by Boggs (2001), and by the present author is given in Table 3. In interpreting the significance of SSDS, Mills (1983, p. 83) state that "*Ultimately, for the best diagnostic results, soft-sediment deformation structures should be studied in association with all other available lithologic, structural and paleontological information*".

4. Origin of SSDS

4.1. Challenges in distinguishing palaeoearthquakes

In order to classify a given deposit as a "seismite", one should first establish a clear link between earthquake shaking and related SSDS. The problem is that an

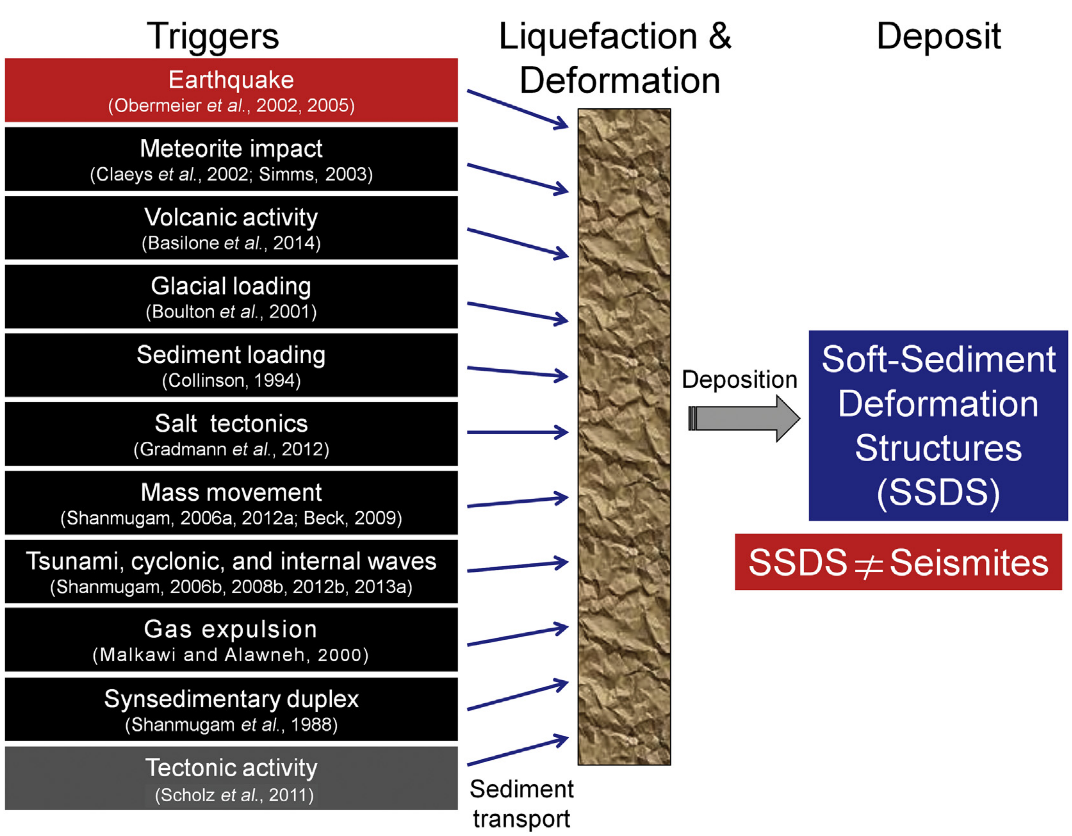

Fig. 16 Selected types of triggers, state of liquefaction, and SSDS. There are 21 triggers and they are all directly or indirectly responsible for sediment transport, deposition, and liquefaction (Table 4). In reflecting published literature, earthquakes and tectonic activity are listed as two different types. However, earthquakes are an integral component of global tectonics (Kearey *et al.*, 2009). Note that both tectonic and non-tectonic triggers go through liquefaction in developing SSDS. Also note that earthquake is one of many triggers that develop SSDS. SSDS are not seismites. Thin blue arrows: One or more sediment transport processes with or without flow transformations (Fisher, 1983). Thick grey arrow: Final deposition. SSDS = Soft-sediment deformation structures. See Shanmugam (2006a, 2006b, 2012a, 2013, 2015, 2016a) for discussion of examples of triggers shown here. Relevant references include: Basilone *et al.*, 2014, Beck, 2009, Gradmann *et al.*, 2012, Malkawi and Alawneh, 2000, Obermeier *et al.*, 2002, Scholz *et al.*, 2011.

earthquake is a triggering mechanism, whereas SSDS are the products of liquefaction. Liquefaction is a phenomenon of sediment state (Allen, 1984) that occurs between the time of trigger and the time of formation of SSDS (Fig. 16). Many triggering mechanisms can lead to a state of liquefaction (Fig. 16). At present, there are no unique criteria to distinguish liquefaction induced by earthquake from liquefaction induced by meteorite impact or sediment loading, or other triggers (Fig. 16). Although researchers have acknowledged this trigger-related problem (Moretti, 2000; Owen, 1987; Owen *et al.*, 2011), the continued application of the seismite nomenclature by researchers, emphasizing the earthquake as the sole trigger, is rather disturbing (see articles in this issue). In nature, dish structures formed by liquefaction associated with earthquakes will look the same as dish structures associated with sediment loading. Unlike primary sedimentary structures that can be used to infer depositional processes, such as traction and suspension (Sanders, 1963), SSDS cannot be used to distinguish one trigger from the other. However, there are claims of recognizing triggers (Moretti and Sabato, 2007; Owen and Moretti, 2011). In order to clarify the lingering sedimentological problems associated with triggers, it is necessary to review some fundamental aspects of triggers and process sedimentology.

A triggering mechanism is defined here as the primary process that causes the necessary changes in the physical, chemical, and geotechnical properties of the soil, which results in the loss of shear strength that initiates the sediment failure and movement. Commonly, triggering processes are considered "external" with respect to the site of failure (Shanmugam, 2015). In continental margins, several triggering mechanisms may work concurrently or in tandem (*e.g.*, earthquake-triggered tsunamis). Sowers (1979) articulated the challenge of identifying the single trigger mechanism that is solely responsible for the failure as follows: "*In most cases, several 'causes' exist simultaneously; therefore, attempting to decide which one finally produced failure is not only difficult but also technically incorrect. Often the final factor is nothing more than a trigger that sets a body of earth in motion that was already on the verge of failure. Calling the final factor the cause is like calling the match that lit the fuse that detonated the dynamite that destroyed the building the cause of the disaster*".

Although more than one triggering mechanism can cause a single process (*e.g.*, debris flow) at a given site, there are no objective criteria to distinguish either the triggering mechanism or the transport process from the depositional record yet (Dott, 1963; Middleton and Hampton, 1973; Mulder *et al.*, 2011; Shanmugam,

Table 3 Soft-sediment deformation structures (SSDS) suggested by various authors and those documented in this study.

Allen (1984)	• Convolute lamination • Load cast • Heavy mineral sag • Passively deformed bedding • Dish structure • Fold and sand mound • Sheet slump • Imbricate structure • Deformed cross bedding
Collinson (1994)	• Load cast • Flame structure • Pseudonodule • Convolute bedding • Mud diapir • Dish and pillar structure • Sediment injection • Sand volcano • Synsedimentary fault • Sediment shrinkage • Compaction-induced structure • Early chemical precipitation
Boggs (2001)	• Slump structure • Load and founder structure • Injection (fluidization) structure • Fluid-escape structure • Desiccation structure • Impact structure
This article	• Microfold (Fig. 2) • Convolute bedding (Fig. 3A) • Slumped unit with microfold (Fig. 3B) • Slump fold (Fig. 4) • Sandy slump, classic SSDS (Fig. 5) • Muddy slump (Fig. 6) • Brecciated-clast layer (Fig. 7) • Tensional fault (Fig. 8A) • Load cast (Fig. 8B) • Boudin (Fig. 9A) • Rotated flame structure (Fig. 9B) • Dish structure (Fig. 10A) • Pipe (Fig. 10B) • Liquefied sand with pillar (Fig. 11A) • Steep clay-rich layer (Fig. 11B) • Liquefied sand blob (Fig. 12A) • Pinch-out sand layer (Fig. 12B) • Deformed cross bedding (Fig. 13A) • Passively deformed layer (Fig. 13B) • Clastic injection with drag (Fig. 14A) • Clastic injection with offshoot (Fig. 14B) • Folded clastic injection with clast (Fig. 15A) • Sand-filled microfracture (Fig. 15B) • Duplex-like structure (Fig. 18) • Clastic injection with ptygmatic folding (Fig. 23A) • Clastic injection beneath main sand layer (Fig. 25C) • Stretched clasts in slump folds (Fig. 31C)

1996, 2006b, 2012b). This is a fundamental tenet of process sedimentology. The other unresolved issue is flow transformation in sediment-gravity flows. Fisher (1983) proposed four types of transformations for sediment-gravity flows: 1) Body transformation; 2) Gravity transformation; 3) Surface transformation; 4) Elutriation transformation. Flow transformations cannot be established without knowing: 1) Initial flow behavior; 2) Transport mechanisms; 3) Final flow behavior. There are, however, no established criteria for recognizing initial flow behavior and transport mechanisms in the depositional record (Carter, 1975; Dott, 1963; Lowe, 1982; Middleton, 1993; Middleton and Hampton, 1973; Postma, 1986; Shanmugam, 1996; Stanley *et al.*, 1978; Talling *et al.*, 2007; Walton, 1967). For example, sediment of a turbidite bed on the seafloor could have been transported as a debris flow and underwent flow transformation into a turbidity current at the time of deposition (see experiments by Hampton, 1972). Therefore, one cannot interpret transport mechanism from the depositional record using seismic data, outcrop or core data. The corollary is that one cannot interpret triggering mechanisms (triggers) from the depositional record (*i.e.*, SSDS; see Fig. 16). Nevertheless, an understanding of different triggering mechanisms is necessary in comprehending the complexities associated with liquefaction and deformation (Fig. 16).

There are at least 21 triggering mechanisms that can initiate sediment failures in subaerial and submarine environments on Earth (Shanmugam, 2015) (Table 4). These mechanisms are grouped into three major categories based on their duration of activity: 1) Short-term events that last for only a few minutes to several hours, days or months (*e.g.*, earthquakes, volcanic eruptions, meteorite impacts, tsunamis, tropical cyclones, monsoon floods, *etc.*); 2) Intermediate-term events that last for hundreds to thousands of years (*e.g.*, tectonic events, glacial maxima and loading, depositional loading, gas hydrate decomposition, *etc.*); 3) Long-term events that last for thousands to millions of years, such as lowstands of sea level (Shanmugam, 2012a, 2012b). Conceivably, some intermediate-term events may last for a longer duration. The point here is that short-term events and long-term events are markedly different in their duration. In short, SSDS do not and cannot reveal anything about triggering mechanisms (Fig. 16).

4.2. Duplex-like structures

As a rule, a genetic term must represent a single depositional process (Table 1). 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; Seilacher, 1969). The distinction between tectonics and earthquakes is not always clear-cut because earthquakes can be and often are integral parts of tectonic activities. Ruff (1996, p. 91), for example, stated that "*Subduction zones generate most of the world's seismicity, and all of the largest earthquakes*". Nevertheless, Allen (1975) discussed the challenges in recognizing seismicity in the geologic record.

For illustrating this fundamental problem, I have selected duplex-like structures (i.e., sigmoidal deformation structure) (Figs. 17 and 18). In the classification of SSDS by Allen (1984), duplex-like structures are analogous to imbricate structures (Table 3). This duplex-like structure is a special kind of deformation feature that has been observed in deep-water sandy lithofacies in the Pennsylvanian Jackfork Group in the Ouachita Mountains (Shanmugam and Moiola, 1995; Shanmugam *et al.*, 1988). Conventionally, duplex features have been attributed to tectonic deformation of lithified units (Boyer and Elliott, 1982) (Fig. 19). However, a tectonic origin for the sigmoidal slices is considered unlikely in the Jackfork Group because of observed opposing directions of imbrication in stratigraphically adjacent units (Fig. 18). Such opposing orientations would require an unrealistic tectonic history. Therefore, the imbricate slices (i.e., duplexes) have been attributed to sedimentary slumping (Shanmugam *et al.*, 1988). This conclusion was based, in part, on an experimental model of a small-scale duplex structure generated in soft plaster in the laboratory (Shanmugam *et al.*, 1988, their Fig. 3). Sigmoidal deformation structures with imbricate slices have also been generated in flume experiments on sandy debris flows (Marr *et al.*, 2001; Shanmugam, 2000) (Fig. 20A). Glacial debris flows also are known to generate imbricate bedding in Alaska (Fig. 20B). Boulton et al. (2001) discussed generation of sediment deformation beneath glaciers. Ni *et al.* (2015) attributed the origin of duplex-like structures in the Jurassic strata of western Qaidam Basin, China, to synsedimentary slumping, but related to earthquakes.

In light of knowledge gained from experiments and field observations (Fig. 21A), a depositional model for the origin of duplex-like structures in submarine channels has been proposed using three stages (Fig. 21B).

Stage 1: Deposition of sediments by axial sediment-gravity lows in a submarine channel.

Stage 2: Mass flows, triggered by sediment failure along the right-hand channel wall, glided over the sediment from stage 1 in a perpendicular direction, causing duplex 1. Note that the dip direction of

Table 4 Types and duration of triggering mechanisms of sediment failures that control sediment transport, deposition, and liquefaction. Compiled from several sources. Updated after Shanmugam (2016a). The change in numbering is to reflect the change in duration of triggering events.

Type of triggering mechanism	Environment of sediment emplacement	Duration of triggering mechanism
1. Earthquake (Heezen and Ewing, 1952; Henstock *et al.*, 2006)	Subaerial and submarine	Short-term events: A few minutes to several hours, days or months
2. Meteorite impact (Barton *et al.*, 2009/2010; Claeys *et al.*, 2002)	Subaerial and submarine	
3. Volcanic activity (Tilling *et al.*, 1990)	Subaerial and submarine	
4. Tsunami wave (Shanmugam, 2006b)	Subaerial and submarine	
5. Rogue wave (Dysthe *et al.*, 2008)	Submarine	
6. Cyclonic wave (Bea *et al.*, 1983; Prior *et al.*, 1989; Shanmugam, 2008b)	Subaerial and submarine	
7. Internal wave and tide (Shanmugam, 2013)	Submarine	
8. Ebb tidal current (Boyd *et al.*, 2008)	Submarine	
9. Monsoonal rainfall (Petley, 2012)	Subaerial	
10. Groundwater seepage (Brönnimann, 2011)	Subaerial and submarine	
11. Wildfire (Cannon *et al.*, 2001)	Subaerial	
12. [a]Human activity (Dan *et al.*, 2007)	Subaerial and submarine	
1. [b]Tectonic events: (a) Tectonic oversteepening (Greene *et al.*, 2006); (b) Tensional stress on the rift zone (Urgeles *et al.*, 1997); (c) Oblique seamount subduction (Collot *et al.*, 2001); among others	Subaerial and submarine	Intermediate-term events: Hundreds to thousands of years
2. Glacial maxima, loading (Elverhøi *et al.*, 1997, 2002); Glacial meltwater (Piper *et al.*, 2012)	Submarine; Submarine	
3. Salt movement (Prior and Hooper, 1999)	Submarine	
4. Depositional loading (Behrmann *et al.*, 2006; Coleman and Prior, 1982)	Submarine	
5. Hydrostatic loading (Trincardi *et al.*, 2003)	Submarine	
6. Ocean-bottom current (Locat and Lee, 2002)	Submarine	
7. Biological erosion in submarine canyon (Dillon and Zimmerman, 1970; Warme *et al.*, 1978)	Submarine	
8. Gas hydrate decomposition (Maslin *et al.*, 2004; Popenoe *et al.*, 1993; Sultan *et al.*, 2004)	Submarine	
1. Sea-level lowstand (Damuth and Fairbridge, 1970; Shanmugam and Moiola, 1982, 1988; Vail *et al.*, 1991)	Submarine	Long-term events: Thousands to millions of years

[a] Although human activity is considered to be the second most common triggering mechanism (next to earthquakes) for known historic submarine mass movements (Mosher *et al.*, 2010), it is irrelevant for interpreting ancient rock record.
[b] Some tectonic events may extend over millions of years.

duplex 1 is opposite to the flow direction of mass flows above.

Stage 3: Mass flows, triggered by sediment failure along the left-hand channel wall, glided over the sediment in a perpendicular direction, causing duplex 2. This synsedimentary origin of duplexes is a more realistic explanation than the conventional tectonic origin for explaining field disposition of beds. From an overall kinematic style viewpoint, representing either rooted or gravity-driven (Waldron and Gagnon, 2011), the proposed duplex origin is strictly a gravity-driven deformation.

4.3. *Clastic injections*

According to Einsele *et al.* (1996, p. 2): "*In-situ earthquake structures may be termed to as 'seismites', including sand dikes, sand blows, and mud volcanoes......*". The problem here is the expansion of the original meaning of the term "seismites" to include clastic injections of complex and multiple origins. General triggering mechanisms of injections are: 1) Sedimentary slumping (Truswell, 1972); 2) Sedimentary depositional loading (Hiscott, 1979; Shanmugam *et al.*, 1994; Surlyk, 1987); 3) Glacial loading (Le Heron and Etiene, 2005); 4) Tectonic stress (Peterson, 1966); 5) Earthquake-induced liquefaction (Obermeier, 1989, 1998); 6) Igneous intrusion (Andersen *et al.*, 1998); 7) Vertical migration of fluid from within the basin (Brooke *et al.*, 1995); 8) Impact origin (Srurkel and Ormö, 1997). According to Jolly and Lonergan (2002), earthquakes and depositional processes are the two most commonly cited triggering mechanisms of clastic injections.

Shanmugam (2012a) published a large number of core photographs showing a multitude of clastic injections in both sandstone and mudstone lithofacies from various localities around the world that include

Fig. 17 Outcrop photograph showing duplex-like structures (*i.e.*, sigmoidal deformation structures) and laterally extensive nature (arrow). Pennsylvanian, Jackfork Group, DeGray Spillway East Wall Section, Ouachita Mountains, Arkansas. After Shanmugam *et al.* (1988), with permission from Geological Society of America (GSA).

many petroleum-producing reservoirs (Figs. 14, 15, 22 and 23). I have attributed a synsedimentary origin for all these injections (SSDS). However, ptygmatic folding is also associated with tectonic activity (Godfrey, 1954). Major sandstone injections have been associated with Pliocene mega-tsunami deposits in Chile (Le Roux *et al.*, 2008). Obermeier *et al.* (2005) documented a variety of clastic injections associated with seismic activity (Fig. 24). In particular, earthquake-induced sand injections contain angular mud fragments (Fig. 24).

Based on the ubiquitous occurrence of sandstone dikes in mudstone that occur immediately beneath thick units of main sands composed of sandy mass-transport deposits (SMTD) (Fig. 25), a model has been proposed in which clastic injections are genetically related to loading induced by deposition of SMTD

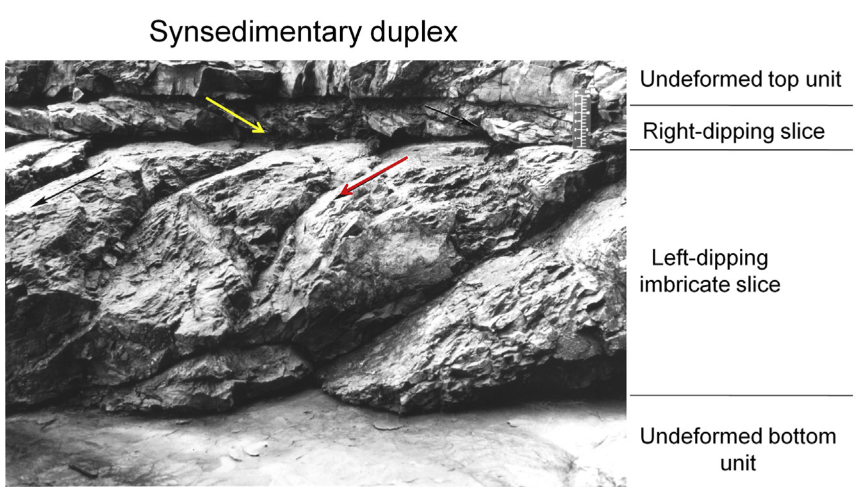

Fig. 18 Outcrop photograph showing two adjacent sigmoidal deformation structures (*i.e.*, duplex-like structures) with opposing dips of imbricate slices. Pennsylvanian, Jackfork Group, DeGray Spillway East Wall Section, Ouachita Mountains, Arkansas. After Shanmugam *et al.* (1988), with permission from Geological Society of America (GSA).

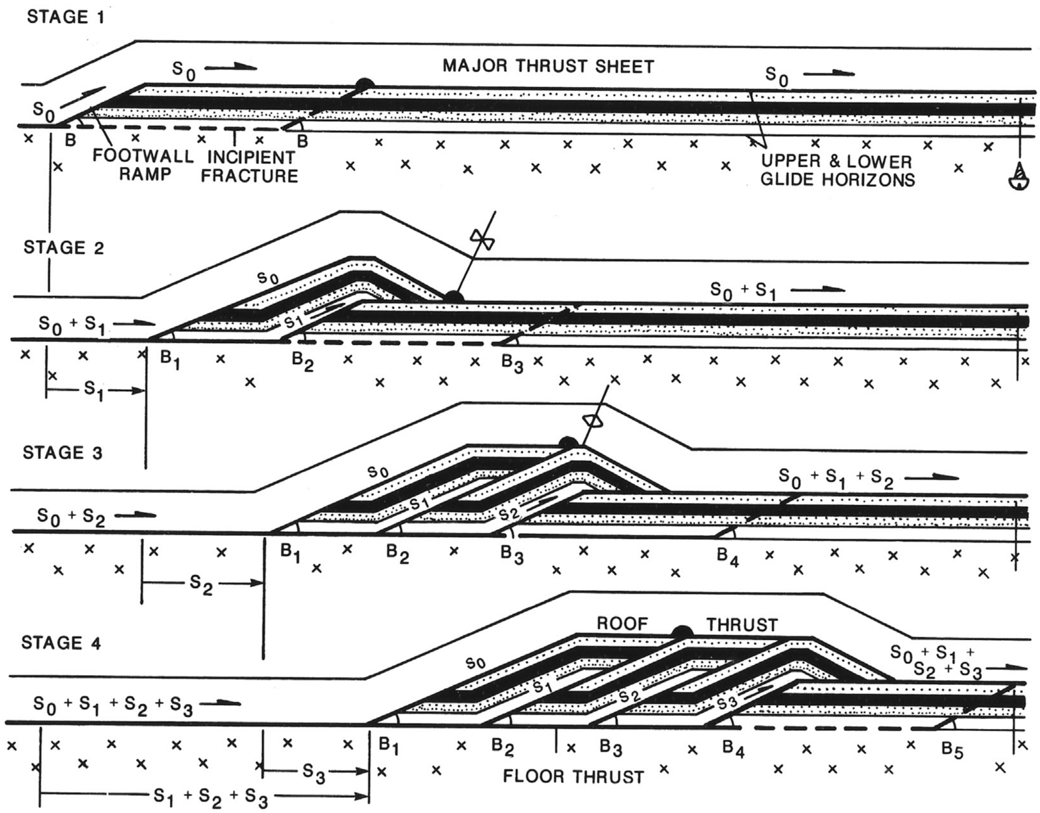

Fig. 19 Theoretical stages of development of duplex-like structures in thrust tectonics. Simplified after Boyer and Elliott (1982). Diagram from Shanmugam *et al.* (1988), with permission from Geological Society of America (GSA).

(Fig. 26). In this model (Shanmugam *et al.*, 1994), the following sequence of events is proposed:

1) Sediment failures on the upper slope generate pockets of sandy slumps, sandy slides, and sandy debrites.
2) Rapid burial of these sandy deposits by subsequent muddy debris flows and related processes results in sealing of these pockets of sand with an early overpressuring.
3) As subsequent sandy slumps or slides travel over the buried sand pockets, loading and liquefaction of sealed sand result.

Surlyk (1987) reported that the Upper Jurassic Hareelv Formation of Jameson Land, East Greenland, occurs in an area of 60–75 km^2. It consists of 200–500 m of black shale with thick, closely spaced sandstone bodies. The sandstones fill deep, steep-walled gullies and elongate scours, or form more regular, laterally extensive, parallel-sided, but erosive gully mouth or lobe deposits. Gully-lobe sands are characterized by sand injections, such as sills (Fig. 27A). Deep-water sandy debrites in my study areas are commonly associated with SMTD (Shanmugam, 2012a), often in faulted zones (Fig. 27B).

4.4. *Brecciated-clast layers*

Agnon *et al.* (2006), based on their field study of Dead Sea Basin in the Middle East, proposed that "intraclast breccia layers" be used as a diagnostic criterion for recognizing earthquake-induced deposits. These breccia types are invariably associated with tectonic faults. However, such breccia layers are common in the subsurface in my study areas, such as the North Sea (Figs. 7A and 8A), Nigeria (Fig. 7B), and Bay of Bengal (Shanmugam *et al.*, 2009), among others (Shanmugam, 2012a). Composition of the brecciated clasts in these cases is similar to that of the host mudstones, suggesting a local provenance. The problem is that these brecciated clasts are common deposits of sandy debris flows, and there is no reason to invariably invoke an earthquake origin. The implications of interpreting different types of breccias as seismites are discussed in a companion paper (Shanmugam, 2017).

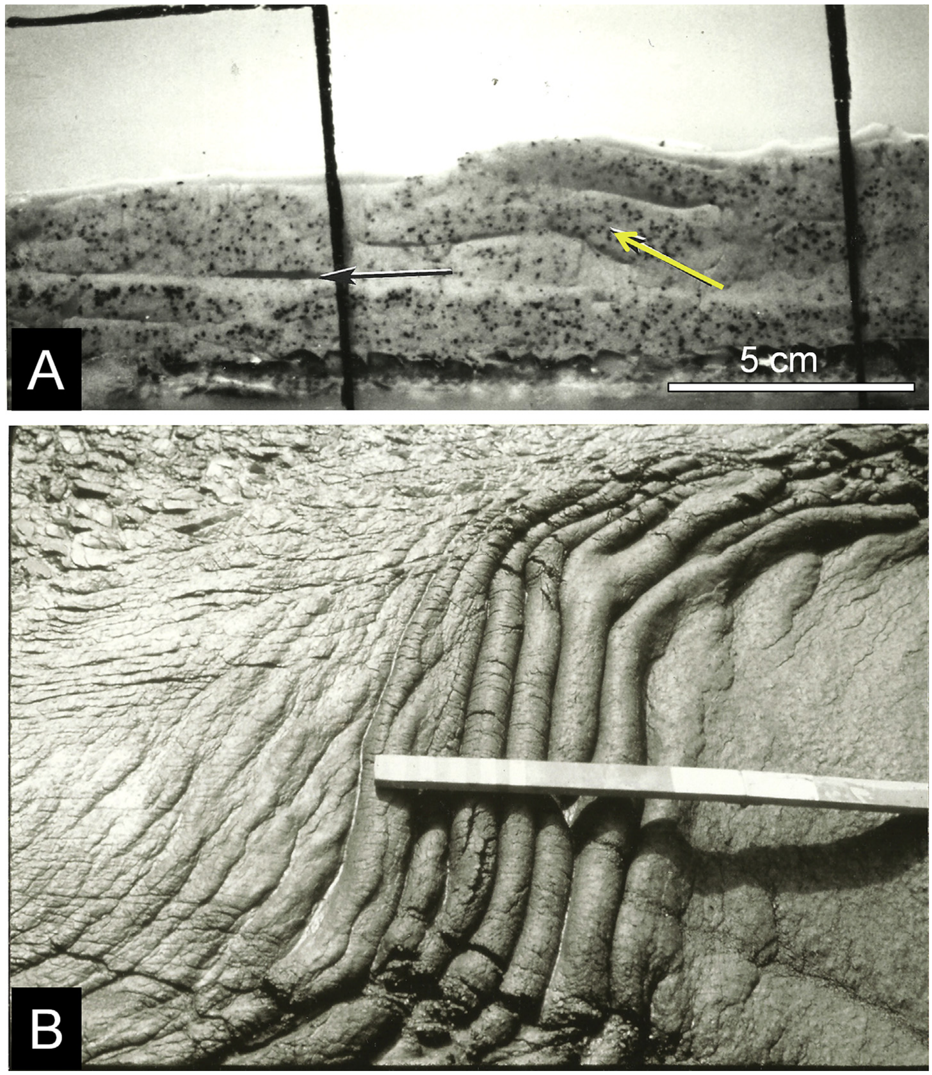

Fig. 20 A—Side view of flume tank showing sandy debris flows with imbricate slices (inclined arrow). Such imbrications develop in sandy debris flows when the front of a flow freezes, the body of the flow breaks and thrusts over the slice in the front due to compression. Similar features (duplex-like structures) in the rock record have been ascribed to synsedimentary duplex-like structures (Shanmugam *et al.*, 1988). Flow direction is from right to left. Photo from Shanmugam (2000), with permission from Elsevier; B—Subaerial slurry flows (*i.e.*, plastic debris flow with movement from left to right) showing development of synsedimentary folding in the frontal zone of Matanuska Glacier, Alaska (Lawson, 1981). This folding is analogous to the origin of imbricate slices in experiments on sandy debris flows (see Fig. 21A). Photo courtesy of G. D. Klein.

4.5. SSDS in the subsurface

A detailed account of various subsurface case studies of deep-water petroleum reservoirs has been given in my earlier publications (Shanmugam, 2006a, 2012a; Shanmugam *et al.*, 1994, 1995, 2009). These studies include Gulf of Mexico (Fig. 28), North Sea (Figs. 25 and 29), Equatorial Guinea (Fig. 30), and Bay of Bengal (Fig. 31), among others. A striking stratigraphic and sedimentologic characteristic of these deep-water sands is that they are invariably underlain by muddy units with SSDS. This stratigraphic architecture provides compelling evidence for sediment loading being the primary cause of SSDS. Two specific cases are discussed here.

4.5.1. Mass-movement related SSDS

In their core study of Gryphon—Harding areas on the U.K. Continental Shelf (UKCS), Shanmugam *et al.* (1995) reported sandstone sills and dikes. Purvis *et al.* (2002) reported a range of injection structures in the Gryphon Field from thin, centimeter-scale dikes to meter-scale clastic injections. In the Gryphon Field, the Lower Eocene reservoir exhibits well-developed “blocky” log motifs (Fig. 29A). In cored interval, clean

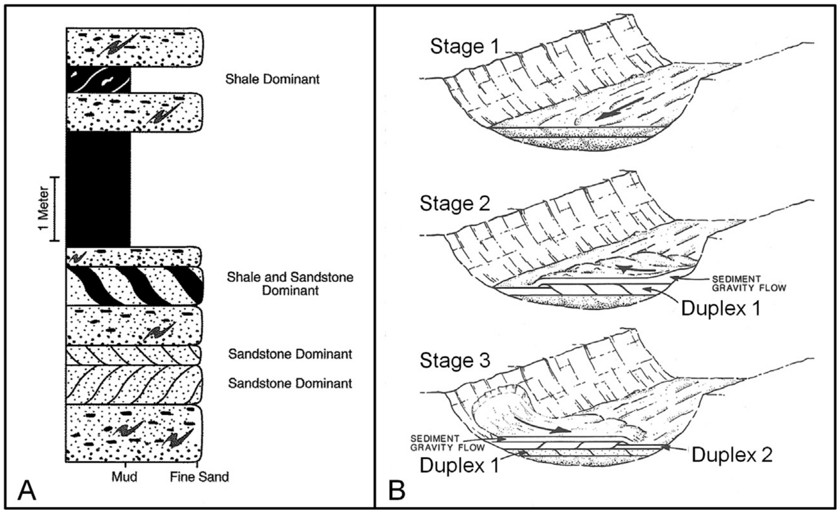

Fig. 21 A—An ideal stratigraphic column with duplex-like structures of different composition; B—Three stages of development of duplex-like structures with opposing dips in a submarine channel. Stage 1—Deposition from axial sediment gravity flows. Stage 2—Deformation of unlithified sediment into duplex 1 by mass flows triggered from right-hand channel wall. Stage 3—Deformation of unlithified sediment into duplex 2 by mass flows triggered from left-hand channel wall. From Shanmugam *et al.* (1988), with permission from Geological Society of America (GSA).

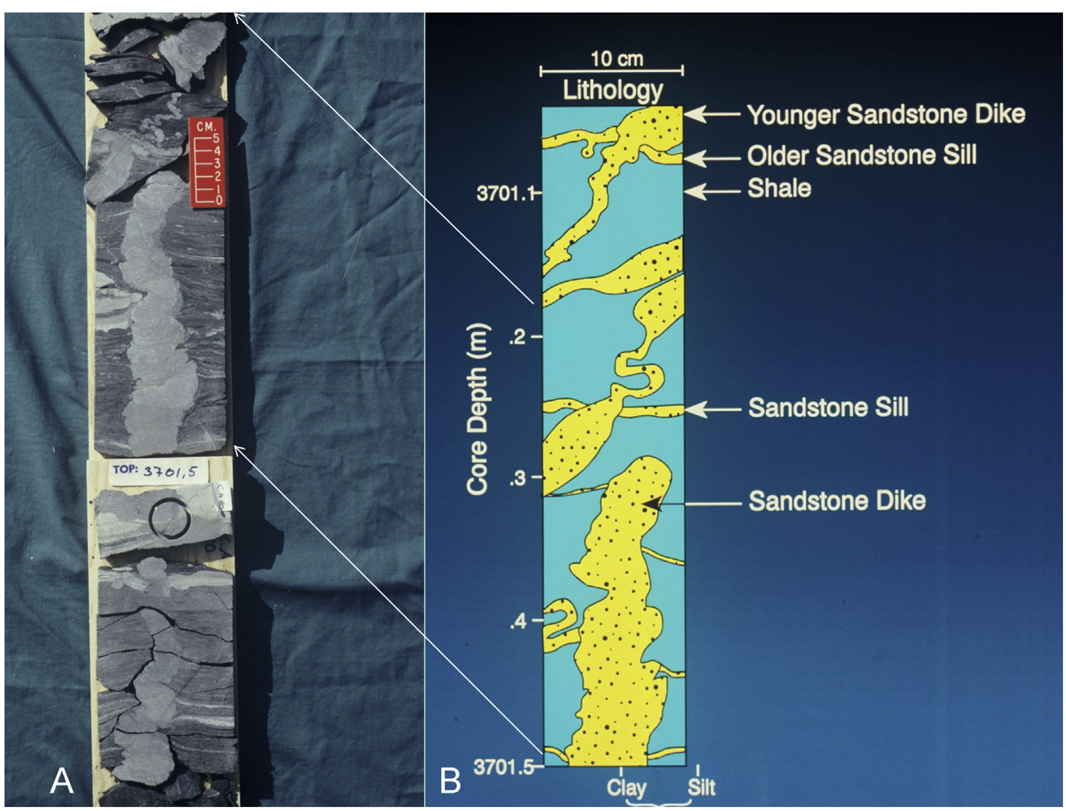

Fig. 22 A—Core photograph showing ptygmatically folded sandstone injection; B—Sketch showing the relative timing of different injection events. Agat Formation, Cretaceous, offshore Norway. Figure from Shanmugam (2012a), with permission from Elsevier. Copyright Clearance Center's RightsLink: Licensee: G. Shanmugam. License Number: 3880791279258. License Date: June 2, 2016.

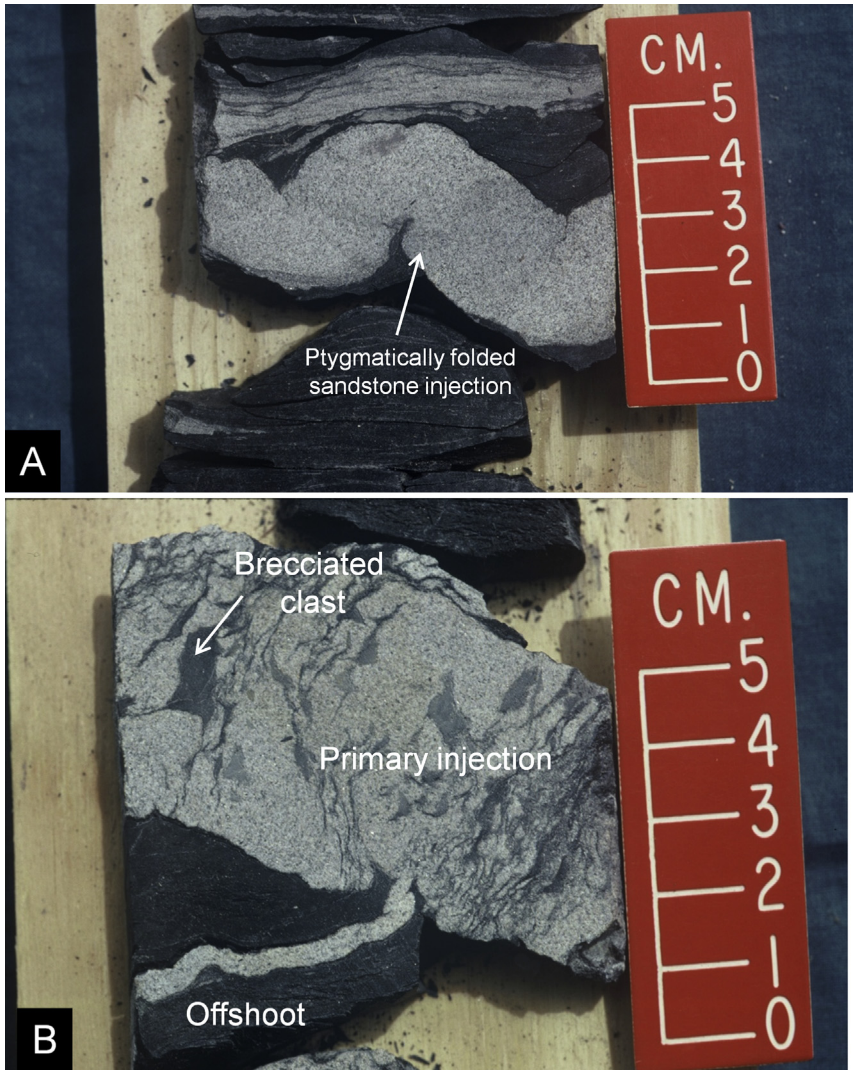

Fig. 23 A—Core photograph of a sandstone injection showing ptygmatic folding of a dike due to compaction (arrow), Pliocene, offshore Nigeria; B—Core photograph showing the primary injection and branching offshoots of the secondary injection. Figures from Shanmugam (2012a), with permission from Elsevier. Copyright Clearance Center's RightsLink: Licensee: G. Shanmugam. License Number: 3880791279258. License Date: June 2, 2016.

massive sand beds are common. The sands are poorly sorted with 5%—15% matrix and show sharp upper contacts, floating mudstone clasts (up to 15 cm in diameter; Fig. 29C), primary (basal) glide planes, steep internal shear planes (Fig. 29B), and water-escape structures. These features suggest deposition from sandy mass-transport deposits, such as sandy slides, slumps, and debrites. The nearly 400 ft (122 m) of continuous core in the 9/18b-7 well makes it possible to calibrate core-scale features with seismic-scale features using synthetic seismograms (Shanmugam *et al.*, 1995).

The decollement is the basal contact of the 400 ft (122 m) thick sand with underlying Balder tuff (Fig. 29B). The chalk-like texture of the Balder tuff apparently provided a slippery shear surface for sandy mass movements. As a consequence, the underlying muddy lithofacies is dominated by soft-sediment deformation features (SSDS) (Fig. 29B). This case, quite analogous to clastic injections associated with sediment loading discussed earlier (Fig. 25), is strictly a sediment loading phenomenon associated with deep-water mass movements. In submarine sliding, the role of pore-water pressure and related liquefaction is discussed elsewhere (Shanmugam, 2015). Alves (2015) reviewed submarine slide blocks and associated soft-sediment deformation in deep-water basins. Odonne *et al.* (2011) discussed soft-sediment deformation from submarine sliding using examples from the Eocene Sobrarbe Delta (Ainsa, Spanish Pyrenees) and the Mid-Cretaceous Ayabacas Formation (Andes of Peru).

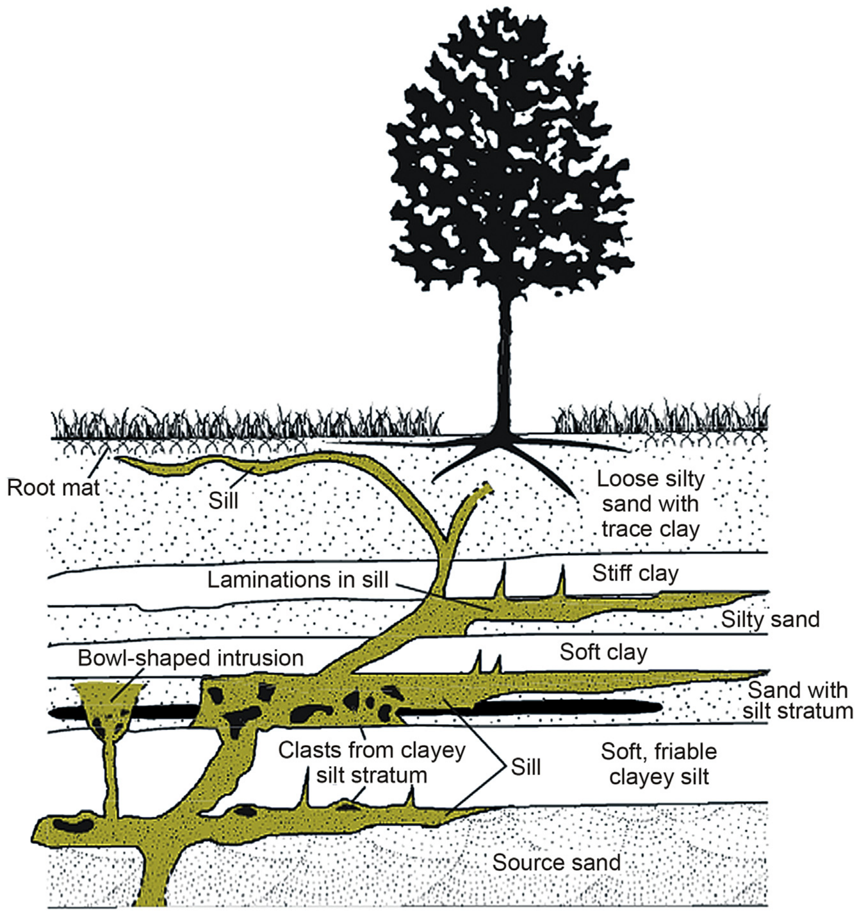

Fig. 24 Schematic section showing the occurrence of seismic-liquefaction induced sand injections in the subsurface. This scenario is applicable to both subaerial and submarine environments that are subjected to seismic shaking. Note mud clasts in sand injections. Originally from Obermeier *et al.* (2005). Figure from Shanmugam (2012a), with permission from Elsevier. Copyright Clearance Center's RightsLink: Licensee: G. Shanmugam. License Number: 3880791279258. License Date: June 2, 2016. See also Obermeier (1996).

4.5.2. Canyon-related SSDS

The Krishna—Godavari (KG) Basin is located on the eastern continental margin of India in the Bay of Bengal (Fig. 31A). A comprehensive study, based on integration of modern seafloor bathymetry, conventional cores, and seismic attributes, was carried out (Shanmugam *et al.*, 2009). The cored Pliocene intervals in three wells represent the Pliocene deep offshore component of Krishna—Godavari Basin. The modern seafloor bathymetry of our study area reveals that the upper-slope setting is characterized by widespread mass-transport deposits and submarine canyons.

A submarine canyon model was proposed on the basis of lithofacies features of the cored intervals (Fig. 31B). The canyon is filled by sandy debrites and sandy tidalites. Below the canyon wall, the mudstone unit shows slump folding, steeply dipping fabric, brecciated mudstone clasts, floating sandstone fragments, and sandy injections (Fig. 31). Similar deformational features have been reported from the Miocene—Pliocene deposits associated with collapsed submarine canyon walls in North—Central Chile (Le Roux *et al.*, 2004). Near the canyon wall (Fig. 31), the canyon-fill facies is composed of sandy debrites (*i.e.*, floating quartz granules and mudstone clasts in massive sand), muddy slumps (*i.e.*, contorted layers and shearing in mudstone), and sandy tidalites (*i.e.*, mud-draped ripples in fine sand). In the KG Basin, the development of SSDS both within the canyon and immediately beneath the canyon wall (Fig. 31B) is a consequence of local mass-transport deposition, sediment loading, and related deformation.

5. Multiple origins of SSDS

In line with the theme of this special column of “Multi-origin of soft-sediment deformation structures

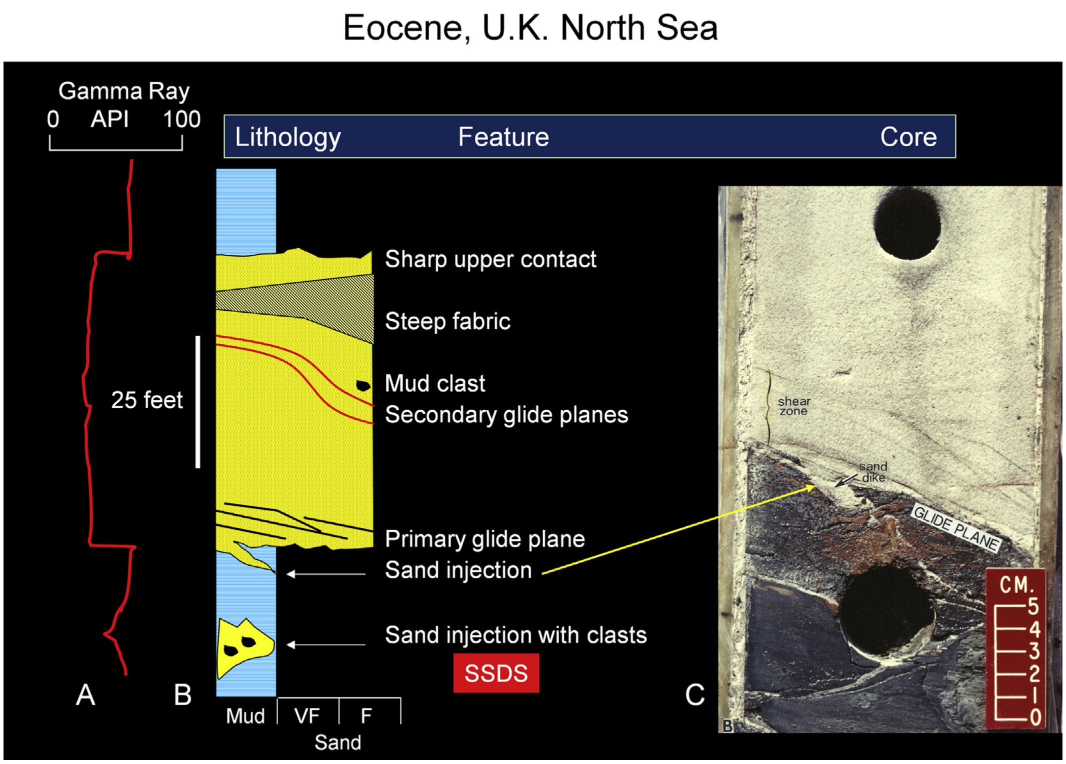

Fig. 25 A—Sketched blocky wireline log motif of a sandy slide/slump unit; B—Sedimentological log showing details. VF = Very fine sand; F = Fine sand; Primary glide plane (decollement) = The basal primary slip surface along which major displacement occurs; Secondary glide plane = Internal slip surface along which minor displacement occurs; Mud clasts = Occurrence of mud clasts at some distance above the basal contact; C—Core photograph showing an upper sand interval (light color) and a lower mudstone interval (dark color). The basal contact (arrow) is interpreted as a primary glide plane (decollement) of a sandy slide/slump. Additional core photographs of this cored interval are published elsewhere (Shanmugam, 2012a, his Figs. 3.10, 3.12, 3.13, 3.14). Shear zone = Basal interval of a rock unit that has been crushed and brecciated by many subparallel fractures due to shear strain. Note a sand dike (*i.e.*, injection) at the base of shear zone. Eocene, U.K. North Sea. SSDS = Soft-sediment deformation structures. Modified after Shanmugam (2012a), with permission from Elsevier.

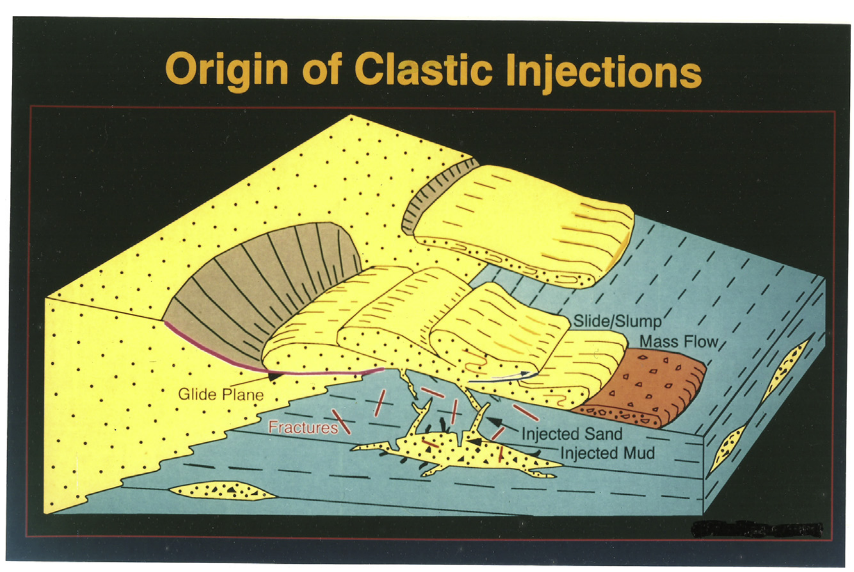

Fig. 26 A model for the origin of sandstone injections controlled by depositional loading. See text for details. After Shanmugam *et al.* (1994), with permission from American Association of Petroleum Geologists (AAPG).

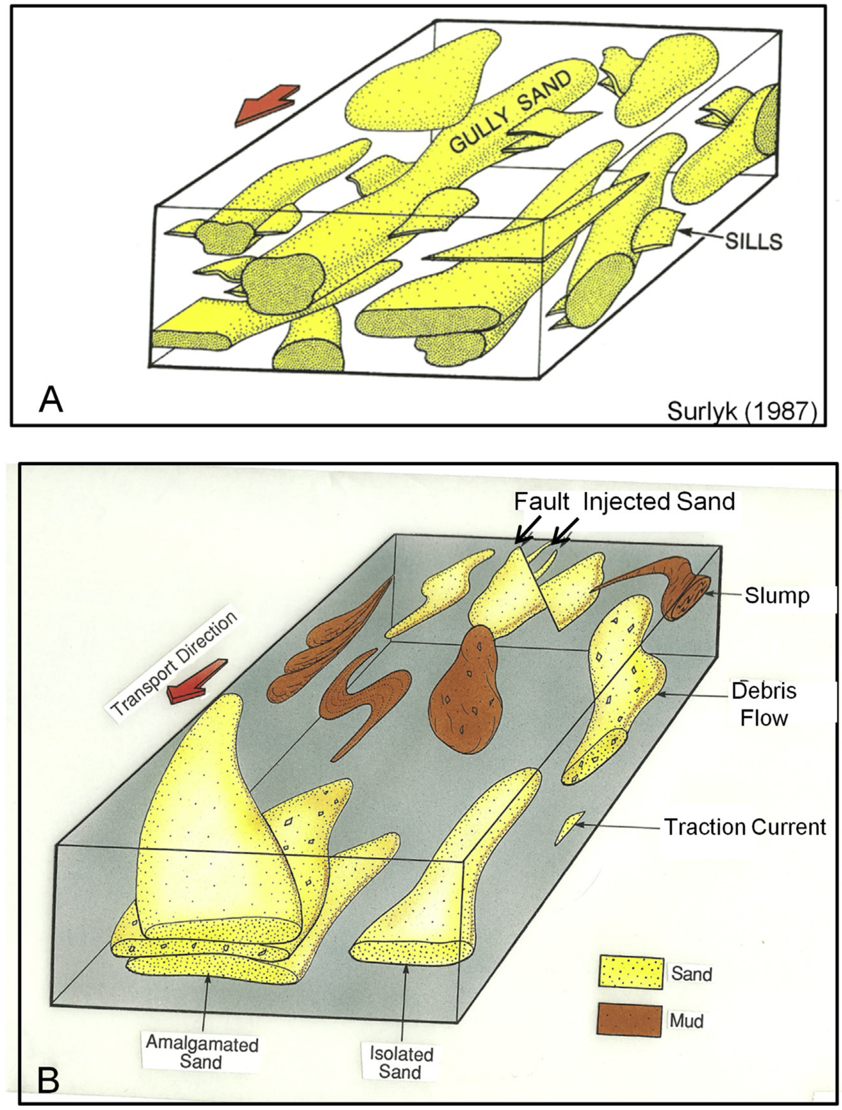

Fig. 27 A—Gully-lobe sands characterized by sand injections, such as sills. From Surlyk (1987), with permission from American Association of Petroleum Geologists (AAPG); B—Depositional model showing sandy debrites with injections associated with faulting induced by high rates of sedimentation.

and seismites" in the *Journal of Palaeogeography*, let us examine the multiple controlling factors of SSDS in the Krishna—Godavari (KG) Basin, Bay of Bengal. An important requirement for the formation of SSDS is liquefaction (Allen, 1984). The underpinning factor that induces conditions suitable for liquefaction is excess pore-water pressure (*i.e.*, overpressure). Various aspects of overpressure zones in the KG Basin have been investigated by researchers from academia, government, and the petroleum industry (Chatterjee *et al.*, 2015; Goud and Bhavana, 2010; Jain *et al.*, 2012; Samanta *et al.*, 2010; Singha and Chatterjee, 2014). In describing the complexity of factors associated with overpressuring in the KG Basin, Dewangan *et al.* (2010, p. 1628) state that "*Since the study area is located in shale tectonics regime where Miocene sequences are known to be overpressured, we interpret the zones of no coherent reflections as Miocene shale diapirs. The upward movement of shale diapirs has folded the overburden layer and resulted in the formation of numerous faults/fractures. These faults act as permeable pathways for fluid/gas movement facilitating the formation of gas hydrate and cold seeps close to shale diapiric mound*".

Multiple triggering mechanisms for the origin of SSDS in the KG Basin are expected given the location that is affected not only by tsunamis (Fig. 32A) but also by other phenomena, such as cyclones, monsoons, *etc.* (Fig. 32C). Due to multiple factors, the location of the KG Basin on the eastern continental margin is ideal for

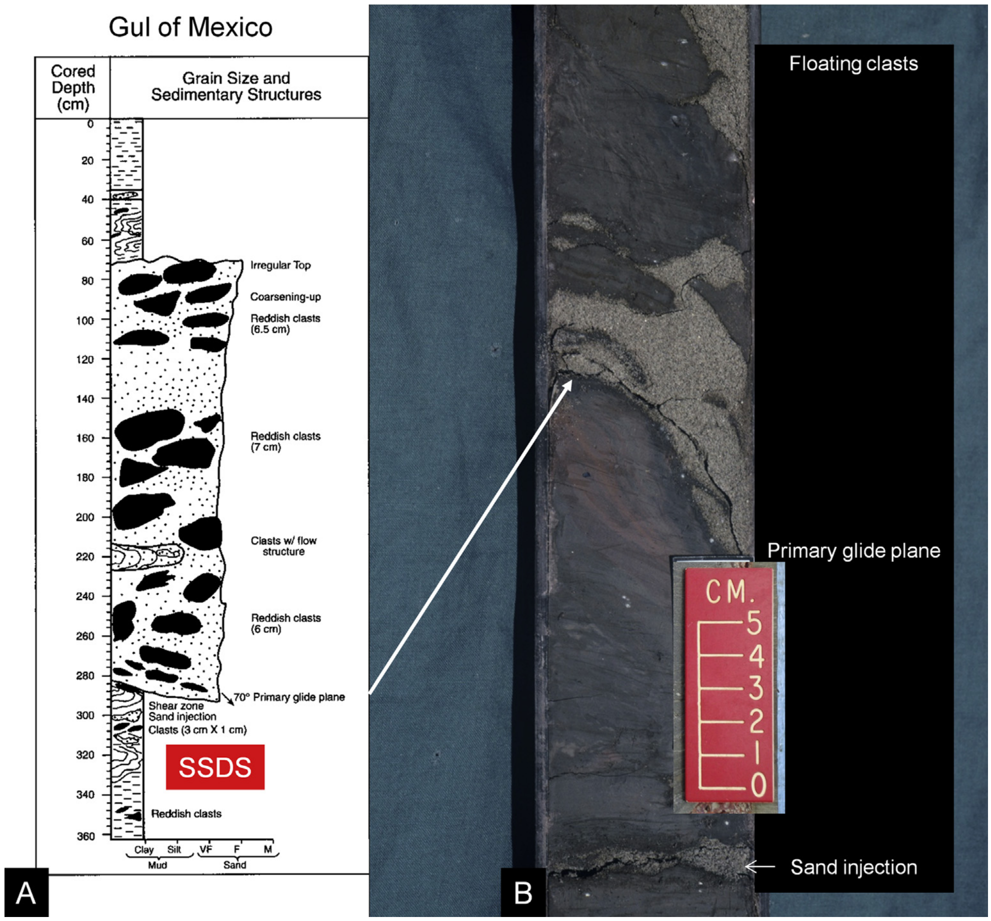

Fig. 28 A—Sedimentological log showing complex sedimentary features. Note thick interval of sand with floating mudstone clasts. IG 45—20, East Breaks Area, Holocene—Pleistocene, Gulf of Mexico. Water depth: 1416 m. IG 45, Ida Green Cruise # 45; B—Core photograph showing sand injection in the underlying mudstone, basal shear surface of the sand, overall inverse grading of the sandy unit, and floating mudstone clasts. This sandy unit perhaps represents a transitional stage between sandy slump and sandy debris flow. Arrow shows stratigraphic position. SSDS = Soft-sediment deformation structures. Figure from Shanmugam (2012a), with permission from Elsevier. Copyright Clearance Center's RightsLink: Licensee: G. Shanmugam. License Number: 3880791052847. License Date: June 2, 2016.

sediment failures and related overpressure, liquefaction, and development of SSDS.

The following factors are listed in the order of their importance for inducing liquefaction in the KG Basin:

1) **Tsunami waves.** The best known example is the 2004 Indian Ocean Tsunami (NOAA, 2005). A total of 128 tsunamis with 998 run-ups (*i.e.*, maximum height of wave above sea level up the shoreline) occurred in the Indian Ocean region during 416—2007 (Shanmugam, 2008b). Of these, 48 tsunamis affected the Bay of Bengal over a period of 270 yr (*i.e.*, one tsunami every sixth year). At this rate, more than 3000 tsunamis would have occurred during the present highstand. These tsunamis were directly linked to earthquakes (see Shanmugam, 2008b, his Table 3). Young *et al.* (2009) discussed the significance of tsunamis in the Bay of Bengal and their role on liquefaction.
2) **Cyclonic waves** (*i.e.*, typhoons). At the rate of 10 cyclones per year during 1891—2000 in the Bay of Bengal (Mascarenhas, 2004), 200,000 cyclones would have occurred during the present highstand (Shanmugam, 2008b, his Fig. 7B). Appropriately, the Bay of Bengal is known as the storm-surge capital of the world (see Chu *et al.*, 2002). The significance of cyclones on liquefaction has been discussed by various researchers in general (Finn *et al.*, 1983; Lee and Foo, 1990; Madsen, 1978; Okusa, 1985) and with particular reference to the 2005 Hurricane Katrina in the U.S. (Robertson *et al.*, 2007) and the 2009 Typhoon Morakot in Taiwan, China (Hale *et al.*, 2012).

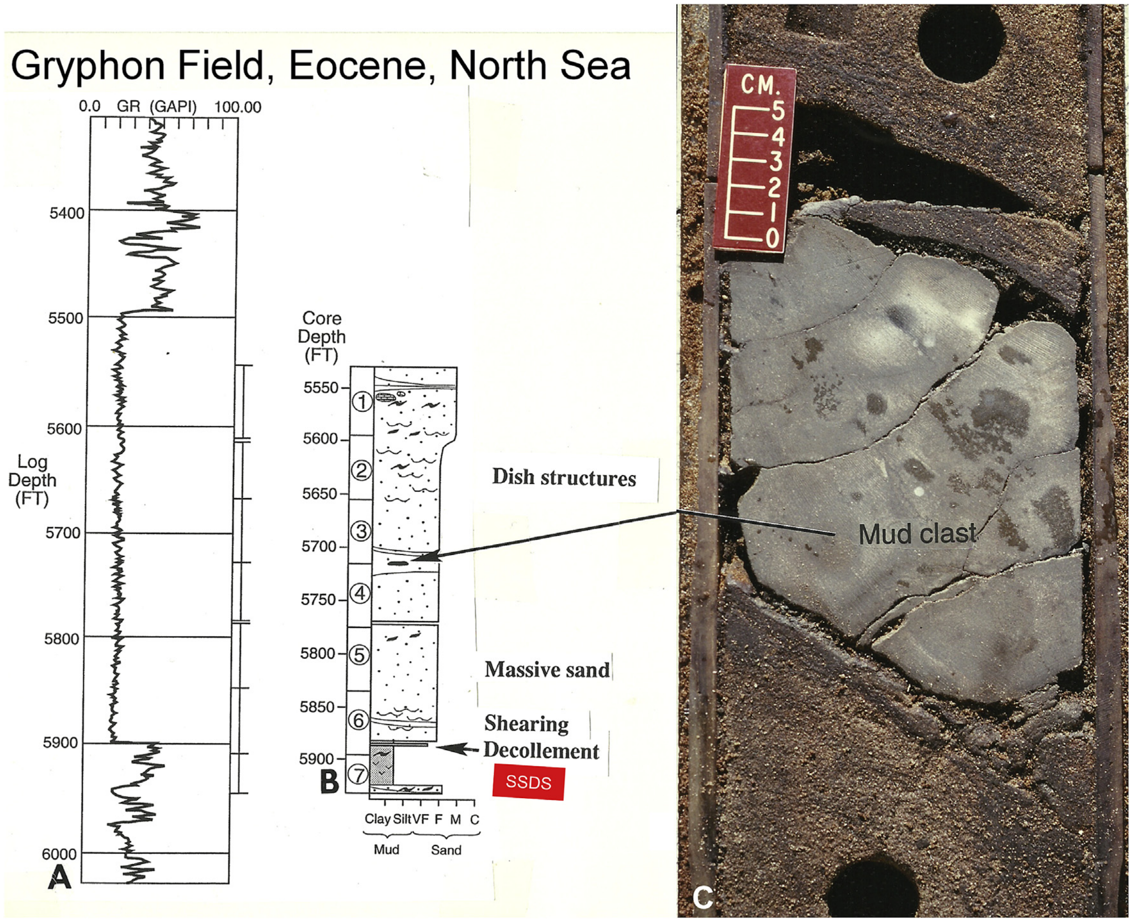

Fig. 29 Depositional characteristics of the Lower Eocene sand, Gryphon Field Area, U.K. North Sea. A—Well-developed blocky log motif. Lower Eocene, Gryphon Field, Kerr-McGee 9/18b-7; B—Depth-tied sedimentological log showing facies distribution; C—Core photograph showing large mudstone clasts in fine-grained massive sand, suggesting deposition from sandy debris flow. SSDS = Soft-sediment deformation structures. After Shanmugam *et al.* (1995), with permission from American Association of Petroleum Geologists (AAPG).

3) **Dominance of mass movements in an upper-slope canyon setting** (Shanmugam *et al.*, 2009). Aspects of liquefaction associated with mass movements have been discussed in Shanmugam (2015).
4) **Monsoon-related rapid sedimentation** (Solheim *et al.*, 2007).
5) **Shelf-edge deltaic sedimentation** (Bastia *et al.*, 2006).
6) **Seafloor-fault scarps and related sedimentation** (Forsberg *et al.*, 2007).
7) **Earthquakes** (Sukhtankar *et al.*, 1993).
8) **Shale diapirs** (Dewangan *et al.*, 2010).
9) **Gas hydrates** (Ramana *et al.*, 2006).

10) **Ebb-tidal currents** (Narasimha Rao, 2001; Shanmugam *et al.*, 2009).

11) **Internal waves and tides** (Antony *et al.*, 1985; LaFond and Rao, 1954).

Given the above empirical evidence, SSDS in the KG Basin are likely products of multiple triggering mechanisms.

6. Lateral extent of SSDS

The impressive lateral extent of depositional units with SSDS, irrespective of their origin, has been documented worldwide. In the Coal Measures (Carboniferous) of South Wales, for example, a unit with ball-and-pillow structures (SSDS) has been traced at the same horizon for over 15 km (Allen, 1982; Kuenen, 1948). Mutti (1992) correlated a Lower Eocene deep-water slump unit for nearly 18 km in South—Central Spain. Basin—plain turbidite beds, some with internal convolute laminae, have been documented to extend over hundreds of kilometers (see Shanmugam, 2006a). But these beds can be

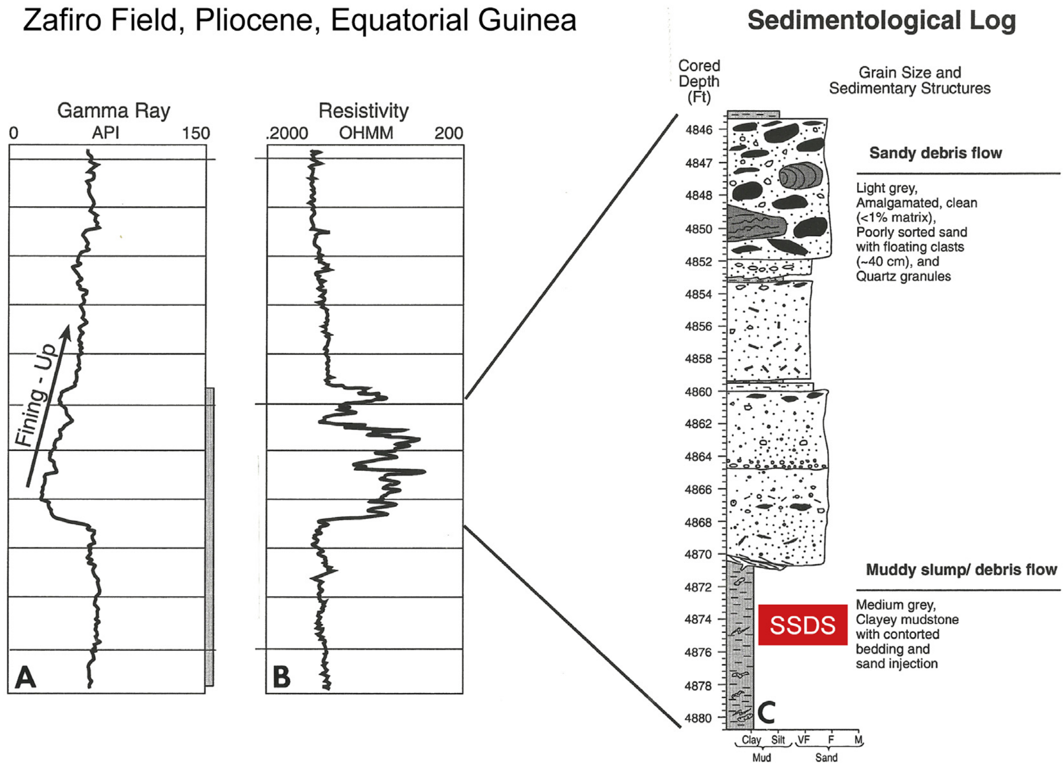

Fig. 30 A—Gamma-ray log showing fining-up motif for a cored interval (shaded vertical bar); B—Resistivity log; C—Sedimentological log showing amalgamated massive sandy units with increasing amount of mudstone clasts near the top. Zafiro 2 well, Pliocene, Zafiro Field, offshore Equatorial Guinea. SSDS = Soft-sediment deformation structures. Figure from Shanmugam (2012a), with permission from Elsevier. Copyright Clearance Center's RightsLink: Licensee: G. Shanmugam. License Number: 3880791052847. License Date: June 2, 2016.

explained by simple syndepositional mechanisms unrelated to earthquakes.

In emphasizing the lateral extent of seismites, Simms (2003, p. 557) stated that "*A 2—4 m thick seismite, in places overlain by a previously unreported tsunamite, can be traced across 250,000 km^2 of the outcrop and subcrop of the latest Triassic (Rhaetian) Cotham Member of the Penarth Group, United Kingdom, an extent unique for the British Phanerozoic. Its consistent thickness, intensity of deformation, and preferred orientations of slump-fold axes indicate a seismic event of M >10 with an epicenter 600 km W or NW of central Britain*". Such impressive extents are difficult to reconcile with theoretical and empirical analyses. Allen (1986, his Fig. 1), utilizing earthquake magnitude and distance from the epicenter in Japan (see Kuribayashi and Tatsuoka, 1975), has shown that sites of liquefaction with potential for SSDS can be induced at sites as far away as 700 km from the epicenter of an M 7.5 earthquake. Allen (1986) also discussed the limitations of predicting lateral extent of SSDS induced by earthquakes. Correlation of deformational intervals over long distances has been used as a criterion for recognizing palaeoseismites (Owen and Moretti, 2011; Sims, 1975). However such a criterion is untenable. Selected examples are:

1) As noted earlier, Kirkland and Anderson (1970) correlated centimeter-thick SSDS (Fig. 2) of tectonic origin in the Castile Formation of Permian Age in the Delaware Basin, New Mexico and Texas, for 113 km (see also Kirkland *et al.*, 2000, their Fig. 10).
2) In general, SSDS related to earthquakes with the magnitude of 5—7 occur within a distance of <20 km away from the epicenter (Papadopoulos and Lefkopoulos, 1993).
3) The spatial distribution and lateral changes of seismites and SSDS (Alfaro *et al.*, 2010; Rodríguez-Lopez *et al.*, 2007) are much more complex than a simple relationship between earthquake and a large areal extent of SSDS.
4) Pointing to this problem, Van Loon and Pisarska-Jamroży (2014, p. 7) state that "*However logical, the criterion of a large areal extent is, as a rule,*

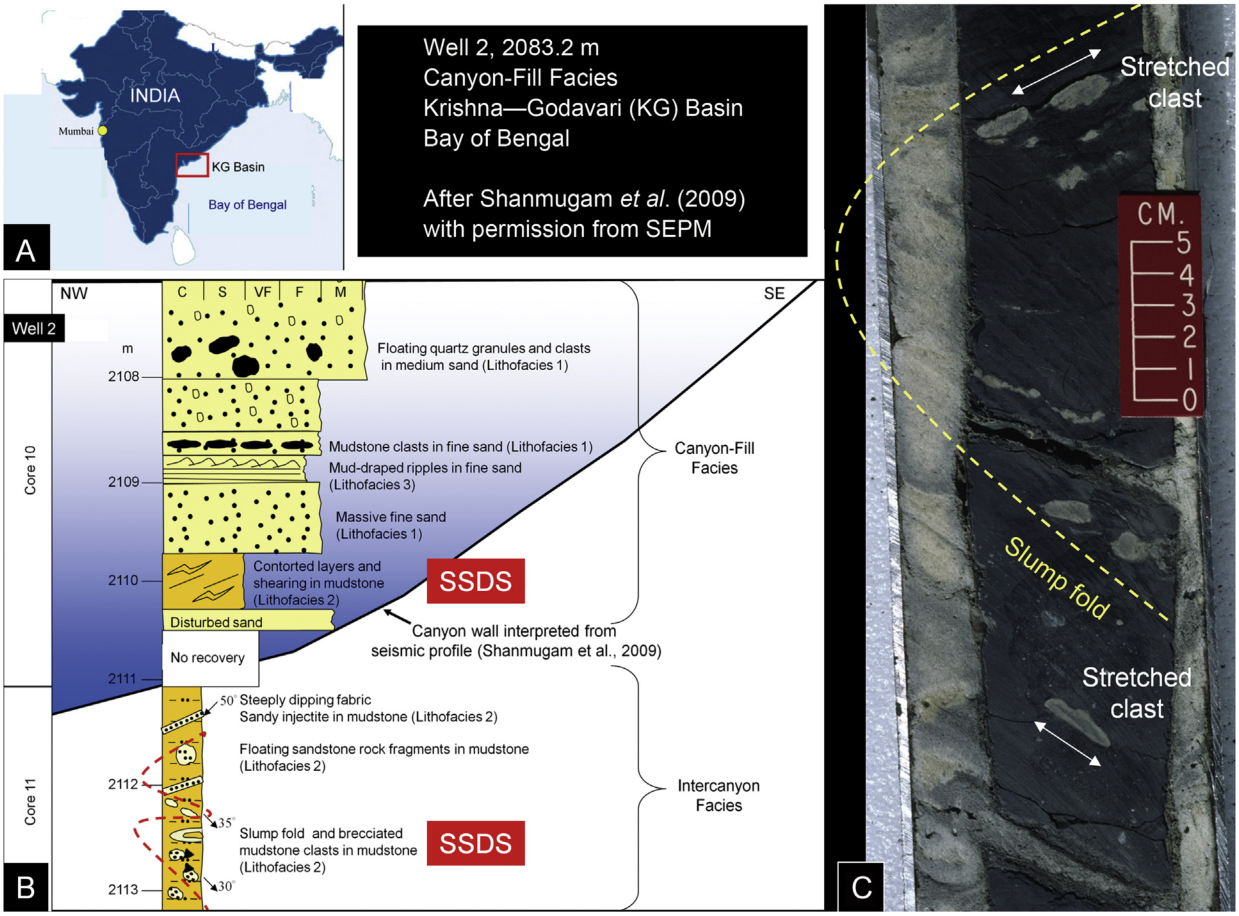

Fig. 31 A—Index map showing the location of the Krishna—Godavari (KG) Basin on the eastern continental margin of India, Bay of Bengal; B—An example of canyon-fill facies is composed of sandy debrites, sandy tidalites, and muddy slumps. The inter-canyon facies is composed of muddy slumps and debrites with sand injections in core. Severe sediment deformation is evident both below and above the canyon wall. The lack of core recovery at the canyon wall may be due to extreme sediment deformation; C—Core photograph showing slump fold (dashed line) and stretched clasts in mudstone. Well 2, 2083.2 m, canyon-fill facies. Krishna—Godavari (KG) Basin, Bay of Bengal (see also Fig. 32 for location). SSDS = Soft-sediment deformation structures. After Shanmugam *et al.* (2009), with permission from Society for Sedimentary Geology (SEPM).

hardly applicable in practice because it may be impossible to trace a seismite over a long distance: it may be tectonically disturbed or eroded away locally".

6.1. Tsunami-related deposits

Tsunami deposits, known to contain deformational features (Shanmugam, 2012b), have also been correlated over long distances (Bourgeois, 2009; Pinegina and Bourgeois, 2001). In the Mediterranean Sea, a 12-m thick tsunami deposit covers an area of at least 1100 km^2 in the Ionian Abyssal Plain (Hieke, 1984). Although this layer does not contain deformational features, it is indeed an extensive tsunami-emplaced deposit. The layer was related to tsunami generated by the collapse of the Santorini Caldera about 3500 yrs B.P. This volcanic event was responsible for the extensive layer of tsunami deposits (see also Cita *et al.*, 1996).

The most recent major example is the documentation of the laterally extensive tsunami deposits along the southeastern coast of Tamil Nadu (India) emplaced by the 2004 Indian Ocean Tsunami (Srinivasalu *et al.*, 2009). Wave heights of the 2004 Indian Ocean Tsunami reached up to 15 m. The coastline of Sumatra, near the fault boundary, received waves over 10 m tall, while those of Sri Lanka and Thailand received waves over 4 m (NOAA, 2005). On the other side of the Indian Ocean, Somalia and the Seychelles were struck by waves approaching 4 m in height. Wave height

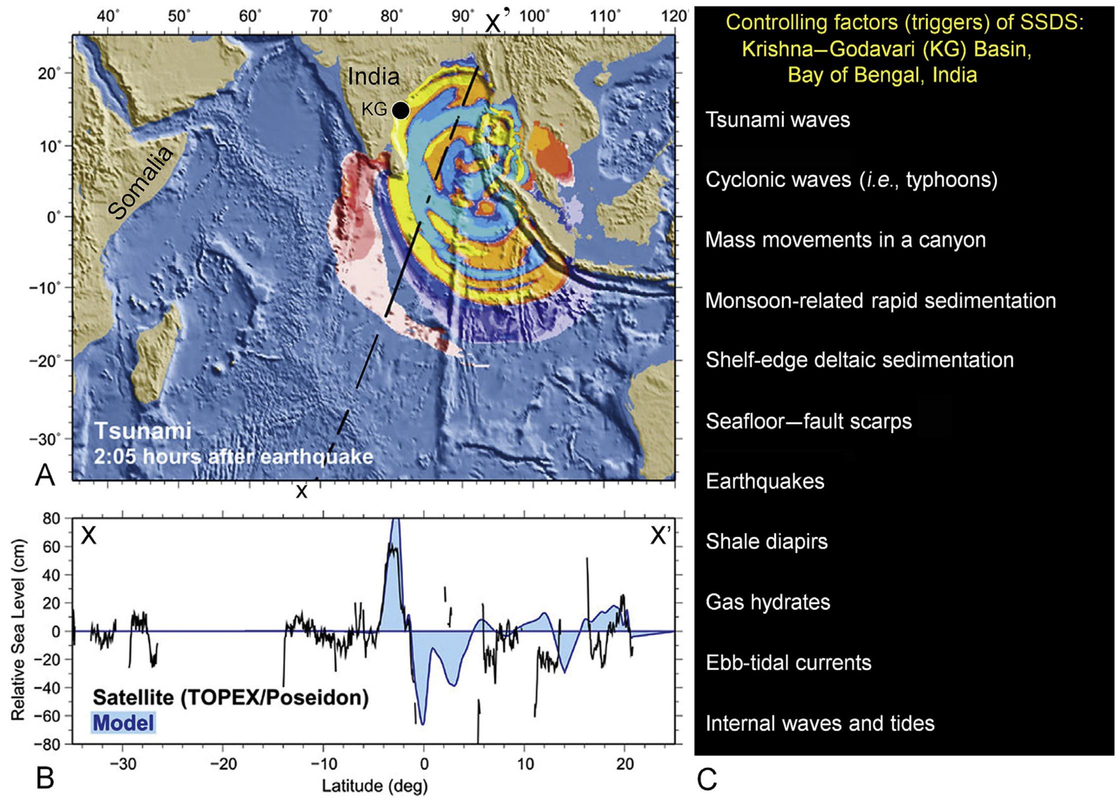

Fig. 32 A—Map showing propagating tsunami waves away from the epicenter towards the Krishna—Godavari (KG) Basin in the Bay of Bengal (solid dot) of the 2004 Indian Ocean Earthquake on December 26, 2004. The epicenter was located 3.307°N—95.947°E off the west coast of Sumatra. Measurements of sea level were made from space using the satellite (Jason-1) two hours after the earthquake; B—Plot of relative sea level along the transect X—X′; C—Controlling factors of SSDS in the KG Basin, Bay of Bengal (see text for details). Modified after NOAA (2005).

measured from space, two hours after the earthquake, reached 60 cm near the east coast of India (Fig. 32).

6.2. *Meteorite impact-related deposits*

The top ten meteorite-impact structures in the world are listed in Shanmugam (2012a, his Table 5.3). Meteorite impacts of various ages have been documented in North America (Shanmugam, 2012a, his Fig. 5.3). Schulte *et al.* (2010) reviewed the geological significance of the third largest Chicxulub asteroid impact at the K-Pg boundary on northern Yucatan, Mexico (Fig. 33). This K-Pg event generated not only major mass movements directly by the impact-induced seismic shock (Brawlower *et al.*, 1998; Busby *et al.*, 2002; Day and Maslin, 2005; Norris and Firth, 2002), but also by the impact-triggered tsunamis (Claeys *et al.*, 2002; Smit *et al.*, 1996). Chicxulub-event triggered MTDs and other deposits at the K-Pg boundary have been documented all around the Gulf of Mexico (Fig. 33) (Bourgeois *et al.*, 1988; Claeys *et al.*, 2002; Grajales-Nishimura *et al.*, 2000; Lawton *et al.*, 2005; Smit *et al.*, 1996; Takayama *et al.*, 2000). The problem is that there are presently no criteria to distinguish tsunamis-related deposits associated with earthquakes from tsunamis-related deposits associated with meteorite impacts.

6.3. *Order of triggers*

In acknowledging the problems associated with identifying triggers, Shiki (1996, p. 254) state that "*Many problems concerning various event deposits, however, remain unsolved and are subjects for future studies*".

Fig. 34 illustrates some of the real-world challenges that have been reported in the past two decades (Shanmugam, 2006a, 2006b, 2008a, 2008b, 2012a). For example, an earthquake can trigger tsunami waves, which in turn can trigger mass movements that in turn can trigger tsunami waves again. All these can occur simultaneously. Tappin (2004) discussed an example of submarine slump-generated tsunamis. Although it is well documented that earthquakes invariably cause

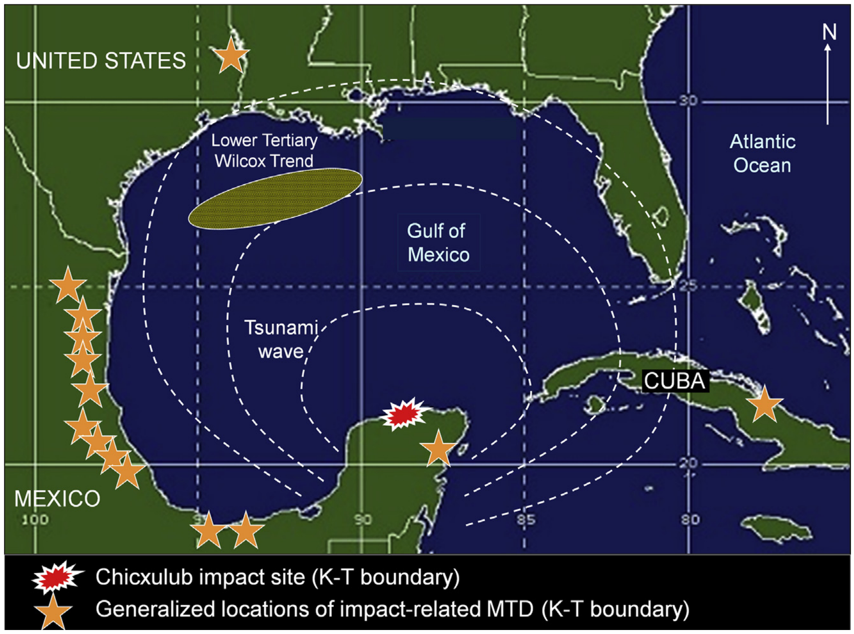

Fig. 33 Map showing the site of Chicxulub meteorite impact at the K—T boundary (i.e., K-Pg boundary) in Yucatan, Mexico. Note that the widely used term "K-T boundary" in the last century has been replaced with the term "K-Pg boundary" in this article because the term "Tertiary (Period)" has been replaced by the term "Paleogene (Period)" in the geological time scale. Stars represent approximate locations of mass-transport deposits (MTD) and tsunami-related deposits associated with the Chicxulub impact at the K—T boundary (Bourgeois *et al.*, 1988; Claeys *et al.*, 2002; Grajales-Nishimura *et al.*, 2000; Lawton *et al.*, 2005; Smit *et al.*, 1996; Takayama *et al.*, 2000). Dashed lines represent suggested tsunami wave propagation. Base map credit: NOAA Satellite and Information Service. http://www.ssd.noaa.gov/imagery/gmex.html. Location of Chicxulub impact: http://www.unb.ca/passc/ImpactDatabase/NorthAmerica.html. Accessed May 31, 2010. Generalized outline of Lower Tertiary Wilcox Trend: From several sources (*e.g.*, Meyer *et al.*, 2007). Figure from Shanmugam (2012a), with permission from Elsevier. Copyright Clearance Center's RightsLink: Licensee: G. Shanmugam. License Number: 3880791279258. License Date: June 2, 2016.

faulting and related mass-transport deposits (MTD), MTD can also trigger earthquakes. For example, Pankow et al. (2014) documented triggering of earthquakes after a massive MTD ("landslide") on April 10, 2013 at the Bingham Canyon copper mine near Salt Lake City, Utah, USA.

7. Implications for petroleum reservoirs

The importance of sand injections in evaluating petroleum reservoirs has been discussed by various researchers (Hurst and Cartwright, 2007; Purvis *et al.*, 2002; Shanmugam, 2006a, 2012a; Shanmugam *et al.*, 1993, 1994, 1995; among others). Sand injections occur in all sizes and shapes and allow both vertical and lateral fluid communication between sandstone bodies. Some of these sandstones are commonly oil-stained (Fig. 35A), suggesting that these clastic injections have served as conduits for fluid migration. In some cases, oil-stained sandstones occur along the slump-fold axis (Fig. 35B). Therefore, for developing realistic geological models and for dynamic reservoir simulation of deep-water sequences, aspects of clastic injections are important.

In discussing the importance of SSDS in evaluating petroleum reservoirs, Zheng *et al.* (2015, p. 33) state that "*These deformed sedimentary layers are favorable for the accumulation of oil and gas; for example, sedimentary dikes can cut through many layers and serve as conduits for fluid migration. Sedimentary faults and fractures induced by earthquakes can act as oil and gas migration channels or store petroleum products as well*".

8. Conclusions

1) During a period of 82 years (1931—2013), 39 genetic terms were introduced. On the average, a genetic term is being introduced every two years. Of the 39 terms, only ten are meaningful in understanding the true depositional origin (*e.g.*, turbidites), the rest are just jargons (*e.g.*, seismites, tsunamites, fluxoturbidites, *etc.*).
2) The introduction of the genetic term "seismites" by Seilacher (1969), based on a brief study of 10 m of outcrop of the Miocene Monterey Formation in California without a sound scientific analysis, is a misnomer.

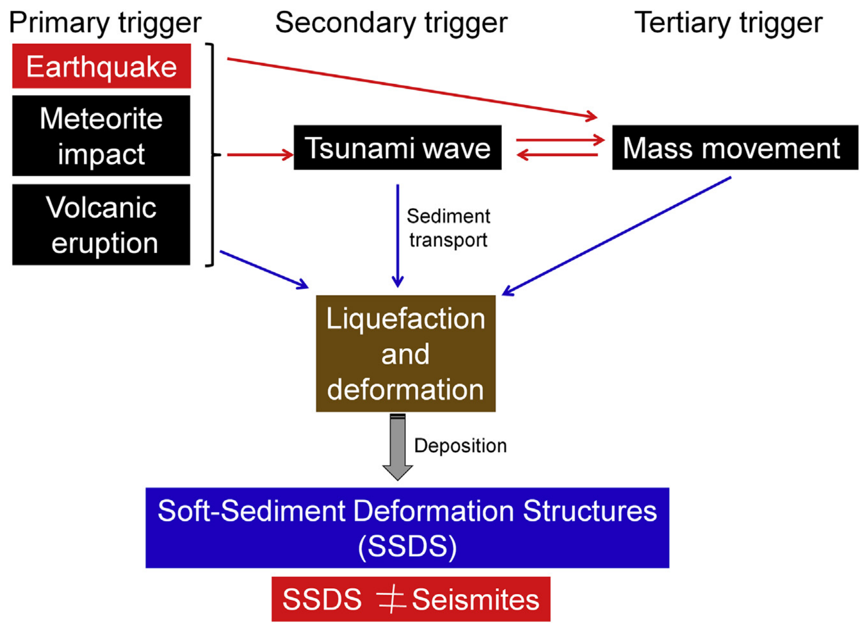

Fig. 34 Diagram illustrating complex interrelationships among the order of triggers, sediment transport, state of liquefaction, and deposition of SSDS. There are 21 triggers and they are all directly or indirectly responsible for transport processes, depositional mechanisms, and related liquefaction (Table 4). Note that an earthquake can trigger tsunami waves that in turn can trigger mass movements. Thin red arrows: Triggering of other triggers. Thin blue arrows: One or more sediment transport processes with or without flow transformations (Fisher, 1983). Thick grey arrow: Final deposition. Note that mass movement can function both as a trigger and as a transport process. See Shanmugam (2006a, 2006b, 2012a) for discussion of examples of triggers shown here.

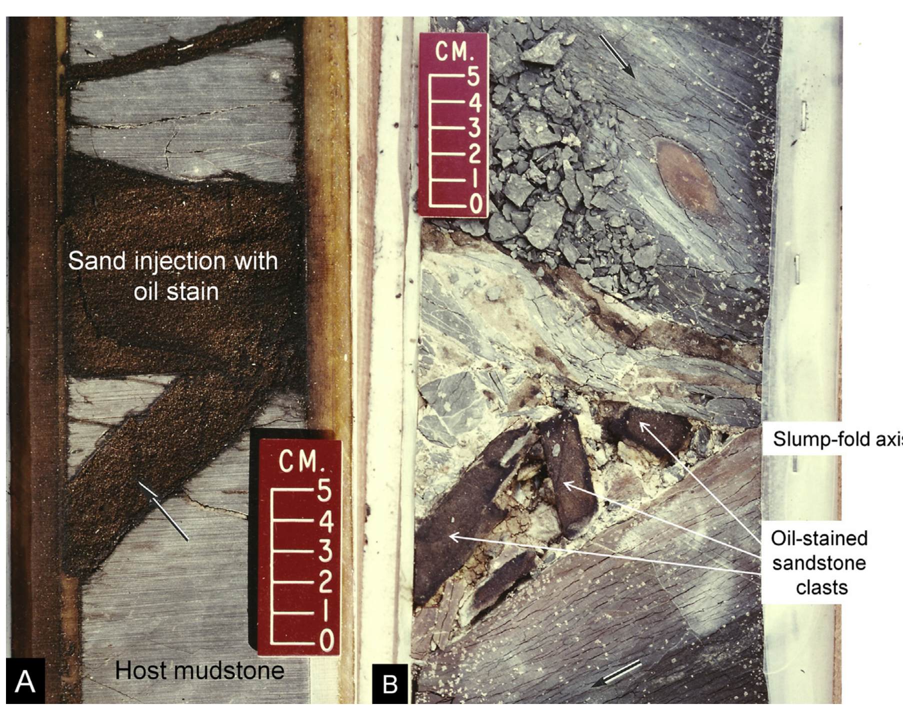

Fig. 35 A—Core photograph showing straight branching (offshoot) of a sand injection (arrow). Dark-coloration of sandstone is due to oil staining. Eocene, U.K. North Sea. From Shanmugam (2012a), with permission from Elsevier; B—Core photograph showing oil-stained sandstone clasts caught along the slump-fold axis. Middle Eocene, Central Graben, U.K. North Sea. From Shanmugam (2012a), with permission from Elsevier. Copyright Clearance Center's RightsLink: Licensee: G. Shanmugam. License Number: 3880791052847. License Date: June 2, 2016.

3) Although the genetic term is popular in some circles, the vertical seismic sequence with four internal divisions (a, b, c, and d) has failed to have a worldwide acceptance. In other words, the global geologic community has accepted the cosmetic nomenclature, but rejected the vertical sequence.
4) The genetic term, which implies earthquake, represents a triggering mechanism. Unlike depositional processes, the influence of individual triggering mechanisms is not preserved in the sedimentary record.
5) Soft-sediment deformation structures (SSDS), commonly used as the criterion for recognizing palaeoearthquake, are products of liquefaction. However, liquefaction can be induced by any one of 21 different triggering mechanisms.
6) Brecciated clasts, typically associated with earthquake-induced deposits in the Dead Sea Basin (Middle East), are also common depositional products of debris flows.
7) Lateral extent of SSDS, used as a criterion for recognizing palaeoearthquake, is also unreliable because of extensive deposits caused by tsunamis and meteorite impacts.
8) Subsurface case studies of sandstone petroleum reservoirs worldwide suggest that sediment loading is a viable mechanism for explaining the origin of SSDS.
9) The Krishna—Godavari (KG) Basin, located on the eastern continental margin of India, is ideal for sediment failures and related overpressure, liquefaction, and multiple origin of SSDS. More importantly, there are no specific sedimentologic criteria to distinguish SSDS formed by earthquakes from those formed by other mechanisms.
10) For the above reasons, the genetic term “seismites” is obsolete. Therefore, the continued application o the term is futile.
11) In petroleum geology, recognition of SSDS (*e.g.*, clastic injections) can be beneficial because they serve as conduits for petroleum migration.
12) In petroleum exploration, there is a danger of using the triggering mechanism (*e.g.*, earthquakes) to name a deposit (*e.g.*, seismites). This is because a deposit can reflect only the fluid behavior that existed at the time of final moment of deposition. Consequently, the depositional process involved and the related detrital composition are the factors that ultimately control the primary reservoir geometry and quality. In other words, triggering mechanisms are irrelevant in understanding the origin of petroleum reservoirs.

Acknowledgements

I thank Prof. Zeng-Zhao Feng (Editor-in-Chief of *Journal of Palaeogeography*; China University of Petroleum, Beijing) for inviting me to contribute this review. I am indebted to Prof. Yuan-Sheng Du for his suggestion to translate this article into Chinese and include in the Special Publication resulting from “Multi-origin SSDS and seismites” forum to be held at the 14th National Conference of Palaeogeography and Sedimentology at Henan Polytechnic University during September 23—25, 2016. I also thank Prof. Zeng-Zhao Feng for his meticulous translation of this article text into Chinese and Dr. Min Liu for her translation of figures for the Chinese edition. I thank the editor Dr. Min Liu for her excellent editing of the English version and the Associate Editor Yuan Wang for her help. I am thankful D.W. Kirkland for lending core slabs from the Permian Castile Formation, New Mexico and for his valuable discussion on the origin of microfolds. The journal reviewers Prof. Yuan-Sheng Du (State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences, Wuhan), Prof. Tian-Rui Song (Institute of Geology, Chinese Academy of Geological Sciences, Beijing), Dr. D.W. Kirkland, retired Research Scientist from Mobil Oil Corporation (now ExxonMobil), Dallas, Texas, and an anonymous reviewer are thanked for their detailed and helpful comments that considerably improved the quality and clarity of this paper. As always, I am grateful to my wife, Jean Shanmugam, for her general comments. This compilation would not have been possible without the enormous datasets that have been accumulated during my employment with Mobil (1978—2000) and during subsequent consulting works for oil companies and government agencies worldwide.

References

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

Ager, D.V., 1974. Storm deposits in the Jurassic of the Moroccan High Atlas. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 15, 83—93.

Agnon, A., Migowski, C., Marco, S., 2006. Intraclast breccias in laminated sequences reviewed: recorders of paleo-earthquakes. In: Enzel, Y., Agnon, A., Stein, M. (Eds.), *Frontiers in Dead Sea Paleoenvironmental Research*, *GSA Special Paper, 401*, pp. 195—214.

Alexander, J.I.D., Watkinson, A.J., 1989. Microfolding in the Permian Castile formation: an example of geometric systems in multilayer folding, Texas and New Mexico. *GSA Bulletin*, 101, 742—750.

Alfaro, P., 1995. *Neotectónica en la Cuenca del Bajo Segura (Cordillera Bética oriental)* (Ph.D. thesis). Universidad de Alicante, Spain, p. 219.

Alfaro, P., Delgado, J., Estévez, A., Molina, J.M., Moretti, M., Soria, J.M., 2002. Liquefaction and fluidization structures in Messinian storm deposits (Bajo Segura Basin, Betic Cordillera, southern Spain). *International Journal of Earth Sciences (Geologische Rundschau)*, 91, 505—513.

Alfaro, P., Gibert, L., Moretti, M., García-Tortosa, F.J., Sanz de Galdeano, C., Jesús Galindo-Zaldívar, J., López-Garrido, A.C., 2010. The significance of giant seismites in the Plio-Pleistocene Baza palaeo-lake (S Spain). *Terra Nova*, 22, 172—179.

Allen, C.R., 1975. Geological criteria for evaluating seismicity. *GSA Bulletin*, 86, 1041—1057.

Allen, J.R.L., 1982. *Sedimentary Structures*, vol. II. Elsevier, Amsterdam, p. 663.

Allen, J.R.L., 1984. *Sedimentary Structures, Their Character and Physical Basis*. Elsevier, Amsterdam. I, p. 593 and II, pp. 343–663.

Allen, J.R.L., 1986. Earthquake magnitude-frequency, epicentral distance, and soft-sediment deformation in sedimentary basins. *Sedimentary Geology*, 46, 67—75.

Alves, T.M., 2015. Submarine slide blocks and associated soft-sediment deformation in deep-water basins: a review. *Marine and Petroleum Geology*, 67, 262—285.

Andersen, J.C.Ø., Rasmussen, H., Nielsen, T.F.D., Rønsbo, J.G., 1998. The Triple Group and the Platinova gold and palladium reefs in the Skaergaard intrusion: stratigraphic and petrographic relations. *Economic Geology and the Bulletin of the Society of Economic Geologists*, 93, 488—509.

Antony, M.K., Murthy, C.S., Reddy, G.V., Rao, K.H., 1985. Sub-surface temperature oscillations and associated flow in the western Bay of Bengal. *Estuarine, Coastal and Shelf Science*, 21, 823—834.

Arrhenius, G., 1963. Pelagic sediments. In: Hill, M.N. (Ed.), *The Sea*, vol. 3. Wiley, New York, pp. 655—727.

Barrett, P.J., 1966. Effects of the 1964 Alaskan earthquake on some shallow-water sediments in Prince William Sound, southeast Alaska. *Journal of Sedimentary Petrology*, 36, 992—1006.

Barton, R., Bird, K., Hernández, J.G., Grajales-Nishimura, J.M., Murillo-Muñetón, G., Herber, B., Weimer, P., Koeberl, C., Neumaier, M., Schenk, O., Stark, J., 2009/2010. High impact reservoirs. *Oilfield Review*, 21, 14—29.

Basilone, L., Lena, G., Gasparo-Morticelli, M., 2014. Synsedimentary-tectonic, soft-sediment deformation and volcanism in the rifted Tethyan margin from the Upper Triassic—Middle Jurassic deep-water carbonates in Central Sicily. *Sedimentary Geology*, 308, 63—79.

Bastia, R., Nayak, P., Singh, P., 2006. Shelf delta to deepwater basin: a depositional model for Krishna—Godavari Basin. In: *American Association of Petroleum Geologists, International Conference, Perth, Australia*. http://www.searchanddiscovery.net/documents/2007/07011bastia/index.htm.

Bates, R.L., Jackson, J.A., 1980. *Glossary of Geology*, second ed. American Geological Institute, Falls Church, Virginia, p. 751.

Bea, R.G., Wright, S.G., Sicar, P., Niedoroda, A.W., 1983. Wave induced slides in South Pass Block 70, Mississippi Delta. *Journal of Geotechnical Engineering*, 109, 619—644.

Beck, C., 2009. Lake sediments as Late Quaternary palaeoseismic archives: examples in north-western Alps and clues for earthquake-origin assessment of sedimentary disturbances. *Earth-Science Reviews*, 96, 327—344.

Behl, R.J., 1999. Since Bramlette (1946): the Miocene Monterey Formation of California revisited. In: Moores, E.M., Sloan, D., Stout, D.L. (Eds.), *Classic Cordilleran Concepts: a View from California*, *GSA Special Paper, 338*, pp. 301—313.

Behrmann, J.H., Flemings, P.B., John, C.M., 2006. Rapid sedimentation, overpressure, and focused fluid flow, Gulf of Mexico continental margin. *Scientific Drilling*, 3, 1—17.

Boggs Jr., S., 2001. *Principles of Sedimentology and Stratigraphy*, third ed. Prentice Hall, New Jersey, p. 726.

Boulton, G.S., Dobbie, K.E., Zatsepin, S., 2001. Sediment deformation beneath glaciers and its coupling to the subglacial hydraulic system. *Quaternary International*, 86, 3—28.

Bouma, A.H., 1962. *Sedimentology of Some Flysch Deposits, a Graphic Approach to Facies Interpretation*. Elsevier, Amsterdam, p. 168.

Bourgeois, J., 2009. Geologic effects and records of tsunamis. In: Robinson, A.R., Bernard, E.N. (Eds.), *The Sea, Volume 15: Tsunamis*Harvard University Press, pp. 53—91.

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

Boyd, R., Ruming, K., Goodwin, I., Sandstrom, M., Schröder-Adams, C., 2008. Highstand transport of coastal sand to the deep ocean: a case study from Fraser Island, southeast Australia. *Geology*, 36, 15—18.

Boyer, S.E., Elliott, D., 1982. Thrust systems. *AAPG Bulletin*, 66, 1196—1230.

Bramlette, M.N., 1946. The Monterey formation of California and the origin of its siliceous rocks. *USGS Professional Paper*, 212, 80.

Brawlower, T.J., Paull, C.K., Leckie, R.M., 1998. The Cretaceous–Tertiary boundary cocktail: Chicxulub impact triggers margin collapse and extensive sediment gravity flows. *Geology*, 26, 331—334.

Briggs, Derek E.G., 2014. Adolf Seilacher (1925—2014) Palaeontologist who pioneered analysis of trace fossils. *Nature*, 509, 428.

Brönnimann, C.S., 2011. *Effect of Groundwater on Landslide Triggering* (Ph.D. thesis). École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, p. 239.

Brooke, C.M., Trimble, T.J., Mackay, T.A., 1995. Mounded shallow gas sands from the Quaternary of the North Sea: analogues for the formation of sand mounds in deep water Tertiary sediments? In: Hartley, A.J., Prosser, D.J. (Eds.), *Characterisation of Deep Marine Clastic Systems, Geological Society Special Publications 94*. Geological Society, London, pp. 95—101.

Busby, C.J., Yip, G., Blikra, L., Renne, P., 2002. Coastal landsliding and catastrophic sedimentation triggered by Cretaceous–Tertiary bolide impact: a pacific margin example? *Geology*, 30, 687—690.

Cannon, S.H., Kirkham, R.M., Parise, M., 2001. Wildfire-related debris-flow initiation processes, Storm King Mountain, Colorado. *Geomorphology*, 39, 171—188.

Carter, R.M., 1975. A discussion and classification of subaqueous mass-transport with particular application to grain flow, slurry flow, and fluxoturbidites. *Earth-Science Reviews*, 11, 145—177.

Chang, A., Grimm, K.A., 1999. Speckled beds: distinctive gravity-flow deposits in finely laminated diatomaceous sediments, Miocene Monterey Formation, California. *Journal of Sedimentary Research*, 69, 122—134.

Chatterjee, R., Singha, D.K., Paul, S., Mukhopadhyay, M., 2015. Overpressure zones in relation to in-situ stress for the Krishna–Godavari Basin, eastern continental margin of India: implications for hydrocarbon prospectivity. In: Mukerjee, S. (Ed.), *Petroleum Geosciences: Indian Contexts*. Springer Geology, Springer International Publishing, Switzerland, pp. 127—142.

Chu, J.H., Sampson, C.R., Levine, A.S., Fukada, E., 2002. *The Joint Typhoon Warning Center Tropical Cyclone Best-Tracks, 1945—2000*. NRL Reference Number: NRL/MR/7540-02-16. http://metocph.nmci.navy.mil/jtwc/best_tracks/TC_bt_report.

Cita, M.B., Camerlenghi, A., Rimoldi, B., 1996. Deep-sea tsunami deposits in the eastern Mediterranean: new evidence and depositional models. *Sedimentary Geology*, 10, 155—173.

Claeys, P., Kiessling, W., Alvarez, W., 2002. Distribution of Chicxulub ejecta at the Cretaceous–Tertiary boundary. In: Koeberl, C., MacLeod, K.G. (Eds.), *Catastrophic Events and Mass Extinctions: Impacts and Beyond*, *GSA Special Paper*, *356*, pp. 55—68.

Coleman, J.M., Prior, D.B., 1982. Deltaic environments. In: Scholle, P.A., Spearing, D. (Eds.), *Sandstone Depositional Environments*, *AAPG Memoir*, *31*, pp. 139—178.

Collinson, J.D., 1994. Sedimentary deformational structures. In: Maltman, A. (Ed.), *The Geological Deformation of Sediments*. Chapman & Hall, London, pp. 95—125.

Collot, J.Y., Lewis, K., Lamarche, G., Lallemand, S., 2001. The giant Ruatoria debris avalanche on the northern Hikurangi margin, New Zealand: result of oblique seamount subduction. *Journal of Geophysical Research*, 106, 19271—19297.

Crawford, F.D., 1971. Petroleum potential of Santa Maria province, California. In: Cram, I.H. (Ed.), *Future Petroleum Provinces of the United States — Their Geology and Potential*. American Association of Petroleum Geologists, Tulsa, pp. 316—328.

Damuth, J.E., Fairbridge, R.W., 1970. Equatorial Atlantic deep-sea sands and ice age aridity in tropical South America. *GSA Bulletin*, 81, 585—601.

Dan, G., Sultan, N., Savoye, B., 2007. The 1979 Nice harbour catastrophe revisited: Trigger mechanism inferred from geotechnical measurements and numerical modeling. *Marine Geology*, 245, 40—64.

Davies, G.R., 1997. Interpretites: the new universal, non-genetic, non-descriptive classification of sedimentary products and environments. *Canadian Society of Petroleum Geologists*, *Reservoir*, 24, 22—23.

Day, S., Maslin, M., 2005. Linking large impacts, gas hydrates, and carbon isotope excursions through widespread sediment liquefaction and continental slope failure: the example of the K–T boundary event. In: Kenkmann, T., Hörz, F., Deutsch, A. (Eds.), *Large Meteorite Impacts III*, *Geological Society of America Special Paper 384*. Geological Society of America, Boulder, pp. 239—258.

Dewangan, P., Ramprasad, T., Ramana, M.V., Mazumdar, A., Desa, M., Badesab, F.K., 2010. Seabed morphology and gas venting features in the continental slope region of Krishna—Godavari Basin, Bay of Bengal: implications in gas-hydrate exploration. *Marine and Petroleum Geology*, 27, 1628—1641.

Dill, R.F., 1969. Earthquake effects on fill of Scripps Submarine Canyon. *Geological Society of America Bulletin*, 80, 321—328.

Dillon, W.P., Zimmerman, H.P., 1970. Erosion by biological activity in two New England submarine canyons. *Journal of Sedimentary Petrology*, 40, 542—547.

Dott Jr., R.H., 1963. Dynamics of subaqueous gravity depositional processes. *AAPG Bulletin*, 47, 104—128.

Du, Y.S., 2011. Discussion about studies of earthquake event deposit in China. *Journal of Palaeogeography (Chinese Edition)*, 13, 581—590 (in Chinese with English abstract).

Dysthe, K., Krogstad, H.E.,Műller, P., 2008. Oceanic rogue waves. *Annual Reviews of Fluid Mechanics*, 40, 287—310.

Dzulynski, S., Ksiazkiewicz, M., Kuenen, Ph.H., 1959. Turbidites in flysch of the Polish Carpathian Mountains. *GSA Bulletin*, 70, 1089—1118.

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

Elverhøi, A., De Blasio, F., Butt, F.A., Issler, D., Harbitz, C.B., Engvik, L., Solheim, A., Marr, J.G., 2002. Submarine mass-wasting on glacially-influenced continental slopes: processes and dynamics. In: Dowdeswell, J.A., O'Cofaigh, C. (Eds.), *Glacier-Influenced Sedimentation on High-Latitude Continental Margins*, *Geological Society Special Publications, London*, *203*, pp. 73—87.

Elverhøi, A., Norem, H., Anderson, E.S., Dowdeswell, J.A., Fossen, I., Haflidason, H., Kenyon, N., Laberg, J.S., King, E.L., Sejrup, H.P., Solheim, A., Vorren, T.O., 1997. On the origin and flow behavior of submarine slides on deep-sea fans along the Norwegian-Barents Sea continental margin. *Geo-Marine Letters*, 17, 119—125.

Ettensohn, F.R., Rast, N., Brett, C.E., 2002. Ancient seismites. *GSA Special Paper*, 359, 190.

Ettensohn, R., Zhang, C., Gao, L., Lierman, R.T., 2011. Soft-sediment deformation in epicontinental carbonates as evidence of paleoseismicity with evidence for a possible new seismogenic indicator: accordion folds. *Sedimentary Geology*, 235, 222—233.

Ezquerro, L., Moretti, M., Liesa, C.L., Luzóna, A., Simóna, J.L., 2015. Seismites from a well core of

palustrine deposits as a tool for reconstructing the palaeoseismic history of a fault. *Tectonophysics*, 655, 191–205.
Feldhausen, P.H., Stanley, D.J., Knight, R.J., 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*. Tecnoprint, Bologna, pp. 203–226.
Feng, Z.Z., Bao, Z.D., Zheng, X.J., Wang, Y., 2016. Researches of soft-sediment deformation structures and seismites in China — a brief review. *Journal of Palaeogeography*, 5(4), 311–317. http://dx.doi.org/10.1016/j.jop.2016.06.001.
Finn, W.D.L., Siddharthan, R., Martin, G.R., 1983. Response of seafloor to ocean waves. *Journal of Geotechnical Engineering Division, ASCE*, 109, 556–572.
Fisher, R.V., 1983. Flow transformations in sediment gravity flows. *Geology*, 11, 273–274.
Flint, R.F., Sanders, J.E., Rodges, J., 1960. Diamictite: a substitute term for symmictite. *GSA Bulletin*, 71, 1809–1810.
Forsberg, C.F., Solheim, A., Kvalstad, T.J., Vaidya, R., Mohanty, S., 2007. Slope instability and mass transport deposits on the Godavari River Delta, East Indian margin from a regional geological perspective. In: Lykousis, V., Sakellariou, D., Locat, J. (Eds.), *Submarine Mass Movements and Their Consequences: 3rd International Symposium, Advances in Natural and Technological Hazards Research*, vol. 27. Springer, pp. 19–27.
Gani, R., 2004. From turbid to lucid: a straightforward approach to sediment gravity flows and their deposits. *Sedimentary Record*, 3, 4–8.
Gao, H.C., Zheng, R.C., Chen, F.L., Zhu, B.B., Song, P., Liu, X.Y., Fu, X.N., 2010. Recognition and significance of seismites of the Paleogene Shahejie Formation in Dongpu Sag. *Journal of Palaeogeography (Chinese Edition)*, 12, 384–398 (in Chinese with English abstract).
Gaudin, M., Berne, S., Jouanneau, J.M., Palanques, A., Puig, P., Mulder, T., Cirac, P., Rabineau, M., Imbert, P., 2006. Massive sand beds attributed to deposition by dense water cascades in the Bourcart canyon head, Gulf of Lions (northwestern Mediterranean Sea). *Marine Geology*, 234, 111–128.
Godfrey, J.D., 1954. The origin of ptygmatic structures. *Journal of Geology*, 62, 375–387.
Gong, Y.M., 1988. Tempestite, seismite and tsunamite: a discussion of several sedimentological terms. *Geological Review*, 34, 481–482 (in Chinese).
Goud, K.M., Bhavana, P.R., 2010. Prediction of high pressures in HP–HT well — a case study from KG Basin, east coast of India. In: *8th Biennial International Conference and Exposition on Petroleum Geophysics*. Society of Petroleum Geophysics, Hydrerabad, India, p. 93.
Gradmann, S., Beaumont, C., Ings, S.J., 2012. Coupled fluid flow and sediment deformation in margin-scale salt-tectonic systems: 1. Development and application of simple, single-lithology models. *Tectonics*, 31. TC4010.
Grajales-Nishimura, J.M., Cedillo-Pardo, E., Rosales-Domínguez, C., Morán-Zenteno, D., Alvarez, W., Claeys, P., Ruíz-Morales, J., García-Hernández, J., Padilla-Avila, P., Sánchez-Ríos, A., 2000. Chicxulub impact: the origin of reservoir and seal facies in the southeastern Mexico oil fields. *Geology*, 28, 307–310.
Greb, S.F., Ettensohn, F.R., Obermeier, S.F., 2002. Developing a classification scheme for seismites. In: *GSA North-central and Southeastern Section Annual Meeting Abstracts with Programs*.
Greene, H.G., Murai, L.Y., Watts, P., Maher, N.A., Fisher, M.A., Paull, C.E., Eichhubl, P., 2006. Submarine landslides in the Santa Barbara Channel as potential tsunami sources. *Natural Hazards and Earth System Sciences*, 6, 63–88.
Grimm, K.A., Orange, D.L., 1997. Synsedimentary fracturing, fluid migration, and subaqueous mass wasting; intrastratal microfractured zones in laminated diatomaceous sediments, Miocene Monterey Formation, California, USA. *Journal of Sedimentary Research*, 67, 601–613.
Hale, R.P., Nittrouer, C.A., James, T., Liu, J.T., Keil, R.G., Ogston, A.S., 2012. Effects of a major typhoon on sediment accumulation in Fangliao Submarine Canyon, SW Taiwan. *Marine Geology*, 326–328, 116–130.
Hampton, M.A., 1972. The role of subaqueous debris flows in generating turbidity currents. *Journal of Sedimentary Petrology*, 42, 775–793.
Harland, W.B., Herod, K.N., Krinsley, D.H., 1966. The definition and identification of tills and tillites. *Earth-Science Reviews*, 2, 225–256.
He, B., Qiao, X., 2015. Advances and overview of the study on paleo-earthquake events: a review of seismites. *Acta Geologica Sinica (English Edition)*, 89, 1702–1746.
Heezen, B.C., Ewing, M., 1952. Turbidity currents and submarine slumps, and the 1929 Grand Banks earthquake. *American Journal Science*, 250, 849–873.
Helwig, J., 1970. Slump folds and early structures, northeastern Newfoundland Appalachians. *Journal of Geology*, 78, 172–187.
Henstock, T.J., McNeill, L.C., Tappin, D.R., 2006. Seafloor morphology of the Sumatran subduction zone: surface rupture during megathrust earthquakes? *Geology*, 34, 485–488.
Hieke, W., 1984. A thick Holocene Homogenite from the Ionian Abyssal Plain (Eastern Mediterranean). *Marine Geology*, 55, 63–78.
Hiscott, R.N., 1979. Clastic sills and dikes associated with deep-water sandstones, Tourelle Formation, Ordovician, Quebec. *Journal of Sedimentary Petrology*, 49, 1–10.
Hollister, C.D., 1967. *Sediment Distribution and Deep Circulation in the Western North Atlantic* (Ph.D. thesis). Columbia University, New York, p. 467.
Hsü, K.J., 1989. *Physical Principles of Sedimentology*. Springer-Verlag, New York, p. 233.
Hurst, A., Cartwright, J., 2007. Sand injectites: implications for hydrocarbon exploration. *AAPG Memoir*, 87, 288.
Isaacs, C.M., Pisciotto, K.A., Garrison, R.E., 1983. Facies and diagenesis of the Miocene Monterey Formation, California: a summary. In: Siever, R., Iijima, A., Hein, J.R. (Eds.), *Siliceous Deposits in the Pacific Region, Developments in Sedimentology*, vol. 36, pp. 247–282.
Jain, C.K., Yerramilli, S.S., Yerramilli, R.C., 2012. A case study on blowout and its control in Krishna–Godavari (KG) Basin, East Coast of India: safety and environmental

perspective. *Journal of Environment and Earth Science*, 2, 49—60.

Jewell, H.E., Ettensohn, F.R., 2004. An ancient seismite response to Taconian far-field forces: the Cane Run Bed, Upper Ordovician (Trenton) Lexington Limestone, Central Kentucky (USA). *Journal of Geodynamics*, 37, 487—511.

Jolly, R.J.H., Lonergan, L., 2002. Mechanisms and control on the formation of sand intrusions. *Journal of the Geological Society, London*, 159, 605—617.

Kale, M.G., Pundalik, A.S., Duraiswami, R.A., Karmalkar, N.R., 2016. Soft sediment deformation structures from Khari River section of Rudramata member, Jhuran Formation, Kutch: a testimony of Jurassic seismites. *Journal of the Geological Society of India*, 87, 194—204.

Kastens, K.A., Cita, M.B., 1981. Tsunami induced sediment transport in the Abyssal Mediterranean Sea. *GSA Bulletin*, 89, 591—604.

Kearey, P., Klepeis, K.A., Vine, F.J., 2009. *Global Tectonics*, third ed. Wiley-Blackwell, p. 496.

Kennett, J.P., Fackler-Adams, B.N., 2000. Relationship of clathrate instability to sediment deformation in the Upper Neogene of California. *Geology*, 28, 215—218.

Khvorova, I.V., 1978. Terrigenous clastic formations of oceans and certain seas. *Lithologiya i Polenzye Iskopaemye*, 3, 3—24.

Kirkland, D.W., Anderson, R.Y., 1970. Microfolding in the Castile and Todilto Evaporites, Texas and New Mexico. *GSA Bulletin*, 81, 3259—3282.

Kirkland, D.W., Denison, R.E., Dean, W.E., 2000. Parent brine of the Castile Evaporites (Upper Permian), Texas and New Mexico. *Journal of Sedimentary Research*, 70, 749—761.

Klein, G.D., 1971. A sedimentary model for determining paleotidal range. *GSA Bulletin*, 82, 2585—2592.

Klein, G.D., 1998. Clastic tidalites — a partial retrospective view. In: Alexander, C.R., Davis, R.A., Henry, V.J. (Eds.), *Tidalites: Processes and Products*, *Special Publication 61*. SEPM, Tulsa, pp. 5—14.

Kuenen, Ph.H., 1948. Slumping in the Carboniferous rocks of Pembrokeshire. *The Quarterly Journal of the Geological Society of London*, 104, 365—380.

Kuenen, Ph.H., 1957. Sole markings of graded greywacke beds. *Journal of Geology*, 65, 231—258.

Kuenen, Ph.H., 1967. Emplacement of flysch-type sand beds. *Sedimentology*, 9, 203—243.

Kuenen, Ph.H., Migliorini, C.I., 1950. Turbidity currents as a cause of graded bedding. *Journal of Geology*, 58, 91—127.

Kuribayashi, E., Tatsuoka, F., 1975. Brief review of liquefaction during earthquakes in Japan. *Soils Found*, 15, 81—92.

Labaume, P., Mutti, E., Seguret, M., 1987. Megaturbidites: a depositional model from the Eocene of the SW-Pyrenean foreland basin, Spain. *Geo-Marine Letters*, 7, 91—101.

LaFond, K.G., Rao, C.P., 1954. Vertical oscillations of tidal periods in the temperature structure of the sea. *Andhra University Memoirs*, 1, 109—116.

Lawson, D.E., 1981. Mobilization, movement and deposition of active subaerial sediment flows, Matanuska Glacier, Alaska. *Journal of Geology*, 90, 279—300.

Lawton, T.F., Shipley, K.W., Aschoff, J.L., Giles, K.A., 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*, 33, 81—84.

Le Heron, D.P., Etiene, J.L., 2005. A complex subglacial clastic dyke swarm, Sólheimajökull, Southern Iceland. *Sedimentary Geology*, 181, 25—37.

Le Roux, J.P., Gómez, C., Fenner, J., Middleton, H., 2004. Sedimentological processes in a scarp-controlled rocky shoreline to upper continental slope environment, as revealed by unusual sedimentary features in the Neogene Coquimbo Formation, north-central Chile. *Sedimentary Geology*, 165, 67—92.

Le Roux, J.P., Nielsen, S.N., Kemnitz, H., Henriquez, A., 2008. A Pliocene mega-tsunami deposit and associated features in the Ranquil Formation, southern Chile. *Sedimentary Geology*, 203, 164—180.

Lee, F.H., Foo, S.L., 1990. Undrained cyclic loading on a saturated dense sand stratum. *Géotechnique*, 40, 451—465.

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. *Lithologiya i Polenzye Iskopaemye*, 4, 3—28.

Locat, J., Lee, H.J., 2002. Submarine landslides, advances and challenges. *Canadian Geotechnical Journal*, 39, 193—212.

Logan, W.E., 1863. *Report on the Geology of Canada*. John Lovell, Montreal, Canada, p. 464.

Lowe, D.R., 1975. Water escape structures in coarse grained sediments. *Sedimentology*, 22, 157—204.

Lowe, D.R., 1979. Sediment gravity flows: their classification, and some problems of application to natural flows and deposits. In: Doyle, L.J., Pilkey, O.H. (Eds.), *Geology of Continental Slopes*, *SEPM Special Publication, 27*, pp. 75—82.

Lowe, D.R., 1982. Sediment gravity flows, II. Depositional models with special reference to the deposits of high-density turbidity currents. *Journal of Sedimentary Petrology*, 52, 279—297.

Lowe, D.R., LoPiccolo, R.D., 1974. The characteristics and origins of dish and pillar structures. *Journal of Sedimentary Petrology*, 44, 484—501.

Madsen, O.S., 1978. Wave-induced pore pressures and effective stresses in a porous bed. *Géotecnique*, 28, 377—393.

Malkawi, A.I.H., Alawneh, A.S., 2000. Paleoearthquake features as indicators of potential earthquake activities in the Karameh Dam Site. *Natural Hazards*, 22, 1—16.

Maltman, A., 1984. On the term soft-sediment deformation. *Journal of Structural Geology*, 6, 589—592.

Maltman, A., 1994a. Introduction and overview. In: Maltman, A. (Ed.), *The Geological Deformation of Sediments*. Chapman & Hall, London, pp. 1—35.

Maltman, A., 1994b. Deformation structures preserved in the rocks. In: Maltman, A. (Ed.), *The Geological Deformation of Sediments*. Chapman & Hall, London, pp. 261—307.

Marr, J.G., Harff, P.A., Shanmugam, G., Parker, G., 2001. Experiments on subaqueous sandy gravity flows, the role of clay and water content in flow dynamics and depositional structures. *GSA Bulletin*, 113, 1377—1386.

Martín-Chivelet, J., Palma, R.M., López-Gómez, J., Kietzmann, D.A., 2011. Earthquake-induced soft-sediment deformation structures in Upper Jurassic open-marine microbialites (Neuquén Basin, Argentina). *Sedimentary Geology*, 235, 210—221.

Mascarenhas, A., 2004. Oceanographic validity of buffer zones for the east coast of India: a hydrometeorological perspective. *Current Science*, 86, 399—406.

Maslin, M., Owen, M., Day, S., Long, D., 2004. Linking continental slope failures and climate change: testing the gun hypothesis. *Geology*, 32, 53—56.

Mazumder, R., Van Loon, A.J., Arima, M., 2006. Soft-sediment deformation structures in the Earth's oldest seismites. *Sedimentary Geology*, 186, 19—26.

Mazumder, R., Van Loon, A.J., Malviya, V.P., Arima, M., Ogawa, Y., 2016. Soft-sediment deformation structures in the Mio-Pliocene Misaki Formation within alternating deep-sea clays and volcanic ashes (Miura Peninsula, Japan). *Sedimentary Geology*, in press, http://dx.doi.org/10.1016/j.sedgeo.2016.02.010.

Merriam, D.F., Neuhauser, K.R., 2009. Seismite indicates Pleistocene earthquake activity in Ellis County, Kansas. *Transactions of the Kansas Academy of Science*, 112, 109—112.

Meyer, D., Zarra, L., Yun, J., 2007. From Baha to Jack — evolution of the lower Tertiary Wilcox trend in the deepwater Gulf of Mexico. *The Sedimentary Record*, 5, 4—9.

Middleton, G.V., 1993. Sediment deposition from turbidity currents. *Annual Review of Earth and Planetary Sciences*, 21, 89—114.

Middleton, G.V., Hampton, M.A., 1973. Sediment gravity flows: mechanics of flow and deposition. In: Middleton, G.V., Bouma, A.H. (Eds.), *Turbidites and Deep-Water Sedimentation*, *Pacific Section SEPM*, pp. 1—38. Los Angeles, California.

Mills, P.C., 1983. Genesis and diagnostic value of soft-sediment deformation structures — a review. *Sedimentary Geology*, 35, 83—104.

Mohindra, R., Bagati, T.N., 1996. Seismically induced soft-sediment structures (seismites) around Sumdo in the lower Spiti valley (Tethys Himalaya). *Sedimentary Geology*, 101, 69—83.

Montenat, C., Barrier, P., Ott d'Estevou, P., Hibsch, C., 2007. Seismites: an attempt at critical analysis and classification. *Sedimentary Geology*, 196, 5—30.

Moretti, M., 2000. Soft-sediment deformation structures interpreted as seismites in Middle–Late Pleistocene Aeolian deposits (Apulian foreland, southern Italy). *Sedimentary Geology*, 135, 167—179.

Moretti, M., Sabato, L., 2007. Recognition of trigger mechanisms for soft-sediment deformation in the Pleistocene lacustrine deposits of the Sant'Arcangelo Basin (Southern Italy): seismic shock vs. overloading. *Sedimentary Geology*, 196, 31—45.

Moretti, M., Van Loon, A.J., 2014. Restrictions to the application of 'diagnostic' criteria for recognizing ancient seismites. *Journal of Palaeogeography*, 3, 162—173.

Mosher, D.C., Shipp, R.C., Moscardelli, L., Chaytor, J.D., Baxter, C.D.P., Lee, H.J., Urgeles, R., 2010. *Submarine Mass Movements and Their Consequences*. In: *Advances in Natural and Technological Hazards Research*, vol. 28. Springer, p. 786.

Mulder, T., Migeon, S., Savoye, B., Faugères, 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*, 22, 112—120.

Mulder, T., Philippe, R., Faugères, J.-C., Gérard, J., 2011. Reply to the discussion by Roger Higgs on 'Hummocky cross-stratification-like structures in deep-sea turbidites: Upper Cretaceous Basque basins (Western Pyrenees, France)' by Mulder *et al.*, Sedimentology, 56, 997–1015. *Sedimentology*, 58, 571—577.

Mutti, E., 1992. *Turbidite Sandstones*. Special Publication. Agip, Milan, p. 275.

Mutti, E., Ricci Lucchi, F., Segure, T.M., Zanzucchi, G., 1984. Seismoturbidites: a new group of resedimented deposits. In: Cita, M.B., Ricci Lucchi, F. (Eds.), *Seismicity and Sedimentation*. Elsevier Scientific Publication, Amsterdam, pp. 103—116.

Mutti, E., Tinterri, R., Remacha, E., Mavilla, N., Angella, S., Fava, L., 1999. *An Introduction to the Analysis of Ancient Turbidite Basins from an Outcrop Perspective*. In: *AAPG Continuing Education Course Note Series 39*, p. 61. Tulsa, Oklahoma.

Narasimha Rao, T.V., 2001. Time-dependent stratification in the Gauthami—Godavari estuary. *Estuaries*, 24, 18—29.

Natland, M.L., 1967. New classification of water-laid clastic sediments. *AAPG Bulletin*, 51, 476.

Ni, L.T., Zhong, J.H., Shao, Z.F., Li, Y., Mao, C., Liu, S., 2015. Characteristics, genesis, and sedimentary environment of duplex-like structures in the Jurassic sediments of Western Qaidam Basin, China. *Journal of Earth Science*, 26, 677—689.

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

Norris, R.D., Firth, J.V., 2002. Mass wasting of Atlantic continental margins following the Chicxulub impact event. In: Koeberl, C., MacLeod, K.G. (Eds.), *Catastrophic Events and Mass Extinctions: Impacts and Beyond*, *GSA Special Paper*, *356*, pp. 79—95.

Obermeier, S., Pond, E., Olson, S., Green, R., 2002. Paleoliquefaction studies in continental settings. *GSA Special Paper*, 359, 13—27.

Obermeier, S.F., 1989. The New Madrid earthquakes: an engineering-geologic interpretation of relict liquefaction features. *U.S. Geological Survey Professional Paper*, 1336-B, 114.

Obermeier, S.F., 1996. Use of liquefaction-induced features for paleoseismic analysis — an overview of how seismic liquefaction features can be distinguished from other features and how their regional distribution and properties of source sediment can be used to infer the location and strength of Holocene paleo-earthquakes. *Engineering Geology*, 44, 1—76.

Obermeier, S.F., 1998. *Seismic Liquefaction Features: Examples from Paleoseismic Investigations in the Continental United States*. *U.S. Geological Survey*, *Open-File Report*, pp. 98—488. http://pubs.usgs.gov/of/1998/of98-488/.

Obermeier, S.F., Olson, S.M., Green, R.A., 2005. Field occurrences of liquefaction-induced features: a primer for engineering geologic analysis of paleoseismic shaking. *Engineering Geology*, 76, 209—234.

Odonne, F., Callot, P., Debroas, E.J., Sempere, T., Hoareau, G., Maillard, A., 2011. Soft-sediment deformation from submarine sliding: favourable conditions and triggering mechanisms in examples from the Eocene Sobrarbe delta (Ainsa, Spanish Pyrenees) and the Mid-Cretaceous Ayabacas Formation (Andes of Peru). *Sedimentary Geology*, 235, 234—248.

Okusa, S., 1985. Wave-induced stresses in unsaturated submarine sediments. *Géotechnique*, 35, 517—532.

Owen, G., 1987. Deformation processes in unconsolidated sands. In: Jones, M.E., Preston, R.M.F. (Eds.), *Deformation of Sediments and Sedimentary Rocks, Geological Society, London, Special Publications, 29*, pp. 11—24.

Owen, G., Moretti, M., 2011. Identifying triggers for liquefaction-induced soft-sediment deformation in sands. *Sedimentary Geology*, 235, 141—147.

Owen, G., Moretti, M., Alfaro, P., 2011. Recognising triggers for soft-sediment deformation: current understanding and future directions. *Sedimentary Geology*, 235, 133—140.

Pankow, K.L., Moore, J.R., Hale, J.M., Koper, K.D., Kubacki, T., Whidden, K.M., McCarter, M.K., 2014. Massive landslide at Utah copper mine generates wealth of geophysical data. *GSA Today*, 24(1), 9.

Papadopoulos, G.A., Lefkopoulos, G., 1993. Magnitude-distance relation for liquefaction in soil from earthquakes. *Bulletin of the Seismological Society of America*, 83, 925—938.

Peterson, G.L., 1966. Structural interpretation of sandstone dikes, Northwest Sacramento Valley, California. *GSA Bulletin*, 77, 833—842.

Petley, D., 2012. Global patterns of loss of life from landslides. *Geology*, 40, 927—930.

Pinegina, T.K., Bourgeois, J., 2001. Historical and paleotsunami deposits on Kamchatka, Russia: long-term chronologies and long-distance correlations. *Natural Hazards and Earth System Sciences*, 1, 177—185.

Pinto, J.A., Warme, J.E., 2008. Alamo Event, Nevada: Crater stratigraphy and impact breccia realms. In: Evans, K.R., Horton Jr., J.W., King Jr., D.T., Morrow, J.R. (Eds.), *The Sedimentary Record of Meteorite Impacts, GSA Special Paper, 437*, pp. 99—137.

Piper, D.J.W., Deptuck, M.E., Mosher, D.C., Hughes-Clarke, J.E., Migeon, S., 2012. Erosional and depositional features of glacial meltwater discharges on the eastern Canadian continental margin. In: Prather, B.E., Deptuck, M.E., Mohrig, D.C., Van Hoorn, B., Wynn, R.B. (Eds.), *Application of the Principles of Seismic Geomorphology to Continental-Slope and Base-of-Slope Systems: Case Studies from Seafloor and Near-Seafloor Analogues, SEPM Special Publication, 99*, pp. 61—80.

Piper, D.J.W., Shor, A.N., Hughes Clarke, J.E., 1988. The 1929 'Grand Banks' earthquake, slump, and turbidity current. In: Clifton, H.E. (Ed.), *Sedimentologic Consequences of Convulsive Geologic Events, GSA Special Paper, 229*, pp. 77—92.

Pluenneke, J.L., 1976. *Comparative Analysis of Debrites, Turbidites, and Contourites* (M.S. thesis). Texas A&M University, College Station, p. 93.

Pomar, L., Morsilli, M., Hallock, P., Bádenas, B., 2012. Internal waves, an under-explored source of turbulence events in the sedimentary record. *Earth-Science Reviews*, 111, 56—81.

Popenoe, P., Schmuck, E.A., Dillon, W.P., 1993. The Cape Fear Landslide: slope failure associated with salt diapirism and gas hydrate decomposition. In: Schwab, W.C., Lee, H.J., Twichell, D.C. (Eds.), *Submarine Landslides: Selected Studies in the U.S. Exclusive Economic Zone, U.S. Geological Survey Bulletin, 2002*, pp. 40—53.

Postma, G., 1986. Classification of sediment gravity-flow deposits based on flow conditions during sedimentation. *Geology*, 14, 291—294.

Prior, D.B., Hooper, J.R., 1999. Sea floor engineering geomorphology: recent achievements and future directions. *Geomorphology*, 31, 411—439.

Prior, D.B., Suhayda, J.N., Lu, N.Z., Bornhold, B.D., Keller, G.H., Wiseman, W.J., Wright, L.D., Yang, Z.S., 1989. Storm wave reactivation of a submarine landslide. *Nature*, 341, 47—50.

Purvis, K., Kao, J., Flanagan, K., Henderson, J., Duranti, D., 2002. Complex reservoir geometries in a deep water clastic sequence, Gryphon Field, UKCS: injection structures, geological modeling and reservoir simulation. *Marine and Petroleum Geology*, 19, 161—179.

Ramana, M.V., Ramprasad, T., Desa, M., Sathe, A.V., Sethi, A.K., 2006. Gas hydrate-related proxies inferred from multidisciplinary investigations in the Indian offshore areas. *Current Science*, 912, 183—189.

Rizzini, A., Passega, R., 1964. Évolution de la edimentation et orogenèse, Vallée du Santerno, Apennin Septentrional. In: Bouma, A.H., Brouwer, A. (Eds.), *Turbidites, Developments in Sedimentology*, vol. 3. Elsevier, Amsterdam, pp. 65—74.

Robertson, I.N., Riggs, H.R., Yim, S.C.S., Young, Y.L., 2007. Lessons from Hurricane Katrina storm surge on bridges and buildings. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 133, 463—483.

Rodríguez-Pascua, M.A., Calvo, J.P., De Vicente, G., Gómez-Gras, D., 2000. Seismites in lacustrine sediments of the Prebetic Zone, SE Spain, and their use as indicators of earthquake magnitudes during the Late Miocene. *Sedimentary Geology*, 135, 117—135.

Rodríguez-Lopez, J.P., Merléndez, N., Soria, A.R., Liesa, C.L., Van Loon, A.J., 2007. Lateral variability of ancient seismites related to differences in sedimentary facies (the syn-rift Escucha Formation, Mid-Cretaceous, Spain). *Sedimentary Geology*, 201, 461—484.

Roy, S.K., Banerjee, S., 2016. Soft sediment deformation structures in the Andaman Flysch Group, Andaman Basin: evidence for Paleogene seismic activity in the Island Arc. *Beri Sedimentologi*, 35, 55—64.

Ruff, L.J., 1996. Large earthquakes in subduction zones. In: Bebout, G.E., Scholl, D.W., Kirby, S.H., Platt, J.P. (Eds.),

Subduction Top to Bottom, first ed., *Geophysical Monograph Series*, pp. 91—104.
Samanta, M.K., Vadiraj, K.V., Das, D., Josyulu, B.S., Rangachari, V., 2010. Pressure regimes and the occurrence of hydrocarbons in Offshore East Coast, Krishna–Godavari Basin, India. In: *Petrotech-2010, 31 October–3 November 2010, New Delhi, India*. Paper ID: 20100047.
Sanders, J.E., 1963. Concepts of fluid mechanics provided by primary sedimentary structures. *Journal of Sedimentary Petrology*, 33, 173—179.
Sayles, R.W., 1931. Bermuda during the Ice Age. *Proceedings of the National Academy of Sciences of the United States of America*, 66, 382—467.
Scholz, H., Frieling, D., Aehnelt, M., 2011. Synsedimentary deformational structures caused by tectonics and seismic events — examples from the Cambrian of Sweden, Permian and Cenozoic of Germany. In: Sharkov, E. (Ed.), *New Frontiers in Tectonic Research — General Problems, Sedimentary Basins and Island Arcs*, pp. 183—218. Chapter 9.
Schulte, P., Alegret, L., Arenillas, I., Arz, J.A., Barton, P.J., Bown, P.R., Bralower, T.J., Christeson, G.L., Claeys, P., Cockell, C.S., Collins, G.S., Deutsch, A., Goldin, T.J., Goto, K., Grajales-Nishimura, J.M., Grieve, R.A.F., Gulick, S.P.S., Johnson, K.R., Kiessling, W., Koeberl, C., Kring, D.A., MacLeod, K.G., Matsui, T., Melosh, J., Montanari, A., Morgan, J.V., Neal, C.R., Nichols, D.J., Norris, R.D., Pierazzo, E., Ravizza, G., Rebolledo-Vieyra, M., Reimold, W.U., Robin, E., Salge, T., Speijer, R.P., Sweet, A.R., Urrutia-Fucugauchi, J., Vajda, V., Whalen, M.T., Willumsen, P.S., 2010. The chicxulub asteroid impact and mass extinction at the Cretaceous–Paleogene boundary. *Science*, 327, 1214—1218.
Seilacher, A., 1969. Fault-graded beds interpreted as seismites. *Sedimentology*, 13, 155—159.
Seilacher, A., 1984. Sedimentary structures tentatively attributed to seismic events. *Marine Geology*, 55, 1—12.
Shanmugam, G., 1984. Rock names challenged. *Geotimes*, 29, 6.
Shanmugam, G., 1996. High-density turbidity currents, are they sandy debris flows? *Journal of Sedimentary Research*, 66, 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*, 17, 285—342.
Shanmugam, G., 2006a. *Deep-Water Processes and Facies Models: Implications for Sandstone Petroleum Reservoirs*. In: *Handbook of Petroleum Exploration and Production*, vol. 5. Elsevier, Amsterdam, p. 476.
Shanmugam, G., 2006b. The tsunamite problem. *Journal of Sedimentary Research*, 76, 718—730.
Shanmugam, G., 2008a. Deep-water bottom currents and their deposits. In: Rebesco, M., Camerlenghi, A. (Eds.), *Developments in Sedimentology, Chapter 5, Contourites*, vol. 60. Elsevier, Amsterdam, pp. 59—81.
Shanmugam, G., 2008b. The constructive functions of tropical cyclones and tsunamis on deepwater sand deposition during sea level highstand: implications for petroleum exploration. *AAPG Bulletin*, 92, 443—471.
Shanmugam, G., 2009. Comment on "Late Holocene Rupture of the Northern San Andreas Fault and Possible Stress Linkage to the Cascadia Subduction Zone" by C. Goldfinger, K. Grijalva, R. Bürgmann, A.E. Morey, J.E. Johnson, C. Hans Nelson, J. Gutiérrez-Pastor, A. Ericsson, E. Karabanov, J.D. Chaytor, J. Patton, and E. Grácia. *Bulletin of the Seismological Society of America*, 99, 2594—2598.
Shanmugam, G., 2012a. *New Perspectives on Deep-water Sandstones: Origin, Recognition, Initiation, and Reservoir Quality*. In: *Handbook of Petroleum Exploration and Production*, vol. 9. Elsevier, Amsterdam, p. 524.
Shanmugam, G., 2012b. Process-sedimentological challenges in distinguishing paleo-tsunami deposits. *Natural Hazards*, 63, 5—30.
Shanmugam, G., 2013a. Modern internal waves and internal tides along oceanic pycnoclines: challenges and implications for ancient deep-marine baroclinic sands. *AAPG Bulletin*, 97, 767—811.
Shanmugam, G., 2013b. Comment on "Internal waves, an underexplored source of turbulence events in the sedimentary record" by L. Pomar, M. Morsilli, P. Hallock, and B. Bádenas [Earth-Science Reviews, 111 (2012), 56—81]. *Earth-Sci. Rev.*, 116, 195—205.
Shanmugam, G., 2015. The landslide problem. *Journal of Palaeogeography*, 4(2), 109—166.
Shanmugam, G., 2016a. Submarine fans: a critical retrospective (1950–2015). *Journal of Palaeogeography*, 5(2), 110—184.
Shanmugam, G., 2016b. *Slides, Slumps, Debris Flows, Turbidity Currents, and Bottom Currents*. In: *Reference Module in Earth Systems and Environmental Sciences*. Elsevier. Online.
Shanmugam, G., 2016c. The contourite problem. In: Mazumder, R. (Ed.), *Sediment Provenance*. Chapter 9. Elsevier, in press, http://dx.doi.org/10.1016/j.jop.2016.06.002.
Shanmugam, G., 2017. The fallacy of interpreting SSDS with different types of breccias as seismites amid the multifarious origins of earthquakes: Implications. *Journal of Palaeogeography*, 6(1).
Shanmugam, G., Bloch, R.B., Mitchell, S.M., Beamish, G.W.J., Hodgkinson, R.J., Damuth, J.E., Straume, T., Syvertsen, S.E., Shields, K.E., 1995. Basin-floor fans in the North Sea: sequence-stratigraphic models vs. sedimentary facies. *AAPG Bulletin*, 79, 477—512.
Shanmugam, G., Lehtonen, L.R., Straume, T., Syversten, S.E., Hodgkinson, R.J., Skibeli, M., 1994. Slump and debris flow dominated upper slope facies in the Cretaceous of the Norwegian and Northern North Seas (61°N—67°N): implications for sand distribution. *AAPG Bulletin*, 78, 910—937.
Shanmugam, G., Moiola, R.J., 1982. Eustatic control of turbidites and winnowed turbidites. *Geology*, 10, 231—235.
Shanmugam, G., Moiola, R.J., 1988. Submarine fans: characteristics, models, classification, and reservoir potential. *Earth-Science Reviews*, 24, 383—428.
Shanmugam, G., Moiola, R.J., 1995. Reinterpretation of depositional processes in a classic flysch sequence (Pennsylvanian Jackfork Group), Ouachita Mountains, Arkansas and Oklahoma. *AAPG Bulletin*, 79, 672—695.

Shanmugam, G., Moiola, R.J., Sales, J.K., 1988. Duplex-like structures in submarine fan channels, Ouachita Mountains, Arkansas. *Geology*, 16, 229—232.
Shanmugam, G., Shrivastava, S.K., Das, B., 2009. Sandy debrites and tidalites of Pliocene reservoir sands in upper-slope canyon environments, Offshore Krishna–Godavari Basin (India): implications. *Journal of Sedimentary Research*, 79, 736—756.
Shanmugam, G., Spalding, T.D., Rofheart, D.H., 1993. Process sedimentology and reservoir quality of deep-marine bottom-current reworked sands (sandy contourites), an example from the Gulf of Mexico. *AAPG Bulletin*, 77, 1241—1259.
Shao, C., Fan, T.L., Guo, Y.J., Cheng, P., Sun, Y., Wang, H.R., 2012. Discovery of seismites in the Upper Cretaceous Yaojia Formation in Daqing Placanticline of Songliao Basin and its geological significance. *Journal of Palaeogeography (Chinese Edition)*, 14, 719—726 (in Chinese with English abstract).
Shiki, T., 1996. Reading of trigger records of sedimentary events — a problem for future studies. *Sedimentary Geology*, 104, 244—255.
Simms, M.J., 2003. Uniquely extensive seismite from the latest Triassic of the United Kingdom: evidence for bolide impact? *Geology*, 31, 557—560.
Sims, J.D., 1975. Determining earthquake recurrence intervals from deformational structures in young lacustrine sediments. *Tectonophysics*, 29, 141—152.
Singha, D.K., Chatterjee, R., 2014. Detection of overpressure zones and a statistical model for pore pressure estimation from well logs in the Krishna–Godavari Basin, India. *Geochemistry, Geophysics, Geosystems*, 15, 1009—1020.
Smit, J., Roep, T.B., Alvarez, W., Montanari, A., Claeys, P., Grajales-Nishimura, J.M., 1996. Coarse-grained, clastic sandstone complex at the K/T boundary around the Gulf of Mexico: deposition by tsunami waves induced by the Chicxulub impact? In: Ryder, G., Gartner, S., Fastovsky, D. (Eds.), *The Cretaceous–Tertiary Event and Other Catastrophes in Earth History, GSA Special Paper, 307*, pp. 151—182.
Solheim, A., Forsberg, C.F., Yang, S., Kvalstad, T.J., Longva, O., Rise, L., 2007. The role of geological setting and depositional history in offshore slope instability. In: *2007 Offshore Technology Conference, Houston, Texas, 30 April—3 May, OTC Paper no. 18720*, p. 8.
Song, T., 1988. A probable earthquake-tsunami sequence in Precambrian carbonate strata of the Ming Tombs District, Beijing. *Chinese Science Bulletin*, 33, 1121—1124.
Song, T., Einsele, G., 1996. Proterozoic sedimentary facies and their depositional environments in the Ming Tombs District, Beijing. In: *Field Trip Guide of 30th International Congress*. Geological Publishing House, Beijing, pp. 1—24. T201.
Sowers, G., 1979. *Introductory Soil Mechanics and Foundations: Geotechnical Engineering*, fourth ed. Prentice Hall, New Jersey, p. 640.
Srinivasalu, S., Rajeshwara Rao, N., Thangadurai, N., Jonathan, M.P., Roy, P.D., Ram Mohan, V., Saravanan, P., 2009. Characteristics of 2004 tsunami deposits of the northern Tamil Nadu coast, southeastern India. *Boletín de la Sociedad Geológica Mexicana*, 61, 111—118.
Srurkel, B.F.F., Ormö, J., 1997. Impact-related clastic injections in the marine Ordovician Lockne impact structure, Central Sweden. *Sedimentology*, 44, 793—804.
Stanley, D.J., 1981. Unifites: structureless muds of gravity flow origin in Mediterranean basins. *Geo-Marine Letters*, 1, 77—83.
Stanley, D.J., Palmer, H.D., 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., Kelling, G. (Eds.), *Sedimentation in Submarine Canyons, Fans, and Trenches*. Dowden, Hutchinson & Ross, Inc., Stroudsburg, Pennsylvania, pp. 85—115.
Stöffler, D., 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*. http://www.bgs.ac.uk/scmr/docs/paper_12/scmr_paper_12_1.pdf.
Stow, D.A.V., Amano, K., Batson, B.S., Brass, G.W., Corrigan, J., Raman, C.V., et al., 1990. 31. Sediment facies and processes on the distal Bengal Fan, Leg 116. In: Cochran, J.R., Stow, D.A.V., et al. (Eds.), *Proceedings of the Ocean Drilling Project, Leg 116, Scientific Results, Ocean Drilling Program, College Station, Texas*, pp. 377—396.
Stow, D.A.V., Hunter, S., Wilkinson, D., Hernández-Molina, F.J., 2008. The nature of contourite deposition. In: Rebesco, M., Camerlenghi, A. (Eds.), *Contourites, Developments in Sedimentology*, vol. 60. Elsevier, Amsterdam, pp. 143—156. Chapter 9.
Su, D.C., Sun, A.P., 2012. Typical earthquake-induced soft-sediment deformation structures in the Mesoproterozoic Wumishan Formation, Yongding River Valley, Beijing, China and interpreted earthquake frequency. *Journal of Palaeogeography*, 1, 71—89.
Sukhtankar, R.K., Pandian, R.S., Guha, S.K., 1993. Seismotectonic studies of the coastal areas of India, Pakistan, Bangladesh, and Burma. *Natural Hazards*, 7, 201—210.
Sultan, N., Cochonat, P., Canals, M., Cattaneo, A., Dennielou, B., Haflidason, H., Laberg, J.S., Long, D., Mienert, J.J., Trincardi, F., Urgeles, R., Vorren, T.O., Wilson, C., 2004. Triggering mechanisms of slope instability processes and sediment failures on continental margins: A geotechnical approach. *Marine Geology*, 213, 291—321.
Surlyk, F., 1987. Slope and deep shelf gully sandstones, Upper Jurassic, East Greenland. *AAPG Bulletin*, 71, 464—475.
Surpless, K.D., Ward, R.B., Graham, S.A., 2009. Evolution and stratigraphic architecture of marine slope gully complexes: Monterey Formation (Miocene), Gaviota Beach, California. *Marine and Petroleum Geology*, 26, 269—288.
Takayama, H., Tada, R., Matsui, T., Iturralde-Vinent, M.A., Oji, T., Tajika, E., Kiyokawa, S., Garcia, D., Okada, H., Hasegawa, T., Toyoda, K., 2000. Origin of the Peñalver Formation in northwestern Cuba and its relation to K/T boundary impact event. *Sedimentary Geology*, 135, 295—320.
Talling, P.J., Wynn, R.B., Masson, D.G., Frenz, M., Cronin, B.T., Schiebel, R., Akhmetzhanov, A.M.,

Dallmeier-Tiessen, S., Benetti, S., Weaver, P.P.E., Georgiopoulou, A., Zühlsdorff, C., Amy, L.A., 2007. Onset of submarine debris flow deposition far from original giant landslide. *Nature*, 450, 541—544.

Tappin, D.R., 2004. Submarine slump-generated tsunamis. *Marine Geology*, 203, 199—200.

Tian, Y., Zhong, J.H., Wang, S.B., Tao, H.S., Liu, S.G., Li, Y., Sun, N.L., Shao, Z.F., Ni, L.T., 2015. Seismites and their geological significances of the Triassic Yanchang Formation in Fuxian exploration area, Ordos Basin. *Journal of Palaeogeography (Chinese Edition)*, 17, 541—552 (in Chinese with English abstract).

Tilling, R.I., Topinka, L., Swanson, D.A., 1990. *Eruptions of Mount St. Helens, Past, Present, and Future*. U.S. Geological Survey Special Interest Publication, p. 56.

Trincardi, F., Cattaneo, A., Correggiari, A., Mongardi, S., Breda, A., Asioli, A., 2003. Submarine slides during relative sea level rise: two examples from the eastern Tyrrhenian margin. In: Locat, J., Mienert, J. (Eds.), *Submarine Mass Movements and Their Consequences*. Kluwer Academic Publishers, Dordrecht, pp. 469—478.

Truswell, J.F., 1972. Sandstone sheets and related intrusions from Coffee Bay, South Africa. *Journal of Sedimentary Research*, 42, 578—583.

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

Urgeles, R., Canals, M., Baraza, J., Alonso, B., Masson, D., 1997. The most recent megalandslides of the Canary Islands, El Golfo debris avalanche and Canary debris flow, west El Hierro Island. *Journal of Geophysical Research*, 102, 20305—20323.

Vail, P.R., Audemard, F., Bowman, S.A., Eisner, P.N., Perez-Cruz, P., 1991. The stratigraphic signatures of tectonics, eustasy and sedimentology — an overview. In: Einsele, G., Ricken, W., Seilacher, A. (Eds.), *Cycles and Events in Stratigraphy*. Springer-Verlag, Berlin, pp. 618—659.

Van der Lingen, G.J., 1969. The turbidite problem. *New Zealand Journal of Geology and Geophysics*, 12, 7—50.

Van Loon, A.J., 2009. Soft-sediment deformation structures in siliciclastic sediments: an overview. *Geologos*, 15, 3—55.

Van Loon, A.J., 2014. The life cycle of seismite research. *Geologos*, 20, 61—66.

Van Loon, A.J., Pisarska-Jamroży, M., 2014. Sedimentological evidence of Pleistocene earthquakes in NW Poland induced by glacio-isostatic rebound. *Sedimentary Geology*, 300, 1—10.

Vivas, V., Macsotay, O., Furrer, M., Alvarez, E., 1988. Injectitas clásticas asociadas a desplomes en sedimentitas batiales del Cretáceo Superior de Venezuela nor-oriental. *Boletín de la Venezolana de Geología*, 34, 3—33.

Waldron, J.W.F., Gagnon, J.F., 2011. Recognizing soft-sediment structures in deformed rocks of orogens. *Journal of Structural Geology*, 33, 271—279.

Walton, E.K., 1967. The sequence of internal structures in turbidites. *Scottish Journal of Geology*, 3, 306—317.

Warme, J.E., Slater, R.A., Cooper, R.A., 1978. Bioerosion in submarine canyons. In: Stanley, D.J., Kelling, G.K. (Eds.), *Sedimentation in Submarine Canyons, Fans, and Trenches*. Dowden, Hutchinson & Ross, Inc., Stroudsburg, Pennsylvania, pp. 65—70.

Wheeler, R.L., 2002. Distinguishing seismic from non-seismic soft sediment structures: criteria from seismic-hazard analysis. In: Ettensohn, F.R., Rast, N., Brett, C.E. (Eds.), *Ancient Seismites, GSA Special Paper, 359*, pp. 1—11.

Wizevich, M.C., Simpson, E.L., Hilbert-Wolf, H.L., Tindall, S.E., 2016. Development of large-scale seismites in Upper Cretaceous fluvial sandstones in a fault-proximal setting. *Sedimentology*, in press, http://dx.doi.org/10.1111/sed.12283.

Young, Y.L., Joshua, A., White, J.A., Xiao, H., Borja, R.I., 2009. Liquefaction potential of coastal slopes induced by solitary waves. *Acta Geotechnica*, 4, 17—34.

Zhang, C., Wu, Z., Gao, L., Wang, W., Tian, Y., Ma, C., 2007. Earthquake-induced soft-sediment deformation structures in the Mesoproterozoic Wumishan Formation, North China, and their geologic implications. *Science in China, Earth Science*, 50, 350—358.

Zheng, L., Jiang, Z., Liu, H., Kong, X., Li, H., Jiang, X., 2015. Core evidence of paleoseismic events in Paleogene deposits of the Shulu Sag in the Bohai Bay Basin, east China, and their petroleum geologic significance. *Sedimentary Geology*, 328, 33—54.