The landslide problem

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Abstract  The synonymous use of the general term “landslide”, with a built-in reference to a sliding motion, for all varieties of mass-transport deposits (MTD), which include slides, slumps, debrites, topples, creeps, debris avalanches etc. in subaerial, sublacustrine, submarine, and extraterrestrial environments has created a multitude of conceptual and nomenclatural problems. In addition, concepts of triggers and long-runout mechanisms of mass movements are loosely applied without rigor. These problems have enormous implications for studies in process sedimentology, sequence stratigraphy, palaeogeography, petroleum geology, and engineering geology. Therefore, the objective of this critical review is to identify key problems and to provide conceptual clarity and possible solutions. Specific issues are the following: (1) According to “limit equilibrium analyses” in soil mechanics, sediment failure with a sliding motion is initiated over a shear surface when the factor of safety for slope stability ($F$) is less than 1. However, the term landslide is not meaningful for debris flows with a flowing motion. (2) Sliding motion can be measured in oriented core and outcrop, but such measurement is not practical on seismic profiles or radar images. (3) Although 79 MTD types exist in the geological and engineering literature, only slides, slumps, and debrites are viable depositional facies for interpreting ancient stratigraphic records. (4) The use of the term landslide for high-velocity debris avalanches is inappropriate because velocities of mass-transport processes cannot be determined in the rock record. (5) Of the 21 potential triggering mechanisms of sediment failures, frequent short-term events that last for only a few minutes to several hours or days (e.g., earthquakes, meteorite impacts, tsunamis, tropical cyclones, etc.) are more relevant in controlling deposition of deep-water sands than sporadic long-term events that last for thousands to millions of years (e.g., sea-level lowstands). (6) The comparison of $H/L$ (fall height/runout distance) ratios of MTD in subaerial environments with $H/L$ ratios of MTD in submarine and extraterrestrial environments is incongruous because of differences in data sources (e.g., outcrop vs. seismic or radar images). (7) Slides represent the pre-transport disposition of strata and their reservoir quality (i.e., porosity and permeability) of the provenance region, whereas debrites reflect post-transport depositional texture and reservoir quality. However, both sandy slides and sandy debrites could generate blocky wireline (gamma-ray) log motifs. Therefore, reservoir characterization of deep-water strata must be based on direct examination of the rocks and related process-specific facies interpretations, not on wireline logs or on seismic profiles and related process-vague facies interpretations. A solution to these problems is to apply the term “landslide” solely to cases in which a sliding motion can be empirically determined. Otherwise, a general term MTD is appropriate. This decree is not just a quibble over semantics; it is a matter of portraying the physics of mass movements accurately. A precise interpretation of a depositional facies (e.g., sandy slide vs. sandy debrite) is vital not
only for maintaining conceptual clarity but also for characterizing petroleum reservoirs.

Key words debris flows, landslides, mass-transport deposits (MTD), slides, slumps, soil strength, triggering mechanisms, reservoir characterization

1 Introduction

The general term “landslide” is very popular. A cursory Google search of the term landslide has yielded 6,100,000 results. The reason is that the topic of landslides is of interest to researchers in a wide range of scientific disciplines, which include sedimentology, oceanography, geomorphology, volcanology, seismology, glaciology, areology (i.e., geology of Mars), deep-sea structural engineering, highway engineering, soil mechanics, climate change, eustasy, natural hazards, and petroleum exploration and production. Not surprisingly, each scientific community has arrived at its own nomenclatural scheme (Hansen, 1984). However, there is no conceptual link between different schemes on landslides. Consequently, the term landslide means different things to different populace. This conceptual disconnect and its consequences are the primary focus of this paper.

Since the early recognition of subaerial “landslides” in 186 BC in China (Li, 1989), their common occurrences in subaerial and submarine environments have been well documented worldwide (Figure 1). In subaerial settings, for example, fault-induced alluvial fans are dominated by mass-transport deposits (McPherson et al., 1987). Aspects of subaerial, sublacustrine, and submarine landslides have been reviewed adequately during the past 140 years (Baltzer, 1875; Howe, 1909; Reynolds, 1932; Ladd, 1935; Sharpe, 1938; Ward, 1945; Popov, 1946; Eckel, 1958; Yatsu, 1967; Hutchinson, 1968; Zaruba and Mencl, 1969; Blong, 1973; Crozier, 1973; Coates, 1977; Woodcock, 1979; Hansen, 1984; Varnes, 1984; Brabb and Harrod, 1989; Schwab et al., 1993; Hampton et al., 1996; Elverhøi et al., 1997; Locat and Lee, 2000, 2002; Hungr et al., 2001; Dykstra, 2005; Glade et al., 2005; Solheim et al., 2005a; Masson et al., 2006; Shanmugam, 2009, 2012a, 2013a; Moernaut and De Batist, 2011; Shipp et al., 2011; Clague and Stead, 2012; Krastel et al., 2014, among others). On Earth, landslides have been recognized on bathymetric images (Figure 2) (Greene et al., 2006), on seismic profiles (Figure 3) (Solheim et al., 2005b) (Gee et al., 2006), in outcrops (Heim, 1882; Macdonald et al., 1993), and in conventional cores (Shanmugam, 2006a, 2012a). On Mars, landslides have been interpreted using shaded-relief map of the Thaumasia Plateau (Thermal Emission Imaging System infrared [THEMIS IR]) by Montgomery et al. (2009, their Figure 9).

1.1 Importance of mass-transport deposits (MTD)

Mass-transport deposits (MTD) are important not only because of their volumetric significance in the sedimentary record (Gamboa et al., 2010), but also because of their frequent impacts on human lives both socially and economically (USGS, 2010; Petley, 2012). Since the birth of modern deep-sea exploration by the voyage of H.M.S. Challenger (December 21, 1872–May 24, 1876), organized by the Royal Society of London and the Royal Navy (Murray and Renard, 1891), oceanographers have made considerable progress in understanding the world’s oceans. Nevertheless, the physical processes that are responsible for transporting sediment downslope into the deep sea are still poorly understood. This is simply because the physics and hydrodynamics of these processes are difficult to observe and measure directly in deep-marine and extraterrestrial environments. This observational impediment has created an enormous challenge for understanding and communicating the mechanics of gravity-driven downslope processes with clarity. Furthermore, deep-marine environments are known for their complexity of processes and their deposits, composed not only of mass-transport deposits but also of bottom-current reworked deposits (Shanmugam, 2006a, 2012a). Thus a plethora of confusing concepts and classifications exists.

MTD constitute major geohazards on subaerial environments (Geertsema et al., 2009; Glade et al., 2005; Jakob and Hungr, 2005; Kirschbaum et al., 2010). They are ubiquitous on submarine slopes (Figure 1) and are destructive (Hampton, et al., 1996). Submarine mass movements may bear a tsunamigenic potential and are capable of methane gas release into the seawater and atmosphere (Urgelles et al., 2007). The U.S. Geological Survey (USGS, 2010) has compiled data on worldwide damages caused by large subaerial and submarine MTD in the 20th and 21st centuries (Table 1). Annual losses associated with MTD have been estimated to be about 1–2 billion dollars in the U.S. alone (Schuster and Highland, 2001). Recently, the Oso landslide, which occurred on March 22, 2014 near Seattle
Figure 1  Map showing 50 examples (locations) of submarine (black triangle) and subaerial (white triangle) mass-transport deposits (MTD) that are often erroneously called “landslides” (see Tables 1, 2, and 5). Submarine and subaerial classification of each MTD denotes its depositional setting. Note locations of core studies (numbered yellow circles) and outcrop studies (numbered red circles) of deep-water successions carried out by the present author worldwide on MTD and SMTD (see Table 3 for details). 28 Submarine MTD: Bering, Bering Sea (Karl et al., 1996; Nelson et al., 2011); Goleta, U.S. Pacific Margin (Greene et al., 2006); Monterey, U.S. Pacific Margin (Paul et al., 2005); Alika, Hawaii, Pacific (Normark et al., 1993); East Breaks, U.S. Gulf of Mexico (McGregor et al., 1993); Mississippi, U.S. Gulf of Mexico (Weimer, 1989, 1990; McAdoo et al., 2000; Nelson et al., 2011); Grand Banks, North Atlantic, Canada (Heezen and Ewing, 1952; Piper and Aksu, 1987; Bornhold et al., 2003); Currituck, U.S. Atlantic Margin (Locat et al., 2009); Hatteras, U.S. Atlantic Margin (Embley, 1980); Amazon, Equatorial Atlantic (Damuth et al., 1988; Piper et al., 1997); Alexander Island, Antarctica (Macdonald et al., 1993); Weddell Sea, Antarctica (Gales et al., 2014); Jan Mayen Ridge, Norwegian–Greenland Sea (Laberg et al., 2014); Storegga, Norwegian Sea (Bugge et al., 1987; Haflidason et al., 2005); Nice, Mediterranean Sea (Dan et al., 2007); Nile, Mediterranean Sea (Newton et al., 2004); Canary, SW off Morocco, North Atlantic (Masson et al., 1997); Mauritania-Senegal, W Africa, North Atlantic (Jacobi, 1976); Zaïre (formerly known as Congo), W Africa, S Atlantic (Shepard and Emery, 1973); Owen Ridge, Oman coast, Indian Ocean (Rodriguez et al., 2013); Agulhas, SE Africa, Indian Ocean (Dingle, 1977); KG (Krisha-Godavari Basin), Bay of Bengal, NE Indian Ocean (Shanmugam et al., 2009); Bassein, NE Indian Ocean (Moore et al., 1976); Brunei, NW Borneo Margin (Gee et al., 2007); Kutei, Makassar Strait, Indonesia (Jackson, 2004); Unnamed, offshore New South Wales/Queensland, Australia (Clarke et al., 2012); Bass, SE Australia (Mitchell et al., 2007); Ruatoria, Hikurangi Margin, New Zealand (Collot et al., 2001). 22 Subaerial MTD: Alaska, State of Alaska, U.S. (USGS, 2010); Frank, Canada (Cruden and Hungr, 1986); Mt. St. Helens, State of Washington, U. S. (Schuster, 1983; Tilling et al., 1990); Markagunt, State of Utah, U. S. (Hacker et al., 2014); Thistle, State of Utah, U. S. (USGS, 2010); Vargas, Venezuela (USGS, 2010); Nevado del Ruiz, Colombia (Pierson, 1990); Ancash, Peru (USGS, 2010); Santiago, Chile (Sepúlveda et al., 2006); Rio de Janeiro, Brazil (USGS, 2010); Rio Colorado, Argentina (USGS, 2010); Elm, Swiss Alps (Heim, 1882); Aqaba, Gulf of Aqaba (Klinger et al., 1999); Bududa, Uganda (USGS, 2010); Kolka, Russia (North Ossetia) (USGS, 2010); Saidmerah, Iran (Harrison and Falcon, 1938); Usoy, Tajikistan (Bolt et al., 1975; USGS, 2010); Baikal, Olkhon Island (Lake Baikal, Siberia) (Tyszkowski et al. 2014); Gansu, China (USGS, 2010); Yigong, Tibet (USGS, 2010); Kyoto, Japan (USGS, 2010); Leyte, Philippines (USGS, 2010); Blank world map credit: http://upload.wikimedia.org/wikipedia/commons/8/83/Equirectangular_projection_SW.jpg (accessed December 27, 2014).


MTD vary in size greatly. The world’s largest submarine MTD is the Agulhas Slump in SE Africa (Dingle, 1977), which is 20,331 km³ in size (Figure 1, Table 2). This submarine MTD is 10 times volumetrically larger than the world’s largest subaerial MTD (Markagunt gravity slide, southwest Utah, Figure 1), which is 2,000 km³.
in size (Table 2). On Mars, MTD of immense dimensions (e.g., 3,000 km wide) have been studied (Montgomery et al., 2009, their Figure 9). Large submarine MTD have important implications for developing deep-water petroleum reservoirs. In fact, many petroleum reservoirs currently produce oil and gas from sandy mass-transport deposits (SMTD) worldwide (Shanmugam, 2006a, 2012a). Petroleum-related examples are: (1) the occurrence of submarine landslides in all continental margins that are areas of active petroleum exploration (Mienert et al., 2002, their Figure 1); (2) potential petroleum reservoirs associated with a submarine landslide located off Baltimore Canyon on the U.S. Atlantic margin (Malahoff et al., 1978); (3) the location of the Ormen Lange gas field inside the Storegga Slide scar, offshore Norway (Solheim et al., 2005a; Bryn et al., 2005); (4) petroleum-producing reservoirs composed of SMTD and associated sand injections in the North Sea, including the Gryphon Field (Shanmugam et al., 1995; Purvis et al., 2002; Duranti and Hurst, 2004), Norwegian Sea (Shanmugam et al., 1994), Gulf of Mexico (Shanmugam, 2006a, 2012a), Mexico (Grajales-Nishimura et al., 2000), Brazil (Shanmugam, 2006a), Nigeria (Shanmugam, 1997), Australia (Meckel, 2010), China (Zou et al., 2012), and the Bay of Bengal, India (Shanmugam et al., 2009); (5) the use of 3-D seismic data in predicting reservoir properties of submarine landslides in the Saguenay Fjord, Canada (Hart et al., 2001); (6) reservoir characterization of SMTD (Meckel, 2011); and (7) hydrocarbon traps associated with MTD (Beaubouef and Abreu, 2010; Alves and Cartwright, 2010). Furthermore, MTD form a significant component of deep-water stratigraphy in the Espírito Santo Basin, SE Brazil, where MTD constitute more than 50% of Eocene-
Figure 3  Seismic profile showing transparent (homogeneous) to chaotic internal reflections of slide deposits (SD). Note continuous and parallel internal reflections of contourite deposits (CD). The Storegga Slide on the mid-Norwegian continental margin. TNU=Local slip plane. Profile courtesy of A. Solheim. Modified after Solheim et al. (2005b). With permission from Elsevier Copyright Clearance Center’s RightsLink: Licensee: G. Shanmugam. License Number: 3570801423159. License Date: February 16, 2015.

Table 1  Worldwide large subaerial and submarine mass-transport deposits (MTD), their sizes (volume), triggering mechanisms, and damages in the 20th and 21st Centuries. The term “landslide” was originally used to describe these examples. Modified after USGS (2010).

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Name and type</th>
<th>Triggering mechanism</th>
<th>Size, damage, and loss of human life</th>
</tr>
</thead>
</table>
| 1911 | Tajikistan | Usoy MTD | Usoy earthquake, magnitude 7.4 | 2,000,000,000 m³
|      |          |               |                      | 54 deaths                           |
| 1914 | Argentina | Rio Barrancas and Rio Colorado debris flow | Failure of ancient MTD dam | 2,000,000 m³
|      |          |               |                      | Length of flow: 300 km              |
| 1919 | Indonesia (Java) | Kelut MTD | Eruption of Kelut Volcano | 185 km (length)
|      |          |               |                      | Lahars caused 5,110 deaths, and destroyed or damaged 104 villages |
| 1920 | China (Gansu), Haiyuan | Loess flows, MTD | Haiyuan earthquake, magnitude 8.5 | 50,000 km² (area)
|      |          |               |                      | 100,000+ deaths                      |
| 1920 | Mexico | Rio Huitzilapan debris flows | Earthquake, magnitude 6.5–7.0 | >40 km (length)
|      |          |               |                      | 600–870 deaths                      |
| 1921 | Kazakh Republic | Alma-Ata debris flow | Snow melt, subsequent rainfall | 500 deaths                            |
| 1933 | China (Sichuan) | Deixi MTD | Deixi earthquake, magnitude 7.5 | >150,000,000 m³
<p>|      |          |               |                      | 2,500 deaths                         |</p>
<table>
<thead>
<tr>
<th>Year</th>
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<th>Triggering mechanism</th>
<th>Size, damage, and loss of human life</th>
</tr>
</thead>
<tbody>
<tr>
<td>1938</td>
<td>Japan (Hyogo)</td>
<td>Mount Rokko MTD</td>
<td>Rainfall</td>
<td>505 deaths or missing, 130,000 homes were destroyed or badly damaged.</td>
</tr>
<tr>
<td>1941</td>
<td>Peru</td>
<td>Huaraz debris flow</td>
<td>Failure of moraine dam</td>
<td>10,000,000 m³; 4,000–6,000 deaths</td>
</tr>
<tr>
<td>1945</td>
<td>Peru</td>
<td>Cerro Condor-Senca MTD</td>
<td>Erosional under-cutting</td>
<td>5,500,000 m³; 13 bridges were destroyed.</td>
</tr>
<tr>
<td>1949</td>
<td>Tajikistan (Tien Shan Mts.)</td>
<td>Khait MTD</td>
<td>Khait earthquake, magnitude 7.4</td>
<td>245,000,000 m³; 7,200 deaths</td>
</tr>
<tr>
<td>1953</td>
<td>Japan (Wakayama)</td>
<td>Arida River MTD</td>
<td>Rainfall Major typhoon (cyclone)</td>
<td>1,046 deaths</td>
</tr>
<tr>
<td>1953</td>
<td>Japan (City of Kyoto)</td>
<td>Arida River MTD</td>
<td>Rainfall</td>
<td>336 deaths; 5,122 homes were destroyed.</td>
</tr>
<tr>
<td>1958</td>
<td>Japan (Shizuoka)</td>
<td>Kanogawa MTD</td>
<td>Rainfall</td>
<td>1,094 deaths; 19,754 homes were destroyed.</td>
</tr>
<tr>
<td>1960</td>
<td>Chile</td>
<td>Rupanco region MTD</td>
<td>Valdivia earthquake, magnitude 7.5, preceded by heavy rain</td>
<td>40,000,000 m³; 210 deaths</td>
</tr>
<tr>
<td>1962</td>
<td>Peru (Ancash)</td>
<td>Nevados Huascaran MTD</td>
<td>Not known</td>
<td>13,000,000 m³; 4,000–5,000 deaths</td>
</tr>
<tr>
<td>1963</td>
<td>Italy (Friuli–Venecia Giulia)</td>
<td>Vaiont Reservoir MTD</td>
<td>Not known</td>
<td>250,000,000 m³; 2,000 deaths</td>
</tr>
<tr>
<td>1964</td>
<td>United States (Alaska)</td>
<td>Alaska earthquake MTD (also known as “Prince William Sound earthquake”)</td>
<td>Alaska earthquake, magnitude 9.0</td>
<td>211,000,000 m³; submarine MTD at Seward; Turnagain Heights MTD, 9,600,000 m³; Loss: $280,000,000 (1964 dollars); 122 deaths</td>
</tr>
<tr>
<td>1965</td>
<td>China (Yunnan)</td>
<td>MTD</td>
<td>Not known</td>
<td>450,000,000 m³; 444 deaths.</td>
</tr>
<tr>
<td>1966</td>
<td>Brazil (Rio de Janeiro)</td>
<td>MTD</td>
<td>Rainfall</td>
<td>1,000 deaths</td>
</tr>
<tr>
<td>1970</td>
<td>Peru (Ancash)</td>
<td>Nevados Huascaran MTD</td>
<td>Earthquake, magnitude 7.7</td>
<td>30,000,000–50,000,000 m³; 18,000 deaths</td>
</tr>
<tr>
<td>1974</td>
<td>Peru</td>
<td>Mayummarca MTD</td>
<td>Rainfall</td>
<td>1,600,000,000 m³; 450 deaths</td>
</tr>
<tr>
<td>1976</td>
<td>Guatemala</td>
<td>Guatemala earthquake MTD</td>
<td>Guatemala earthquake, magnitude 7.5</td>
<td>10,000 MTDs over an area of 16,000 km²; 200 deaths</td>
</tr>
<tr>
<td>1980</td>
<td>China (Yichang, Hubei)</td>
<td>Yanchihe MTD</td>
<td>Mining activity-occurred on man-made layered slopes</td>
<td>150,000,000 m³; 284 deaths</td>
</tr>
<tr>
<td>1980</td>
<td>United States (Washington)</td>
<td>Mount St. Helens MTD</td>
<td>Eruption of Mount St. Helens volcano</td>
<td>This is the world’s largest historical MTD. 3,700,000,000 m³; 250 homes, 47 bridges, 24 km of rail, and 298 km of highway were destroyed; 57 deaths.</td>
</tr>
<tr>
<td>1983</td>
<td>United States (Utah)</td>
<td>Thistle MTD</td>
<td>Snow melt and subsequent rainfall</td>
<td>21,000,000 m³; This is the most expensive disaster to fix in U.S. history with a loss of $600,000,000 (1983 dollars).</td>
</tr>
<tr>
<td>Year</td>
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<td>Name and type</td>
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<td>Size, damage, and loss of human life</td>
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</tr>
<tr>
<td>1983</td>
<td>China (Gansu)</td>
<td>Saleshan MTD</td>
<td>Rainfall</td>
<td>35,000,000 m³&lt;br&gt;237 deaths</td>
</tr>
<tr>
<td>1983</td>
<td>Ecuador</td>
<td>Chunchi MTD</td>
<td>Rain and/or snow (wettest year of century)</td>
<td>1,000,000 m³&lt;br&gt;150 deaths</td>
</tr>
<tr>
<td>1985</td>
<td>Colombia (Tolima)</td>
<td>Nevado del Ruiz debris flows</td>
<td>Eruption of Nevado del Ruiz volcano</td>
<td>23,000 deaths</td>
</tr>
<tr>
<td>1985</td>
<td>Puerto Rico (Marayes)</td>
<td>MTD</td>
<td>Rainfall from tropical storm</td>
<td>129 deaths</td>
</tr>
<tr>
<td>1985</td>
<td>Papua, New Guinea (East New Britain)</td>
<td>Bairaman MTD</td>
<td>Bairaman earthquake, magnitude 7.1</td>
<td>200,000,000 m³</td>
</tr>
<tr>
<td>1987</td>
<td>Ecuador (Napo)</td>
<td>Reventador MTD</td>
<td>Reventador earthquakes, magnitude 6.1 and 6.9 and rainfall</td>
<td>75,000,000–110,000,000 m³&lt;br&gt;1,000 deaths</td>
</tr>
<tr>
<td>1987</td>
<td>Venezuela</td>
<td>Rio Limon, debris flow</td>
<td>Rainfall</td>
<td>2,000,000 m³&lt;br&gt;210 deaths</td>
</tr>
<tr>
<td>1987</td>
<td>Colombia</td>
<td>Villa Tina MTD</td>
<td>Pond leakage</td>
<td>20,000,000 m³&lt;br&gt;217 deaths</td>
</tr>
<tr>
<td>1988</td>
<td>Brazil</td>
<td>Rio de Janeiro and Petropolis MTD</td>
<td>Rainfall</td>
<td>Approximately 300 deaths</td>
</tr>
<tr>
<td>1989</td>
<td>China (Huaying, Sichuan)</td>
<td>Xikou MTD</td>
<td>Rainfall</td>
<td>221 deaths</td>
</tr>
<tr>
<td>1991</td>
<td>China (Zhaotong, Yunan)</td>
<td>Touzhai MTD</td>
<td>Rainfall</td>
<td>18,000,000 m³&lt;br&gt;216 deaths</td>
</tr>
<tr>
<td>1991</td>
<td>Chile</td>
<td>Antofagasta debris flows</td>
<td>Rainfall</td>
<td>500,000,000–700,000,000 m³&lt;br&gt;“Hundreds” of deaths were reported.</td>
</tr>
<tr>
<td>1993</td>
<td>Ecuador</td>
<td>La Josefina MTD</td>
<td>Mine excavation and heavy rainfall</td>
<td>20,000,000–25,000,000 m²&lt;br&gt;13 bridges destroyed</td>
</tr>
<tr>
<td>1994</td>
<td>Colombia (Cauca)</td>
<td>Paez MTD</td>
<td>Paez earthquake, magnitude 6.0</td>
<td>250 km² (area)&lt;br&gt;272 deaths</td>
</tr>
<tr>
<td>1998</td>
<td>Northern India (Malpa Himalaya Region)</td>
<td>Large MTD</td>
<td>Rainfall</td>
<td>221 deaths</td>
</tr>
<tr>
<td>1998</td>
<td>Italy (Campania)</td>
<td>MTD</td>
<td>Rainfall</td>
<td>More than 100 individual slope failures</td>
</tr>
<tr>
<td>1998</td>
<td>Honduras, Guatemala, Nicaragua, El Salvador</td>
<td>MTD</td>
<td>Rainfall</td>
<td>Hurricane Mitch caused torrential rainfall. Approximately 10,000 deaths</td>
</tr>
<tr>
<td>1999</td>
<td>Venezuela (Vargas, northern coastal area)</td>
<td>MTD</td>
<td>Rainfall</td>
<td>Nearly 1m of heavy rain fall in a 3-day period. There were as many as 30,000 deaths. Loss: $1,900,000,000 in 2001 U.S. dollars</td>
</tr>
<tr>
<td>1999</td>
<td>Taiwan</td>
<td>MTD</td>
<td>Chi–Chi earthquake, magnitude 7.3</td>
<td>11,000 km² (area)&lt;br&gt;158 deaths</td>
</tr>
<tr>
<td>2000</td>
<td>Tibet</td>
<td>Yigong MTD</td>
<td>Meltwater from snow and glacier</td>
<td>100,000,000 m³&lt;br&gt;109 deaths</td>
</tr>
</tbody>
</table>
### Table 1, continued

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Name and type</th>
<th>Triggering mechanism</th>
<th>Size, damage, and loss of human life</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>El Salvador</td>
<td>MTD, lateral spreading, liquefaction</td>
<td>2 earthquakes; 1/13/2001: magnitude 7.7 2/13/2001: magnitude 6.6</td>
<td>The January earthquake caused MTD over a 25,000 km² area, (including parts of Guatemala). The February earthquake caused MTD over a 2,500 km² area. ~585 deaths</td>
</tr>
<tr>
<td>2002</td>
<td>Russia (North Ossetia)</td>
<td>Kolka Glacier debris flows</td>
<td>Detachment of large glacier, causing a debris flow</td>
<td>Travel distance: 19.5 km; 110,000,000 m³ volume of glacial ice deposited 2,000,000–5,000,000 m³ of ice debris at end of runout; 125 deaths</td>
</tr>
<tr>
<td>2003</td>
<td>Sri Lanka (Ratnapura and Hambantota)</td>
<td>MTD</td>
<td>Rainfall</td>
<td>24,000 homes and schools destroyed, 260 deaths</td>
</tr>
<tr>
<td>2003</td>
<td>United States (San Bernardino County, California)</td>
<td>Debris flows</td>
<td>Rainfall</td>
<td>&gt;1,000,000 m³ (total volume) 16 deaths</td>
</tr>
<tr>
<td>2005</td>
<td>Pakistan and India</td>
<td>MTD</td>
<td>Kashmir earthquake, magnitude 7.6</td>
<td>Thousands of MTD 25,500 deaths</td>
</tr>
<tr>
<td>2006</td>
<td>Philippines (Leyte)</td>
<td>MTD</td>
<td>Rainfall</td>
<td>15,000,000 m³ 1,100 deaths</td>
</tr>
<tr>
<td>2008</td>
<td>China (Sichuan)</td>
<td>MTD</td>
<td>Wenchuan earthquake, magnitude 8.0</td>
<td>15,000 MTD, and 20,000 deaths Still being assessed</td>
</tr>
<tr>
<td>2008</td>
<td>Egypt (East Cairo)</td>
<td>Al–Duwayqa MTD</td>
<td>Destabilization due to man-made construction</td>
<td>Affected area was 6,500 m³ volume and rocks weighed about 18,000 tons. 107 deaths</td>
</tr>
<tr>
<td>2010</td>
<td>Uganda (Bududa)</td>
<td>Debris flows</td>
<td>Heavy rainfall</td>
<td>400+ deaths Still being assessed</td>
</tr>
<tr>
<td>2010</td>
<td>Brazil (Rio De Janeiro)</td>
<td>Debris flows</td>
<td>Heavy rainfall</td>
<td>350 deaths Still being assessed</td>
</tr>
</tbody>
</table>

Table 2  Comparison of large-volume (> 100 km³) mass-transport deposits (MTD) in submarine environments with four of the largest MTD in subaerial environments. Note that the world’s largest submarine MTD (20,331 km³) is 10 times volumetrically larger than the world’s largest subaerial MTD (2000 km³). The term “landslide” was used to describe many of these examples by the original authors. Locations of selected examples are shown in Figure 1. Compiled from several sources.

<table>
<thead>
<tr>
<th>MTD (Reference)</th>
<th>Volume in km³</th>
<th>Environment (Age)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Agulhas slump SE African margin (Dingle, 1977)</td>
<td>20,331</td>
<td>Submarine (Post-Pliocene)</td>
<td>The world’s largest submarine MTD triggered by earthquakes</td>
</tr>
<tr>
<td>2. Chamais slump SE African margin (Dingle, 1980)</td>
<td>17,433</td>
<td>Submarine (Neogene)</td>
<td>Triggered by earthquakes</td>
</tr>
<tr>
<td>3. Nuuanu debris avalanche, NE Oahu, Hawaii (Normark et al., 1993; Moore et al., 1994)</td>
<td>5000</td>
<td>Submarine (2.7 Ma, Ward, 2001)</td>
<td>Triggered by volcanic activity; Debris avalanche is a velocity-based term (see text).</td>
</tr>
<tr>
<td>4. Storegga slide Offshore Norway (Bugge et al., 1987; Haflidason et al., 2005)</td>
<td>2400–3200</td>
<td>Submarine (8100 yrs BP)</td>
<td>Triggered by earthquakes</td>
</tr>
<tr>
<td>MTD (Reference)</td>
<td>Volume in km³</td>
<td>Environment (Age)</td>
<td>Comments</td>
</tr>
<tr>
<td>-----------------</td>
<td>---------------</td>
<td>-------------------</td>
<td>----------</td>
</tr>
<tr>
<td>5. WMTD, Amazon fan Equatorial Atlantic (Piper et al., 1997)</td>
<td>2000</td>
<td>Submarine (Late Pleistocene)</td>
<td>WMTD: Western mass-transport deposits. Possibly triggered during falling sea level (Damuth et al., 1988)</td>
</tr>
<tr>
<td>6. Insular slope slide Puerto Rico (Schwab et al., 1993)</td>
<td>1500</td>
<td>Submarine (Quaternary?)</td>
<td>Triggered by earthquakes</td>
</tr>
<tr>
<td>7. Brunei slide NW Borneo (Gee et al., 2007)</td>
<td>1200</td>
<td>Submarine (Quaternary?)</td>
<td>Triggered by sediment loading, gas hydrates, and earthquakes</td>
</tr>
<tr>
<td>8. Saharan debris flow NW African Margin (Embley, 1976; Embley and Jacobi, 1977; Gee et al., 1999)</td>
<td>600–1100</td>
<td>Submarine (60,000 yrs BP)</td>
<td>Long-runout volcaniclastic debris flows of over 400 km on gentle slopes that decrease to as little as 0.05º</td>
</tr>
<tr>
<td>10. Slump complex, Israel (Frey-Martinez et al., 2005)</td>
<td>1000</td>
<td>Submarine (Plio–Quaternary)</td>
<td>Triggered by earthquakes</td>
</tr>
<tr>
<td>11. Bassein slide Sund Arc, NE Indian Ocean (Moore et al., 1976)</td>
<td>900</td>
<td>Submarine (Late Quaternary)</td>
<td>Triggered by earthquakes</td>
</tr>
<tr>
<td>12. Alika 1 and 2 debris avalanches, NE Oahu, Hawaii (Normark et al., 1993)</td>
<td>200–800</td>
<td>Submarine (300,000–105,000 yrs BP)</td>
<td>Triggered by volcanic activity; Debris avalanche is a velocity-based term (see text).</td>
</tr>
<tr>
<td>13. Nile MTC offshore Egypt (Newton et al., 2004)</td>
<td>670</td>
<td>Submarine (Quaternary)</td>
<td>MTC = Mass-transport complex; triggered by rapid sedimentation</td>
</tr>
<tr>
<td>14. Copper River slide Kayak Trough Northern Gulf of Alaska (Carlson and Molnia, 1977)</td>
<td>590</td>
<td>Submarine (Holocene)</td>
<td>Possibly triggered by earthquakes and rapid sedimentation</td>
</tr>
<tr>
<td>15. MTC 1, Trinidad (Moscardelli et al., 2006)</td>
<td>242</td>
<td>Submarine (Plio–Pleistocene)</td>
<td>MTC 1 = Mass-transport complex 1; triggered by tectonic activity and rapid sedimentation</td>
</tr>
<tr>
<td>17. The 1929 Grand Banks MTD, off the U.S. Atlantic coast and Canada (Heezen and Ewing, 1952; Piper and Aksu, 1987; Driscoll et al., 2000; Bornhold et al., 2003)</td>
<td>185–200</td>
<td>Submarine (1929)</td>
<td>Triggered by earthquakes, magnitude 7.2</td>
</tr>
<tr>
<td>18. Currituck slide U.S. Atlantic Margin (Locat et al., 2009)</td>
<td>165</td>
<td>Submarine (24–50 ka)</td>
<td>Triggered by earthquakes and high pore pressure</td>
</tr>
<tr>
<td>19. East Breaks slide (western lobe) NW Gulf of Mexico (McGregor et al., 1993)</td>
<td>~160</td>
<td>Submarine (15–20 ka)</td>
<td>Possibly triggered by salt tectonism</td>
</tr>
</tbody>
</table>
Table 2, continued

<table>
<thead>
<tr>
<th>MTD (Reference)</th>
<th>Volume in km³</th>
<th>Environment (Age)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>20. MTD, Mississippi Canyon area Gulf of Mexico (McAdoo et al., 2000)</td>
<td>152</td>
<td>Submarine (Holocene)</td>
<td>Triggered by salt tectonism and rapid sedimentation</td>
</tr>
<tr>
<td>22. Owen Ridge Oman coast, Arabian Sea (Rodriguez et al., 2013)</td>
<td>40</td>
<td>Submarine (Holocene)</td>
<td>Retrogressive slumps</td>
</tr>
<tr>
<td>23. Markagunt gravity slide, SW Utah (USA) (Hacker et al., 2014)</td>
<td>1700–2000</td>
<td>Subaerial 21–22 Ma</td>
<td>The world’s largest prehistoric subaerial volcanic MTD</td>
</tr>
<tr>
<td>24. Saidmarreh Slide Kabir Kuh anticline, SW Iran (Harrison and Falcon, 1938)</td>
<td>20</td>
<td>Subaerial (10,370+/–120 years BP, Shoaei and Ghayoumian, 1998)</td>
<td>The world’s second largest prehistoric subaerial MTD triggered by earthquakes</td>
</tr>
<tr>
<td>26. Usay, Tadzhik Republic (Formerly USSR) (Bolt et al., 1975)</td>
<td>2.0</td>
<td>Subaerial (1911)</td>
<td>The world’s second largest historic subaerial MTD triggered by earthquakes, magnitude = 7.4 (USGS, 2010)</td>
</tr>
</tbody>
</table>

Oligocene strata (Gamboa et al., 2010). Because the petroleum industry is moving exploration increasingly into the deep-marine realm to meet the growing demand for oil and gas, a clear understanding of deep-marine MTD is of great economic interest. For this reason, detailed descriptions of 7,832 meters of conventional cores from 123 wells, representing 32 petroleum fields worldwide (Table 3), provide the empirical data in this review.

1.2 Description of the problem

The basic problem stems from our failure to follow a sound and commonly applied concept for classifying MTD. In acknowledging this chronic problem, Camerlenghi et al. (2010, p. 506) state, “For typology, we selected the following terms according to the terminology in the original manuscripts: Debris Avalanche; debris flow; deep-seated failure (when recognized mainly in deep penetration seismic profiles rather than bathymetric maps); glide; gravitational collapse; mass failure; mass transport; mass wasting; megaturbidite; slide; slump. Such terms often describe similar deposits. For the time being we have not modified the terminology. It is obvious that a unified terminology is needed for correct understanding and comparison of sedimentary deposits originated from submarine sediment mass transport.” There is absolutely no sedimentological basis for equating large turbidites (i.e., megaturbidites) with slumps, slides, or debris avalanches. The current complacent usage of superfluous nomenclature is not only confusing but unnecessary. Clearly, there is a need for conceptual clarity, which is one of the objectives of this article.

The conceptual and nomenclatural problems are not unique to MTD. Similar problems are associated with turbidites (Sanders, 1965; Shanmugam, 1996) and tsunamiites (Shanmugam, 2006b). What is troubling is that the problems of MTD are tightly intertwined with those of turbidites and tsunamiites. This conceptual interconnection has led to a long lexicon of 79 types of MTD, which include normal turbidites, high-density turbidites, seismoturbidites, megaturbidites, fluxoturbidites, atypical turbidites, and tsunamiites (Table 4).

Since the first use of the term “landslide” by James Dwight Dana in 1838 (Cruden, 2003), it has been adopted for a number of different downslope mass-transport processes that operate not only in subaerial (Shreve, 1968; Coates, 1977; Cruden, 1991; Highland and Bobrowsky, 2008), sublacustrine (Moernaut and De Batist, 2011), and submarine (Prior and Coleman, 1979; Schwab et al., 1993;
Table 3  Summary of deep-water case studies, based on description of core and outcrop, carried out by the present author on MTD and SMTD (1974–2011). Note that most SMTD examples are petroleum-bearing deep-water reservoirs. Modified after Shanmugam (2014b).

<table>
<thead>
<tr>
<th>Location symbol and number in Figure 1</th>
<th>Case studies</th>
<th>Thickness of core and outcrop described*</th>
<th>Comments (This paper)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Gulf of Mexico, U.S. (Shanmugam et al., 1988b)</td>
<td>1. Mississippi fan, Quaternary, DSDP Leg 96</td>
<td>~ 500 m DSDP core (selected intervals described)</td>
<td>Mass-transport deposits, turbidites, bottom-current reworked sands</td>
</tr>
<tr>
<td>2. California (Shanmugam and Clayton, 1989; Shanmugam, 2006a, 2012a)</td>
<td>9. Midway Sunset Field, upper Miocene, onshore</td>
<td>650 m Conventional core 3 wells</td>
<td>Sandy mass-transport deposits and bottom-current reworked sands</td>
</tr>
<tr>
<td>3. Ouachita Mountains, Arkansas and Oklahoma, U.S. (Shanmugam and Moiola, 1995)</td>
<td>10. Jackfork Group, Pennsylvanian</td>
<td>369 m 2 outcrop sections</td>
<td>Sandy mass-transport deposits and bottom-current reworked sands common</td>
</tr>
<tr>
<td>7. U.K. Atlantic Margin (Shanmugam et al., 1995)</td>
<td>26. Faeroe area, Paleocene, west of the Shetland Islands 27. Foinaven Field, Paleocene, west of the Shetland Islands</td>
<td>Thickness included in the North Sea count 1 well Conventional core 1 well</td>
<td>Sandy mass-transport deposits and bottom-current reworked sands common</td>
</tr>
</tbody>
</table>
### Table 3, continued

<table>
<thead>
<tr>
<th>Location symbol and number in Figure 1</th>
<th>Case studies</th>
<th>Thickness of core and outcrop described*</th>
<th>Comments (This paper)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11. Equatorial Guinea (Famakinwa et al., 1996; ; Shanmugam, 2006a, 2012b)</td>
<td>32. Zafiro Field, Pliocene, offshore 33. Opalo Field, Pliocene, offshore</td>
<td>294 m Conventional core 2 wells</td>
<td>Sandy mass-transport deposits and bottom-current reworked sands common</td>
</tr>
<tr>
<td>12. Gabon (Shanmugam, 2006a, 2012a)</td>
<td>34. Melania Formation, lower Cretaceous, offshore (includes four fields)</td>
<td>275 m Conventional core 8 wells</td>
<td>Sandy mass-transport deposits and bottom-current reworked sands common</td>
</tr>
<tr>
<td>13. Bay of Bengal, India (Shanmugam et al., 2009)</td>
<td>35. Krishna–Godavari Basin, Pliocene</td>
<td>313 m Conventional core 3 wells</td>
<td>Sandy debrites and tidalites common</td>
</tr>
<tr>
<td>Kutei Basin, Makassar Strait (Saller et al., 2006)</td>
<td>Kutei Basin, Miocene</td>
<td>2 wells? (Saller et al., 2006, 2008a, 2008b)</td>
<td>Discussion of problematic turbidites (Shanmugam, 2008a, 2013c, 2014a)</td>
</tr>
</tbody>
</table>

Total thickness of rocks described by the author 11,463 m

* The rock description of 35 case studies of deep-water systems comprises 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 (2000–2011). Global studies of cores and outcrops include a total of 7832 meters of conventional cores from 123 wells, representing 32 petroleum fields worldwide (Shanmugam, 2013d). These modern and ancient deep-water systems include both marine and lacustrine settings.

** The Peira Cava outcrop section was originally described by Bouma (1962), and later by Pickering and Hilton (1988, their Figure 62), among others.

### Table 4

Nomenclature of 79 different types of mass-transport processes and their deposits with overlapping and confusing meanings. Compiled from several sources. Updated after Shanmugam (2012a).

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Characteristics</th>
<th>Reference</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Landslide: Type 1 (First classification by J. D. Dana in 1862) (see Cruden, 2003)</td>
<td>Refers to three processes: rock slides, earth spreads, and debris flows</td>
<td>Cruden (2003)</td>
<td>Impractical * (MTD or SMTD)**</td>
</tr>
<tr>
<td>2. Landslide: Type 2 (GSA Thematic Volume)</td>
<td>A general term used for various moderately rapid gravity-induced mass movements, which exclude creep and solifluction</td>
<td>Coates (1977)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>3. Landslide: Type 3 (AGI Glossary)</td>
<td>A general term for a variety of gravity-induced downslope mass movements, which include creep and solifluction</td>
<td>Bates and Jackson (1980)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>Nomenclature</td>
<td>Characteristics</td>
<td>Reference</td>
<td>Comments</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------------</td>
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<td>----------</td>
</tr>
<tr>
<td>4. Landslide: Type 4 (NATO Workshop)</td>
<td>A sudden movement of earth and rocks down a steep slope</td>
<td>Saxov (1982) (See also Cruden, 1991)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>5. Landslide: Type 5 (USGS Handbook)</td>
<td>A downslope movement of rock or soil, or both, occurring on the surface of rupture in which much of the material often moves as a coherent or semi-coherent mass with little internal deformation</td>
<td>Highland and Bobrowsky (2008) (See also Eckel, 1958)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>6. Fall or rockfall</td>
<td>Freefall of material from steep slopes</td>
<td>Varnes (1978)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>7. Sand fall</td>
<td>Freefall of material at submarine canyon heads</td>
<td>Shepard and Dill (1966)</td>
<td>Impractical (SMTD)</td>
</tr>
<tr>
<td>8. Topple</td>
<td>Tilting without collapse</td>
<td>Varnes (1978)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>9. Slide</td>
<td>Coherent mass with translational movement</td>
<td>Dott (1963)</td>
<td>Slide</td>
</tr>
<tr>
<td>10. Slump</td>
<td>Coherent mass with rotational movement and internal deformation</td>
<td>Dott (1963)</td>
<td>Slump</td>
</tr>
<tr>
<td>11. Translational slump</td>
<td>Translational movement</td>
<td>Milia et al. (2006)</td>
<td>Translational movements associated with slides (Dott., 1963), MTD</td>
</tr>
<tr>
<td>12. Drained slump</td>
<td>Slumping without excess pore pressure</td>
<td>Morgenstern (1967)</td>
<td>Impractical (MTD)</td>
</tr>
<tr>
<td>13. Undrained slump</td>
<td>Slumping with excess pore pressure</td>
<td>Morgenstern (1967)</td>
<td>Impractical (MTD)</td>
</tr>
<tr>
<td>14. Toreva-block (Named after the village of Toreva in Arizona, USA)</td>
<td>Backward rotational slip</td>
<td>Reiche (1937)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>15. Spread</td>
<td>Lateral extension accommodated by shear or tensile fractures</td>
<td>Varnes (1978)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>17. Debris avalanche</td>
<td>Extremely fast-moving debris flows</td>
<td>Varnes (1978)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>18. Cohesionless debris avalanche</td>
<td>Rolling, cascading, and collision of rock fragments on steep underwater slopes</td>
<td>Prior and Bornhold (1990)</td>
<td>Impractical (SMTD)</td>
</tr>
<tr>
<td>20. Debris slide</td>
<td>Slow-moving mass that breaks up into smaller blocks</td>
<td>Varnes (1978)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>21. Flow slide (two words)</td>
<td>Disintegrating subaerial slide in coarse material where a temporary transfer of part of the normal stress onto the fluids of the void space, with a consequent sudden decrease in strength</td>
<td>Koppejan et al. (1948) (see also Rouse, 1984)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>22. Flow slide (two words)</td>
<td>High-velocity, transitional type between slumps and debris lows</td>
<td>Shreve (1968)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>23. Flowslide (one word)</td>
<td>Basal dense layer with viscoplastic behavior in stratified submarine sediment flows</td>
<td>Norem et al. (1990)</td>
<td>SMTD and associated turbidite</td>
</tr>
<tr>
<td>Nomenclature</td>
<td>Characteristics</td>
<td>Reference</td>
<td>Comments</td>
</tr>
<tr>
<td>------------------------------</td>
<td>--------------------------------------------------------------------------------</td>
<td>-------------------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>24. Marine flow slide</td>
<td>Liquefied marine sand with high porosity and high pore-water pressure</td>
<td>Koning (1982)</td>
<td>Impractical (SMTD)</td>
</tr>
<tr>
<td>25. Retrogressive flow slide</td>
<td>Occurring along banks of noncohesive clean sand or silt and showing repeated fluctuations in porewater pressure</td>
<td>Andersen and Bjerrum (1967)</td>
<td>Impractical (SMTD)</td>
</tr>
<tr>
<td>26. Deep creep</td>
<td>Slow moving mass of bedrock (Synonym: rock flow)</td>
<td>Varnes (1978, his Figure 2.2)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>27. Soil creep</td>
<td>Slow moving mass of fine soil</td>
<td>Varnes (1978, his Figure 2.2)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>28. Seasonal creep</td>
<td>Slow moving mass within the soil horizon affected by seasonal changes in soil moisture and temperature</td>
<td>Hansen (1984)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>30. Progressive creep</td>
<td>Slow moving mass associated with slopes reaching point of failure by other mass movements</td>
<td>Hansen (1984)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>31. Talus creep</td>
<td>Slow moving large angular rock fragments on a gentle slope (Synonym: scree creep)</td>
<td>Sharpe (1938)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>32. Slump-creep</td>
<td>Slow moving multiple processes</td>
<td>Carter and Lindqvist (1975)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>33. Mass creep</td>
<td>Slow moving submarine slope sediments due to repeated loading effects by earthquakes</td>
<td>Almagor and Wiseman (1982)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>34. Rock-glacier creep</td>
<td>Slow moving tongue of the rock glacier</td>
<td>Sharpe (1938)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>35. Solifluction (Soil flow of Varnes, 1978)</td>
<td>Slow moving waterlogged soil over permafrost layers</td>
<td>Anderson (1906)</td>
<td>Impractical (MTD)</td>
</tr>
<tr>
<td>36. Earth flows</td>
<td>Slow-to fast-moving fine soil</td>
<td>Varnes (1978)</td>
<td>Impractical (MTD)</td>
</tr>
<tr>
<td>37. Sturzstrom (Synonym: rock avalanche)</td>
<td>Fast-moving debris flows</td>
<td>Hsü (1975, 2004)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>38. Inertia flow</td>
<td>Grain avalanching</td>
<td>Bagnold (1954)</td>
<td>SMTD</td>
</tr>
<tr>
<td>39. Grain flow</td>
<td>Sediment support by grain collision</td>
<td>Middleton and Hampton (1973)</td>
<td>SMTD</td>
</tr>
<tr>
<td>40. Fluidized flow</td>
<td>Full sediment support by upward intergranular flow</td>
<td>Middleton and Hampton (1973)</td>
<td>Impractical (SMTD)</td>
</tr>
<tr>
<td>41. Liquefied flow</td>
<td>Partial sediment support by upward intergranular flow</td>
<td>Lowe (1976)</td>
<td>Impractical (SMTD)</td>
</tr>
<tr>
<td>42. Turbidity current</td>
<td>Sediment support by fluid turbulence</td>
<td>Middleton and Hampton (1973)</td>
<td>Turbidite, not MTD</td>
</tr>
<tr>
<td>43. Sand flow</td>
<td>A flow of wet sand that is subjected to fluctuations in pore-water pressure</td>
<td>Varnes (1958)</td>
<td>Impractical (SMTD)</td>
</tr>
<tr>
<td>44. Loess flow</td>
<td>Intermediate stage between “liquefaction flow” and “sand flow” with increasing grain size</td>
<td>Coates (1977)</td>
<td>Impractical (MTD)</td>
</tr>
<tr>
<td>Nomenclature</td>
<td>Characteristics</td>
<td>Reference</td>
<td>Comments</td>
</tr>
<tr>
<td>----------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------------</td>
<td>----------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>45. “High-density turbidity current”</td>
<td>Stratified lower debris flow and upper turbidity current</td>
<td>Kuenen (1951)</td>
<td>Debrite and turbidite (Shanmugam, 1996)</td>
</tr>
<tr>
<td>46. Sandy debris flow</td>
<td>Sandy flow with plastic rheology and laminar state</td>
<td>Shanmugam (1996)</td>
<td>Sandy debrite</td>
</tr>
<tr>
<td>47. Cohesionless liquefied sandflow</td>
<td>Sliding-related sandy mass flows</td>
<td>Nemec (1990, his Figure 32)</td>
<td>Impractical SMTD</td>
</tr>
<tr>
<td>49. Slurry flow</td>
<td>Cohesive debris flows</td>
<td>Carter (1975a)</td>
<td>Impractical MTD</td>
</tr>
<tr>
<td>50. Slurry flow</td>
<td>Synonym for “High-density turbidity current”</td>
<td>Lowe and Guy (2000)</td>
<td>Impractical MTD or SMTD</td>
</tr>
<tr>
<td>51. Lahar</td>
<td>Volcaniclastic debris flow</td>
<td>Bates and Jackson (1980)</td>
<td>MTD or SMTD</td>
</tr>
<tr>
<td>52. Nuée ardente</td>
<td>Decoupling of pyroclastic flows (i.e., stratified flows)</td>
<td>Fisher (1995)</td>
<td>Impractical MTD</td>
</tr>
<tr>
<td>53. Cascading dense water event</td>
<td>Analogous to “sand fall” of Shepard and Dill (1966)</td>
<td>Gaudin et al. (2006)</td>
<td>Impractical (SMTD)</td>
</tr>
<tr>
<td>54. Dense flow</td>
<td>Basal high-concentration layer in stratified sediment flows</td>
<td>Norem et al. (1990)</td>
<td>SMTD and associated turbidite</td>
</tr>
<tr>
<td>55. Fluidized cohesion-less-particle flow</td>
<td>Basal high-concentration layer in stratified sediment flows</td>
<td>Friedman et al. (1992)</td>
<td>SMTD and associated turbidite</td>
</tr>
<tr>
<td>56. Liquefied cohesionless coarse-particle flow</td>
<td>Basal high-concentration layer in stratified sediment flows</td>
<td>Sanders and Friedman (1997)</td>
<td>SMTD and associated turbidite</td>
</tr>
<tr>
<td>57. Slide</td>
<td>Basal high-concentration layer in stratified sediment flows</td>
<td>Kuenen (1951)</td>
<td>Impractical MTD or SMTD</td>
</tr>
<tr>
<td>58. Flowing-grain layer</td>
<td>Basal high-concentration layer in stratified sediment flows</td>
<td>Sanders (1965)</td>
<td>SMTD and associated turbidite</td>
</tr>
<tr>
<td>59. Laminar inertia-flow</td>
<td>Basal high-concentration layer in stratified sediment flows</td>
<td>Postma et al. (1988)</td>
<td>SMTD and associated turbidite</td>
</tr>
<tr>
<td>60. Laminar sheared layer</td>
<td>Basal high-concentration layer in stratified sediment flows</td>
<td>Vrolijk and Southard (1997)</td>
<td>SMTD and associated turbidite</td>
</tr>
<tr>
<td>61. Traction carpet</td>
<td>Basal high-concentration layer in stratified sediment flows</td>
<td>Dzulynski and Sanders (1962)</td>
<td>SMTD and associated turbidite</td>
</tr>
<tr>
<td>62. Avalanching flow</td>
<td>Basal high-concentration layer in stratified sediment flows</td>
<td>Sanders (1965)</td>
<td>SMTD and associated turbidite</td>
</tr>
<tr>
<td>63. Mass flow</td>
<td>Basal high-concentration layer in stratified sediment flows</td>
<td>Friedman et al. (1992)</td>
<td>SMTD and associated turbidite</td>
</tr>
<tr>
<td>64. Mass flow</td>
<td>Plastic flow with shear stress distributed throughout the mass</td>
<td>Nardin et al., (1979)</td>
<td>MTD or SMTD</td>
</tr>
<tr>
<td>65. Laminar mass flow</td>
<td>Gradational processes involving sand flows, slumping, sliding, and spontaneous liquefaction</td>
<td>Carter (1975b)</td>
<td>SMTD</td>
</tr>
<tr>
<td>66. Granular mass flow</td>
<td>Concentrated grain (&gt; 0.06 mm)-fluid mixtures in rock avalanches, debris flows, and pyroclastic flows</td>
<td>Iverson and Vallance (2001)</td>
<td>Impractical SMTD</td>
</tr>
<tr>
<td>Nomenclature</td>
<td>Characteristics</td>
<td>Reference</td>
<td>Comments</td>
</tr>
<tr>
<td>------------------------------</td>
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</tr>
<tr>
<td>67. Hyperpycnal flow</td>
<td>Sinking river water that has higher density than basin water</td>
<td>Bates (1953), Mulder et al. (2003)</td>
<td>Impractical MTD</td>
</tr>
<tr>
<td>68. Dense flow</td>
<td>Multiple processes</td>
<td>Gani (2004)</td>
<td>SMTD and associated turbidite</td>
</tr>
<tr>
<td>69. Hybrid flow</td>
<td>Multiple processes</td>
<td>Houghton et al. (2009)</td>
<td>SMTD and associated turbidite</td>
</tr>
<tr>
<td>70. Tsunamite (deposit)</td>
<td>“Rope-ladder texture” and multiple processes</td>
<td>Michalik (1997)</td>
<td>Impractical MTD</td>
</tr>
<tr>
<td>72. Olistostrome (deposit)</td>
<td>Submarine gravity sliding or slumping</td>
<td>Flores (1955); Hsü (1974)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>73. Gravitite (deposit)</td>
<td>Debris flows</td>
<td>Natland (1967)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>74. Gravite (deposit)</td>
<td>Slide, slump, debris flow, dense flow, and turbidity current</td>
<td>Gani (2004)</td>
<td>Impractical (MTD or SMTD)</td>
</tr>
<tr>
<td>75. Fluxoturbidite (deposit)</td>
<td>Sand avalanche</td>
<td>Dzulynski et al. 1959</td>
<td>Impractical (SMTD)</td>
</tr>
<tr>
<td>(See Hsü, 2004 for a critique of this term)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>76. Seismoturbidite (deposit)</td>
<td>Large-scale mass flows</td>
<td>Mutti et al. (1984)</td>
<td>Impractical (SMTD)</td>
</tr>
<tr>
<td>77. Megaturbidite (deposit)</td>
<td>Large-scale debris flows</td>
<td>Labaume et al. (1987)</td>
<td>Impractical (SMTD)</td>
</tr>
<tr>
<td>78. Atypical turbidite (deposit)</td>
<td>Slumps, debris flows, and sand flows</td>
<td>Stanley et al. (1978)</td>
<td>Impractical (SMTD)</td>
</tr>
<tr>
<td>79. Duplex-like structures (deposit)</td>
<td>Slumps and debris flows</td>
<td>Shanmugam et al. (1988a)</td>
<td>Impractical (MTD)</td>
</tr>
</tbody>
</table>

* In some cases, it is impractical to interpret a specific process from the rock record. In such cases, a non-specific term of MTD or SMTD is preferred.

**MTD = Mass-transport deposits. SMTD = Sandy mass-transport deposits.**

Hampton et al., 1996; Locat and Lee, 2000, 2002; Masson et al., 2006; Feeley, 2007; Twichell et al., 2009) environments on Earth, but also in extraterrestrial environments on Venus (Malin, 1992), Mars (Lucchitta, 1979; McEwen, 1989; Montgomery et al., 2009), and Saturn’s satellite Iapetus (Singer et al., 2012), among others. At present, the literal meaning of the word landslide is totally lost in the geologic and engineering literature. For example, (1) Hungr (1995, p. 610) states, “...rapid landslides such as debris flows, debris avalanches, rock slide avalanches, large scale liquefaction failures, and slides...” in describing subaerial mass-transport processes. (2) Twichell et al. (2009, their Figure 2d) labeled the toe of the “Curtituck landslide” as “Debris flow deposit” on a 3.5 kHz seismic profile from the U.S. Atlantic margin. (3) Singer et al. (2012, p. 574) state that “Here we analyse images from the Cassini mission and report numerous long-runout landslides on Iapetus, an icy satellite of exceptional topographic relief...We use the ratio of drop height to runout length as an approximation for the friction coefficient of landslide material.” The above three examples, selected among many other similar ones, reveal the following fundamental problems:

- The use of the term landslide, with a built-in reference to a sliding motion, to represent topples without a sliding motion or debris flows with a flowing motion is er-
raneous (Varnes, 1978). In acknowledging this basic problem, Brabb (1991, p. 52) state “Note that Varnes prefers the term ‘slope movements’. I will use the more familiar ‘landslides’ in this paper, even though many processes are loosely termed ‘landslides’ involve little or no true sliding.” This practice of postponing conceptual problems is chronic in this domain. For example, Hansen (1984, p. 1) states that “Demands for standardized terminology are common, and certainly moves have been made to improve definition (Varnes, 1978). As yet the move towards what might be called an impossible ideal is slow, but it still remains a worthy aim.” Disappointingly, Varnes (1984) himself abandoned his own valuable aim and reverted back to the popular and confusing usage of the term “landslide” for a variety of mass-transport processes that involve little or no sliding motion.

- Aspects of sediment failure and related sliding can be measured in modern subaerial environments by installing piezometers and inclinometers (Duncan and Wright, 2005, their Figure 2.7), but such measurements are impractical in modern deep-marine and extraterrestrial environments.

- Motion types can be determined by direct examination of ancient strata in core or outcrop, but the distinction between sliding and flowing motions cannot be ascertained from seismic or radar images.

- The synonymous use of the term landslide for high-velocity debris avalanches is indefensible. This is because there are no objective criteria to distinguish low-velocity flows from high-velocity flows in the depositional record on Earth (Shanmugam, 2006a, 2012a). Nor is there any technique to measure velocity of mass movements on other planets.

- The measure of H/L (fall height/runout length) ratios of MTD on other planets using radar images and comparison of such data with H/L ratios of MTD on Earth derived from outcrop or seismic data is incompatible.

- Although MTD on the U.S. Atlantic margin have been described as submarine landslides by Twichell et al. (2009), cores from some of these landslides are indeed composed of debrites (Embley, 1980).

The current landslide problem, somewhat analogous to the turbidite problem (Van der Linzen, 1969) and the tsunamiite problem (Shanmugam, 2006b; Luczyński, 2012) encountered earlier, requires a rigorous scrutiny of fundamental issues. Therefore, the primary objective here is to bring clarity to the classification of subaerial and submarine downslope processes by combining sound principles of fluid mechanics, soil mechanics, labora-

1.3 Limitations and organization

There are limitations in organizing this paper in a conventional format with a coherent theme. First, this review is a blend of nomenclatural, conceptual, theoretical, experimental, observational, and interpretational issues. As such, it is difficult to devote the same rigorous attention to details on each issue. For example, unlike sedimentological studies of landslides on Earth, rock-based sedimentological data of landslides on Mars and Venus are totally lacking. Second, the emphasis of submarine MTD in this article is intentional because of their global economic importance in petroleum exploration and production. Third, contrary to the popular usage of the term “landslide” for all types of MTD by other researchers, this paper advocates the strict application of the term solely to a single MTD type. Fourth, in minimizing a tedious text, portions of the paper are organized using numbered or bulleted pithy statements. Fifth, in maintaining some continuity and clarity, selected text and figures are reused from the author’s previous publications.

By necessity, this iconoclastic review is organized, rather unorthodoxly and disjointedly, under the following main headings:

- Mechanics of sediment failure and sliding
- Nomenclature and classification
- Recognition of the three basic types of MTD
- Triggering mechanisms
- Long-runout mechanisms
- Reservoir characterization
2 Mechanics of sediment failure and sliding

Sediment failures on continental margins are controlled by the pull of gravity, the source of the material (bedrock vs. regolith), the strength of the soil (grain size, mineralogy, compaction, cementation, etc.), the weight of the material, the slope angle, the pore-water pressure, and the planes of weaknesses. In order to evaluate sediment failures in general, one needs to conduct a slope stability analysis for describing the sediment behavior and sediment strength during loading or deformation.

2.1 Soil strength and slope stability

The most fundamental requirement of slope stability is that the shear strength of the soil must be greater than the shear stress required for equilibrium (Duncan and Wright, 2005; Shanmugam, 2014a). The two conditions that result in slope instability are (1) a decrease in the shear strength of the soil and (2) an increase in the shear stress required for equilibrium. The decrease in the shear strength of the soil is caused by various in situ processes, such as an increase in pore-water pressure, cracking of the soil, swelling of clays, leaching of salt, etc. The increase in shear stress is induced by loads at the top of the slope, an increase in soil weight due to increased water content, seismic shaking, etc.

A common method for calculating the slope stability is the ‘Limit equilibrium analyses’ in soil mechanics. A stable slope can be maintained only when the factor of safety for slope stability (F) is larger than or equal to 1 (Duncan and Wright, 2005, their equations 6.1 and 13.2):

\[ F = \frac{S}{\tau} \]

where

\[ S = \text{Available shear strength, which depends on the soil weight, cohesion, friction angle, and pore-water pressure.} \]
\[ \tau = \text{Equilibrium shear stress, which is the shear stress required to maintain a just-stable slope. It depends on the soil weight, pore-water pressure, and slope angle.} \]

The shear stress is equal to the maximum shear stress which can be absorbed by the slope without failure and can be defined by the Mohr-Coulomb failure criterion:

\[ S = c + \sigma \tan \varphi \]

where

\[ S = \text{Available shear strength (Figure 4A)} \]
\[ c = \text{Cohesion (nonfrictional) component of the soil strength} \]
\[ \sigma = \text{Total normal stress acting on the failure surface} \]
\[ \varphi = \text{Angle of internal friction of the soil} \]

By combining the equations of shear strength and Mohr-Coulomb failure criterion, the factor of safety (F) can be expressed as:

\[ F = \frac{c + \sigma \tan \varphi}{\tau} \]

A sediment failure is initiated when the factor of safety for slope stability (F) is less than 1 (Figure 4B). In other words, the sliding motion along the shear surface commences only when the driving gravitational force exceeds the sum of resisting frictional and cohesive forces. Initial porosity of the sediment plays a critical factor in controlling the behavior of the shear surface (Anderson and Riemer, 1995). Based on an experimental study on landslides initiated by rising pore-water pressures, Iverson et al. (2000) reported that even small differences in initial porosity had caused major differences in mobility. For example, wet sandy soil with 50% porosity contracted during slope failure, partially liquefied, and accelerated to a speed of over 1 m s\(^{-1}\), whereas the same soil with 40% porosity dilated during failure, slipped episodically, and traveled at a slow velocity of 0.2 cm s\(^{-1}\). Finally, soil strength differs between drained and undrained conditions (Terzaghi et al., 1996; USACE, 2003; Duncan and Wright, 2005).

Slides occur commonly on modern slopes of 1°–4° (Booth et al., 1993) (Figure 5). Contrary to the popular belief, most submarine slides occur on gentle slopes of less than 4°, sometimes even at 0.25°. Submarine slides on slopes greater than 10° are rare (Figure 5).

2.2 The role of excess pore-water pressure

Terzaghi (1936) first recognized that pore-water pressure controls the frictional resistance of slopes, which has remained the most important concept in understanding landslide behaviour. A founding principle of slope stability is that a rise in pore-water pressure reduces the shear strength of the soil (Skempton, 1960). The shear strength of soil, in particular clays, is controlled by the frictional resistance and interlocking between particles (i.e., physical component), and interparticle forces (i.e., physicochemical component) (Karacz and Shanmugam, 1974; Parchure, 1980; Hayter et al., 2006). Furthermore, bed density and shear strength of soil increase with increasing consolidation (Hanzawa and Kishida, 1981; Dixit, 1982). A rise in pore-water pressure occurs when the saturated soil is stressed, and when the porosity cannot increase or the pore fluid cannot expand or escape through fractures. The ex-
cess pore-water pressure has been considered a vital factor in explaining the origin of subaerial mass-transport processes (Johnson, 1984; Anderson and Sitar, 1995; Iverson, 1997, 2000; Iverson et al., 1997; Jakob and Hungr, 2005). Iverson (1997), based on studies of coarse-grained subaerial debris flows, has developed a model in which excess pore-water pressure causes liquefaction of the sediment and thereby strongly reduces internal friction and increases sediment mobility or runout distances.

Excess pore-water pressures have also been considered a characteristic property in explaining long-runout submarine MTD (Suhayda and Prior, 1978; Hampton et al., 1996; Iverson et al., 1997; Gee et al. 1999; Major and Iverson, 1999). Submarine debris flows have lower yield strengths than subaerial debris flows due to entrainment of sea water (Pickering et al., 1989) and elevated pore-water pressure (Pierson, 1981).

Laboratory measurements of pore-water pressure have shown that the front of the subaqueous clayey debris flow exhibits hydroplaning (Mohrig et al., 1998) on a thin layer of water, which causes low bed friction. Fronts of sandy debris flows show a fluidized head where bed friction is minimal (Ilstad et al., 2004). A 5-m thick submarine sandy debris flow, with a long-runout distance of over 400 km downslope of the Canary Islands, has been attributed to the development of excess pore-water pressure due to loading induced by a pelagic debris package (Gee et al., 1999, their Figure 12). Problems associated with long-runout MTDs are discussed below (Section 6).

3 Nomenclature and classification

3.1 Landslide versus mass transport

Although the term landslide is deeply entrenched in the literature, there are inherent problems associated with the usage.

1) For his first paper, Varnes (1958) used the title “Landslide types and processes” that included fall, topple, spread, translational slide, rotational slide, and flow. But for his second paper, Varnes (1978) changed the paper title to “Slope movement types and processes” to represent the same six processes, namely (a) fall, (b) topple, (c) spread, (d) translational slide, (e) rotational slide, and (f) flow (Figure 6). In abandoning the term landslide, Varnes (1978, p. 11) eloquently explained that “One obvious change is the
term slope movements, rather than landslides, in the title of this paper and in the classification chart. The term landslide is widely used, and no doubt, will continue to be used as an all inclusive term for almost all varieties of slope movements, including some that involve little or no true sliding. Nevertheless, improvements in technical communication require a deliberate and sustained effort to increase the precision associated with the meaning of words, and therefore the term slide will not be used to refer to movements that do not include sliding.” This cautionary note, which has been obviously ignored by other researchers, is the underpinning principle of this paper.

2) The term landslide literally implies sliding motion of a rigid body of earth or land along a shear surface. But debris flows, considered to be a part of the landslide family in some classifications (Cruden, 1991), are characterized by intergranular movements, not shear-surface movements (Shanmugam et al., 1994; Iverson et al., 1997).

3) The AGI Glossary of Geology (Bates and Jackson, 1980, p. 349) defined a landslide as “A general term covering a wide variety of mass movement landforms and processes involving the downslope transport, under gravitational influence, of soil and rock material en masse. Usually the displaced material moves over a relatively confined zone or surface of shear.” This definition, although implies that the shear-surface movement is a critical factor (see Figure 4B), includes a variety of mass movements.

4) According to Cruden (1991), “A landslide is the movement of a mass of rock, earth or debris down a slope”. This broad definition includes not only slides, but also debris flows. There are at least five different definitions of the term landslide with conflicting meanings (Table 4).

5) Geertsema et al. (2009, p. 59) state that “Landslides include debris flows and slides, earth flows and flowslides, rock falls, slides, and avalanches, and complex landslides involving both rock and soil.” On the one extreme, the term landslide has been applied without any implication for a specific process (Gee et al., 2007; Camerlenghi et al., 2010), but on the other extreme, the term landslide represents only one category within a larger phenomenon called mass movements (Coates, 1977).

6) The U.S. Geological Survey uses the term landslide to include debris avalanche and creep with velocity connotations (Highland and Bobrowsky, 2008). However, velocities of transport processes cannot be interpreted from bathymetric images of modern seafloor or by examining the ancient rock record in core and outcrop (see Section 3.4 on ‘Classification based on transport velocity’ below).
7) Even the International Geoscience Programme (IGCP-585), now called E-MARSHAL (Earth’s continental margins: assessing the geohazard from submarine landslides) uses the word landslide for all submarine mass movements (E-MARSHAL, 2013).

8) Similarly, the Springer journal “Landslides” (Editor-in-Chief: Kyoji Sassa) defines that “Landslides are gravitational mass movements of rock, debris or earth”, without a distinction between landslides and mass movement. Credit: http://www.springer.com/earth+sciences+and+geography/natural+hazards/journal/10346 (accessed December 27, 2014).

The use of the term landslide is inappropriate as a general term to represent both the shear-surface ‘sliding’ motion of a rigid body and the intergranular ‘flowing’ motion of a plastic mass (Shanmugam et al., 1994). A more appropriate general term is “mass transport” or “mass movement”, which represents the failure, dislodgement, and downslope movement of either sediment or glacier under the influence of gravity. The advantage of the general term “mass transport” is that there is no built-in reference to a sliding motion. Nor is there any reference to sediment or glacier.

3.2 Classification based on types of movement and material

Varnes (1978, his Figure 2.1) classified subaerial mass-transport processes into six movement-based types: (1) falls (2) topples, (3) translational slides, (4) rotational kinds, (5) spreads, and (6) flows (Figure 6). Further, Varnes (1978) added the prefix “rock” to the process names and established the material-based types: (1) rock fall (2) rock topple, (3) rock slide, (4) rock slump, (5) rock spread, and (6) rock flow or deep creep. Although the spreads,
topples, and falls could be observed in modern subaerial environments, the deposits of these three processes in the ancient rock record would not have any distinguishing attributes. This is because deposits of spreads, topples, and falls would resemble debrites (i.e., deposits of debris flows). Therefore, these three types are not adopted in the present article (Figure 6).

3.3 Classification based on mechanical behavior

Dott (1963, his Figure 7) proposed the most meaningful and practical classification of subaqueous mass-transport processes. It is somewhat analogous to the most widely accepted classification of subaerial mass-transport processes by Varnes (1958). In this scheme, subaqueous processes are broadly classified into (1) elastic, (2) elastic and plastic, (3) plastic, and (4) viscous fluid types based on mechanical behavior (Figure 7). The elastic behavior represents rockfall; the elastic and plastic behavior comprises slide and slump; the plastic behavior represents debris flow, and the viscous fluid represents Newtonian turbidity current. The importance of Dott's (1963) classification is that mass-transport processes do not include turbidity currents (Figure 7C). In this classification, a rockfall refers to sudden falling of rock fragments on steep slopes, such as submarine canyonheads. Because recognition of rockfall in the ancient record is impractical, it is not considered here as a separate type. In short, mass-transport processes are composed of three basic types: (1) slide, (2) slump, and (3) debris flow (Figure 7). I have adopted Dott's (1963) classification in this review because theoretical analysis (Shanmugam, 1996), experimental observations (Shanmugam, 2000; Marr et al., 2001), and empirical data (Table 3) overwhelmingly show that turbidity currents are not mass-transport processes.

The underpinning principle of Dott's (1963) classification is the separation of solid from fluid mode of transport based on sediment concentration. In the solid (elastic and plastic) mode of transport, high sediment concentration is the norm (25%–100% by volume, Figure 7B). Mass-transport mechanisms are characterized by solid blocks or aggregate of particles (mass). In contrast, individual particles are held in suspension by fluid turbulence in turbidity currents (Dott, 1963; Sanders, 1965). Turbidity currents are characterized by low sediment concentration of 1%–23% by volume (Figure 7B). In other words, turbidity currents are innately low in flow density. A simple analogy to high-volume sediment transport by mass-transport processes is the human transport by a double-decker bus with a capacity to carry 73 passengers at a time (Figure 8A). In contrast, low-volume sediment transport by turbidity currents is analogous to human transport by a microcar with a capacity to carry only two passengers at a time (Figure 8B). Clearly, mass transport is a much more efficient mechanism for moving sediment downslope than a turbidity current. Mass transport can operate in both subaerial and subaqueous environments, whereas turbidity currents can operate only in subaqueous environments. The advantage of this classification is that physical features preserved in a deposit directly represent the physics of sediment movement that existed at the final moments of deposition.

3.4 Classification based on transport velocity

The concept of velocity-based classification was first introduced by Sharpe (1938) and later adopted by Varnes (1958, 1978) for subaerial processes. There are at least 10 different factors that are commonly used in classifying landslides by various authors (Hansen, 1984, Table 1.1). These factors are: (1) climate, (2) material moved, (3) coherence of material, (4) size of material, (5) geology, (6) type of movement, (7) speed of movement, (8) medium of movement: water/air/ice, (9) triggering mechanisms, and (10) morphological attributes. These 10 conflicting philosophies and related classifications have resulted in the current conceptual and nomenclatural crisis (Table 4). The velocity-based terms, such as avalanches, have also been adopted for downslope subaqueous processes when interpreting seismic and bathymetric data (Wynn et al., 2000; Lewis and Collot, 2001; Masson et al., 2006). Examples of velocity-based terms are as follows:

1) The term flow slide has been used for high-velocity subaerial processes that could be considered a transitional type between slumps and debris flows (Shreve, 1968; Rouse, 1984).

2) A slow-moving mass that breaks up into smaller blocks as it advances is called debris slide, whereas a fast-moving mass that breaks up into smaller blocks as it advances is called debris avalanche (Varnes, 1978). The velocity of debris avalanches is 5 m·s⁻¹ (Cruden and Varnes, 1996; see also Hungr et al., 2001).

3) Catastrophic (fast-moving) debris flows are called sturzstrom (Hsü, 1975, 2004).

4) The term creep refers to a slow-moving mass movement (Bates and Jackson, 1980). There are nine kinds of creep depending on material and movement: (a) deep creep, (b) soil creep, (c) seasonal creep, (d) continuous creep, (e) progressive creep, (f) talus creep, (g) slump creep, (h) mass creep, and (i) rock-glacier creep (Shan-
Although fast-moving and slow-moving mass-transport processes have been classified using absolute velocity values (Cruden and Varnes, 1996; Hungr et al., 2001), these velocity-based terms are not based on empirical data. For example, it is difficult to measure velocities of processes in modern deep-water environments because of common destruction of velocity meters by catastrophic mass-transport events (Inman et al., 1976; Shepard and Marshall, 1978).

Cable breaks were used to estimate velocity of submarine mass-transport processes, triggered by the 1929 Grand Banks earthquake in offshore Newfoundland, Canada, which traveled at a speed of 67 km·h⁻¹ (Piper et al., 1988). But such velocity values are not based on direct measurements. Therefore, we do not know whether those cables were broken by slumps, debris flows, or turbidity currents. More importantly, there are no sedimentological criteria to determine the absolute velocities of sediment movement.
in the ancient rock record. This is because sedimentary features preserved in the deposits cannot and do not reflect absolute transport velocities. The practice of determining flow velocity from grain size using the Hjulström Diagram, meant for fluvial processes (Sundborg, 1956), is inapplicable to MTD. This is because grain size is not proportional to flow velocity in mass-transport processes. In California, for example, it has been well documented that a slow-moving (at velocities of a few centimeter per day) debris flow with strength can detach a house from its foundation and transport it downslope. The other complication is that a debris flow can transform into turbidity current (Hampton, 1972), which is called surface transformation (Fisher, 1983). But there are no objective sedimentological criteria for interpreting flow transformation from the depositional record. In other words, the velocity-based terms are impractical and therefore meaningless for interpreting the ancient geologic record.

3.5 Classifications with emphasis on turbidity currents

A plethora of classifications on deep-water processes and facies models, with a skewed emphasis on turbidity currents, exists (Bouma, 1962; Mutti and Ricci Lucchi, 1972; Middleton and Hampton, 1973; Lowe, 1982; Stow, 1985; Pickering et al., 1989; Mutti, 1992; Mulder, 2011; Talling et al., 2012). Middleton and Hampton (1973) proposed a classification, based on sediment-support mechanisms, in which turbidity currents were considered as mass flows. Some authors (Nardin et al., 1979, their Table 3; Nemec,
1990, his Figure 6; Martinsen, 1994, his Figure 5.1; Mulder and Cochonat, 1996, their Figure 11 and 13; Locat and Lee, 2002, their Figure 2) have included turbidity currents as a type of mass movement or mass flow following the classification of Middleton and Hampton (1973), whereas others (Shanmugam, 2006a; Moscardelli and Wood, 2008) have excluded turbidity currents from mass-transport processes following the classification of Dott (1963). I have already emphasized the theoretical, experimental, and empirical basis for adopting the Dott’s (1963) classification. In confusing the issue further, some authors have even classified debris flows as turbidity currents (Mutti et al., 1999).

Of significance in the above compilation is the vertical facies model for deposits of high-density turbidity currents (HDTC) with R1, R2, R3, S1, S2, and S3 internal divisions for sands and gravels in ascending order (Lowe, 1982). This model was derived solely from the study of ancient rock record using outcrops. The primary attraction to this model in the petroleum industry is that it allows one to interpret ancient deep-water coarse sandstone and conglomerate deposits as turbidites (Mutti, 1992; Mulder, 2011). Despite some recent cosmetic changes in nomenclature (Talling et al., 2012, their Figure 3) and other attempts to explain the basic turbidite facies models (Postma et al., 2014, their Figure 13), there is absolutely no empirical evidence (i.e., vertical sediment concentration profiles and grain-size measurements) for the existence of sandy and gravelly turbidity currents in modern oceans (Shanmugam, 2012a). Thus far, none of the published claims of turbidity currents in modern environments (Heezen and Ewing, 1952; Inman et al., 1976; Hay et al., 1982; Dengler and Wilde, 1987; Normark, 1989; Piper et al., 1999; Khrigounoff et al., 2003; Parsons et al., 2003; Xu et al., 2004; Crookshanks and Gilbert, 2008) has offered verifiable empirical data on natural sandy and gravelly turbidity currents (Shanmugam, 2012a). Nor has anyone ever documented the complete vertical Lowe Sequence with R1, R2, R3, S1, S2, and S3 divisions in modern deep-sea sands and gravels in DSDP and ODP sediment cores. When the very existence of natural sandy and gravelly turbidity currents is in doubt, outcrop-based facies models of HDTC (Lowe, 1982; Postma et al., 2014) are irrelevant in understanding the true origin of deep-water sandy deposits. In terms of fluid rheology and flow state, the concept of HDTC is a euphemism for sandy debris flows (Shanmugam, 1996). Unlike HDTC, however, sandy mass-transport processes and their deposits have been documented extensively by direct observations, underwater photographs, and remote sensing techniques in modern submarine canyons (Shepard and Dill, 1966), on modern submarine fan lobes (Gardner et al., 1996), and on modern continental rise (USGS, 1994). In short, any classification of deep-water medium-coarse sands and gravels as turbidites is dubious.

3.6 Excessive synonyms

Various classifications have given birth to a surplus of synonyms for mass-transport processes and their deposits (Reiche, 1937; Varnes, 1958, 1978; Hsu, 1974; Nardin et al., 1979; Bates and Jackson, 1980; Nemec, 1990; Palanques et al., 2006; Gaudin et al., 2006; Shanmugam, 1996, 2006b; Camerlenghi et al., 2010; Tappin, 2010; Festa et al., 2014). Selected examples are:

- Landslide = slope movement = mass movement = mass transport = mass wasting
- Submarine landslide = megaturbidite = homogenite
- Mass-transport complex (MTC) = mass-transport de-
posit (MTD) = submarine mass failure (SMF)  
- Translational landslide = translational slip = block slide = glide = slide  
- Rotational landslide = rotational slip = toreva block = slump  
- Muddy debris flow = mud flow = cohesive debris flow = slurry flow = mass flow  
- Debrite = olistostrome = sedimentary mélange  
- Sandy debris flow = granular flow = cohesionless debris flow = density-modified grain flow = cohesionless liquefied sandflow = grain flow = mass flow = high-density turbidity current = hyperconcentrated flow = slurry flow = mass flow = slump = slide = glide = slide  
- Flow slide = liquefaction slide  
- Rock avalanche = debris avalanche = sturzstrom  
- Sand fall = cascading densewater event = sand avalanche = grain flow = mass flow.

This excessive use of synonyms is, obviously, not only not necessary but even a reason for much confusion.

4 Recognition of the three basic types of MTD

Subaerial “landslides” were recognized as early as in 186 BC in China (Li, 1989). Nevertheless, only during the past few decades, techniques of systematic recognition and mapping have been developed (Brabb, 1991; Lee, 2005). Also, Geographical Information Systems (GIS) have become an important part of databases on landslide research (e.g., Dikau et al., 1996). However, the ultimate recognition of individual types of MTD in the rock record must be based on principles of process sedimentology.

4.1 Process sedimentology

Process sedimentology is the key to recognizing the basic MTD types in core and outcrop. Sanders (1963) published the pioneering paper on process sedimentology entitled ‘Concepts of fluid mechanics provided by primary sedimentary structures’. The discipline is concerned with the detailed bed-by-bed description of siliciclastic (and calciclastic) sedimentary rocks for establishing the link between the deposit and the physics and hydrodynamics of the depositional process. Basic requirements, principles, and methods of this discipline are: (1) a knowledge of physics, with emphasis on soil mechanics and fluid mechanics (Sanders, 1963; Brush, 1965), (2) the application of uniformitarianism principle, (3) the pragmatic, accurate, precise, and consistent description of the rock, (4) the preservation of absolute distinction between description and interpretation, (5) the documentation of excruciating details in sedimentological logs, (6) the interpretation of processes using exclusively primary sedimentary structures, (7) the mandatory consideration of alternative process interpretations, (8) the total exclusion of facies models, (9) the quantification of depositional facies, and (10) the routine use of common sense. A major problem in sedimentological studies is the failure to adopt the basic principles of process sedimentology, which has prompted lively debates on the deep-water petroleum-producing reservoirs of the Kutei Basin, Indonesia (Figure 1) (Dunham and Saller, 2014; Saller et al., 2006; Shanmugam, 2008a, 2014a).

Of the three basic types of mass-transport processes, namely slides, slumps, and debris flows (Figure 7), the terms slide and slump are used for both a process and a deposit. The term debrite is used for deposit of a debris flow. The prefix ‘sandy’ is used for lithofacies that have grain size values greater than 0.06 mm (sand and gravel) and have concentration value equal to or above 20% by volume (Figure 7D). The three sandy SMTD types are emphasized here because of their reservoir potential. Criteria for recognizing MTD and SMTD types in core and outcrop have been developed by integrating my rock description (Table 3) with published information by other researchers (Dott, 1963; Helwig, 1970; Johnson, 1970; Fisher, 1971; Hampton, 1972; Middleton and Hampton, 1973; Enos, 1977; Dingle, 1977; Woodcock, 1976, 1979; Cook, 1979; Lowe, 1982; Maltman, 1987, 1994; Pickering et al., 1989; Collinson, 1994). Numerous outcrop and core photographs of features associated with sandy slides, sandy slumps, and sandy debrites were published elsewhere (Shanmugam, 2012a).

4.2 Slides

A slide is a coherent mass of sediment or a rigid body that moves along a planar glide plane and shows no internal deformation (Figure 7A). Such sliding movements are also common in glaciers (Easterbrook, 1999). Submarine slides can travel hundreds of kilometers on continental slopes. Long-runout distances of up to 810 km for slides have been documented for submarine MTD (Table 5).

Some of the best studied seismic examples of submarine MTD are in the area of the Storegga Slide on the mid-Norwegian continental margin (Solheim et al., 2005b). Even in these cases, the authors acknowledged the practical difficulties in distinguishing slides from debrites on seismic profiles. This is because both slides and debrites
Table 5 Comparison of long-runout MTD on Earth (submarine and subaerial) with Venus, Iapetus, and Mars (extraterrestrial). The term “landslide” was used to describe many of these examples by the original authors. Locations of selected examples are shown in Figure 1. Long-runout MTD provide empirical data for developing depositional models for deep-water sandstone petroleum reservoirs. The change in numbering is to reflect the change in type of environment (subaerial, submarine, and extraterrestrial). Compiled from several sources.

<table>
<thead>
<tr>
<th>Name and location</th>
<th>Runout distance (km)</th>
<th>Environment</th>
<th>Data</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Storegga slide, Norwegian continental margin (Bugge et al., 1987; Jansen et al., 1987; Haflidason et al., 2005)</td>
<td>810</td>
<td>Submarine</td>
<td>Seismic and GLORIA side-scan sonar images, and core</td>
<td>Slide, slump, and debris flow</td>
</tr>
<tr>
<td>2. Agulhas, SE Africa (Dingle, 1977)</td>
<td>750</td>
<td>Submarine</td>
<td>Seismic</td>
<td>Slide and slump</td>
</tr>
<tr>
<td>4. Canary debris flow, NW African Margin (Masson et al., 1997)</td>
<td>600</td>
<td>Submarine</td>
<td>Seismic and core</td>
<td>Debris flow</td>
</tr>
<tr>
<td>5. Hatteras, U.S. Atlantic Margin (Embley, 1980)</td>
<td>~500</td>
<td>Submarine</td>
<td>Seismic and core</td>
<td>Slump and debris flow</td>
</tr>
<tr>
<td>6. Mauritania–Senegal, NW African Margin (Jacobi, 1976)</td>
<td>~300</td>
<td>Submarine</td>
<td>Seismic and core</td>
<td>Slump and debris flow</td>
</tr>
<tr>
<td>7. Nuuanu, NE Oahu (Hawaii) (Normark et al., 1993; Moore et al., 1994)</td>
<td>235</td>
<td>Submarine</td>
<td>GLORIA side-scan sonar images</td>
<td>Mass transport</td>
</tr>
<tr>
<td>8. Wailau, N Molokai (Hawaii) (Normark et al., 1993)</td>
<td>&lt;195</td>
<td>Submarine</td>
<td>GLORIA side-scan sonar images</td>
<td>Mass transport</td>
</tr>
<tr>
<td>10. Clark, SW Maui, Hawaii (Normark et al., 1993)</td>
<td>150</td>
<td>Submarine</td>
<td>GLORIA side-scan sonar images</td>
<td>Mass transport</td>
</tr>
<tr>
<td>11. N Kauai, N Kauai, Hawaii (Normark et al., 1993)</td>
<td>140</td>
<td>Submarine</td>
<td>GLORIA side-scan sonar images</td>
<td>Mass transport</td>
</tr>
<tr>
<td>12. East Breaks (West), Gulf of Mexico (McGregor et al., 1993)</td>
<td>110</td>
<td>Submarine</td>
<td>Seismic and core</td>
<td>Slump and debris flow</td>
</tr>
<tr>
<td>13. Grand Banks, Newfoundland (Heezen and Ewing, 1952; Driscoll et al., 2000; Bornhold et al., 2003)</td>
<td>&gt;100</td>
<td>Submarine</td>
<td>Seismic and core</td>
<td>Mass transport and turbidity current*</td>
</tr>
<tr>
<td>14. Ruatoria, New Zealand (Collot et al., 2001)</td>
<td>100</td>
<td>Submarine</td>
<td>Seismic</td>
<td>Mass transport</td>
</tr>
<tr>
<td>15. Aila–2, W Hawaii (Hawaii) (Normark et al., 1993)</td>
<td>95</td>
<td>Submarine</td>
<td>GLORIA side-scan sonar images</td>
<td>Mass transport</td>
</tr>
<tr>
<td>16. Kaena, NE Oahu (Hawaii) (Normark et al., 1993)</td>
<td>80</td>
<td>Submarine</td>
<td>GLORIA side-scan sonar images</td>
<td>Mass transport</td>
</tr>
<tr>
<td>17. El Golfo, western Canary Islands (Masson et al., 2002)</td>
<td>65</td>
<td>Submarine</td>
<td>Seismic</td>
<td>Mass transport</td>
</tr>
<tr>
<td>18. Bassein, Bay of Bengal (Moore et al., 1976)</td>
<td>55</td>
<td>Submarine</td>
<td>Seismic</td>
<td>Slide and debris flow</td>
</tr>
<tr>
<td>19. Kidnappers, New Zealand (Lewis, 1971)</td>
<td>45</td>
<td>Submarine</td>
<td>Seismic</td>
<td>Slump and slide</td>
</tr>
</tbody>
</table>
Table 5, continued

<table>
<thead>
<tr>
<th>Name and location</th>
<th>Runout distance (km)</th>
<th>Environment</th>
<th>Data</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>21. Ranger, Baja California (Prior and Coleman, 1984)</td>
<td>35</td>
<td>Submarine</td>
<td>Seismic</td>
<td>Mass transport</td>
</tr>
<tr>
<td>1. Osceola mudflow, Mount Rainier (Vallance and Scott, 1997)</td>
<td>120</td>
<td>Subaerial</td>
<td>Outcrop</td>
<td>Mass transport</td>
</tr>
<tr>
<td>2. Nevado del Ruiz, Colombia (Pierson, 1990)</td>
<td>103</td>
<td>Subaerial</td>
<td>Outcrop</td>
<td>Mass transport (The world’s largest historical subaerial MTD)</td>
</tr>
<tr>
<td>3. Pine Creek and Muddy River lahars, Mount St. Helens (Pierson, 1985)</td>
<td>31</td>
<td>Subaerial</td>
<td>Outcrop</td>
<td>Mass transport (The world’s second largest prehistoric subaerial MTD)</td>
</tr>
<tr>
<td>4. Saidmarreh slide, Zagros fold-thrust belt, SW Iran (Roberts and Evans, 2009)</td>
<td>19</td>
<td>Subaerial</td>
<td>Outcrop</td>
<td>Mass transport</td>
</tr>
<tr>
<td>1. Venus (Malin, 1992)</td>
<td>5–50</td>
<td>Extraterrestrial (Venus)</td>
<td>Radar images by the Magaellan spacecraft</td>
<td>Mass transport</td>
</tr>
<tr>
<td>2. Iapetus, a satellite of Saturn (Singer et al., 2012, their Figure 5)</td>
<td>7–80</td>
<td>Extraterrestrial (Iapetus)</td>
<td>Cassini mission images</td>
<td>Mass transport</td>
</tr>
<tr>
<td>3. Thaumasia Plateau (Montgomery et al., 2009, their Figure 9)</td>
<td>2500</td>
<td>Extraterrestrial (Mars)</td>
<td>Thermal Emission Imaging System infrared [THEMIS IR]</td>
<td>Mass transport</td>
</tr>
</tbody>
</table>

* See Shanmugam (2012a) for discussion on the evidence for turbidity currents

Exhibit homogeneous (i.e., transparent) to chaotic reflections (Figure 3). In distinguishing slides from debrites, Solheim et al. (2005b) used additional criteria, such as the existence of a headwall as well as sidewalls. Similar problems of recognizing individual depositional facies (e.g., slides vs. debrites) on seismic profiles have been acknowledged by Tripansas et al. (2008) and Twichell et al. (2009). In recognizing slides, McAdoo et al. (2000) used bathymetry and GLORIA (Geological Long-Range Inclined Asdic) side-scan sonar data. But such large-scale images are unreliable for distinguishing the sliding motion from flowing motion. These real-world examples reveal the limitations of relying on seismic data for distinguishing specific types of deep-water depositional facies. The solution is to examine the rocks directly by using core or outcrop.

Slides are capable of transporting gravel and coarse-grained sand because of their inherent strength. General characteristics of slides are:

- Blocky log motif (Figure 9A). Cored interval of this log motif (Figure 9B) reveals complex internal features in core (Figure 10B)
- Primary basal glide plane or décollement (core and outcrop) (Figure 10B)
- Basal shear zone (core and outcrop) (Figure 10C)
- Secondary internal glide planes (core and outcrop) (Figure 10B)
- Preservation of original strata from the provenance region (Figure 11)
- Multiple internal layers within a single slide unit (Figure 11)
- Subaerial to shallow-water facies encased in deep-water host muddy facies (Figure 11)
- Associated slumps (Figure 11)
- Sheet-like geometry (Figure 11)

In submarine environments, slides tend to occur on continental margins commonly near the shelf-slope breaks, in submarine canyons, and in fjords. However, long-runout slides may occur in basinal settings as well. Slides are commonly associated with triggering events such as earthquakes, meteorite impacts, volcanic activities, glacial loading, sediment loading, cyclones, and tsunamis.

### 4.3 Slumps

A slump is a coherent mass of sediment that moves on a concave-up glide plane and undergoes rotational move-
ments causing internal deformation (Figure 7A). Slumps
represent rotational shear-surface movements. Slumps are
able of transporting gravel and coarse-grained sand be-
cause of their inherent strength. General characteristics of
slumps are:
- Basal zone of shearing (core and outcrop)
- Slump folds (Helwig, 1970) interbedded with unde-
formed layers (core and outcrop) (Figure 12)
- Irregular upper contact (core and outcrop)
- Chaotic bedding in heterolithic facies (core and out-
crop)
- Rotated elongate grains (Maltman, 1987) (Micro-
scopic)
- Steeply dipping and truncated layers (core and out-
crop) (Figure 12)
- Associated slides (core and outcrop) (Figure 11)
- Chaotic facies in high-resolution seismic profiles.
In submarine environments, slumps tend to occur com-
monly on slope settings.

4.4 Debrites
A debris flow is a sediment flow with plastic rheology
and laminar state from which deposition occurs through
freezing en masse. The terms debris flow and mass flow
are used interchangeably because each exhibits plastic
flow behavior with shear stress distributed throughout the
mass (Nardin et al., 1979). In debris flows, inter-granular
movements predominate over shear-surface movements.
Although most debris flows move as incoherent mass, some plastic flows may be transitional in behavior between coherent mass movements and incoherent sediment flows (Marr et al., 2001). Debris flows may be mud-rich (i.e., muddy debris flows), sand-rich (i.e., sandy debris flows), or mixed types.

For the first time, to understand mechanics of sandy debris flows (SDF) and their deposits and to distinguish them from turbidites, a Mobil-funded experimental flume study was carried out at St. Anthony Falls Laboratory (SAFL), University of Minnesota (1996–1998). Experiments clearly showed that SDF transport coarse sediment as plastic laminar flow (basal layer), emplacing massive sands (Shanmugam, 2000; Marr et al., 2001). Debris flows are capable of transporting gravel and coarse-grained sand because of their inherent strength. In contrast, turbidity currents cannot transport coarse sand and gravel in turbulent suspension (Shanmugam, 2012a). These experimental studies yielded diagnostic depositional features that are the key to recognizing deep-water massive sands as sandy debrites (Shanmugam, 2000).

General characteristics of muddy and sandy debrites are:
- Floating or rafted mudstone clasts near the tops of sandy beds (core and outcrop) (Figure 13); clasts can also be dispersed throughout the sediment interval
- Floating armored mudstone balls in sandy matrix (core and outcrop)
- Planar clast fabric (core and outcrop) (Figure 13). Planar clast fabric can be used to infer laminar flow conditions (Fisher, 1971; Enos, 1977; Shanmugam and Benedict, 1978), a flow state common to debris flow.
- Projected clasts (core and outcrop) (Shanmugam and Benedict, 1978)
- Imbricate clasts in outcrop (van Loon, 1972; Shanmugam and Benedict, 1978; Brown and Bell, 2007) and in experiment (Major, 1998)
- Brecciated mudstone clasts in sandy matrix (core and
5 Triggering mechanisms

A critical analysis of types of triggering mechanisms is important in understanding the timing of sediment failures that control emplacement of deep-water reservoirs. In the petroleum industry, most deep-water sands are believed to be deposited during periods of sea-level lowstands (Figure 19A) (Vail et al., 1991). However, such conceptual models are not supported by empirical data (Shanmugam, 2008b, 2012a). Because deep-water SMTD constitute important petroleum reservoirs worldwide (Table 3), this topic is pertinent in this review.

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. Wieczorek and Snyder (2009, p. 245), for example, state that “The term landslide trigger refers specifically to an external stimulus, such as intense rainfall, rapid snowmelt, earthquake, volcanic eruption, or stream or coastal erosion. These stimuli initiate an immediate or near-immediate landslide movement by rapidly increasing shear stresses or porewater pressures, by ground acceleration due to seismic activity, by removing lateral support, by reducing the strength of slope materials, or by initiating debris-flow activity.”

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 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.”

5.1 Classification based on duration

Although more than one triggering mechanism can
cause a single process (e.g., debris flow) at a given site, there are no objective criteria yet to distinguish either the triggering mechanism or the transport process from the depositional record (Shanmugam, 2006b, 2012b; Mulder et al., 2011). This is because what is preserved in the deposit reflects the final moment of deposition, not transport (Middleton and Hampton, 1973). During the long transport history, a sediment-gravity flow can and does undergo flow transformation (Fisher, 1983; Shanmugam, 1996; Talling et al., 2007). 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 either seismic data or core data. Nevertheless, an understanding of different triggering mechanisms is necessary in evaluating sediment failures (Locat and Lee, 2005; Masson et al., 2006; Feeley, 2007; Piper et al., 2012a). There are at least 21 triggering mechanisms that can initiate sediment

**Figure 13** Core photograph of a massive fine-grained sandstone unit showing a large floating mudstone clast (above the scale). Note planar clast fabric (i.e., long axis of clast is aligned parallel to bedding surface), revealed by the inferred part of the clast, suggesting deposition from a laminar sandy debris flow. Note the occurrence of other mudstone clasts of different sizes immediately adjacent to the large clast. Also note sharp and irregular upper bedding contact (top of photo). Such features are indicative of flow strength and deposition from freezing of laminar plastic flows (Enos, 1977; Shanmugam and Benedict, 1978; Fisher, 1971). Paleocene, North Sea. Modified after Shanmugam (20012a). With permission from Elsevier.
failures in subaerial and submarine environments on Earth (Table 6). These mechanisms are grouped into three major categories based on their duration of activity (Table 6): (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.), and (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.

Brönnimann (2011) has recognized seven triggering mechanisms associated with hydrogeology: (1) suction, (2) rising pore-water pressure, (3) seepage forces, (4) inner erosion, (5) liquefaction, (6) over pressure, and (7) mechanisms related to high plasticity. Although these processes are important in affecting slope stability, they are not considered here as principal triggering mechanisms, with the exception of groundwater seepage (Table 6). The reason is that the excess pore-water pressure, for example, is a piezometric response in situ to external forces, such as rainfall, glacial loading, human activity, etc. Furthermore, the in-situ lithologic properties are closely tied to controlling pore-water pressures and related sediment failures. These complications are evident in the 1979 sediment failure that occurred at the Nice international airport in southern France. The 1979 Nice incident has been attributed to a combination of both external and internal factors (Dan et al., 2007, their Figure 20). These complications are illustrated in Figure 14.

1) Internal lithologic factor (Figure 14A): The presence of a high-permeability sand layer, which served as a freshwater conduit, was significant in increasing the sensitivity of the surrounding clay by leaching.

2) External human factor (Figure 14B): The international airport was constructed on a platform enlarged by land-filling material. The 1979 expansion of the airport apparently resulted in local loading beneath the embankment, which was responsible for softening of the mechanical properties of the sensitive clay layer and for its ‘creeping’ movement.

3) External meteorological factor (Figure 14C): Intense rainfall over the entire Var drainage basin and the Nice coast in southern France two weeks before the 1979 event was vital in pre-conditioning the site for a potential slope failure.

Table 6 Types and duration of triggering mechanisms of sediment failures. Compiled from several sources. Updated after Shanmugam (2012a, 2012b, 2013a). The change in numbering is to reflect the change in duration of triggering events.

<table>
<thead>
<tr>
<th>Types of triggering</th>
<th>Environment of sediment emplacement</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Earthquake</td>
<td>Subaerial &amp; submarine</td>
<td></td>
</tr>
<tr>
<td>(Heezen and Ewing, 1952; Henstock et al., 2006)</td>
<td></td>
<td></td>
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<tr>
<td>2. Meteorite impact</td>
<td>Subaerial &amp; submarine</td>
<td></td>
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<tr>
<td>(Claeys et al. 2002; Barton et al., 2009/2010)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Volcanic activity</td>
<td>Subaerial &amp; submarine</td>
<td></td>
</tr>
<tr>
<td>(Tilling et al., 1990)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Tsunami waves</td>
<td>Subaerial &amp; submarine</td>
<td></td>
</tr>
<tr>
<td>(Shanmugam, 2006b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Rogue waves</td>
<td>Subaerial &amp; submarine</td>
<td></td>
</tr>
<tr>
<td>(Dysthe et al., 2008)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Cyclonic waves</td>
<td>Marine</td>
<td></td>
</tr>
<tr>
<td>(Bea et al., 1983; Prior et al., 1989; Shanmugam, 2008b)</td>
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<tr>
<td>7. Internal waves and tides (Shanmugam, 2013b, 2013c, 2013d, 2014b)</td>
<td></td>
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<tr>
<td>8. Ebb tidal current</td>
<td>Subaerial</td>
<td></td>
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<tr>
<td>(Boyd et al., 2008)</td>
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<td>9. Monsoonal rainfall</td>
<td>Subaerial</td>
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<td>(Petley, 2012)</td>
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<tr>
<td>10. Groundwater seepage</td>
<td>Subaerial &amp; submarine</td>
<td></td>
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<td>(Brönnimann, 2011)</td>
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<td>11. Wildfire</td>
<td>Subaerial</td>
<td></td>
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<tr>
<td>(Cannon et al., 2001)</td>
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<tr>
<td>12. *Human activity (Dan et al., 2007)</td>
<td>Subaerial &amp; submarine</td>
<td></td>
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</table>
### Table 6, continued

<table>
<thead>
<tr>
<th>Types of triggering</th>
<th>Environment of sediment emplacement</th>
<th>Duration</th>
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</thead>
<tbody>
<tr>
<td>1. <strong>Tectonic events:</strong> (a) tectonic oversteepening (Greene et al., 2006); (b) tensional stresses on the rift zones (Urgeles et al., 1997); (c) oblique seamount subduction (Collot et al., 2001), among others</td>
<td>Subaerial &amp; submarine</td>
<td>Intermediate-term events: hundreds to thousands of years</td>
</tr>
<tr>
<td>2. Glacial maxima, loading (Elverhoi et al., 1997, 2002); glacial meltwater (Piper et al., 2012b)</td>
<td>Submarine</td>
<td>Submarine</td>
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<tr>
<td>3. Salt movement (Prior and Hooper, 1999)</td>
<td>Submarine</td>
<td>Submarine</td>
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<tr>
<td>4. Depositional loading (Coleman and Prior, 1982; Behrmann et al., 2006)</td>
<td>Submarine</td>
<td>Submarine</td>
</tr>
<tr>
<td>5. Hydrostatic loading (Trincardi et al., 2003)</td>
<td>Submarine</td>
<td>Submarine</td>
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<tr>
<td>6. Ocean-bottom currents (Locat and Lee, 2002)</td>
<td>Submarine</td>
<td>Submarine</td>
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<tr>
<td>7. Biological erosion in submarine canyons (Dillon and Zimmerman, 1970; Warme et al., 1978)</td>
<td>Submarine</td>
<td>Submarine</td>
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<tr>
<td>8. Gas hydrate decomposition (Popenoe et al., 1993; Sultan et al., 2004; Maslin et al., 2004)</td>
<td>Submarine</td>
<td>Submarine</td>
</tr>
</tbody>
</table>

* 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.

** Some tectonic events may extend over millions of years.


4) Internal geotechnical factor (Figure 14C): After a period of rainfall, seepage of fresh ground water through the high-permeability sand layer into the surrounding clay had caused an increase in the pore-water pressure, which led to the reduction of the effective shear strength that resulted in the Nice sediment failure on October 16, 1979. As a result, a part of the airport extension, which was built to be a harbor, collapsed into the Mediterranean Sea. Although the pore-water pressure was the last factor involved in a long-line of processes that caused the sediment failure, it was not the sole triggering mechanism.

### 5.2 Sea-level lowstand model

In the petroleum industry, the sea-level lowstand model is the perceived norm for explaining the timing of deep-water sands. Saller et al. (2006), for example, attributed the timing of reservoir sands in the Kutei Basin in the Makassar Strait, Indonesian Seas (Figure 1, black triangle) to a lowstand of sea-level. Nevertheless, the location of the Kutei Basin (Figure 1, black triangle) is frequently affected by earthquakes, volcanoes, tsunamis, tropical cyclones, monsoon floods, the Indonesian throughflow, and M2 baroclinic tides (M2 represents the main lunar semidiurnal tidal constituent with a period of 12.42 h) (see Shanmugam, 2008a, 2012a, 2014a). These daily activities of the solar system (e.g., earthquakes, meteorite impacts, tsunamis, cyclonic waves, etc.) do not come to a halt during sea-level lowstands. In tectonically and oceanographically tumultuous locations, such as the Indonesian Seas, the short-term events are the primary triggering mechanisms of deepwater sediment failures and they occur in a matter of hours or days during long periods of both highstands and lowstands (Shanmugam, 2008b).

Deep-water petroleum-bearing Paleocene sand (100 m thick) of the Lower Tertiary Wilcox trend, which occurs above the K–T boundary in the BAH #2 wildcat test well, has been interpreted as “lowstand” turbidite fan in the northern Gulf of Mexico (Meyer et al., 2007, their Figure 3). However, because of the opportune location of the Lower Tertiary Wilcox trend and the stratigraphic position and age, the drilled Paleocene sand could alternatively be attributed to the Chicxulub impact and related seismic shocks and tsunamis (Figure 15). Tsunami-related deposition on continental margins has been discussed by Shanmugam (2006b). Contrary to the conventional wisdom on the timing of deposition of deep-water sands during periods of sea-level standst, earthquakes, meteorite impacts (Barton et al., 2009/2010), tsunamis (Figure 16), tropical cyclones (Figure 17), initiate SMTD suddenly in a matter of hours or days during the present sea-level highstand.
However, there are no established criteria to distinguish SMTD associated with tsunamis (Figure 18) from those associated with tropical cyclones (Shanmugam, 2012b). This is an important area of future research.

The Hurricane Hugo (Hubbard, 1992), which passed over St. Croix in the U.S. Virgin Islands on 17 September 1989, had generated winds in excess of 110 knots (204 km h\(^{-1}\), Category 3 in the Saffir-Simpson Scale) and waves 6–7 m in height. In the Salt River submarine canyon (>100 m deep), offshore St. Croix, a current meter measured net down-canyon currents reaching velocities of 2 m s\(^{-1}\) and oscillatory flows up to 4 m s\(^{-1}\). Hurricane Hugo had caused erosion of 2 m of sand in the Salt River Canyon at a depth of about 30 m. A minimum of 2 million kg of sediment were flushed down the Salt River Canyon into deep water (Hubbard, 1992). The transport rate associated with Hurricane Hugo was 11 orders of magnitude greater than that measured during fair-weather period. In the Salt River Canyon, much of the soft reef cover (e.g., sponges) had been eroded away by the power of the hurricane. Debris composed of palm fronds, trash, and pieces of boats found in the canyon were the evidence for storm-generated debris flows. Storm-induced sediment flows during the present highstand have also been reported in a submarine canyon off Bangladesh (Kudrass et al., 1998), in the Capbreton Canyon, Bay of Biscay in SW France (Mulder et al., 2001), in the Cap de Creus Canyon in the Gulf of Lions (Palanques et al., 2006), and in the Eel Canyon, California (Puig et al., 2003), among others. These alternative real-world highstand possibilities are often overlooked because of the prevailing mindset of the sea-level lowstand model.

**Figure 14** Illustration of the 1979 sediment failure that occurred at the Nice international airport in southern France. The Nice sediment failure has been attributed to a combination of both external and internal factors (Dan et al., 2007). A—Internal (in situ) lithologic factor composed of clay and sand layers; B—Human factor involving the building of airport embankment; C—External meteorological and internal geotechnical factors. See text for details. Diagram is based on the concept of Dan et al., (2007, their Figure 20). With permission from Elsevier Copyright Clearance Center’s RightsLink: Licensee: G. Shanmugam. License Number: 3571710918661. License Date: February 18, 2015.
The reasons for sand deposition in the deep sea during highstands are: (1) narrow shelf width and headward erosion of submarine canyons (Schwalbach et al., 1996); (2) increasing monsoon intensity (Goodbred, 2003) and related deep-water sedimentation (Weber et al., 1997); (3) sediment bypassing of the shelf (Kuehl et al., 1989); (4) rates of delta progradation and formation of highstand shelfedge deltas (Burgess and Hovius, 1998); (5) high sediment supply (Carvajal and Steel, 2006); (6) cyclones (Kudrass et al., 1998; Shanmugam, 2008b); and (7) tsunamis (Shanmugam, 2006a, 2006b). In discussing the La Jolla highstand fan in the California borderland, Covault et al. (2007, p. 786) state, “Contrary to widely used sequence stratigraphic models, lowstand fans are only part of the turbidite depositional record, and this analysis reveals that a comparable volume of coarse clastic sediment has been deposited in California borderland deep-water basins regardless of sea level.”

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 (Figure 19). Empirical data also show that 140,000 tsunamis would have occurred during the present highstand interval in the Pacific Ocean alone (Figure 19). In other words, sand deposition can and does occur during periods of sea-level highstands (Figure 19). For these reasons, the lowstand model is obsolete for explaining the triggering of deep-water SMTD worldwide (Shanmugam, 2007, 2008b).

In light of the existing wealth of empirical data associ-
ated with tsunamis, tropical cyclones, meteorite impacts, earthquakes, etc., future petroleum exploration cannot afford to continue the application of obsolete sea-level models in understanding the timing and emplacements of deep-water sands (Shanmugam, 2007).

6 Long-runout mechanisms

An understanding of long-runout mechanisms is important not only for academic reasons, but also for economic reasons. For example, long-runout MTD (Table 5) provide empirical data for developing predictive depositional models for deep-water sandstone petroleum reservoirs in the subsurface.

6.1 Basic concept

The basic premise of long-runout MTD is that they travel further than the distance predicted by simple frictional models. Heim’s (1932) study of the subaerial ‘Elm Slide’ in the Swiss Alps has been the source of the following basic equations for understanding the mobility of MTD:

1) \( H/L = \tan \varphi \), where \( H \) represents the vertical fall height, \( L \) represents the runout distance, and \( \varphi \) is the Coulomb angle of sliding friction (e.g., Griswold and Iverson, 2008).

2) \( H/L \alpha V^{1/2} \), where \( V \) is the initial volume of the moving mass (e.g., McEwen, 1989).

3) \( H/L = 1 \), where \( L \) is the normal-runout distance (Figure 20A) (e.g., Collins and Melosh, 2003).

4) \( H/L \leq 1 \), where \( L \) is the long-runout distance (Figure 20B) (e.g., Hampton et al., 1996).

Although there are many documented cases of long-runout MTD in both subaerial (Table 5) and submarine (e.g., submarine slides in Hawaii with more than 200 km of runout distances, Moore et al., 1989) environments with

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**Figure 16** Depositional model showing the link between tsunamis and deep-water deposition. A—1—Triggering stage in which earthquakes trigger tsunami waves. 2—Tsunami stage in which an incoming (up-run) tsunami wave increases in wave height as it approaches the coast. 3—Transformation stage in which an incoming tsunami wave erodes and incorporates sediment, and transforms into sediment flows; B—4—Deposition stage in which outgoing (backwash) sediment flows (i.e., debris flows and turbidity currents) deposit sediment in deep-water environments. Suspended mud created by tsunami-related events would be deposited via hemipelagic setting. After Shanmugam (2006b). With permission from SEPM.
runout distances measuring up to 100 times their vertical fall height and high speeds of up to 500 km·h⁻¹ (Martinsen, 1994), the geologic community was reluctant to accept mechanisms that attempted to explain MTD that travel farther and faster than expected. A major turning point on the skepticism over long-runout MTD occurred on May 18, 1980 when the Eruption of Mount St. Helens in the U.S. generated impressive long runout subaerial MTD that were captured on videotapes (see The Learning Channel, 1997).

### 6.2 Subaerial environments

There are at least 20 potential mechanisms that could explain the mechanical paradox of long-runout MTD (Terzaghi, 1950; Brunsden, 1979; Schaller, 1991, among others). Selected examples of subaerial mechanisms are:

1. Lubrication by liquefied saturated soil entrained during transport (Heim, 1882; Hungr and Evans, 2004)
2. Dispersive pressure in grain flows (Bagnold, 1954)
3. Fluidization by entrapped air (Kent, 1966)
4. Cushion of compressed air beneath the slide (Shreve, 1968)
5. Fluidization by dust dispersions (Hsü, 1975), akin to grain flows (Bagnold, 1954)
6. Spontaneous reduction of friction angle at high rates of shearing (Scheidegger, 1975; Campbell, 1989)
7. Vaporization of water at the base and related excess pore-water pressure (Goguel, 1978)
8. Frictional heating along a basal fluid-saturated shear zone and related rise in pore-water pressure (Voight and

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**Figure 17** A—Highstand sedimentological model showing calm shelf waters and limited extent of sediment transport in the shoreface zone (short green arrow) during fair-weather periods. Shoreface bottom-current velocities during fair weather are in the range of 10–20 cm s⁻¹ (Snedden et al., 1988). The shelf edge at 200 m water depth separates shallow-water (shelf) from deep-water (slope) environments; B—Highstand sedimentological model showing sediment transport on the open shelf, over the shelf edge, and in submarine canyons during periods of tropical cyclones (storm weather) into deep water (long red arrow). Mass-transport processes are commonly induced by intense hurricanes (e.g., 2005 Hurricane Katrina in the U.S. Gulf Coast). Modified after Shanmugam (2008b). With permission from AAPG.
9) Self-lubrication by frictionally generated basal melt layers (Erismann, 1979; De Blasio and Elverhøi, 2008; Weidinger and Korup, 2009)
10) Acoustic fluidization (Melosh, 1979)
11) Mechanical fluidization or inertial grain flow (Davies, 1982)
12) Fluidization by volcanic gases (Voight et al., 1983).
13) Excess pore-water pressure (Cruden and Hungr, 1986; Iverson, 1997)
14) Self-lubrication by granular flows acting as basal shear zone (Cleary and Campbell, 1993)
15) Seismic energy released during meteorite impacts, proposed for Mars (Akers et al., 2012), is also applicable to Earth.

6.3 Submarine environments

Submarine environments with long-runout MTD have been broadly grouped into five types: (1) fjords, (2) active river deltas on the continental margin, (3) submarine canyon-fan systems, (4) open continental slopes, and (5) oceanic volcanic islands and ridges by Hampton et al. (1996). To this list, a sixth type ‘glacially-influenced continental margins’ (Elverhøi et al., 1997) needs to be added. Submarine MTD with long-runout distances of over 100 km commonly occur on slopes of less than 2° on the U.S. Atlantic Continental Slope (Figure 5). Several potential mechanisms are available for explaining long-runout submarine MTD over low-angle slopes:

1) Hydroplaning (Mohrig et al., 1998)
2) Excess pore-water pressure (Pierson, 1981; Gee et al., 1999)
3) Elevated gas pressure (Coleman and Prior, 1988)
4) Dispersive pressure in grain flows (Bagnold, 1954; Norem et al., 1990)
5) Self-lubrication by granular flows acting as basal shear zone (Cleary and Campbell, 1993)
6) Self-lubrication at the base of gas-hydrate stability window that coincides with the base of MTD (Bugge et al., 1987; Cochonat et al., 2002).

Figure 18 Published sedimentological features claimed to be associated with tsunami-related deposits by other authors. These features are also claimed to be associated with cyclone-related deposits by different authors. See review by Shanmugam (2012b). With permission from Springer Copyright Clearance Center’s RightsLink: Licensee: G. Shanmugam. License Number: 3570270421988. License Date: February 15, 2015.
7) Flow transformation (Talling et al., 2007)
8) Seismic energy released during meteorite impacts, proposed for Mars (Akers et al., 2012), is also applicable to Earth.

Of various mechanisms listed above, the hydroplaning concept (Mohrig et al., 1998) has gained acceptance (McAdoo et al., 2000; Shanmugam, 2000; Marr et al., 2001; Elverhøi et al., 2002; Ilstad et al., 2004; De Blasio et al., 2006). Nevertheless, the hydroplaning mechanism is inapplicable to explaining long-runout debris flows in subaerial and extraterrestrial environments.

### 6.4 Extraterrestrial environments

Analogous to subaerial and submarine environments on Earth, there are numerous published examples of long-runout MTD on other planets of the Solar System (Table 5). Although submarine MTD show much longer runout distances than those of subaerial MTD on Earth, the longest runout distance of 2500 km has been documented for an extraterrestrial MTD on Mars (Montgomery et al., 2009, their Figure 9). The following mechanisms have been offered for explaining long-runout MTD on extraterrestrial environments:

1) Self-lubrication by released groundwater, wet debris, or mud (Lucchitta, 1979, 1987)
2) Aqueous pore-pressure support (Harrison and Grimm, 2003)
3) Continental-scale salt tectonics coupled with overpressured fluids (Montgomery et al., 2009)
4) Movement on ice (De Blasio, 2011)
5) Movement on evaporitic salt (De Blasio, 2011)
6) Friction reduction during flash heating (Singer et al., 2012)
7) Seismic energy released during meteorite impacts (Akers et al., 2012). Similar explanations were offered previously for landslides on the Moon (Guest, 1971; Howard, 1973).

### 6.5 H/L ratio problems

Although the H/L model has been influential for nearly a century, many problems still remain.

1) Because the original work by Heim (1932) was...
written in German, there have been differences of opinion among later workers as to the meaning of the German nomenclature used by Heim to describe the type of motion, ranging from sliding (Shreve, 1968) to flowing (Hsü, 1975).

2) The $H/L$ ratios for submarine MTD are lower ($0.001 - 0.3$, Hampton et al., 1996, their Table 5) than those for subaerial counterparts ($1.6 - 21$, Ritter et al., 1995). The model underestimates the extent of runout distance ($L$) for water-saturated debris flows (Iverson, 1997; Griswold and Iverson, 2008) and if the volumes of moving mass exceed about $106 \text{ m}^3$ (Heim, 1932; Hsü, 1975; Scheidegger, 1973). Also, the model does not take into account the effect of runout-path topography on the distal or lateral limits of inundation (Griswold and Iverson, 2008).

3) At a given value of $H/L$, the Martian MTD are typically about 50 to 100 times more voluminous than the terrestrial counterparts (McEwen, 1989). However, there is no universally accepted physical basis for explaining the equation $H/L \alpha V^{-1}$ (Dade and Huppert, 1998).

4) Dade and Huppert (1998) have used $L/H$ as a measure of the efficiency of MTD movement, which is the inverse of the friction coefficient ($H/L$).

5) On Earth, submarine MTD are much larger in size than subaerial MTD (Hampton et al., 1996), and submarine MTD travel longer distances than subaerial MTD (Figure 21) (Hampton et al., 1996, their Table 1; and Elverhøi et al., 2002, their Table 1).

6) Venusian MTD (Malin, 1992, his Figure 11) and Martian MTD (Collins and Melosh, 2003, their Figure 1) travel longer distances than those on Earth’s subaerial environments (Figure 22).

7) The $H/L$ model has been applied to both ‘landslides’ and ‘debris flows’ without acknowledging the basic differences in sediment movement between the two processes (McEwen, 1989; Malin, 1992; Hampton et al., 1996; Ab-

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**Figure 20** Conceptual models showing sliding movement of a rigid body in subaerial environments. A—An ideal model in which the predicted runout length ($L$) is equal to vertical fall height ($H$) (e.g., Collins and Melosh, 2003); B—Long-runout model in which the runout length ($L$) exceeds the vertical fall height (e.g., Hampton et al., 1996); C—Basic equations derived from the work of Heim (1932) on the ‘Elm Slide’ in the Swiss Alps.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
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</thead>
<tbody>
<tr>
<td>Ideal model $H/L = 1$</td>
<td>Long-runout model $H/L &lt; 1$</td>
<td>Equations derived from the study of ‘Elm Slide’ (Heim, 1932)</td>
</tr>
<tr>
<td>(1) $H/L = \tan \phi$ (Griswold and Iverson, 2008)</td>
<td>(2) $H/L \alpha V$ (McEwen, 1989)</td>
<td></td>
</tr>
<tr>
<td>$H =$ Vertical fall height</td>
<td>$L =$ Runout distance</td>
<td></td>
</tr>
<tr>
<td>$\phi =$ Coulomb angle of friction</td>
<td>$V =$ Initial volume</td>
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$H$, $L$, $\phi$, $V$
Figure 21  Plot of \( H/L \) (vertical fall height/length of runout) ratio versus volume of submarine MTD by Hampton et al. (1996). For comparison, the average value for subaerial MTD (upper curve) proposed by Scheidegger (1973) is shown. Note the upper-bound values from Edgers and Karlsrud (1982) for submarine (upper curve) and subaerial (lower curve) MTD. Redrawn from Hampton et al. (1996). With permission from American Geophysical Union.

Figure 22  Plot of \( H/L \) (vertical fall height/length of runout) ratio vs. volume of MTD on Mars and Earth. Filled circles = Data points from Valles Marineris on Mars (McEwen, 1989, his Table 1). Filled squares = Data points for dry-rock avalanches of nonvolcanic origin on Earth (Scheidegger, 1973; Hsü, 1975). Lines are linear least-squares fits. Redrawn from McEwen (1989). With permission from Geological Society of America.
lay and Hürlimann, 2000; McAdoo et al., 2000; Elverhøi et al., 2002; Legros, 2002; Collins and Melosh, 2003; Geertsema et al., 2009; Singer et al., 2012). The problem is that slides represent a rigid-body sliding motion over a shear surface (Varnes, 1978; Dott, 1963), whereas debris flows represent an intergranular flowing motion (Shanmugam et al., 1994; Iverson et al., 1997).

8) In subaerial environments on Earth, H/L ratios were measured from outcrops (Heim, 1932), but in submarine environments H/L ratios were measured using bathymetric and/or side-scan sonar images (McAdoo et al., 2000). On Mars, H/L ratios were measured from the Viking Orbiter images (McEwen, 1989). Clearly, there is no consistency among these methodologies.

9) Unlike on Earth, field measurements of motion type and direct examination of the rock in situ are impractical in distinguishing slides from debris flows on other planets. Nevertheless, Malin (1992) interpreted slides and debris flows on Venus based on types of landforms seen on radar images acquired from the Magellan spacecraft. Costard et al. (2002) interpreted debris flows based on the observation of small gullies on Mars, seen on images obtained from the Mars Observer Camera (MOC) aboard the Mars Global Surveyor spacecraft, and using the similarities of Martian gullies with gullies in East Greenland. Miyamoto et al. (2004) interpreted debris flows on Mars using MOC images and numerical simulation. The problem is that debris depositional facies should be interpreted using cm-scale primary sedimentary features in core or outcrop for establishing plastic rheology and laminar state of the debris flow (see ‘Recognition of Depositional Facies’ section above). Such detailed observations cannot be made using seismic data and radar images.

After over 130 years of research, since the work of Heim (1882), there is still no agreement on a unified scientific theory on long-runout MTD. The reason is that each case is unique. More importantly, there are no consistencies in concepts, nomenclatures, data sources, and methodologies when investigating MTD on different planets.

7 Reservoir characterization

An accurate depiction of depositional facies is crucial in reservoir characterization of deep-water MTD. However, there are cases in which the use of the term landslide has created unnecessary confusion. For example, Welbon et al. (2007, p. 49) state, “Landslides can consist of rotational slips, translational slide blocks, topples, talus slopes, debris flows, mudslides and compressional toes which combine in different proportions to form complex landslides…” Processes of landslide deformation include slip on discrete surfaces, distribution of shear within the landslide, vertical thinning and lateral spreading through shear, fluidization, porosity collapse and loss of material from the top or toe of the complex. These processes control the quality of the resultant reservoirs.” This reservoir characterization raises the following fundamental questions:

- What are the criteria for distinguishing deposits of topples with no sliding motion from those of debris flows with flowing motion in core or on seismic profiles?
- Does the porosity collapse occurs in deposits of topples?
- If so, what are the criteria to recognize porosity collapse in deposits of topples in the subsurface?
- What is the point in including a landform (talus slope) along with a process (debris flow) under the term landslide? For clarity, reservoir characterization of deep-water sands must identify the process-specific depositional facies, such as slides, slumps, debrites, etc.

In reservoir characterization, wireline (e.g., gamma-ray) log motifs are the basic subsurface data that are routinely used by the petroleum industry. Interpreting a process-specific depositional facies (e.g., slide vs. debrite) from a log motif, without corresponding sediment core, is impossible. For example, analogous to sandy slide blocks that are sandwiched between deep-water mudstones in outcrops (Figure 11), long runout sandy debrite bodies (Figure 23) are likely to generate blocky motifs on wireline logs in the subsurface (Figure 24A). In distinguishing sandy slides (Figure 24B) from sandy debrites (Figure 24C) in the ancient stratigraphic record, direct examination of the rocks is crucial.

The other issue is the differences in reservoir quality between slides and debrites. Large sandy slides commonly contain multiple original strata (Figure 11). In cases where lithified strata are transported as sandy slides almost intact, the slipped bodies are likely to represent original porosity and permeability (i.e., pre-transport reservoir quality) from the provenance (Figure 24B). On the other hand, debrites are likely to represent post-transport depositional texture and reservoir quality (Figure 24C). Furthermore, if a sandy slide unit contains two sandstone reservoirs with an intervening shale layer, the shale layer could act as a permeability barrier (Figure 24B). In such cases, a single slide unit would have to be characterized as two separate petrophysical flow units. By contrast, a single debrite unit, without a permeability layer, would be characterized as a single petrophysical flow unit (Figure 24C).
Figure 23  Conceptual model showing long-runout sandy debrite blocks away from the shelf edge. Based on studies of sandy debris flows and their deposits in flume experiments (Shanmugam, 2000; Marr et al., 2001), documentation of long-runout sandy debris flows in modern oceans (Gee et al., 1999) and interpretation of long-runout ancient “olistolith” (Teale and Young, 1987). This model is useful in developing deep-water depositional models for sandstone reservoirs of debrite origin. After Shanmugam (2012a). With permission from Elsevier Copyright Clearance Center’s RightsLink: Licensee: G. Shanmugam. License Number: 3577110946798. License Date: February 27, 2015.

Figure 24  A—Hypothetical wireline log showing blocky motif for both sandy slide and sandy debrite units (compare with Figures 10A and 11). Blocky gamma ray (wireline) log motifs, among other motifs, are basic subsurface data that are routinely used by the petroleum industry (e.g. Shanmugam et al., 1995). The primary control of log motif is sediment texture (i.e., sand vs. mud), not individual primary sedimentary structures. Without direct examination of the rocks for sedimentary structures, distinguishing between a slide and a debrite facies is impossible from wireline log motifs alone; B—Hypothetical sedimentological log of a sandy slide unit, composed of three original layers representing pre-transport strata and texture from the provenance region, with basal shear surface and sand injection. 1. Sandstone. 2. Shale. 3. Sandstone. Note that layer 2 (shale) may act as a permeability barrier and that layer 3 (upper sandstone) and layer 1 (lower sandstone) may behave as two separate flow units during production; C—Hypothetical sedimentological log of a sandy debrite unit with floating mudstone clasts and quartz granules (red circles). This debrite sandstone without permeability barrier would behave as a single flow unit. VF = Very fine sand; F = Fine sand; M = Medium sand.
8 Ending the problem

The term “landslide” has been in use in a variety of scientific domains since 1838 without conceptual clarity. During the past 175 years, our failure to adopt a sound process-specific terminology has resulted in 79 superfluous MTD types in the geologic and engineering literature. This profligate period of “kicking the can down the road” must end now. Only slides, slumps, and debrites can be meaningfully interpreted in the sedimentary record. Therefore, the term “landslide” should be restricted solely to MTD in which a sliding motion can be empirically determined. A precise interpretation of a depositional facies (e.g., sandy slide vs. sandy debrite) is vital not only for maintaining conceptual clarity but also for characterizing petroleum reservoirs. Clarity matters in science.

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