Journal of Palaeogeography
2015, 4(2): 109−166
DOI: 10.3724/SP.J.1261.2015.00071

Review

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

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Received: 2014−10−24 Accepted: 2014−12−29

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 (Urgeles *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