Journal of Palaeogeography, 2017, ■(■): 1—70

Available online at www.sciencedirect.com

ScienceDirect

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

Multi-origin of soft-sediment deformation structures and seismites

Global case studies of soft-sediment deformation structures (SSDS): Definitions, classifications, advances, origins, and problems

G. Shanmugam

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

Abstract Soft-sediment deformation structures (SSDS) have been the focus of attention for over 150 years. Existing unconstrained definitions allow one to classify a wide range of features under the umbrella phrase "SSDS". As a consequence, a plethora of at least 120 different types of SSDS (*e.g.*, convolute bedding, slump folds, load casts, dish-and-pillar structures, pockmarks, raindrop imprints, explosive sand—gravel craters, clastic injections, crushed and deformed stromatolites, *etc.*) have been recognized in strata ranging in age from Paleoproterozoic to the present time. The two factors that control the origin of SSDS are prelithification deformation and liquidization. A sedimentological compendium of 140 case studies of SSDS worldwide, which include 30 case studies of scientific drilling at sea (DSDP/ODP/IODP), published during a period between 1863 and 2017, has yielded at least 31 different origins. Earthquakes have remained the single most dominant cause of SSDS because of the prevailing "seismite" mindset. Selected advances on SSDS research are: (1) an experimental study that revealed a quantitative similarity between raindrop-impact cratering and asteroid-impact cratering; (2) IODP Expedition 308 in the Gulf of Mexico that documented extensive lateral extent (>12 km) of mass-transport deposits (MTD) with SSDS that are unrelated to earthquakes; (3) contributions on documentation of pockmarks, on recognition of new structures, and on large-scale sediment deformation on Mars.

Problems that hinder our understanding of SSDS still remain. They are: (1) vague definitions of the phrase "soft-sediment deformation"; (2) complex factors that govern the origin of SSDS; (3) omission of vital empirical data in documenting vertical changes in facies using measured sedimentological logs; (4) difficulties in distinguishing depositional processes from tectonic events; (5) a model-driven interpretation of SSDS (*i.e.*, earthquake being the singular cause); (6) routine application of the genetic term "seismites" to the "SSDS", thus undermining the basic tenet of process sedimentology (*i.e.*, separation of interpretation from observation); (7) the absence of objective criteria to differentiate 21 triggering mechanisms of liquefaction and related SSDS; (8) application of the process concept "high-density turbidity currents", a process that has never been documented in modern oceans; (9) application of the process concept "sediment creep" with a velocity connotation that cannot be inferred from the ancient record; (10) classification of pockmarks, which are hollow spaces (*i.e.*, without sediments) as SSDS, with their problematic origins by fluid expulsion, sediment degassing, fish activity, *etc.*; (11) application of the Earth's climate-change model; and most importantly, (12) an arbitrary

E-mail address: shanshanmugam@aol.com.

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

http://dx.doi.org/10.1016/j.jop.2017.06.004

distinction between depositional process and sediment deformation. Despite a profusion of literature on SSDS, our understanding of their origin remains muddled. A solution to the chronic SSDS problem is to utilize the robust core dataset from scientific drilling at sea (DSDP/ODP/IODP) with a constrained definition of SSDS.

Keywords Soft-sediment deformation structures (SSDS), Prelithification deformation, Liquidization, Pockmarks, Impact cratering, Scientific drilling

Received 17 February 2017; accepted 14 June 2017; available online xxx

1. Introduction

Since the early documentation of soft-sediment deformation structures (SSDS) in the 19th century by Logan (1863) and by other pioneers of that period (Buckland, 1842; Cunningham, 1839; Dana, 1849; Darwin, 1851; Lyell, 1851; Redfield, 1843; Sorby, 1859), a multiplicity of SSDS had been studied in various domains. Examples are:

1) Documentation of SSDS in a wide range of continental, coastal, and marine sedimentary environments worldwide (Fig. 1) by various authors (Alfaro *et al.*, 2016; Allen, 1984; Brandes and Winsemann, 2013; Brodzikowski and Van Loon, 1980; Cloud, 1960; Coleman, 1976; Ettensohn *et al.*, 2002; Eyles and Clark, 1985; Festa *et al.*, 2014; Glennie and Evamy, 1968; Gregory, 1969; Helwig, 1970; Hempton and Dewey, 1983; Hibsch *et al.*, 1997; Hubert-Ferrari *et al.*, 2017; Huuse *et al.*, 2010; Jones and Preston,

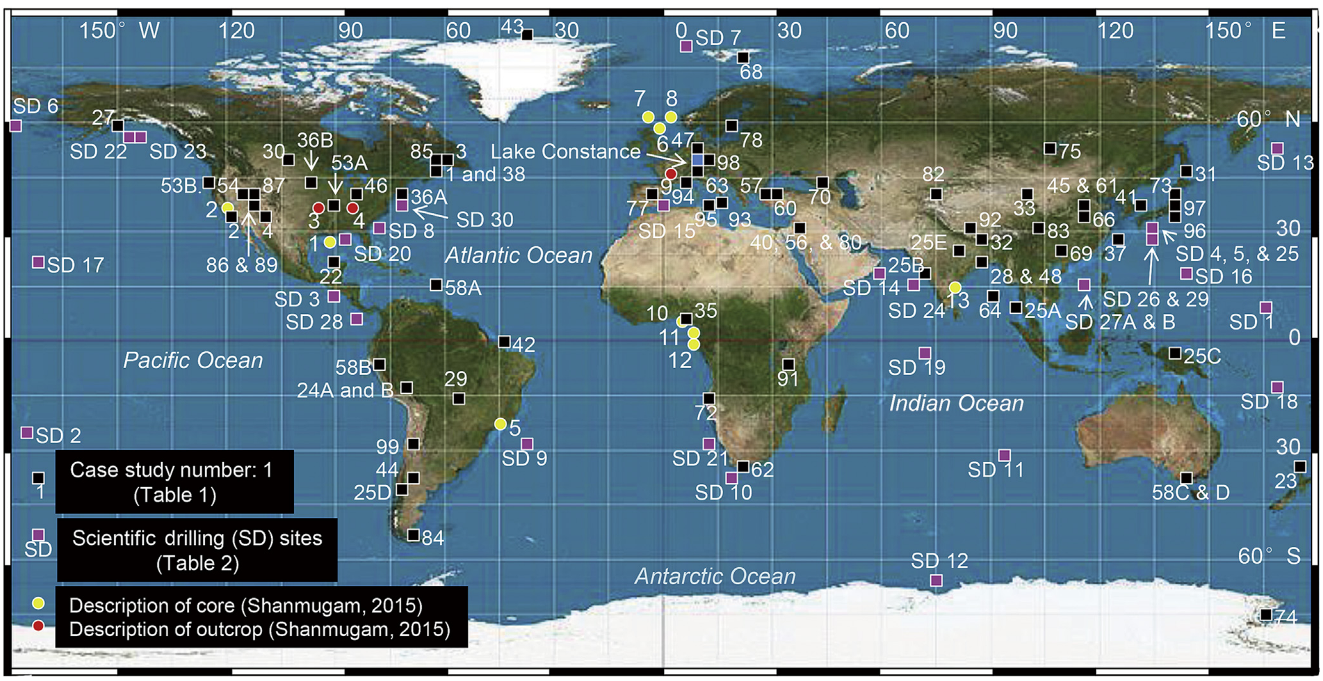

Fig. 1 Map showing locations of case studies of soft-sediment deformation structures (SSDS) (filled black squares) listed in Table 1. Scientific drilling sites (see Table 2) are shown by filled purple squares. Countries like Spain and Italy have a high number of published case studies (see Table 1), but not all of them are shown here due to limited space on the map. Note that this review also includes all my previous studies of deep-water systems (filled yellow and red circles) that contain a variety of SSDS (see Table 3 in Shanmugam, 2016a). My study localities are: (1) Gulf of Mexico, (2) California, (3) Ouachita Mountains, (4) Southern Appalachians, (5) Brazil, (6) U.K. North Sea, (7) U.K. Atlantic Margin, (8) Norwegian Sea and vicinity, (9) French Maritime Alps, (10) Nigeria, (11) Equatorial Guinea, (12) Gabon, and (13) Bay of Bengal. These modern and ancient deep-water systems include both marine and lacustrine settings (Shanmugam, 2012a, 2015). Distribution of modern pockmarks in Lake Constance in Germany, shown by a filled blue square, is discussed by Wessels *et al.* (2010).