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Review article

Submarine slide blocks and associated soft-sediment deformation in deep-water basins: A review

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ABSTRACT

Three-dimensional (3D) seismic and outcrop data are used to review the significance of submarine slide blocks and associated soft-sediment deformation structures in deep-water basins. Submarine slide blocks are generated during major instability events in a variety of geological settings and their size exceeds that of boulders, which are <4.1 m. Slide blocks can be ~500 m high by >4.5 km long on a number of continental margins, presenting internal folding, thrusting and rolling over basal breccia-conglomerate carpets. In addition, soft-sediment deformation structures such as foliated strata, intrafolial folds, tiling, bookshelf sliding and dilational jogs reflect important shearing within blocks and their basal glide planes. This work proposes that buried blocks and associated coarse-grained debrites are capable of forming prolific reservoir intervals for hydrocarbons and mineralization. Three-dimensional leakage factor models show the bulk of fluid flow to be focused in vertical and horizontal surfaces within, and immediately below displaced blocks. The generation of large slide blocks can also mark the sudden release of overburden pressure, and result in the loss of seal competence above existing hydrocarbon fields. Ultimately, this review clarifies the present-day understanding on the modes of formation of submarine slide blocks, confirming their economic importance in deep-water basins throughout the world.

1. Introduction

Stratigraphic intervals containing large slide blocks are common in deep-water basins, being a consequence of major slope instability events (Kvalstad et al., 2005; Jenner et al., 2007; Deptuck et al., 2007). Slide blocks comprise relatively undeformed strata of metre to kilometre scales preserved within a fine-grained matrix with diverse lithologies, including coarse-grained sands, conglomerates and breccias (e.g. Duffield et al., 1982; Moore et al., 1995; Talling et al., 2007). As a result, stratigraphic units containing slide blocks can form prolific hydrocarbon reservoirs such as those in the Eocene of South Texas, USA (Ogiesoba and Hammes, 2012), in the Gulf of Mexico (Edwards, 2000) or offshore Nigeria (Clayton et al., 1998; Apotria et al., 2004; Bruso et al., 2004). When buried at lower-crust depths, slide blocks can also contain important mineralization, particularly when forming different strata from the matrix rock in which they are included (Wendorff, 2000, 2005a, 2005b, 2011).

In this work, the terms 'submarine slide block', or 'block' as used herein, refer to large volumes of undeformed to moderately deformed strata generated in submarine environments and transported by mass-wasting processes (Borgomano, 2000; Emmerich et al., 2005; Graziano, 2001; Kvalstad et al., 2005; Spence and Tucker, 1997). Most blocks slide over a well defined shear plane that is irregular or indented (Embley, 1980; Hampton et al., 1998; Hühnerbach and Masson, 2004; Masson et al., 2006; Moscardelli et al., 2006). Over these basal shear planes, transporting distances of more than 100 km are effectively recorded by outrunner blocks, particularly on the flanks of active volcanoes (Masson, 1996; Masson et al., 2002) and tectonically active slopes (Roep and Fortuin, 1996; De Blasio et al., 2006). Blocks can have a sedimentary or a tectonic origin, and are often included in sets of strata specifically generated in submarine instability events, called Mass-Transport Deposits (MTDs) or Complexes (MTCs) on seismic data, or olistostromes at outcrop. As shown in this paper, the internal structure and size of blocks reflect distinct downslope transporting styles, which include rotational sliding, gliding, block drag, skipping, toppling, free fall, and translation over high-density flows. Important soft-sediment deformation is recorded at the base of displaced blocks.

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Individual blocks recognised on seismic, sidescan sonar or bathymetric data are usually >5–10 m long, with the largest features approaching 500 m in height by >4.5 km in length (Alves, 2010; Dunlap et al., 2010, 2013; Alfaro and Holz, 2014; Gamboa and Alves, 2015a; Principaud et al., 2015). Blocks, or *megaclasts* as defined by Blair and McPherson (1999), are by definition larger than boulders (>4.1 m) and show characteristic features in deep-marine settings around the world. These features are:

a) Blocks are commonly associated with slope instability events triggered by major tectonic phases, most of which relate to important uplift, exhumation and erosion of the upper crust (Fortuin, 1978; Roep and Fortuin, 1996; Dunlap et al., 2013).
b) Large fields of blocks accompany the transport of significant volumes of sediment into sedimentary basins (Drzewiecki and Simó, 2002; Di Francesco et al., 2010; Perotti et al., 2012).
c) Blocks comprise allochthonous strata displaced over significant distances, and can include successions uncharacteristic of the basins in which they accumulate (Bosellini et al., 1993; Odonné et al., 2011).

This paper reviews the significance of submarine slide blocks in geological and economic terms, at a time when deep-water stratigraphic successions reveal their presence throughout the world, from East Canada to the South Atlantic, Australia and Gulf of Mexico. After the methodology section, this work presents a summary of published case-studies in the geological record. Later, three-dimensional (3D) seismic data from SE Brazil and SE Japan are interpreted to describe diagnostic features of submarine slide blocks (Figs. 1 and 2). New data from two of the best exposed Miocene palaeoslopes in Europe, the Ierapetra Basin in SE Crete and the Tabernas-Sorbas Basin in SE Spain, are used to describe soft-sediment kinematic indicators at outcrop (metre) and borehole (centimetre) scales (Figs. 1 and 3). An attempt has been made in this work to clearly distinguish soft-sediment deformation structures from later tectonic structures (e.g., Postma et al., 1993). The remobilisation and deformation styles of blocks at sub-seismic scales are also described. The discussion will be centred on four key research questions:

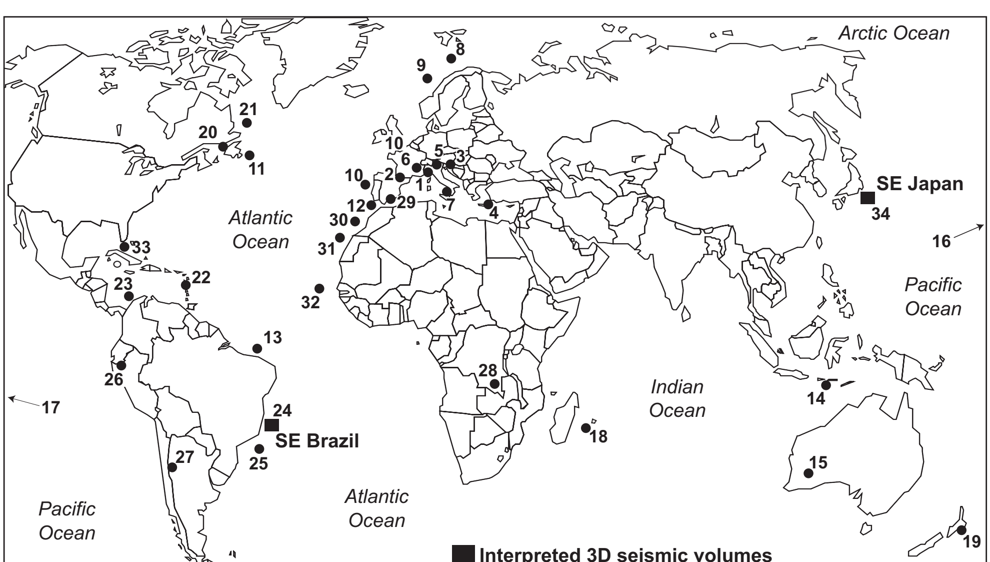
1) What pre-conditioning factors contribute to the generation of submarine slide blocks?
2) What structural and geotechnical parameters control block displacement on continental slopes?
3) What are the key structural and kinematic markers of block movement at seismic and outcrop scales?
4) What structures recognised in individual blocks control post-depositional fluid flow and seal unit competence?

2. Methodology

This work uses three-dimensional (3D) seismic data from the upper continental slope of Espírito Santo (SE Brazil) and the accretionary wedge of SE Japan (Nankai Trough), the latter of which was chosen to illustrate glide plane geometries (Figs. 1 and 2). Outcrop data from two Late Miocene palaeoslopes in SE Crete and SE Spain are used as analogues for the structures observed on seismic data (Fig. 1).

The seismic volume interpreted in SE Brazil has a bin spacing of 12.5 m, a 2 ms vertical sampling window, and was acquired with a 6×5700 m array of streamers. Data processing included resampling, spherical divergence corrections and zero-phase conversions undertaken prior to stacking, 3D pre-stack time migration using the Stolt algorithm and one-pass 3D migration. Published borehole data from Deep Sea Drilling Program (DSDP) Sites 356 (Kumar et al., 1997) and 515/516 (Barker, 1983; Barker et al., 1983; Gambôa et al., 1983), as well as the works of Bruhn and Walker (1997), Chang et al. (1992), Meisling et al. (2001), Viana et al. (2003), Fiduk et al. (2004) and França et al. (2007), were used to identify and date seismic-stratigraphic units with submarine slide blocks. Based on the dominant frequency of the interpreted seismic volume (40 Hz), vertical seismic resolution varies between 12 and 19 m in block-laden strata.

In SE Japan, a 3D volume in water depths ranging from 1750 m to 3200 m was used (Figs. 1 and 2b). The interpreted volume has an inline spacing of 12.5 m, for a crossline spacing of 18.75 m, and was acquired with a 2-source array with four receiver cables spaced 150 m apart. A 4500 m long receiver cable with 360 receiver groups



Key locations referred to in this paper
1 - West Liguria (Italy)
2 - Pyrenees
3 - Slovenia and Friuli Basin (Italy)
4 - SE Crete
5 - Italian Dolomites
6 - SE France
7 - Stromboli (Aeolian Islands)
8 - Barents Sea (Norway)
9 - Storegga Slide (Norway)
10 - West Iberia
11 - Newfoundland (East Canada)
12 - SW Iberia
13 - Equatorial Brazil
14 - Sumba Island (Indonesia)
15 - SW Australia
16 - Hawaiian islands
17 - Marquesas Islands
18 - La Reunion
19 - New Zealand
20 - Appalachians (Cow Head Gp.)
21 - Labrador Sea
22 - Lesser Antilles
23 - North Colombia margin
24 - SE Brazil (Espirito Santo)
25 - SE Brazil (Santos Basin)
26 - Peru
27 - Argentina (San Juan)
28 - PanAfrican Orogen (DR Congo)
29 - Tabernas and Sorbas Basins
30 - West Morocco
31 - Canary islands
32 - Fogo island (Cape Verde)
33 - Great Bahamas Bank
34 - SE Japan (Nankai Trough)

Figure 1. Location map of the studied 3D seismic volumes and outcrop locations referred to in this paper. Outcrop areas in SE Crete and SE Spain are indicated by locations 4 and 29.