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Shear zone liquefaction in mass transport deposit emplacement: A multi-scale integration of seismic reflection and outcrop data

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ABSTRACT

We present the integrated outcrop-geophysical study of two mass transport complexes, the exhumed Specchio unit in the Northern Apennines of Italy and the Holocene Poverty unit in the Hikurangi margin of New Zealand. The combination of micro- to meso-scale structural, stratigraphic and sedimentologic analyses carried on continuous three-dimensional outcrops, with large-scale structural and morphologic data deriving from seismic/acoustic imaging of the present-day continental margins, allow important considerations on submarine landslide processes and mechanisms through the broader (up-scaled and down-scaled) understanding of the mass transport-related structural associations. We compare the discontinuous high-amplitude, reverse-polarity reflectors observed within the Poverty with the syn-sedimentary, ductile shear zones found within the Specchio mass transport complex. The seismic signature of such structures suggests localized fluid overpressure along detachment/thrust zones due to shearing and loading of undrained, water-saturated, fine-grained material, developed along with the slide mass movement. The outcrop expression of these structures is tentatively attributed to m- to tens of m-thick shear zones comprising large amounts of sedimentary matrix which separate and accommodate the differential movements of the internal slide components (e.g. slide blocks, olistoliths). The sedimentary matrix is an unsorted, lithologically mixed medium characterized by a scale-invariant "block-in-matrix" fabric (i.e. brecciated, mud-supported), that injects, sustain and surrounds discrete slide elements (from particles to blocks) and interpreted as a hyper-concentrated (liquefied/fluidized) suspension of water and scattered sediments developed in fluid overpressure conditions. We highlight the fundamental role of shearing-related liquefaction as one of the main factors controlling slide mobility through the "lubrication" of the internal and basal friction forces. The analysis of such features can therefore provide important information for the characterization of mass transport deposits developed from potentially catastrophic, long run-out mass transport events, and consequently, to better understand their possible socio-economic impact in terms of tsunamigenic potential.

1. Introduction

The recent achievements in marine geology on seafloor and sub-seafloor mapping allow important consideration on recent to modern submarine landslides, giving general clues on their overall morphology and areal extent (Canals et al., 2004; Frey-Martinez et al., 2006; Gee et al., 2007; Bull et al., 2009). One of the main challenges arising from these studies revolves around the characterization of the complex internal anatomy of such deposits, and thus, the correct understanding of the genetic mechanisms and processes, which is crucial for offshore hydrocarbon exploration, and geohazard assessment and mitigation (see Hampton et al., 1996; Mosher et al., 2009; Kawamura et al., 2012).

Most of the internal structures of a slide body are developed at the meso-scale (meters to ten of meters), and therefore hardly recognizable through geophysical methods being well below the standard seismic resolution. Moreover, the high internal heterogeneities and the combined occurrence of materials with different degrees of consolidation contribute to complicate the seismic signal, resulting in acoustic artifacts and transparent zones. On the other hand, at the outcrop scale, these internal structures can be observed and described in detail (Lucente and Pini, 2003; Callot et al., 2008a, 200b; Ogata et al., 2012a), and, depending on the quality and the continuity of the exposures, such analyses could be up-scaled to fit to the seismic field of observation. In this framework we believe that a systematic comparison with fossil mass transport deposits cropping out in orogenic belts (i.e. sedimentary

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mélanges) would strongly contribute in solving these problems (Festa et al., 2010a, 2010b, 2012). Currently, apart from the general and useful review of the mass transport deposits' seismic-scale structures provided by Bull et al. (2009) and the preliminary (and generally conceptual) attempt of comparison between seismic and outcrop data recently proposed by Bull and Cartwright (2010), there is still a general lack of works using an integrated approach in the study of submarine landslides. This leads to a gap in the basic knowledge of the meso-scale internal processes and related structures, and their relationship with larger scale features.

We present an attempt to combine and integrate geophysical and outcrop data in order to establish a continuity of observation at different scales, crucial for the study of vertically- and laterally-extensive submarine landslide deposits. Whereas the standard subsurface and seafloor imagery technology provides the gross morphology, areal extension and internal organization of a mass transport deposit, often providing a complete picture of a mass transport complex, the highest resolution of multi-channel seismic reflection data required to image such features is ca. 5 m or coarser. On the other hand, outcrop studies allow multi-scale analyses (depending on the exposure conditions), providing resolution from the microscopic scale up to the cartographic scale (comparable with the geophysical scale). Through the study of comparable onland and offshore analogs it is virtually possible to fill the mutual gaps of the two different approaches, allowing the construction of a more comprehensive and better-constrained framework.

The aim of this work is to address these issues providing a detailed integration of structural data coming from geophysical and outcrop examples characterized by comparable scales and depositional settings. We present a compilation of outcrop data coming from the Specchio mass transport complex, belonging to the Eocene–Oligocene intra-slope basin succession (i.e. Epiligurian Units) developed atop the exhumed Ligurian accretionary wedge in the Northern Apennines in Italy (Ogata et al., 2012a,b). These field-based observations are tentatively up-scaled and compared to the Holocene Poverty mass transport complex of the Hikurangi margin in New Zealand (Mountjoy and Micallef, 2012).

2. Geological background and case studies overview

Our data come from two examples of large submarine mass failures emplaced in subduction/collision-related wedge top depositional settings and characterized by comparable physiographic and depositional contexts. The Specchio mass transport complex is an ancient, exhumed example from the Northern Apennines of Italy, while the Poverty mass transport complex comprises Holocene slide deposits emplaced in an active subduction system off the East Coast of New Zealand (Fig. 1). These two examples are well suited for comparison as they are of a similar scale (both in terms of areal extension and thickness), depositional setting (i.e. intra-slope, wedge-top) and overall internal architecture (i.e. stacking/amalgamation of more events). These general common features are summarized in the table of Fig. 1C.

2.1. The Specchio mass transport complex

The upper Priabonian–lower Rupelian Ranzano Unit of the Epiligurian succession of the Northern Apennines represents a perfect example of syn-orogenic, siliciclastic infilling of an intra-slope, wedge-top mini-basin (i.e. small-scale) system characterized by depocenters about 5–10 km in size. These structurally confined basins were located atop the deforming Ligurian oceanic accretionary prism during its tectonic transport toward the eastern sectors, following the complex continental convergence between African (Adria) and European plates, in a time interval comprised between the latest stages of the Alpine orogenesis and the inflection (i.e. flexural down-bending) of the Apenninic foreland (Castellarin, 1994; Mutti et al., 1995; Martelli et al., 1998; Cavazza et al., 2004; Marroni et al., 2010).

The analyzed Specchio unit is a mass transport complex hosted in the middle-basal part of the Ranzano Sandstone stratigraphic succession (Martelli et al., 1998), which is mainly constituted by proximal, coarse-grained, low efficiency (sensu Mutti, 1992) turbidite deposits accumulated in relatively deep water setting (middle–upper bathyal depth; Di Giulio et al., 2002). This mass transport complex is characterized by an estimated areal extent conservatively calculated around ~1.500 km^2 and an average thickness of ~100 m, and it is generated by the rapid, polyphased accumulation of at least three mass transport deposits characterized by different paleo-transport directions: 1) a basal one(s), coming from the southern sectors, of mixed extra- and intrabasinal composition, originated from shallow-tectonic positive structures (e.g. anticline culminations) and other topographic highs close to the depocentral areas, 2) a middle one, coming from the northern sectors, of mainly intrabasinal composition, originated from structural highs located in a relatively distal position from the main depocenters, and 3) an upper one(s) coming from northern sectors, composed of shallow-water related sediments failed from the basin margins, in proximal position with respect to the inferred feeding areas (i.e. coastal areas) (Fig. 2). In this framework, the Specchio unit is thought to represent the rapid sedimentary response to a general rearrangement of the source-depositional system, operated by the synergic effect of an active syn-sedimentary tectonism and sea level changes, possibly acting together from the Early Oligocene (Ogata et al., 2012b).

In terms of sedimentary processes, each individual depositional event comprises a bipartite flow made up by a lower matrix-dominated and an upper block-dominated parts (Ogata et al., 2012a, b) which in turn correspond to debris flows and blocky flows, respectively (in the sense of Mutti et al., 2006). The local occurrence of slump-type deformations (i.e. coherent slide movement achieved through syn-sedimentary shear zones; see Ogata et al., 2012a) is restricted to the sand-dominated substrate and the internally folded oversized blocks. The matrix composition and amalgamation, and the various expressions of post-emplacement fluid escape and depressurization acting together, suggest that the Specchio mass transport deposits are composed by (i) a cohesive upper part (i.e. block-dominated portion), behaving as a relatively coherent sheet of separated, passively-transported rafts ("rigid plug" of Middleton and Hampton, 1973), and (ii) a non-cohesive, lower part (i.e. matrix-dominated portion) behaving as a non-Newtonian fluid (hyperconcentrated suspension in the sense of Mutti, 1992). In this framework, the matrix itself is thought to support internal slide elements (from mm-sized clasts to m-sized blocks) due to its yield strength, whereas at larger scale, the matrix-dominated portion is inferred to sustain the entire flow through the upward and dispersive forces of the fluid excess pressure, reducing the basal/internal frictions and enhancing the slide mobility (Ogata et al., 2012a,b; Pini et al., 2012). The same mechanisms have been also hypothesized for some modern, long run-out submarine landslides (Mulder and Alexander, 2001).

2.2. The Poverty mass transport complex

The modern mass transport complex discussed in this paper occurs on the upper slope of the Hikurangi Margin, an active subduction margin off the East Coast of New Zealand (Fig. 3) (Lewis and Pettinga, 1993; Barnes et al., 2010).

The Poverty mass transport complex, also referred to as the Poverty Debris Avalanche in literature, is the result of slope modification within the Poverty re-entrant (Mountjoy and Micallef, 2012). The Poverty re-entrant is a margin-scale morpho-tectonic feature interpreted to be the result of seamount impacts from the incoming Pacific Plate, initiating approximately 1 Ma ago (Pedley et al., 2010). The structural and sedimentary post-impact reconfiguration of the margin is achieved by the development of submarine canyon and slope–gully systems, as well as large-scale mass failures (Orpin, 2004; Walsh et al., 2007; Mountjoy et al., 2009; Pedley et al., 2010). In this area, Quaternary