Marine and Petroleum Geology 26 (2009) 1849–1865

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Tectonically-driven mud volcanism since the late Pliocene on the Calabrian accretionary prism, central Mediterranean Sea

D. Praeg [a,*], S. Ceramicola [a], R. Barbieri [b], V. Unnithan [c], N. Wardell [a]

[a] Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), Borgo Grotta Gigante 42/c, Sgonico, 34010 Trieste, Italy
[b] Dipartimento di Scienze della Terra e Geoambientali, Università di Bologna, Via Zamboni 67, 40126 Bologna, Italy
[c] Jacobs University Bremen, School of Engineering and Science, Campus Ring 1, 28759 Bremen, Germany

A R T I C L E I N F O

Article history:
Received 30 June 2008
Received in revised form
18 March 2009
Accepted 23 March 2009
Available online 12 April 2009

Keywords:
Accretionary prism
Mediterranean
Seismic
Mud volcanoes
Pie
Cones
Caldera
Interfingering
Subsidence
Extrusion
Tectonism
Fluids

A B S T R A C T

Mud volcanoes recently discovered on the offshore Calabrian Arc are investigated at two sites 60 km apart, in water depths of 1650–2300 m, using swath bathymetry, 2D&3D multichannel seismic and cores. The seabed and subsurface data provide information on their formation and functioning in relation to tectonic activity during the rapid Plio-Quaternary advance of the accretionary prism. Fore-arc extension and thrust-belt compression are seen to have involved two main phases of activity, separated by a regional unconformity recording a mid-Pliocene (3.5–3.0 Ma) tectonic reorganization. The two sites of mud volcanism lie in contrasting tectonic settings (inner fore-arc basin vs central fold-and-thrust belt) and record differing forms of seabed extrusive activity (twin mud cones and a caldera vs a broad mud pie). At both sites, subsurface data show that mud volcanism took place throughout the second tectonic phase, since the late Pliocene; differing forms of mud extrusion were accompanied by subsidence to form depressions beneath and within extrusive edifices up to 1.5 km thick. The basal subsidence depressions point to sources within the succession of thrusts underlying the inner to central Arc, consistent with microfossils within cored mud breccias from both sites that are derived from strata as old as Late Cretaceous.

These results are argued to support a model of mud volcanism in which deeply-rooted fluid conduits drive a process of near-surface sediment mobilization. The onset of extrusive activity is inferred to have been triggered by the mid-Pliocene tectonic reorganization, the change in stress fields (which post-dates the migration of frontal compression across the area by >4 Ma) opening pathways for the release of overpressured fluids from deep within the accretionary prism. The rising fluids interacted with shallow (<2 km) geological structures (thrusts, basins) to cause the formation and progressive evacuation of mud chambers, resulting in the growth of mud volcanoes within subsidence depressions. It is hypothesised that lowering of the base of the extrusive edifices by subsidence and thickening led to the formation of internal mud chambers that remobilized previously extruded material, a process that could account for the common lack of internal structure observed on seismic profiles. Differing forms of mud extrusion (mud pie, mud cones, caldera) are attributed to episodic activity driven by the evolving dynamics of the mud chambers over the last ≥3 Ma.

1. Introduction

Mud volcanoes occur in passive and active tectonic settings worldwide, but are most common in accretionary prisms along subducting plate margins (Higgins and Saunders, 1974; Dimitrov, 2002; Kopf, 2002). In such settings, tectonically-generated pore fluid overpressures at depth are relieved by the upward migration and expulsion of fluids, gases and solids, resulting in a variety of possible intrusive bodies and/or extrusive edifices (Brown and Westbrook, 1988; Brown, 1990; Kopf, 2002; Deville et al., 2003). Analyses of modern and fossil examples support a model of mud volcanoes as deeply-rooted vertical structures, in which surface activity is driven by one or more mud chambers that form above the zone of overpressures, in response to the rise of fluids along focused conduits that may extend to depths of kilometers (Deville et al., 2003; Planke et al., 2003). The functioning of such structures over time is inferred to be coupled to the inherently heterogenous structures and episodic dynamics of accretionary prisms (Higgins and Saunders, 1974; Brown, 1990; Kopf et al., 1998, 2001; Dimitrov,

* Corresponding author.
E-mail address: dpraeg@ogs.trieste.it (D. Praeg).

0264-8172/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpetgeo.2009.03.008

2002; Bonini, 2007). However, despite advances in the seismic imaging of mud volcanoes (Van Rensbergen et al., 1999; Graue, 2000; Davies and Stewart, 2005; Evans et al., 2006), little is known about their initiation and operation over geological timescales.

The Mediterranean region contains mud volcanoes in a variety of settings, modern and fossil, subaerial and submarine, tectonically passive and active (e.g. Kopf, 2002). Most are found along two main accretionary systems, formed above subduction zones (Fig. 1 inset) related to the opening of the western and closing of the eastern Mediterranean basins in response to the convergence of Africa and Europe (Jolivet and Faccenna, 2000). The accretionary system of the eastern Mediterranean Sea contains one of the world's highest abundances of mud volcanoes (Kopf, 2002), identified over 25 years ago from core samples of mud breccia and initially attributed to a model of mud diapirism (Cita et al., 1981, 1996; Camerlenghi et al., 1992, 1995). Scientific drillling of two such features on the Mediterranean Ridge showed them to record sediment extrusion and localized subsidence over at least the last 1 Ma, during dewatering of the accretionary prism from depths of up to 7 km (Robertson, 1996; Robertson and Kopf, 1998). Seabed imagery have subsequently revealed a wide variety of extrusive features (mud cones, pies, ridges) and possible intrusive forms (e.g. Ivanov et al., 1996; Cronin et al., 1997; Huguen et al., 2004), displaying relations to seabed and near-surface structures (folds, faults) that are argued to support a fundamental tectonic control on their occurrence and activity (Fusi and Kenyon, 1996; Galindo-Zaldivar et al., 1996; Robertson and Kopf, 1998; Kopf et al., 1998, 2001; Kopf, 2002). Onshore within the Apenninic-Maghrebide chain of Italy, tectonic controls are also inferred for many modern mud volcanoes (Higgins and Saunders, 1974; Martinelli & Judd, 2004; Bonini, 2007, 2009), while the increasing recognition of fossil equivalents (e.g. Catalano et al., 2002; Clari et al., 2004; Conti et al., 2007) confirms that mud volcanism has been an integral feature of the Neogene history of the accretionary system (Malinverno & Ryan, 1986).

The offshore Calabrian Arc forms the tip of the Apenninic-Maghrebide accretionary system, which has migrated rapidly SE since the late Miocene, latterly to meet the westernmost Mediterranean Ridge (Fig. 1; Jolivet and Faccenna, 2000; Chamot-Rooke et al., 2005). In contrast to the Mediterranean Ridge, the seabed geology of the Calabrian Arc has received little attention over the last 25 years, since the acquisition of a regional dataset of shallow seismic profiles and sediment cores (Rossi and Sartori, 1981; Barbieri et al., 1982). These data did not result in the identification of mud volcanoes, although cores of 'chaotic deposits' that were ascribed to compressive tectonism (Barbieri et al., 1982; Morlotti et al., 1982) could also be described as mud breccias. However, given the example of the adjacent Mediterranean Ridge, it became apparent that mud volcanoes were likely to be found on the Calabrian Arc (Fusi and Kenyon, 1996; Sartori, 2003; Fusi et al., 2006). For this reason, a systematic search for seepage activity was undertaken in 2005 during a campaign of the Italian research vessel OGS Explora, in the context of the EC-funded projects HERMES and HYDRAMED. The first regional swath bathymetric coverage of the Calabrian Arc (Fig. 1) revealed many probable mud volcanoes, proven at two sites by coring and the acquisition of seismic reflection data (Ceramicola et al., 2006; Ceramicola and Praeg, 2007). These two sites, referred to as the Madonna dello Ionio and Pythagoras mud volcanoes, have been explored during HERMES campaigns using remotely operated vehicles and found to contain evidence of ongoing seepage activity (see Foucher et al., 2009).

An overview of the Calabrian Arc cold seep province will be presented elsewhere. In this article, we focus on a study area spanning 100 km of the inner to central accretionary prism and containing the Madonna dello Ionio and Pythagoras mud volcanoes (Fig. 1), where information is available from swath bathymetry, grids of seismic data and cores (Figs. 2 and 3). Our aim is to examine the causes and nature of mud volcanic activity over time in relation to tectonism within the advancing accretionary prism. Below we show that the seabed and subsurface data provide information both on Plio-Quaternary tectonic phases and on the coeval formation, growth and subsidence of the mud volcanoes. The results are then discussed in terms of a model of tectonically-driven fluid fluxes interacting with near-seabed structures.

2. Geological setting

The arcuate Apennine-Maghrebide accretionary complex of Italy has formed above a NW-dipping subducting slab that rolled-back through the Neogene to open SE ward-younging back-arc basins in the western Mediterranean Sea (Malinverno and Ryan, 1986; Patacca et al., 1990; Doglioni et al., 1996; Gueguen et al., 1998; Jolivet and Faccenna, 2000; Faccenna et al., 2001). Rapid opening of the southern Tyrrhenian Sea since the late Miocene, c. 10 Ma, was accompanied by an outward migration of frontal compression, such that the SE tip of the Arc migrated up to 300 km towards the Ionian domain (Gueguen et al., 1998). The average rate of advance of the Calabrian Arc of 30 km/Ma exceeds that of the Mediterranean Ridge, argued to be one of the fastest growing accretionary prisms on Earth (cf. Kastens, 1991; Kopf et al., 2003).

Within the accretionary complex, the migration of frontal compression towards the Ionian domain was accompanied by extension to form sedimentary basins that now outcrop in Calabria and extend across adjacent offshore areas (Fig. 1). Studies of the onshore Crotone Basin show that its fill dates back to the late Miocene (Tortonian) and records deposition within an overall tensional regime, punctuated by compressional episodes (Roda, 1964; van Dijk, 1990, 1991, 1994; Zecchin et al., 2004, 2006; Capraro et al., 2006), suggested to span a transition from foredeep to thrust-top to fore-arc basinal settings (Roveri et al., 1992). Basin-wide unconformities of mid-Messinian, mid-Pliocene and mid-Pleistocene age are interpreted to record changes in the dynamics of the accretionary complex linked to episodic roll-back of the subducting slab (van Dijk, 1990, 1991, 1994; van Dijk and Okkes, 1991; van Dijk and Scheepers, 1995). The mid-Pliocene unconformity, recognized throughout the southern Apennines, is inferred to mark a change in the direction of back-arc extension and slab retreat from W–E to NW–SE, following collision with continental crust of the Apullian margin (Gueguen et al., 1998; Sartori, 2003; Guarnieri, 2006; Doglioni et al., 1996). The mid-Pleistocene unconformity coincides with a tectonic reorganization c. 0.8–0.5 Ma that marked the end of significant slab retreat and the onset of km-scale uplift of Calabria (Goes et al., 2004; Mattei et al., 2007).

The offshore Calabrian Arc extends 160 km seaward, descending gently ($\leq 1^{\circ}$) from the base of the inner slope in c. 1500 m water depth to a frontal thrust in depths of over 4000 m (Fig. 1). Deep seismic profiles show the landward-thickening accretionary wedge to be dominated by imbricate NW-dipping reflections that meet seaward-dipping reflections of the Calabrian backstop beneath the fore-arc basins (Fig. 1b; Cernobori et al., 1996; Monaco et al., 1996; Finetti, 1982, 2005). Studies using shallow seismic profiles have recognized three main seabed morpho-structural zones (Rossi and Sartori, 1981; Barone et al., 1982; Fabbri et al., 1982; CNR, 1983; Boccaletti et al., 1984), which can be seen on swath bathymetric data (Fig. 1a): 1) the inner Spartivento-Crotone fore-arc basins, up to 30 km wide, which contain sedimentary successions up to 2 s thick, including inferred Messinian evaporites; 2) a central area of irregular relief, where the Messinian is thin or absent and faults (reverse and normal) with seabed expression are observed; 3) an