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Mass wasting events and their impact on the formation and preservation of submarine ore deposits

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ABSTRACT

Mass wasting and landform modifying events have a profound impact on hydrothermal processes in terrestrial environments. Mass wasting events in submarine settings also modify hydrothermal systems and their associated mineralisation. We present evidence of a dynamic environment impacting on ore formation at the historically exploited Pb-Zn-(Ag) mineralisation of Triades, Milos island (Greece), formed in a submarine setting. Galena-sphalerite veins and barite-quartz gangue precipitated in the near subsurface or after exhalation of boiling hydrothermal fluids. Field evidence indicates that mineralisation was extensively reworked by debris flow events during formation. The mineral paragenetic sequence is consistent with a Pb-Zn-(Ag) massive sulphide system, and analogous to the early stages of a Kuroko-type deposit, but Triades lacks massive sulphide bodies. We suggest that mass wasting events literally truncated the developing mineral deposit as it formed on the seafloor, destroying massive sulphide bodies and limiting the development of the ore mineral assemblages. Mass wasting processes in volcanogenic massive sulphide systems are ore-destructive, with little opportunity for "telescoping", unlike terrestrial equivalents. Shallow marine systems in terrains subject to mass wasting may have low preservation potential, or may be classified as epithermal-like vein systems rather than stockwork portions of massive sulphide deposits.

1. Introduction

In the terrestrial environment it is recognised that landscape processes can significantly affect mineral deposit evolution; sector collapse at the Luise volcano had a profound impact on the formation of the giant Ladolam epithermal gold deposit (Müller et al., 2002), and progressive paleosurface degradation plays a key role in telescoping hydrothermal ore deposits (Sillitoe, 1994). However, most conceptual models of mineral deposit formation in the submarine environment envisage that mineralisation takes place in a relatively static landscape. The volcanic lithofacies of submarine and emergent volcanoes show that dome degradation, passive and explosive eruptions, and syn- and post-eruptive mass-wasting events dramatically alter the submarine landscape (Leat et al., 2010; Wright, 1996; Wright et al., 2008; Wright and Gamble, 1999), which in turn will significantly modify extant magmatic-hydrothermal and geothermal systems.

Milos island, Greece, has on-land exposures of well-preserved, young (< 3 Ma) submarine and mineralized volcanic edifices. Using sites on Milos as analogues for seafloor mineralisation (e.g. Petersen et al., 2014), here we show mass wasting events in the shallow (< 1000 m) marine environment influence deposit style and metal inventories, and negatively impact on the resource prospectivity of the seafloor.

1.1. Geological setting and submarine mineralisation of Milos

Milos is centrally located within the South Aegean Active Volcanic Arc (SAAVA) and consists of 3.5–0.1 Ma calc-alkaline volcanic domes, lavas and pyroclastic deposits built on a Mesozoic basement and upper Miocene–lower Pliocene marine sediments (Fytikas et al., 1986; Stewart and McPhie, 2006). The oldest volcanic deposits (late Pliocene) were submarine, transitioning to subaerial eruptive activity in the mid-Pleistocene (Stewart and McPhie, 2006; Stewart and McPhie, 2004). The modern, active geothermal system is considered transitional between marine and terrestrial, with contributions from magmatic volatiles, seawater, and meteoric-derived water (Naden et al., 2005).

Milos hosts a range of economic mineralisation, including marine exhalative Mn at Vani (Papavassiliou et al., 2017); epithermal Au-Ag at Profitis Ilias and Chondro Vouno (Kilias et al., 2001; Naden et al., 2005); and Zn-Pb-(Ag) deposits at Triades (Marschik et al., 2010) and

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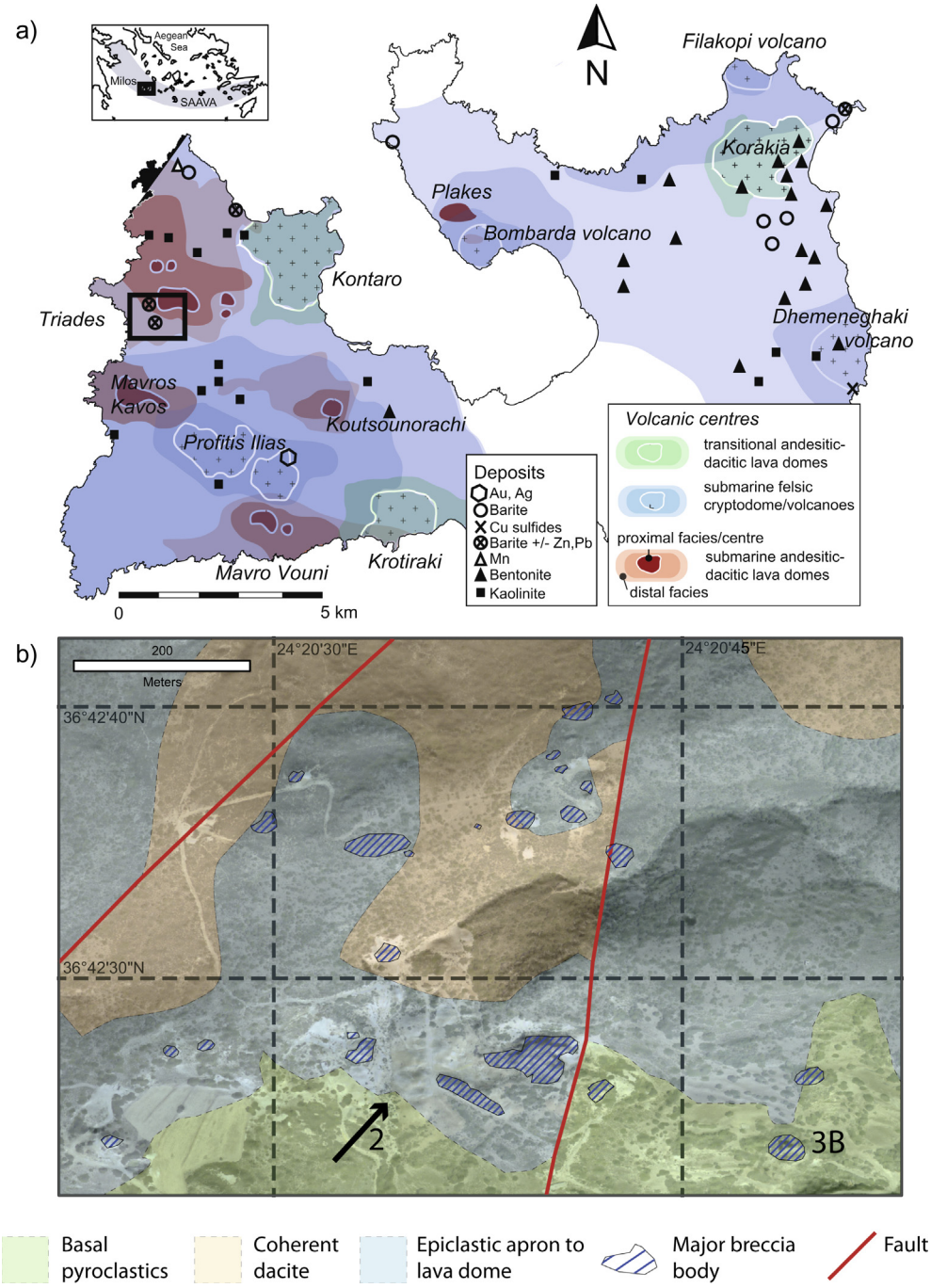

Fig. 1. (A) Simplified geological map of Milos island, showing main volcanic centres. Inset map shows position of Milos in the South Aegean Active Volcanic Arc (SAAVA). Black box shows location of map (B), a location map of the largest barite breccia domes. Arrow marks view direction for Fig. 2. Dome photographed in Fig. 3B (the main source of sulphide samples) is marked in the southeast corner of the map.

neighbouring Galana (Fig. 1). The deposits at Triades were mined from the late 19th to the early 20th century, initially for lead and zinc, and later for silver; silver reserves were estimated at 10 Mt ore at 500 ppm Ag (Liakopoulos et al., 2001). The Triades area is dominated by tuffs, hyaloclastites and debris flow deposits punctuated by partially extrusive andesitic to dacitic domes and lavas (Stewart and McPhie, 2006). Marine fossils (*Pecten* sp., *Ostrea* sp.) are contained within the volcanic sediments, confirming a relatively shallow marine environment (Marschik et al., 2010). Volcanism records emergence, determined by SHRIMP U-Pb zircon crystallisation ages from a submarine dacite at 2.18 Ma, and a subaerial equivalent at 1.44 Ma (Stewart and McPhie, 2006). Mineralisation at Triades has previously been identified as a product of a submarine hydrothermal system, classified as either Kuroko-style volcanogenic massive sulphide (VMS; Hauck, 1988; Kalogeropoulos and Mitropoulos, 1983; Vavelidis and Melfos, 1998) or intermediate to high sulphidation type epithermal mineralisation (Alfieris et al., 2013; Marschik et al., 2010).

1.2. Mass wasting deposits at Triades

In the Triades area, coherent lava domes have brecciated margins and debris aprons of hyaloclastite and reworked autobreccia (Stewart and McPhie, 2006). Intact lava domes are still present as steep-sided topographic highs (Figs. 2 and 3). The seafloor palaeotopography was