

Neotethyan Late Cretaceous volcanic arc hydrothermal vent fauna

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ABSTRACT

The barite-polymetallic ore zone of the Late Cretaceous Madneuli volcanogenic massive sulfide (VMS) deposit in the Republic of Georgia contains large tube worm fossils that represent the first ancient hydrothermal vent fauna to be identified from a volcanic arc setting and very likely the shallowest ancient example yet found. The fossil tube walls are formed of an unusual quartz, barite, pyrite, and galena mineral assemblage, rather than only pyrite as in other vent fossils; this probably reflects the low-temperature, high-salinity vent chemistry at the time of preservation, as deduced from fluid inclusion analyses. The Madneuli vent fauna is one of three examples that occurred over a time span of ~6 m.y. in an area of the Neotethyan Ocean that was tectonically complex as the present-day west Pacific. The ancient and modern vent faunas appear to occur in a similar range of tectonic settings and bathymetry.

Keywords: hydrothermal vents, sulfides, paleoecology, Tethys, Georgian Republic.

INTRODUCTION

Since their discovery in 1977, hydrothermal vent communities have radically altered our view of life in the deep sea (see review by Van Dover, 2000). The primary energy source at vent sites is geochemical, in the form of reduced compounds (particularly hydrogen sulfide) in the vent fluid, and the primary producers in the associated communities are prokaryotes. A variety of bacteria form symbiotic relationships with some of the animal groups that dominate the biomass of vent communities: vestimentiferan and some alvinellid polychaete tube worms, vesicomyid clams and bathymodiolin mussels, and some provannid gastropods and bresiliid shrimp (e.g., Van Dover, 2000). Vent communities were first identified on segments of the Atlantic and east Pacific mid-ocean spreading ridges in the 2–3 km depth range. Subsequent exploration in the west Pacific has found similar faunas in a much greater diversity of tectonic settings associated with volcanic arcs, including on submerged arc volcanoes in as little as 345 m of water (e.g., Embley et al., 2004; De Ronde et al., 2003; Kojima, 2002).

The present fossil record of hydrothermal vent communities is sparse, with only 22 unequivocal occurrences (Little, 2002). These are found within volcanogenic massive sulfide (VMS) deposits representing a variety of tectonic settings. The majority of these fossils are found in Silurian to Devonian accreted arc-related terranes in the Ural Mountains, Russia, or Tethyan Late Cretaceous to early Cenozoic

suprasubduction-related ophiolites (Haymon et al., 1984; Oudin et al., 1985; Boirat and Fouquet, 1986; Little, 2002; Little et al., 1999a, 1999b, 2004). Up until now, ancient examples equivalent to modern volcanic arc vent communities were lacking. Here, we report worm tube fossils from the Late Cretaceous Madneuli VMS deposit in the Republic of Georgia. These fossils represent the first hydrothermal vent community from a paleo-volcanic arc setting and very likely represent the shallowest ancient example yet found. This occurrence significantly extends our knowledge of Neotethyan hydrothermal vent faunas during the Mesozoic in terms of paleogeographic occurrence, tectonic setting, and paleobathymetry. The preservation style of the Madneuli worm tube fossils also differs from all other known vent fossils.

GEOLOGIC BACKGROUND

The Madneuli barite-gold-copper-polymetallic VMS is the major deposit ($>70 \times 10^6$ t of ore before mining) of the Bolnisi mining district in

the southeast part of the Republic of Georgia (Fig. 1), and it is presently being mined in an open pit (Arevadze et al., 1983; Magalashvili, 1995; Tvalchrelidze, 1990). It is underlain by mineralized stockworks and is formed of tectonized, mainly stratiform ore bodies, which show consistent patterns of ore zonation. These zones are, from the base upward: (1) copper-pyrite (chalcopyrite, pyrite, quartz, and minor sphalerite, chalcocine, epidote, anhydrite, galena, and fluorite), (2) barite-polymetallic ore (barite, sphalerite, pyrite, galena, and minor chalcopyrite and marcasite), and (3) gold-bearing quartzites (quartz, barite, calcite, and pyrite) (Arevadze et al., 1983; Magalashvili, 1995, 2004). Zones 1 and 2 show evidence of zone refinement and multiple veining by higher-temperature sulfide minerals (e.g., chalcopyrite). Fluid inclusion studies of the ores give homogenization temperatures of 260–370 °C and 180–270 °C in the copper-pyrite and barite-polymetallic ores, respectively (Kekelia et al., 1993). The ore deposit is hosted by a lower volcanic unit of bimodal andesitic to

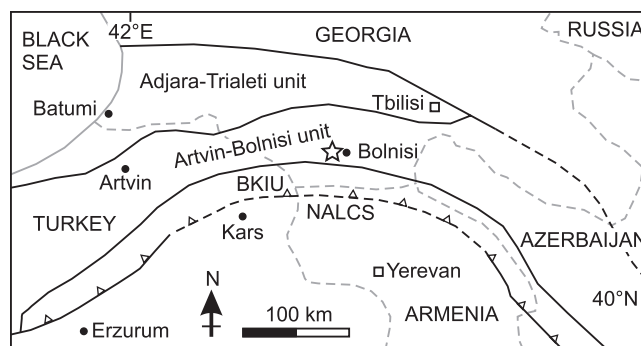


Figure 1. Map of tectono-stratigraphic units in southern Transcaucasus-eastern Pontides region (modified from Yilmaz et al., 2000). White star shows location of Bolnisi mining district. BKUI—Bayburt-Karabakh imbricated unit, NALCS—North Anatolian-Lesser Caucasus suture.

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rhyodacitic volcanoclastic rocks, including fine- to medium-grained tuffs, all of which have been extensively altered hydrothermally. After a short period of quiescence, an upper volcanic unit was deposited, which consists of unaltered, ore-free volcanoclastic and effusive rocks of rhyolite-rhyodacitic composition, including thin vesicular and massive lavas, lava breccias, and ignimbrites (Arevadze et al., 1983; Magalashvili, 1995, 2004; Rubinstein et al., 1983). Both units were then intruded by dikes, which have been K/Ar dated to between 85 and 83 Ma, equivalent to the Santonian (Rubinstein et al., 1983; Dudauroi et al., 1990). The Madneuli VMS and host volcanic sequences have been interpreted by Magalashvili (1995, 2004) to be a Turonian-age submarine volcanic arc hydrothermal system, where the mineral zonation of the ore bodies was caused by varying fluid temperatures. Later subaerial effusive-pyroclastic activity in the early Santonian formed a collapse caldera-type structure, leading to the partial dismemberment of the underlying volcanics and ores.

The Bolnisi area lies within the Artvin-Bolnisi unit, which forms the northern part of the southern Transcaucasus and the central part of the eastern Pontides of Turkey and is located between the Adjara-Trialeti unit to the north and the Bayburt-Karabakh imbricated unit to the south (Yilmaz et al., 2000) (Fig. 1). These three units represent a volcanic arc complex that formed mainly during the Late Jurassic to Campanian time interval on the southern margin of the Eurasian continental plate by subduction of the Neotethys Ocean and subsequent collision of the Anatolian-Iran continental plate (e.g., Yilmaz et al., 2000). According to Yilmaz et al. (2000), during the Mesozoic, the Adjara-Trialeti, Artvin-Bolnisi, and Bayburt-Karabakh units represent, from north to south, respectively, juvenile backarc, arc, and forearc basins that formed above a northward-dipping subduction system. Extensive volcanic activity in the Artvin-Bolnisi unit occurred between the Aptian-Albian and the Campanian, and rocks of this age are overlain unconformably by Maastriichtian to Paleocene shallow-marine limestones and terrigenous clastic turbidites (Yilmaz et al., 2000). The Aptian-Albian to Campanian volcanic units are shallow-marine to subaerial volcanoclastics, rhyolite, andesite, dacite, and basalt. There is evidence for emergence toward the top of the sequence in the form of ignimbrite-type pyroclastics and interbedded coals.

Materials

An 80 × 60 × 50 mm block of ore containing four tubular fossils (Fig. 2) was collected from the Madneuli deposit in 1990 by Omar Khutsishvili (deceased) near the foot of quarry face number 1030 from close to the top of the barite-polymetallic ore zone (specimen code

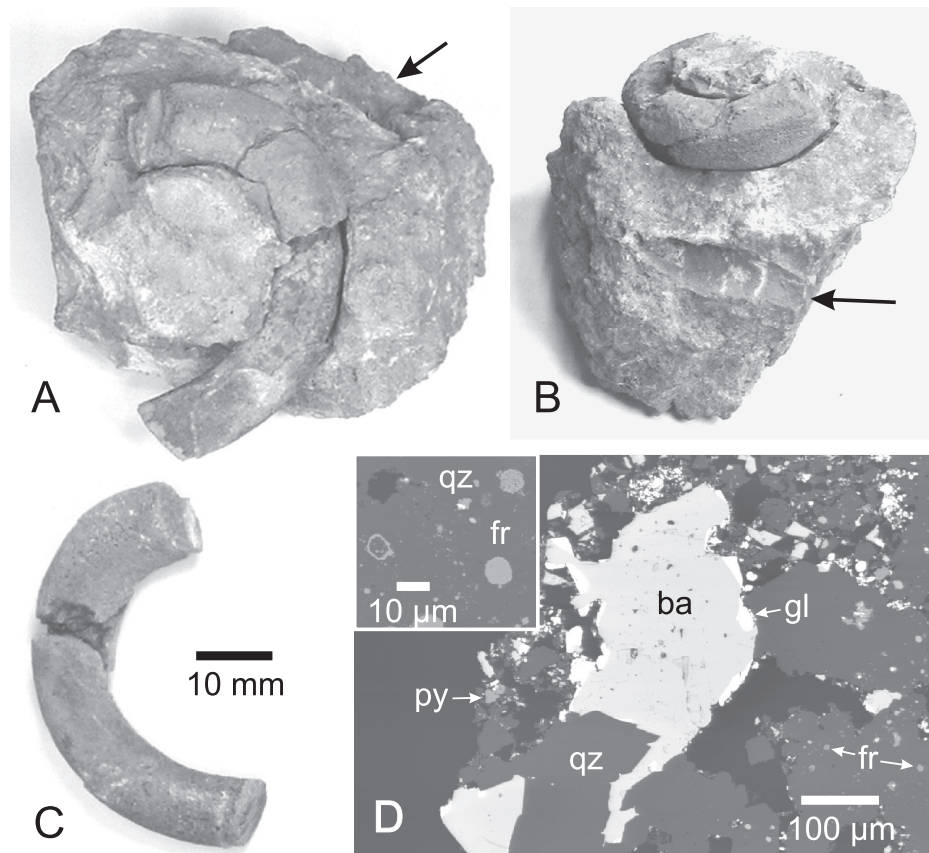


Figure 2. Madneuli tube worm fossils. **A–B:** Ore block in two orientations to show the two tubes exposed on the surface; arrow points to the straighter specimen lacking an internal mold. **C:** U-shaped tube internal mold removed from the block and inverted to show other side from that seen in A. **D:** Backscattered-electron images of mineralogy of U-shaped tube internal mold; ba—barite, qz—quartz, gl—galena, py—pyrite, fr—framboidal pyrite. Inset: detail of framboids. Scale is the same for A, B, and C.

365–1, Georgian National Museum, Tbilisi). Polished blocks for scanning electron microscopy (SEM) and standard fluid inclusion wafers were made from sulfides and barite that form one of the tubes and the matrix.

OBSERVATIONS

The ore block matrix consists predominantly of intergrown quartz and barite, with lesser amounts of sphalerite, pyrite, and galena. Two of the tubular fossils are exposed on its surface; the other two are only partially exposed (Figs. 2A–2C). One of the exposed fossils is a cylindrical U-shaped internal mold that is 96.0 mm long and has a maximum diameter of 13.1 mm (Figs. 2A–2C). It is formed mostly of quartz, containing euhedral pyrite crystals and framboids, and later barite with galena overgrowths (Fig. 2D). A thin wall, <1 mm thick, delimits the internal mold from the matrix, and this has the same mineralogy as the mold and the matrix, although the crystal size is finer. The other exposed tubular fossil is a straight external mold with partially exposed wall, 35.2 mm long and 11.9 mm in

diameter (Figs. 2A and 2B). The two partially exposed tubular fossils are both straight and have maximum lengths and diameters of 20.8 and 8.8, and 6.5 and 6.8 mm, respectively.

Barite crystals in the block matrix contain primary liquid-filled inclusions that are 10–20 μm in diameter and that have salinities of 18.7–20.4 equivalent wt% NaCl ($n = 20$). A few primary inclusions also contain vapor bubbles that give homogenization temperatures of 159–215 °C ($n = 3$), but it is likely that these have leaked.

INTERPRETATIONS AND DISCUSSION

Tube Fossil Identification

The Madneuli tubular structures are fossils, rather than abiogenic structures such as fluid conduits, because they have thin, distinct tube walls, they are cylindrical, and one is U-shaped; fluid conduits (e.g., chimneys) have irregular cross sections and often show branching patterns (e.g., Herrington et al., 1998). Because of a paucity of morphological characters, we cannot identify the Madneuli fossils with any certainty, but we suggest that they were most

likely formed by polychaete worms, possibly siboglinids (vestimentiferans). This is because the closest analog at modern vent sites in terms of size and shape are the tubes of some siboglinids (particularly *Riftia*), chaetopterids, and the larger alvinellids (e.g., *Alvinella*), which can become replaced by sulfide minerals (Haymon et al., 1984; Maginn et al., 2002). There are other tubicolous polychaetes at modern vent sites, but these are not as good of analogs for the Madneuli tubes because they are all smaller and either live in areas away from active mineralization, and are thus less likely to be preserved as fossils (serpulids), or form particulate mucous tubes, also with low preservation potential (ampharetids). The Madneuli tubes are also similar to the tubular fossil *Yamankasia rifeia* from the Early Silurian Yaman Kasy VMS of the Ural Mountains (Little et al., 1999b).

Paleoenvironmental Analysis

Because the Madneuli worm tubes occur in a VMS deposit and are similar to other vent fossils, we are confident that they represent a Late Cretaceous volcanic arc hydrothermal vent fauna. An important implication of this interpretation is that the Madneuli deposit was an exhalative ore body. The fluids trapped as inclusions in the barite matrix are relatively cool (<60 °C, as indicated by lack of vapor bubbles in the inclusions) and contrast with the >250 °C fluids recorded by Kekelia et al. (1993) in the sulfide mineralization. Elevated salinities could be explained by phase separation into brines and low salinity vapor, but analyses of modern vent fluids have only shown 2× to 3× seawater chlorinity, not the 5× recorded here (see Von Damm, 1995; Lüders et al., 2001), and the temperature of the inclusions is too low for this to have occurred. The likeliest explanation is that the high-salinity fluids were generated in a shallow, near-surface evaporitic environment akin to the brine pool depositional environment of the Irish-type sulfide deposits (Banks and Russell, 1992; Boyce et al., 1983).

Most volcanic arc vents that form seafloor massive sulfides of a similar size to the Madneuli deposit are found in water >1 km (e.g., Herzig and Hannington, 1995; De Ronde et al., 2003). However, recent findings on the East Diamante Volcano, Mariana arc (345 m), and on Volcano 19, Tonga arc (385 m), show that analogous vent deposits with characteristic vent animals (e.g., vestimentiferan tube worms and bathymodiolin mussels) can form in much shallower water (Embley et al., 2004; Stoffers, et al., 2006). An upper limit may, in fact, be ~200 m; shallower volcanic arc vent sites have neither substantial seafloor sulfide deposits nor associated chemosynthetic macrofauna (e.g., Tarasov et al., 2005). The Madneuli vent may have also formed at depths <1 km because the

overlying volcanics show evidence of having been formed in shallow water or even subaerial settings (e.g., Yilmaz et al., 2000), and there are fine tuff beds in the host rocks. Although paleobathymetric analysis of volcanic rocks is extremely problematic, Busby (2005) recently suggested that the presence of fine ash, such as found in the Madneuli host volcanics, might distinguish effusive from explosive silicic deep-water (>1 km) volcanism. If we are correct in our paleobathymetric estimation for the Madneuli vent fauna, then this is almost certainly the shallowest ancient example yet found. Fluid inclusions from sulfides that host vent communities in the Urals and the Troodos ophiolite indicate that they formed in 1.6 and 2.5 ± 0.3 km of water, respectively (Little et al., 2002).

Comparisons with Vent Faunas from Other Neotethyan Sites and Elsewhere

The Madneuli fauna shares worm tube fossils with other ancient vent communities, all of which contain worm tube fossils of various sizes and taxonomic affinity (Little, 2002). Although like Silurian examples, the Madneuli fossils differ from other Mesozoic vent worm tubes in that they are significantly larger and do not have external flanges and concentric growth lines (Little et al., 1999a, 2004; Haymon et al., 1984). This almost certainly means they were made by different species (and possibly different polychaete groups), because while the size difference could relate to different stages of maturity, none of the ~600 collected Mesozoic vent tubes approaches the diameter of the Madneuli tubes. The Madneuli worm tubes also differ from all other fossil examples because they have a tube wall formed of quartz, barite, pyrite, and galena, rather than only pyrite. This is not taxonomically significant

because some tubes of the modern siboglinid worm *Ridgeia* from the Juan de Fuca Ridge are mineralized by silica and barite prior to being replaced by sulfides (Cook and Stakes, 1995). The most likely explanation is that the range of minerals replacing vent worm tubes reflects the vent chemistry at the time of preservation.

The Madneuli vent fauna is the first ancient example from a volcanic arc. Silurian and Devonian vent faunas from the Urals lived in forearc, back-arc, and rifted-arc sites (e.g., Little et al., 1999b; Herrington et al., 2005), but the VMS deposits from analogous felsic volcanic arc settings to the Madneuli deposit (the “Baimak-type” sulfides) do not contain fossils (Herrington et al., 2005).

During the Mesozoic the Neotethys had a paleogeographic complexity rivaling that of the present west Pacific tectonic regime, with numerous microcontinental blocks separated by ocean basins of varying sizes that contained spreading centers and subduction zones, the exact positions of which are subject to different interpretation (e.g., Robertson, 2004; Stampfli and Borel, 2002) (Fig. 3). Over a time span of ~6 m.y. in the Late Cretaceous, hydrothermal vent faunas occurred at a volcanic arc on the north Neotethyan margin in the Turonian (Madneuli) and on the south Neotethyan margin in suprasubduction settings in the Cenomanian (Semail, 96–94 Ma; Haymon et al., 1984) and the Turonian (Troodos, 91 ± 1.4 Ma; Little et al., 1999a) (Fig. 3). Undoubtedly, these represent only a fraction of the hydrothermal vent communities that were present in the area in the Late Cretaceous, but they do give us an indication that Neotethyan vent faunas occurred in a similar range of tectonic settings as modern vent communities.

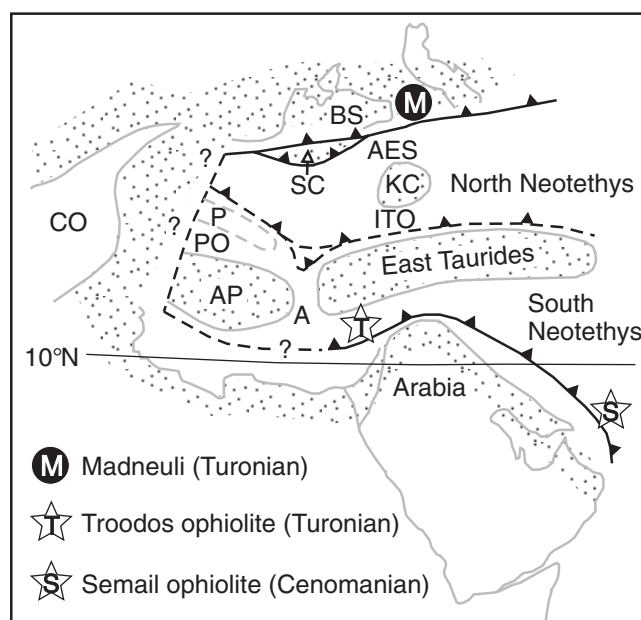


Figure 3. Paleogeographic reconstruction of eastern Neotethyan region in Late Cretaceous (modified from Robertson, 2004). Stipple pattern—land; solid and dashed black lines with teeth represent subduction zones (associated putative spreading ridges not shown). Codes: lettered stars—suprasubduction zone vent communities, lettered black circle—volcanic arc vent community, A—Antalya, AES—Ankara-Erzincan suture, AP—Apulia, BS—Black Sea, CO—Carpathian ocean, KC—Kirsehir continent, ITO—Inner Tauride ocean, P—Pelagonian microcontinent, PO—Pindos ocean, SC—Sakarya continent.

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