Mud volcanism on the Mediterranean Ridge: Initial results of Ocean Drilling Program Leg 160

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ABSTRACT

Drilling during Ocean Drilling Program Leg 160 (April–May, 1995) revealed important new evidence concerning the internal composition, depositional processes, and age of two mud volcanoes within the Mediterranean Ridge accretionary complex. Holes were drilled at ca. 2000 m water depth on the crest areas, across the flanks of the mud volcanoes, and onto adjacent deep-sea sediments. The main depositional units forming the flanks of both mud volcanoes are debris flows ("mud breccias") composed of a volumetrically dominant mud matrix, containing clasts of mainly clay, mudstone, siltstone, sandstone, and limestone. More variable muddy, silty, and sandy sediments were recovered from the crestal areas of both volcanoes. The lowest mud-volcano units drilled include well-sorted medium- to coarse-grained sediments, mainly composed of clay, that were deposited partly by turbidity currents. The mud-volcano sediments are associated with background deep-sea sediments that allow dating by using microfossils. The Milano mud volcano is at least 1.75 Ma, and is apparently now dormant, and the Napoli mud volcano started prior to, or during, 1.5–1.2 Ma and is currently active. Pore fluids at Napoli, and to a lesser extent at Milano, indicate the presence of halite of presumed latest Miocene age beneath the volcanoes. Hydrocarbon gas is venting from the crest of the Napoli mud volcano, and gas was also detected on the crest of the Milano mud volcano. Methane hydrates (clathrates) are also inferred to exist beneath the crest of the Milano mud volcano. The mud volcanoes are located above a shallowly dipping subduction zone in an area where the accretionary complex is apparently being thrust northward over a backstop of continental crust, related to initial collision of the African and Eurasian plates. Mud volcanism may have begun when backthrusting punctured a seal of latest Miocene evaporites, allowing the escape of overpressured materials.

INTRODUCTION

Ocean Drilling Program Leg 160 (March–April 1995) investigated the anatomy and age of mud volcanoes on the northern flank of the Mediterranean Ridge accretionary complex, located ~150 km south of Crete (Emeis et al., 1996, Fig. 1). These features were believed to represent mud diapirism and/or mud volcanism and form part of a regional "cobblestone topography" (Kastens, 1991). Mud volcanoes are commonly recognized in seismic profiles and on surface images of marine sediments, but their internal nature and longevity remain largely unknown. Such areas of active mud volcanism include (1) subduction complexes (e.g., in Barbados, Cascadia, Indonesia [Java, Sumatra, Timor], the Makran; Brown and Westbrook, 1988) and (2) within thick sedimentary basins subject to tectonic instability and/or sediment loading (e.g., Gulf of Mexico, Black Sea; Limonov et al., 1994). The mud volcanoes studied during this leg form part of the "Olimpi Field," which is elongated subparallel to the east-northeast to west-southwest tectonic grain of the Mediterranean Ridge accretionary complex (Camerlenghi et al., 1992, 1995). They were initially documented by Italian expeditions (Cita et al., 1981, 1989), and recently active fluid vents associated with bacteria and other chemosynthetic organisms were discovered (Limonov et al., 1994; Cita et al., 1994, 1995; Corselli and Bossi, 1996).

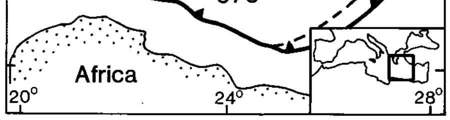

Figure 1. Outline map of Mediterranean Ridge showing location of Milano mud volcano (Site 970) and Napoli mud volcano (Site 971) drilled during Ocean Drilling Program Leg 160; solid line indicates toe of Mediterranean accretionary complex; dashed line marks other tectonic features. Inset: location in the Mediterranean Sea.

Leg 160 investigated two contrasting mud volcanoes, the Milano, which is conical, and the Napoli, which is flat-topped and has flanks surrounded by a shallow moatlike feature. Both are somewhat asymmetric structures. Inward-dipping reflectors underlie the flanks of both volcanoes (Fig. 2). Interpretation of deep-tow side-scan data suggests that individual mud volcanoes vary greatly in scale and size within the "Olimpi Field" (Limonov et al., 1994). In addition to well-defined volcanolike structures, there are large areas of "mud breccias" and "mud domes" that are partly buried beneath pelagic sediments.

During Leg 160 a transect of holes as deep as 200 m was drilled from the flanks to the crest of the Milano and Napoli mud volcanoes at water depths of ca. 2000 m. One relatively deep hole in the flank of each structure was also geophysically logged. The main aim of drilling was to test previous hypotheses that the mud volcanoes were alternatively mud diapirs composed of semirigid protruded material, or depositional structures consisting of fluid-rich sediments. On the basis of piston coring, previous workers had proposed both intrusive and extrusive processes (Camerlenghi et al., 1992; Staffini et al., 1993; Premoli Silva et al., 1996).

MILANO MUD VOLCANO

Nannofossil oozes, nannofossil clays, and sapropels (i.e., organic-rich muds) of early late Pleistocene age were cored at an outermost hole beyond the mud volcano (Hole 970B; Fig. 2A). These sediments are interbedded with poorly consolidated, thin- to medium-bedded sands and silts presumably shed from the mud volcano. Some intervals are tilted, and there are small normal and reverse faults. A hole in the outer flank area (Hole 970A) revealed alternations of clast-rich mud-supported sediments ("mud breccias") and normal hemipelagic sediments (Fig. 3). Using the Formation MicroScanner (FMS), the lowest interval penetrated there was identified as matrix-supported conglomerate. The lowest interval actually cored is pelagic sediment, dated as 1.75 Ma. This is

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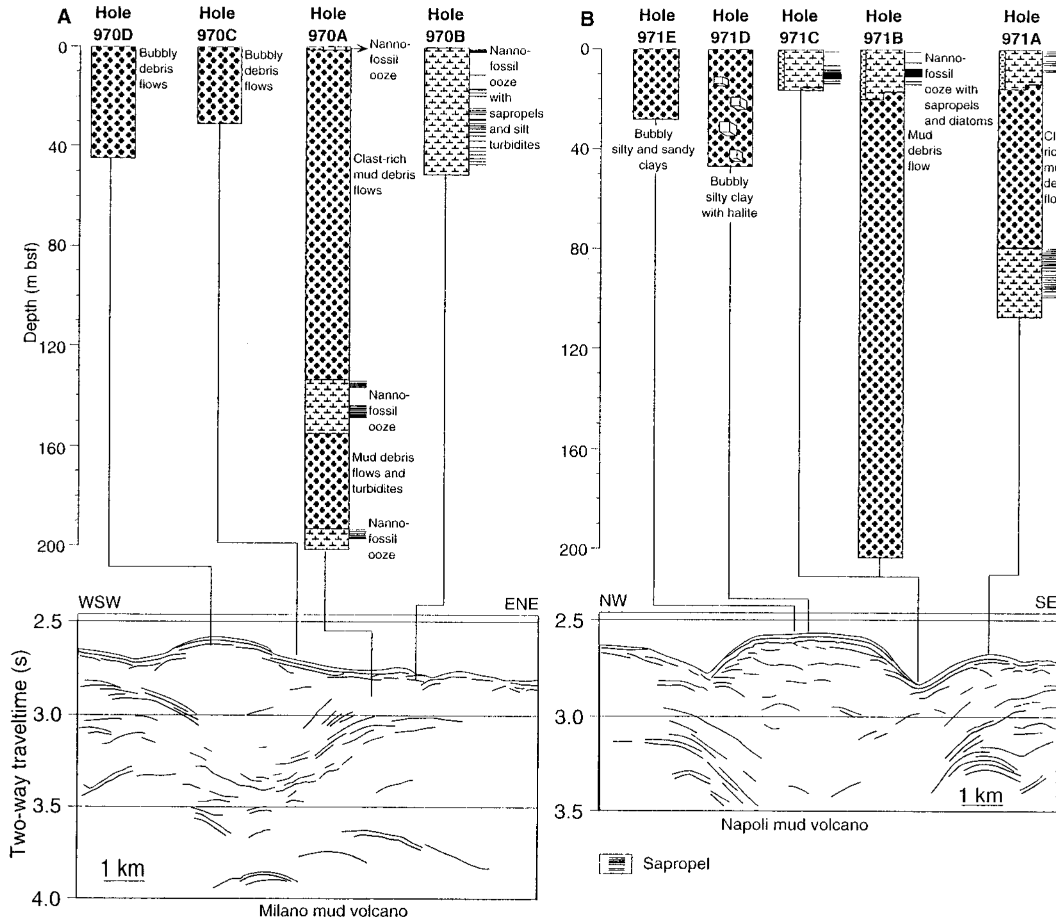

Figure 2. Summary of lithostratigraphy of Milano (A) and Napoli (B) mud volcanoes drilled during Ocean Drilling Program Leg 160. Seismic reflectors visible within two mud volcanoes are indicated. Note presence of inward-dipping reflectors beneath both flanks of Napoli and Milano structures. bsf is below sea floor.

overlain by mud debris flows and coarse-grained turbidites, in which the FMS clearly images numerous clasts (<5 cm to 50 cm in diameter). Overlying these is a thin interval of pelagic sediment, dated as ca. 0.99–1.5 Ma. This, in turn, is overlain by a thick, clast-rich, mud-supported sedimentary interval with local thin sapropels, and finally by an uppermost pelagic interval (<1 m) dated as <0.26 Ma. By contrast, two holes on the inner flank (Hole 970C) and on the crest (Hole 970D) of the Milano mud volcano recovered bubbly (i.e., gaseous) muddy, silty, and sandy sediments.

NAPOLI MUD VOLCANO

A succession on the outer flank (Hole 971A; Fig. 2B) begins with normal hemipelagic sediments and sapropels dated 0.46–1.5 Ma (i.e., within the large *Gephyrocapsa* zone). This interval is followed by clast-rich, matrix-supported sediments, in which the clasts are mainly calcareous and range from several millimetres to a few centimetres in diameter. The succession ends with ~20 m of nannofossil ooze, nannofossil clay and turbidites, dated as <1.5 Ma. Next, a thick unit of matrix-supported clast-rich muddy sediments was recovered on the inner flank (Hole 971B) and dated between 0.26 and 0.46 Ma. Intervals with scattered clasts (<5 cm) alternate with more homogeneous silty clay. Downhole logs (especially natural gamma and resistivity) reveal layers that correspond to relatively sandy intervals. Overlying this are hemipelagic sediments, including sapropels. Hole 971C was drilled at the same location as Hole 971B, revealing an expanded sequence that probably resulted from redeposition of fine-grained sediment from the crestal area of the mud volcano into a surrounding moatlike depression. On the crest of the Napoli mud volcano (Hole 971D), bubbly silty clay was recovered, with scattered small (<5 cm) clasts of mudstone and siltstone. Angular to subrounded clasts of coarsely crystalline halite (up to 3 cm diameter) were noted within thin, silty layers, together with a few subrounded halite-cemented mudstone clasts (<5 cm diameter). Finally, bubbly clays and silts with thin (several centimetres), sandier layers were recovered at another crestal site (Hole 971E), together with a few small (<3 cm) clasts of mudstone and fine-grained carbonate. Rare nannofossils of Pleistocene age are present in the upper part of the section, and reworked Miocene nannofossils are common throughout.

SEDIMENT CLAST AND MATRIX TYPES

Well-consolidated, matrix-supported, clast-rich muddy sediments dominate the flanks of both mud volcanoes (Fig. 3). These are the well-known "mud breccias" of Cita et al. (1981). The matrix ranges from silty clay to rare sandy silt, and includes nannofossils, foraminifers, clay, quartz, and rock fragments. Nannofossils and planktic foraminifer assemblages within the matrix are dominantly of middle Miocene age. However, Eocene, Oligocene, and middle Miocene nannofossils are also present. In addition, Pleistocene microfossils are present in the matrix of the Napoli mud volcano. Clasts vary from mainly subangular to subrounded, and are less-commonly angular, or rounded. Lithologies include poorly consolidated sandstone and siltstone, weakly to well-consolidated calcareous claystone and mudstone, together with calcite- (or locally quartz) cemented sandstone and siltstone. Sandstone clasts are mainly of plutonic igneous and metamorphic origin, and could have been derived from Crete, or North Africa, where similar rocks are exposed. There are also shallow-water carbonate clasts with calcareous algae, polyzoans, and reworked pelagic carbonate. The clasts in both volca-

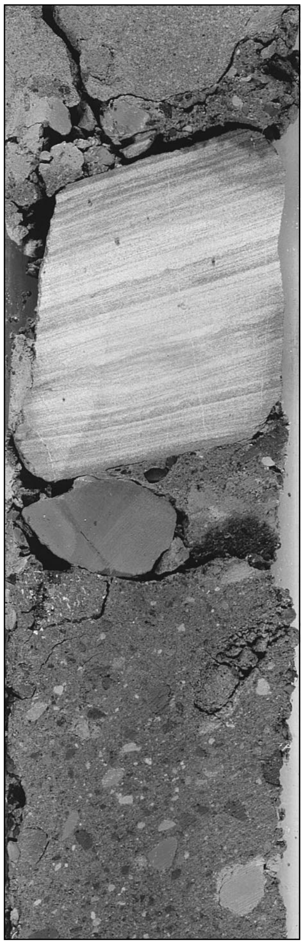

Figure 3. Photograph of cored debris flow "mud breccia." Lower part shows typical clay clasts in muddy and silty matrix. Upper parts include clast of well-lithified laminated quatzose sandstone (fine grained). Sample location: Site 97A, Core 10×, section 1, 55–80 cm.

noes contain the following biota: (1) nannofossils and planktic foraminifers of early-middle Miocene (i.e., Burdigalian-Langhian) age; (2) mixed nannofossil and planktic foraminifer assemblages of middle Miocene, Oligocene, and Eocene ages, together with Cretaceous nannofossils; and (3) brackish-water-type ostracods of late Messinian–early Pliocene age in the Milano mud volcano.

GEOCHEMICAL PROCESSES

The presence of clathrates (i.e., methane hydrates) is inferred in the crest of the Milano mud volcano on the basis of the evidence of abnormally low pore-water salinities (Holes 970C and 970D). These low values are probably due to the decomposition of clathrates that took place immediately after core recovery. Low levels of sulfate in this hole could relate to intense bacterial sulfate reduction in the presence of methane. Pure methane is abundant as gas bubbles in the uppermost 30 m below the crest of the Milano mud volcano (Hole 970D), but methane concentrations drop sharply below this, consistent with the formation of methane hydrate at relatively shallow depths. Levels of higher hydrocarbons also increase downward relative to methane.

Hydrocarbon gas is abundant in the Napoli mud volcano, where methane/ethane ratios vary from 10 to 40 overall and remain constant with depth (Holes 971A, 971B, 971D, and 971E). In contrast to the Milano mud volcano, clathrate was not detected. The gas in the Napoli mud volcano also contains several higher hydrocarbons up to hexane that are currently being identified. Pore waters from the crest holes are saturated with halite. There are marked local variations in potassium content that suggest that brine of more than one source may be present (i.e., in the lower part of Hole 971A). Very high alkalinity throughout (~80 mmol/L in Holes 971D and 971E) probably reflects microbial consumption of methane. Sulfate decreases sharply downward in Hole 971B, probably owing to high rates of bacterial sulfate reduction by methane combined with an organic matter–rich substrate. A single temperature measure ment of 16.1 °C was obtained in Hole 971D at 45 m below the sea floor, which is 2 °C above normal bottom-water temperatures.

DISCUSSION

Several lines of evidence favor the construction of the Milano and Napoli mud volcanoes by mainly extrusive, rather than intrusive, processes (Fig. 4, A and B): (1) the interbedding and lateral interfingering of undisturbed pelagic sediments (at Milano); (2) the absence of evidence of forceful injection (i.e., shearing or scaly clay development; (3) the presence of regular layering of clast-rich and clast-poor intervals, as revealed by the FMS; and (4) systematically younger ages upward in both volcanoes. However, we assume that an intrusive core is likely to be present beneath the crestal areas at greater depths than drilled (>50 m).

Stratified debris flows and turbidites at the base of the Milano flank succession (Hole 970A) are interpreted as a relatively early phase of mud-volcano construction. A reflector of probably latest Miocene age, interpreted as evaporite, is inferred to lie just beneath (>50 m). We hypothesize that the early mud-volcano sediments were erupted as an unstable volcaniclastic cone, subject to slumping and generation of debris flows and high-density turbidity currents. This was followed by copious extrusions of matrix-supported, clast-rich muds, interpreted as subaqueous massive debris flows. These flows were possibly ponded within a bathymetric moat, as is present around the Napoli structure today. Inward-dipping seismic reflectors beneath the flanks of both mud volcanoes dip increasingly steeply downward, which may reflect progressive subsidence during mud volcanism. The crestal sediments at both volcanoes lack major debris flows. A possible explanation is that clast-rich mud flows were erupted on the flanks of the volcano rather than on the crest. An alternative is that crestal debris-flow eruptions bypassed the flank sites. The halite on the Napoli crest was introduced in crystalline form and as halite-cemented clasts, presumably from underlying latest Miocene evaporites.

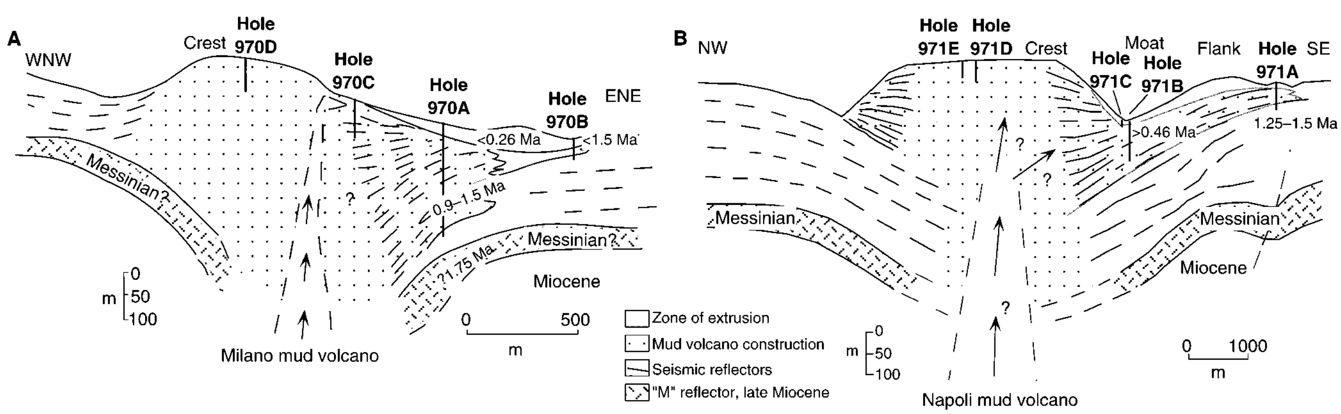

Figure 4. Interpretation of anatomy of Milano (A), and Napoli (B) mud volcanoes. See text for explanation.

Hydrocarbon gases appear to be continuously flowing to the surface of the Napoli mud volcano. Evidence of hydrocarbon gas was also noted on the crest of the Milano mud volcano. The presence of methane hydrates in the crest of the Milano mud volcano (but not at Napoli) could reflect the existence of high pore-fluid temperatures and salinities (up to 300 g/kg) that were sufficiently high to suppress clathrate formation.

TECTONIC SCENARIOS

Modern marine mud volcanoes elsewhere (e.g., Barbados, Cascadia, Gulf of Mexico) are characterized by extremely thick, rapidly deposited, and hence overpressured sedimentary piles. Within accretionary complexes the main engine of mud volcanism is subduction. There is increasing evidence that the angle of dip of the subduction zone below the Mediterranean Ridge is unusually shallow, i.e., $<5°$ (Kastens et al., 1992; De Voogd et al., 1992; Dickman et al., 1995; Mascle et al., 1995). An alternative view is that the angle of subduction is steeper (i.e., $>20°$) (Hirschleber et al., 1994; Camerlenghi et al., 1995). In the shallow-dip subduction model, mud-volcano material could have been derived from relatively shallow depths of 5–7 km. Preliminary petrographic and clay mineralogical studies do not reveal obvious evidence of deep-burial diagenesis or metamorphism of either the clasts or the matrix of the mud volcanoes (Robertson et al., 1996). Instead, the age and character of the clasts are consistent with derivation from a relatively shallow, partly Miocene succession beneath. The higher hydrocarbons could have flowed laterally from greater depths within the accretionary wedge.

In a simple model, the mud volcano material was possibly expelled above a shallowly dipping subduction zone. The decollement may have been located within latest Miocene evaporites, in which case Miocene sediment could have come either from the downgoing slab or from the overlying forearc basin. However, there are several complicating factors: (1) the Mediterranean Ridge was draped by evaporites in the latest Miocene (Kastens et al., 1992), and evaporites are thought to underlie both mud volcanoes; (2) the Mediterranean Ridge is believed to be in the process of collision with the African plate; and (3) the mud-volcano field is believed to lie in an area of backthrusting of the Mediterranean Ridge accretionary wedge over a backstop of continental crust to the north (Truffert et al., 1993; Camerlenghi et al., 1995). In addition, translational tectonics may play a role in this area (Limonov et al., 1994). The actual tectonic setting is thus potentially complex and remains poorly understood. One possibility is that mud volcanism was initiated when backthrusting punctured a seal of latest Miocene evaporite, allowing overpressured materials to escape. Eruption was initially forceful, apparently building up a clastic cone, and was followed by more quiescent extrusion of much larger volumes of mud-debris flows. Post-cruise work to resolve outstanding problems is in progress.

CONCLUSIONS

Activity of the Milano mud volcano began at or before 1.75 Ma, and it is probably now dormant, whereas the Napoli mud volcano dates from prior to or during 1.5–1.2 Ma and is currently active. A lower clastic interval at Milano may relate to early eruption and was followed by more quiescent extrusion of multiple mud-debris flows that interfinger with surrounding hemipelagic sediments. Contrasting relatively fine grained, clast-poor, muddy, silty, and sandy sediments accumulated on the crestal areas of both mud volcanoes. The presence of underlying Messinian salt is indicated by saturated pore-fluid compositions at both Napoli and Milano and by the evidence of halite clasts at Napoli. We saw evidence of active venting of hydrocarbon gas at Napoli, and minor gas is present at the Milano crestal site. Methane hydrates are inferred to be present at Milano, but not at Napoli. The driving force in mud volcanism was possibly collision-related backthrusting of the Mediterranean Ridge accretionary complex that may have punctured a seal of Messinian evaporate and allowed overpressured materials to escape.

ACKNOWLEDGMENTS

We thank all those who sailed with us on the *Joides Resolution*, especially the marine technicians, for their invaluable support. Casey Moore provided helpful comments on an earlier draft of the manuscript.

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Manuscript received June 28, 1995
Revised manuscript received December 7, 1995
Manuscript accepted December 19, 1995