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The Modena-Reggio mud volcanoes (northern Italy): an actualistic model for the interpretation of Miocene authigenic carbonates related to fluid expulsion

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Abstract

The paper examined physical, geochemical and geological features, and fluid expulsion processes of fossil seep carbonates and recent mud volcanoes in the northern Apennines. Chaotic brecciated deposits associated with short "eruptive" periods of the Modena-Reggio mud volcanoes (Regnano) are debris flows made of polygenic breccias floating in a viscous mud. These deposits show a number of analogies with monogenic and polygenic brecciated lithofacies of the Miocene methane derived authigenic carbonates of the northern Apennines. Similarities between the examined fossil seep carbonates and mud volcanoes include also the type of fluids which consist mainly of methane mixed with connate waters and clay mud, and their isotopic signatures strongly depleted in $\delta^{13}C$ values.

The comparison between recent and fossil diapiric-related structures has been useful for constraining the nature of the fossil seepage pathway, understanding fluid expulsion processes and reconstructing models of chemoherm evolution. In particular, this investigation suggests that brecciated structures and exotic clasts in ancient chemoherms are due to the offscraping and chaotic mixing of sediments during the rapid rise of methanogenic fluids along diapiric conduits or fractures, following similar processes and mechanisms as in chaotic deposits associated with mud volcanoes.

Key words: Mud volcanoes, Polygenic breccias, Chemoherms, Northern Apennines, Miocene.

Introduction

Mud volcanoes are conical, slightly elevated edifices formed as a result of the emission of argillaceous material and fluids (water, brine, gas, oil) on the Earth's surface or on the sea floor (Milkov, 2000). Diapiric processes related to mud volcanoes are responsible for the genesis of many chaotic deposits, such as mélanges, chaotic breccias and various deformed sediments (Barber et al., 1986; Barber and Brown, 1988; Orange, 1990; Brown and Orange, 1993).

The usual activity of mud volcanoes consists of gradual and progressive outflows of semi-liquid material called mud breccia or diapiric mélange. Explosive and paroxysmal activity are interpreted as responsible of ejecting mud, ash and decimetric-metric clasts. Mud volcano breccias are composed of a mud matrix, which supports a variable quantity of chaotically distributed angular to rounded rock clasts, ranging in diameter from a few millimeters to several meters (Camerlenghi et al., 1992; Dimitrov, 2002). Clasts are of various lithologies and provenances, being derived from rocks through which the mud has passed on its way to the surface or to the sea floor. Slumps and slides can also affect the entire structure of the mud volcanoes, even if gradients are very low.

The occurrence of mud volcanoes is controlled by several factors, such as tectonic activity, sedimentary loading due to rapid sedimentation, the existence of thick, fine-grained sediments and continuous hydrocarbon generation (Treves, 1985; Ivanov et al., 1996; Limonov et al., 1996; Milkov, 2000; Dimitrov, 2002).

Present-day submarine mud volcanoes are often associated with peculiar biological and geological features, such as chemosynthetic communities, methane-derived authigenic carbonates and chaotic breccias, and with gas hydrates (Reed et al., 1990; Fusi and Kenyon, 1996; Olu et al., 1997; Lance et al., 1998; Orange et al., 1999; Aloisi et al., 2000; Kopf et al., 2001; Ben-Avraham et al., 2002; Bohrmann et al., 2002; Mazurenko et al., 2002; Van Rensbergen et al., 2002; Wiedicke et

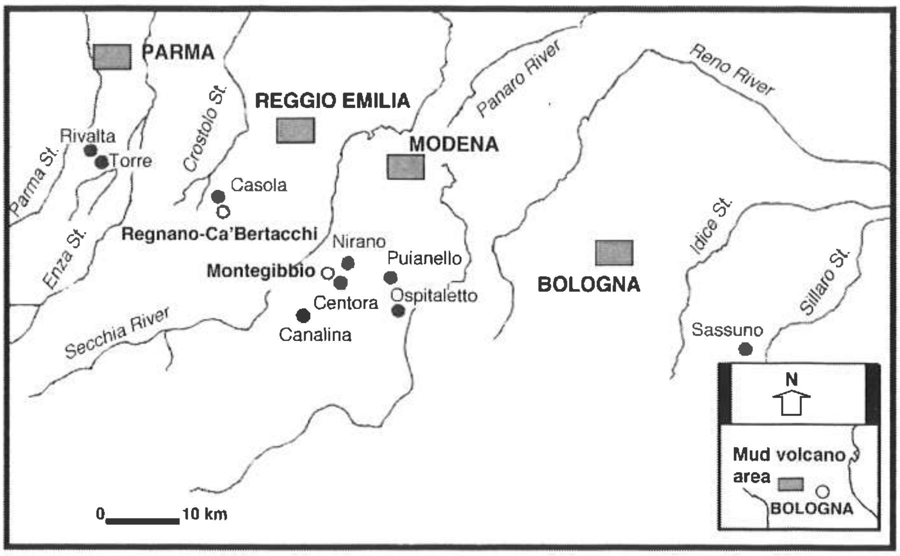

Fig. 1 - Distribution of subaerial mud volcanoes (black circles) in Emilia-Romagna Apennines: blank circles indicate the studied mud volcanoes.

al., 2002). For these reasons, the morphology and distribution of fossil methane-derived carbonates (chemoherms) and the associated brecciated structures (Goedert and Squires, 1990; Beauchamp and Savard, 1992; Bitter et al., 1992; Gaillard et al. 1992; Campbell and Bottjer, 1993; Kelly et al., 1995; Kauffmann et al., 1996; Peckmann et al., 1999) have been interpreted as indicators of palaeoseep occurrences (Aiello et al., 2001; Conti and Fontana, 2002).

In the northern Apennines, many carbonate authigenic deposits (chemoherms) are concentrated in middle-late Miocene pelitic successions of epi-Ligurian satellite and foredeep basins (Ricci Lucchi and Vai 1994; Conti and Fontana, 1998, 1999a, 1999b). These carbonate bodies have a negative carbon isotope composition ($\delta^{13}C$ values range from -20‰ to -60‰ PdB), and often contain a chemosynthetic fauna indicating a methane-related origin for the carbonates (Clari et al., 1994; Taviani, 1994; Terzi et al., 1994; Conti et al., 1996; Cavagna et al., 1999); monogenic and polygenic breccias are a common feature.

The present study aims to compare the Modena-Reggio mud volcano polygenic breccias with similar structures in the Miocene cold seep carbonates of the northern Apennines. The comparison between recent and fossil diapiric-related structures can improve understanding of the genesis of peculiar chaotic deposits associated to chemoherms.

Mud volcanoes of the northern Italy

Northern Italy subaerial mud volcanoes are reported since the historical descriptions of Pliny, Spallanzani (1795), Biasutti (1907), and Stoppani (1908). Mud volcano list was updated by Mucchi (1966) and Scicli (1972); further observations are published by Ferrari and Vianello (1985) and Martinelli (1999). They occur along the external compressional margin of the Apennine chain and are concentrated in the Emilia-Romagna Region (Parma, Reggio Emilia, Modena and Bologna Apennines) (Fig. 1). The distribution of mud volcanoes and other spontaneous hydrocarbon emissions follows two main Apennine-oriented (NW/SE) belts (Borgia *et al.*, 1986; Minissale *et al.*, 2000). The first belt is located along the Po Plain foothills, the second one is more internal and runs nearly parallel to the main Apenninic divide. Mud volcanoes prevalently crop out in argillaceous dominant rock types belonging to different tectonic and stratigraphic units of the Apennine chain.

Apennine mud volcanoes are characterized by various morphological features; usually cones do not exceed the height of 50 cm except for Nirano and Regnano, and quasi-desert open areas (tassik of Higgins and Saunders, 1974) rarely reach several thousands square meters. Main vents are typically associated with lateral or satellite craters; sometimes they collapse to form a caldera-type crater which can be filled up by water

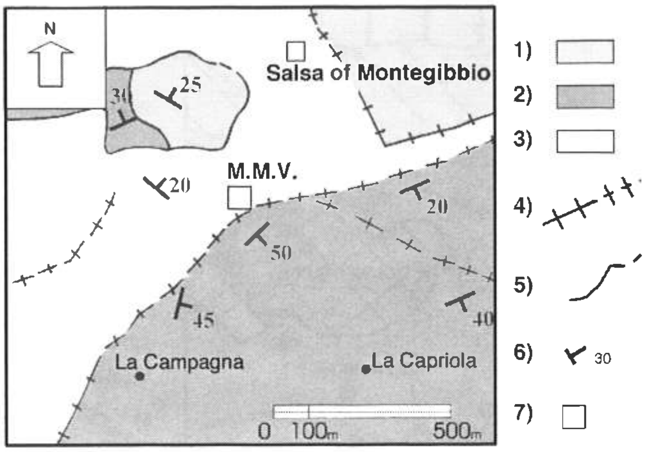

Fig. 2 - Schematic geological map of the area around Montegibbio mud volcano (M.M.V.).
Legend: 1) Pliocene units (Petrolio Stream Shales); 2) epi-Ligurian units (Ranzano, Antognola, Bismantova and Termina Fms); 3) basal epi-Ligurian mélanges (Val Fossa and Val Tiepido Mélanges); 4) vertical fault (dashed when inferred); 5) stratigraphic boundary (dashed when inferred); 6) bedding; 7) mud volcano.

forming small pools bubbling clay and gas (called salses). Gas is composed dominantly of methane with minor amounts of carbon dioxide, hydrogen sulphide and nitrogen (Gorgoni, 1998). The activity of subaerial Apennine mud volcanoes shows similarities with submarine mud volcanoes: short violent eruptions (few hours or days) alternate with long periods (decades) of quiescence with quiet degassing and fluid emission (Gorgoni, 1998; Martinelli, 1999). Type of emission and extruded materials reflect the pattern of activity. Eruptive and paroxysmal periods are characterized by large volumes of chaotic sediments ranging from mud breccia with scattered clasts (grain-size varying from a fine-grained sand to pebble) to polygenic breccias (pebble and cobble size) with a muddy matrix (Montegibbio, Regnano).

Methane outbursts and explosive extrusions are particularly intense during seismic activity, suggesting a close link between gas expulsion and tectonic events. Quiescence periods are characterized by gas-rich saline waters, liquid hydrocarbons and mud emissions with scarce sand-size rock fragments. The geological setting also controls the type of emission. Fluid mud emissions are dominant in mud volcanoes related to argillaceous geological substratum (Plio-Quaternary blue-grey claystones), whereas lithified rock fragments occur in mud volcanoes related to a substratum with a prevailing block-in-clayey matrix texture (sedimentary mélanges within Ligurian and epi-Ligurian formations).

The Montegibbio and Regnano mud volcanoes

Geological setting

The Montegibbio mud volcano is located on a gentle slope on the foothills near Sassuolo in the Modena Apennines (Fig. 1). It occurs in the basal epi-Ligurian mélanges (Val Fossa and Val Tiepido Mélanges), interbedded at the base of the Mt Piano Fm (epi-Ligurian Sequence) and derived from submarine debris and mud flows (Bettelli and Panini, 1989) (Fig. 2). These chaotic deposits are composed of a heterometric polygenic breccia with a varicoloured shaly matrix; the clasts are shale and silty shale blocks, fine to coarse-grained sandstones, siliceous calcilutites, siltstones, green and pink marly limestones, ranging from few millimetres to 25-30 cm. Provenances are from Ligurian and epi-Ligurian formations. In the north-eastern side, a vertical tectonic contact separates the Val Fossa Mélange from the Pliocene Petrolio Stream Shales and Termina Marls (Fig. 2). In the southern side, the Val Fossa Mélange is in tectonic contact with the Ranzano and Antognola Formations of the epi-Ligurian sequence. The geological setting is also complicated by the presence of normal and strike-slip faults that intersect the mud volcano area. All the area around the Montegibbio mud volcano is rich of fluid emissions (Gasperi et al., 1989; Capozzi et al., 1994).

The Regnano mud volcano is located on the axis of the Viano syncline (Fig. 3), at the inter-

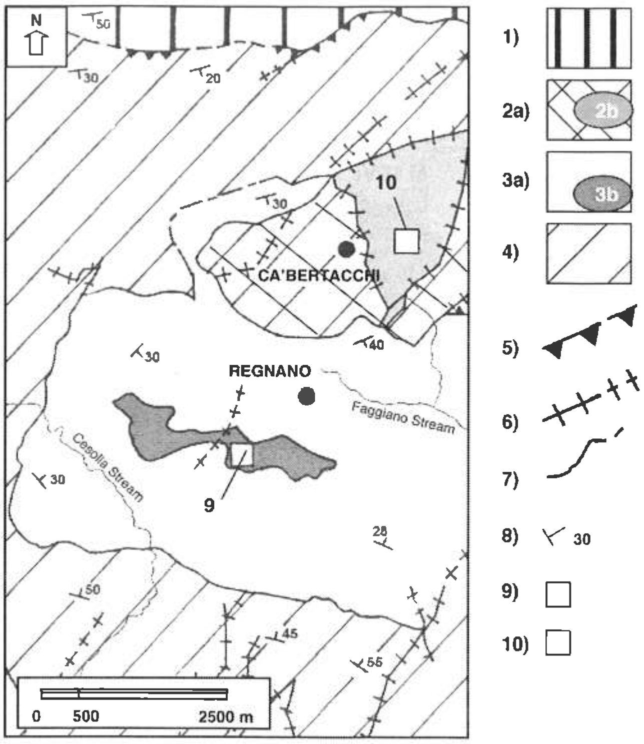

Fig. 3 - Schematic geological map of the Viano syncline, with the location of the Regnano and Ca' Bertacchi mud volcanoes. Legend: 1) Messinian/Pleistocene units (Gessoso-Solfifera Fm., Lugagnano Clays); 2a) upper epi-Ligurian units: Antognola Fm. with the Grassano Mélange (2b), and Bismantova Fm; 3a) lower epi-Ligurian units: Monte Piano and Ranzano Fms. with a sedimentary mélange (3b) composed of chaotic polygenic breccias with a mud matrix of Ligurian provenance; 4) Ligurian units (Palombini Shales, Varicoloured Shales, Scabiazza Sandstones, Monte Cassio Flysch, Viano Shales); 5) thrust fault (dashed when inferred); 6) vertical fault (dashed when inferred); 7) stratigraphic boundary (dashed when inferred); 8) bedding; 9) Regnano mud volcano; 10) Ca' Bertacchi mud volcano.

section of minor faults and one important fault ortogonal (SW-NE) to the axis of the Apennine chain (Capozzi and Picotti, 2002). The Viano syncline has a WNW/ESE trend and includes mainly Ligurian and epi-Ligurian deposits with a thickness of about 1500 m. From bottom to top Ligurian units are represented by Palombini Shales, Varicoloured Shales, Scabiazza Sandstones, Monte Cassio Flysch and Viano Shales. The epi-Ligurian deposits include the Mt Piano and Ranzano Fms with intercalations of chaotic deposits. The Regnano mud volcano occurs on top of a sedimentary mélange composed of chaotic polygenic breccias with a mud matrix of Ligurian provenance, testifying a close relationship between extruded sediments and substratum typology. A second mud volcano (Ca' Bertacchi) is located in a sedimentary mélange (Grassano Mélange) intercalated within the Antognola Fm of the epi-Ligurian sequence (Fig. 3). On the northern limb of the Viano syncline, Ligurian units and associated epi-Ligurian deposits overthrust deformed Messinian clastics; the Upper Pliocene-Lower Pleistocene mudstones unconformably cap the eroded ramp anticline associated with this thrust.

Morphology and activity

The Montegibbio and Regnano mud volcanoes in the Modena-Reggio Apennines alternate periods of slow continuous mud expulsion, with gas bubbles and liquid hydrocarbons, with periods of paroxysmal activity with poligenic breccia extrusion (Gorgoni, 1998).

At present, the explosive processes of the Montegibbio mud volcano are exhausted (the last paroxystic event was documented at the end of nineteenth century) and the volcano activity consists of two little springs of liquid muds. Field survey around the mud volcano reveals the characteristic conical shape and the presence of scattered clasts (variable in size from cm to dm) of Ligurian provenance. Historical reports (see Gorgoni, 1998) describe numerous phases of paroxystic activity, accompanied by tremors and rumbles and by the ejection of clasts and rocks of different shape and size forming a chaotic mud-matrix breccia with abundant decimetric clasts. During these periods it has been also documented an increasing volume of expelled mud, and the main cone was about 3 meters high, with many satellite vents around it.

The Regnano mud volcano area (0,5-1 km^2)

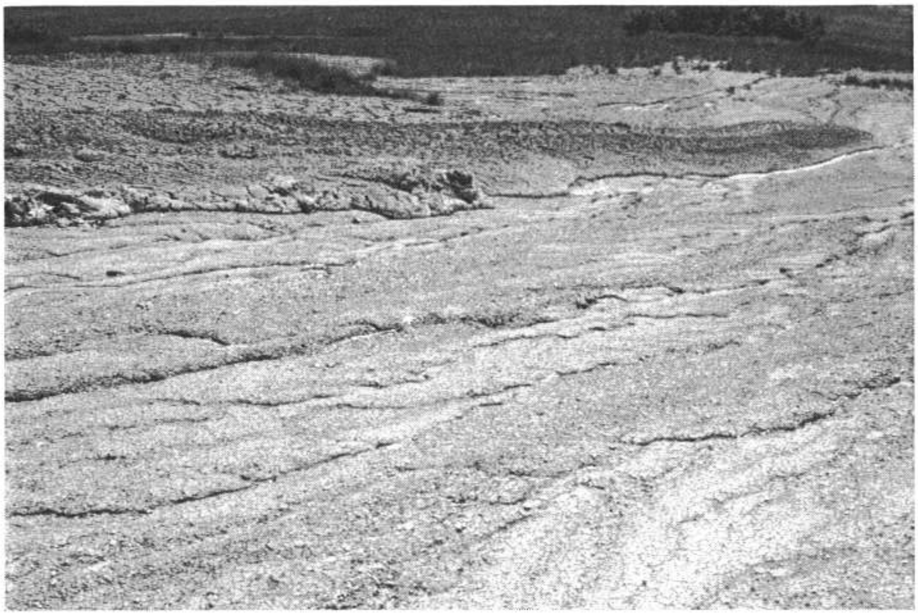

Fig. 4 - Regnano mud volcano: mud flow sheets and lobes. Note chaotically distributed clasts in the flows.

consists of the superposition of several sheets of broad fan-shaped or tongue-like mud breccia flows (Figs 4, 5), extending for 1 km towards the valley of the Tresinaro Stream. At present, mud volcano is spreading-out a very liquid mud with bubbles of gassy hydrocarbons. Capozzi and Picotti (2002) indicate that fluids consist of methane, oil and "saline" connate waters mixed with clay mud; the range of temperature of the saline water is in equilibration with the temperature of the surrounding fluid. Isotopic analyses of the fluid show strongly depleted $\delta^{13}C$ values.

The main vent has a conic shape and is few meter high (2-3 m); few craters and two little active satellitary cones with springs of muddy water also occur. The morphology of the main cone ra-

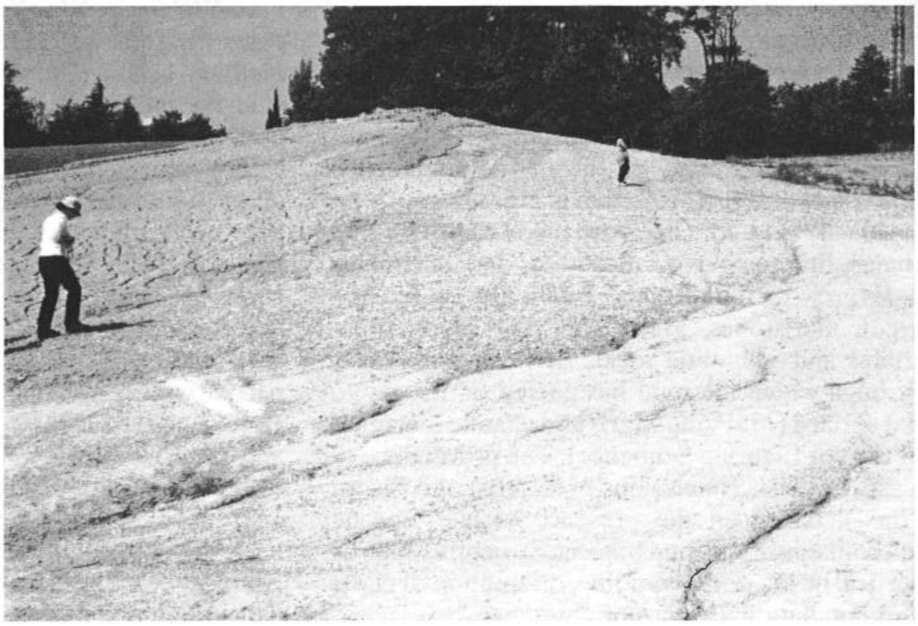

Fig. 5 - Regnano mud volcano: main cone and mud breccia flows.

Fig. 6 - Regnano mud volcano: particular of the polygenic breccia made up of angular to subangular clasts.

pidly evolves as a result of mud expulsion processes. At the end of 80's, the mud volcano complex was formed by a large spring of liquid muds with a minor cone near the top of a gentle mound. In the spring of 1999 the mud volcano had a paroxystic activity, with rumbles and tremors, related to Apennine earthquakes. In this event, the mud flows and sheets (2 meter-high and 200 meter-long, with a plano-conical shape) included high amounts of clasts of various lithologies, shapes and sizes (Fig. 6). The mud viscosity is related to the precipitation rate, the percentage of gassy hydrocarbon, and clasts.

Mud volcano breccia is composed of a light grey to brown mud matrix, supporting variable amounts of chaotically distributed angular to moderately rounded clasts of heterogeneous lithologies and size (15-20 cm in average, rarely up to 40 cm) (Fig. 6). Clasts are made of brown silty shales, fine to coarse sandstones, dark siltstones, pale grey to dark veined calcilutites, pink and green marlstones, green and pink marly limestones and ophiolitic rocks, deriving from rocks through which the mud has passed on its way to the surface (Mt Piano Marls and chaotic mélanges of the epi-Ligurian Sequence). The provenance of clasts confirms conclusions of Capozzi and Picotti (2002), based on the presence of late Eocene microfossils in the mud breccia. Structures such as vertical or horizontal grading, orientation of clasts and lamination are rare or absent.

Cold seep carbonates

Discontinuos carbonate masses and blocks called "*Lucina* limestones ", cropping out in the Tuscan-Romagna region of the northern Apennines, are interpreted as fossil equivalents of modern methanogenic carbonate bioaccumulations (Clari et al., 1994; Terzi et al., 1994). Bacteria play an important role in the precipitation of these authigenic carbonates: *Lucina* limestone communities were sustained by the sulphide generated in the pore waters of the sulfate-reducing zone through anaerobic bacterial oxidation of methane seepage; methane-oxiding bacteria provide the energy source for sulfate reducers and both processes result in the production of bicarbonate and hydrogen sulfide. Several features allow to interpret "*Lucina* limestones" as a fossil equivalent of the sedimentary products of present-day colds seeps (crust, slabs, mounds and chimneys of authigenic carbonates and sulphides), that have been discovered on the sea floor in a great variety of geological settings both along passive continental margins (Hovland et al., 1987; Brooks et al., 1987; Roberts et al., 1990, Roberts and Aharon, 1994; Paull et al., 1995; Barry et al., 1996) and in the accretionary prisms associated with active continental margins (Kulm et al., 1986; Ritger et al., 1987; Sibuet et al., 1988; Corselli and Basso, 1996). These features are: (1) unique fauna depending on chemosynthesis as the principal

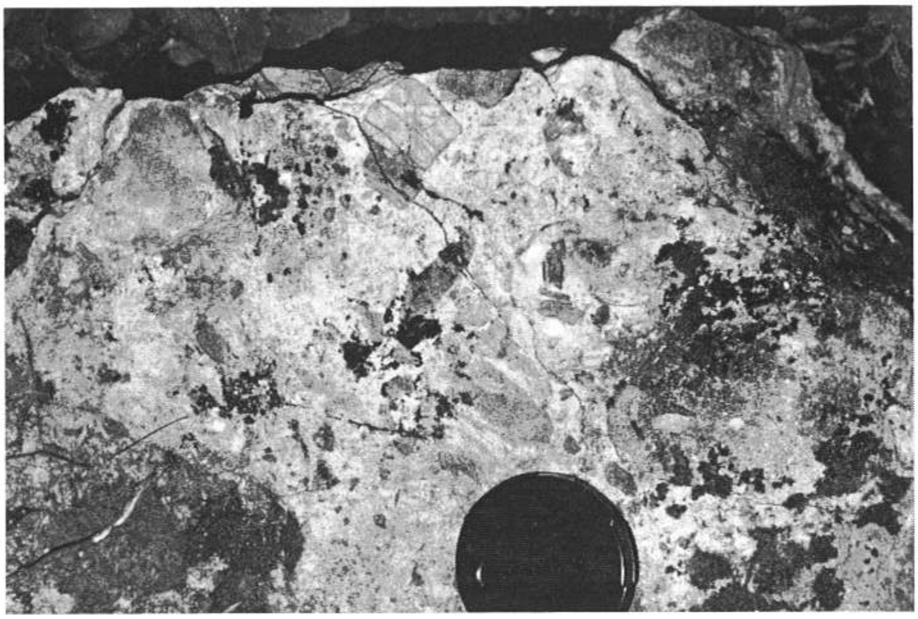

Fig. 7 - Fossil extraformational polygenic breccia (seep carbonates of the epi-Ligurian Sequence): clasts derive from Ligurian and epi-Ligurian formations.

metabolic pathway (Mac-Donald et al., 1989); (2) anomalously negative carbon isotope composition of the carbonates derived from oxidized hydrocarbons ($\delta^{13}C$ values = -16‰ to -58 ‰ PDB from Terzi et al., 1994); (3) compositional and sedimentological similarities with carbonates from cold vents in modern oceans. The fossil carbonate blocks, varying in lithology from limestones, marly limestones, calcareous marls to calcarenites and calcareous sandstones, consist of authigenic carbonates (calcite, dolomite and aragonite), associated with variable amounts of sulphides (pyrite), and allogenic silicates. Carbonate blocks occur within fine-grained turbidites and hemipelagites deposited in the northern Apennine foredeep (Cervarola, Marnoso-arenacea Fm and associated closure pelites) and satellite epi-Ligurian basins during middle-late Miocene (Conti and Fontana, 1998, 1999a, 2002). Carbonate buildups (chemoherms of Roberts and Aharon, 1994) show a variety of morphologies: lenticular-amygdaloid or scattered irregular bodies, pinnacles, irregular thickened levels ranging in diameter from a few centimetres to several decametres. The maximum thickness is about 30 m. Inside chemoherms, numerous large shells and internal moulds of mussels and clams are present, with articulated and disarticulated valves often densely packed.

Two types of chaotic breccias can be distinguished in fossil chemoherms: polygenic and monogenic intraformational breccias. Breccias are clast-to matrix-supported; they form units ranging in thickness from some centimetres to a few metres, randomly distributed and often interdigitated with fine-grained carbonate cemented sediments, and in some cases involved in debris or grain flows. Fluidal textures are observed. The clast-supported breccias are cemented by iron-free sparry calcite. In the matrix-supported breccias the space between clasts is commonly filled by sandy sediment from the surrounding rocks or, in the case of wide spaces, with bivalve coquina. Breccia levels may contain scattered fossils and are commonly intercalated with carbonate levels rich in disarticulated and/or articulated shells.

Polygenic breccias - Clasts are of various origin, both extraformational and intraformational, chaotically floating in the authigenic micritic matrix. The lithic population is dominated by carbonate, pelitic and arenaceous rock types; fossils are rare and usually disarticulated or made of bivalve coquina in micrites or grainstones. Clasts are heterometric (from some mm to 30-40 cm in diameter) generally angular, rarely subangular or moderately rounded. In some cases clast size gradually decreases from the base to the top of chemoherms. This type of breccias is located at the base of carbonate masses usually included in sedimentary intervals characterized by various kinds of sediment instability and chaotic deposits (Conti and Fontana, 2002). Extraformational clasts are from various sources such as Ligurian,

Fig. 8 - Fossil intraformational polygenic breccia (seep carbonates of the Marnoso-arenacea foredeep): clasts derive from the same carbonate rocks of chemoherms or from the intraformational lithotypes of the surrounding foredeep turbidites and hemipelagites. Note disarticulated clams and clasts of various dimensions.

sub-Ligurian, epi-Ligurian or foredeep arenaceous turbidites (Tuscan units) older than those including chemoherms; allochthonous clasts can also derive from olistostromes slid off Ligurian nappe front and intercalated within foredeep or epi-Ligurian sequences (Fig. 7). Intraformational clasts are made of chemoherm carbonates or are supplied by lithotypes of the surrounding foredeep turbidites and hemipelagites enclosing chemoherms (Fig. 8). Polygenic intraformational breccias occur at several levels of the authigenic carbonatic bodies, interfingered with fine-grained carbonates.

Monogenic intraformational breccias - Heterometric angular clasts, ranging in size from some mm to 5-10 cm, brown to yellow in colour, are composed of the same authigenic micrite of the chemoherms (Fig. 9). Fossils are usually reworked and disarticolated; layers of shell detritus are also present. In many cases, monogenic breccias pass gradually to a dense network of non-systematic carbonate-filled veins and microfractures, irregularly connected to pipes and conduits.

Several studies indicate that seep carbonates are usually associated with other indicators of fluid emission, and particularly with mud volcanoes (Jollivet et al., 1990; Kobayashi et al., 1992; Olu et al., 1997; Cavagna et al., 1998; Orange et al., 1999; Aloisi et al., 2000, Milkov, 2000). The corings on the flanks of submarine mud volcanoes show the interlayering of chaotic mud flows and pelagic sediments, confirming that during paroxysmal periods chaotic brecciated deposits are extruded. Mud domes and volcanoes, being a preferential pathway for methane-rich rising fluids, often contain gas-hydrate bearing sediments and are the locus of abundant authigenic precipitation of carbonates. In addition, diapiric processes generating mud volcanoes are considered to be responsible for the genesis of many chaotic deposits, such as diapiric mélanges, chaotic mud flows and breccias and various deformed sediments, previously interpreted as sedimentary olistostromes or tectonic mélanges (Barber et al., 1986; Barber and Brown, 1988; Orange, 1990; Ujiiè, 2000). In this view, many fossil chaotic deposits, especially when associated with seep carbonates, could be related to fluid diapirism (Dela Pierre et al., 2002).

Origin of brecciated structures: the role of fluid expulsion mechanisms

The main driving mechanisms for mud volcano formation are related to high pore-fluid pressure and density inversion. Brown and Westbrook (1988) and Brown (1990) pointed out that the abundance of methane in many mud diapirs greatly assists in propelling mud breccias because of the reduction in viscosity and density associated

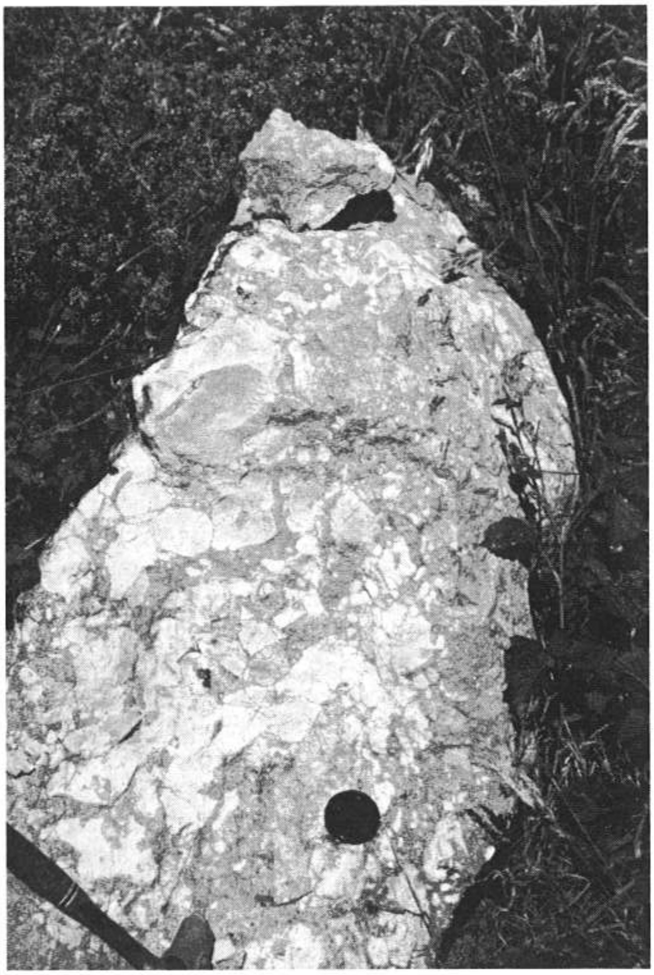

Fig. 9 - Fossil intraformational monogenic breccia (seep carbonates of the Marnoso-arenacea foredeep): clasts derived from the autobrecciation of the authigenic micrite of the chemoherms.

with the expansion of methane bubbles. High pore-fluid pressure, induced by tectonic stresses and/or sedimentary processes such as expansion of gases trapped in fine-grained sediments, plays an important role. Hydrofracturing caused by pore-fluid pressure leads to the formation of mud breccias and chaotic deposits (Pickering et al., 1988; Brown and Orange, 1993). High values of pore-fluid pressure influence also the intensity and style of eruptive processes: large clasts are extruded during maximum paroxysmal periods (Dimitrov, 2002).

In the Regnano mud volcano (Capozzi and Picotti, 2002), clast provenances indicate that breccia originates from the base of epi-Ligurian sequence (Mt Piano and Ranzano Fms.), which enclose intercalations of sedimentary mélanges with chaotic polygenic breccias in a mud matrix. The Regnano mud volcano occurs on top of these chaotic deposits, thus suggesting a relationship between extruded sediments and substratum typology. Mud breccias with polygenic clasts are associated with a geological substratum including sedimentary mélanges and olistostromes. It is possible that the block-in-matrix textures of these poorly consolidated chaotic deposits favour the extrusion of exotic sediments and the upward migration of fluids. Paroxysmal activity is probably related not only to high-pore fluid pressure but also to a cap action of an high concentration of angular clasts: during quiescent periods only fluid mud can be extruded resulting in an impoverishment of the muddy matrix and consequently in relatively higher concentration of blocks. After this phase violent outbursts of blocks and clasts, usually in correspondance with seismic events, took place.

Similar driving mechanisms can be invoked for the formation of fossil brecciated carbonates: variable flow rates, due to different values of pore-fluid pressure, controlled carbonate precipitation as laminated crusts, in or near the mouth of methane seep on the sea floor, and gas ponding and explosion resulting in different styles of brecciation. As hydrocarbon-rich fluids and gases are slowly transported to the seafloor, microbial communities oxidize the hydrocarbons and induce the precipitation of authigenic carbonates (micrite facies with articulated fossils). Monogenic breccias suggest in situ brecciation of semi-consolidated sediment and mark sites where methane is episodically and explosively released at shallow subsurface depth during moderate to rapid flux of fluids. Strong vertical fluxes of fluids induce conditions prone to polygenic breccias and chaotic mixing of sediments. Confirming this, only disarticulated fossils or coquina debris occur in brecciated lithofacies. Intense expulsion events are episodic, each flow deposit has a limited hydrocarbon charge and sulphide-producing potential and alternates with large accumulations of bivalve communities. Polygenic breccias reflect an intense activity of extrusion and explosion, with the tearing off of clasts of the surrounding deposits (host sediments or chemoherm facies) or with the raising and chaotic mixing of underlying exotic sediments during the rapid fluid rise along diapiric conduits or fractures. An intense sediment instability, probably related to fluid expulsion processes (Conti and Fontana, 2002), is responsible for the genesis of polygenic extra-formational breccias because of the emplacement of submarine slides of extraformational source in seep environments (foredeep and epi-Ligurian basins). The association of extraformational clasts cemented by authigenic carbonates and chemoherm lithofacies, and their distribution in limited outcrops of lenticular or pinnacle-like morphology, can be explained supposing a vertical sediment mixing related to diapiric and fluid expulsion processes. Chaotic deposits related to gravitational mass transports show a wider lateral extension and distribution and, in some cases, a more regular internal organization.

Following the diapiric driving mechanism, chaotic deposits associated to seep carbonates, such as sedimentary mélanges or debris flow deposits could be reinterpreted in the light of shale diapirism. On the other hand mud diapirism and fluid expulsion can cause large scale gravity driven mass movements.

Therefore, a number of mechanisms, including fluidization of sediments and reworking for gravity mass transport, may operate to induce some type of brecciation or chaotic deposits.

Conclusions

Documentation of composition and architecture of polygenic breccias actually extruded from craters of the Modena-Reggio mud volcanoes has allowed insight into the genesis of similar chaotic deposits associated with ancient cold seep chemoherms in the northern Apennines.

Both cold seeps and mud volcanoes result from the rising and expulsion of variable amounts of hydrocarbon-rich fluids at the sea floor or in emerged areas, and are the locus of abundant brecciated sediments.

In the light of this preliminary inspection on northern Italy mud volcanoes, the Regnano and Montegibbio mud volcanoes result of particular interest because of the typology of paroxysmal activity. They show the same pattern of activity as submarine mud volcanoes: they present short eruptive periods with emission of chaotic breccias floating in a viscous mud, thus producing debris flows. Polygenic breccias extruded from their cones and craters show sedimentological features similar to monogenic and polygenic brecciated lithofacies observed in fossil methane-derived carbonates. These similarities indicate that auto-brecciated structures and exotic sediments in fossil chemoherms are probably related to the mixing of sediments during the rapid fluid rise along diapiric conduits or fractures, following the same processes and mechanisms as in chaotic deposits associated with shale diapirs and mud volcanoes.

Fossil seep carbonates and mud volcanoes not only represent the result of similar fluid expulsion processes but also share several physical, geochemical and geological features such as: - fluids consist of "saline" waters (connate waters), hydrocarbon gases (primarily methane) and oil mixed with clay mud; - isotopic analyses show strongly depleted $\delta^{13}C$ values; - the presence of a population of active sulphate reducing bacteria (by comparison with modern seep carbonates); - the occurrence of chaotic deposits and polygenic breccias; - the existence of thick, fine-grained, plastic sediments in the enclosing sedimentary succession; - the control of tectonic activity.

Our data also suggest a relationship between extruded sediments and substratum typology:

mud breccias with polygenic clasts are associated with a geological substratum including sedimentary mélanges and olistostromes. It is possible that the block-in-matrix textures of these poorly consolidated chaotic deposits favour the offscraping of exotic sediments and also the upward migration of fluids.

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