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DEEP-SEA FLUID EXPULSION AND RELATED PRODUCTS IN THE MIOCENE FOREDEEP AND SATELLITE BASINS OF THE NORTHERN APENNINES, ITALY

Leaders:
D. Fontana, S. Conti, P. Clari, M. Taviani

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Front Cover:
Panoramic view of the Castagno d'Andrea chemoherm
(Middle Miocene, northern Apennines)

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Introduction

In the last two decades, researchers have convincingly documented that both hot and cold fluid expulsion on the deep sea floor is a widespread, almost worldwide phenomenon whose hydrological, geological and biological implications are multifold. Defluidization has been shown to be conducive to: (i) precipitating a variety of authigenic minerals, primarily carbonates (calcite, aragonite, dolomite), sulfides and sulphates; (ii) imposing distinct chemical signatures in sediments, rocks, biota, and water; (iii) sustaining unusual microbial consortia and macrofaunal communities.

Beginning with the mid-80s, submarine investigations revealed the presence of localized deep-sea seepage of light hydrocarbon-rich fluids (cold seeps) in many different geodynamic settings of the world's oceans (e.g., Paull et al., 1984, 1992; Kulm et al., 1986; Aharon and Sen Gupta, 1994; Aharon, 2000; Bohrmann et al., 1998, 2002). As observed earlier at hydrothermal vent sites, modern loci of hydrocarbon-rich fluid seepage are characterized by a significantly high benthic biomass, represented by microbial consortia and chemosynthetic macro-assemblages, typically dominated by endosymbiont-bearing bivalves, including clams (lucinaceans, *Solemya*, vesicomyids etc.), modiolid mussels (e.g., *Bathymodiolus, Modiolus*), as well as gastropods (e.g., *Thalassonerita*, *Provanna*), and tube worms (Pogonophora). These communities, in analogy with those found around hydrothermal vents, are basically sustained by a chemosynthetic food chain exploiting the bacterial oxidation of methane and/or hydrogen sulfide (Van Dover, 2000, with references therein). Cold seepage may promote the formation of authigenic carbonates, which can be recognized in the geological legacy of the earth since the Phanerozoic and possibly earlier (Barbieri et al., 2001; Campbell et al., 2002).

At present, it is widely recognized that the most reliable indicators of fossil cold seeps are: 1) anomalously negative carbon isotope compositions of the carbonates, commonly with ∂ 13C as low as 40‰ PDB; 2) peculiar macrofossils assemblages, and 3) specific biomarkers (e.g. Campbell and Bottjer, 1993; Aharon et al., 1992; Aharon, 2000; Taviani, 2001; Peckmann et al., 2001, 2002; Campbell et al., 2002).

One of the best geological examples of ancient cold seeps is represented by the so-called "*Lucina* limestone" (Calcare a *Lucina*) of the Apennine chain, the object of this excursion. These isotopically-light carbonates, often enclosing large bivalve assemblages (mainly giant lucinids, hence the name), show evidence of a long and complex history of methane-rich fluid venting through the sea floor during the building of the Apennine chain in the late Tertiary. Although known since the 19th century (for a historical account see Conti et al., 1996; Vai and Ricci Lucchi, 1994; Taviani, 2001, with references therein), the *Lucina* limestones were later reinterpreted as being linked to methane seepage, beginning with Clari et al.'s (1988) study of the Miocene Marmorito limestone of Piedmont. Such an interpretation has been since extended to other areas of the northern Apennines (Ricci Lucchi and Vai, 1994; Clari et al.,1994; Berti et al., 1994; Terzi et al., 1994; Taviani, 1994, 1996, 2001; Conti et al., 1996; Cavagna et al., 1999; Conti and Fontana 1999, 2002; Barbieri et al., 2000, 2001; Peckmann et al., 2001). These on-going studies clearly demonstrate that the *Lucina* limestones represent one of the best geological examples of cold-vent related processes, comparable to the Tertiary counterparts described from the Mesozoic-Tertiary of Japan and Eastern North-Pacific convergent margins (e.g. Campbell and Bottjer, 1993; Shibasaki and Majima, 1997; Campbell et al., 2002; Peckmann et al., 2002).

Regional geologic setting

The northern Apennine is made up of thrust sheets accreted to the Adriatic foreland. After the consumption of the oceanic lithosphere under the European craton, the ensuing Apennine orogeny (Oligocene to Recent) was due to an ensialic subduction with a progressive northeastward migration of the foredeep-compressional front. Syntectonic clastic sediments were deposited ahead of the thrust front, in narrow and elongate foredeep basins (Tuscan and Umbro-Romagna domains). They were also deposited in small discontinuous basins (epi-Ligurian satellite basins), perched on deformed oceanic elements of the Apennine accretionary wedge (Ligurian units), and also on deformed sedimentary units (Subligurian units), overlying the thinned continental crust of the Adriatic margin. During the advancement of the Ligurian nappe system (with its epi-Ligurian cover deposits), materials constituting olistostromes slid off the front of the nappe and were

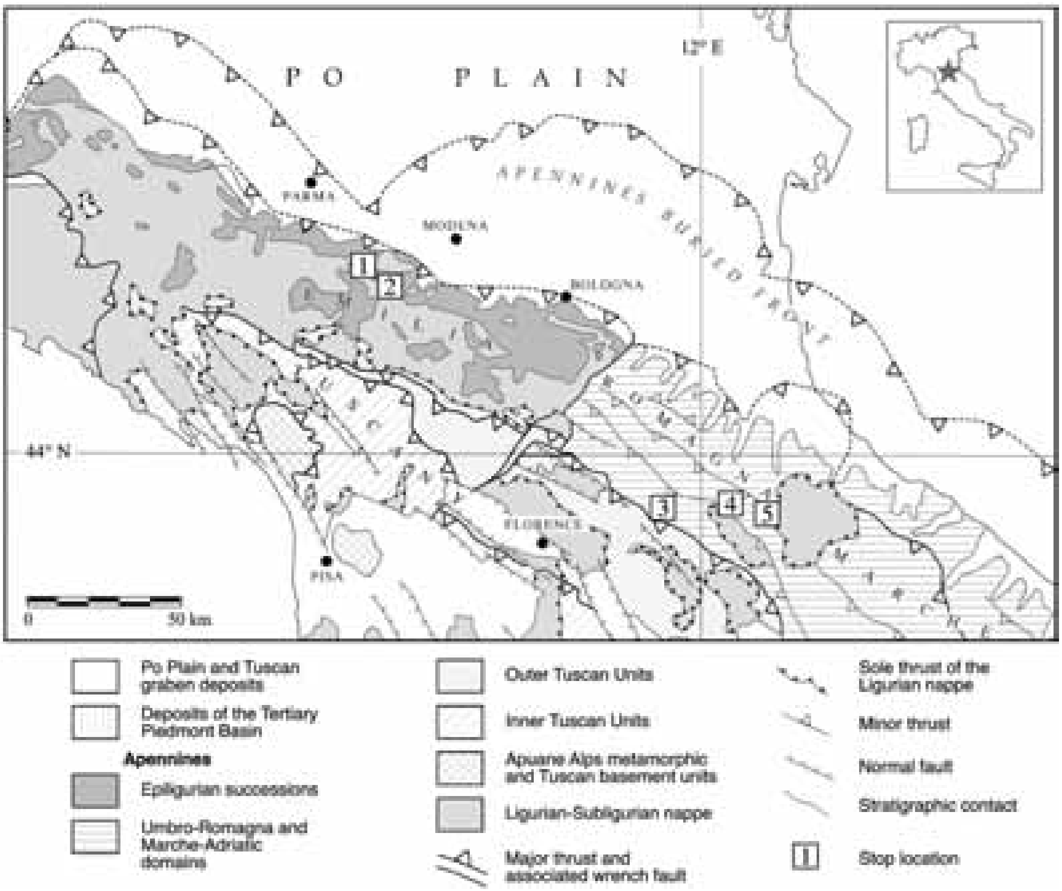

Figure 1- Schematic geological map of the main Apennine units (modified from Pini, 1999).

intercalated in slope-foredeep sequences.

Carbonate lithosomes and blocks called "*Lucina* limestones", interpreted as fossil equivalents of modern methane-derived carbonate products, crop out extensively in various tectonic domains and basin types of the northern Apennines. They occur from internal tectonic zones (Piedmont Tertiary basins, epi-Ligurian and minor basins) to external zones of the foredeep (Figs. 1, 2). In the Mediterranean basin, the majority of identified chemoherms are stratigraphically concentrated in Middle-Upper Miocene successions (e.g., Aharon et al., 1992; Conti and Fontana, 1999; Taviani, 2001).

The epi-Ligurian Eocene-Miocene sediments consist of various depositional sequences: chemoherms are abundant in the Middle-Late Miocene outer shelf-slope deposits. In the Miocene foredeep, chemoherms occur in large turbiditic bodies (Mt. Cervarola and Marnoso-arenacea Formations) and in slope hemipelagites (Vicchio and Verghereto Marls, and Ghioli di letto mudstones).

Chemoherms in epi-Ligurian satellite basins occur in primary position, whereas in the large turbiditic bodies of the foredeep, they are autochthonous to moderately reworked, and are concentrated in pelitic intervals, which usually are partially or totally involved in intraformational slumps.

Chemoherm characteristics

Sedimentological attributes: Dominant rock types are calcilutitic limestones, marly limestones and calcarenites, cemented by authigenic micrite, associated with minor neoformed pyrite, biogenic particles and siliciclastic detritus. Carbonate lithosomes (chemoherms of Roberts and Aharon, 1994) show a variety of morphologies: lenticular-amygdaloid or scattered irregular bodies, pinnacles, irregularly-thickened levels, ranging in diameter

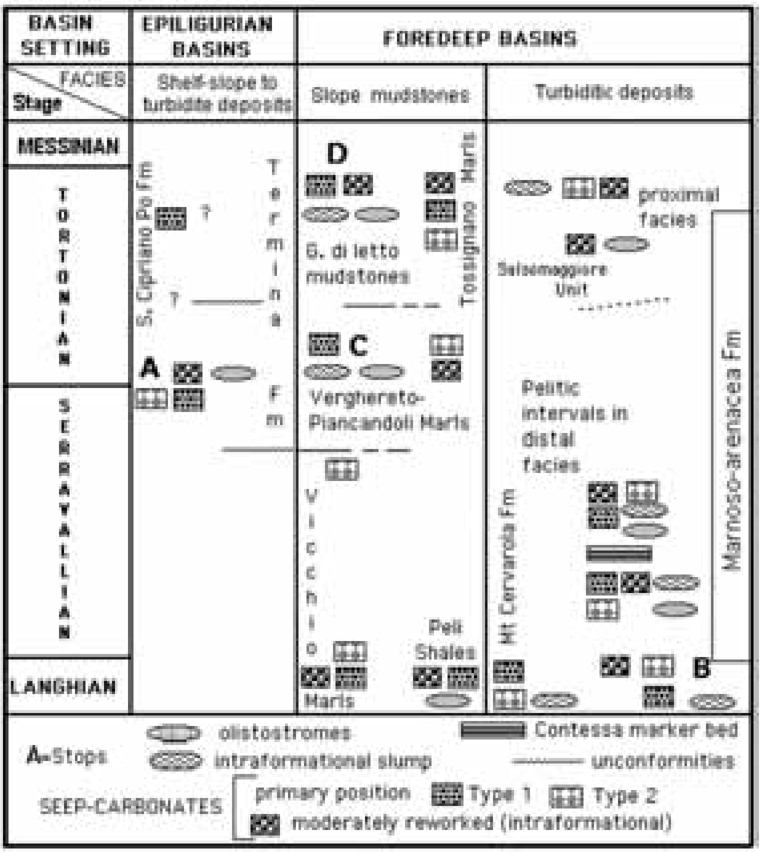

Figure 2 - Geologic framework of chemoherms of the northern Apennines

separated by thin pelitic levels, thus suggesting periodic growth.

Chaotic breccias represent peculiar structures of the Apenninic chemoherms (Conti and Fontana, 1999, 2002); they form levels, ranging in thickness from some centimeters to a few meters, commonly interdigitated with fine-grained carbonate- cemented sediments, and in some cases involved in debris or grain flows. Clasts are of a different origin, both extraformational and intraformational, chaotically floating in the authigenic micritic matrix; they are heterometric (from some mm to 30-40 cm in diameter) and generally angular. Extraformational clasts are from various sources, such as Ligurian and epi-Ligurian units, or foredeep arenaceous turbidites, older than those including chemoherms. Allochthonous clasts can also derive from olistostromes which have slid off Ligurian nappe fronts. Intraformational clasts are made of chemoherm carbonates, or are supplied by lithotypes of the surrounding foredeep turbidites and hemipelagites.

Monogenic autoclastic breccias are also present, made of angular clasts of micrite deriving from fragmentation of the chemoherms. In many cases, these breccias pass gradually to a dense network of non-systematic carbonate-filled veins and microfractures, irregularly connected to pipes and conduits.

from a few centimeters to several decameters (e.g., Conti and Fontana, 1999, 2002; Taviani, 2001). The maximum thickness is about 30 m. These chemoherms are often very fossiliferous, being characterized by the occurrence of isolated or densely-packed bivalves (Taviani, 1994, 2001).

Several characteristics allow two types of primary chemoherms to be distinguished. The first type (Type 1) consists of calcilutitic to calcarenitic levels, composed of a horizontal repetition of few decametric to heptometric carbonate bodies (pinnacles and lenses), with a close distribution, separated by marly and arenitic mudstones. Their dimension ranges from 10 m to 100 m; the thickness is very irregular (5-30 m). The second type, (Type 2), consists of numerous marly-calcareous lenses or irregular column-like bodies, with a diameter from 20 cm to 5 m, and a thickness from 20-30 cm to 3 m. Carbonate bodies are horizontally and vertically scattered and are not related to a precise stratigraphic level: many consist of several lenticular units vertically stacked and

Isotopic signature The strongly negative $\partial^{13}C$ signature characterizing most carbonate phases of the *Lucina* limestone is recognized as the best evidence of a methane-related origin (e.g., Ritger et al., 1987; Hovland et al., 1987; Campbell, 1992; Roberts and

Aharon, 1994; Campbell et al., 2002; Peckmann et al., 2002).

The extremely depleted carbon isotope composition of methane (∂^{13}C ranging from -35‰ to -50‰ for thermogenic methane and less than -60‰ for biogenic methane; Claypool and Kaplan, 1974, in Beauchamp and Savard, 1992) leads to this unusually negative isotopic signature of the derived carbonate phases. The actual range of ∂^{13}C of the resulting carbonates depends on the relative contributions of carbon from methane and from other sources – i.e. the inorganic bicarbonate pool and marine organic carbon (Paull et al., 1992).

Oxygen isotopic measurements yielded ∂^{18}O values of 0.1‰ to 4.9‰ relative to the PDB standard. The relatively narrow range of the positive ∂^{18}O values is an indication that carbonates are precipitated and/or recrystallized from sea water at relatively low temperatures.

Concerning the Miocene *Lucina* limestones, the carbon isotopic signatures of a vast number of samples indicate values comprised between - 16‰ to -58‰ PDB (e.g., Terzi et al., 1994; Taviani, 2001).

Fossil content.

Macrofossils. The most common macrofossil remains enclosed in the *Lucina* limestones are represented by body fossils of large infaunal and semi-infaunal bivalves (family Lucinidae; Mytilidae, Vesicomyidae, Thaysiridae and Solemyidae, in order of relative abundance), containing endosymbiotic bacteria; vent-related taxa, such as lucinid and vesicomyid clams, and modiolid mussels, are locally abundant (Taviani 1994, 1996, 2001). Lucinids are generally preserved as composite molds of articulated shells, often still in life position. Original shell material is often completely dissolved. Many resulting molds are deformed by compaction processes. In other specimens the cavity left by the dissolution of the shell is filled by internal sediments and calcitic cements. Recent species belonging to lucinaceans and vesicomyids, host in the gills symbiotic sulfide-oxidizing bacteria, whereas no living species is known to possess the methane-oxidizing symbionts which have been found in other vent-related organisms, such as some modiolid mussels (e.g., Brooks et al., 1987), that have been also identified in some Tortonian *Lucina* limestones (Taviani, 1994, 2001). These *Lucina* limestones are also characterized by a very depleted carbon isotopic composition, suggesting that methane seepage was a predominant source of carbon. The *Lucina* limestone communities were by and large sustained by the sulfide generated in the pore waters of the sulfate-reducing zone, through anaerobic bacterial oxidation of a diffuse flux of methane. The bacterial oxidation of methane can occur both aerobically and anaerobically, in the pore waters of the oxic and sulfate-reducing zones respectively. When an upward flux of methane enters the sulfate-reducing zone, methane-oxiding bacteria provide the energy source for sulfate reducers and the coupled process results in the production of bicarbonate (HCO3-) and hydrogen sulfide (H2S-) (Hovland et al., 1987; Jørgensen, 1992; Ritger et al., 1987; Beauchamp and Savard, 1992). In the genetic environment of the *Lucina* limestones, the supply of sulfide was not completely exhausted through the formation of authigenic pyrite, but could sustain symbiotic and free-living chemotrophic bacteria; it eventually diffused upwards through the sediments, reaching the oxic zone.

Microbial assemblages. Filaments and/or biomolecular signatures assigned to bacterial mats have been observed in some *Lucina* limestones, from Piedmont to the Romagna Apennines (Cavagna et al., 1999; Peckmann et al., 1999; Barbieri et al., 2000).

Genesis of the Lucina limestones

A reconstruction of the successive genetic and diagenetic stages of the *Lucina* limestone may be thus delineated:

1) An area of diffuse methane-rich fluid venting was colonized by a dense, specialized fauna, and this community was dominated by large infaunal lucinid clams. These were sustained by a chemosynthetic food chain supported by sulfide. As observed for living species, the clams lived buried into the sediment, close to the interface between oxic and anaerobic (sulfate-reducing) zones. They fed tapping the pore waters of the sulfate-reducing zone, which was rich in sulfide produced by sulfate-reducing bacteria and bacterial anaerobic oxidation of methane. In the oxic pore water of the sediments surrounding living clams, aerobic oxidation of migrating methane caused a decrease in pH (Matsumoto, 1990), and a consequent dissolution of skeletal carbonate. In present-day seep environments, dissolution of bivalve shells is severe and affects both infaunal and epifaunal forms. Traces of dissolution are present also on living specimens (Callender et al., 1992). The *post-mortem* dissolution of lucinid shells was completed near the sediment/water interface, as evidenced by the sedimentary fills of the shell cavities.

2) With continuing sedimentation, the oxic/anoxic interface slowly migrated upwards, and the sediments,

Figure 3 - Montebaranzone (Sarsetta) eastern side: numerous methane-derived marly calcareous lens Type 2 chemoherms), enclosed in pelitic sediments rich in organic matter. Note the gradual lateral transition to the host sediments

enclosing dead and partially or completely leached lucinids shells, passed through the sulfate-reducing zone. Here, the precipitation of the finely crystalline, 13C depleted, authigenic carbonates forming the *Lucina* limestone groundmass took place in the pores of the siliciclastic sediment. In the pore waters of the sulfate-reducing zone, in fact, the alkalinity was drastically increased by HCO3- produced by anaerobic methane oxidation.

Authigenic carbonate precipitation in the sulfate-reducing zone in many cases was not sufficient to prevent compaction of the sediments during burial, as indicated by deformation of lucinids composite molds.

In other cases a more substantial precipitation of authigenic carbonate cement not only inhibited burial compaction, but reduced the pore space, blocking diffuse fluid flow. Methane-charged fluids were then channelled through a network of cavities, consisting of shell-dissolution voids, burrows and fractures. Sediment infilling and carbonate cement precipitation progressively reduced, and eventually plugged, also this network of cavities. Internal sediments and cements still show an overall negative ∂13C, but single values can vary due to the existence of microenvironments characterized by a different percentage of available methane-derived carbon.

DAY 1

Modena- Reggio Emilia Apennines

Stop 1:

Poggio di Montebaranzone (Sarsetta)

Panoramic view of a type 2 chemoherm (Fig. 3).

Outcrop description- From base to top: 1) pelitic marls, interbedded with scattered marly calcareous lenses, very rich in bivalves (mainly lucinids) (Upper Serravallian); 2) resedimented sandstones with coquina debris (tempestites ?), interbedded with fossiliferous pelitic marls lacking in lucinids Early Tortonian); 3) medium to coarse grained turbiditic sandstones, with thin levels of debrites (Montebaranzone Sandstones - Tortonian) 4) polygenic clayey breccias (Montebaranzone-Montardone olistostrome), derived from submarine mud flows and debris flows detached from Ligurian formations (Tortonian)

Figure 4 - Panoramic view of the southern side of the "Sasso delle Streghe" chemoherm (Type 1). Note lateral extension and thickness of the outcrop (the Sasso delle Streghe is the carbonatic pillar in the middle of the picture).

Stratigraphy- Termina Formation (late Serravallian-Tortonian)
Environment- inner slope
Paleontology- Lucinid clams
Structural setting- northern limb of the Montebaranzone-Montardone syncline
Remarks- Primary position of the carbonate lenses, as testified by the gradual transition to the surrounding sediments, concords with the stratification and the articulated and sometimes still *in situ* bivalves.
References: Conti et al., 1996, Conti and Fontana,1999, 2002.

Stop 2:

Sasso delle Streghe (ROCCA S. Maria) (Various giant type 1 chemoherms). This stop is subdivided into two parts:
2a) Le Prade (panoramic view)
Purpose: In order to observe the vertical and lateral development of chemoherms passing laterally to the Termina Marls.
Outcrop description- marly carbonate lens and column-like decametric body, very rich in bivalves (mainly lucinids and vesicomyids), gradually passing to poorly-stratified pelitic marls (Upper Serravallian). This unit is bounded at its top by the Montebaranzone Sandstones and is in tectonic contact laterally with the Montebaranzone-Montardone olistostrome (see previous stop).
Structural setting- southern limb of the Montebaranzone-Montardone syncline.
2b) Sasso delle Streghe (in the past, better known as the "Rock of the Clams") (Figs 4, 5).
The Sasso delle Streghe is an example of type 1 chemoherm occurring in primary position in an epi-Ligurian satellite basin. It is enclosed in marly sediments of the inner slope environment of the Termina Formation; the age of the formation is late Serravallian to Tortonian.
Lithology- This chemoherm is formed by a carbonate decametric column-like body made up by calcarenites, marly limestones, locally bioturbated; the limestone is in places highly fossiliferous and contains abundant macrofossils, not equally distributed, of mostly large articulated bivalves either sparsely distributed or in clusters. Brecciation is conspicuous, resulting in widespread brecciated structures, whose clasts are partly sourced from older carbonate Ligurian units, associated with disarticulated shells and bivalve coquina.
At a microscopic scale, samples consist of micrites, fossiliferous micrites and biomicrites,

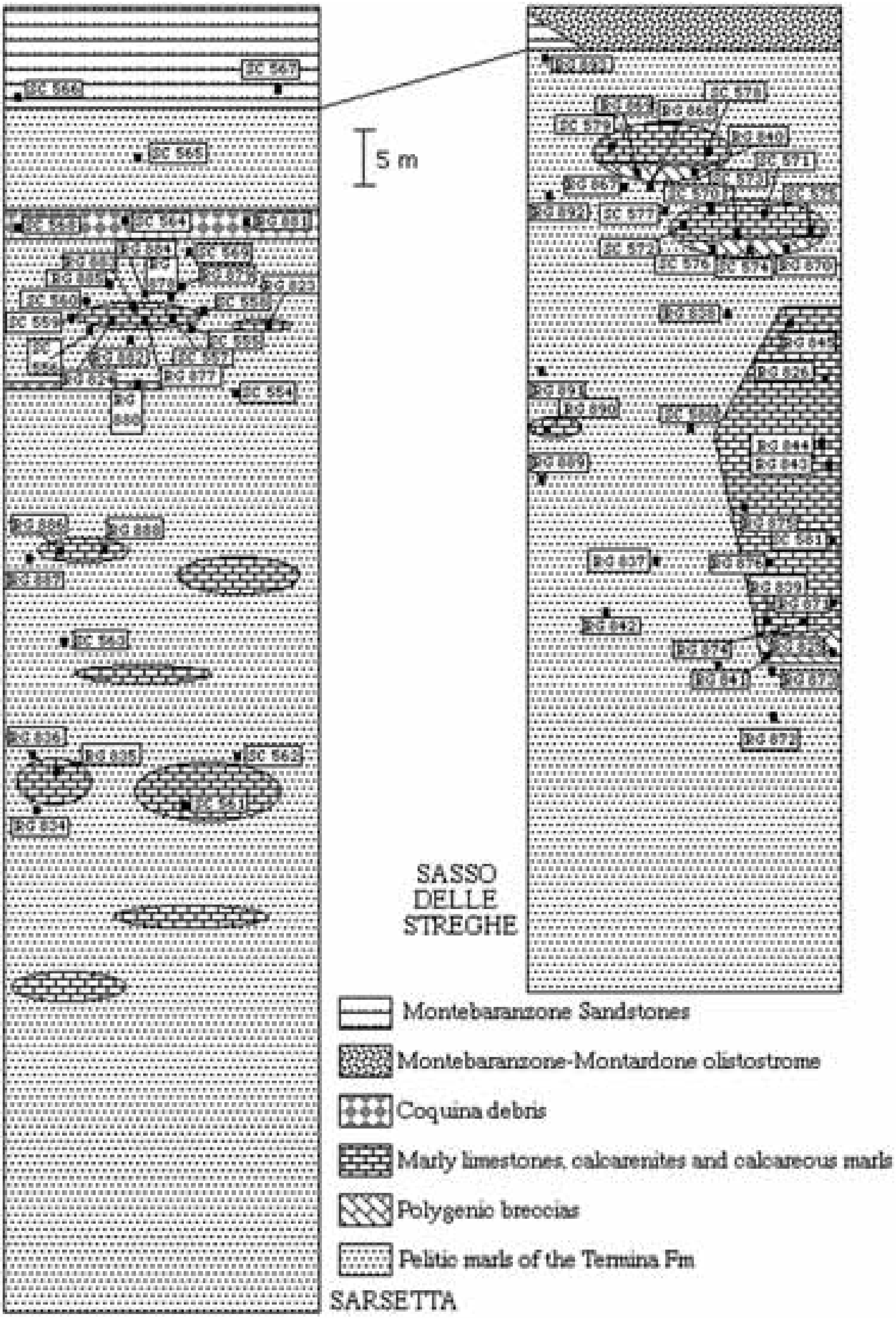

Figure 5 - Detailed stratigraphy of the epi-Ligurian outcrops (numbers refer to studied samples).

Figure 6 - Castagno d'Andrea (Marnoso-arenacea Fm). Three chemoherms (type 1) are enclosed within a pelitic interval, up to 50-80 m thick, characterized by intraformational slumps (above the carbonate blocks) and carbonate breccias. Breccias occur at the base of the carbonate bodies (on the lefthand side of the photo).

containing variable amounts of biogenic particles, chiefly planktonic foraminifera, that are scattered widespread in the carbonate groundmass or are locally concentrated. Fragments of macrofossils are also present. Micritic cement is dominant and pervasive, associated with neoformed pyrite. Terrigenous components are absent or limited to scarce and fine-grained quartz grains and mica flakes. Randomly-oriented networks of veins are present in most samples.

Stratigraphy- Termina Formation (Upper Serravallian-Tortonian). The contact between chemoherm and enclosing pelitic sediments is transitional.

Environment- probably inner slope (based on associated bivalves).

Venting related features- $\partial^{13}C$ depleted isotopic signatures (-21 up to –37‰), intraformational and extraformational breccias, irregular vuggy and spongy fabrics, dense networks of non-systematic veins, neptunian dykes, and autoclastic fractures, filled by carbonate, or enclosing pelitic-arenaceous sediments.

Paleontology- Fossil assemblages dominated by semi-infaunal clams, mostly giant lucinids and vesicomyids (*Calyptogena* sp.).

Remarks- Primary position of the carbonate lenses, very rich in articulated and sometimes still *in situ* lucinids, reworked position (related to fluid expulsion processes) for the breccias, which are sometimes characterized by disarticulated bivalves and coquina debris.

References: Conti et al., 1996; Conti and Fontana 1999, 2002; Taviani, 2001.

DAY 2

Tuscan-Romagna Apennines

Overview of the Marnoso-arenacea Fm (Langhian-Serravallian) and Outer Tuscan units at Mt. Falterona (Lower Miocene). Panoramic view of huge landslides detached from the Mt Falterona slopes.

Stop 3:

La Pianaccia - Castagno d'Andrea

Chemosynthetic carbonates are enclosed in the Miocene foredeep units, in pelitic intervals intercalated in the turbidite succession of the Marnoso-arenacea Fm.. Three main chemoherms (type 1) are recognizable within a pelitic succession for a total thickness of 30-40 m (Fig.6).

Lithology - Chemoherms consisit of a few, large bodies, conformant to the surrounding sediments, and are made up of biomicritic marly limestones rich in articulated bivalves, brecciated marly limestones, calcarenitic limestones with disarticulated bivalves, and intraformational breccias. Different types of polymictic and monomictic breccias are present, commonly concentrated at the base of chemoherms.

At a microscopic scale, samples consist of micrites, and fossiliferous micrites, containing abundant terrigenous components, and variable amounts of biogenic particles, such as planktonic foraminifera and fragments of macrofossils.

Enclosing formation- Marnoso-arenacea Fm (Langhian)

Depositional environment- basin plain turbidites

Structural setting- The argillaceous interval enclosing chemoherms is 200m thick and 20km wide and consists of fine-grained turbidites and hemipelagites. It strikes parallel to the structural trends of the chain.

Venting-related features- $\partial^{13}C$ depleted isotopic signature (-16‰ up to –41‰), botryoidal aragonite, polygenic intraformational breccias, irregular vuggy and spongy fabrics, dense network of non systematic veins, neptunian dykes and autoclastic fractures filled by carbonate, doughnut structures.

Fossil assemblage- specialized faunas (large lucinids)

Additional information- The upper portion of the pelitic interval is involved in an intraformational slump. Towards the east, it is possible to recognize the thrust of the Outer Tuscan Units over the Umbro-Romagna Units.

References: Conti and Fontana, 1999, 2002.

Stop 4:

S. Sofia, Case Rovereti

The Case Rovereti (Figs. 7, 8) is an example of methanogenetic limestone; it consists of a large block and minor blocks resting upon hemipelagic marls.

Lithology- This chemoherm is made up of a highly fossiliferous massive dark gray calcilutite; macrofossils are large and articulated and, in places, there are densely-packed bivalves.

Stratigraphy- The contact between chemoherm and underlying pelitic sediments, attributable to the Verghereto Marls (Tortonian), is covered.

Environment- probably outer slope, paleobathymetry is possibly between 400-700 m (based on associated molluscs)

Figure 7 - Slope hemipelagites of the Verghereto Marls (Case Rovereti): an artificial disposal of chemoherm blocks.

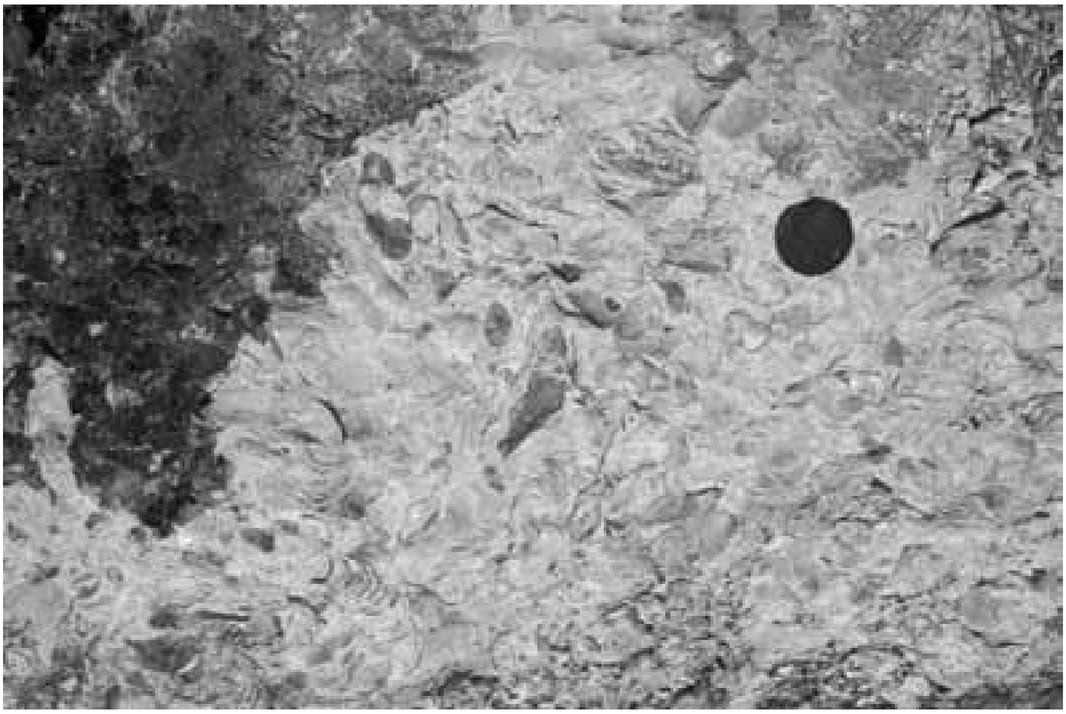

Figure 8 - Close view of densely packed and embricated mussel shells (Case Rovereti).

Figure 9 - Montepetra. Foredeep slope-closure pelites (Ghioli di letto mudstones): panoramic view of two chemoherms.

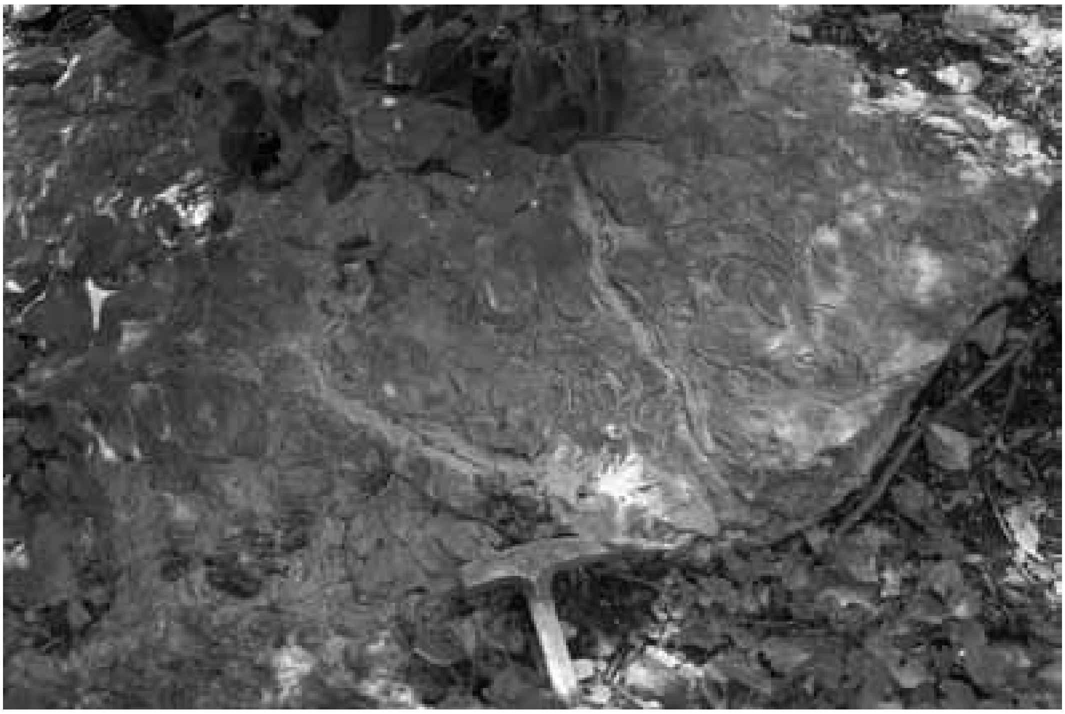

Figure 10 - Montepetra: concentration of lucinid clams.

Venting related features- $\partial^{13}C$ depleted isotopic signature (-27 up to –42‰) and very unusual biota.
Paleontology- Fossil assemblages illustrate distinct facies of infaunal and semi-infaunal lucinids (*Lucina* spp.), and vesicomyids (?*Calyptogena*), epifaunal mussels (?*Modiolus*), and gastropods (*Thalassonerita*, *Homalopoma*, *Buccinum*).
Remarks- This outcrop documents a substantial phase of methane-enriched defluidization during the Apennine orogeny.
References- Terzi et al., 1994; Taviani, 1994, 1996, 2001.

Stop 5:
Montepetra
(chemoherms and chaotic levels) (Figs 9, 10):
The Lucinid deposits in this area are made of limestone blocks, up to 10 meters thick, enclosed in slope hemipelagites of the Miocene Marnoso-arenacea foredeep succession.
Lithology- dark biomicritic marly limestones, very rich in disarticulated bivalves, brecciated marly limestones, calcarenitic limestones with articulated lucinids.
Enclosing formation- “Ghioli di letto” mudstones (Upper Tortonian), representing the pelitic closure of the topmost of the Marnoso-arenacea Fm..
Depositional tectonofacies- slope marls of the foredeep.
Structural setting- strata gently dipping towards ESE, and close to the thrust of the allochthonous Val Marecchia sheet over the Lower Pliocene Argille Azzurre Fm..
Venting related features- $\partial^{13}C$ depleted isotopic signature (-13‰ up to –48‰), intraformational and extraformational breccias, irregular vuggy and spongy fabrics, dense networks of non-systematic veins, neptunian dykes, and autoclastic fractures filled by carbonate, or by the enclosing pelitic-arenaceous sediment.
Paleontology- specialized biota (*?Modiolus*, unidentif. mussel, lucinids, buccinid gastropods)
Additional information- Some of the lucinid blocks are reworked, being intercalated within a chaotic interval extending from Mercato Saraceno to the upper Marecchia Valley. However, the correspondence between the lithofacies of seep-carbonates and those of the host sediments, suggests that these blocks have undergone only minor and moderate displacement. The marly-pelitic chaotic interval (Upper Tortonian-

Figure 11 - Montepetra. Panoramic view of the Messinian-Pliocene boundary

Lower Messinian) is made up of intraformational slumps, Ligurian olistostromes, Ligurian and Epiligurian olistoliths, and channelised resedimented sandstones (S. Agata Feltria sandstones). These lithologies can be observed in the vicinity of the chemoherm outcrops, as well as at the Messinian-Pliocene boundary (Fig. 11), and at the thrust between the Ligurides and the Umbro-Romagna deposits.

References: Taviani 1994, 1996, 2001; Conti and Fontana, 1999, 2002.

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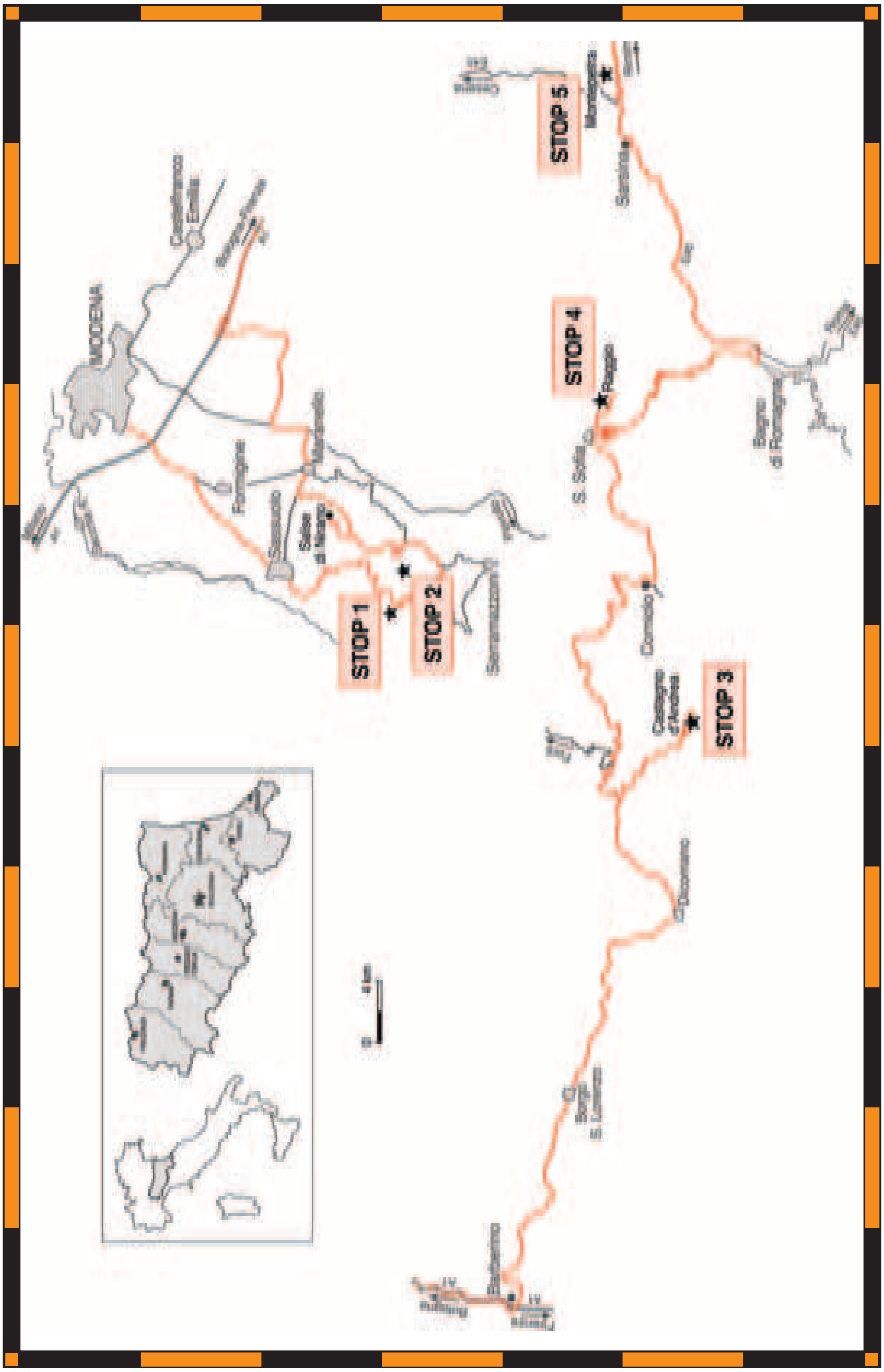
field trip itinerary

FIELD TRIP MAP



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