Interaction of tectonic, sedimentary and diapiric processes in the origin of chaotic sediments: an example from the Messinian of Torino Hill (Tertiary Piedmon Basin, northwestern Italy)

Interaction of tectonic, sedimentary, and diapiric processes in the origin of chaotic sediments: An example from the Messinian of Torino Hill (Tertiary Piedmont Basin, northwestern Italy)

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ABSTRACT

Geologic mapping and integrated stratigraphic and structural observations of a gyp- sum quarry from northwestern Italy allow evaluation of the relative contributions, the time relationships, and the causative links between tectonic, sedimentary, and diapiric processes in the genesis of chaotic sediments of Messinian age. Three chaotic units are exposed in the quarry: together, they make up a composite chaotic unit that is unconform- ably overlain by post-chaotic sediments. Unit 1 is composed of blocks of primary evaporites that are juxtaposed to marine marls by sub- vertical transpressive faults and are parallel to the fault surfaces. Unit 2 unconformably overlies Unit 1, and consists of a lenticular sedimentary body containing both angular and rounded blocks, randomly distributed in a fine-grained matrix. Unit 3 consists of a 10-m-wide body bounded by transpres- sive faults, and pierces both Units 1 and 2. It is composed of strongly deformed muddy deposits that envelop blocks of gypsum and carbonate rocks. Between the core and the margins, various zones have been defined based on the increasing amount of deforma- tion toward the margins. The post-chaotic sediments unconformably overlie both Units 1 and 2, sealing the main fault systems.

The composite chaotic unit is related to thrust propagation during a regional phase of deformation, and is the result of different evolutionary stages, in each of which a sin- gle genetic mechanism prevailed. Tectonic faulting prevailed during stage 1 and was responsible for the formation of a tectonically disrupted assemblage (Unit 1). During stage 2, gravity-driven sedimentary phenomena, related to slope oversteepening triggered by ongoing thrust propagation, resulted in the deposition of Unit 2. Gravity sliding was favored by the mechanical weakening of sediments caused by tectonic faulting. Over- pressure conditions resulting from the rapid deposition of Unit 2 triggered the rise of a diapir (Unit 3) that pierced Units 1 and 2. The involvement of methane-rich fluids in the formation of the diapir is suggested by the occurrence of blocks of methane-derived carbonates, found not in the quarry, but just outside it.

Keywords: chaotic deposits, tectonics, sedimentary processes, diapiric processes, Messinian, Tertiary Piedmont Basin.

INTRODUCTION

Chaotic rock bodies, or mélanges, are common components of ancient orogenic belts and present-day accretionary complexes (e.g., Hsü, 1968; Aalto, 1981; Cloos, 1982; Cowan, 1985; Barber and Brown, 1988; Orange, 1990; Orange et al., 1993; Onishi and Kimura, 1995; Orange and Underwood, 1995; Pini, 1999; Cowan and Pini, 2001). Their origin is commonly attributed to (1) tectonic disruption and mixing of originally coherent sequences, responsible for the forma- tion of tectonic mélanges that, depending on the degree of stratal disruption, retain the original composition of the parent succession (broken formations, Hsü, 1968; type I mélanges, Lash, 1987; tectonosomes, Pini, 1999) or may include exotic blocks (e.g., Hsü, 1973; Raymond, 1984; Şengör, 2003); (2) gravitational submarine downslope movements (olistostromes, Beneo, 1956; Flores, 1956; Abbate et al., 1970; type II mélanges, Lash, 1987); or (3) shale diapirism caused by the rising toward the seafloor of over-pressured, fluid-permeated fine-grained sediments (type III mélanges, Lash, 1987).

Despite valuable criteria having been proposed to discriminate among these mechanisms (e.g., Orange, 1990; Orange and Underwood, 1995; Pini, 1999), the recognition of the role played by each of them in the geological record is problematic, due to the strong facies convergence of their products and to the fact that later deformation and metamorphism often obscure the prevailing forming processes. Moreover, these mechanisms are not mutually exclusive, and can coexist and interact in a complex way: for example, tectonic movements provide favor- able conditions for gravity sliding through both the creation of topography and the mechanical weakening of sediments, and may also encourage shale diapirism by creating conduits for mud extrusion (e.g., Kopf, 2002; Chamot- Rooke et al., 2005). In the same way, the load- ing provided by the rapid deposition of slumps and slides may generate the overpressure neces- sary for the intrusion of mud diapirs (e.g., Col- lison, 1994) and the extrusion of mud volcanoes (Sautkin et al., 2003) that, in turn, can create a topography able to trigger further sliding (e.g., Clennell, 1992).

The study of both modern (e.g., Brown and Westbrook, 1988; Reed et al., 1990; Barry et al., 1996; Maslin et al., 1998; Bouriak et al., 2000; Diaz del Rio et al., 2003) and ancient examples

(e.g., Conti and Fontana, 2002, 2005; Clari et al., 2004; Lucente and Taviani, 2005) indicates a close genetic link between gas hydrate decom- position, tectonics, shale diapirism, and mass wasting. Gas hydrate decomposition can pro- vide large amounts of gas-rich fluids (generally methane) that migrate upward through faults. This process can induce shale diapirism and mud volcanism, and can also cause sedimentary instability through the reduction of the shear strength of the overlying sediments (Henriet and Meniert, 1998).

Nonmetamorphic Messinian chaotic sedi- mentary bodies in the Northern Apennines, Sic- ily and Spain, have been described (e.g., Rov- eri et al., 2003; Artoni et al., 2004; Lucente et al., 2005; Manzi et al., 2005), and their genesis has been attributed to large-scale slope failure, probably triggered by thrusting during an intra- Messinian tectonic phase (Roveri et al., 2003).

In the Tertiary Piedmont Basin, the Messinian succession is largely made up of chaotic sedi- ments (Fig. 1) that, due to the lack of later defor- mation and metamorphism, are suitable for the study of the mechanism(s) responsible for their formation (Dela Pierre et al., 2002; Irace, 2004; Festa et al., 2005; Irace et al., 2005). Previous studies have pointed out that they are the result of mass-wasting events linked to intra-Messinian tectonics. Moreover, the contribution of the rise

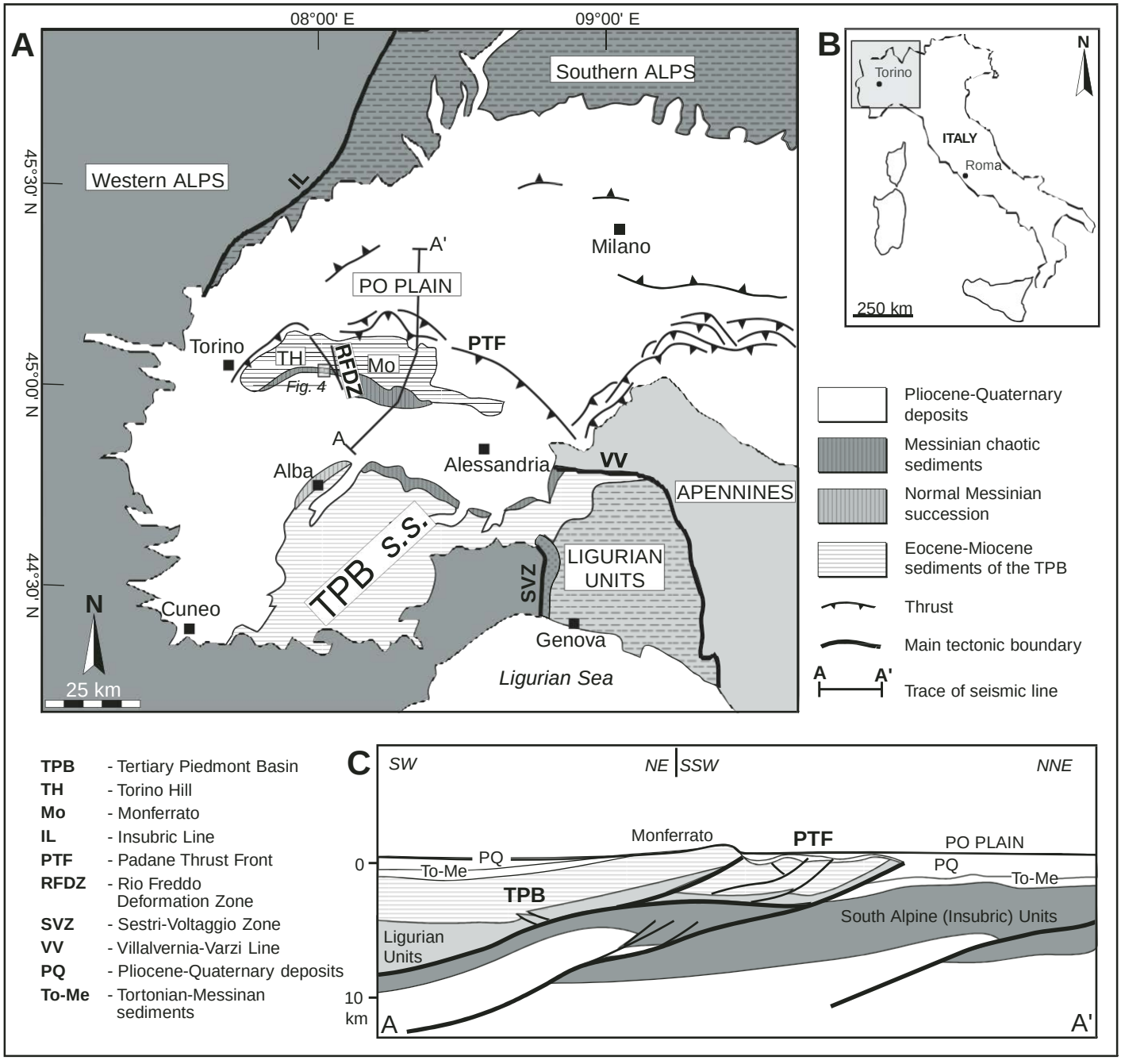


Figure 1. (A) Structural sketch map of northwestern Italy (modified from Bigi et al., 1990). (B) Location of Figure 1A. (C) Geological cross section across the Po Plain (modified from Bello and Fantoni, 2002).

of methane-rich fluids through the sedimentary column and related shale diapirism is suggested by the common occurrence of blocks of authi- genic methane-derived carbonates in the chaotic sediments. However, relationships among tectonic, sedimentary, and diapiric processes are not yet clear, mainly because limited outcrop conditions hamper the reconstruction of the geometry of the dismembered sedimentary bodies.

In this paper we present a detailed study, including geologic mapping and integrated stratigraphic and structural observations, of the Moncucco gypsum quarry, located on the southern flank of Torino Hill (Fig. 1A). Quarrying has provided an excellent outcrop that offers a unique opportunity to consider the contributions of tectonic, gravitational, and diapiric processes in the genesis of the Messinian chaotic sediments, their time relationships, and causative links.

REGIONAL GEOLOGIC SETTING

The Tertiary Piedmont Basin is composed of upper Eocene–Messinian sediments deposited unconformably, after the mesoalpine collisional event, on both alpine metamorphic rocks and Apennine Ligurian units (e.g., Gelati and Gnaccolini, 1988; Castellarin, 1994; Mutti et al., 1995; Roure et al., 1996). Deposition of these sediments was strongly influenced by synsedimentary compressional tectonics related to the building of the Apennine thrust belt. As a consequence, several tectono-sedimentary domains, deposited on different crustal blocks and characterized by different sedimentary features, developed during the Cenozoic (e.g., Biella et al., 1997). They are the Tertiary Piedmont Basin (sensu stricto, s.s.) to the south, and the Monfer- rato–Torino Hill to the north; their relationships are masked by Pliocene–Quaternary deposits (Fig. 1A) that are locally as thick as 2000 m (Mosca, 2006).

Both the Tertiary Piedmont Basin s.s. and the Monferrato–Torino Hill are overthrust to the north onto the Po Plain foredeep, along the late Neogene to Quaternary Padane thrust front (Fig. 1C), currently buried below the Quaternary Po Plain deposits (Dalla et al., 1992; Castellarin, 1994; Falletti et al., 1995).

The Torino Hill succession unconformably overlies a metamorphic basement buried at a depth of 2–3 km (Biella et al., 1997), interpreted as the South Alpine basement (Mosca, 2006). The Monferrato succession is developed on Cretaceous–lower Eocene nonmetamorphic Ligurian units (e.g., Biella et al., 1997). The magnetic basement is buried at a depth of 8–10 km (Cassano et al., 1986; Miletto and Polino, 1992). The Torino Hill and Monferrato successions are separated by the Rio Freddo deformation zone, a regional northwest-southeast–striking transpressional fault zone that corresponds to the surface expression of a deep-seated steep shear zone (Piana and Polino, 1995; Piana, 2000).

The Torino Hill succession consists of upper Eocene–lower Messinian deep-water deposits composed of alternating hemipelagic muds and arenaceous to conglomeratic resedimented beds (Bonsignore et al., 1969). This succession was deformed by three contractional faulting stages of Rupelian, Burdigalian, and Serravallian age (Festa et al., 2005). A fourth deformational phase of late Messinian age (the intra-Messin- ian phase) is evidenced by the emplacement of Messinian chaotic sediments, the object of this paper. Regional north-south shortening, related to the northward migration of the Padane thrust front, prevailed during the intra-Messinian phase. This caused only minor displacement along the preexisting fault systems (northwest-southeast and northeast-southwest striking) of the Torino Hill and Monferrato domains, which underwent southward tilting (Festa et al., 2005).

STRATIGRAPHY OF MESSINIAN SEDIMENTS OF THE TERTIARY PIEDMONT BASIN

The Tertiary Piedmont Basin is a classic area for Messinian stratigraphy (Mayer-Eymar, 1867; Sacco, 1889–1890). After the publication of the deep-dessication model of the Mediterranean (Hsü et al., 1973), Sturani (1973, 1978) provided an updated description of the Piedmont Messin- ian succession in the southern part of the Tertiary Piedmont Basin (Alba region, Fig. 1A), where a normal succession is present. This succession starts with deep-water pre-evaporitic marine sediments (Sant'Agata Fossili marls) of Tortonian–early Messinian age (Sturani and Sampò, 1973), followed by shallow-water primary evaporites, referred to as the Gessoso Solfifera Formation. This transition, described as very sharp, would point to the sudden drop of sea level heralding the Mediterranean salinity crisis (Cita et al., 1978). The Gessoso Solfifera Formation is followed by post-evaporitic continental and brackish-water sediments, correlatable to the Lago Mare deposits of the Mediterranean area.

Further research has shown that the Alba succession is a local exception. In large sectors of the Tertiary Piedmont Basin (Fig. 1A), Messin- ian sediments comprise the Valle Versa chaotic complex, with a maximum outcrop thickness of 200 m, and are attributed to the lower part of the post-evaporitic interval (Irace, 2004).

In the Monferrato and Torino Hill areas, the Valle Versa chaotic complex forms a lenticu- lar sedimentary body (Fig. 2) that unconform- ably overlies lower Oligocene–lower Messinian marine sediments (Dela Pierre et al., 2002); in the Moncucco quarry, the complex overlies primary evaporites (see following). The upper boundary is a discontinuity surface separating the Valle Versa chaotic complex from lower Pliocene marine deposits (Argille Azzurre Formation) or locally (Moncucco) from brackish-water post-evaporitic Lago Mare sediments (see following).

The Valle Versa chaotic complex consists of a fine-grained unconsolidated matrix, made up of mud breccias (see following), that envelops blocks of different size and composition, includ- ing gypsum and a wide range of carbonate facies. Gypsum blocks range in size from meters to several hundreds of meters, and consist of primary selenites. Carbonate blocks are smaller (a few decimeters to several tens of meters) and are composed of evaporitic vuggy carbon- ates, skeletal facies of early Messinian age, and methane-derived carbonates. These include dif-

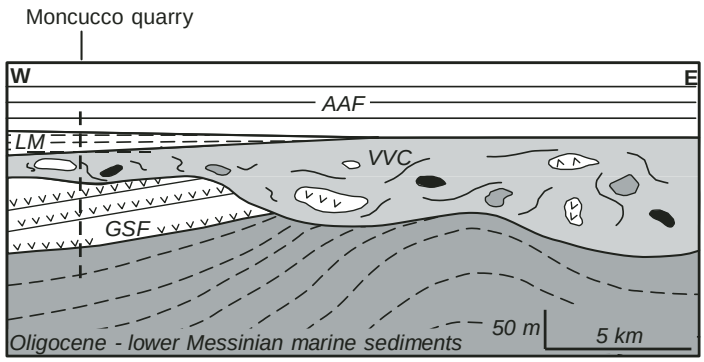


Figure 2. Stratigraphic scheme of the Messinian succession of Torino Hill and Monferrato. GSF—Gessoso Solfifera Formation; VVC—Valle Versa chaotic complex; LM—Lago-Mare deposits; AAF—Argille Azzurre Formation (lower Pliocene). The vertical dashed bar indicates the position of the Moncucco quarry.

ferent types of rocks (thinly laminated peloidal carbonates, clast- and mud-supported breccias with remains of chemosymbiotic bivalves) that share the same isotopic signature (very nega- tive $\delta^{13}C$ values ranging from –25‰ to –50‰ [Peedee belemnite]) of the carbonate cements. The presence of these rocks, considered to be authigenic carbonates formed by the rise of methane-rich fluids toward the basin floor (Clari et al., 1988, 1994; Cavagna et al., 1999), strongly suggests the role of shale diapirism in the formation of the Valle Versa chaotic complex (Dela Pierre et al., 2002). Moreover, the chaotic succession exposed at Verrua Savoia, at the northern edge of the Monferrato domain, has recently been interpreted as the geological record of the activity of a Messinian mud volcano (Clari et al., 2004), further supporting the role played by diapirism in the genesis of the Valle Versa chaotic complex.

MONCUCCO GYPSUM QUARRY

The most visually striking characteristic of the Moncucco quarry is the chaotic setting of the upper Miocene sediments (Figs. 3A, 3B, and 4). Three chaotic units (Units 1, 2, and 3) are recognized due to their geometric and stratigraphic position, their internal organization, and the nature (tectonic versus sedimentary) of their bounding surfaces. These units form a compos- ite chaotic unit that is in turn unconformably overlain by post-chaotic sediments.

Composite Chaotic Unit

Unit 1

Unit 1 is composed of upper Tortonian to lower Messinian hemipelagic muds (Sant'Agata Fossili marls) and disrupted blocks of primary evaporites (Gessoso Solfifera Formation).

The Gessoso Solfifera Formation is mostly preserved in 200-m-thick blocks (A and B in Figs. 3A and 4) bounded at the top by an angu- lar unconformity. In block A a cyclic evaporite succession, ~80 m thick, is present. It consists of an alternation of decimeter-thick black mudstone beds and selenitic gypsum tabular bodies, 10–30 m thick. Three stacked cycles, each one formed by a mudstone-gypsum couple, can be seen in this block (Fig. 5A). The uppermost bed is made up of gypsum-rudites that are also found in block B. Other smaller gypsum blocks, rang- ing is size from meters to several tens of meters, are also present (e.g., block C, Fig. 3C).

The largest Gessoso Solfifera Formation block (A in Fig. 4) is juxtaposed against the Sant'Agata Fossili marls along a north-northwest–south-southeast shear zone. This consists of two subparallel main faults (Fig. 5A), hundreds of meters long, linked by northwest-southeast synthetic oblique reverse faults (Fig. 4). The low-angle intersection of these two fault systems isolates 10-m-wide lenticular tectonic slices and defines a map-scale S-C dextral-transpressive shear zone, sealed to the south by the angular unconformity at the base of Unit 2 (Fig. 4).

Similar structural associations are observable at the mesoscale. At this scale the Sant'Agata Fossili marls are deformed by a scaly fabric that, close to the main faults, consists of millimeter- to centimeter-spaced pervasive shear lenses (L sensu Naylor et al., 1986) identified by the interlacing of R and P shears (Fig. 5B), often displaying shiny and striated surfaces. The associations of R and P shears and the kinematic indicators on shear surfaces are consistent with right-lateral transpressive movements (Fig. 5B). Away from the main faults the pervasive- ness of the scaly fabric decreases, whereas its spacing increases; an S-C fabric, defined by centimeter- to decimeter-sized lithons, can be observed (Fig. 3D). Shear directions deduced from S-C fabric indicate right-lateral transpressive movements. Far from the faults, the degree of stratal disruption gradually decreases and the bedding of the Sant'Agata Fossili marls is still recognizable.

Elongated, lozenge-shaped gypsum blocks (i.e., blocks C and F, Fig. 4A), 1 m to several meters in size, are tectonically enclosed in the Sant'Agata Fossili marls. Their long axes are parallel to the mesoscale shear zones and the main fault surfaces (Fig. 3C). This defines a structurally ordered block-in-matrix fabric that coincides with the structural fabric observed, at different scales, in the Sant'Agata Fossili marls matrix. Also, block A is strongly aligned to the main fault surfaces.

Unit 2

Unit 2 comprises the Valle Versa chaotic complex, which is attributed to the post-evaporitic interval of the Messinian (Irace, 2004). In the quarry it unconformably overlies the disrupted assemblage of Unit 1 (Fig. 4). On the gypsum beds, the discontinuity surface is karstic (Fig. 3A), and is attributed to an intra-Messinian phase of subaerial exposure of gypsum on which Pliocene and Quaternary karst phenomena are superposed (Fioraso and Boano, 2002; Fioraso et al., 2004).

The Valle Versa chaotic complex gives rise to a lenticular sedimentary body that changes in thickness laterally from 30 m to zero, but reaches a thickness of 100 m outside the quarry (Irace, 2004). The Valle Versa chaotic com- plex consists of both angular and rounded hard blocks, varying from a decimeter to several meters, floating with a random distribution in a muddy matrix (Fig. 3E). A highly disordered setting that strongly contrasts with the structural order of Unit 1 can be seen here.

The blocks consist of primary selenitic gyp- sum and resedimented gypsum-rudites, evapo- ritic vuggy carbonates, carbonate breccias, and fossiliferous micritic limestones, which result from cementation of the Sant'Agata Fossili marls (Figs. 6A, 6C) and often show features (coated grains, circumgranular cracks) inter- preted as due to pedogenesis (Irace, 2004). No blocks of methane-derived carbonates have been found at Moncucco. These rocks are a common facies just outside the quarry.

The matrix surrounding the blocks consists of mud breccias, which are composed of light colored clays containing angular clasts, a millimeter to a few centimeters in size, of dark mudstones and less commonly of whitish marls and black sandstones (Fig. 6B). These sediments are characterized by an isotropic texture, defined by the lack of a preferred orientation of the clasts. They are comparable to the brecciated matrix described in the olistostromes of Sicily (e.g., Beneo, 1956; Rigo de Righi, 1956) and the Apennines (Abbate et al., 1970; Pini, 1999).

Micropaleontological analyses performed on five samples collected in the matrix have revealed scarce and badly preserved upper Tortonian to lower Messinian planktonic foraminifera, interpreted as reworked (E. Bicchi, 2005, personal commun.).

Unit 3

Unit 3 consists of a 10-m-wide chaotic body, bounded by north-northeast–south-southwest transpressive faults (Figs. 4 and 7A), that pierces Units 1 and 2. It is composed of strongly deformed Sant'Agata Fossili marls that envelop blocks of gypsum and carbonate rocks (mainly consisting of evaporitic vuggy limestones), decimeters to several meters in size.

Three zones between the core and the margins have been defined on the basis of increasing amounts of deformation toward the margins (Fig. 7B).

1. The core zone, 8–10 m wide, is where the Sant'Agata Fossili marls are lightly deformed and do not show a pervasive scaly cleavage. This suggests disaggregation and intergranular flow of the clay grains in a nonconsolidated sediment (Knipe, 1986). The bedding is folded by strongly asymmetric cylindrical folds with irregular arcuate axial trends and steeply plunging axes (Fig. 7A). Angular and loosely clustered blocks of gypsum and evaporitic carbonates (e.g., blocks D and E in Figs. 7A and 8A), 1 m to several tens of meters in size, are randomly distributed in the Sant'Agata Fossili marls matrix.

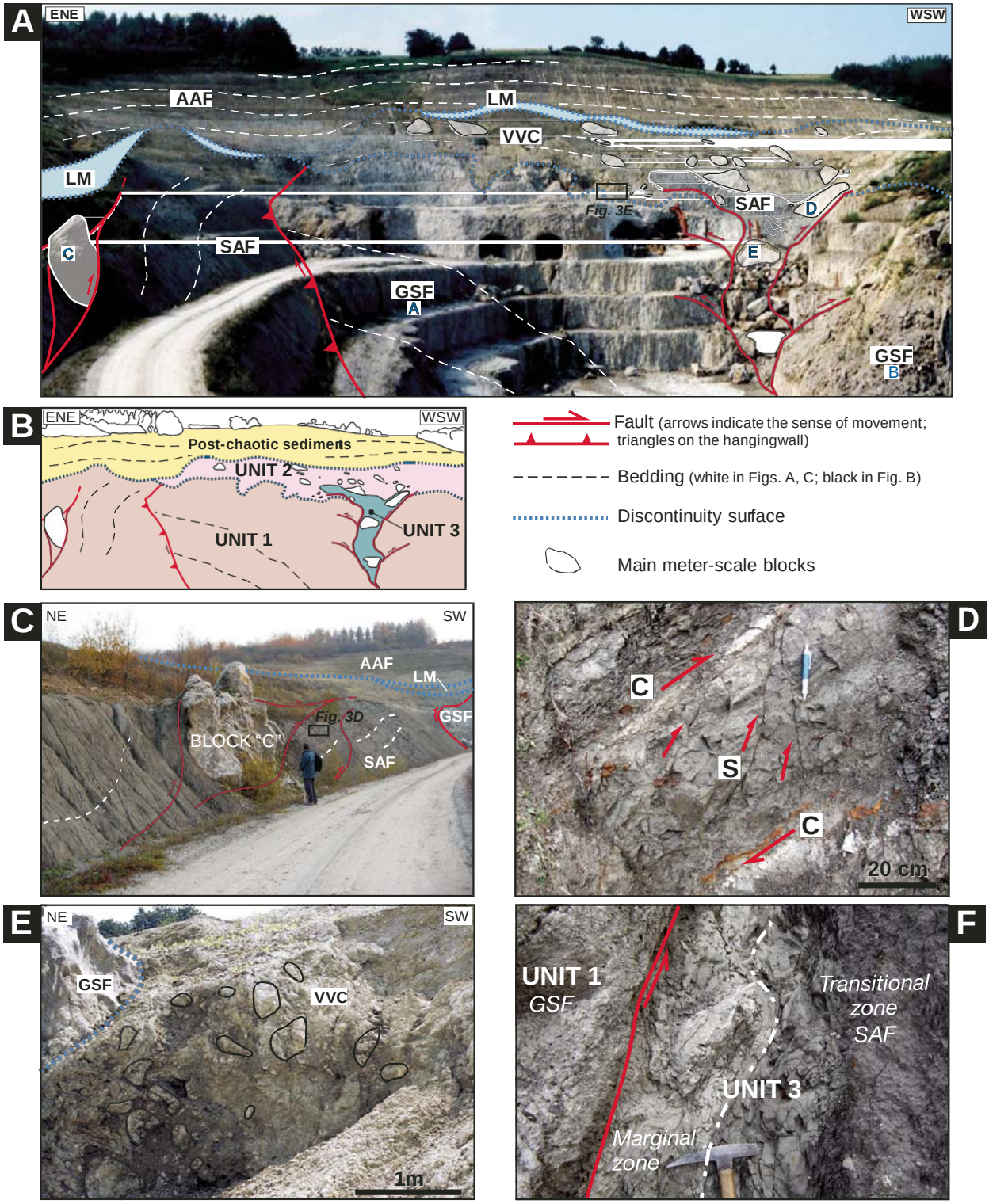


Figure 3. (A) Panoramic view of the Moncucco quarry. SAF—Sant'Agata Fossili marls (upper Tortonian-lower Messinian); GSF—Gessoso Solfifera Formation (Messinian); VVC—Valle Versa chaotic complex (upper Messinian); LM—Lago-Mare deposits (upper Messinian); AAF—Argille Azzurre Formation (lower Pliocene). Capital letters (A–E) indicate the blocks described in the text. (B) Drawing of Figure 3A, showing the distribution of the three chaotic units discussed in the text. (C) Unit 1: lozenge-shaped gypsum block tectonically included within the SAF (block C, Fig. 3A). Symbols as in A. (D) Unit 1: S-C structures in the SAF marls. The C planes coincide with the bedding surfaces. Red arrows indicate the sense of shear. Location in C. (E) Unit 2: VVC: angular to rounded gypsum and carbonate blocks floating in a fine-grained matrix. See A for location. (F) Tectonic contact separating Unit 1 and Unit 3. The boundary between the marginal and the transitional zones is also shown (white dotted line). See Figure 7A for location.

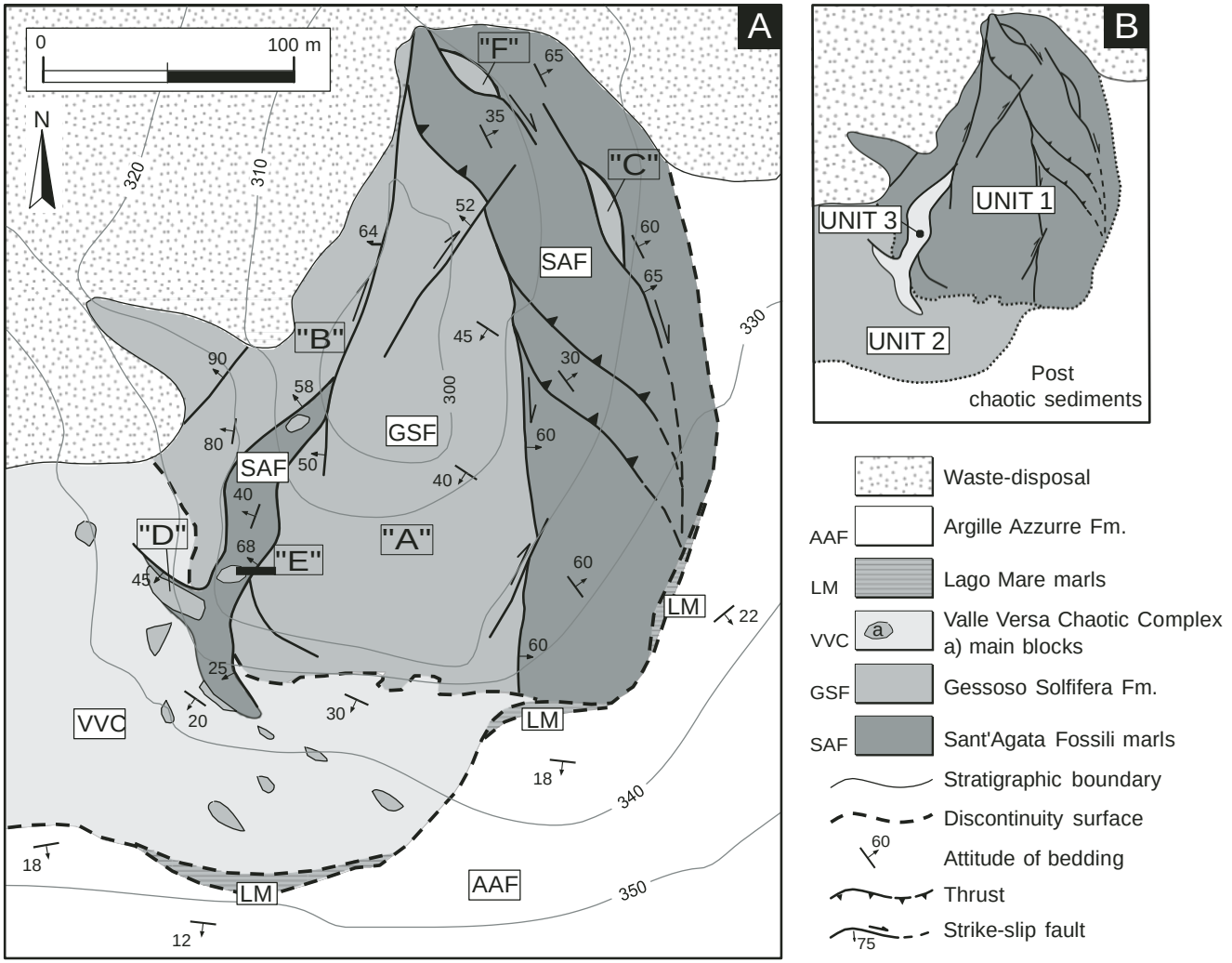


Figure 4. (A) Geological map of the Moncucco quarry. The capital letters (A–F) indicate the blocks discussed in the text. (B) Distribution of the chaotic units.

2. The transitional zone is 50–100 cm wide (Fig. 7B); the intensity of scaly cleavage deformation gradually increases toward the margins, up to define decimeter-sized shear zones. The bedding of the Sant'Agata Fossili marls is highly disrupted here. Centimeter- to decimeter-sized scaly cleavage and S-C fabric, parallel to the margins, indicate opposing sense of shear on the opposite margins of the structure (oblique-sinistral and oblique-dextral transpressive movements on the southeastern and northwestern margins, respectively; Fig. 7C). Long-axis blocks of gypsum, carbonates, fault breccias, and cemented mud breccias (wrenched from the host rocks) float in the Sant'Agata Fossili marls (Fig. 8C). These blocks, a few centimeters to decimeters in size, are rotated and elongated par- allel to the scaly cleavage and the shear zones. In places, lightly deformed wedge-shaped areas (a few centimeters in size) similar to pressure shadows (Fig. 8D) are observed at the terminations of the blocks. Wisps and tails of broken disaggregated material coming off these blocks are spread along the shear zones in the matrix.

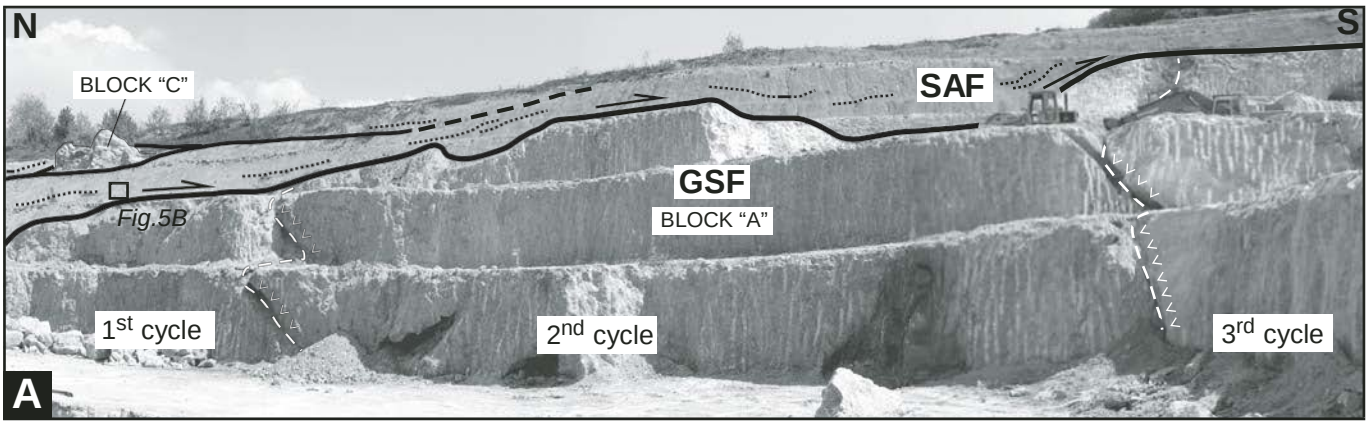
Higher up, where Unit 3 pierces Unit 2, blocks belonging to the Valle Versa chaotic complex and/or wrenched from the host rocks, with decimeter- to meter-sized long axes, are rotated parallel to the margins of Unit 3.

3. The marginal zone (Fig. 7B) separates the transitional zone from the host rocks (Figs. 3F and 8A). This consists of a thin collar (~10–30 cm wide) of mud breccias, composed of green to brown clays enveloping angular clasts, 1 mm to centimeters in size, of whitish marls and black sands. In contrast to the mud brec- cias of Unit 2, fluidal features characterize these sediments. They are evidenced by the alignment of elongated clasts to the external boundaries of Unit 3 (Fig. 8B). Toward the host rock, the mud breccias show the same characteristics, but are cemented by carbonates.

The faults bounding the diapir displace the north-northwest–south-southeast faults, but it is not clear if they represent the reactivation of minor tectonic surfaces related to Unit 1 or newly formed faults.

Post-Chaotic Sediments

The composite chaotic unit is followed by well-bedded marls that unconformably overlie both the Valle Versa chaotic complex (Unit 2) and the Sant'Agata Fossili marls (Unit 1), seal- ing the main fault systems. These sediments contain brackish-water ostracods and molluscs that allow correlation to the upper Messinian Lago Mare sediments of the Mediterranean region. They are followed in sharp contact by lower Pliocene marine sediments, through a



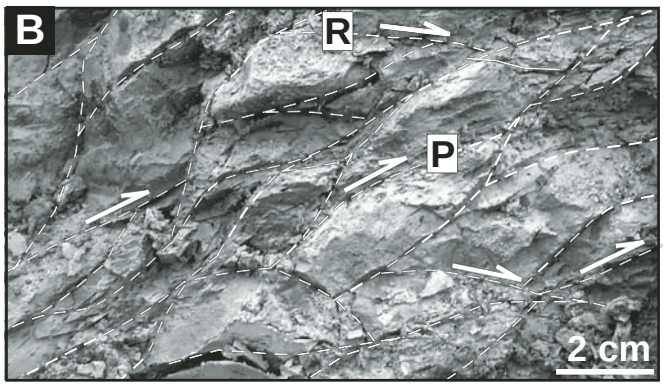


Figure 5. Unit 1. (A) Cyclic organization of the Gessoso Solfifera Formation (GSF, block "A"), evidenced by the alternation of decimeter-thick mudstone beds (white dashed lines) and thick selenitic gypsum beds, their base outlined by white V-shaped symbols (top to the right). The transpressive faults juxtaposing the gypsum blocks "A" and "C" to the Sant'Agata Fossili marls (SAF) can be seen. Black dotted lines indicate the bedding of SAF. Diggers on the right give scale. (B) Centimeter-spaced L shear lenses defined by the interlacing of R and P shears (white dashed lines) in the Sant'Agata Fossili marls. Arrows indicate the sense of shear. See A for location.

black sandy bed very rich in organic matter recognized in many sites in the Mediterranean region (Cita et al., 1978; Roveri et al., 2003).

DISCUSSION

The possible processes responsible for the production of chaotic sediments, i.e., tectonics, diapirism, and mass flows, are not mutually exclusive, but rather can operate together or sequentially (Lash, 1987). However, in the geologic record the distinction of the role played by each of these mechanisms and their causative links are difficult to evaluate because of the strong facies convergence of the resulting rock bodies, which are often physically separated and do not show preserved vertical and lateral relationships. On the contrary, in our example the stratigraphic and crosscutting relationships among different chaotic products (Units 1, 2, and 3) can be observed in outcrop, and the prevailing mechanisms responsible for the formation of each unit are still recognizable. They operated sequentially in a short time span (corresponding to the lower part of the post-evaporitic interval; i.e., after deposition of the evaporites but prior to deposition of upper Messinian Lago Mare sediments) and were triggered by regional tectonic deformation related to the northward migration of the Padane thrust front during the intra-Messinian phase (Dela Pierre et al., 2002; Irace, 2004; Festa et al., 2005). Four evolution- ary stages can be recognized (Fig. 9).

Stage 1

Unit 1 was formed during Stage 1. Our observations indicate that this is a tectonically disrupted unit (sensu Cowan and Pini, 2001) resulting from the in situ tectonic dismemberment of the pre-evaporitic (Sant'Agata Fossili marls) and evaporitic succession (Gessoso Solfifera Formation) deposited in response to the Messinian salinity crisis (Fig. 9).

Although it may be difficult to differentiate between gravity-related and tectonic deformation in poorly consolidated sediments (Ineson, 1985; Maltman, 1994), the following factors allow us to favor tectonic faulting as the main contributory process: (1) the repetition, at different scales, of similar structural associations that are all consistent with right-lateral transpres- sive movements; (2) the structurally ordered block-in-matrix fabric and the elongated and lozenge shape of the blocks, which are distinc- tive features of other disrupted units in tectonic mélanges (e.g., Pini, 1999); (3) the alignment of the blocks to the mesoscale shear zones and the scaly fabric observed in the Sant'Agata Fossili marls matrix, which suggests that the gypsum blocks are tectonic slices wrenched from the Gessoso Solfifera Formation during its tectonic juxtaposition to the Sant'Agata Fossili marls and aligned parallel to the direction of tectonic transport; and (4) the decrease of stratal disruption far away from the faults.

Map-scale observations support this interpretation. They indicate that the faults juxtaposing the blocks of Unit 1 represent the intra-Messinian reactivation of splays of major northwest-southeast faults linked to the Rio Freddo deformation zone (Festa et al., 2005). Dextral-transpressive reactivation of these faults is consistent with north-south regional shortening related to the northward migration of the Padane thrust front (Festa et al., 2005). Intra-Messinian tectonic movements caused the tilting upward of the gypsum blocks, their alignment parallel to the faults, and their juxtaposition to the underlying Sant'Agata Fos- sili marls. The karst surface developed above the evaporites suggests subaerial exposure of the tectonically disrupted unit during this stage.

Stage 2

During this stage, Unit 2 (Valle Versa cha- otic complex) was deposited on the disrupted

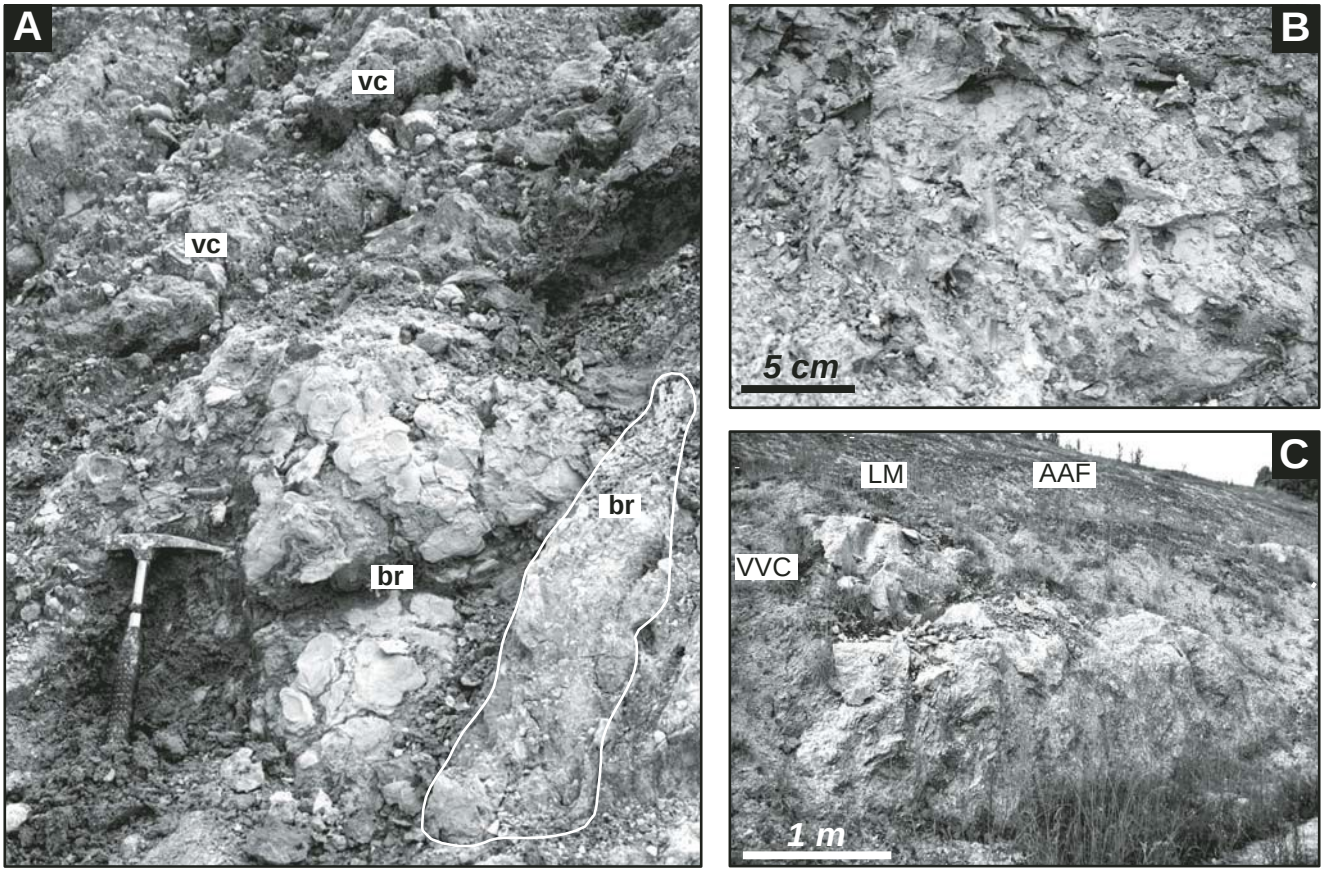


Figure 6. Unit 2. (A) Decimeter-scale blocks, consisting of clast-supported carbonate breccias (br) and evaporitic vuggy carbonates (vc). The hammer is 30 cm long. (B) Matrix of the Valle Versa chaotic complex (VVC). Dark colored mudstone clasts, floating in a light colored clayey groundmass, are visible. (C) Meter-scale gypsum block in the upper part of the VVC. The post-chaotic sediments are also visible. White dotted lines indicate the discontinuity surfaces at the base of Lago Mare marls (LM) and Argille Azzurre Formation (AAF).

blocks of Unit 1 (Fig. 9). The characteristics of the Valle Versa chaotic complex (lower and upper depositional contacts being discontinuity surfaces, the totally chaotic arrangement of the deposits that contain blocks widely ranging of size and randomly distributed in the matrix, the occurrence of a brecciated matrix composed of isotropic mud breccias) are consistent with an origin caused by gravity sliding. The compositions of the largest blocks (mostly composed of gypsum and evaporite carbonates) and of the matrix, in which millimeter-sized clasts from the Sant'Agata Fossili marls have been found, indicate that the previously disrupted upper Miocene succession was the source of the Valle Versa chaotic complex. The conditions in which these sediments have been deposited cannot be evaluated precisely. However, the following factors allow us to speculate that the Valle Versa chaotic complex was deposited by subaerial debris-flows: (1) the karstic surface below the Valle Versa chaotic complex; (2) the occurrence of hard blocks of Sant'Agata Fossili marls with clear pedogenic features; and (3) the lack of sedimentary structures and fossils indicative of deposition in a marine environment.

These deposits could represent the proxi- mal portion of coeval submarine chaotic facies recently imaged by seismic data south of Torino Hill, where they are buried below a thick cover of Pliocene–Quaternary sediments (Mosca, 2006).

The mechanisms that favored sediment fail- ure must be looked for in tectonic deformation related to the northward migration of the Padane thrust front. This process had two main effects: (1) the southward tilting of the Monferrato and Torino Hill domains, that induced slope over-steepening necessary to trigger sediment failure, leading to deposition of thick debris flows on the inner side of a positive relief related to ongo- ing thrust propagation; and (2) the mechanical weakening of the sediments by the north-northeast–south-southwest strike-slip faults, responsible for the disruption of the upper Miocene succession. Studies on modern slides indicate that fault activity could represent a potential triggering mechanism for slope instability (e.g., Bugge et al., 1988; Mulder and Cochonat, 1996; Gee et al., 2005).

Stage 3

Both Unit 1 and Unit 2 are crosscut by Unit 3, the intrusive contacts of which suggest its dia- piric origin (Fig. 9). This is confirmed by the opposing sense of shear on the opposite margins of the structure (e.g., Orange, 1990) and by the threefold zonation of deformation and the block-in-matrix arrangement inside of it. These features are consistent with extrusion mechanisms ("extrusion like toothpaste" sensu Higgings and Saunders, 1967) of poorly consolidated and overpressured fine-grained sediments under metastable conditions (e.g., Barber et al., 1986).

The distribution, size, and shape of the cemented blocks floating in the matrix are related to differences of velocity gradient of the poorly consolidated Sant'Agata Fossili marls (acting as a viscous fluid) migrating through

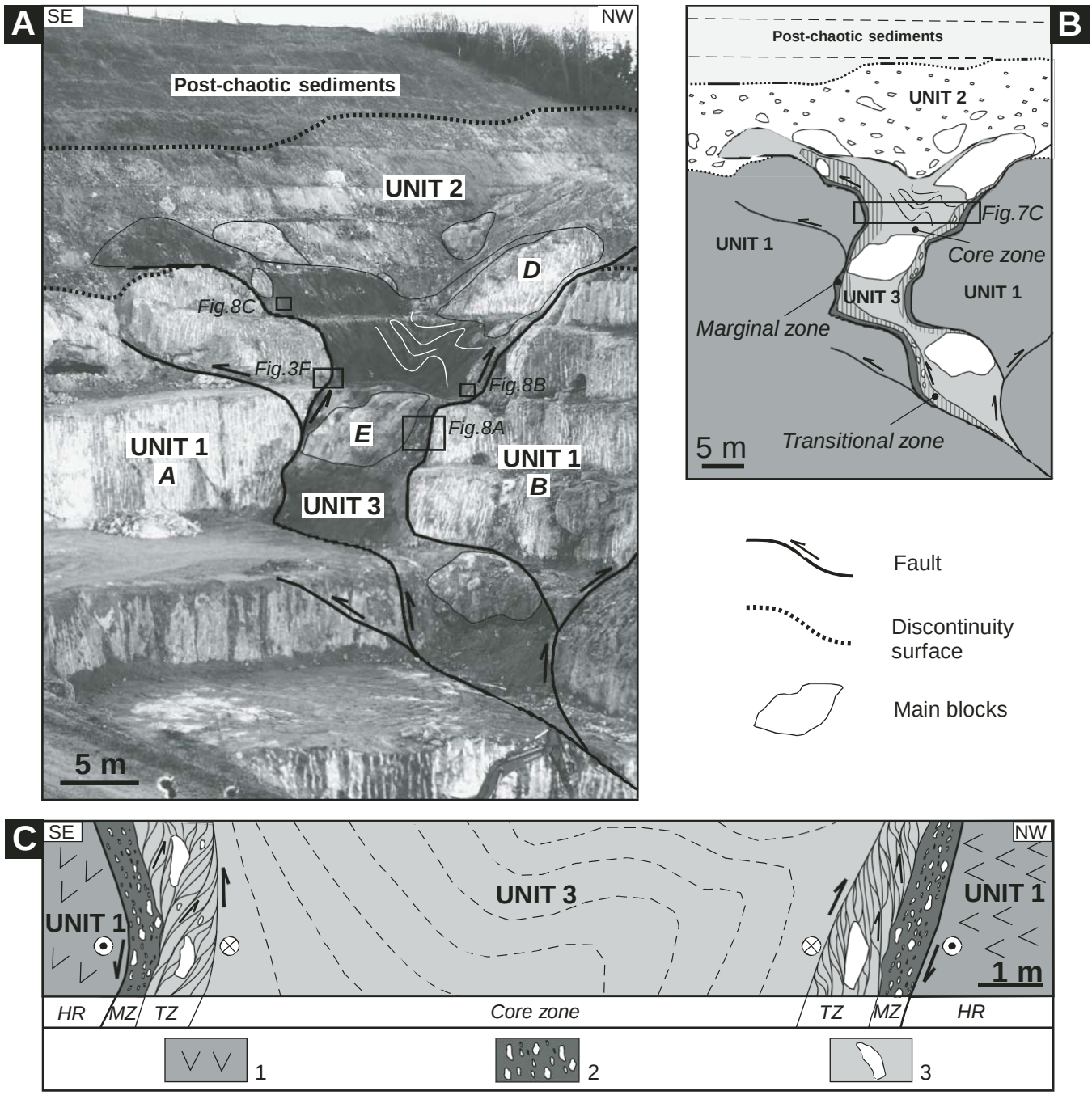


Figure 7. Unit 3. (A) Panoramic view showing the relationships of Unit 3 with Units 1 and 2. The north-northeast–south-southwest bounding faults are clearly visible. White lines indicate the bedding of the Sant'Agata Fossili marls (SAF). Capital letters indicate the blocks discussed in the text. (B) Drawing of A, showing the three zones distinguished within Unit 3. (C) Cross section of Unit 3. HR—host rocks; MZ—marginal zone; TZ—transitional zone; 1—selenitic gypsum of Unit 1 (the V-shaped symbols open toward the top of the beds); 2—fluidal mud breccias; 3—blocks in the transitional zone. The bedding of SAF in the core zone is shown (black dotted lines). Opposing senses of shear on the opposite margins of the structure are clearly indicated by the orientation of S-C fabric in the transitional zones. See B for location.

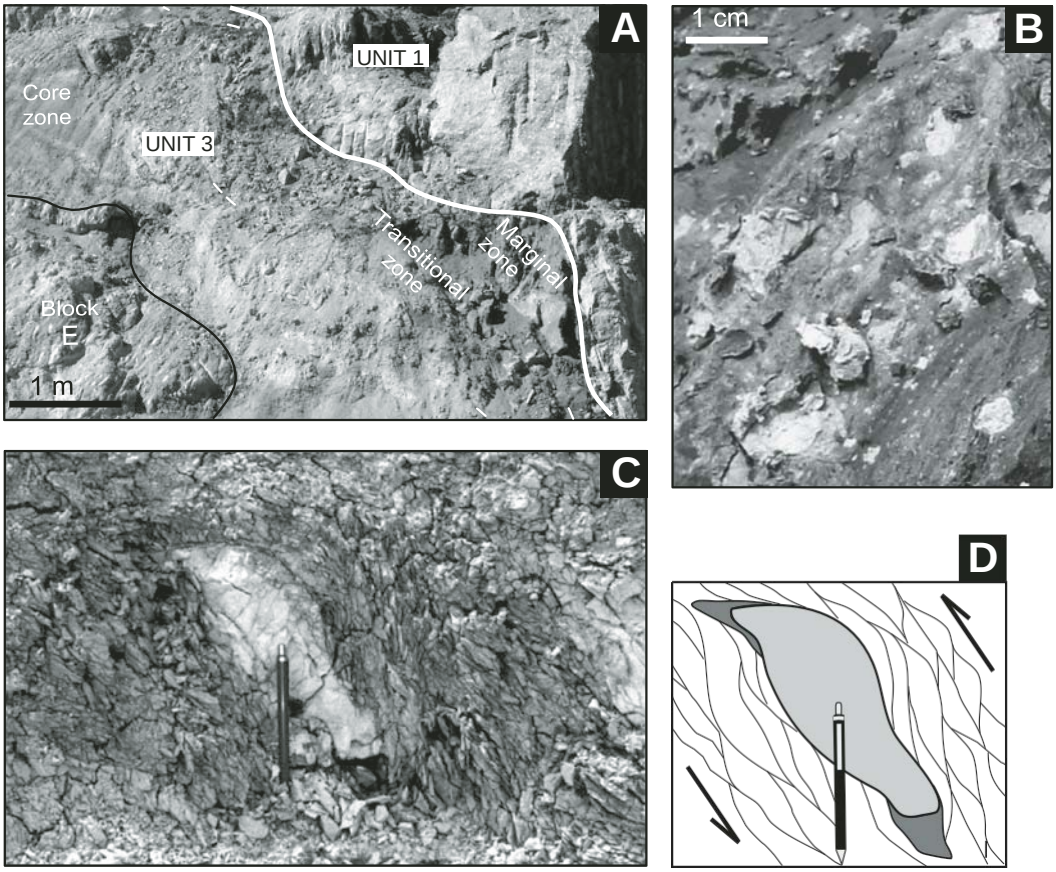


Figure 8. Unit 3. (A) Detail of the northwest margin, showing the three zones recognized within Unit 3. (B) Close-up of the mud breccias composing the marginal zone: whitish marly clasts floating in a clayey matrix are visible. Fluidal features, evidenced by the alignment of elongated clasts, are recognizable. See Figure 7A for location. (C) Detail of the transitional zone: long-axis carbonate block wrapped by strongly deformed muddy sediments (Sant'Agata Fossili marls) with a pervasive scaly cleavage. The pencil is 14 cm long. (D) Drawing of C, showing the relationships between the carbonate block and the scaly cleavage. The arrows indicate the sense of shear. A sort of pressure shadow can be seen at the terminations of the block (dark gray areas).

rigid host rocks (selenitic gypsum), as described both in theoretical models (e.g., Komar, 1972; Bishop, 1978) and ancient diapirs (e.g., Barber and Brown, 1988; Brown and Westbrook, 1988; Orange, 1990; Brown and Orange, 1993). In particular, the occurrence of randomly distributed large and angular blocks only in the core of the diapir (blocks D and E, Fig. 7A), the alignment of long-axis blocks to the scaly cleavage (Fig. 8C), and their increased clustering toward the external zones are consistent with an increase in velocity gradient toward the marginal contacts (Komar, 1972; Orange, 1990).

In contrast to the marginal zones of other ancient diapiric mélanges, in which the mélange matrix displays an intense scaly cleavage (Barber et al., 1986; Orange, 1990; Brown and Orange, 1993; Orange and Underwood, 1995), in our example a narrow zone of fluidal mud breccias has been observed at the contact between the diapir and the host rocks (Figs. 3F and 8B). These sediments likely formed in response of the upward movement of wet, unconsolidated, and overpressured clays entraining slightly more coherent clasts during their ascension (e.g., Kopf, 2002; Sautkin et al., 2003). They played a role in the diapir emplacement, forming a collar of scarcely viscous, quasi-fluid material that encouraged the rise of the more viscous, main diapiric body, confining it from the rigid host-rock.

The emplacement of the diapir resulted in the reorganization of Unit 2 through the rotation of its blocks parallel to the diapir margins and the mixing of a tongue of Sant'Agata Fossili marls (emplaced by diapirism) with the sedimen- tary chaotic body (Fig. 9), and could also have induced the local uplift and the gentle bending of Unit 2; however, no evidence of these last processes have been found.

Shale diapirism is caused by overpressure conditions that in turn could be the result of tectonic and/or gravity-driven sedimentary load- ing, density inversion, and gas (generally meth- ane) generation and migration (Kopf, 2002). Mechanical discontinuities (e.g., faults, bedding surfaces, joints) often provide preferential pathways for mud expulsion (e.g., Bishop, 1978; Brown and Westbrook, 1988; Orange, 1990; Cartwright, 1994; Losh et al., 1999).

At Moncucco, the rise of the diapir could have been caused by a combination of sedimentary loading and strike-slip faulting. Rapid burial of low-permeability layers (Sant'Agata Fossili marls) belonging to previously disrupted Unit 1 may have caused pore-fluid dissipation, which resulted in pore pressure exceeding hydrostatic pressure and the sediment becoming overpressured (e.g., Maltman, 1994). At the same time, the north-northeast–south-southwest strike-slip faults could have favored the emplacement of the diapir, working as preferential conduits for the upward migration of the overpressured, fluid-rich muds (e.g., Bishop, 1978; Kopf, 2002; Chamot-Rooke et al., 2005). Tectonic faulting may have also played a prominent role in the fracturing of the evaporites, which usually pro- vide an impermeable layer, preventing extrusion of deeper overpressured sediments to the surface (Camerlenghi et al., 1995).

Direct evidence that the fluids involved in the emplacement of the diapir were rich in meth- ane has not been found at Moncucco. However, the occurrence of several blocks of cold-seep carbonates in the Valle Versa chaotic complex close to Moncucco and other sectors of Monferrato and Torino Hill strongly suggests the role played by methane.

Stage 4

The complex and interrelated processes that produced the composite chaotic unit faded out in late Messinian time with the unconformable deposition above it of the Lago-Mare sediments

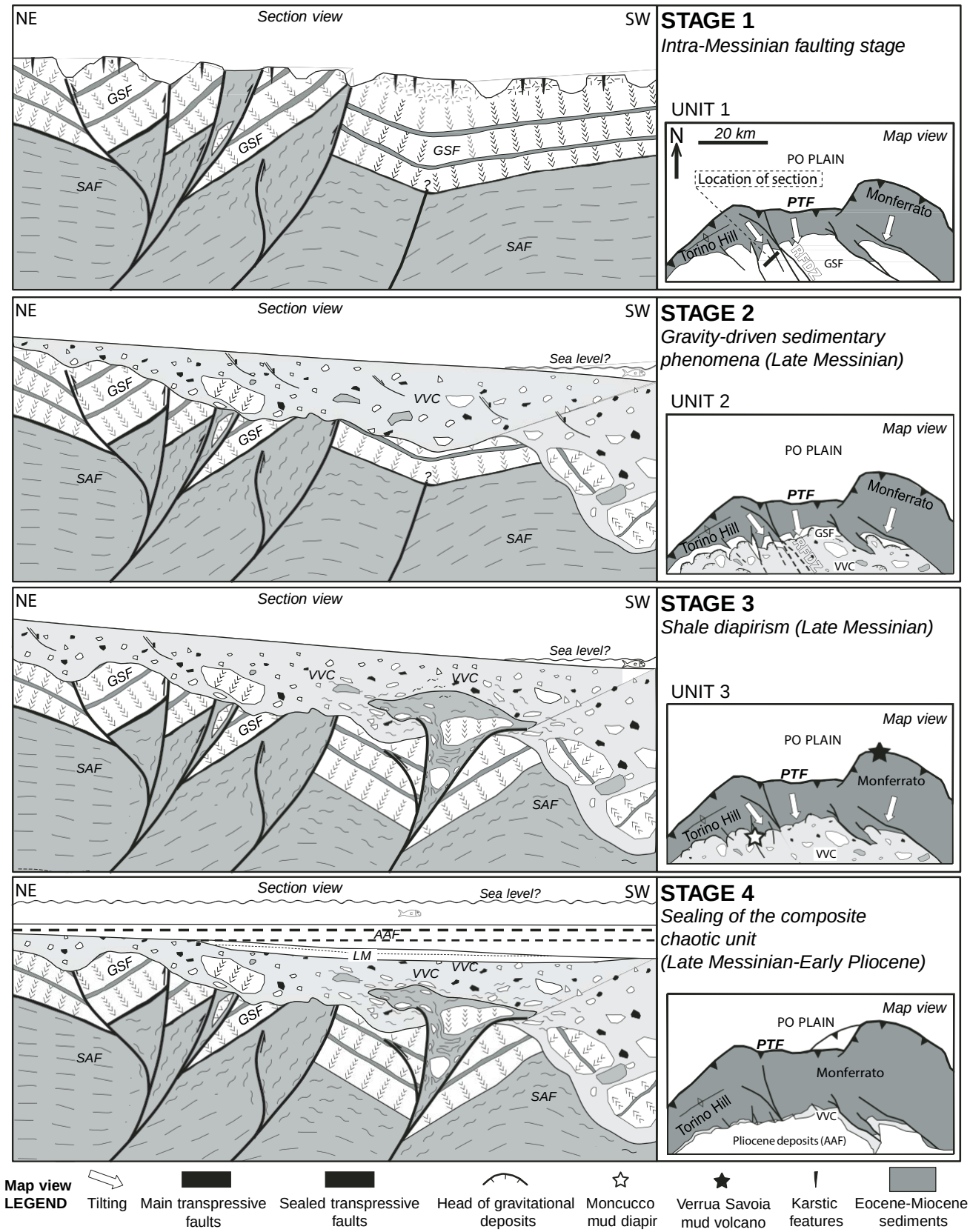


Figure 9. Multistage evolution of the Messinian composite chaotic unit. SAF—Sant'Agata Fossili marls; GSF—Gessoso Solfifera Formation; VVC—Valle Versa chaotic complex; LM—Lago Mare marls; AAF—Argille Azzurre Formation; PTF—Padane thrust front; RFDZ—Rio Freddo deformation zone. For more details, see the text.

(Fig. 9). These sediments were deposited during an interval of tectonic quiescence (Roveri et al., 2003), and record the filling of the basin by hyposaline waters. They are overlain by the lower Pliocene Argille Azzurre Formation, which evidences the reestablishment of fully marine conditions.

CONCLUSIONS

The relative contributions of tectonic fault- ing, gravitational, and diapiric processes in the genesis of a Messinian composite chaotic unit have been evaluated. It appears that these mech- anisms affected each other. Faulting was respon- sible for the disruption of the originally coherent stratigraphic succession, favoring the failure of mechanically weakened sediments and encouraging shale diapirism through the creation of mechanical discontinuities working as conduits for the rising of overpressured sediments. In our example, loading provided by deposition of gravitative chaotic sediments could have contributed (together with the circulation of methane-rich fluids in the sedimentary column) to diapir intrusion, which in turn caused a partial reorganization of the dismembered sediments produced by the other two processes.

The imprint of tectonic deformation is recognizable in Unit 1 by the structurally ordered block-in-matrix fabric and by the scale-independent deformation pattern of the muddy sediments, consistent with regional shortening related to the intra-Messinian tectonic event.

The key features of gravity driven sedimen- tary phenomena (Unit 2) can be seen in the lower and upper depositional contacts, the lack of any orientation of the hard blocks, their random distribution within the matrix, and the brecciated texture of the matrix, which consists of isotropic mud breccias lacking any preferred orientation of the clasts. Intrusive contacts displayed by Unit 3, the threefold zonation of deformation inside it, and the opposing sense of shear on its opposite margins are the most striking evidence, well recognized in outcrop, of shale diapirism. An additional criterion is the presence of blocks of methane-derived carbonates (Clari et al., 2004), not found in the quarry, but just outside it. An unusual feature is the thin envelope of fluidal mud breccias at the contact between the diapir and the host rocks. This collar of scarcely viscous material promoted the rise of the more viscous main diapiric body, confining it from the rigid host rocks.

Large volumes of Messinian chaotic sedi- ments characterize the Tertiary Piedmont Basin and other parts of the Mediterranean area. In these sedimentary bodies, only the imprint left by gravitational movements can be seen. However, it must be taken into account that in the highly mobile geodynamic setting where these deposits formed, slope failure was likely to be the prevailing process, able to completely conceal the traces of both tectonic faulting and shale diapirism: the role played by these latter mechanisms in the genesis of the chaotic sediments could thus be underestimated.

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