Italian Journal of Engineering Geology and Environment
www.ijege.uniroma1.it

THE GEOLOGY OF THE SAN LEO CLIFF (NORTHERN APENNINES, ITALY)

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EXTENDED ABSTRACT

L'obiettivo principale di questo lavoro è dedurre l'assetto geologico della rupe di San Leo dalle sezioni naturali esposte nelle sue stesse pareti rocciose. I line-drawing delle pareti rocciose, abbinati a una carta geologica dettagliata e inquadrati in uno schema tettono-stratigrafico, permettono di ricostruire un modello geologico tridimensionale della rupe di San Leo. L'interpretazione dei dati raccolti consente inoltre di stabilire le relazioni tra litostratigrafia, tettonica e geomorfologia che controllano l'evoluzione di questa spettacolare e delicata emergenza paesaggistica della Val Marecchia. Dal punto di vista della litostratigrafia, gli elaborati prodotti hanno messo in luce inaspettate variazioni di spessore e litologia nella successione epiligure. Sono state inoltre riscontrate tre discordanze angolari, delle quali la prima si trova alla base del primo membro della Formazione di San Marino (SMN1), la seconda alla base del terzo membro della stessa Formazione (SMN3) e la terza alla base del primo membro della Formazione di Monte Fumaiolo (MFU1). Dal punto di vista della tettonica, nella successione epiligure sono state individuate faglie a basso angolo e ad alto angolo. Le faglie a basso angolo sono tutte normali, mentre quelle ad alto angolo sono in gran parte normali e in piccola parte trascorrenti. Le più antiche tra le superfici di taglio a basso angolo (Langhiano) sono listriche e scollate alla base del membro MFU1; alcune di esse terminano verso l'alto all'interno dello stesso membro, manifestando una crescita sin-sedimentaria; l'intero sistema di superfici di taglio si è probabilmente sviluppato nella testata di una frana sottomarina. Alla base delle pareti W, S ed E della Rupe di San Leo è stata individuata una grande faglia normale a basso angolo (Pliocene inferiore), che ribassa verso NE una parte delle unità liguri e l'intera successione epiligure; il tetto della faglia ha subito un basculamento verso SW di circa 20°, che attesta la geometria listrica della superficie di faglia. Insieme alle faglie dello stesso tipo che affiorano al M. Fumaiolo, M. Perticara-Maioletto, Tausano, San Marino, Montebello, Torriana e Verucchio (fig. 1), la faglia di San Leo può essere inserita in un modello d'avanzata per scivolamento gravitativo della coltre della Val Marecchia. Le faglie ad alto angolo (Pliocene superiore – Attuale) hanno due direzioni principali: le faglie NNW-SSE sono normali, mentre le faglie W-E sono almeno in parte trascorrenti destre. Queste faglie e le fratture che le accompagnano svincolano grandi volumi di ammasso roccioso, predisponendoli a fenomeni di crollo. La frana del 2014 (Borgatti *et alii*, 2015), riconducibile alle stesse cause predisponenti, costituisce l'ultimo evento nell'evoluzione della rupe di San Leo, la cui morfologia attuale è il risultato di una lunghissima serie di crolli (Benedetti *et alii*, 2011).

IJEGE, Special Issue 2 (2024): 05-16, DOI: 10.4408/IJEGE.2024-02.S-01
E-ISSN 2035-5688 | ISSN 1825-6635 / ©Author(s)

ABSTRACT

The main objective of this work is to deduce the geologic setting of the San Leo cliff from the natural sections exposed in its own rock walls. The line-drawings of the rock walls, coupled with a detailed geologic map and framed in a tectono-stratigraphic scheme, allow us to reconstruct a 3D geological model of the San Leo cliff. The interpretation of the collected data also allows us to establish the relationships between lithostratigraphy, tectonics and geomorphology that control the evolution of this spectacular and delicate landscape emergency of Val Marecchia. The 2014 landslide (Borgatti *et alii*, 2015) has been only the latest event in the evolution of the San Leo cliff, where fractures and faults of Late Pliocene to Present age have predisposed rock masses to fall, so that the current slope morphology is the result of a very long series of rockfalls (Benedetti *et alii*, 2011).

Keywords: *San Leo cliff, 3D geological model, Northern Apennines, Emilia Romagna region, Val Marecchia, epi-Ligurian succession, rockfall.*

INTRODUCTION

San Leo is in the heart of the Montefeltro countryside of north-eastern Italy and stands on a hill approximately 660 m above sea level. The famous historical-artistic aspects of the San Leo village, inhabited since Roman times, are elegantly summarized in Borgatti *et alii* (2015). The San Leo village stands at the top of a limestone and sandstone cliff of approximately 0.5 km^2, bordered by vertical to overhanging rock walls up to 100 m high, above gentle clayey slopes. The San Leo cliff is subject to lateral spreads and related rockfalls, rockslides and topples, whereas the underlying clays are subject to earth slides and flows. This work concerns the geologic setting of the San Leo cliff, which is complicated by angular unconformities and polyphase deformation. The main objective of this work is to deduce the stratigraphic and tectonic setting of the San Leo cliff from the natural sections represented by its own rock walls. The line-drawings of the rock walls, coupled with a detailed geologic map and framed in a tectonic-stratigraphic scheme, allow us to sketch the 3D arrangement of rock masses and discontinuities, identifying the lithologic and structural factors that control the evolution of the slopes surrounding the San Leo cliff.

METHODOLOGY

Data acquisition

Data were acquired in the following ways. (a) Examination of recent cartography: the geological maps of the CARG project (Sheets Cesena, Rimini, Mercato Saraceno and San Marino); an unpublished geological map by Badioli (2012); some elaborates from a technical report about the 2014 landslide (Lucente, 2014). (b) Close survey of the most accessible outcrops (village and surrounding road, medieval fortress, S rock wall). (c) Remote survey of the less accessible outcrops (E, NNE, NNW rock walls and NW edge of the cliff). (d) Targeted surveys at M. San Severino, Tausano, San Marino and M. Fumaiolo, to frame the San Leo succession in the regional context. (e) Systematic geological interpretation of ground photographs and drone video recordings.

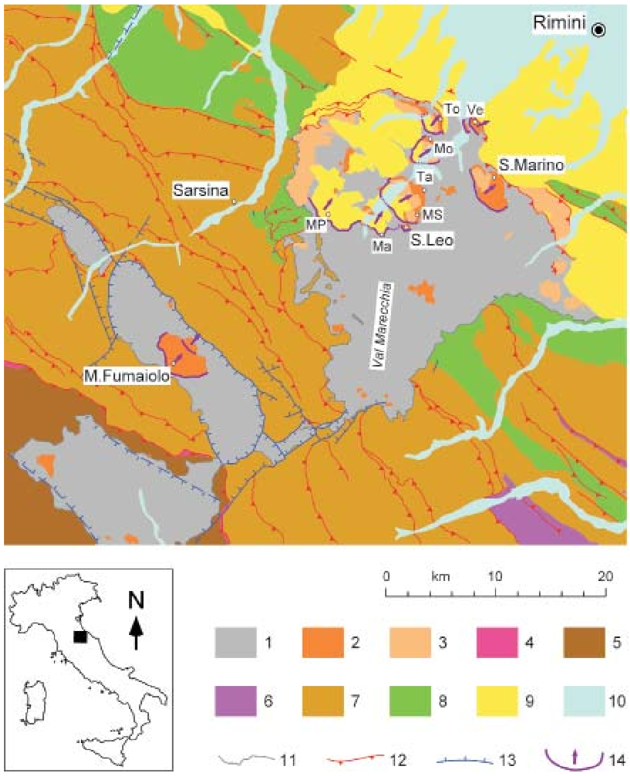

Fig. 1 - Schematic geological map of the Val Marecchia nappe (from Barchi *et alii 2001, modified). LEGEND: 1 - Ligurian and epi-Ligurian units (Aptian – Aquitanian); 2 - epi-Ligurian units (Burdigalian - Langhian); 3 - epi-Ligurian units (Serravallian - Messinian); 4 - Tuscan foreland units; 5 - Tuscan foredeep units (Rupelian – Aquitanian); 6 - Umbria-Marche foreland units; 7 - Umbria-Romagna and Marche foredeep units (Burdigalian – Lower Messinian); 8 - Romagna and Marche foredeep units (Upper Messinian - Lower Pliocene); 9 - neo-autochthonous marine units (Lower Pliocene - Lower Pleistocene); 10 – alluvial deposits (Upper Pleistocene – Holocene); 11 – base of the Val Marecchia nappe; 12 - overthrusts; 13 - high-angle extensional faults; 14 - low-angle, listric normal faults displacing the Ligurian - epi-Ligurian succession. PLACE NAMES: MP – M. Perticara; Ma – Maioletto; MS – M. San Severino; Ta – Tausano; Mo – Montebello; To – Torriana; Ve – Verucchio*

Representation of data in map view

A 1/2000 scale geological map was created (reduced version in Plate I), first by tracing the exposed parts of the geological boundaries on a drone orthophoto (Lucente, 2014), then interpolating the non-exposed parts of the same boundaries;

on the slightly steep slopes, the geological boundaries were interpolated by intersection with the level curves of the available topographic bases (pre-collapse 2006 and post-collapse 2014); in the rock walls, where the level curves are affected by serious interpolation errors, the geological boundaries were completed with the help of ground photographs and drone video recordings.

Representation of data in line-drawings

The geological boundaries exposed in the rock walls were traced on mosaics of ground photographs, with the support of drone video recordings to frame the outcrops from various points of view. The line drawings served not only to show boundaries that cannot be represented in map view, but also to sketch the 3D shape of the geological bodies that make up the San Leo cliff.

REGIONAL FRAMEWORK

The San Leo cliff is a small chunk of the epi-Ligurian succession of the Val Marecchia nappe, which in turn is a large Klippe of the Ligurian nappe of the northern Apennines (Fig. 1; Lucente *et alii*, 2002). The nappe advanced from SW to NE during the sedimentation of the foredeep succession in the Tuscan, Umbria-Romagna and Marche-Padan domains (Fig. 2). The current front of the nappe rests in the Po Plain subsurface. In the San Leo cliff, the epi-Ligurian succession is represented by the San Marino Formation (Burdigalian) and the lower member of the M. Fumaiolo Formation (Langhian).

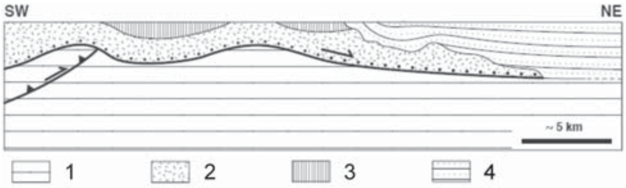

Fig. 2 - Simplified tectonic-stratigraphic scheme of the Val Marecchia (from De Feyter, 1991, modified). LEGEND: 1 - Umbria-Marche-Romagna succession and post-evaporitic pre-nappe succession ("paleo-autochthon"); 2 - Ligurian units ("allochthon"); 3 - epi-Ligurian succession ("semi-alIochthon"); 4 - post-evaporitic post-nappe succession ("neo-autochthon"). The San Leo cliff is a small chunk of the epi-Ligurian succession

A very large stratigraphic gap separates the San Marino Fm. from the underlying Ligurian units (Argille Varicolori Formation, Sillano Formation, M. Morello Formation). The San Marino Fm. and the M. Fumaiolo Fm. derive from the initially carbonate, then hybrid and finally siliciclastic shelf succession which sedimented on the Ligurian units during their advance over the Tuscan units (Ruggieri, 1958; Ricci Lucchi, 1964; Ricci Lucchi, 1986; Ricci Lucchi & Ori, 1985). With the subsequent advance of the nappe over the Umbria-Romagna and Marche-Padan units, the epi-Ligurian shelf was dismembered, to the point that today its remains are scattered from the Casentino to the Padan Apennine margin (Fig. 1). Since the 1950s, the dismemberment of the epi-Ligurian shelf has been linked to a gravitational advance of the Val Marecchia nappe, which was interpreted by Ruggieri (1958) as a huge earth flow (Fig. 3, A).

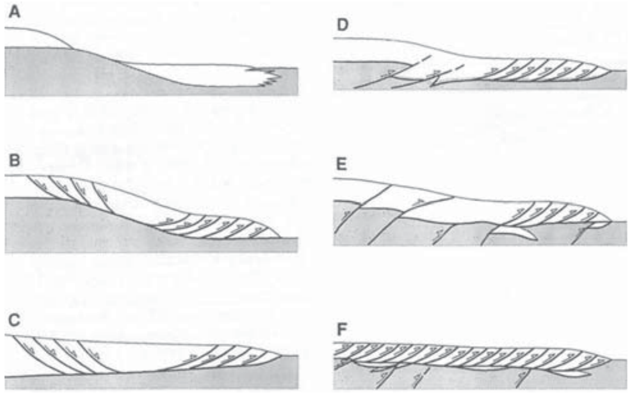

Fig. 3 - Nappe advancement models (from De Feyter, 1991): LEGEND: A - stacking of olistostromes; B - gravitational sliding (De Jager, 1979); C - gravitational expansion (Elliott, 1976); D - compressional tectonics and gravitational sliding (Ricci Lucchi & Ori, 1985); E - compressional tectonics (Castellarin & Pini, 1987); F - essentially gravitational sliding (De Feyter, 1991)

However, several studies conducted in the 1970s and 1980s (summary in De Feyter, 1991) showed that such a generalized flow was not compatible with the structural arrangement of the Ligurian units. Various models based on sliding instead of flowing were therefore developed (Fig. 3, B-F), differing from each other due to the greater or lesser importance given to gravitational tectonics compared to compressive tectonics. The model recently adopted within the CARG project (Cornamusini *et alii*, 2015) is an evolved version of the De Feyter's model (1991; Fig. 3, F), which explains the emplacement of the nappe with the gravitational stacking of a sequence of allochthonous bodies in a subsident basin. Inside the nappe, the allochthonous units thrust over other allochthonous units, while in the frontal area of the nappe the allochthonous units thrust over both semi-allochthonous and neo-autochthonous units. In our opinion, the CARG project authors did not provide sufficient evidence to link the allochthon-on-allochthon overthrusts to the nappe advance, mainly because such overthrusts were not datable. Without considering such overthrusts, a more unitary model can be introduced. In our opinion, the gravitational sliding model proposed by De Jager (1979; Fig. 3, B) is the one that best explains the dismemberment of the epi-Ligurian shelf, by the development inside the nappe of an imbricated system of extensional faults, detached right at the base of the nappe. The low-angle normal fault at the foot of the San Leo cliff (Plate I, Fig. 4) fits perfectly into this model, similarly to other faults that are found at the foot of many cliffs in Val Marecchia (Fig. 1). In addition to an extensional "detachment zone", the De Jager's model includes a compressional "accumulation zone", which in theory should correspond to the frontal area of the nappe. According to this model, the accumulation zone is characterized by an imbricated system of overthrusts, associated with the extensional faults of the detachment zone in a common context of retrogressive propagation. In Val Marecchia, however, the few datable overthrusts are more recent than the extensional faults: in fact, the allochthonous units thrusted over semi-allochthonous and neo-autochthonous units when the nappe had already reached its current position, and the epi-Ligurian succession had already been dismembered. The only extensional faults that can be coeval with the exposed overthrusts are the Perticara – Maioletto fault (Cornamusini *et alii*, 2015, pages 54-55) and probably the San Leo fault (Fig. 1, Fig. 4, Plate I). The older extensional faults, such as those of Torriana, Verucchio and San Marino (Fig. 1) could instead be associated with overthrusts currently buried by the Plio-Quaternary succession of the Padan Apennine margin (Capozzi *et alii*, 1997; Martelli *et alii*, 2005, section A-A').

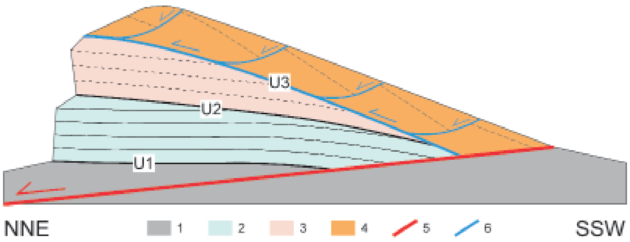

Fig. 4 - Not to scale tectonic-stratigraphic scheme of the San Leo cliff, which incorporates data from all the rock walls and is mainly inspired by the outcrop of Fig. 12. LEGEND: 1 – Argille Varicolori Fm. (AVR) and other Ligurian units; 2 - San Marino Fm., SMN1 and SMN2 members; 3 - San Marino Fm., SMN3 member; 4 - Monte Fumaiolo Fm., MFU1 member; U1, U2, U3: angular unconformities; 5: low-angle normal fault between AVR and SMN/MFU; 6: low-angle shear surfaces detached at the base of MFU1

STRATIGRAPHY

The proposed tectonic-stratigraphic scheme (Fig. 4) depicts the San Leo cliff as a chunk of semi-allochthonous epi-Ligurian succession resting on allochthonous Ligurian units. From the hills N of the cliff, all units of the scheme can be seen in overview (Fig. 5).

Ligurian Units

The Argille Varicolori Formation (AVR, Aptian – Ypresian p.p.) is the lowest unit of the succession represented on the geological map of Plate I. This unit is composed of polychrome shales with discontinuous layers of calcarenites, calcilutites, fine sandstones, siltstones and marls (Cornamusini *et alii*, 2009). The Sillano Formation (SIL, Cenomanian p.p. – Ypresian p.p.) has not been differentiated from AVR; it crops out mainly to the E of the San Leo cliff. The M. Morello Formation (MLL, Ypresian p.p. – Lutetian) has not been differentiated from AVR; it crops out near the SE edge of the San Leo cliff. The stratigraphic boundary between the Ligurian units and the epi-Ligurian succession is an angular unconformity, characterized by a time hiatus that includes all the epi-Ligurian units from the Bartonian to the Aquitanian. This stratigraphic boundary only crops out at the foot of the NNE and NNW rock walls of the San Leo cliff (Figs. 4, 6). At the foot of all other rock walls the same boundary has been displaced by a low-angle normal fault (Plate I, Fig. 4).

Epi-Ligurian Succession

In the San Leo cliff, the lowermost epi-Ligurian unit is the San Marino Formation (SMN, Burdigalian), which is composed of three members (SMN1, SMN2 and SMN3). Due to scale and perspective limitations, in our geological map (Plate I) SMN is represented by two units only: the lower one corresponds to members SMN1+SMN2, while the upper one

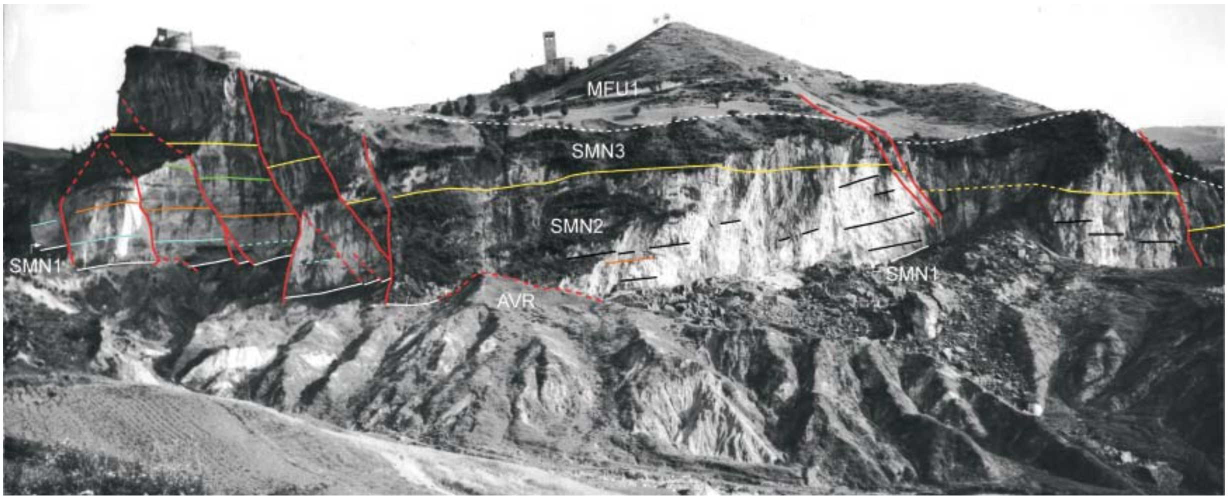

Fig. 5 - Overview of the San Leo cliff from the NNW (photo Belli 1920-1930). The photo, prior to the rockfalls of 2006 and 2014, shows the Ligurian clays and the whole epi-Ligurian succession: the rock walls expose a thin and discontinuous SMN1, a thick SMN2, and a SMN3 of quite variable thickness; the gentle slopes on top of the cliff are modeled in the erodible MFU1

corresponds to the SMN3 member. The SMN1 member crops out at the foot of the NNE and NNW rock walls of the cliff; it consists of a single layer of calcirudite, with sporadic clasts derived from the Ligurian units (Fig. 6).

Fig. 6 - Stratigraphic boundary between AVR (hidden by vegetation) and SMN1, that is only a few meters thick

alternated to calcareous and polymictic rudites (Cornamusini, 2009). In the San Leo succession, the SMN2 member of is made up of light gray biocalcarenite banks, from plane-parallel in the NNE rock wall (Figs. 7, 8) to variously dipping in the NNW rock wall (Fig. 11). The banks are separated by slightly darker layers, characterized by a high frequency of microfractures sub-perpendicular to the bedding planes.

The biocalcarenites are homogeneous but not isotropic, since many collapsed blocks have been shattered into slabs delimited by bedding planes. In some collapsed blocks and in some banks of the NNE rock wall a low order crossbedding is visible, but remote sensing does not allow us to attribute a systematic value to these data. In the San Leo cliff, the thickness of the SMN2 member is maximum near the NE edge (about 100 m, Fig. 5), and minimum near the NW edge (about 40 m, Fig. 5). Probably, the succession of the NW edge of the San Leo cliff was originally contiguous to that of M. San Severino, in which the biocalcarenite banks do not exist. The M. San Severino succession is in fact composed of calcirudites (SMN1), massive biocalcarenites associated with calcirudites (SMN2) and cross-bedded hybrid calcarenites (SMN3). N of M. San Severino, biocalcarenite banks crop out again in a short stretch of the road between Castelnuovo and Varco Rite, while they are lacking in the Tausano succession, where the SMN2 member is mainly made up of organogenic rhodolite and Bryozoans limestones. In the San Marino succession, the SMN2 member consists of thick-bedded biocalcarenites up to a maximum thickness of 150 m. In the N slope of M. Fumaiolo, thick-bedded biocalcarenites crop

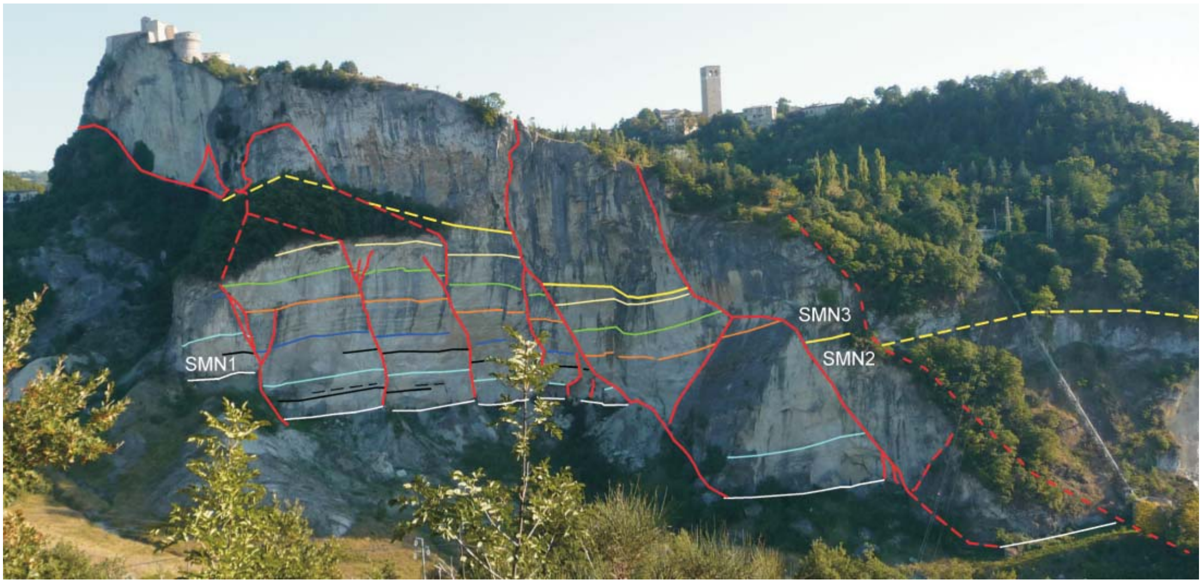

Fig. 7 - The NNE rock wall before the 2014 rockfall (photo Guerra 2011). The SMN2 member is stratified in banks, while the SMN3 member has a cross-bedded structure that cannot be seen from afar. The SMN2/SMN3 boundary is an angular unconformity. The whole succession is displaced by high-angle, WSW dipping extensional faults

This layer can be correlated by facies and composition with the SMN1 member cropping out at M. San Severino, Tausano and San Marino, but its thickness is minimal (about 3 m at San Leo compared to 50 m at San Marino). Similar layers are intercalated in the SMN 2 member of the Monte Fumaiolo succession, but their limited lateral continuity may not allow a correlation up to San Leo. In the San Marino succession, the SMN1 member is composed of massive to poorly stratified coarse biocalcarenites,

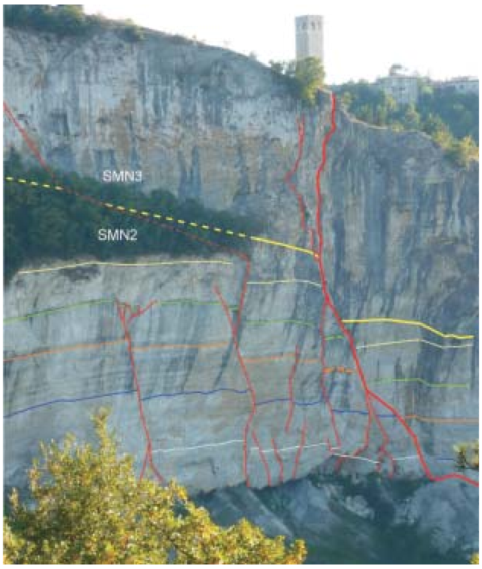

Fig. 8 - Detail of the NNE rock wall before the 2014 rockfall (photo Guerra 2011). The banks and thick layers of the SMN2 member have fair lateral continuity. The unconformable SMN2/SMN3 boundary has ambiguous morphological evidence: a ledge in the altered rock wall, and a roof in the fresh rock wall

out near the Hermitage of S. Alberico, just below the SMN2/SMN3 boundary. In the San Leo succession, the stratigraphic SMN2/SMN3 boundary is probably an angular unconformity, for the following reasons: there is no evidence of heteropia between the lower unit and the upper unit; the contact is marked by a sharp upward increase in the siliciclastic component of the arenites; the contact surface truncates the banks of the SMN2 member in the E sector of the NNE rock wall (Figs. 8, 9), in the NNW rock wall (Fig. 11), and in the NW edge of the cliff (Fig. 12).

In the San Leo succession, the SMN3 member consists of hybrid calcarenites in thin to thick layers, locally obliterated by intense bioturbation; sedimentary bodies of metric to decametric thickness are organized as a large-scale crossbedding, locally detectable from a distance (Fig. 10). The thickness of the SMN3 member is about 100 m near the SE edge of the cliff, 30 m in the NNW rock wall, 60 m near the SW edge and 0 m in the W rock wall, where the lower member of the M. Fumaiolo Formation (MFU1, Langhian) rests unconformably on the SMN2 member (Figs. 5, 12). The thickness variation of the SMN3 member is a peculiarity of the San Leo cliff, in contrast with the notable lateral continuity of the same member at a regional scale, which allows its correlation between the successions of M. Fumaiolo, San Leo, Tausano and San Marino. The SMN3 member is composed of hybrid biocalcarenites in medium to thick layers, with low-angle cross-lamination. A progressive increase in the non-carbonate, mainly glauconitic fraction marks the transition

Fig. 9 - The NNE rock wall after the 2014 rockfall. The unconformable SMN2/SMN3 boundary has taken on unambiguous morphological evidence as a roof. Above this boundary, the main scarp of the 2014 rockfall was determined by a large pre-existing fracture; below the same boundary, the main scarp developed by breaching fresh rock. Laterally, the falling rock masses were released by pre-existing high-angle normal faults

to the overlying M. Fumaiolo Fm. (Cornamusini, 2009). In the San Leo cliff, the stratigraphic SMN/MFU boundary is probably an angular unconformity, for the following reasons: there is no evidence of heteropia between the two units; the contact is very sharp, and marked by erosional "pockets" on top of SMN3 (Fig. 13); in the internal courtyard of the San Leo fortress, a borehole intercepted two arenite beds very rich in glauconite, indicating condensed sedimentation just a few meters below the boundary; in the W rock wall of the cliff, MFU1 truncates the SMN2/SMN3 boundary at an angle of about 10° (Fig. 12); the overall change in SMN3 thickness suggests a concave-up shape for the (erosional?) surface of the SMN/MFU boundary.

Fig. 10 - The SMN3 calcarenites are thin-bedded and cross-bedded, with foresets of decametric amplitude

Fig. 11 - The NNW rock wall after the 2006 rockfall. The banks of the SMN2 member show an average dip to the ENE, and thickness variations that were not noticed in the NNE rock wall. The SMN2/SMN3 boundary is an angular unconformity. High-angle extensional faults dip to the WSW, as in the rock walls E and NNE. The MFU1 member is hidden by wood in the gentle slopes on top of the cliff

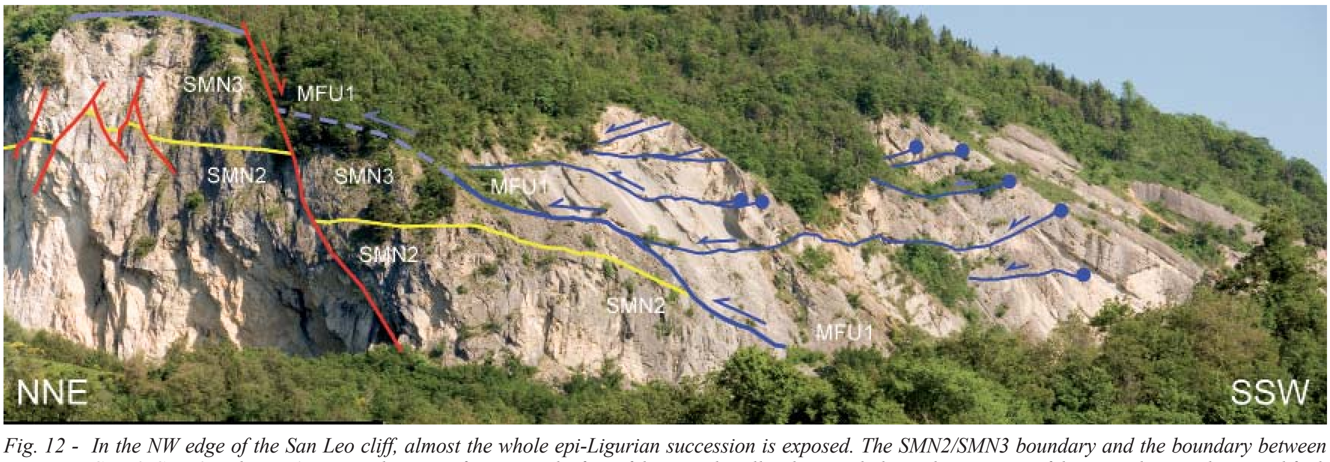

Fig. 12 - In the NW edge of the San Leo cliff, almost the whole epi-Ligurian succession is exposed. The SMN2/SMN3 boundary and the boundary between SMN2, SMN3 and MFU1 are angular unconformities. The foot of the W rock wall is the morphological expression of the major low-angle normal fault that lowers the epi-Ligurian succession to the NE. The base of MFU1 coincides with the detachment surface of an imbricated system of low-angle shear surfaces; many shear surfaces terminate upwards within MFU1 (solid blue circles), thus revealing their syn-sedimentary growth

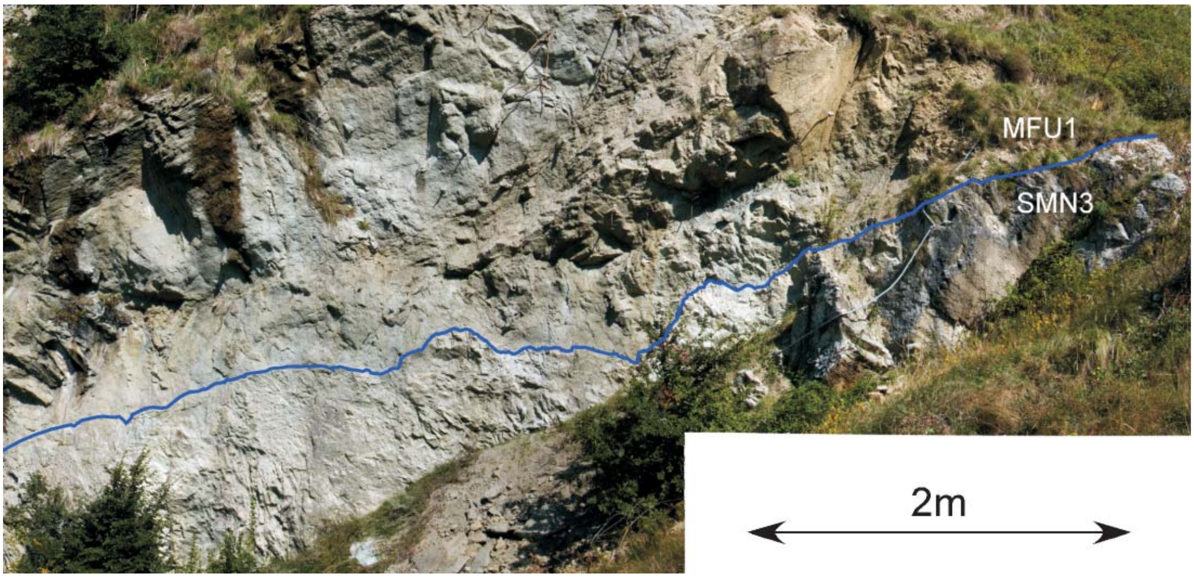

Fig. 13 - Detail of the SMN3/MFU1 angular unconformity, cropping out in the S rock wall of the San Leo cliff near the village gate. The top of the SMN3 member is irregular, with erosional "pockets"

Fig. 14 - Cross-bedded structure in a thick layer of sandstone belonging to the MFU1 member

In the San Leo succession, MFU is only represented by its lower member (MFU1), whereas at M. San Severino and Tausano the upper member (MFU2) also crops out. The MFU1 member is composed of sandstones and hybrid calcarenites in banks and layers, amalgamated or interbedded with sandy marls. The sandstone banks are characterized by internal plane-parallel and cross-bedded structures (Fig. 14). The sandstone composition is hybrid and rich in glauconite grains (Cornamusini, 2009). Hybrid calcarenites are represented only by sporadic layers in the lower part of the MFU1 member.

TECTONICS

Syn-sedimentary structures (Langhian)

In the San Leo cliff, the MFU1 member of the M. Fumaiolo Fm. embeds an imbricated system of extensional shear surfaces,

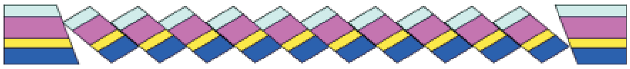

Fig. 15 - Rotation of shear surfaces, due to the "domino effect

detached on a level close to the SMN/MFU boundary. In outcrop, that detachment level is geometrically confined in a decimetric thickness of homogeneous and structureless sandstone (Fig. 13). In the absence of clay layers or other beds of persistent mechanical weakness, this detachment surface could have been activated shortly after sedimentation, due to liquefaction of loose sand. This hypothesis is supported by the overall brittle-ductile behavior of MFU1 (ramp angles from 20° to 60°), and by some growth evidence in the youngest shear surfaces of the system (W rock wall, Fig. 12). Probably, the whole system of shear surfaces has developed by gravity in the head of a large slump. The average strike of the shear surfaces is SSE-NNW. Dip direction and dip angle of the shear surfaces depend on the rotation they have undergone, in at least two successive phases. The first phase is syn-sedimentary and is due to the "domino effect" generated by sliding on the same surfaces (Fig. 15), while the second phase is post-sedimentary. The cumulative effect of these rotations was a tilt towards the SW which reduced the dip angle of the shear surfaces, in some cases up to reverse their dip from ENE to WSW (Figs. 12, 19).

Post-sedimentary structures (Early Pliocene)

The foot of the San Leo cliff coincides with the boundary between the Ligurian units and the epi-Ligurian succession, which is stratigraphic only at the foot of the NNE and NNW rock walls (Figs. 5, 7, 11). At the foot of the other rock walls, the contact is a tectonic NE-dipping ramp, which lowers the epi-Ligurian succession and part of the underlying Ligurian units

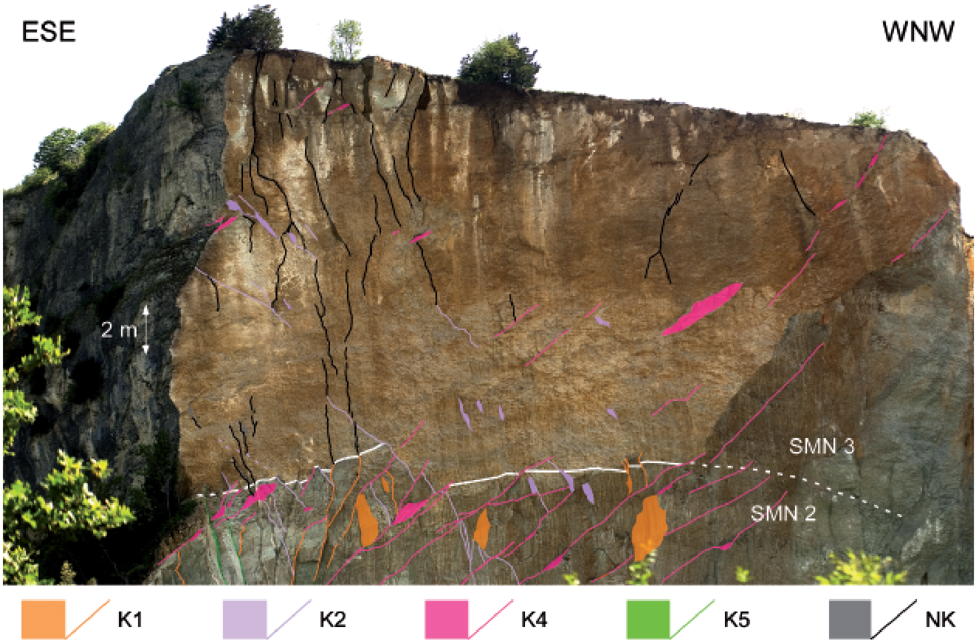

Fig. 16 - Detail of the NNE rock wall after the 2014 rockfall. Discontinuity lines and surfaces are color-coded as in Fig. 17. Typical dip directions/angles: K1 – 250/85; K2 – 230/85; K4 – 62-52; K5 – 305/85. The most prominent discontinuity surface (K3 – 28/83) coincides with the large, rusted rock face exposed by the 2014 landslide. Black lines and surfaces (NK) highlight gaping fractures, possibly belonging to the K1 family, that are particularly insidious for the stability of the E rock wall.

towards the NE (Plate 1, Fig. 4). At the SW edge of the cliff (Fig. 12), the angle between the ramp and the bedding planes of MFU1 is about 25°; near the village gate (Fig. 19), the angle between the ramp and the SMN/MFU boundary is about 28°; near the NW edge of the cliff (Fig. 12), the angle between the ramp and the SMN2/SMN3 boundary is about 30°. This ramp can be interpreted as part of a listric normal fault, probably detached at the base of the Val Marecchia nappe and consistent with the gravitational emplacement of the nappe itself. Rotational slip on this listric fault has caused the epi-Ligurian succession to tilt towards the SW. The current dip angle of the least deformed layers of MFU1 (SW edge, Fig. 12) roughly equals the overall rotation of the fault hangingwall, that can be estimated as 20°.

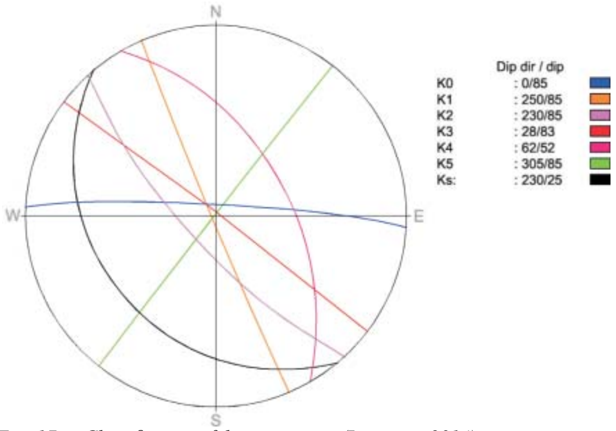

Fig. 17 - Classification of discontinuities (Lucente, 2014)

Post-sedimentary structures (Late Pliocene – Present)

All faults described in this paragraph have displaced the boundary between the Ligurian units and the epi-Ligurian succession after the rotational slip described in the previous paragraph. Observing the San Leo cliff from the N, a regular staircase of extensional faults dipping to the WSW is perceived (Figs. 5, 7, 8, 9, 11, 12). The average strike of these faults is NNW-SSE, and their dip angle is about 70°. The throws of the main faults are multi-decametric. The geometry of these faults is not perfectly planar, as it was determined by the activation in shear of pre-existing discontinuities that were not entirely parallel to each other. The best documented fault of this system crops out in the E rock wall (Fig. 18), at the base of which it displaces the low-angle normal fault between the Ligurian units and the epi-Ligurian succession (Plate 1). The strike of this fault is controlled by two discontinuity sets (Fig. 17): the central-northern part of the fault belongs to the K1 family, whereas the southern part belongs to the K2 family. On the rock wall, fault surfaces with giant striae (Fig. 18) allow us to attribute a left trans-tensional slip to K1, with a prevalence of the extensional component. In the main faults that cross the NNE rock wall (Figs. 7-9), other giant striae suggest instead an almost purely extensional slip. The rare faults striking E-W, derived from the activation in shear of the K0 family, are particularly interesting for their right-lateral slip.

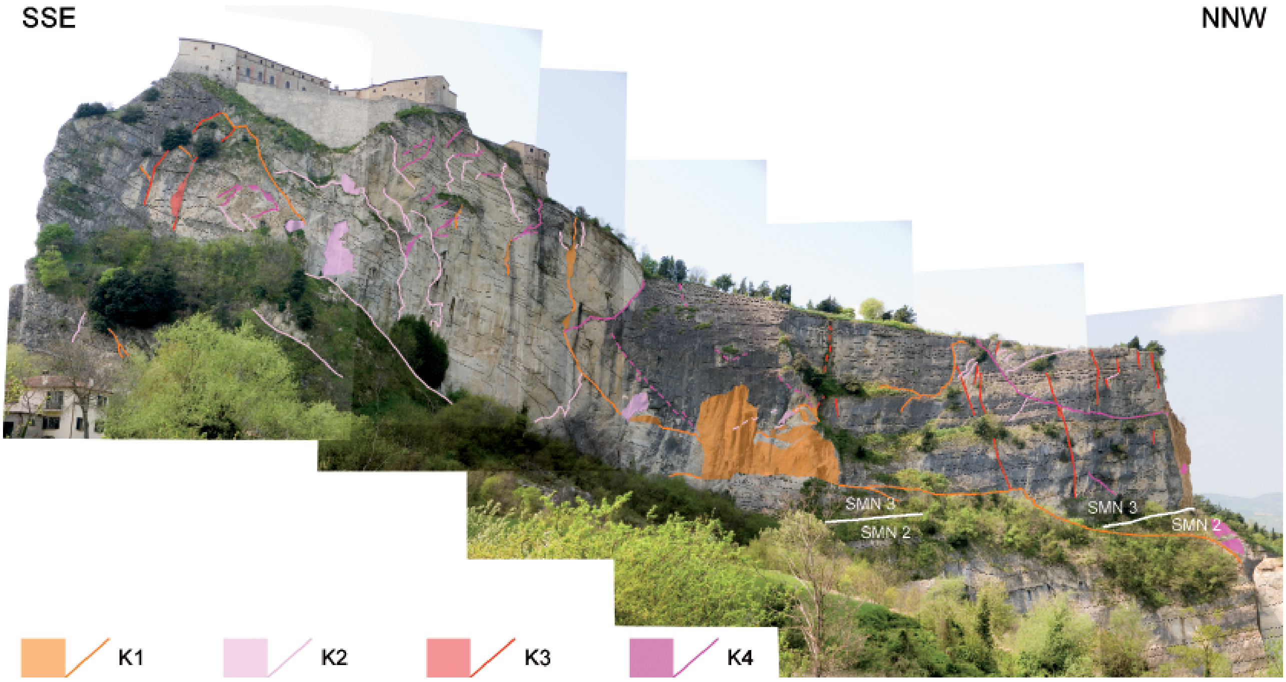

Fig. 18 - The E rock wall. Discontinuity lines and surfaces are color-coded as in Fig. 17. Typical dip directions/angles: K1 – 250/85; K2 – 230/85; K3 – 28/83; K4 – 62-52. The foot of the rock wall is the morphological expression of the low-angle normal fault that lowers the epi-Ligurian succession towards the NE; this fault doesn't crop out, as it was displaced and partially hidden by high-angle faults (K1, K2) which lower the epi-Ligurian succession towards the WSW. The slip surfaces of these high-angle faults crop out in the rock wall above; in the largest exposed surface, giant striae testify to the left trans-tensional kinematics of the K1 family

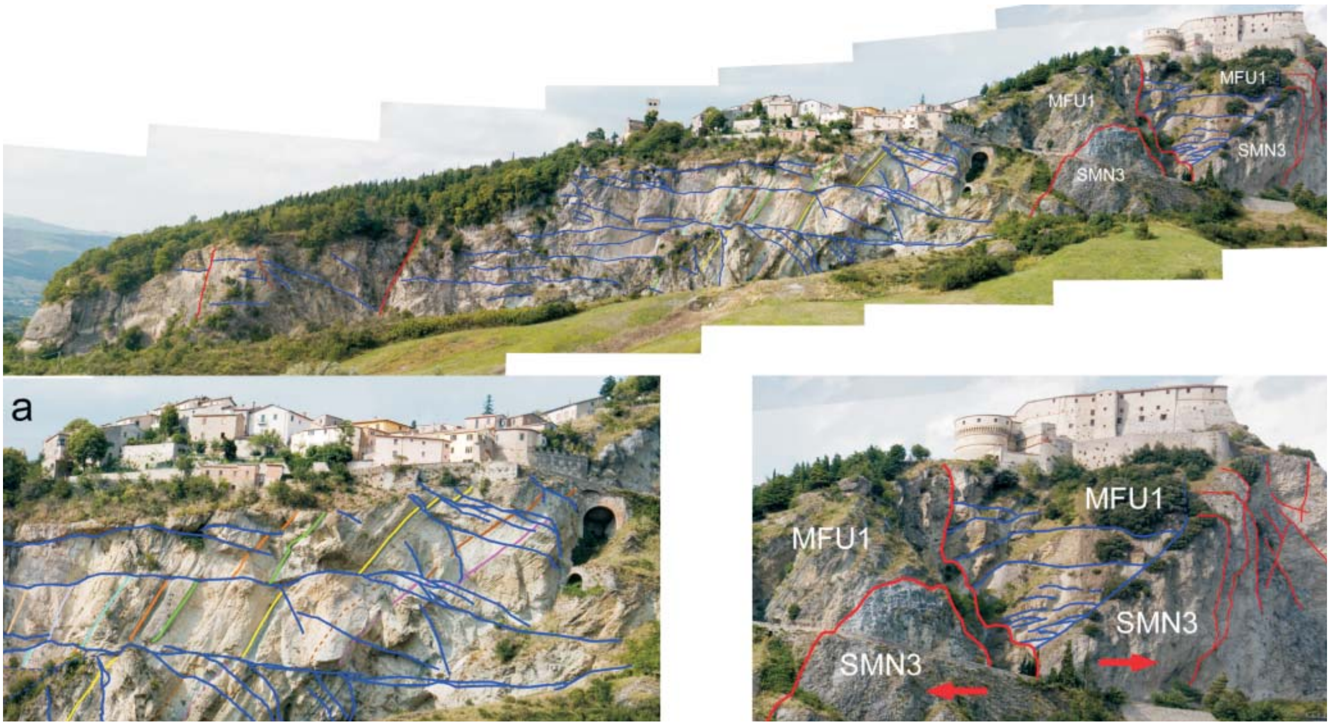

Fig. 19 - From the SW edge of the San Leo cliff to the village gate, the foot of the S rock wall coincides with the tectonic contact between the Ligurian units and MFU1. Higher in the rock wall, the imbricated system of shear surfaces embedded in MFU1 is most evident (detail a). From the village gate to the SE edge the SMN3 member reappears, but the boundary between the latter and MFU1 is partially masked by a right strike-slip fault (detail b)

The most evident of these faults is the one that runs from the SE edge of the cliff almost to the village gate, placing the upper part of the San Marino Fm. (S side) alongside the lower part of the M. Fumaiolo Fm. (N side). Over time, with erosion, the unit exposed in the S side of the fault has been reduced to a thin diaphragm, a sort of limestone "screen" that hides the lower part of the M. Fumaiolo Fm. (Fig. 19b). The chronological relationships between extensional faults and strike-slip faults are not clear, although the occurrence of trans-tensional faults may suggest a simultaneous activation of the two types of slip.

GEOMORPHOLOGY

The morphology of the San Leo cliff depends strictly on the stratigraphy and tectonics of the epi-Ligurian succession. The cliff is made up of two different rock masses: the San Marino Fm. (SMN) and the M. Fumaiolo Fm. (MFU). In the SMN unit, made up of relatively resistant calcarenites, landforms depend in part on bedding planes, but above all on high-angle fractures and faults, striking NNW-SSE and E-W (Late Pliocene – Present). The rhomboidal plan shape of the San Leo cliff (Plate I) and the steepness of its rock walls are strongly conditioned by these discontinuities. Fractures and faults have predisposed giant rock mass volumes to fall, so that the current slope morphology is the result of a very long series of rockfalls (Benedetti *et alii*, 2011). From this perspective, the 2014 landslide is only the latest event in the geomorphological evolution of the San Leo cliff. In the MFU unit, made up of relatively weak sandstones, landforms depend both on bedding planes and on the very complex system of syn-sedimentary shear surfaces that crops out from the S wall to the NW edge of the San Leo cliff (Figs. 12, 19). The determination of the boundaries to be traced in our geological map (Plate I) was favored by criteria based on morpho-selection, since the mapped units have different resistance to erosion. From this point of view, the most evident boundary is the one between the Ligurian units and the epi-Ligurian succession. The original stratigraphic boundary only crops out at the foot of the NNE and NNW rock walls of the San Leo cliff. At the foot of all other rock walls, the same boundary has been displaced by a low-angle normal fault (Early Pliocene). This way, in the NE sector of the cliff the Ligurian clays (AVR) are in contact with calcarenites (SMN), while in the south-western sector of the cliff the Ligurian clays (AVR) are in contact with sandstones (MFU). Another boundary enhanced by morpho-selection is that between calcarenites (SMN) and sandstones (MFU); for instance, this boundary separates the rocky spur of the medieval fortress (SMN) from the gentle, wooded hill of the San Leo village (MFU).

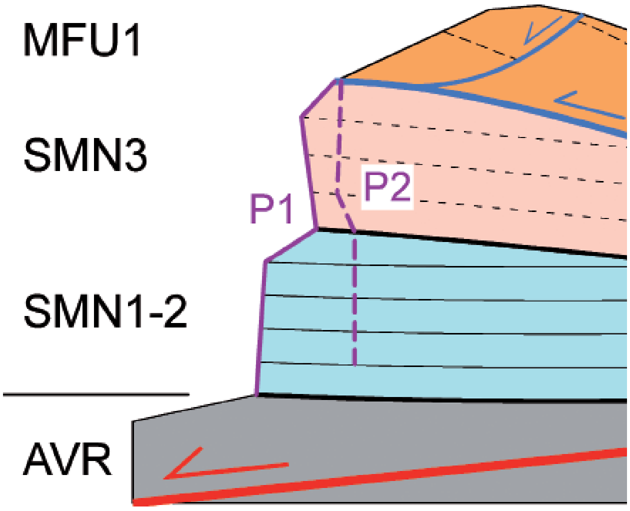

Fig. 20 - Two idealized erosion profiles of the NNE rock wall (see also Borgatti *et alii, 2015, p. 391, fig. 6)*

Subtle morpho-selection effects within the SMN unit are highlighted by two idealized erosion profiles inspired by the NNE rock wall of the San Leo cliff (Fig. 20). The profile P1 shows how washout, disintegration and small collapses gradually create a ledge along the SMN2/SMN3 boundary and an overhang in the SMN3 unit (Fig. 8). The profile P2 shows how, in case of major collapses as the 2014 rockfall (Fig. 9), a previous ledge is replaced by a rocky roof at the base of SMN3. Both profiles were useful for tracing the SMN2/SMN3 boundary from afar.

CONCLUSIONS

The line-drawings of the natural sections exposed in the rock walls of the San Leo cliff, coupled with a detailed geologic map and framed in a tectonic-stratigraphic scheme, allow us to reconstruct an overall 3D geological model and find the structural reasons for the state of fracturing and disjunction between the blocks that guide the evolution of the slopes surrounding the San Leo cliff. From the interpretation of the collected data, new stratigraphic details and a well-defined deformation chronology were obtained. From a stratigraphic point of view, attention was paid to lateral variations of thickness and lithology in the epi-Ligurian succession. Three angular unconformities were found, of which the first is located at the base of the first member of the San Marino Fm. (SMN1), the second at the base of the third member of the San Marino Fm. (SMN3) and the third at the base of the first member of the M. Fumaiolo Fm. (MFU1). From a tectonic point of view, low-angle and high-angle faults have been identified in the epi-Ligurian succession; all the low-angle faults are normal, while many of the high-angle faults are normal and a few are strike-slip. The oldest low-angle shear surfaces (Langhian) are listric and detached at the base of the MFU1 member; some of them terminate upwards within the same member, revealing their syn-sedimentary growth. Probably, the whole Langhian shear surface system has developed in the head of a submarine slump. At the base of the W, S and E walls of the San Leo cliff, an important low-angle normal fault (Early Pliocene) has been identified, which lowers the Ligurian -

epi-Ligurian succession to the NE and is probably connected to the Perticara-Maioletto fault (W of San Leo). The fault hangingwall has been tilted to the SW of about 20°, due to the listric geometry of the fault surface. The same geometry can be envisaged in many other cases. Such listric faults, which are probably detached at the base of the Ligurian allochthon, should be accurately surveyed and dated, as they can help elaborate a gravitational sliding model for the advancement of the Val Marecchia nappe. The high-angle faults that cut across the Ligurian units and the whole epi-Ligurian succession (Late Pliocene – Present) have two main strikes: the NNW-SSE faults are normal, while at least some of the W-E faults are right strike-slip. High-angle faults and fractures can release giant rock masses, predisposing them to collapse. The 2014 rockfall has been predisposed this way and is just the latest event in the evolution of the San Leo cliff, whose current morphology is the result of a very long series of rockfalls.

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Received July 2024 - Accepted August 2024