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SCIENCE

## Geology of Monte Gallo (Palermo Mts, NW Sicily)

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### ABSTRACT

The promontory of Monte Gallo (Palermo, NW Sicily) is a spectacular site where Upper Triassic-Eocene carbonate platform rocks and Quaternary continental to marine deposits are well exposed. A Mesozoic-Paleogene rock succession allows the potential visitor to easily detect the features and the evolution of the Panormide carbonate platform, a shallow-water paleogeographic domain of the Southern Tethyan margin. Quaternary deposits, as well many landforms, enable the visitor to directly identify the interplay between climate changes, tectonics and fluctuations of marine level that occurred during the Quaternary Period. A detailed geological map (1:15,000 mapping scale) is presented, accompanied by a stratigraphic correlation of logged sections and morpho-stratigraphic and tectonic schemes of the area, aimed at highlighting the geological heritage of Monte Gallo in support of the establishment of a Geosite. The Geological Map and relevant explanatory notes should be used as cartographic support and as a field trip guide for possible geological itineraries.

### ARTICLE HISTORY

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### 1. Introduction

Monte Gallo is an isolated carbonate massif (Figure 1/ Geological Sheet) located in the northern sector of the Palermo Mts, near Mondello (Palermo) (Figure 1(b)). The study area is included in the topographic base map 1:25,000 'Mondello' (249 II NO) edited by I.G. M. (*Istituto Geografico Militare*, the mapping agency of Italy). Though the mountain consists of a slightly elevated top area (maximum height 561 m a.s.l. at Pizzo della Sella), it shows a strong relief being bounded by cliffs hundreds of metres in height overlooking 'Conca d'Oro' (the plain on which Palermo city stands out) and the Tyrrhenian Sea (see the Geological Map). For its location and for the fauna and flora biodiversity it is a very interesting natural site. The 'Oriented Natural Reserve of Monte Gallo', comprised in the Regional Plane of Parks and Reserve of the Regione Siciliana, consists of an emerged 5.86 km<sup>2</sup> extended area and an adjacent protected marine area, where the sand substrate is populated by the *Posidonia oceanica* Delille.

The occurrence of Jurassic bauxites in the shallow-water carbonate succession of Monte Gallo has offered an excellent site for the reconstruction of the Mesozoic-Paleogene Panormide carbonate platform geological history (Di Stefano, Mallarino, Mindszenty, & Nicchitta, 2002; Ferla, Censi, & Meli, 2002 and references thereafter).

The Quaternary deposits, outcropping along the coastal sector of Monte Gallo, are the result of alternations of continental and marine sedimentation (Di Maggio, Agate, Contino, Basilone, & Catalano, 2009;

Hugonie, 1982 and references thereafter). The littoral deposits with *Persististrombus latus* (Gmelin) have provided important fossil collections (e.g. Ruggieri & Milone, 1974).

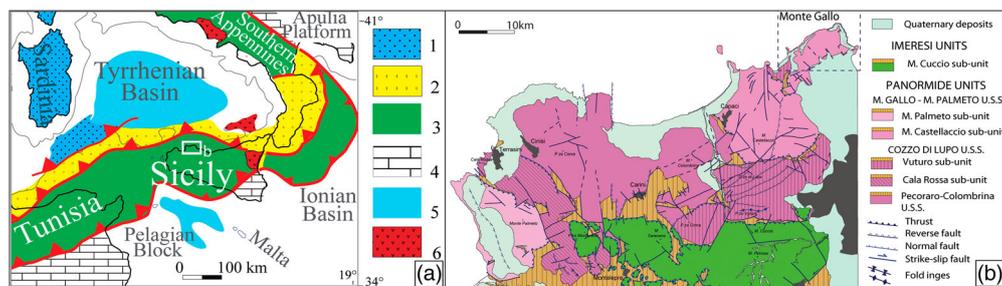
Geomorphological studies (Di Maggio, 2000; Hugonie, 1982) have showed the existence of an isolated relief produced by tectonics and affected by planation processes, karst phenomena, coastal processes and water erosion during the Quaternary age.

Recent field investigations, partly conducted in the frame of the Italian Official Geologic Cartography (1:50,000 scale map, CARG project, Catalano et al., 2013a), have highlighted new discovery about the Mesozoic carbonates and the Quaternary outcropping deposits.

The main purpose of this work, describing the results of detailed field mapping, is to give new information about the geological heritage of the region that, accomplished with the previously mentioned geomorphological, naturalistic and cultural aspects, is able to justify the proposition of a Geosite for the Monte Gallo area.

A Geosite, as defined by the IUGS (International Union of Geological Science) and by the UNESCO, is a locality where it is possible recognized a relevant geologic, geomorphologic, paleontologic, mineralogic, etc. interest and for this reason to be considered and preserved as cultural and landscape heritage (Wimbledon, 1997).

The definition of geological framework is an essential procedure, proposed by ProGEO (the European Association for the Conservation of the Geological Heritage) and used since the IUGS's Global Geosites



**Figure 1.** (a) Schematic structural map of Central Mediterranean (after Catalano et al., 2013b): (1) Corsica-Sardinian units; (2) Calabrian Arc and Kabylia; (3) Maghreb-Sicilian-Southern Apennine nappes and deformed foreland; (4) foreland and mildly folded foreland; (5) areas with superimposed extension; (6) Plio-Quaternary volcanites. (b) Tectonic map of the Palermo Mountains and location of the study area (after Catalano et al., 2013a).

Project, for the inventory of Geosites with scientific value.

In areas rich in interesting geological features, a thematic map is a fundamental tool for identification and protection of the geological heritage, in order to promote institution, improvement and exploitation of a Geosite. A geological map offers the possibility of fruition also through the proposition of geological itineraries for geotourism (Eder & Patzak, 2004; Strasser et al., 1995).

The Geological Map of Monte Gallo illustrated here, accomplished by schemes at its margin and explanatory notes, may be used as a cartographic support and as a field trip guide for the geological heritage of the area. In this view, some oriented pathways are suggested (Geological itineraries in supplementary materials).

## 2. Geological setting

The Sicilian orogen, located in the centre of the Mediterranean at the NE corner of the Pelagian platform of North Africa, links the Southern Apennine and the Calabrian Arc to the Tellian and Atlas systems of North Africa (Figure 1(a)).

The Sicilian Fold and Thrust Belt (FTB) is a segment of the Apennine-Tyrrhenian System, whose building up refers both to the post-collisional convergence between Africa and a complex 'European' crust (Bonardi et al., 2003) and to the coeval roll-back of the subduction hinge of the Adriatic Ionian-African lithosphere (Catalano et al., 2013b; Doglioni, Merlini, & Cantarella, 1999 and references thereafter).

The study area is located in the Palermo Mts (Figure 1(b)), the northernmost sector of the emerged Sicilian FTB (Figure 1(a)), which results from the piling up of deep-water and carbonate platform tectonic units (Imerese and Panormide, Catalano et al., 2013b and references thereafter). The Panormide tectonic units consist of geologic bodies, 900–1200 m thick and 4–8 km<sup>2</sup> wide, stacked with ramp and flat geometry S- and SW-verging with the interposition of the Oligo-Miocene Numidian flysch deposits, postdating

the time of tectonic emplacement (Abate, Catalano, & Renda, 1978).

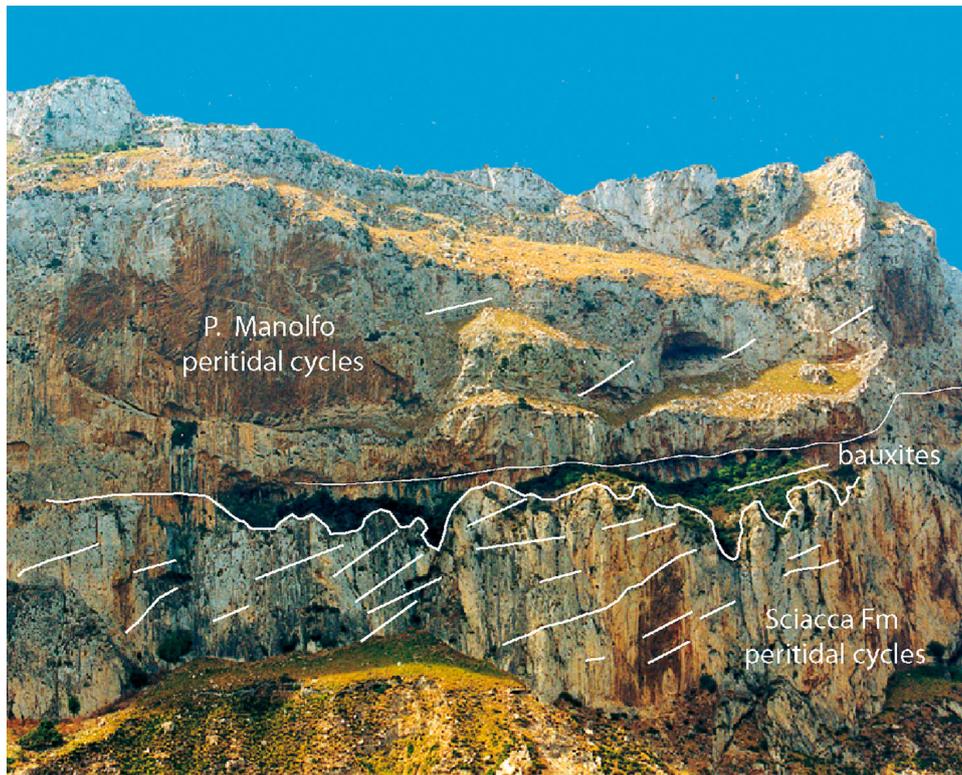
In the Monte Gallo area (Figure 1(b)) the tectonic relationships between the Monte Gallo and Cozzo di Lupo tectonic units are highlighted. These are progressively superimposed along N–S trending thrust (Figure 4/Geological Sheet). High angle normal faults, related to the Plio-Quaternary extensional and trans-tensional tectonic events due to the opening of Tyrrhenian Sea (Gueguen, Doglioni, & Fernandez, 1998; Malinverno & Ryan, 1986), dissect the older structures and are responsible for the present-day setting (Figure 4/Geological Sheet).

The investigated rock bodies, now incorporated into the Sicilian FTB, originated from the deformation of the Mesozoic-Cenozoic sedimentary cover of the Sicilian sector of the African continental margin (Catalano & D'Argenio, 1978). They are represented by shallow-water carbonate deposits pertaining to the Upper Triassic-Eocene Panormide succession. This succession is characterized by Bahamian-type facies, with periodic subaerial exposure and continental sedimentation (Basilone, 2015; Di Stefano et al., 2002).

## 3. Methodologies

Field mapping was carried out using published base maps (Regional Technical Cartography – CTR – Regione Siciliana) at a 1:2000–1:10,000 scale map. Google Earth and aerial images were analysed in order to recognize the main morphostructural features. The geological map is presented at a scale of 1:15,000 in a Transverse Mercator Projection.

Both physical-stratigraphy and facies analyses were applied along several stratigraphic sections that were measured and sampled to define the lithological and sedimentological characteristics of the recognized units and to define their stratigraphic relationships. Mesozoic carbonates have been classified using the more recent lithostratigraphic nomenclature (Basilone, 2012), although most of formations are informal, that are not validated by the Italian Commission of Stratigraphy and the Quaternary deposits were subdivided



**Figure 2.** Angular unconformity between the Upper Triassic dolomitized peritidal limestone of the Sciacca Fm and the Upper Jurassic-Lower Cretaceous Pizzo Manolfo peritidal limestone. Bauxites fill the irregular erosional and karst surface (northern side of Monte Gallo).

in unconformity-bounded stratigraphic units (UBSUs, ISSC-Salvador *et al.*, 1994).

Carbonate microfacies were described by using Dunham's classification and were dated by Mesozoic benthonic and planktonic calcareous fossil biozonations (Camoin, 1983; Chiocchini, Farinacci, Mancinelli, Molinari, & Potetti, 1994; Montanari, 1965). Quaternary deposits were constrained using Pleistocene biozonation (Cita *et al.*, 2006; Rio, Raffi, & Villa, 1990) and numerical datings (Hearty, Miller, Stearns, & Szabo, 1986; Mauz, Buccheri, Zöller, & Greco, 1997) compared with the Oxygen Isotope Stages (OIS) of the  $\delta^{18}\text{O}$  curve (Shackleton, 1995, Figure 6/Geological Sheet).

Field mapping was integrated with structural and morphostructural analyses at map and mesoscopic scale.

### 3.1. The geological sheet

The included Geological Sheet (A2 format) consists of the Geological Map at a 1:15,000 scale and some sketches displaying various geological elaborates: the correlation of logged sections (Figure 2/Geological Sheet) help to understand the Upper Triassic-Eocene stratigraphic setting of the area; the geomorphological map (Figure 3/Geological Sheet) illustrates the main landforms; the sketches of Figures 5 and 6 display the geometric relationships and the

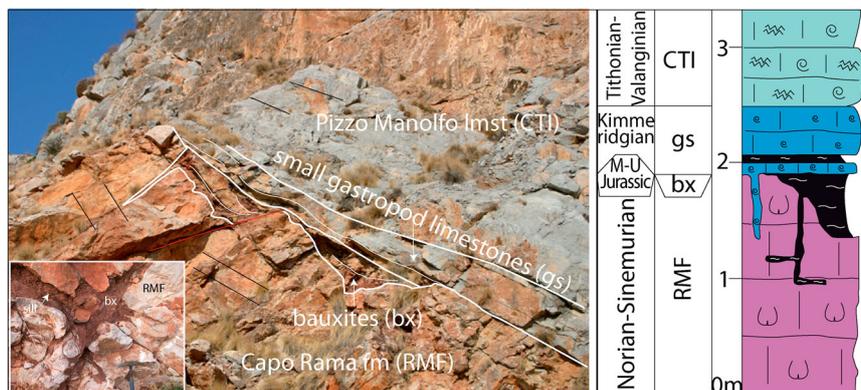
chronological distribution of the mapped Quaternary UBSUs. Some geological cross-sections permit to recognize the stratigraphic relationships among the units and the main tectonic structures of the study area. The structural map of Figure 4 shows tectonic lineaments and possible geological itineraries, where the main geological features are observable along several stops (see Geological itineraries in supplementary materials).

### 3.2. Software

Field data and the associated topographic templates were scanned into a PC using Adobe Photoshop (AP). Adobe Illustrator (AI) was used to draft the geological map and the structural sketch. The map frame was performed with AI and the pictures in the frame and in the text were adapted using both AP and AI. ArcMap was used to overlap the aerial photos (courtesy of ARTA-Regione Siciliana). Three-dimensional analysis of the topography was made using gis-software (Global Mapper).

## 4. Stratigraphy

The Mesozoic and Cenozoic deposits are classified through lithostratigraphy, while the Quaternary deposits are separated into UBSUs. Complete description of the lithological, stratigraphic, sedimentological, paleoenvironmental and paleontological features are



**Figure 3.** Triassic-Jurassic carbonate succession at Spinasanta quarry. The Upper Triassic-Lower Jurassic peritidal limestones of the Capo Rama Fm (RMF) are dislocated by syndimentary faults. The Jurassic red bauxite clays (bx) fill erosional ponds at the top of the RMF and a dense network of neptunian dykes (inset). Kimmeridgian dasycladacean and gasteropods limestone (gs) and Upper Tithonian-Valanginian Pizzo Manolfo limestone (CTI), onlap the older strata.

reported in Tables 1 and 2, in the legend at the margin of the Geological Map and in the supplementary materials (Plates 1–7). The sites where are observable the main geological features of the units are indicated with stops of the geological itineraries reported on Figure 4/Geological Sheet.

#### 4.1. Lithostratigraphy and facies analysis of the Mesozoic-Paleogene carbonates and Cenozoic clastics

The Mesozoic-Paleogene carbonate succession (Figure 2/Geological Sheet) and the Cenozoic clastics consist of:

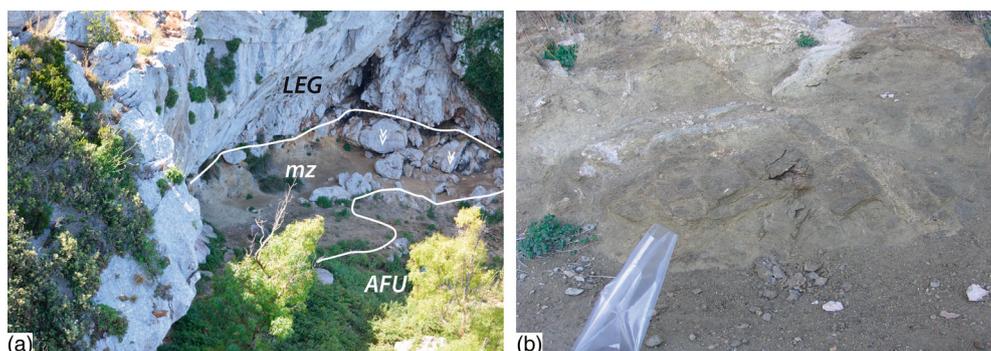
##### 4.1.1. Sciacca Formation (SIA, Norian-Rhaetian)

The whitish peritidal dolostones of the Sciacca Fm (Table 1) extensively outcrop at the foot of the carbonate massif (see Geological Map). The upper 70–150 m of the formation is exposed on the northern side of Monte Gallo, while 30–50 m outcrops at Pizzo Vuturo, where large megalodontid shells are recognizable (Stop 3, green itinerary). The lower boundary is not exposed. The upper one is an erosional surface capped by the deposits of the Capo Rama formation through a

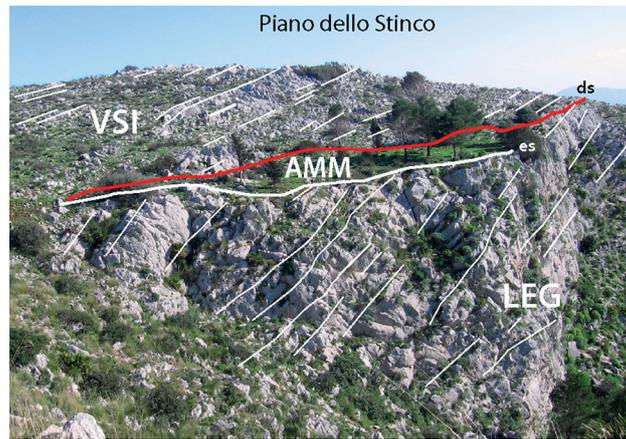
paraconformity (Stop 4 of green itinerary) and by the Jurassic bauxite deposits and the Pizzo Manolfo peritidal limestone through an angular unconformity, as well observable along the whole mountain and especially in its northwestern side (Figure 2 and Stop 6, blue itinerary).

##### 4.1.2. Capo Rama formation (RMF, Norian-Sinemurian)

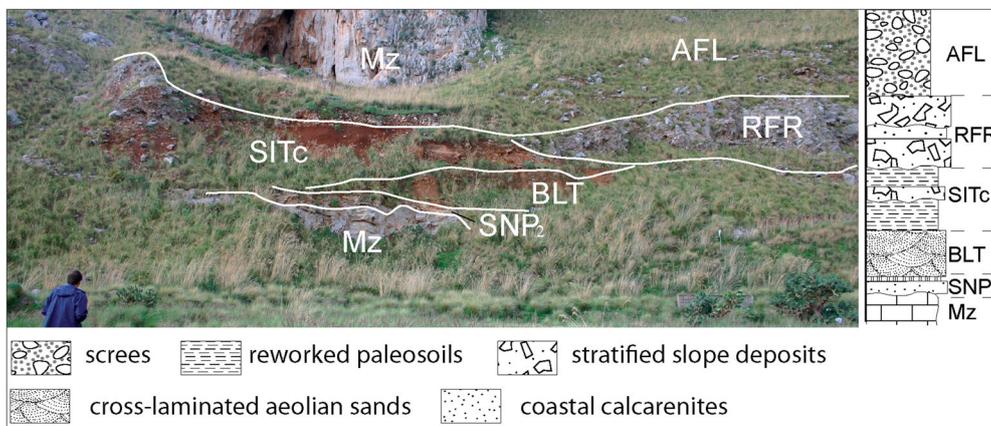
The Capo Rama Fm (Figure 2/Geological Sheet) outcrops along the coastal sector of Monte Gallo and in its southwestern side (0–150 m thick), and thins laterally to disappear in the northern side of the massif (see Geological Map). The lithostratigraphic characteristics of the unit (Table 1 and Plate 1 in supplementary materials) are well exposed in the coastal sector of Mondello (Stop 1, blue itinerary), at Spinasanta quarry (Stop 2, green itinerary) and along the southern side of Pizzo Impiso (see Geological Map). The upper boundary of the unit is a subaerial irregular surface, whose origin was accompanied by large erosion, several paleofaults with small downthrown, a dense network of neptunian dykes vertical and sub-horizontal to the bedding, block-faulting and tilting (Figure 3) and that



**Figure 4.** (a) Outcropping site of the Costa Mazzone clays (mz). AFU: Lower Cretaceous Capo Gallo requienid limestone, LEG: Upper Cretaceous rudistid limestone of the Pellegrino Fm; (b) detail of the darkish sampled clays.



**Figure 5.** Downlap (ds) and erosional relationships (es) among the Eocene Nummulitid limestone of the Valdesi Fm (VSI), the Upper Cretaceous rudistid limestone of the Pellegrino Fm (LEG) and the uppermost Cretaceous pelagic limestone of the Amerillo Fm (AMM).



**Figure 6.** Quaternary stratigraphic section at 'La Fossa' (eastern side of Monte Gallo). Mz, Mesozoic carbonate substrate; SNP<sub>2</sub>, pedogenized beach deposits (Tommaso Natale subsynthem); BLT, aeolian deposits (Polisano synthem); SITc, colluvial deposits (Barcarollo synthem); RFR, stratified slope deposits (Raffo Rosso synthem); AFL, colluvial deposits and screes (Capo Plaia synthem).

was capped by continental sediments (bauxites). Moreover, the topmost portion of the formation is characterized by a dense network of neptunian dykes, vertical and sub-horizontal to the bedding, mostly filled by red bauxite clays and karst products.

#### 4.1.3. Bauxites of Spinasanta (*bx*, Middle-Upper Jurassic)

The brick-red and yellowish bauxite clays are preserved in neptunian dykes (inset in Figure 3) or in little troughs and karren displaying onlap and infilling geometries, as observable in the abandoned quarry of Spinasanta (Stop 2, yellow itinerary).

#### 4.1.4. Gastropods limestone (*gs*, Kimmeridgian)

The calcareous unit (Table 1 and Plate 2 in supplementary materials) outcrops at Spinasanta quarry (Stop 2, yellow itinerary), where it rests with onlap terminations above the peritidal limestone of the RMF and with transitional relationships with *bx* (Figure 3).

#### 4.1.5. Pizzo Manolfo limestone (*CTI*, Upper Tithonian-Valanginian)

The grey shallowing upward peritidal limestone (Table 1 and Plate 3 in supplementary materials) outcrops, 150–300 m thick at Pizzo della Sella (Stop 1, red itinerary), Pizzo Impiso and Pizzo Vuturo (Stop 5, green itinerary), and 70–100 m thick at La Torre (Stop 2, blue itinerary) and Pizzo S. Margherita. The lower unconformity boundary with the RMF is characterized by onlap stratal terminations. It is well observable at Bauso Rosso (western side of the massif, Stop 2, yellow itinerary), where it laterally extended for some hundreds of metres.

#### 4.1.6. Capo Gallo limestone (*AFU*, Upper Barremian-Lower Aptian)

The dark-grey requienid limestone (Table 1, Plate 4 in supplementary materials) has been recently defined as formational unit (Basilone & Lena, 2009) on the basis of its type section reconstructed from Pizzo della Sella (Stop 2, red itinerary). The unit outcrops, 30–

**Table 1.** Main characteristics of the described Mesozoic-Paleogene lithostratigraphic units of the Monte Gallo carbonate succession.

Fms	labels	Texture and lithology	thick (m)	Lower boundary	Geometry	Depositional environment	Fossil content	Age
Valdesi	VSI	Rudstone-grainstone with <i>Nummulites</i> sp., bryozoans, rodophycean algae, echinoid and coral fragments (Pl. 6 in supplementary materials) alternated with coral boundstone and, locally, with thin-bedded white pelagic wackestone with planktonic foraminifers. Thin breccias and pebbly mudstone, mark the lower boundary	15–25	Downlap	Dm-thick strata with tabular geometry	Open shelf and patch reef	Alveolinids ( <i>Fasciolites oblungus</i> (D'Orbigny), <i>F. ellipsoidalis</i> (Schwager), <i>F. schwageri</i> (Checchia-Rispoli), <i>F. giganteus</i> (Checchia-Rispoli), nummulitids ( <i>Nummulites crassus</i> Boubé, <i>N. millecaput</i> Boubé, <i>N. molli</i> (D'Archiac), <i>N. paronai</i> (Prever)), <i>Discocyclus roberti</i> Douvillé, <i>Orbitolites lehmanni</i> Moorkens	Cuisian-Lutezian
Amerillo	AMM	Red and white thin-bedded planktonic foraminifers-bearing mudstone-wackestone and marly limestone	0.4	Onlap and infilling	Thin-bedded stratification	Deep-water	Planktonic foraminifers ( <i>Globotruncana ex gr. lapparenti</i> , <i>Globotruncana ventricosa</i> (White)	Late Cretaceous
Pellegrino	LEG	Darkish-grey caprinid and radiolitic floatstone (Pl. 5a, b in supplementary materials) alternated with bioclastic packstone (Pl. 5, g, h) with benthic foraminifers, hydrozoans, algae, coral fragments, conglomerates with rounded rudistid fragments (Pl. 5c), cm-thick oolitic and bioclastic grainstone. Rare dm-thick fenestral packstone and blackish laminated mudstone (strictly circulation lagoon)	100–200	Downlap	Shallowing upward cycles	Open shelf with isolated reefs that supply the slope	Caprinids ( <i>Caprina schiosensis</i> , <i>Caprinula</i> sp., <i>Ichtyosarcolithes rotundus</i> , caprotinids ( <i>Polyconites verneuilli</i> ), large radiolitic ( <i>Sauvagesia</i> sp., <i>Durania</i> sp., <i>Radiolites sauvagesi</i> , <i>R. nebrodensis</i> ), benthic foraminifera ( <i>Orbitolina</i> ( <i>Conicorbitolina</i> ) <i>conica</i> D'Archiac, <i>Cuneolina</i> cf. <i>pavonia</i> , <i>C. cf. conica</i> , <i>C. cf. cretacea</i> , <i>Trocholina elongata</i> , <i>Actinoporella podolica</i> , <i>Conicospirillina basiliensis</i> , <i>Dicyclus</i> sp., <i>Cornuspira</i> cf. <i>cretacea</i> )	Senonian
Costa Mazzone clays	mz	Brown darkish pelites with rare mm-thick yellowish clays and upwards mm-thick varves-type rhythmic alternations of red-yellowish marls and greenish-to-darkish laminated clays and at the top reddish vacuolar limestones of karst origin	0.5–2.8	Erosional	Pond filling-type	Lacustrine	Azoic	Aptian p.p.- Albian p.p.
Capo Gallo limestone	AFU	Dark-grey wackestone-packstone with requienids (Pl. 4a, b in supplementary materials), large <i>Nerinea</i> sp., algae, benthic foraminifers and microproblematics (Pl. 4d, f, subtidal lithofacies) are alternated to dm-thick fenestral wackestone-packstone with peloids and algae fragments (intertidal lithofacies), and to dm-thick darkish oolitic packstone-grainstone, with abraded and broken ooid grains (Pl. 4c, g, sand bar lithofacies)	30–150	Onlap	Deepening upward facies sequences	Open shelf bordered by sand bar	Caprinids ( <i>Offneria</i> sp., <i>Precaprina</i> sp.), algae ( <i>Cayeuxia</i> sp., <i>Triploporella</i> cf. <i>decastroi</i> Barattolo), benthic forams ( <i>Cuneolina</i> ex. gr. <i>composaurii-laurentii</i> Sartoni and Crescenti, <i>Palorbitolina lenticularis</i> (Blumenbach), <i>P. praecursor</i> (Montanari), <i>Rectodictyonus giganteus</i> Schroeder), <i>Bacinella irregularis</i> Radoicic, <i>Lithocodium</i> sp.), corals	Late Barremian- Early Aptian
Pizzo Manolfo limestone	CTI	Thick-bedded wackestone (rarely packstone) with <i>Nerinea</i> sp., <i>Cayeuxia</i> sp. (Pl. 3a, c in supplementary materials), benthic forams and large oncoid grains, alternated with dm-thick fenestral packstone with peloids and bioclasts and oolitic packstone/grainstone with radial-fibrous ooid grains (Pl. 3b, d)	70–300	Onlap	Shallowing upward cycles	Tidal flat, lagoon, oolitic sand bar	Algae ( <i>Clypeina jurassica</i> Favre & Richard, <i>Campbelliella striata</i> Carozzi, <i>Salpingoporella annulata</i> Carozzi, <i>Actinoporella podolica</i> Alth), benthic forams ( <i>Pseudocyclammina</i> sp., <i>Vercorsella composaurii</i> (Sartoni and Crescenti), <i>V. laurentii</i> (Sartoni and Crescenti), <i>Campanellula capuensis</i> De Castro, <i>Debarina</i> sp., <i>Belorussiella</i> sp.), microproblematics ( <i>Bacinella irregularis</i> Radoicic)	Upper Tithonian- Valanginian
Gastropods limestone	gs	Grey-reddish bioclastic wackestone-packstone with small gastropods, benthic foraminifers and algae (Pl. 2 in supplementary materials) in two beds with tabular geometry (12 cm-thick and 49 cm-thick, respectively)	<1	Onlap with RMF and transitional with bx	Tabular	Lagoon	Algae ( <i>Salpingoporella grudii</i> Radoicic, <i>S. annulata</i> Carozzi), benthic forams ( <i>Montsalevia salevensis</i> Charollais, Bronnimann & Zaninetti, <i>Parurgonina caelinensis</i> Cuvillier, Foury & Pignatti-Morano, <i>Kurnubia palastiniensis</i> Henson)	Kimmeridgian
Bauxites of Spinasanta	bx	Brick-red and yellowish bauxite clays with pisoids fragments, oolite and intraclasts and blackish speleothems	0.25–0.80	Erosional with RMF and SIA	Infilling neptunian dykes	Continental	Azoic	Middle-Upper Jurassic

Capo Rama	RMF	Grey to white shallowing upward peritidal limestone. They consist of massive thick-bedded wackestone-packstone with megalodontids (Pl. 1a, b in supplementary materials), gastropods, algae, ammonites, corals (patch reefs, Pl. 1c), oncoids and peloids (subtidal lithofacies); vadose pisolite (Pl. 1d) and paleokarst cavities, filled by reddish silt and caliche crusts (Pl. 1e), largely occur. They are alternated with dm-thick stromatolitic limestone and dolomitized limestone with planar and undulate laminae and fenestrae (intertidal lithofacies) and with dm-thick liferitic breccias with 'tepee' structures and blackish angular elements (Pl. 1f supratidal lithofacies)	0–150	Para conformity	Peritidal cycles	Inner carbonate platform	Bivalves ( <i>Megalodon</i> cf. <i>gumbeli</i> Stoppani, <i>M. cf. gemmellaro</i> Stoppani, <i>Dicerocardium</i> cf. <i>curioni</i> Stoppani), ammonites, algae ( <i>Ortonella</i> spp., <i>Zonotrichites</i> spp., <i>Thaumatoporella parvovesiculifera</i> Raineri, <i>Solenopora styriaca</i> Flügel, <i>Parachetetes maslovi</i> Flügel), rare dasycladaceans ( <i>Diplopora tubispora</i> Ott, <i>Heteroporella zankli</i> Ott), benthic foraminifers ( <i>Aulotortus</i> spp., <i>Alpinophragmium</i> sp., <i>Aeolisaccus</i> spp., <i>Glomospira</i> spp., <i>Involutina lassica</i> Jones), microproblematics ( <i>Bacinnella irregularis</i> Radoičić, <i>Lithocodium</i> spp., <i>Tubiphytes</i> spp.), hydrozoans ( <i>Heterastridium conglobatum</i> Reuss)	Norian-Sinemurian
Sciaccia	S/A	White-greyish vacuolar peritidal dolostones and dolomitized limestone with large megalodontids, algae and benthic foraminifers in massive beds, alternated with rare cm-thick stromatolitic dolostone and, locally, dm-thick azoic yellowish dolomitized marls	> 150	Not outcrop	Peritidal cycles	Tidal flat, back-reef lagoon	Bivalves ( <i>Megalodon</i> cf. <i>gumbeli</i> , <i>M. cf. gemmellaro</i> Stoppani, <i>Dicerocardium</i> cf. <i>curioni</i> ), gastropods, benthic foraminifers ( <i>Alpinophragmium</i> sp., <i>Aeolisaccus</i> spp., <i>Triasina</i> spp., <i>Aulotortus</i> spp.)	Norian-Rhaetian

40 m thick, at S. Margherita and Pizzo Vuletta (see geological cross-sections in the Geological Sheet) and, 70–150 m thick, at Tiniere and Piano dello Stinco, where the lower boundary, marked by onlap terminations, is observable (Stop 9, yellow itinerary).

#### 4.1.7. Costa Mazzone clays (mz, Aptian p.p.-Albian p.p.)

These continental clays (Table 1), covering with pond filling-lens geometry the top of the AFU, outcrop in the northern side of Piano dello Stinco (Figure 4 and Stop 7, yellow itinerary). For these deposits detailed analyses have pointed out a lacustrine to strictly lagoon the depositional environment formed during a period of emersion of the carbonate platform strata caused by tectonic uplift (Basilone, 2015).

#### 4.1.8. Pellegrino formation (LEG, Cenomanian)

The rudistid limestone of the Pellegrino fm outcrop, 100–200 m thick, at the Pizzo della Sella peak (Stop 3 of red itinerary) and Piano dello Stinco (Stop 5, yellow itinerary), where the main lithostratigraphic characteristics and paleontological content are observable (Table 1, Plate 5 in supplementary materials). A major downlap surface with AFU and mz, associated with submarine erosion and hiatus, characterizes the lower boundary of the unit (Basilone, 2009, 2015) as observable at Piano dello Stinco (Figure 4 and Stop 7, yellow itinerary),

#### 4.1.9. Amerillo formation (AMM, Campanian-Maastrichtian)

The red and white thin-bedded pelagites (Table 1) outcrop, few dm-thick, at Piano dello Stinco, where they onlap the LEG and fill a dense network of neptunian dykes crossing the topmost beds of the Cenomanian rudistid limestone (Stop 8, yellow itinerary).

#### 4.1.10. Valdesi formation (VSI, Cuisian-Lutezian)

The 'nummulitid limestone' of the Valdesi fm (Table 1 and Plate 6 in supplementary materials) outcrop, 20–25 m thick, at Piano dello Stinco (Stop 8, yellow itinerary), where the lower boundary is marked by downlap relationships (Figure 5) accompanied by submarine erosion, evidencing a large hiatus (depositional and erosional).

#### 4.1.11. Numidian flysch (FYN, Upper Oligocene-Lower Miocene)

Brown manganeseiferous clays, with arenaceous and calcareous planktonic foraminifers (*Globorotalia opima* Bolli) and intercalations of quartz-sandstones, outcrop in the Sferracavallo area (western side of the Geological Map), where they unconformably overlie the Mesozoic carbonates of the Cozzo di Lupo tectonic unit (Figure 1(b)).

**Table 2.** Main characteristics of the described Quaternary UBSUs outcropping in the Monte Gallo area.

UBSU	Labels	Texture and lithology	thick m	Lower boundary	Depositional environment	Fossil content	Age	OIS
Capo Plaia synthem	AFL	Colluvial deposits, consisting of heterometric clasts (reworked scree) welded in a clayey matrix (reworked soils) with stone line; scree and debris flow; littoral deposits; chemical carbonates (travertines and speleothems)	10	Erosional or non-depositional unconformity with RFR or older deposits (upper boundary: present-day topographic surface)	Continental to coastal	Continental or coastal organism	Holocene	1
Raffo Rosso synthem	RFR	Cross-laminated aeolian sandstones and sands (few metres thick) with quartz or carbonate grains and stratified slope deposits composed of cemented coarse-to-fine inverse graded clast-supported breccias, involving very angular to sub-rounded carbonate clasts, with an average diameter of 0,5–20 cm (50 cm maximum). They, arranged in several well-sorted levels, 0.5 to 2 m thick, are cyclically alternated with red paleosoils, frequently reworked	20	Non-depositional surface or subaerial erosional unconformity with SIT or older deposits	Talus slope (last glacial climatic event)	Continental gastropods	Upper Pleistocene p.p.	2–4
Barcarello synthem	SIT	Red to yellowish coastal bioclastic calcarenites alternated with parallel and cross-stratified sands and bio-conglomerates consisting of heterometric and polygenic elements with 'Senegalian' faunal assemblage. They are laterally passing to laminated red silty clay (reworked soils) and calcareous breccias intercalation (stone-line structures), welded by red sand matrix (colluvial deposits, 1–5 m-thick)	1–8	Marine erosional surface or continental erosional unconformity with BLT or older deposits	Continental to coastal (warm climatic event)	<i>P. latus</i> (Gmelin), <i>Cantharus viverratus</i> Kiener, <i>Mitra fusca</i> Swainson, <i>Conus testudinarius</i> Martini, <i>Hyothisa hyotis</i> Linnaeus, <i>Ostrea edulis</i> , <i>Glycimeris glycimeris</i> , <i>G. pilosus</i> , <i>Spondylus gaederopus</i> , <i>Patella ferruginea</i> Gmelin, <i>Natica</i> sp., <i>Cerithium lividulum lividulum</i> , <i>C. vulgatum</i> , vermetids, echinoids, algae and corals. The colluvial deposits are rich in continental gastropods and rests of vertebrates of the 'Elephas mnaidriensis faunal complex'	Upper Pleistocene p.p.	5
Polisano Synthem	BLT	Cross-stratified and laminated quartz and carbonate aeolian low classed fine sands and sandstones, red or yellow in colour. Rare angular carbonate clasts and blocks, related to local rock or debris falls, are interlayered	1–3	Subaerial erosional or non-depositional surface with SNP <sub>2</sub> or older deposits	Aeolian dunes (glacial climatic event)	Continental gastropods	Uppermost Middle Pleistocene	6
Tommaso Natale subsynthem	SNP <sub>2</sub>	Litho- and bioclastic calcarenites with hummocky cross-stratification and sands with cross and parallel laminations, paleocurrent traces and bioturbations, locally algal boundstone	1–5	Ravinement surface with MRS or older deposits	Coastal (warm climatic event)	Bivalves ( <i>Corbula revoluta</i> , <i>Chlamys multistriata</i> Ansell, <i>Ostrea edulis</i> , <i>Pecten jacobaeus</i> , Linneo, <i>Spondylus</i> spp., <i>Glycimeris</i> spp.), gastropods ( <i>Patella caerulea</i> , <i>Cymatium fcoides</i> , <i>Cantharus viverratus</i> ), corals ( <i>Cladocora caespitosa</i> , <i>Astroides calycularis</i> ), brachiopods ( <i>Megathiris detruncata</i> ), cirripeds, echinoderms ( <i>Arbacia lixula</i> ), fish fragments	Middle Pleistocene p.p.	7
Marsala synthem	MRS	Yellowish poorly cemented fossiliferous carbonate sands with a minor content of clays rich in bioturbations (i.e. <i>Glossifungites</i> ) alternated with yellow bio- and lithoclastic well-cemented oblique, parallel and cross-laminated calcarenites and calcirudites rich in mollusc fragments; minor content in quartz grains and intercalation of conglomerates, 1–2 m-thick, with carbonate and siliceous elements, deriving from the dismantling of the Meso-Cenozoic substrate	0,5–5	Ravinement surface cutting the tectonically deformed Meso-Cenozoic carbonate substrate (angular unconformity)	Foreshore to shoreface	Bivalves ( <i>Glycimeris</i> spp., <i>P. jacobaeus</i> , <i>C. multistriata</i> , <i>C. septemradiata</i> (Müller), <i>Arctica islandica</i> Linneo, <i>Ostrea edulis</i> , <i>Volga rugosa</i> , <i>Noripes latteus</i> , <i>Cerithium creanatus</i> , <i>Rissoa cimex</i> , <i>Bittium reticulatum</i> , <i>Clanculus jussei</i> ), gastropods ( <i>Patella</i> spp.), corals, bryozoans, sponges, calcareous algae, vermetids, scafopods, echinoderms, benthic foraminifers ( <i>Hyalinea balthica</i> Merla & Ercoli), ostracods ( <i>Aurila</i> sp., <i>Denodocitere prava</i> , <i>Cimbourilia latisolea</i> ), nannofossils (small <i>Gephyrocapsa</i> biozone), rare planktonic foraminifers ( <i>Globorotalia truncatulinoides excelsa</i> )	Lower Pleistocene (Emilian-Sicilian)	(1.5– 0.8 My)

OIS numerical datings: [Mauz et al. \(1997\)](#) and [Hearty et al. \(1986\)](#).

## 4.2. Quaternary UBSUs

Lower and upper boundaries of Quaternary deposits consist of regionally extended unconformities (locally marked by paleosoils), such as ravinement surfaces, subaerial surfaces due to water erosion and non-depositional surfaces. Significant environmental changes during the Quaternary, due to tectonics (block-faulting or uplifting) and to climate fluctuations, appear to originate in both unconformity surfaces and deposits (Di Maggio et al., 2009).

Paleontological data, numerical datings (Hearty et al., 1986; Mauz et al., 1997) and stratigraphic relationships constrained the age of the synthem (Table 2, Figures 5, 6/Geological Sheet).

La Fossa, located in the eastern side of the Monte Gallo complex (Stop 3, blue itinerary), is an interesting site to observe the stratigraphic relationships and the lithological characteristics (Table 2; Plate 7 in supplementary materials) of most of the described synthem (Figure 6).

### 4.2.1. Marsala synthem (MRS, *Emilian-Sicilian*)

The bioclastic calcarenites (Table 2, Plate 7a, b) of this synthem outcrop around the Monte Gallo carbonate massif. In the coastal sectors they display seaward dipping planar stratification. Lower boundary is a ravinement surface with the tectonically deformed Mesozoic-Cenozoic substrate (Figure 5/Geological Sheet).

### 4.2.2. Tommaso Natale subsynthem (SNP<sub>2</sub>, *Middle Pleistocene p.p., OIS 7*)

This unit is included within the regional scale Partinico synthem (SNP, Di Maggio et al., 2009). A coastal terrace represents the geomorphic expression of the unit (Figure 6). The lower boundary is a ravinement surface carved on MRS or older deposits (Figure 5/Geological Sheet and Stop 3, blue itinerary).

### 4.2.3. Polignano synthem (BLT, *uppermost Middle Pleistocene, OIS 6*)

The aeolian deposits of this synthem outcrop at the foot of the eastern and southern side of Monte Gallo

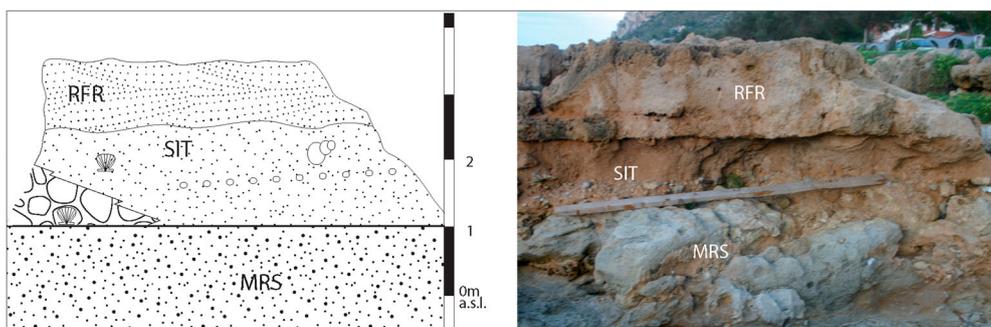
(see Geological Map and Stop 1 both of yellow and green itineraries, Figure 4/Geological Sheet). These lithologies (Table 2, Plate 7c in supplementary materials) have been quarried, extracting materials for ornamental use, and highlighting interesting sedimentary structures (dunes and ripple marks, Stop 1, yellow itinerary). The lower boundary, locally pedogenized, is a subaerial erosional or a non-depositional surface with the SNP<sub>2</sub> (Figure 5/Geological Sheet) or Mesozoic carbonate substrate.

### 4.2.4. Barcarello synthem (SIT, *Upper Pleistocene p.p., OIS 5*)

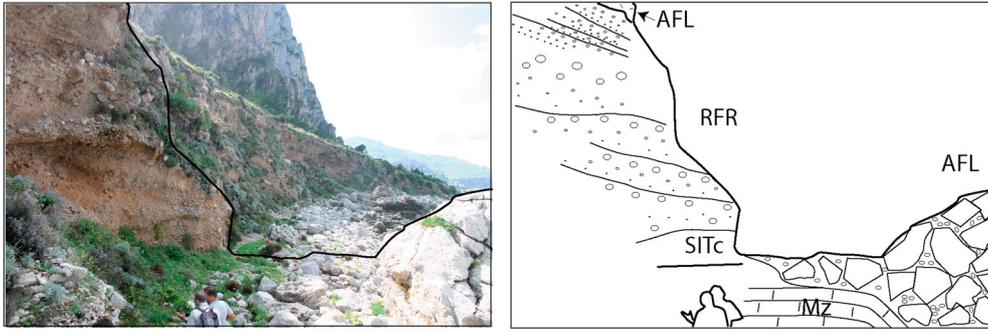
It consists of marine deposits (i.e. ‘*Strombus* limestone’, Auct.) laterally passing to welded colluvial deposits (Table 2, Plate 7d, e in supplementary materials). They outcrop with discontinuity along the coastal sector of the study area, at an altitude up to about 25 m a.s.l. The lower boundary is a marine abrasion surface laterally extending to a continental erosion surface and cutting the BLT deposits or older rocks (Figure 5/Geological Sheet). The main lithological and paleontological characteristics of the synthem are well exposed at Punta di Barcarello and Sferracavallo historical sites (Figure 7, Stops 1 and 2, black itinerary).

### 4.2.5. Raffo Rosso synthem (RFR, *Upper Pleistocene p.p., OISs 4–2*)

The synthem consists of aeolian deposits (Figure 7), few metres thick, occurring along the coastal plain, and stratified slope deposits, outcropping at the foot of the steep slopes (Table 2, Plate 7f in supplementary materials). The lower boundary is a subaerial erosion or non-depositional surface, frequently marked by paleosoils and/or caliche crusts, with the SIT or older deposits (Figure 7 and Figure 5/Geological Sheet). Stratigraphic features, geometric relationships and lithological characteristics are observable at the Stop 3 of black itinerary (Figure 4/Geological Sheet), where the type section of the unit is here proposed (Figure 8).



**Figure 7.** Natural section at Sferracavallo site (Stop 1, black itinerary) showing the lithofacies of the Barcarello synthem (coastal conglomerates and calcarenites, SIT) and the unconformity boundaries with the Marsala (coastal calcarenites, MRS) and the Raffo Rosso (aeolian sands, RFR) synthem.



**Figure 8.** The stratified slope deposits of the Raffa Rosso synthem (RFR) overlay with erosion of the colluvial deposits of the Barcarello synthem (SITc) are followed upwards by the colluvial deposits (left) and stone berm deposits (right) of the Capo Plaia synthem (AFL). Northern side of Monte Gallo (Stop 3, black itinerary).

#### 4.2.6. Capo Plaia Synthem (AFL, Holocene, OIS 1)

In this synthem are comprised slope screes (dt), litoral (li), alluvial/colluvial deposits (co) and chemical carbonates, as karst pisoid, travertine and speleothem (Table 2, Plate 7g, h in supplementary materials). The lower boundary is a variously originated unconformity surface with the RFR deposits or older rocks (Figure 5/ Geological Sheet, Figure 8). The upper boundary is the present-day topographic surface, frequently marked by soils.

### 5. Geomorphological outlines

Monte Gallo consists of both two peaks with sharp ridges (Pizzo Vuturo, 509 m a.s.l.; Pizzo della Sella, 561 m a.s.l.) and a flat top (Piano dello Stinco, 541 m a.s.l.), separated by cut-off dry valleys (Figure 3/ Geological Sheet).

In the flat top of Piano dello Stinco, a hanging relict of an old and gentle erosional land surface occurs. It is a patch of a planation surface, which can be traced back to the cycles of quasi-planation affecting Sicily and Apennines during the final phases of construction of the chain (Amato & Cinque, 1999).

Sharp ridges and flat top are bounded by broad steep slopes hundreds of metres high, which are abandoned coastal cliffs. Only in the northern slope (Malpasso area) a stretch of cliff is still active. These cliffs result from original fault scarps produced by important extensional block-faulting, occurring during the Calabrian (Hugonie, 1982) and responsible for the fragmentation

and ‘isolation’ of the structural high of Monte Gallo, and the sinking and drowning of the structural low of Conca d’Oro (Figure 5/ Geological Sheet). The cliffs are currently degraded and affected by weathering, landslides and talus accumulation at their foot.

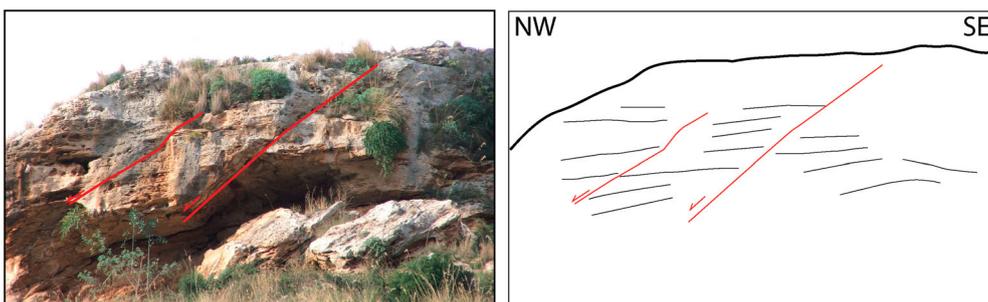
Widespread karren and caves, some hanging relicts of abandoned fluviokarst valleys and open dolines affect the top areas and the slopes. Fluviokarst valleys active only during the heavy rainfalls down-cut the southern and southeastern slopes of Monte Gallo. Alluvial fans are situated at the mouth of the valleys.

Coastal terraces linked to marine high-stands phases of Middle-Upper Pleistocene age (Mauz et al., 1997) are present along the Conca d’Oro. The Tyrrhenian (OIS 5e) terrace surfaces are developed up to about 15–25 m a.s.l. Post-Tyrrhenian uplifting rates reach values between about 0.08 and 0.15 m/kyr (Catalano et al., 2013a).

### 6. Tectonics

The Monte Gallo relief is a main antiform structure mostly bordered by several different-trending normal faults (Figure 4/ Geological Sheet and geological cross-sections):

- (1) Jurassic NW–SE-oriented dip-slip faults (30–70° dipping to SW), showed at Spinasanta quarry (Figure 3), where the original paleokarst cavities and open fractures, just at the top of the RMF, appear reactivated by younger tectonics;



**Figure 9.** Dip-slip normal faults cutting the Middle Pleistocene aeolian cross-laminated sandstones of the Polisano synthem.

- (2) NNE–SSW-oriented faults (70° dipping in average), whose kinematic analysis reveal reverse components and left strike-slip movements, have been recognized along the western side of the massif and at Pizzo della Sella and Pizzo Impiso southern side;
- (3) E–W-, NE–SW- and NNE–SSW-oriented dip-slip faults with hundreds of metres of downthrown bound the whole carbonate massif (Figure 4/Geological Sheet). This tectonic acted during the Early Pleistocene, creating the accommodation spaces for the sedimentation of the Marsala synthem;
- (4) younger faults, similarly oriented to the previous ones, cut the Middle Pleistocene aeolian deposits of the BLT synthem (Figure 9).

## 7. Conclusions

Detailed geological field works, stratigraphic, paleontological, sedimentological and facies analyses, accomplished by structural and geomorphological surveys, have permitted to define the geological map of the Monte Gallo area.

Lithostratigraphic criteria and physic-stratigraphy methods permitted to distinguish formations and UBSUs. The structural analysis confirmed the setting of major tectonic units and evidences different tectonic phases.

Thus, the collected data show that the studied area has particular geological attributes, such as to give significant importance from the points of view of science and landscape.

The illustrated main geological features, which can be easily recognized and followed on the territory using the Geological Sheet of Monte Gallo, include (i) stratigraphic and sedimentological aspects of the outcropping shallow-water carbonates and continental clays; (ii) the spectacularly exposition of the several Mesozoic–Paleogene unconformities and (iii) Quaternary unconformity surfaces and deposits (UBSUs). These features concur with the proposal of the institution of a geosite in the Monte Gallo area.

So the Geological Sheet is an enhancement tool of the geological heritage of Monte Gallo; it and its explanatory notes may be used as a field trip guide for researchers and geotourists.

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