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BY
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GEOMORPHOLOGICAL SETTING OF MADONIE GEOPARK (ITALY)

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Abstract: The Madonie Natural Park is characterized by relevant zoological and botanic aspects and by geological features so remarkable that since 2001 it has been incorporated into the European Geoparks Network. The Park is marked by a wide massif know as Madonie Mountains. In this area, segment of the Maghrebide-Apenninic chain, successions of Meso-Cenozoic lithologies and late- and post-orogenic deposits occur. The geomorphological setting is extremely varied and includes many landscapes characterising several Sicilian areas; it results from the interaction between geomorphological processes, tectonic movements and climatic changes. It is possible to identify five distinct sectors, each corresponding to a particular landscape unit marked by a typical assemblage of landforms, related to the geological and structural setting and to a distinctive geomorphological agent.

Key words: Madonie Mountains, Geopark, Geomorphology, Sicily.

1. Introduction

The Madonie Natural Park is an area of great geological interest: in them rocks encompassing the last 200 million years and representing all aspects of Sicilian geology, except for active volcanism, outcrop. Since 2001 it has been incorporated into the European Geoparks Network.

The Madonie Geopark comprises the Madonie Mountains which represent the central western portion of the Sicilian Apennine chain stretching along the northern coast of Sicily.

Its position in the central portion of the Sicilian Apennine, its geological-structural setting and the morphodynamic processes acting in it make this mountain group a fundamental area for knowledge and reconstruction of the geological history of the Apennine-Maghrebide chain and thus of the central Mediterranean.

Because of these features, the Madonie constitute an exceptional study area, as well as a teaching "gymnasium" for generations of university students in Geological and Natural Sciences. The geological aspects of this area also stimulate the interest of visitors not particularly expert in sciences of the earth, who are not insensitive to the beauty of the several landscapes occurring.

2. Geological background

In the Madonie Mountains (fig. 1), segment of the Maghrebide-Apenninic chain, successions of Meso-Cenozoic lithologies and late- and post-orogenic deposits occur (Catalano *et al.*, 2004). The Meso-Cenozoic successions are made up of: clayey-marly and arenitic rocks belonging to the Sicilide Domain (Upper Cretaceous-Lower Miocene); clay with intercalation of sandstone levels of the Numidian Domain (Upper Oligocene-Lower Miocene); mainly carbonate deposits of the Panormide Platform (Upper Trias-Middle Oligocene); alternations of shales, marls, radiolarites, and carbonates of the Imerese Basin (Upper Trias-Oligocene). Molasse (Terravecchia Formation, Upper Tortonian-Lower Messinian), evaporitic and reef (Messinian) or pelagic ("Trubi", Lower Pliocene) deposits cover such successions. Miocene overthrusts and Plio-Pleistocene fault systems are responsible for the existing tectonic setting.

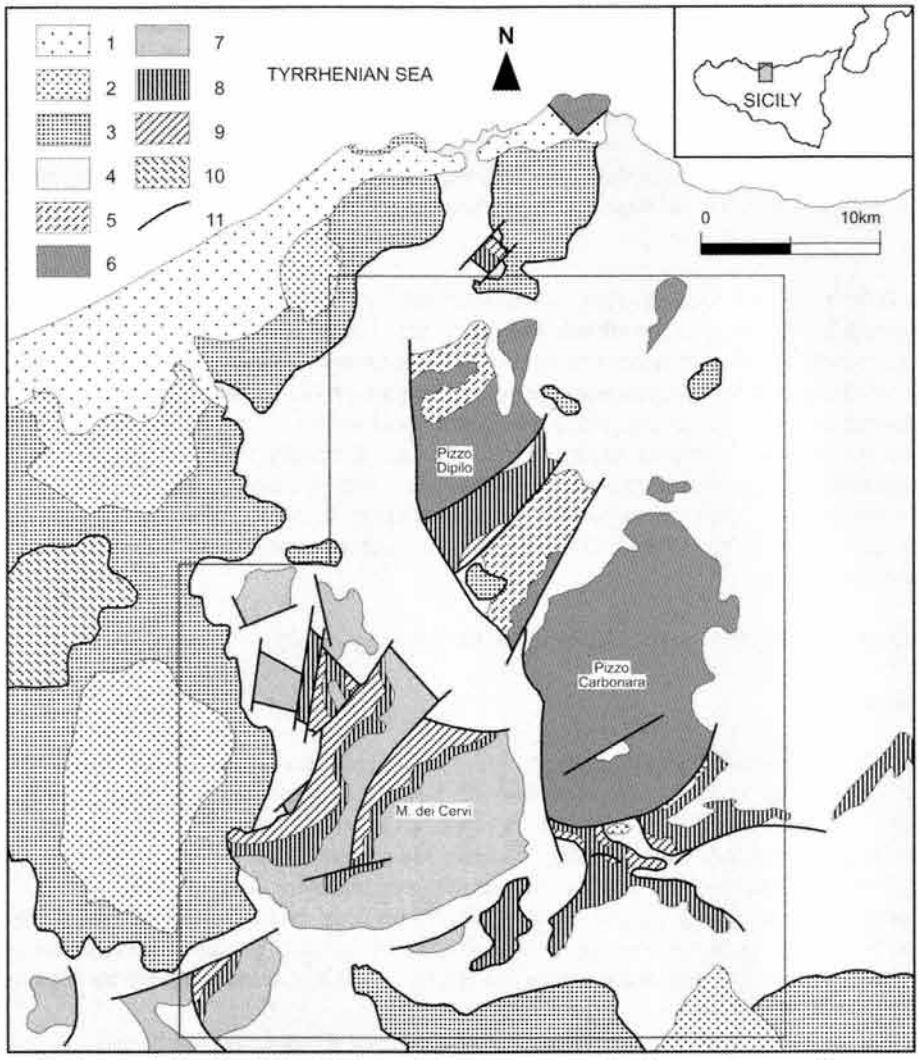

***Fig. 1** – Geological sketch of the Madonie Mountains area. 1: clastic deposits (Quaternary); 2: pelagic limestones, Trubi (Lower Pliocene), evaporites (Messinian), clays, sandstones and conglomerates, Terravecchia Formation, and reef deposits (Upper Tortonian - Lower Messinian). SICILIDE DOMAIN - 3: clays, marls and marly calcilutites, Argille Varicolori (Upper Cretaceous - Lower Miocene). NUMIDIAN DOMAIN – 4: mainly clayey deposits, Numidian Flysch (Upper Oligocene - Lower Miocene). PANORMIDE DOMAIN – 5: marly clays and calciluitites, Gratteri Formation (Upper Eocene - Middle Oligocene); 6: mainly carbonate deposits (Upper Triassic - Middle Oligocene). IMERESE DOMAIN AND ITS MARGIN – 7: alternations of shales, marls, radiolarites and carbonates (Jurassic - Oligocene); 8: slope dolostones, Fanusi Formation (Upper Triassic - Liassic); 9: marls, calcilutites and cherty limestones (Upper Triassic). LERCARA DOMAIN –10: marls and calcilutites (Middle and Upper Triassic). 11. main tectonic limits. (Agnesi et al. 2000).*

In particular structural building consists of a stack thrust ramps overriding the carbonate platform imbricates (Catalano *et al.*, 2004). From North to South they are made up of the Imerese and Panormide Units that are overthrust by the Numidian nappe and, in places, by remnants of the Sicilide nappe. The uppermost level is represented by: i) Miocene molasse deposits, Messinian

evaporites and Lower Pliocene Trubi limestones that appear folded, faulted and detached from their substrate; ii) Upper Pliocene-Lower Pleistocene clastic carbonate deposits.

3. Gemorphological setting

Geomorphological setting of Madonie area is extraordinarily varied and includes many of the morphological features characterising several Sicilian areas. This setting results from the interaction between different geomorphological processes and Pleistocene tectonic movements and climatic changes. It is possible to find the coexistence of landforms resulting from different morphodynamic processes, the most recent of which wholly or partially modified earlier landforms (fig. 2).

On the basis of the geomorphological setting five sectors occur: a) carbonate tablelands; b) carbonatic-siliceous-marly relief; c) dolomite relief; d) system of clayey-arenitic slopes; e) alluvial valley floor areas and

***Fig. 2** - Geomorphological sketch. 1: fault slope; 2: structurally-controlled slope; 3: main fault scarps; 4: structural slope; 5: dry valley; 6: fluviokarst canyon; 7: main karst depressions; 8: main landslides; 9: (a) slide – or (b) flow type landslide; 10: wide degraded scarp; 11: DSGSD; 12: "relict surface"; 13: erosion glacis; 14: fluvial terraced surface (Agnesi et al. 1998, modified).*

coastal strip. Each sector corresponds to a particular landscape unit marked by a typical assemblage of landforms related to the geological and structural setting or to a distinctive geomorphological agent.

a) Carbonate tablelands

Carbonate tablelands are located at summit areas (the Carbonara Massif), ranging in elevation between 1,500 m and 1,979 m a.s.l. Upper Trias-Middle Oligocene calcareous and calcareous-dolomite deposits belonging to the Panormide Carbonate Platform outcrop; these rocks present a block fragmentation resulted mainly from NW-SE and NE-SW oriented fault systems.

This sector is made up of a karst landscape where large- medium and small sized surface karst landforms prevail, instead underground cave systems are moderately developed (photo 1).

Small sized landforms (Karren) consist mainly of shafts, grikes, runnels, rills, covered runnels and solution pans. In places the Karren are widespread above large areas, forming Karren fields. These are characterized by isolated blocks separated by wide grikes enlarged by both karst dissolution and cryoclastic processes; each block can also be affected by other types of the above-mentioned Karren.

Photo 1 – *The Piano Battaglia Polje and the karst landscape of the Carbonara Massif.*

Medium- and large-sized landforms consist of dolines, uvala, polje, dry valleys and canyons.

On the plateau, medium and large sized normal solution dolines predominate; these are mainly saucer-shaped and bowl-shaped dolines, vary from 30 to 200 m in diameter, and from a few metres to about 25 m in depth. Dolines occur especially on summit areas - above 1,600 m a.s.l.- of the Carbonara Massif; the most of the depressions are elongated and aligned parallel to main tectonic lines, in NE-SW and NW-SE direction. On steepest slopes, asymmetrical semi-open or open dolines prevail. Asymmetrical dolines are also related to the more prolonged corrosion occurring owing to the greater snow persistence on southeast-facing slopes protected from the dominant winds (Abate & Agnesi, 2004; Macaluso *et al.*, 1994).

On the Carbonara carbonatic plateau also larger depressions, like uvala, are recognizable. Along the slopes of these depressions it is also possible to observe small open dolines located at different heights.

The Piano Battaglia polje is the largest depression in the Madonie karst landscapes. This polje, about 2500 m long and 800 m wide, consists of two sub-depressions (Battaglietta and Piano Battaglia), separated by a sill located at 1,600 m a.s.l. The polje is elongated along ENE – WSW direction and bounded by steep carbonate fault slopes. The floor is made up of soil and clays, ascribed to Numidian Flysch, which drain stream waters and melting snow waters into a swallow-hole located at the base of the south-eastern slope (Inghiottitoio della Battaglietta).

In this sector fluviokarst landforms like dry valley and canyon occur. Dry valleys develop along the main discontinuity lines, in NE-SW direction, and witness the existence of a palaeohydrographic system which had probably set before the terrigenous overburdens be eroded (Macaluso *et al.*, 1994). Fluviokarst canyons are a few meters long. These were created by the combined action of stream erosion and karst processes, according to the lowering of the local or general erosion base level caused by uplifting of whole area (Agnesi *et al.*, 2000). These valleys were cut either along lines of tectonic weakness or as the result of superimposition phenomena, independently of the geological structure.

Underground karst landscape is not well-developed; in the Madonie area just over 30 caves occur, of which only a few are considered to be significant (Abate & Agnesi, 2004). The existence of so few well-developed caves could be due to dense fractures and micro-fractures system of carbonate rocks, that probably promotes diffuse permeability and homogeneous karst processes rather than the development of large karst drains. The largest caves have mainly vertical development and generally consist of a series of wells alternating with chambers and galleries. These extend along the main tectonic lines and their vertical development is due to the lowering of the local or general base karst level to which the Madonie area has been affected.

The geomorphological setting of this sector is also marked by numerous patches of relict surfaces ("superfici relitte"; Agnesi *et al.*, 2000), located at the top of mounts and along slopes at heights between 800 and 1950 m a.s.l. They are subplanar or slightly undulating landforms which were not destroyed at all thanks to a carbonate substratum at a low erodibility degree. Their genesis is likely due to processes of prevailing lateral erosion occurred throughout prolonged continental periods. The relict surfaces observed are located at an elevation distance ranging from few tens to a hundred of metres, at times bounded by fault escarpments or fault steps. The surfaces are intensely karstified and cut up by mostly dead valleys and fluviokarst canyons.

***Photo 2** – Cuesta - type monoclinal reliefs bounded by fault scarps (eastern slope of Monte dei Cervi).*

The marginal areas of this sector consist of wide steep slopes, hundreds of metres high, joining the mountain zones to the hill and piedmont areas. At the base of these slopes fault and fault line scarps usually occur.

b) Carbonatic-siliceous-marly reliefs;

The geomorphological setting of reliefs made up of carbonatic-siliceous-marly rocks belonging to the Imerese Domain (sector of Monte dei Cervi and the isolated reliefs of Monte d'Oro, Rocca di Sciara and Rocca di Sclafani) is very different. Here steep landforms, tectonic scarps and large talus debris at the foot of slopes prevail; structural landforms are widespread. The main geomorphological processes are due to selective erosion, combined fluvial-karst action and surface and deep landslide movements.

In the Monte dei Cervi area, silicoclastic and Mesozoic-Tertiary deposits of the Imerese Basin outcrop. The structural setting involves a large brachyanticline dislocated by reverse, direct and strike-slip faults. The alternation of lithologies with a different erodibility degree is responsible for developing of structural landforms and relief forms which can be ascribed to deep-seated gravitational slope deformation phenomena (DSGSD, Agnesi *et al.*, 2000a).

Instead, the Plio-Pleistocene tectonics produced numerous blocks where selective erosion has brought about cuestas and hogbacks, often bounded by degraded fault or fault-line scarps (photo 2). Such landform typologies make up the structural highs of Monte d'Oro and Rocca di Sciara as well. In the uppermost areas fluviokarst depressions are present, roughly elongating in E-W direction; these develop along morphoselection depressions.

The southern and eastern slopes of Monte dei Cervi account altogether for wide degraded structural surfaces. In particular, along the southern slope, selective erosion and cataclinal streams action have given birth to flatiron-type structural landforms, while the eastern slope is also affected by gravitational phenomena, involving thick carbonate deposits. In addition, DSGSDs are present – notably lateral spread and block-slide movements - in the northern, eastern and south-eastern areas of Monte dei Cervi, too. Whereas the northern and western sectors of the same relief are bounded by wide fault slopes, developed along the boundary between carbonate rocks of the Imerese *facies* and clayey lithologies of the Numidian Flysch, whose height was probably being increased by selective erosion (Hugonie, 1982; Agnesi *et al.*, 2000b). Fault scarps and slopes, whose bottom was partially exhumed by selective erosion can also be found in the innermost areas of the Monte dei Cervi massif.

c) Dolomite relief

In the Monte Quacella area and along the medium-low parts of the south-eastern slope of Pizzo Dipilo, Triassic-Liassic dolomite and calcareous-dolomite rocks, commonly attributed to the margin of the Panormide Carbonate Platform, outcrop.

Their tectonic superposition over the Oligo-Miocenic clayey deposits of the Numidian Flysch enabled structurally-controlled complex slopes to generate (Monte Quacella eastern slope) and the development of large-scale DSGSD phenomena, too (western slope of the same relief; Agnesi *et al.*, 2000a).

The high degree of erodibility of dolomite and calcareous-dolomite rocks together with their dense fracturing and faulting, triggered physical weathering processes, mostly of cryoclastic type, which were intense especially during the Pleistocene coldest periods, giving origin to thick stratified drift with a various cementation degree. These processes, still active during the coldest winter periods, are the main responsible for slope recession phenomena and pinnacles or nivation niches higher than 1500 m a.s.l. (photo 3).

In general the strong intensity of degradation processes, enabled fluvial deepening processes, responsible for the origin of canyons and of a network of great V shaped valleys, involved the quasi-destruction of the most ancient landforms, except for relict surface and palaeovalleys small strips, located on the top of the relief.

Photo 3 *– Dolomite slope affected by intense physical weathering processes (Anfiteatro della Quacella).*

Photo 4 *– Clayey slopes intensely affected by runoff and mass movement (southern area of the Madonie Geopark).*

d) System of clayey-arenitic slopes

The piedmont and hill areas surrounding the mountain massif consist mainly of clayey rocks with intercalated marly, arenitic or conglomeratic levels. They can be roughly related to theNumidian Flysch (Upper Oligocene-Lower Miocene) and, at a lower extent, to the "Argille Varicolori" of the Sicilide Domain (Upper Cretaceous-Lower Miocene), to the overburden of the Panormide Carbonate Platform (Gratteri Formation, Upper Eocene-Middle Oligocene), to the Terravecchia Formation (Upper Tortonian-Lower Messinian) and to the "Trubi" (Lower Pliocene).

In relation to the outcropping deposits, these areas are ruled by frequent surface landslide movements at a various degree of evolution. Stratified and/or cemented drift, somewhere thicker than 50 m, touching carbonate slopes, allowed DSGSD phenomena to occur. Among the landslides

of kilometric size a particular mention is given here to one on the western slope of Monte Quacella, the Portella Colla landslide, and one at Piano Zucchi, the Vallone Montaspro landslide (Agnesi *et al.*, 2000a).

The Portella Colla landslide is a complex landslide, probably of Late Pleistocene age, stretching between Portella Colla, Monte Quacella, reaching as far as the Imera Settentironale River bed. This landslide is 6,250 m long, between 2000 and 3000 wide, covering an area of 14.5 km^2; its mean thickness is estimated at about 60 m. The head of the landslide is located along the great amphitheatre-type scarp bordering the western slopes of Monte Mufara and Monte Quacella. The landslide is characterized by both surface and deep gravitational deformations whose origin and evolution are due to the superposition of calcareous-dolomite blocks of the Fanusi Formation over marly limestones of the Mufara Formation, overlaying the Numidian Flysch clays. This condition and the increased relief energies following tectonic movements and downcutting stream, triggered differential settlement phenomena, lateral spread and block slide in the carbonatic masses, also involving the massive cemented and/or stratified debris at the base of the western slope of Monte Quacella. These deposits further increased the weight of the landslide body that had formed, triggering rotational slide in the underlying calcareous-marly and clayey rocks that affected this same debris. In the middle-low sector of the landslide body, characterized by the presence of clayey Numidian Flysch terrains, more surface movements, such as slide and flow, occur. Recent movements are related to exceptional meteorological events.

The Vallone Montaspro landslide is a complex movement like multiple rotational slide evolving to flow. The landslide body starts from Piano Zucchi and develops in ESE-WNW direction; it is about 3.5 km long and up to about 1700 m wide. At present, the deepest rupture surfaces are in most cases dormant, whereas the more superficial ones are subject to recurrent reactivations.

The eastern sector of Madonie is less liable to landslide and some landslide bodies appear to be dormant; the steeper slopes, with more regular profiles, are the site of erosion phenomena due to surface streams. Similar geomorphological features are present in the southern piedmont areas, although some landslide areas, where the downcutting and undermining action of stream is more intense, are recognizable.

Clayey slopes are also affected by runoff processes responsible for origin of rills and gullies and complex landforms, like badlands (photo 4).

Where arenitic-conglomeratic intercalations are particularly widespread and feature a monoclinal bedding (south eastern border of the dissected area), selective erosion originated hogback- or cuesta-type structural landforms.

Finally, in all the hill areas nearly flat surfaces occur; usually these landorms are limited in size and develop at the summit or along the slopes of reliefs. Their origin is probably due both to "planation" processes *latu sensu* and to the lateral streams erosion, as also to the rotation of rock masses as a result of landslide movements, with the formation of backtilted areas.

e) *Alluvial valley floor areas and coastal strip.*

This sector is marked by a sub-planar topographic setting. In particular, the valley floor areas are made up of alluvial plain and a succession of fluvial terraces; the coastal areas consist of some orders of wave-cut platforms.

The valley floor areas are characterised by the alluvial plains of the Imera Settentrionale and Pollina river, a few hundred metres wide. The alluvial deposits cover fluvial erosion surfaces or former nearly horizontal surfaces, such as wave-cut platforms, located at coastal strips. Several orders of fluvial terraces are recognizable. Alluvial fans develop at the confluence of the main tributaries into the alluvial plains. They are produced by mass movements (debris or mud flows) or by flooding processes.

The coastal strip is marked by mostly sandy/pebbly beaches, some kilometres long and up to many tens of metres wide, and by some small cliff. Several cycles of marine terraces occur along stretches overlooking the coast. The terraced succession develops from sea level to a height of about 300 metres a.s.l. In particular, up to a height of about 15 m, there is a wide and almost

continuous wave-cut platform, 0.5 to 1 km wide, probably of the Eutyrrhenian age. This platform is interrupted by a degraded palaeocliff up to about 10 m in height. At greater heights there are older marine terraces, related to the Upper and Middle Pleistocene sea-level highstand phases. The younger orders are better preserved, while those older have been reduced to modest relicts by stream downcutting and denudation processes.

4. Conclusions

The Madonie Geopark is characterised by five different landscape units; each unit is marked by a typical assemblage of landforms due to distinctive geomorphological processes, according to the geological setting: 1) *Carbonate tablelands*, made up of Upper Trias-Middle Oligocene calcareous and calcareous-dolomite rocks, where large- medium (polje, uvala, dolines, fluviokarst valleys and karst surfaces) and small sized (Karren) surface karst landforms prevail, instead underground cave systems (mainly vertical caves) are moderately developed. This area is also marked by numerous patches of relict surfaces and is bounded by great fault scarps and slopes; 2) *Carbonatic-siliceous-marly reliefs*, made up of an alternation of basin rocks with different erodibility degree, where structural landforms, tectonic scarps and large talus debris at the foot of slopes are widespread. Landforms due to DSGSD phenomena and fluviokarst valleys occur too; 3) *Dolomite relief*, made up of Triassic-Liassic dolomite and calcareous-dolomite rocks, where pinnacles, nivation niches and debris produced by physical weathering, and deep V shaped valley due to stream downcutting processes predominate; 4) *System of clayey-arenitic slopes*, made up of clayey rocks with intercalated marly, arenitic or conglomeratic levels, where landforms due to surface landslides, DSGSD phenomena, runoff processes and fluvial erosion are frequent; 5) *Alluvial valley floor areas and coastal strip*, mainly made up of fluvial and coastal deposits, where alluvial plains and several orders of marine or fluvial terraces occur.

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