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THE INTERPLAY OF EROSION, INSTABILITY PROCESSES AND CULTURAL HERITAGE AT SAN NICOLA ISLAND (TREMITI ARCHIPELAGO, SOUTHERN ITALY)

ABSTRACT: LOLLINO P. & PAGLIARULO R., *The interplay of erosion, instability processes and cultural heritage at San Nicola Island (Tremiti Archipelago, Southern Italy)*. (IT ISSN 0391-9838, 2008).

The cliffs of the Tremiti Islands, which are located in the Adriatic Sea in the north of the Apulian coastline (Southern Italy), are affected by severe instability processes. From the geological point of view, the Tremiti Islands are made of a sequence of bioclastic limestone, dolomitic limestone, calcilutite and calcarenite, with the age ranging from Paleocene to Middle Pliocene. These rocks are covered by a calcareous crust and loess deposits (Upper Pleistocene- Holocene). The structural set up of the major islands of the Tremiti (San Nicola and San Domino) is controlled by predominant NE-SW and E-W fault systems, which mark the coastlines of the islands. Along the cliffs, severe erosive processes are produced by different factors, as the climate and sea actions, and the effects of these processes are worsened by the seismic activity which affects the evolution of the cliff stability with time. Deeper instability processes are also observed at the Island of San Nicola as an effect of the presence of weak and low-cemented rock formations that are composed of dolomitic calcarenites, at the top of the island, and calcilutites. These processes are mainly represented by block topplings, slidings, rockfalls and roto-translative mass movements in some limited areas. These processes mainly threaten the cultural heritage buildings located on the island, as the Santa Maria Abbey, which have already suffered significant damages in the past. This study has represented the background for the engineering design of both the restoration works of the monumental area and the stabilization works of the cliffs below.

KEY WORDS: Geomorphology, Tectonics, Rock cliff erosion, Landslides, Cultural heritage, Tremiti Archipelago.

INTRODUCTION

Due to severe climate contexts, islands are frequently subject to diffuse coastal instability processes, which are mainly represented by erosion and landsliding, that produce scenarios of active coastal evolution (Sunamura, 1992; Stephenson & Kirk, 2000; Trenhaile, 2008). If such processes are characterised by high evolution rates they may expose the social and economic life of the islands to a risk. In some cases, the instability processes may also induce problems to important cultural heritage buildings located on the islands which need to be preserved. This is the case of the Tremiti Archipelago (Adriatic Sea, Southern Italy) which represents a typical context where weathering and erosional processes along with deeper landslide phenomena act on carbonatic rocks that are morphologically and structurally controlled by the geodynamic evolution. Remarkable cultural heritage buildings lying on these islands are nowadays at risk due to the rapid evolution of erosion processes, rockfalls and mass movements occurring along the rock cliffs delimiting the island coasts. At present, such processes are inducing a narrowing of some portions of the islands with a negative impact on the preservation of the cultural heritage and in general on the future socio-economic life of the islands.

This paper describes some of the results of an original study about the Tremiti Islands, carried out within a research project (1997-2002) supported by the Italian National Research Council (CNR), which is aimed at defining the geological and geotechnical incidences on the evolution of some archaeological sites. The study performed on the Tremiti Islands has firstly been focused to field surveys in order to define both a detailed geological setup of the islands, as there were very few previous data about this topic (Selli, 1971), and the geomorphological processes, such as erosion and landslide processes, which are currently active. Therefore, the outcropping geological sequences have been described taking into account the new geodynamic interpretations of the whole area. Then, the mineralogical and petrographical features as well as the mechanical properties of the lithotypes have been analysed in order to understand the role of the physical and mechanical behaviour of these rock materials on their susceptibility to erosion and lands-

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liding. Moreover, a numerical modelling using the distinct element method has been carried out in order to interpret the failure mechanisms occurring along the rock cliffs and therefore to predict the evolution of the same processes. The geological, geomorphological and geotechnical study has been aimed at discussing the factors controlling the erosional and landslide phenomena and identifying the areas with a high instability hazard, with respect to both the safety of the site, which has a great environmental and touristic value, and the safeguard of the existing cultural heritage. As a consequence, the main interest has been addressed to the Island of San Nicola where the most remarkable examples of cultural heritage are located.

FIG. 2 - San Nicola Island with the harbour, the fortress and Santa Maria Abbey.

DESCRIPTION AND HISTORY OF THE AREA

The archipelago of the Tremiti Islands, located in the Adriatic Sea, about 22 km north of the Apulian coastline, is formed of four islands: San Domino, San Nicola, Caprara and the smallest Cretaccio (fig. 1). Another small island, Pianosa (~ 0,1 km^2), which is far away from the others, also belongs to the Tremiti municipality administration. In the past, the islands were called the *Insulae Diomedaee* after the Greek hero Diomedes, who, according to the legend, was therein buried.

San Domino is the most developed island from the touristic point of view and is also the biggest of the archipelago (2 km^2 surface area). San Domino has been inhabited since the 2^{nd} millennium B.C. and was subsequently visited by the Greeks and Romans. In the year 1000 it was chosen as a hermitage by the Benedictine monks who later left the island and settled in San Nicola.

San Nicola is the most populated island. It is the site of a monastery where a monk named Nicolò was buried. A legend says that each time someone tried to move his corpse off the island a violent storm occurred preventing navigation around the island. In 1045 the Benedictine monks of Montecassino started to built the Abbey of Santa Maria (fig. 2) on the top of San Nicola Island, which became the historical, religious and administrative centre of the Tremiti Islands (Delli Muti, 1965). During 11^{th} and 12^{th} centuries S. Maria Abbey was one of the most important monasteries of the Adriatic Coast of Italy. It is a beautiful synthesis between Byzantine and Romanesque art, according to the typical style of Benedictines and Cistercians (McCledon, 1984). In 1300 it suffered the attack of the pirates who destroyed the fortress and killed the monks. Around 1783, under the king Ferdinando IV, the abbey became a penal colony and this function was kept until the Second World War. In the early 1960s a restoration campaign by the local Superintendency of Monuments revealed the original and medieval fabric of the abbey church.

Caprara is deserted and the island of Cretaccio is a major block of rock, and thus uninhabited.

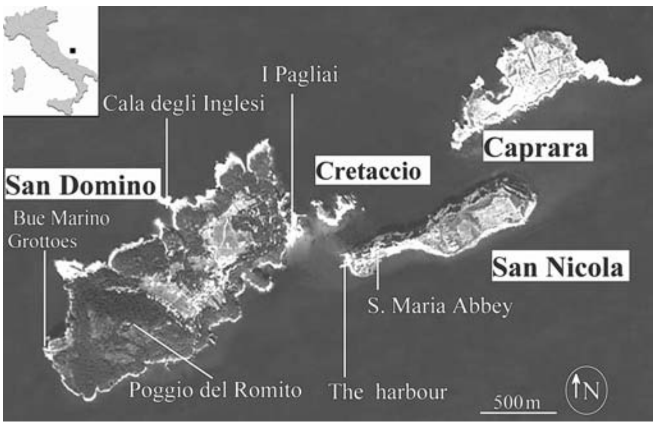

FIG. 1 - The aerial photograph of the study area.

STRUCTURAL SET-UP

The Tremiti Archipelago represents the top of a E-W and NW-SW elongated structural high, along regional strike-slip fault alignments (Gambini & Tozzi, 1996; Ridente & Trincardi, 2002). It shows a gentle (10°÷20°) SE vergent monoclinal setting. Within the complex geodynamic structures of the Mediterranean area the Tremiti Archipelago belongs to the Adria microplate and in particular is located at the northern side of the Apulian foreland (fig. 3). The origin of the structural high, from Upper Pliocene to Late Pleistocene, is related to the tectonic deformation of the Apennine thrust margin (Argnani & *alii*, 1994), which gave rise to the separation of the foreland into two domains defining a boundary in the Adria microplate with different thicknesses and tectonic regimes (Doglioni & *alii*, 1996). Deep seismic reflection data from Italian lithospheric exploration project CROP (Section M-13, Finetti & Del Ben, 2005) show the huge positive Tremiti rose with two major right strike-slip faults (NE-SW) defined north and south by the EW fault zone (Nicolai & Gambini, 2007). This structure is interpreted as the antithetic structure of the Mattinata fault in the Gargano Promontory (Brankman & Aydin, 2004)

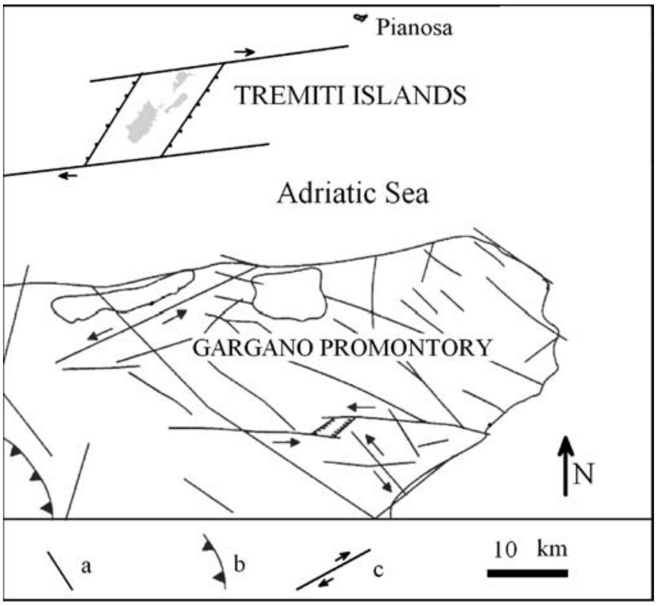

FIG. 3 - Schematic structural setting of the Tremiti Islands and the Gargano Promontory (the area of the islands is not in scale) with evidences of extensive strike-slip and normal faulting and block rotation. a) Main faults; b) Apenninic thrust front; c) faults with a prevailing strike-slip movements (after Andriani & *alii*, 2005; modified).

and confirm the micro- and meso-structural analyses carried out by Montone & Funiciello (1989). Subordinate dip-slip faults are associated with variable orientation from NS to WNW and ESE. Slight folds show NE- SW and WNW-ESE trends.

A mesostructural study has been carried out by Andriani & *alii* (2005) who located the measurement stations along the coastlines. Joints and tension cracks with N-E and N-S trends have been defined together with joints parallel to the local orientation of the coastline.

The fault systems which have been observed are still seismically active (Montone & Funiciello, 1989; Favali & *alii*, 1993; Argnani & *alii*, 1994). In fact, since 1600 the Gargano region has been affected by several seismic events. Most of these events occurred offshore, therefore their epicentre, especially for the oldest ones, is uncertain; the strongest earthquakes which have been recorded are listed in tab. 1. Recently, off the Gargano promontory, three important seismic sequences occurred between 1986 and 1990. In 1986 the first seismic sequence (body wave magnitude m_b = 4.2) was recorded 50 km north of the Tremiti Archipelago and subsequently a second one occurred in 1988 NNE off the Gargano Promontory (m_b = 5.3). In 1989 another earthquake was recorded with the epicentre at the Tremiti Islands (m_b = 4.7, Favali & *alii*, 1993). It is not already clear which are the local effects of seismicity but in the particular geological setting examined the seismic stress may also result in important co-seismic effects, such as the weakening of the rock masses along the joint systems.

TABLE 1 - List of the strongest earthquakes occurred at the Tremiti Islands. The damages are assessed as I_s (x 10) in MCS scale (Database INGV)

Years	Month	Day	Damages I_s (MCS)	Epicentral area	I_{max}	M
1627	07	30	70	CAPITANATA	X-XI	7.0
1875	12	06	60	S. MARCO IN LAMIS	VIII	5.2
1889	12	08	70	APRICENA	VII	5.0
1892	04	20	30	GARGANO	V-VI	4.7
1892	06	06	70	TREMITI ISLANDS	VII	4.7
1893	08	10	20	GARGANO	IX-X	5.2
1894	03	25	–	LESINA	VII	5.0
1904	04	08	–	GARGANO	VII	4.7
1910	06	07	35	CALITRI	IX	5.9
1915	01	13	40	AVEZZANO	X-XI	7.0
1937	07	17	40	SAN SEVERO	VII	4.7
1980	11	23	45	IRPINIA-LUCANIA	X	6.9

GEOLOGY OF THE AREA

The Tremiti Archipelago consists of a discontinuous sequence of carbonatic marine sediments, ranging from Late Paleocene - Early Eocene to Middle - Late Pliocene, overlain by late Pleistocene and Holocene discontinuous continental deposits (fig. 4).

Being a gentle SE-dipping slightly folded monocline structure, the older formation outcrops at the San Domino Island. The thickness of the Bue Marino Formation, which is the oldest one, is about 60 m and the age is Late Paleocene (Selli, 1971). In transgression on these deposits there is the Caprara Formation which has a maximum thickness of 25 m. The age of this formation is attributed to Early Eocene. A continuity of sedimentation characterises the contact between the Caprara Formation and the San Domino Formation which outcrops widely at San Domino, Caprara and Cretaccio islands, in accordance with the framework of the Tremiti Islands. The total thickness of San Domino Formation is about 200 m and it includes different *lithofacies*: stratified yellow-greenish dolomites, calcitic dolomites, doloarenites, recrystallized dolomitic calcarenites, withish *Nummulites* biocalcarenites and biocalcilutites sometimes dolomitized, biostromal banks and breccias in the upper levels referable to Middle-Late Eocene. This formation is overlain by the Cretaccio Formation through a transgressive surface. This is the most widespread unit both in the islands and in the sea floors among them. The lower member is made up of well stratified yellow-greenish and yellow-reddish glauconitic laminate doloarenites, which pass upwards to marly biocalcilutites, yellow-whitish fossilliferous marls, yellow - whitish and occasionally greyish calcisiltites containing yellow limonite clasts. In these deposits soft sediment structures are clearly visible, probably due to liquefaction phenomena triggered by seismic activity. The total thickness of the formation is about 150 m and the age is referred to Middle Miocene. The Cretaccio Formation is overlain by the San Nicola Formation which outcrops at San Nicola Island

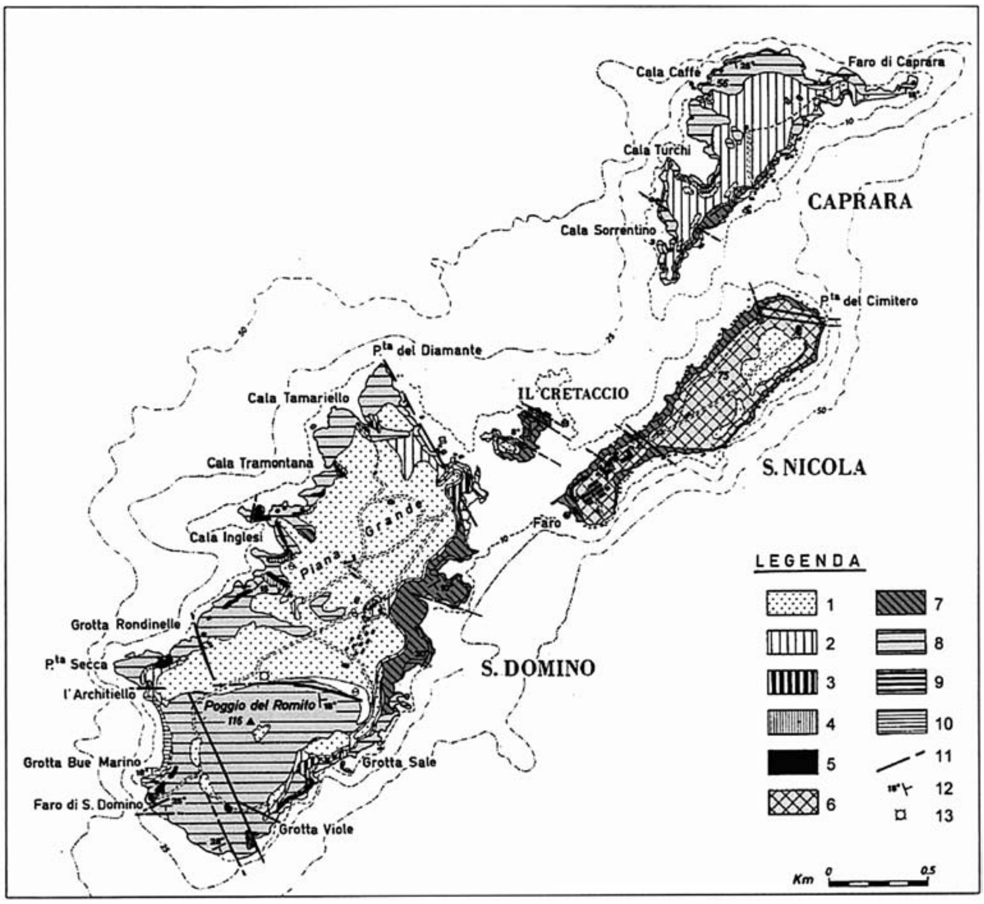

FIG. 4 - Geological sketch of the Tremiti Islands (after Selli, 1971; modified). Legend: 1) Brown loess (Late Pleistocene - Holocene); 2) Calcareous crust (Late - Middle Pleistocene); 3) Yellowish loess (Middle - Late Pleistocene); 4) Loess and reddish gravels (Middle Pleistocene); 5) Conglomerates and marly limestones (Middle Pleistocene); 6) San Nicola Fm. (Middle - Late Pliocene); 7) Cretaccio Fm. (Aquitanian - Tortonian); 8) San Domino (Middle - Late Eocene); 9) Caprara Fm. (Early Eocene); 10) Bue Marino Fm. (Paleocene); 11) Faults; 12) Bedding attitudes; 13) Borehole Tremiti 1.

and is about 35 m thick. It consists of hard recrystallised and fractured dolomitic calcarenites. The Cretaccio Formation and the San Nicola Formation are those mainly affected by the erosion and landsliding processes described in the following sections. Upwards there are white greyish wackestone dolomitic calcisiltites and friable biomicrites. The succession ends with whitish-yellow calcareous travertinoid crusts. According to Cotecchia & *alii* (1995) the crusts are classified as caliche, resulting from capillary action of carbonate solution rising to the surface in dry environments characterised by warm temperatures and low rainfalls. Based on the fossil content the formation can be referred to Middle - Late Pliocene.

The whole succession of continental deposits of the Upper Pleistocene and Holocene can be observed at San Domino. At the base there are well cemented conglomerates with reddish sandy-silty matrix, followed by 2 m thick marly limestones and red marl horizon, which is overlain by eolian deposits (red, yellow and brown loess). The eolian deposits are interbedded by carbonate crusts.

GEOMORPHOLOGICAL OUTLINES

The Tremiti Archipelago is characterised by a slightly rough morphology with a landscape having steep slopes and subtabular tops gently SE dipping due to the monoclinal structure. Locally, slight anticline fold structures dislocated by faults can be noticed, the most important of which is located in San Domino Island at Poggio del Romito, the highest relief of the Tremiti Islands. The coastal morphology is characterized by high rock cliffs (up to about 60 m high at San Nicola) and low relief flat coasts with gently dipping convex slopes. In the areas where the Eocene and Pliocene formations outcrop, the cliffs are approximately sub-vertical with overhanging blocks; slope angles ranging between 50° and 75° instead characterise the cliffs in the Miocene strata of San Nicola Island. The flat coast sectors are slightly indented and contains large pocket beaches (Cala degli Inglesi, Cala Tramontana at San Domino). There is only one sandy beach, Cala delle Arene, which is located at San Domino. Where the Paleogene formations outcrop, the coastline is articulated in caps and promontories (Scoglio dell'Elefante, Punta del Coccodrillo, Punta del Diavolo at San Domino), inlets, small bays and sea caves (Grotta del Bue Marino, Grotta delle Rondinelle, Grotta delle Viole, Grotta del Sale), arches (Architiello at San Domino, Architiello at Caprara) and stacks (Pagliai at San Domino, Scoglietti at Caprara) (fig. 5). Inlets, small bays and sea caves are mainly located along faults and joint systems. Arches and stacks, related to the main fault trends, are produced by wave action, al-

FIG. 5 - Stacks called «I Pagliai» along the coasts of San Domino.

though, locally, notches are not visible. Where Miocene and Pliocene deposits outcrop, due to the rapid recession of the cliffs, the coastline is more regular and large sea caves, inlets and other landforms due to erosive phenomena are less frequent (Andriani & Guerricchio, 1996). Karst processes have mainly produced superficial landform characterised by either joints enlarging by solution or joints filled with residual materials. In the Tremiti Islands groundwater is not present and there is no evidence of karst drainage in the caves.

EROSIONAL AND WEATHERING PROCESSES

The evolution of the coastal morphology of the Tremiti Islands is mainly related to mass movements and selective erosion processes which are at present very active. The factors which play a role (Sunamura, 1992; 1994) in the instability phenomena occurring at the Tremiti Archipelago are summarised in fig. 6.

The weathering processes of the rock materials forming the cliffs are related to the climatic conditions (Stephensons & Kirk, 2000). The climate at the Tremiti Islands is typically Mediterranean and is therefore characterized by an annual trend of temperatures with mild winters and warm and dry summers. The minimum values of the temperature are recorded in January (9.2° C) while the maximum values occur in August (29° C) with peaks reaching up to 38° C. The rainfalls are concentrated in the autumn - winter term (~ 476 mm/yr on average) and the wind regime is characterised by predominant winds coming from the 2nd and 4th quadrant. Sea conditions are stable during summer time while rough seas and strong storms are frequent in the period autumn - winter. These storms are mainly responsible for the erosion processes of the rock cliffs (Trenhaile, 1987; 2008). The impact force of rainfall water, the rain infiltration and the wind erosion remove fine particles from the rock matrix, mainly along either the exposed calcarenite joints (San Nicola Formation) or the calcisiltite and calcilutite (Cretaccio Formation) cliff surfaces. In particular, the Cretaccio Formation is characterised by a high susceptibility to erosion due to a weak cement and a fine grain size. In fact, flaking, pulverization and disaggregation of cement, cracking and dissolution weaken the levels composed of finer particles and make them more friable. This frequently causes overhanging calcarenite blocks due to selective erosion at the contact between the calcarenite and calcilutite formations. Moreover, cyclic wetting-drying processes induces weathering within the most shallow portions of the rocks belonging to both the formations (Trenhaile, 1997). The disintegration of rock resulting from alternate wetting and drying causes the growth of salt crystals (Stephensons & Kirk, 2000). The sea spray action, particularly active during strong storms, contributes to the chemical and salt weathering and to the general degradation of the rock cliff surfaces. The effects of all these processes give rise to a layer of external rock material which is weaker and more erodible. Thermic stresses are also particularly effective on the calcarenite levels.

The above described processes have a larger impact on the coast sectors characterised by high cliffs, as in San Nicola Island, where weak and porous marly calcisiltites are overlain by stiff calcareous and dolomitic rock masses (Cotecchia, 1999; Andriani & Guerricchio, 1996).

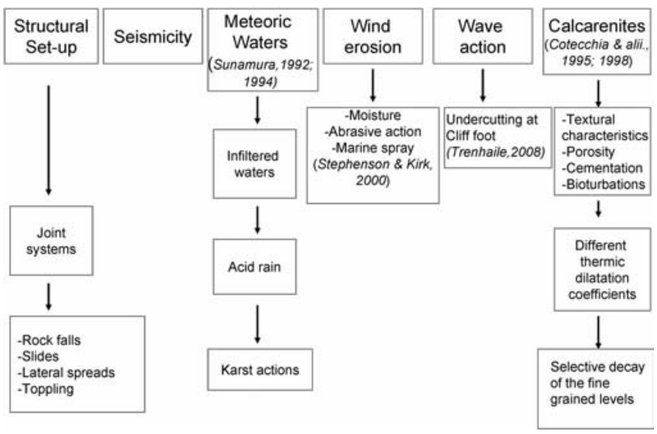

FIG. 6 - Causes influencing the instability phenomena at the Tremiti Archipelago.

MECHANISMS OF COASTAL LANDSLIDING

The instability processes observed along the coasts of the Tremiti Islands are characterised by different mechanisms. At San Domino and Caprara the more diffuse collapse mechanism is represented by rockfalls of small to medium size overhanging rock blocks, which is induced by the gradual undercutting either at the cliff foot, due to the sea erosion at the notch level (fig. 7) (Allison & Kimber, 1998), or at higher levels due to selective erosion phenomena. In particular, these phenomena occur in the Paleogene formations after large sea storms, heavy rainfalls and seismic shocks. Tensile failures are frequent along the sides

FIG. 7 - The N-W coast of San Nicola: the Cretaccio Formation with the overlying San Nicola Formation. Selective erosion between limestone and calcilutite can be seen in the upper part while intense sea erosive processes are visible at the foot of the cliff.

of the top of the islands due to either stress release or concentration of tensile stresses (fig. 8); as a consequence, this induces toppling or sliding of large dislocated blocks (Sunamura, 1978; 1992; 1994; Trenhaile, 1997).

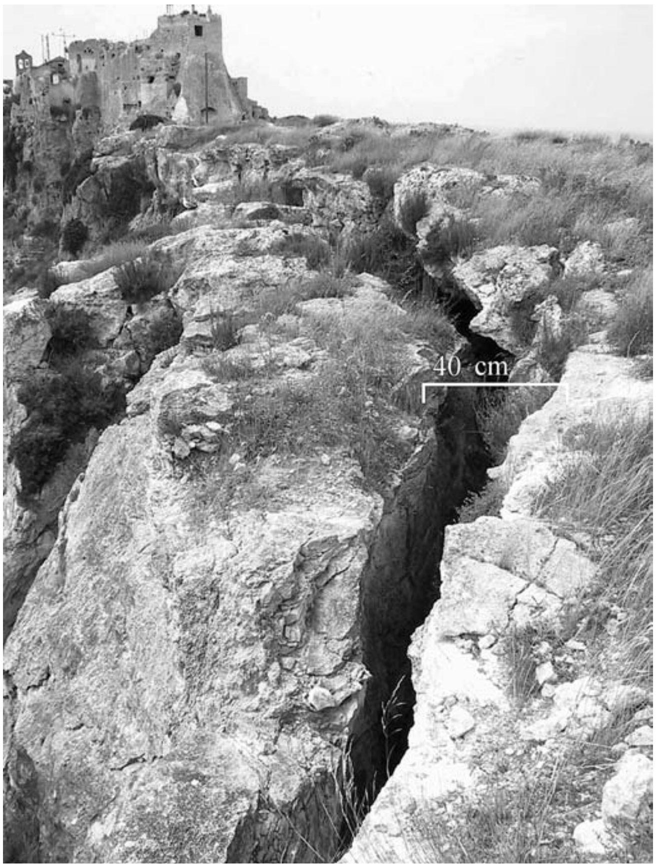

FIG. 8 - Tensile failure within the upper rigid formation at San Nicola.

The instability processes at San Nicola Island are particularly evident and the failure mechanisms of the rock slopes are complex. Landslides mainly occur as rockfalls, topplings and retrogressive slides. All along the coasts of the island, sliding surfaces often start to develop within the weaker Miocene calcilutite and calcisiltite and are characterised by a retrogressive evolution (Allison & Brunsden, 1990). In particular, the deformation processes induce tension stresses at the top of the overlying Pliocene dolomitic calcarenite, which is stiffer. As a consequence, cracks and fractures develop due to the exceeding of the tensile strength of the same rock material. These tension cracks delimit blocks on the top of the slopes which are susceptible of toppling (Kimber & *alii*, 1998).

Rockfalls and topples are also frequent along both the costal sectors adjacent to the Abbey of Santa Maria and are generally produced by either the selective erosion at the contact between the two formations or the action of the climatic agents along the rock joint surfaces (fig. 9). Due to the progression of such processes, nowadays the

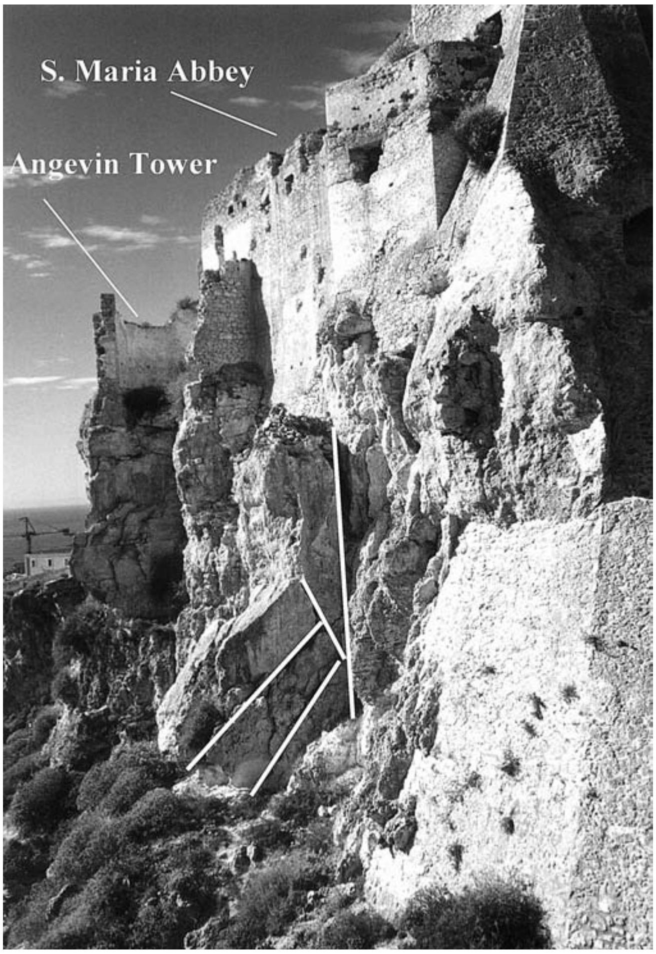

FIG. 9 - Large rock blocks, delimited by white lines, prone to topple on the south-eastern cliff of San Nicola Island. A close-up of the Angevin tower partially collapsed and the external wall of the fortress aligned with the cliff edge.

current profile of the cliffs at both sides of the abbey is aligned with that of the walls of the monumental structure, thus inducing high risk for this important historical building.

Along the southern coast of San Nicola Island, i.e. the harbour area, rockfalls, topples and block slidings can be observed. In particular, block slidings are presumably induced by the rain infiltration within the dip-slope joints which causes the reduction of the shear strength of the joints due to weathering of the rock surfaces.

A geomechanical characterization of the intact rock and of the joints has been carried out at San Nicola Island (Cotecchia & *alii*, 1998). In particular, laboratory tests have been performed on calcarenite and calcilutite intact samples taken along the cliffs of San Nicola Island in order to estimate the main physical and mechanical properties of the two rock materials. In-situ tests (Barton profilometer, Schmidt hammer) and laboratory tests (tilt-test) have instead been performed on exposed joint surfaces in order to define the strength properties of the joints. The main results are summarized in tabs. 2 and 3.

Numerical modelling

Distinct element analyses have been carried out with UDEC 4.0 (2004) in order to study some of the failure mechanisms active at San Nicola Island, the corresponding evolution processes and the factors controlling them by means of a stress-strain discontinuous numerical model. In particular, two cross-sections have been analysed as they are representative of the most important failure mechanisms active at San Nicola (fig. 10): the section 1-1, at north of the island, just under the Santa Maria Abbey walls, and the section 2-2, at south-east of the island, near the harbour area. An elastic-perfectly plastic model with a Mohr-Coulomb failure criterion has been assumed for the intact rock and a Mohr-Coulomb failure criterion has also been chosen to simulate the shear failure of the joints. The strength properties have been adopted in accordance with the laboratory and in-situ tests and are reported in tabs. 2 and 3. The numerical analyses have investigated the effects of the erosion at the sea level on the general stability of the cliff with respect to section 1-1 and the decay of the rock and joint strength properties along the external portion of the rock masses due to the climatic agents, such as salt weathering, sea spray, rain infiltration, wind erosion, wetting-drying cyclic effects with respect to section 2-2. In particular, for the first case (section 1-1), starting from an initial state corresponding to the current cliff geometry the analysis has simulated a progressive erosion at the sea level. The results of the analysis indicate that an erosion up to 10 m from the current cliff foot could produce a general failure mechanism which involves the most external portion of the cliff up to 10 m inwards. This can result in dramatic consequences for the walls of the abbey at the top of the cliff. Fig. 11 shows the displacement vectors which reproduce the failure pattern induced by such erosion process. The effects of climate weathering on the stability of the cliff at section 2-2 has also been simulated by inducing a gradual reduction of the strength properties of the joints in terms of a decrease of the corresponding friction angle. The resulting displacement vectors show that this process induces a sliding of the blocks delimited by dip-slope joints which in turn causes the toppling of the external long and narrow blocks (fig. 12). This failure mechanism agrees well with the behaviour of the cliffs which has been observed in the last decades in areas that are adjacent to those here examined.

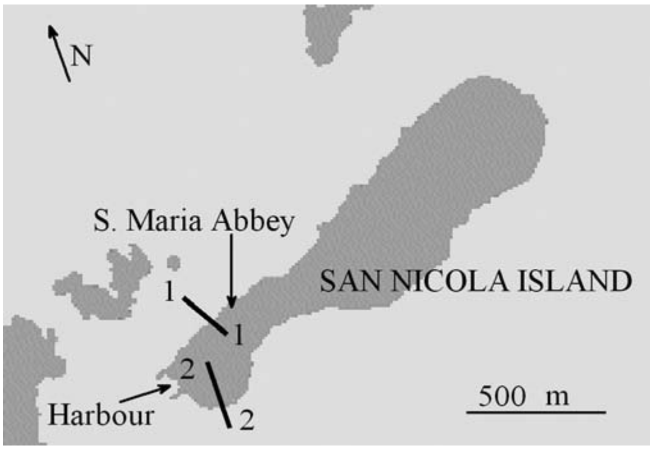

FIG. 10 - The two cross-section traces considered for numerical modelling at San Nicola Island.

TABLE 2 - Physical and mechanical properties of the rock matrix at San Nicola Island

	γ (kg/m³)	E (MPa) Young Modulus	ν Poisson Ratio	φ' Friction angle	c' (MPa) Cohesion	R_t (MPa) Tensile strength
Calcarenite	2300	5000	0.3	42	1.2	1.2
Calcilutite	1800	1500	0.35	32	0.5	0.2

TABLE 3 - Mechanical properties of the rock joints at San Nicola Island

	JRC Joint Roughness Coefficient	JCS (MPa) Joint Wall Compressive Strength	φ'_r (°) Residual Friction Angle
Calcarenite joints	16	52	25
Calcilutite joints	5	24	20

CONCLUDING REMARKS

An integrated study involving geostructural, geomorphological and geomechanical analysis has been carried out in order to investigate the instability processes which

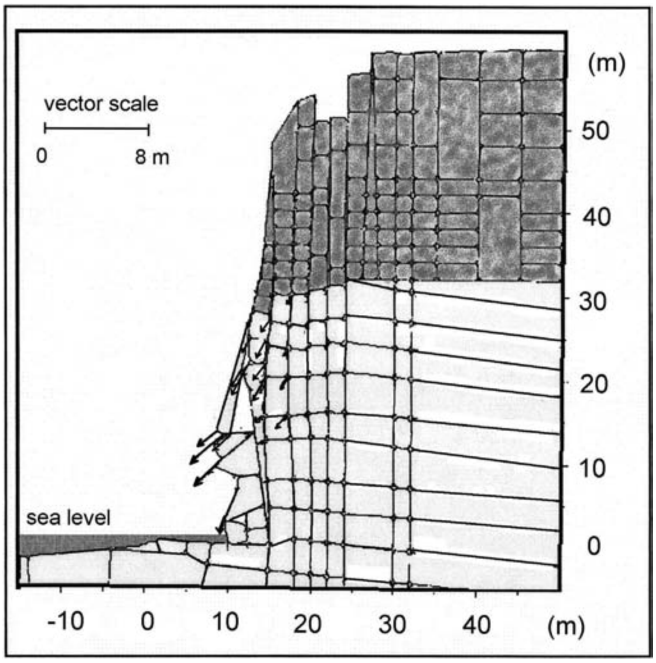

FIG. 11 - Distinct element analysis. Section 1-1: northern cliff of San Nicola Island - displacement vectors and failure pattern due to a 10 m erosion at the sea level.

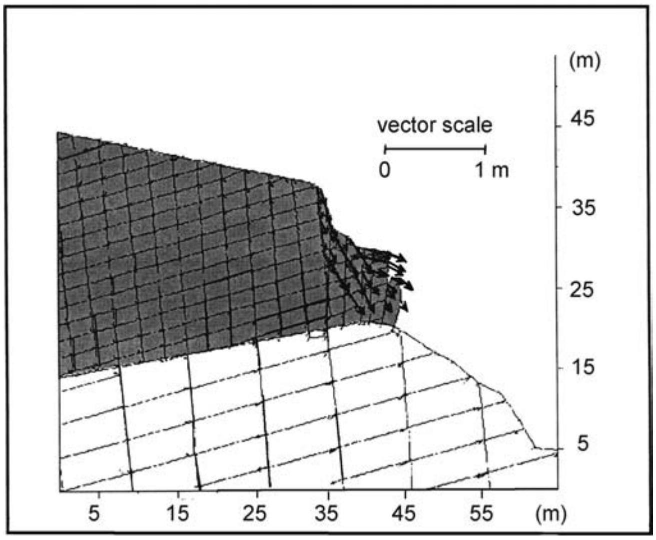

FIG. 12 - Distinct element analysis. Section 2-2: south-eastern cliff of San Nicola Island - displacement vectors and failure pattern due to a decay of the joint mechanical properties.

severely affect the cliffs of the Island of San Nicola, above which the Santa Maria Abbey was built, and the factors controlling them.

Field surveys have shown that the geomorphological evolution of the Tremiti Islands is significantly influenced by weathering and subaerial processes. The morphology of the islands is related to both the geodynamic evolution and the climatic conditions of the area at the regional scale and the resulting landforms are dynamically evolving according to the current morphogenetic processes. In particular, the coastal morphology results from the combined actions of tectonics, sea wave action, wind erosion and rain infiltration. The lithology of the outcropping rocks, which are weak and erodible, is a predisposing factor for different instability processes, such as weathering, erosion and deeper landslide processes. Therefore, the environmental factors produce a gradual weakening of the rock masses in the long term making them prone to selective erosion and landsliding phenomena, which are favoured by the presence of an intensely fractured dolomitic calcarenite formation overlying a weaker calcisiltite and calcilutite formation. Different kinds of failure mechanisms have been observed at San Nicola Island, according to the particular geological setting, such as rockfalls, topplings and lateral spreads with retrogressive evolution. Locally, the presence of artificial and natural rock blocks and debris at the foot of the cliffs represents an effective protection structure to the wave attack during storms. The salt weathering along with the rain infiltration causes chemical degradation of the most external portions of the rocks. The wind erosion is particularly effective on the friable and low cemented calcarenites and biomicrites of the San Nicola Formation. This frequently causes isolated overhanging calcarenite blocks prone to fall. In the eastern side of the island few cases of rock sliding along dip-slope bedding planes have been noticed. At San Domino and Caprara islands, medium-size block rockfalls due to both undercutting processes, mainly at the notch level, and the detachment of overhanging blocks are widespread.

The numerical analyses performed with the distinct element method have indicated an evolution of the cliff behaviour which is consistent with what has been observed in situ. In particular, erosion at the sea level and the weathering of the exposed joint surfaces are some of the most important processes which induce the general or partial collapse of the cliffs.

The interpretation of the erosion and landsliding mechanisms here proposed has represented an important knowledge background to optimize the design criteria for the restoration of the monumental area which includes the Santa Maria Abbey (Cotecchia & *alii*, 1998). At present, this important cultural heritage building is at risk of collapse, since the external walls of the fortress are aligned with the cliff edges.

REFERENCES

ALLISON R.J. & BRUNSDEN D. (1990) - *Some mudslides movement pattern.* Earth Surface Processes and Landforms, 15, 297-311.

ALLISON R.J. & KIMBER O.G. (1998) - *Modelling failure to explain rock slopes change along the Isle of Purbeck coast (UK).* Earth Surface Processes and Landforms, 23(8), 731-750.

ANDRIANI G.F. & GUERRICCHIO A. (1996) - *Caratteri litostratigrafico-tessiturali e geomeccanici delle rocce affioranti nell'isola di San Nicola (Isole Tremiti).* Geologia Applicata e Idrogeologia, 31, 87-105.

ANDRIANI G.F., WALSH N. & PAGLIARULO R. (2005) -*The influence of the geological setting on the morphogenetic evolution of the Tremiti Archipelago (Apulia, Southeastern Italy).* Natural Hazards and Earth System Sciences, 5, 29-41.

ARGNANI A., BORTOLUZZI G., FAVALI P., FRUGONI F., GASPERINI M., LIGI M., MARANI M., MATTIETTI G. & MELE G. (1994) - *Foreland tectonics in the Southern Adriatic Sea.* Memorie della Società Geologica Italiana, 48, 573-578.

BRANKMAN C.M. & AYDIN A. (2004) - *Uplift and contractional deformation along a segmented strike-slip fault system: the Gargano Promontory, southern Italy.* Journal of Structural Geology, 26, 807-824.

COTECCHIA V. (1999) - *Geotechnical vulnerabilità and geological evolution of the Middle Adriatic coastal environment.* Rivista Italiana di Geotecnica, 33(3), 46- 55.

COTECCHIA V., GUERRICCHIO A. & MELIDORO G. (1995) - *Geologia e processi di demolizione costiera dell'isola di S. Nicola (Tremiti).* Geologia Applicata e Idrogeologia, 30, 491-507.

COTECCHIA V., LOLLINO P. & MASTROMATTEI R. (1998) - *Analisi dei processi demolitori naturali e di taluni interventi mirati alla riduzione del rischio ed al restauro monumentale delle Isole Tremiti*. VI Ciclo di Conferenze di Meccanica ed Ingegneria delle Rocce (MIR), Torino, 145-172.

DELLI MUTI F. (1965) - Le Isole Tremiti. Ed. Marietti, Torino, 367 p.

DOGLIONI C., TROPEANO M., MONGELLI F. & PIERI P. (1996) - *Middle-Late Pleistocene uplift of Puglia: an «anomaly» in the apenninic foreland.* Memorie Società Geologica Italiana, 51, 101-117.

FAVALI P., FUNICIELLO R., MATTIETTI G., MELE G. & SALVINI F. (1993) - *An active margin across the Adriatic Sea (Central Mediterranean Sea).* Tectonophysics, 219, 109-117.

FINETTI I. & DEL BEN A. (2005) - *Crustal tectono-stratigraphic setting of Adriatic Sea from new CROP seismic data.* In: I.R. Finetti (Ed.), «CROP Project, 1 Deep Seismic Exploration of the central Mediterranean and Italy». Atlases in Geosciences, vol. 1, Elsevier, 519-547.

GAMBINI R. & TOZZI M. (1996) - *Tertiary geodynamic evolution of the Southern Adria microplate.* Terra Nova, 8, 593- 602.

KIMBER O.G., ALLISON R.J. & COX N. (1998) - *Mechanisms of failure and slope development in rock masses.* Transaction of the Institute of British Geographers, 23(3), 353-370.

MCCLEDON C.B. (1984) - *The church of S. Maria di Tremiti and its significance for the history of Romanesque architecture.* The Journal of the Society of Architectural Historians, 43(1), 5-19.

MONTONE C. & FUNICIELLO R. (1989) - *Elementi di tettonica trascorrente alle Isole Tremiti (Puglia)* Rendiconti della Società Geologica Italiana, 12, 7-12.

NICOLAI C. & GAMBINI R. (2007) - *Structural architecture of the Adria platform-and-basin system.* In: A. Mazzotti, E. Patacca & P. Scandone (Eds.), «Results of the CROP Project Sub Project CROP-04 Southern Apennines (Italy)». Bollettino della Società Geologica Italiana, Special Issue, 7, 21-37.

RIDENTE D. & TRINCARDI F. (2002) - *Eustatic and tectonic control on deposition and lateral variability of Quaternary regressive sequences in the Adriatic basin (Italy*). Marine Geology, 184, 273-293.

SELLI R. (1971) - *Isole Tremiti e Pianosa*. In: G. Cremonini, C. Elmi & R. Selli (Eds.), «Note Illustrative della Carta Geologica d'Italia, F° 156 San Marco in Lamis». Servizio Geologico d'Italia, Roma, 49-64.

STEPHENSON W.J. & KIRK R.M. (2000) - *Development of shore platforms on Kaikoura Peninsula, South Island, New Zealand II: The role of subaerial weathering*. Geomorphology, 32(1-2), 43-56.

SUNAMURA T. (1978) - *Mechanisms of shore platform formation on the southern coast of the Izu Peninsula*. Japan Journal of Geology, 86(2), 211-222.

SUNAMURA T. (1992) - *Geomorphology of rocky coasts*. Wiley, New York, 302 pp.

SUNAMURA T. (1994) - *Rock control in coastal geomorphic processes*. Transactions, Japanese Geomorphological Union, 15(3), 253-272.

TRENHAILE A.S. (1987) - *The geomorphology of rock coasts*. Oxford Univ. Press, Oxford, 388 pp.

TRENHAILE A.S. (1997) - *Coastal Dynamics and Landforms.* Oxford Univ. Press, Oxford 366 pp.

TRENHAILE A.S. (2008)- *Modelling the role of weathering on shore platform development.* Geomorphology, 94, 24-39.

UDEC 4.0 (2004) - Itasca Consulting Group, Minneapolis (USA).

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