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THE IMPACT OF LANDSLIDES ON THE LANDSCAPE EVOLUTION ON THE ISLAND OF ANDROS

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Abstract: This paper presents the impact of landslide phenomena on the landscape evolution of Andros Island. The morphology of Andros Island highly affected by tectonism (extensional deformation), in combination with the highly weathered metamorphic rocks of the Cycladic metamorphic massif are the two main reasons for the landslide phenomena on the island. These landslides have a specific distribution following the slopes with high angles. They are located in high altitude areas very close to the major tectonic structures, or on the side slopes of highly eroded valleys due to running water action. The results of the fieldwork and terrain analysis showed that the landslides are divided into three distinctive groups, corresponding to their scale and formation conditions. The oldest (1st) group of landslides affects very large parts of mountain slopes that have moved downwards due to driving forces not only connected with the tectonic evolution of the area and the deformation faults, but also with the action of weathering and erosion processes. The geological formation of the slope parts is responsible for the generation of the intermediate (2nd) group of landslides. All landslides included in this group of mass movements are manifest in sites which consist of schists with marble intercalations and marble bodies. These formations are intensively fractured. The youngest (3rd) group includes all the synchronous landside phenomena. Such landslide phenomena which affect linear technical works and urban areas are associated to geomorphologic conditions, climatic regime as well as human activities, and are present in numerous places on the island, mainly during high precipitation periods.

Keywords: Andros Island, Attic-Cycladic massif, landscape, landslides

1. Introduction

The landscape of the Islands in the Cyclades Island complex reflects in many ways the impact of the landslide phenomena due to tectonic evolution, geological setting and recent human construction activity (Varnes, 1978, Koukis-Rozos, 1982, Vlcko, 1982, Koukis, 1988). These characteristic morphological features can be easily distinguished on the hillsides and the valleys of the islands. The moderate slopes of the usually well-drained landscape, the weathering susceptibility of the metamorphic rocks, and the lack of vegetation are the main causal factors of the slope failure phenomena, as those reported in the Cyclades islands (Varnes, 1984, Koukis-Ziourkas, 1991, Koukis et al, 1997). To this end, a thorough examination of landslide phenomena throughout the island was carried out from which three categories became discernible. The oldest one has a very good connection with the landscape evolution of the island, but also helps in the manifestation of the other types of landslides, which contribute in turn to the recent landscape evolution.

2. Location and morphology

The area of interest in this paper is Andros Island, located in the northern region of the Cycladic island complex (the Cyclades) in the center of the Aegean Sea (Fig.1). The island area is approximately 380 km^2, making it the second largest island of the Cyclades. The distance from the Attica Peninsula is 55km and only 11km from Euboea Island. This short distance is the main reason for the geological continuity between the metamorphic rocks in the south of Euboea and the northern part of Andros Island.

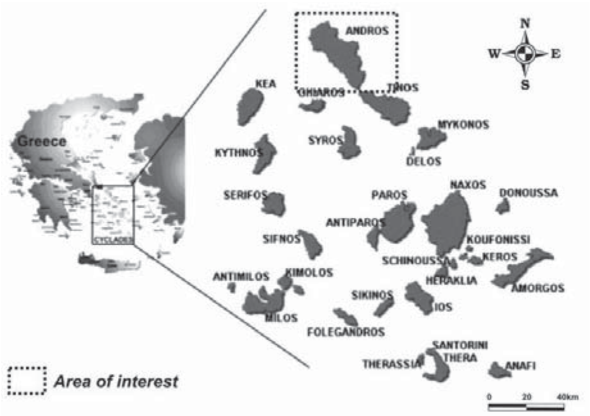


Fig. 1. Location map. Andros Island is situated in the northern part of the Cyclades island complex in the centre of the Aegean Sea.

From a geomorphologic point of view, Andros is a mountainous island with the highest relief situated in the center of the island's longitudinal axis. The highest point is Kouvara peak (994m). The geological basement of the island consisted of metamorphic rocks of the Attic-Cycladic massif. These folded rocks were the initial relief for the fluvial action that shaped the present-day morphology. High denudation rates and channel incision are responsible for the V-shaped valleys with moderate slopes. Also the fluvial action with stream erosion created graded channel profiles.

The drainage network pattern is dendritic in some areas of the northern part while in the southern part it is trellis following the folded topography and tectonic control.

3. Geological Setting – Tectonic regime

The Cyclades Islands – almost a circular alignment of islands around the isle of Delos, a commercial and religious center of Ancient Greece – are located in the center of the Aegean Sea (Fig. 1). They consist of metamorphic rocks which have undergone multiple stages of deformation and metamorphism including high-pressure conditions. This metamorphic rock association is assumed to be part of the crust involved in the Cycladic (Alpine) orogen. The high-pressure metamorphic rocks outcropping on the islands are believed to be the dismembered roots of the mountain belt formed during the Eocene collisional orogenic stage.

After nappe stacking and crust thickening, this orogen experienced collapse due to both gravitational and back arc extensional forces, resulting in crust fragmentation (Lister and Raouzaios, 1996). Exhumation of these rock sequences was the result of simultaneous action of exhumation-erosion, ductile flow and horizontal extension (Brandon and Ring, 1997).

The Attico-Cycladic (as the physical continuation of the Pelagonian) and the Menderes Massif form an arcuate orogen to the north of the present-day active margin which marks the site of the north-eastward subduction of the African plate beneath the Apulian – Anatolian microplate.

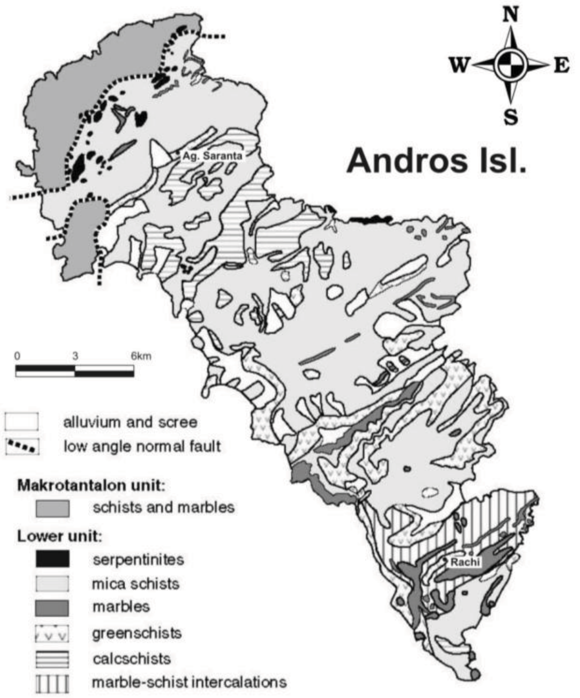
The Cyclades Islands are part of the Attic-Cycladic complex, forging an island belt consisting of multi-metamorphic and deformed crystalline rock culminations, linking continental Greece with Turkey. The complex consists of a stack of tectonic units, which form a nappe pile. The upper nappe contains various intercalated fragments of ophiolites, Permian sedimentary rocks and high temperature metamorphic rocks. In contrast, the lower nappe formations exhibit multiple metamorphic events and consist of a series of thrust sheets containing pre-Alpine basement, Mesozoic marble, metavolcanics and metapelites. The polymetamorphic nature of this lower unit is manifest in: 1) Eocene (~ 42 Ma) high-pressure, blueschist facies metamorphism 2) Oligocene/Miocene (20-25 Ma), normal regional metamorphism and 3) Miocene (14-20 Ma) contact metamorphism associated with the intrusion of I-type granitic rocks (Schliestedt et al., 1987; Altherr et.al., 1979). In this complex, Andros together with Tinos forms the geological and morphological continuation of south-eastern Euboea towards the southeast.

More analytically, on Andros two tectonic units are distinguished (Papanikolaou, 1978). The structurally higher Makrotantalon unit has a thickness of up to 600m and mainly consists of clastic metasediments and marbles while metabasic schists are of subordinate importance (Fig. 2). Fossil findings in the dolomitic carbonates yielded Permian ages (Papanikolaou, 1978).

The tectonic boundary with the lower unit is roughly marked by serpentinites (Fig. 2). Papanikolaou (1978) related tectonic juxtaposition of the two units to thrusting, whereas Durr (1986), Avigad and Garfunkel (1991) and Avigad et al. (1997) suggested that the tectonic contact is a low-angle normal fault related to large-scale extension and exhumation processes.

The lower unit is up to 1200m thick and mainly consists of a volcano-sedimentary sequence that

Fig. 2. A simplified geological map of Andros Island



(after Papanikolaou, 1978; Mukhin, 1996, modified from Brocker and Franz, 2006).

comprises marbles, carbonate-rich schists, clastic metasediments and metabasic rocks (Papanikolaou, 1978). Ferromanganoan metasediments are locally intercalated with metapelitic schists (Reinecke et al., 1985). The complete succession can be subdivided by means of four distinct marble horizons and three prominent green schist layers (Papanikolaou, 1978). Disrupted bodies of meta-ultramafic, meta-gabbroic and meta-acidic rocks (up to several hundred meters in length) are recognized at various stratigraphic levels and are interpreted as olistoliths of metaolistostromes (Papanikolaou, 1978; Mukhin, 1996).

The dominating tectonic feature in the rock formations is a penetrative schistosity associated with isoclinic folding, with axes trending NE-SW. (Jacobshagen, 1986). Additionally younger folds with E-W orientation (80-120) and - as in South Euboea-knickfolds with NNW-SSE are well documented throughout the island.

The main tectonic structure shaping the relief of Andros is an extensional fault on the western side of the island. This active normal fault has a clear spatial association with short, steep footwall drainage basins. Thus this kind of drainage basin asymmetry, responding to differences in the activity of range-bounding faults is very common in the Aegean Sea (Leeder and Jackson, 1993). Because of the nearly linear character of many normal faults and quite readily predictable pattern of subsidence and uplift associated with them (King and Ellis, 1990; King et al., 1988), it is reasonable to develop a conceptual scheme for drainage basins in extensional terrains like Andros Island.

The extensional fault of the west side of Andros (Fig. 3) creates a half-graben with asymmetric footwall uplift. The back-tilted block has long, relatively gentle basins in the eastern part of the is-

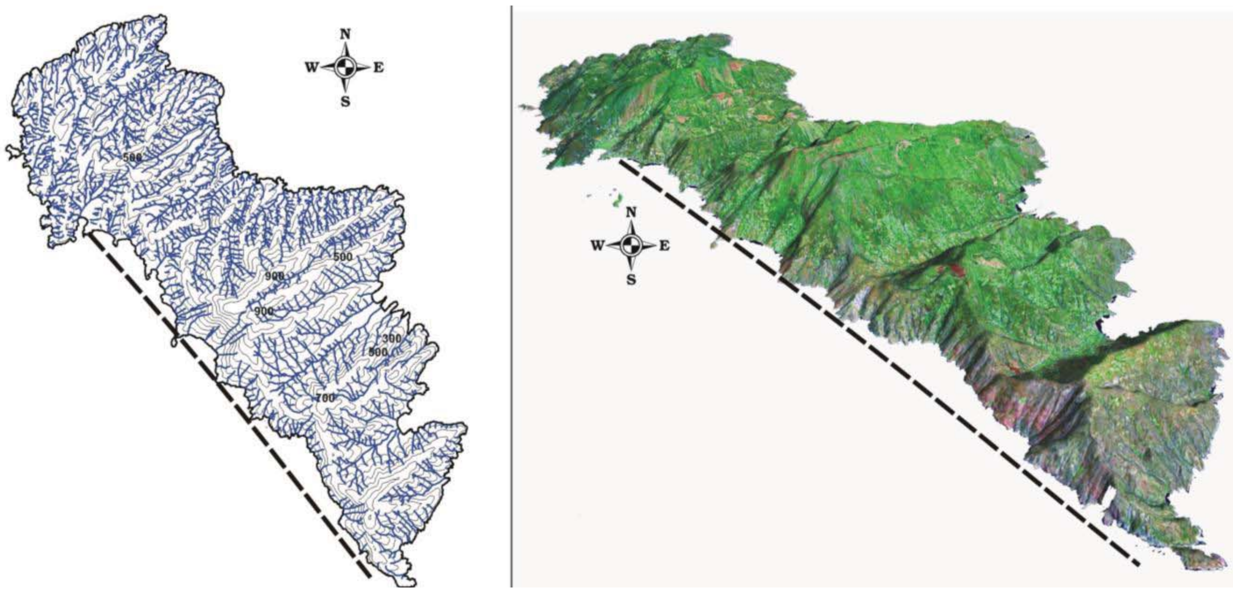


Fig. 3. A view of Andros Island, whose main normal fault causes the submersion of the south-western part of the island landmass. The main axes of the hydrographical basins with a southwest to northeast direction are also developed, mainly in the central division of the island.

land, while the fault scarp is responsible for the very short drainage and steep wall tectonic western coastline (Fig. 3). This major NW-SE tectonic structure is responsible for the morphological control of three quarters of the island's surface and the drainage network evolution.

According to the morphological criteria proposed by Leeder and Jackson (1993), the range-bounding normal fault is an important morphotectonic feature affecting the landscape evolution of the island. Evidence of the high rate of the fault's relative activity is the small - short size and steepness of the basins created. At the same time, the study of the drainage network evolution on the backtilted block surface showed that the initial network followed a respectively initial terrain, created by the folding tectonics that shaped the synclines and anticlines of the island, and formed synclinal (southern part) an anticlinal (central part) valleys on the island.

Network evolution is controlled by fault tectonics in many areas. This tectonic action is owed to a newer extensional tectonic regime forming normal faults with a WSW-ENE orientation (Mercier et al., 1989; Gautier and Brun, 1994). The drainage network evolution is controlled by phenomena like stream piracy and relief inversion.

4. Methodology of the study

Landscape geomorphologic analysis of the island was carried out with the use of the GIS software (MapInfo & Vertical Mapper 3.1). For the terrain analysis a SRTM DEM was used. The SRTM DEM data have been produced using radar images gathered from NASA's shuttle, released in 2003 (Jarvis et al., 2004). SRTM DEM in most cases is more accurate than the 1:50,000 scale cartographically derived (TOPO) DEM, as shown by comparison with field-based measurement of GPS points (Jarvis et al., 2004).

For this study a combination of the SRTM with data from the topographic maps from the Hellenic Military Geographical Service (HMGS), at a scale of 1:50,000, led to a very detailed DEM compilation. The 20m cell size of the DEM was satisfying

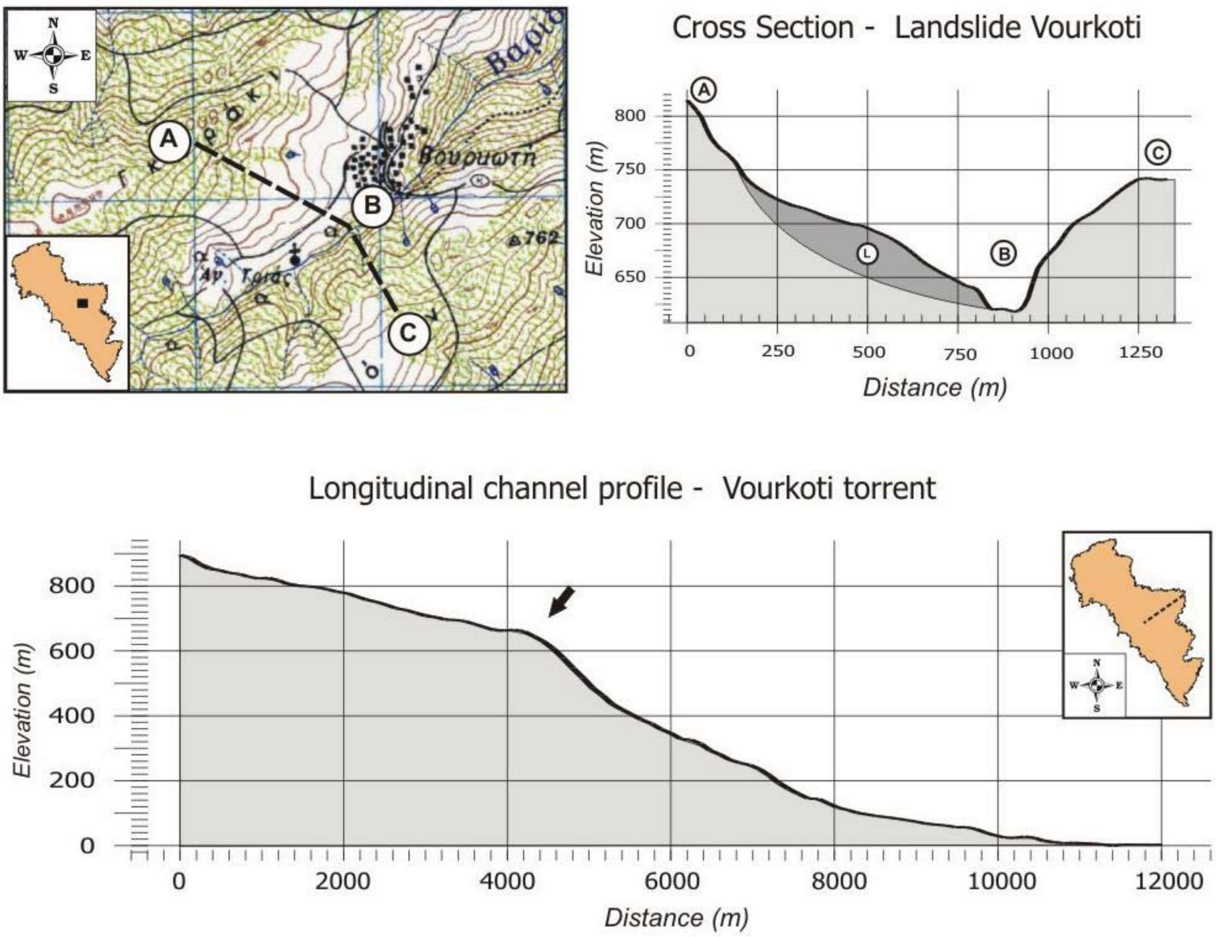


Fig. 4. Cross-section and longitudinal profile of Vourkoti torrent, where an old landslide is manifest.

for the determination of the specific geomorphic features created from landslide phenomena on the island's landscape. The use of the detailed elevation model (DEM) in connection with the derivative data from the GIS analysis (slope map in Fig. 5) led to the determination of the areas with high susceptibility on slope failures.

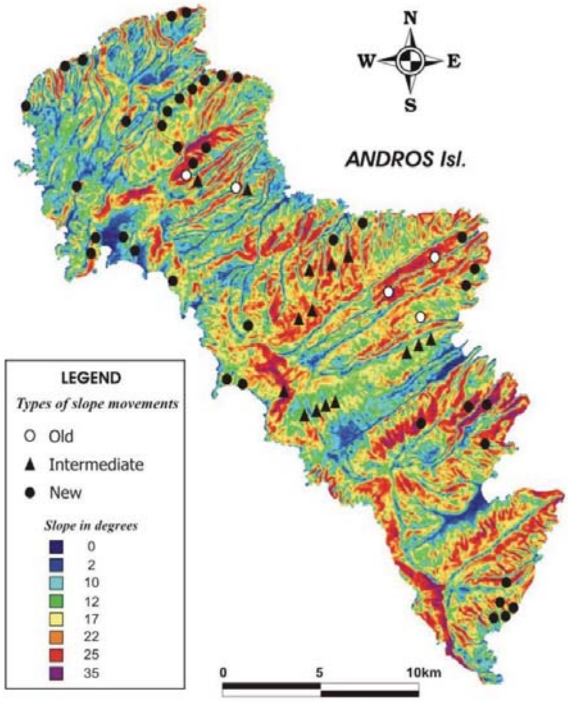


Fig. 5. The distinction and distribution of the three landslide groups on Andros.

The study of the island's morphology preceded the fieldwork. Thus, in the GIS environment, not only the high-risk areas but also the exact locations of the older landslides shaping the island's relief were determined. The scale of these landslide phenomena was medium to large. Finally, all the landslide locations were confirmed in the field.

Also, the drainage network of Andros Island was recorded and the drainage network pattern was estimated. To this end, maps with a scale of 1:50,000 from the HMGS were used. Usually, the drainage network evolution was favoured by the solid rocks of the metamorphic bedrock because of the high rates of the fluvial runoff. In many cases the slope failures are related with and very often accelerated by the fluvial erosion of the streams and the channel incision.

Finally, the GIS database of Andros Island was completed with the creation of the geological background map of the island (Fig 2), by reducing the number of lithological units into classes with similar properties for better results (Jurko et.al. 2005).

In order to shed light on the impact of the landslide phenomena on the landscape evolution of Andros, the detailed recording and study of slope movements, manifest in the various geotectonic unities of the island, were specified. All slope movements encountered were recorded on a map of proper scale and after relevant study, time of manifestation, the causes and triggering factors were determined.

On the base of the above study, the classification of the landslide phenomena into three groups, according to their manifestation and to their degree of influence on landscape evolution, was possible. The first class includes the old landslides, which are closely related to the island's tectonic action, influence big rock masses and are mainly responsible for the changes of the morphological relief. The second class includes the landslides located inside the disturbed rock masses of chaotic structure, resulting from the abovementioned old landslides. New unstable zones were created which caused a ladder-like slope formation and which are reactivated according to the action of triggering factors. This group of landslides includes slope movements that are active even now, contributing to the general evolution of the morphological relief. Finally, the synchronous landslide phenomena are of small extension, which influence landscape evolution only locally.

5. Landslide Phenomena

As focus turned on the landslide phenomena on Andros, meticulous examination throughout the island revealed that these phenomena could be grouped into three time-dependent categories:

5.1. The oldest class of landslides affects very large parts of mountain slopes that have moved downwards due to driving forces connected with the tectonic evolution of the area and the deformation faults, as well as the action of weathering and erosion processes.

The large fault shaping the western regions of Andros caused the submersion of the south-western part of the island (Fig. 3), while the remainder of the island tilted in the same direction. Thus, the erosion in the dominating hydrographic axes with a southwest to northeast direction became more intensive. These axes are joined to a fault set of SW-NE direction, i.e. along the main folded axes that dominate the island. Thus, this set of faults dominates Andros and also helps in turn in the formation of new watercourses in some cases, during the period of the rapid erosion which are sub-parallel to older ones.

The aforementioned tectonic evolution and subsequent rapid weathering and erosion processes have resulted in the appearance of large slope movements, which constitute the island's oldest landslide phenomena. These slope movements mainly developed with their crown along fault lines that belong to the SW-NE set of faults previously mentioned. These movements affected the evolution of the main hydrographical axes, as they blocked certain parts of them. Thus, basins were created behind the blocked parts, where deposition of water transporting soil materials took place, and perhaps pods or small lakes were formed, until the water found new outlets, namely until the complete coverage of the depression and the creation of flat plains. Thus, a peculiar profile from steep to flat and again to steep was formed in most of the centrally located valleys of the island (Fig. 4).

The old landslide in the Vourkoti torrent (Photo 1) is a characteristic example of such phenomena. The part of the valley that is in the form of a small plain can be seen in the lower left-hand side of photo 2a, while before and next to it, the course of the current is much steeper (Photo 2). These phenomena are frequent in the central part of the island, as this part has been mainly affected by the previously described geomorphologic evolution.

Photo 1. The foot of Vourkoti slide (photo looking upstream).

The existence of the overthrust of the Macrotantalon formations on the Agioi Saranta schist formations in the northern part of the island, and the alterations of Raxis marble and schists in the south, which are hard rocky formations (calcitic schists, marbles, amphibolites etc), assists in the creation of hydrographical axes running mainly from north to south or south to north directions, which restricted the manifestation of the above described oldest landslide phenomena on the slopes of those parts.

5.2. The second class of landslides

The geological formation of the slope parts affected by the historical landslides, which consist of schists with marble intercalations and marble bodies, was intensively fractured. This, correlated to the rainwater action (Koukis et al., 1997), groundwater regime, as well as continuous erosion and weathering processes, gave room to the creation of new slope failures in the zone of the previously displaced and disturbed parts of slopes.

As the groundwater regime underwent changes in its courses due to the continuing landscape evolution, some of those places became dry, while in others the groundwater increased in quantity and was discharged in the form of continuous springs. Thus, the secondary factors affecting the slope failures in the first ones, such as groundwater movement and fluctuations, its additional load as well as the high pore water pressure, were eliminated, and the landslides were ''petrified'' as those in the northern slope of the Petalon Mountain, namely between the villages of Vourkoti and Arni (Photo 3).

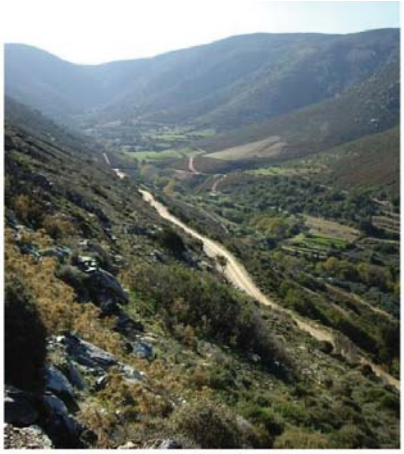
By contrast, in the sites where the groundwater level rose, the landslides of the second group became more intensive, resulting in active landslides present to this day. The most characteristic example of such slope movements are the landslides in the slopes between the villages of Apoikia and Stenies. In that zone of older landslides, the existence of Sariza Springs with high groundwater discharge intensifies the action of the factors affecting younger landslide manifestation (Photo 4).

These new slope failures increase the looseness and disturbance of the geological formations and so the rock mass displaces a chaotic form in the whole zone of slopes from Apoikia to Stenies (Photo 5).

5.3. The synchronous landside phenomena

These landslide phenomena, which affect linear technical works and urban areas, are connected with geomorphologic conditions, climatic regime as well as human activities, and are present in many places around the island, mainly during high precipitation periods.

(a)



(b)

Photo 2. Vourkoti hydrographical axis in the central part of the island. A close view of the displaced part of the slope is shown in photo (a), while the change in the inclination of the current due to an old massive landslide is obvious in photo (b).

Photo 3. View of ''petrified'' younger landslide, on a slope in the central part of the island.

Small rotational slides are the main types of such slope movements (Photo 6). They manifest in natural or artificial slopes that are covered by rather thick weathering mantle, the remolded materials which locally cause the temporary obstruction of traffic (Photo 7).

Sometimes these landslides are more serious as the weathering mantle is thicker and the slope steeper. In these cases, the effects on construction are severe and remedial measures very expensive (Photo 8 & 9).

Another such type of failure is the earth or debris flows, the presence of which is mainly evident in periods of high precipitation. They are flows of weathering materials that are completely saturated due to heavy rainwater, as this water decreases

Photo 4. A general view of Apoikia village, where Sariza Springs exist. In the slope parts above and in the village area, landslide is manifest.

their shear resistance and increases their load. The downward movement of these materials, mainly along hydrographic axes, causes the obstruction of the main road axes and damages their protective walls at locations where the road crosses their course (Photo 10).

Photo 5. The chaotic type of disturbed geological formations.

Photo 6. Rotational slide in weathering mantle of schist formations.

Rock falls and rockslides are also another type of synchronous landsides that are manifested in steep rock slopes. A good example of this type is the slope failure in Aprovatou village (Photo 11) where the tectonic action has favoured high fracture of the rock mass. Finally, the wave erosion undercut the slopes in certain coastal areas where the formations are fractured by the tectonic, causing slab slides or rock falls (Photo 12).

6. Landscape evolution – Discussion

The interpretation of the DEM shows that the elevations of Andros Island range between 0m and 995m a.s.l. Also, the average elevation of the study area is 272 m a.s.l. According to Dikau's (1989) elevation classification, 58.7% of the island's area ranges between 150-600m, while 32.7% is lower than 150m, and 8.6% greater than 600m. In this hilly to mountainous terrain the most frequent slope values ranging from 15^0 – 30^0 cover 54.1% of the island, while the slope values ranging from 5^0 - 15^0 cover 39.8% of the area (Fig. 5). The slope values of 15^0 – 30^0 indicate a highly inclined relief where high weathering processes in combination with mass wasting phenomena like landslides or mudflows (Demek, 1972) occur. In addition, the fluvial erosion creates a linear and elongated drainage network, and forms V-shaped valleys due to high incision rates.

Photo 7. Rotational slide in weathering mantle of schist formations, with marble intercalations, affecting a road axis.

Photo 8. Destruction of a road and small church located downslope, near the village of Kochilou.

The detailed mapping of the Andros landslide phenomena showed that in an area of 380 km^2 more than 50 landslide locations were confirmed in the field (Fig. 5). If we accept the continuity of the geological formations (metamorphic rocks), the landslide phenomena are highly related to the relief inclination. The comparison between the landslide locations and the relief inclination showed that 80% of the mass movements occurred on a relief with slope values ranging from 15^0 to 30^0.

Photo 9. Severe damages of a villa built downslope from the road connecting the villages of Batsi and Gavrion. The cast in situ piles for the protection of the road pavement are also distinguished.

The thorough examination of landslide phenomena throughout Andros Island led to their distinction in three groups: the oldest, the intermediate and the synchronous group of landslides (Fig.5). Also, a very close influence of the landslides that belong to the oldest group and partly to the intermediate one on the landscape evolution is revealed, while the new landslides are mainly evident in recent formations such as weathering mantle and their upper fractured zone, and they mainly affect recent human construction activities.

So, the oldest and intermediate slope movements influence the geological formations of the two tectonic units (lower and upper), from which Andros Island is built, i.e. schists, marbles and serpentinites. These rock formations are fractured, as already mentioned, by two main sets of major faults. The main tectonic feature that caused the submersion of the south-western part of the island and a tilt of the rest (existing part) belongs to a NW-SE set, while the faults from the set with NE – SW direction are the initial pattern for channel incision and valley formation.

The oldest landslide phenomena, that have caused the downward movement of huge rock masses, have mainly been discernible along the faults of the NE – SW set. The slope movements have also resulted in intensive fracturing of the displaced rock masses, which now show a chaotic structure. Moreover, the displaced rock masses have blocked the courses of the relevant hydrographic axes, interrupted the erosion processes and created small

(a) (b)

Photo 10. Obstruction of road pavement (a) and destruction of its protective wall (b), near the Kipri village.

Photo 11. Rock falls and rock slide in the Aprovatou village area.

lakes in which all the erosion materials from the upper part of the torrents became concentrated. The final products were small flat areas in certain places of the main hydrographic axes, with a W-E direction (Fig. 4).

Photo 12. Rock falls and slab slide due to wave erosion, in a northern coast of the island.

In a next stage, the intensive fractured rock masses with a chaotic structure helped in the materialization of the intermediate type of landslides, which contribute in turn in the recent landscape evolution. These loose and disturbed rock masses were very sensitive to landslide triggering factors, such as groundwater (additional load, high pore water pressure, etc). Thus, large slope movements were triggered inside those masses, creating ladder-like landscapes, some sites of which are now the founding ground of main villages, because of water existence in the form of springs and the gentle inclination of the slopes (Photo 4). In some of these sites, a number of landslides are periodically reactive, causing severe problems to residential areas, while in others they are ''petrified'' as the landscape evolution has caused changes in groundwater courses (Photo 3).

Finally, the synchronous landslides are manifest during intensive weathering phenomena in slopes covered by rather thick weathering mantle and/or scree. These slope movements have a rather small impact on the landscape evolution.

7. Concluding remarks

Referring to the above examinations, discussions, and mainly to the results of the landscape geomorphologic analysis, it is obvious that there is a close connection between landslide phenomena and landscape evolution on Andros Island, a member of the Cycladic island complex, through geological time.

At the beginning, the exact locations of the high-risk areas and the older landslides in the GIS environment, and finally their confirmation in the field, led to the differentiation of the landslide phenomena into three groups and revealed their degree of influence on landscape evolution.

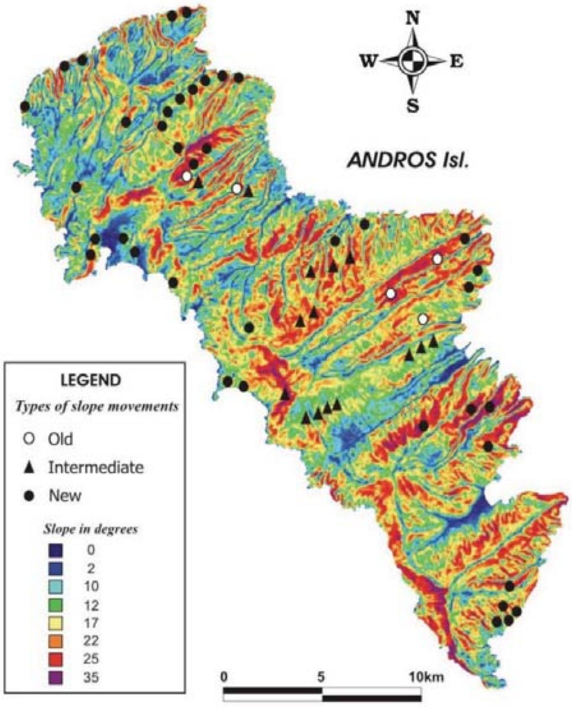


Fig. 5. The distinction and distribution of the three landslide groups on Andros.

The oldest slope movement group, directly connected to the tectonic evolution of the island, is responsible for serious changes in its morphological relief, but also help by formatting disturbed rock masses with chaotic structure and unstable conditions and the manifestation of the second group of slope movements. The latter, some of which are in action even now, are responsible for a ladder-like slope formation, contributing to the synchronous morphological relief of the island. The third group, mainly connected with geomorphologic conditions, climatic regime and human activities, are evident during high precipitation periods. This group causes only restricted changes in the landscape of the island, but usually affect technical works.

Concluding, the apparent close connection of the landslide phenomena with the landscape evolution on this island, which is a characteristic example of the geological and morphological evolution of the Aegean area, can be a valuable tool for the local authorities not only of this island but also for proper land use and good planning of technical works.

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