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PLIO-PLEISTOCENIC EVOLUTION OF RIO MANNU DI MORES VALLEY (LOGUDORO, NORTHERN SARDINIA) (**)

ABSTRACT: SIAS S., *Plio-pleistocenic evolution of Rio Mannu di Mores valley (Logudoro, northern Sardinia).* (IT ISSN 0391-9838, 2002).

This work is part of the research activity carried out on the territory of Logudoro-Mejlogu and its aim is to study the changes in the drainage pattern induced by Plio-Pleistocene volcanic activity. The general trend of this area shows clear tectonic control by geomorphic processes of the size of the Mores-Chilivani plain, which is overestimated with respect to the watercourse that crosses it. This condition is the result of a vast erosive action of denudation of the pre-Miocene basin, fossilised by marine sediments.

On the basis of the acquired data, the evolution of the of the Mannu di Mores river valley should be referred to the early phases of formation of a runoff system, probably in the Upper Messinian-Lower Pliocene. Phases of vertical erosion by Rio Mannu di Mores during the Upper Pliocene-Lower Pleistocene (Villafranchian) are assumed to be a result of uplifting movements, which are clear in the relief inversion of the Pliocenic lava flows dated 2-1.8 M.y.b.p. and in the gravity deformations along the tectonic faults. Alternate phases of linear and lateral erosion have led to the recession of the carbonaceous banks to the west and the exhumation of the volcano-cineritic plane. This structural plane should be considered partly degraded by the water system, whose candlestick geometry shows a selective process induced by a pomiceus-cineritic substrate. Nevertheless, effusive events that have caused stretches of the watercourse to fossilise have affected its dynamics significantly.

This intense extensional phase seems to end in Middle Pleistocene (0.8 M.y.b.p.) since the lava flows referred to this age show a poor relief inversion (0-40 metres), which is also observed in other parts of Logudoro.

From the reconstruction of the evolutionary events, it emerges that in the last few million years the land was affected by a prevalent erosive morphogenesis, which manifested itself in an extended denudation process with the exhumation of Pre-Miocene forms. Through morphochronological correlation (based on absolute dating) with the surfaces buried under the basalt lava flows, a different morphodynamic control of the erosive processes emerged. An important erosive phase due to an uplifting of the territory, which caused important changes from the Upper Pliocene-Villafranchian onwards, is attributable to an initial stage of tectonic control. A prevalent modelling of the slopes into terraced surfaces is attributable to a second stage of palaeoclimatic control. The morphoclimatic action on the modelling of the slopes found its greatest expression during the Upper Pleistocene and the Holocene. This work led to the compilation of a geomorphological map of the area on a 1:25.000 scale, so far lacking, and to the definition of detailed geomorphological features in an area of Logudoro. The most significant results are the recognition of deep gravity deformations and the landslide survey which can be related to one morphoevolutionary event linked with Plio-Pleistocene neo-tectonics.

KEY WORDS: Geomorphology, Runoff, Plio-Quaternary, Sardinia, Italy.

RIASSUNTO: SIAS S., *Evoluzione Plio-pleistocenica della valle del Rio Mannu di Mores (Logudoro, Sardegna settentrionale).* (IT ISSN 0391-9838, 2002).

Il presente lavoro s'inserisce nell'ambito dell'attività di ricerca sul territorio del Logudoro-Mejlogu, finalizzata allo studio delle modificazioni del reticolo idrografico indotte dall'attività vulcanica plio-pleistocenica. L'impostazione generale di quest'area mostra un evidente controllo tettonico dei processi geomorfici della piana di Mores-Chilivani che è sovra-adattata rispetto alle dimensioni del corso d'acqua che l'attraversa. Tale condizione è il risultato di una vasta azione erosiva di denudazione del bacino pre-miocenico, già fossilizzato dai sedimenti marini.

I dati acquisiti, indicano globalmente che l'evoluzione della valle del Rio Mannu di Mores è riferibile all'intervallo Pliocene superiore-Pleistocene inferiore (Villafranchiano) a seguito di movimenti di sollevamento che hanno prodotto un'importante fase di denudazione in tutto il Logudoro. Questa fase erosiva si è manifestata per un periodo relativamente breve ma con intensità, generando un'imponente inversione delle colate vulcaniche. Alcuni di questi, quali il M. Pelao, sono interessati da deformazioni gravitative. Il processo di denudazione mostra che fasi d'erosione lineare si sono alternate a fasi d'erosione laterale: il risultato è l'arretramento verso occidente delle bancate carbonatiche e la riesumazione della superficie vulcano-cineritica. Tale superficie strutturale è comunque da considerare degradata dal sistema idrico. La sua geometria a candelabro evidenzia un processo selettivo indotto dalla caratteristiche petrografico-giaciturali del substrato, anche se sulla dinamica del corso d'acqua hanno influito, in maniera significativa, eventi effusivi che hanno portato alla fossilizzazione di tratti del corsi d'acqua.

Quest'intensa fase erosionale sembrerebbe chiudersi nel Pleistocene medio (0.8 M.a.), giacché le colate riferibili a quest'età presentano scarsa inversione del rilievo (0-40 m).

In conclusione, dalla ricostruzione delle fasi evolutive emerge che, negli ultimi milioni di anni, il territorio è stato oggetto di una prevalente morfogenesi erosiva manifestatasi in un ampio processo di denudazione

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con riesumazione di forme pre-mioceniche. L'azione erosiva si sarebbe manifestata, in un primo stadio a controllo tettonico, dal Pliocene superiore-Villafranchiano, con profondi cambiamenti nel paesaggio pliocenico, ed, in un secondo stadio, a controllo paleoclimatico caratterizzato da una prevalente azione di modellamento dei versanti. L'azione morfoclimatica di modellamento dei versanti avrebbe avuto la sua massima espressione durante il Pleistocene superiore e l'Olocene. Il lavoro ha permesso la realizzazione di una carta geomorfologica in scala 1:25.000, in una area priva di tale cartografia, e di definire nel dettaglio i caratteri geomorfologici di questa parte del Logudoro. I risultati più significativi si sono ottenuti con l'individuazione di deformazioni gravitative e movimenti di frana collegati agli eventi morfoevolutivi dell'area e ai movimenti della neotettonica plio-pleistocenica.

TERMINI CHIAVE: Geomorfologia, Evoluzione del paesaggio, Idrografia, Logudoro, Sardegna.

GENERAL FEATURES

Referring to the cartography of the Servizio Geologico Nazionale, the study area is included in Sheet 193 «Bonorva» of the Carta Geologica d'Italia (Geological Map of Italy) on a 1:100,000 scale; represented in Sheet 480 I «Mores» of the Istituto Geografico Militare on a 1:25,000 scale, while the Cartografia Tecnica Regionale (CTR) (Regional Technical Cartography) is represented in section no. 480030 on a scale of 1:5000.

The Mores-Chilivani valley develops in a NNE direction to include the relief of Punta Sordanu 710 m a.s.l. and M. Zuighe 410 m a.s.l., situated to the east along the buttresses of the Goceano range, and the carbonaceous ridge to the west, whose highest altitude is M. Lachesos at 546 m a.s.l.. In detail, the Goceano ridge, which extends in a NNE-SSW direction, with the highest peak being M. Rasu at 1,258 m a.s.l., proceeds northwards with the Alà dei Sardi mountains on the granitic basement, and southwards with the Marghine range (fig. 1).

The Marghine-Goceano range represents the horst of Ottana and Chilivani-Berchidda halfgrabens, (Carmignani & *alii*, 1994), formed during the Oligocene-Aquitanian as a result of the early translational phases of the Sardinia-Corsica block. The ENE and NNW orientations represent the main tectonic lineaments of the Tertiary of the entire island.

The study area is part of the Coghinas catchment basin, which is the main river of northern Sardinia both in terms of flow rate and extension. This, as is common in the culture of the island, has led to a fragmentation of the name Rio Mannu according to the different places it crosses, in this case «*di Mores*». The source of Rio Mannu is in M. Traessu, at altitudes of about 700-650 metres a.s.l., with 1st and 2nd order tributaries, which cut deep furrows along volcano cineritic slopes with acclivity values of about 35-45%. Rio Mannu crosses the Campu Giavesu plain, a volcanic barrage plain (Sias, 1994, 1997), with some meanders active in the event of abundant precipitation.

Beyond the threshold of the barrage through the opening of an artificial channel, the river flows into the Torralba plain, where it takes on a winding course caused by the basalt flows that fossilised the riverbed in different episodes, forcing the watercourse to change direction continuously. On the plain it receives the Rio Tortu on the hydrographic right, and, on the left, the Rio S. Lucia from the western slope of the Campeda basaltic plateau (700 m a.s.l.), and the Rio Badde Pedrosu from the slope of the Pranu Mannu plateau (about 700 m a.s.l.). The watercourse flows into the Mores-Chilivani plain after crossing a small valley, cut out at the contact between the M. Cujaru flow and Tertiary volcanites. On the Mores-Chilivani plain, it receives the Rio Pizzinnu from the left and from the right the Rio S'Abba Salida, which flows along a deep structural valley. A second tributary flows into Rio Mannu at about the same position as Rio S'Abba Salida: i.e. Rio Adisu dei Padri, which has undergone an evident regressive process on its own alluvium. Beyond the Mores-Chilivani plain, the Rio Mannu proceeds northwards among the granitic reliefs of Gallura and the Tertiary volcanites of the palaeo-horst of Anglona; after the narrow ravine of Casteldoria it flows into the Coghinas plain and then about 100 km to its mouth in the Gulf of Asinara.

PREVIOUS STUDIES

The studies on Logudoro have been mainly on geopetrographic themes related to the finding of Tertiary and Quaternary volcanic series (Federici, 1985; Beccaluva & *alii*, 1976, 1977, 1981, 1983), which led to the construction of a geopetrographic map of Logudoro-Mejlogu on a 1:50,000 scale. Sedimentological-stratigraphic (Pecorini 1968; Pecorini & *alii*, 1988; Cherchi & *alii*, 1982, 1984) and palaeontologic (Pomesano Cherchi, 1971) studies defined the geological stratigraphic framework relating to Miocenic cover that ends the series with Lower Messinian marine deposits that are found under the M. Santo flow. Other investigations concerned the sedimentary succession of the Miocene and the geological-structural layout of the Logudoro (Assorgia & *alii*, 1988; and Martini & *alii*, 1992).

Geomorphologic studies of the area mainly concern the analysis of the morphoclimatic and slope gravity processes (Federici & Ginesu, 1991, 1994; Ginesu, 1990, 1991; Ginesu & Mereu, 1991; Ginesu & Cossu, 1992; Ginesu & Sias, 1993, 1997) which stressed the role of climatic changes in the evolution of the north Sardinian landscape and of gravity phenomena in the evolution of the slopes, while determining important deep deformational structures (D.G.P.V.) in Logudoro-Anglona. Subsequent investigations have led to a chronological classification of morphoclimatic processes (Ginesu, 1991; Marini, 1983), which attributed the terraced areas along the Coloru flow to three different arid-cold stages. The study of the S. Michele deposit (Ginesu & Melis, 1991; Melis & Sias, 1996) showed the existence of three erosive and depositional phases referable to climatic changes, between 500 thousand and 140 thousand years ago, as a function of dated basaltic lava flows. These palaeoclimatic phases were confirmed in the study on the erosive terraces of Rio Funtana Ide (Sias, 1998).

A first geomorphologic and evolutionary interpretation of Logudoro-Mejlogu was proposed with the reconstruction of the palaeo-hydrography buried under Plio-Pleisto-

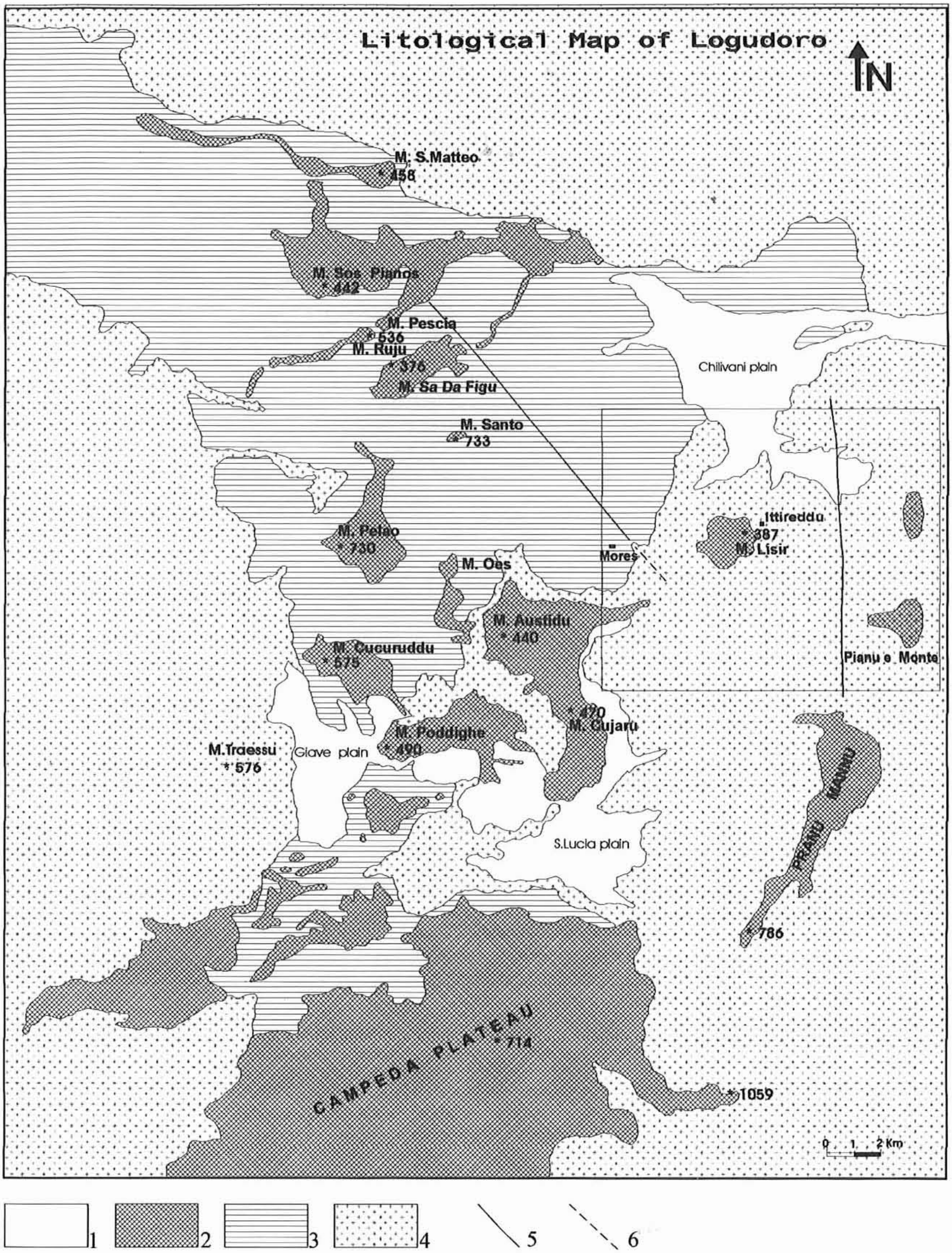


FIG. 1 - Litological sketch map of Logudoro and localization of the study area. 1) Pleistocenic sediments; 2) Plio-Quaternary lava flow; 3) Miocenic sediments; 4) Oligo-miocenic piroclastic deposits; 5) certain fault; 6) probably fault.

cene effusive activity (Sias, 1996; Ginesu & Sias, 1998). Buried and suspended areas, relics of a palaeolandscape referable to the Upper Pliocene, indicate evolutionary stages with reference to the age of the basalt flows.

The aim of this work is to make a further contribution to the knowledge of Logudoro, while focussing on limited areas of the area in order to identify better the processes and forms characterized by the geomorphological aspects that are peculiar to the area. This work also intends to make a contribution to geomorphological cartography, which is totally lacking in this sector of the island.

GEOLOGICAL PICTURE

The structural situation of this area is quite complex as a result of the presence of, and conditioning due to, the formation of sedimentary basins of the Tertiary in a NE-SW direction of Alpine age. They are faults genetically related to the distensive phases, which involved the island from the Upper Oligocene to Lower-Middle Miocene (Carmignani & *alii*, 1994; Cherchi & Montadert, 1982; Lecca & *alii*, 1997), with a revival in the Plio-Lower Pleistocene, related in general to the geodynamic evolution of the western Mediterranean (Cherchi & *alii*, 1978; Marini & Murru, 1983).

The study area shows the transition through two important successions: i.e. the effusive volcanic-pyroclastic cycle of the Oligo-Miocene, and the sedimentary succession of a continental and marine environment of the Middle-Lower Miocene, represented by calcareous-marly and conglomeratic-arenaceous deposits. Most of the area studied is in the middle of two important sedimentary basins: i.e. the Chilivani-Berchidda basin of Aquitanian-Lower Burdingalian age, in an ENE direction, and the Logudoro fossa of the Middle-Upper Burdigalian (Martini & *alii*, 1992; Oggiano & *alii*, 1995) with a NNW orientation (fig. 1). The area has undergone considerable subsidence and is a part of the Sardinia-Corsica rift of Oligo-Miocene age (Assorgia & *alii*, 1988). The synsedimentary basin of Chilivani-Berchidda is a tectonic depression affected by a number of ENE and NNE oriented faults (the Olbia and Tavolara fault) that cross the Hercynian batholith of Gallura.

The study sector is affected by outcroppings of the Oligo-Miocene «calcalkaline» volcanic succession (K/Ar dating between 22 and 13 M.y.b.p.) represented by the lower and upper ignimbritic series made up of variously-cemented pumiceous-cineritic pyroclastic flows (Lecca & *alii*, 1997), with intercalations of arenaceous-cineritic deposits of lacustrine and fluvio-deltaic environment. It outcrops mainly in the eastern sector of the map, near to Palaeozoic relief forms made up of schists and granites of the ridge of Goceano. This gives rise to a monoclinal structure marked by selective erosion with the formation of homoclinal valleys.

Marine sedimentary formation is represented by transgressive arenaceo-conglomeratic sequences of a fluvio-deltaic environment, marls and marly-limestones, and involves extensively the left slope of the Rio Mannu di Mores valley. The transition from the volcano-cineritic succession is represented by deposits that fill the rift in deltaic facies, made up of sandstones, coarse sands, and fluvio-deltaic conglomerates with elements of the Palaeozoic and of Tertiary volcanites. In the upper part there are levels of biocalcarenites, fossiliferous limestones and marls (Assorgia A. & *alii*, 1988).

The Plio-Pleistocene outcroppings are represented by lava flows and cones of detritus of a mainly alkaline nature: alkaline basalts, trachybasalts and subalkaline basalts (Campeda, Pranu Mannu) to a lesser extent (Beccaluva & *alii*, 1981). The Pliocene lava flows (Pianu and Monte, N. ghe Pianu and Pedres, and M. Cordianu) are distinct from those of the Pleistocene due to their greater extension and the N-S alignment of the emission centres. The recent lava emissions, M. Cujaru (0.8 M.y.b.p.), M. Austidu (0.4 M.y.b.p.), and M. Lisir (0.2 M.y.b.p.), whose absolute datings were carried out using the K/Ar method (Beccaluva & *alii*, 1977), are made up of cones of detritus associated with lava flows. The alignment of the effusion centres shows the reactivation of pre-existing fracture systems in a NE-SW and N-S direction in the Plio-Quaternary (Beccaluva & *alii*, 1976).

The recent formations are made up of alluvial deposits of Rio Mannu di Mores and of colluvial deposits that prevail in the lower part of the valley of Mores-Chilivani.

GEOMORPHOLOGICAL PICTURE

The valley of Rio Mannu di Mores is a part of the large denudation basin that includes the Chilivani plain in the north and the Giave-S. Lucia plain in the south. The westward recession of the carbonaceous banks is due to a process of lateral erosion alternating with phases of vertical incision by the watercourse; this erosional activity is controlled by a selective process on the Tertiary volcanic basement.

The right slope of the valley corresponds to a monoclinal structure of lithologies linked to the oligo-miocenic volcanic succession (variously-cemented pumiceo-cineritic ignimbrites) made evident by selective erosion with the formation of homoclinal valleys, crossed by watercourses such as Rio Talere, R. Chercucomida, Riu Calarighes-Adisu dei Padri and the Rio Mannu di Mores itself.

Some incisions in cataclinal position, such as Rio Badde Rosa, Rio Badde Fenuja and Rio Filighedu, whose origin is related to differential erosion by a channelled rill, flow along Rio Calarighes. Rio S'Abba Salida can be framed among the orthoclinal watercourses too; however, there are elements that suggest that a tectonic setting has significantly affected the evolution of this watercourse, which proceeds upstream through the Palaeozoic basement, as far as the Pranu Mannu lava flow front (2.9 M.y.b.p.). The presence of lava flow emission centres (Pianu e Monte, N. ghe Pianu e Padres, M. Cordianu) along the slope, confirms the existence of this fault in a N-S direction, along the Rio valley.

In the plain, we observe the lava flows fronts of M. Cujaru S'Abba Salida (0.8 M.y.b.p.) and M. Austidu (0.4 M.y.b.p.); that have fossilised the valley of the Rio Mannu di Mores and conditioned the evolution of the entire area upstream and downstream from the barrage. Though only the terminal parts of the two lava flows are represented on the map, from their shape and age we can reconstruct the changes undergone by the valley in about 400 thousand years starting from the first effusive manifestations of M. Cujaru. This emission centre shows quite a marked thinning for about 2/3 of the entire flow. On the other hand, M. Austidu took on a very extended shape, with a tunnel-shaped thinning only in the terminal tract, which is visible on the map. This suggests that, for about 400 thousand years from the first emission, in this stretch, the evolution of the valley is characterised mainly by a westward recession of the calcareous levels and by an extension of the valley of Rio Mannu di Mores with poor vertical erosion, as can be seen from the altitudes of the two past emissions on the same plateau. The same process is occurring through erosion by Rio Pizzinnu, which cuts 20 m into the substrate moving the carbonaceous levels westwards for about 500 m from the edge of the M. Austidu lava flow.

As regards slope morphologies, they are linked to surface and area washout processes along the lithostructural surfaces of the monoclinal slope with discharges of debris, mainly concentrated in the cataclinal incisions, fed by erosion of the levels of infravolcanic epiclastites. On the carbonaceous slope, the area washout derives prevalently from colluvial and detritic deposits from erosion of the arenaceous-conglomeratic level, situated at the contact with the volcanic surface.

Gravity phenomena are related to movements along fault lines with probable reactivation during the Plio-Pleistocene, as on M. Lachesos, a relief involved by dislocations and rotational landslides with formation of trenches. Three landslide bodies can also be seen along the western slope of Rio S'Abba Salida, two of which show clear detachment niches. In this case, the movement is determined by the presence of bentonized cineritic levels that make up a sliding plain for the more compact overlying layers. Both landslides have buried alluvial terraces, which on account of the altitude are referable to the same fluvial event. This suggests that the gravity event was contemporaneous and that it could have been related to movement along the fault of Rio S'Abba Salida.

Fluvial morphology shows shapes and deposits due to an intense phase of still ongoing changes in the drainage pattern. Alluvial terraces at altitudes of 240-260 metres, attributable to a resumation of the vertical erosion of the watercourse, are found along Rio Mannu di Mores. A few alluvial terraces have been located at a distance from the present bed. They can be seen along the national road between Mores and Ittireddu just after P.te Ezzu in the Ittireddu direction. These terraces are partly displaced and eroded, as can be seen from the extended area on which partly channelled alluvia are found along the present watershed.

The origin and distribution of these deposits is to be attributed to a change in the direction of the flow of Rio Mannu di Mores and of its tributaries as a result of the fossilisation of fluvial tracts by lava flows. The changes in the fluvial layout of Rio Mannu were initially induced by the lava barrage of M. Cujaru (0.8 M.y.b.p.) and subsequently by that of M. Austidu (0.4 M.y.b.p.), which caused the progressive westward shift of the watercourse. In particular, the effusion of M. Lisir (0.2 M.y.b.p.) which blocked the valley of Rio Calarighes along the gorge of Ittireddu, led to a phenomenon of overflooding along the entire upstream tract. The condition of overflooding, followed by the phase of lava barrage of M. Lisir, is evident in the lateral incisions (cataclinal), at times buried by gravelly and colluvial deposits, where (Rio Badde Rosa) a palaeoplain is also present (Melis, oral communication) which would indicate an erosion standstill with reactivation only in recent times.

Capture phenomena are clearly seen along the fluvial lines, such as in Rio Chercucomida which must have originally been the tract upstream from Rio Calarighes-Adisu dei Padri; today this flows into Rio Mannu di Mores forming a 90° westward deviation. Rio Marcuzzi was also deviated westwards in the direction of Rio Mannu.

Most of the fluvial system shows a regressive character along the main lineations with incisions on the rock associated with re-equilibrium of the longitudinal profiles subsequent to the last cold climatic phase. Regressive erosion, with southward rising of the scarp, is deduced from the presence of erosion slopes and saddles along the bed. A regression, on its own alluvium, is observed in Rio Adisu dei Padri as far as Corona Alta near the town of Ittireddu, where a saddle separates it from the incision of Rio Calarighes. The valley of Rio Calarighes is buried by alluvium, and partly dead as a result of the deviation of Rio Chercucomida in the upstream tract.

Among the forms observed in the study area, some are associated with very ancient evolutionary processes and can therefore be set in the context of the larger forms of the landscape. Edges of suspended surfaces, at the same altitude as those over which lava fields of Pliocenic age flowed, can be seen along the eastern slope; these surfaces have been interpreted as relics of a Pliocene palaeolandscape (Sias, 1997) (fig. 2). The glacis, made up of an erosional surface on the Tertiary volcanitic substrate, has also been interpreted as an ancient form, partly covered by a slope deposit with large blocks that are found up to the limit of the watershed (P.ta Sordanu). The deposit has been interpreted as partly originating from the recession of the lava front of Pranu Mannu, as is shown by the basaltic nature of the pebbles situated near the watershed and partly from erosion of the volcano-cineritic mouths.

THE GEOMORPHOLOGIC MAP

Survey method

The attached geomorphological map was compiled by surveys carried out between 1993 and 1997 on the entire Logudoro and from a detailed survey of the study area between 1999 and 2001. This is the first geomorphological map of the Logudoro on a 1:25,000 scale, using the I.G.M.

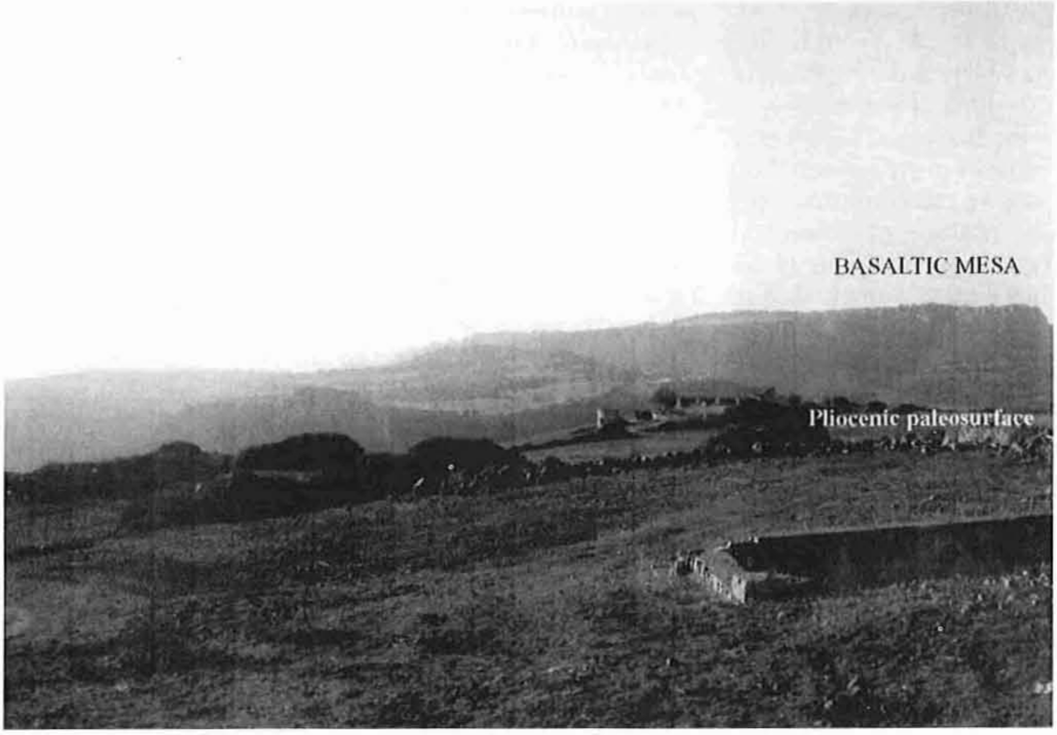


FIG. 2 - In the background, the Pianu e Monte plateau and the pliocenic paleosurface close up.

cartographic base section I Mores of sheet 480. The criteria used to draw up the legend were those proposed by the Geomorphological Map Working Group (1994).

The lithology was distinguished as a function of the chronology taken from the literature, and kept apart from surface deposits indicated with the colour of the morphogenetic agent. The Tertiary volcanic succession was represented as a single pumiceo-cineritic formation.

The Miocenic sedimentary succession was not divided into the two facies, i.e. the continental and the marine, on account of the poor evidence of morphogenesis of the deltaic conglomeratic outcrop, edges of which are present at the transition to the volcanic succession.

The Quaternary lithotypes are represented by basaltic effusions, which were divided into Pliocene and Pleistocene for morphoevolutionary purposes.

It was appropriate to distinguish with two different shades of colour the alluvial deposits along the beds of the main watercourses and attributed to the recent-Holocene (light blue) from those of the Upper Pleistocene along fossil suspended valley lineations (darker blue). A few morphometric indications relating to the size of the slopes are reported. Finally, the hydrographic characteristics of the study area are indicated.

STRUCTURAL FORMS

The structural forms dominate as *cuestas* monoclinal relief forms both in the eastern carbonaceous slope and in the volcanites, and as a morphological low better framed in a denudation surface due to erosion of the Miocene cover. The formation of homoclinal valleys characterises the eastern slope with the development of slopes of layers at different degrees of amplitude around the outcrop of the bank scarp with a W-NW dip.

On the right slope of Rio Calarighes, the surfaces of layers mostly corresponding to structural surfaces or degraded lithostructural surfaces are clearly visible. In particular, Pianu Udduri corresponds to a layer of cineritic ignimbrites (tuffs), which are different from the surrounding rhyolitic ignimbrites. In the panorama of structural forms, M. Zuighe, an outcrop of chalcedonic tuffs, whose linearity has suggested a «filonian» type of origin, appears quite unique; in fact, it forms a long crest in a rectilinear trend whose western tip ends with the M. Ruju relief.

Plio-Pleistocenic volcanic activity caused several vast basaltic lava flows, which were smaller in the Middle-Upper Pleistocene. On the map, the latter are represented by the M. Austidu (0.4 M.y.b.p.) lava flow and by the M. Cujaru one (dated 0.8 M.y.b.p.). The lava flow of M. Lisir (0.2 M.y.b.p.), is even more recent and flowed along a weakly inclined surface towards the junction with Rio di Mores. The centre of emission is marked by a large cone of detritus, which is mined for its pyroclastic material. The Pliocenic lava flows of Pianu e Monte, N. ghe Pedres and M. Cordianu, all in relief inversion, present larger thicknesses.

The Plio-Pleistocene lava flows and a few volcano-cineritic surfaces that outcrop in a sub-horizontal position are indicated as structural surfaces. According to their position, the volcanites that outcrop in the plain at times form weak relief forms, some of which can be distinguished as cuestas, others as isolated rocky peaks.

Among the forms of tectonic origin, the certain and presumed faults have been shown; certain along Rio S'Abba Salida and M. Lachesos.

The Miocenic sedimentary cover outcrops on the right of the valley of Rio di Mores with a well marked limit between the cover and the Tertiary volcanic substrate, which highlights the recession process of the carbonaceous banks. The carbonaceous cover shows a N.NW. oriented position of the layers, giving rise to a cuestas front along the 320-340 metre altitude. Slope steps in concordance with the emergence of more carbonaceous layers are observed along the slopes of the M. Lachesos relief. The valley of Riu Sparghe Abba, which represents the only fluvial incision along the carbonaceous slope, is probably a structural setting.

SLOPE FORMS DUE TO GRAVITY

Slope processes are present both as gravity forms and as washout processes associated with area and channelled erosion.

As regards gravity movements, the landslides observed on the right slope of Rio S'Abba Salida are particularly interesting for their role in the evolutionary context. Three landslide bodies were located, two with a clear detachment niche, while the third shows what is presumably a detachment niche; some were very pronounced, as in Sa Pedrava where a clear escarpment of over 10 metres is visible and the landslide body shows a terminal lobe that has invaded Rio S'Abba Salida. Edges of alluvium under the landslide deposit, which can be observed along the road at about 15-20 metres from the present bed, suggest movement towards the watercourse. On the opposite shore, at the same altitude as this landslide body, we observe the presence of a fluvial erosion niche, caused by the shift of the watercourse as a result of the landslide event.

The position of the landslide body and the position of the erosion niche on the opposite bank, suspended at about 20 metres from the present bed, indicate an age referable to the Middle Pleistocene. Their relatively recent age is confirmed by the finding of a landslide at C. Calchinalzos, where the landslide body is made up of tertiary volcanites and large basalt blocks from the Pianu e Monte lava flow. The gravity movement involved part of the lava flow, along the southern slope, giving rise to the landslide body that is today incised by Rio Calchinalzos and by a deep, narrow gorge on the southern side. Alluvia at about 20-25 metres from the present bed, are referable to the terraces observed in the upstream stretch and can also be seen below this landslide body.

Further downstream, we can see a third landslide body, with material arranged in large blocks immersed in a clayey matrix and with a clear detachment niche. The movement dynamics is brought about by sliding of the rhyolitic banks, along preferential detachment plains made up of bentonite levels, and by alteration of the tufaceous-cineritic substrate. On account of the position of the landslide bodies, but particularly of the fronts, with respect to the actual incision, a nearly contemporary detachment of the phenomena, triggered by Plio-Quaternary tectonic movements along the valley of Rio S'Abba Salida, is hypothesised.

There is evidence of gravity dislocation caused by roto-translational movement of the arenaceous-carbonaceous layers of the Miocene sedimentary formation on the carbonaceous slope of M. Lachesos (fig. 3). The presence of a detachment niche along the slope, near a weak lava flow, suggests a tectonic origin of the slope, and is further evidence of Plio-Pleistocene neotectonics in the territory.

The detrital deposits, derived from area washout, are more abundant along the right slope of the valley of Rio S'Abba Salida and are made up of elements from the erosion of the volcano-cineritic substrate; in the parts further upstream, these deposits show phyllite and quartz elements from the palaeozoic substrate. Colluvial deposits are found along the suspended valleys and, on the upland plains, in contact with the Palaeozoic slope. A few debris gorges are clearly visible along the left slope of Rio S'Abba Salida, which is characterised by considerable acclivity.

On the right slope of Rio Calarighes, there is an abundant presence of detrital material with thicknesses of about 1 metre, along the cataclinal courses and, to a lesser degree, the surfaces of Pianu de Puma, Sa Pattada, Serra de Sorighe, and Badde Ono. The detrital material, which is prevalently arkosic, derives from the erosion of infravolcanic epiclastic levels, while mature rounded elements of tertiary volcanites are present along the surface. In most cases, along the carbonaceous slope we observe a cover of colluvium with a thickness of between 50 and 100 cm, enriched with an arkosic component by erosion of the arenaceo-conglomeratic level.

Erosional scarps derived from slope processes are found along the cataclinal incisions on the eastern slope and are distinguished by different degrees of amplitude. Residual edges of sedimentary formation are present along the right slope of the valley of Rio di Mores and are witness of the recession of the carbonaceous outcrops.

FLUVIAL FORMS AND SURFACE WASHOUT

Hydrography

Along the valley of Rio Mannu di Mores, the drainage pattern is poorly developed and in effect receives important tributaries from the hydrographic right, in the low tract of its course. The system of tributaries is represented by torrential and occasional flow incisions, which favour the imposition of structure on the geometry of the drainage pattern. The structural setting of the drainage pattern is clearly visible in the conformation of the main rivers: Rio Mannu di Mores, Rio Adisu dei Padri, and Rio S'Abba Salida; their *candlestick* geometry indicates a selective process among the volcano-pyroclastic banks that outcrop along the plain.

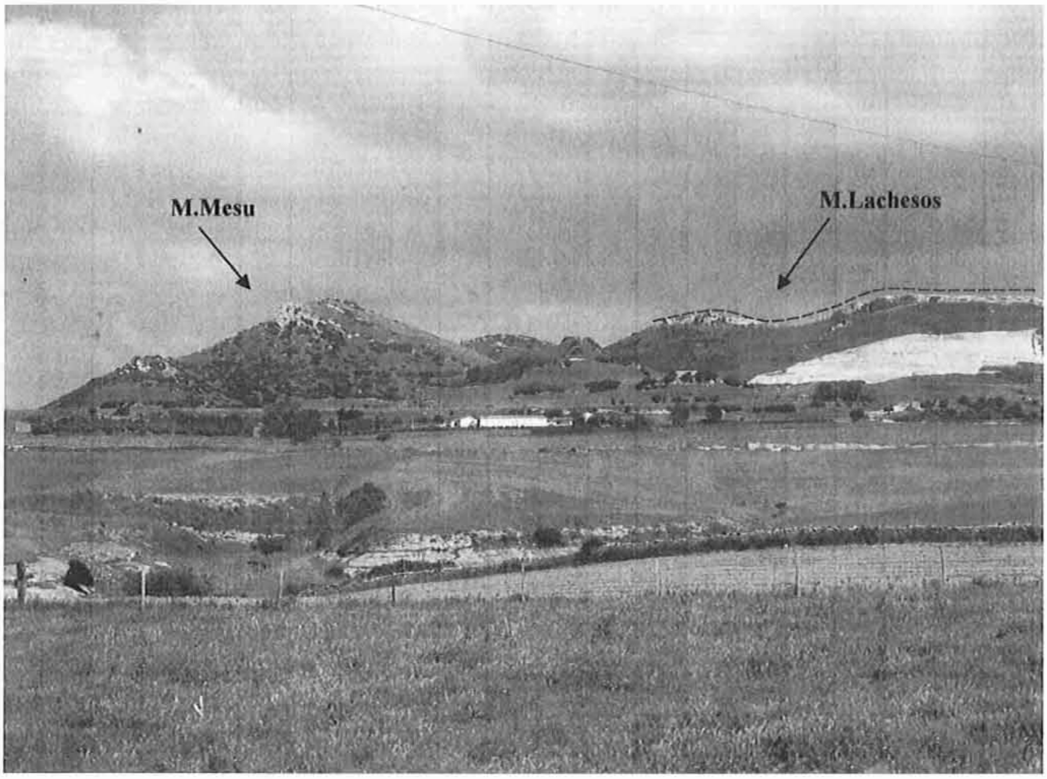


FIG. 3 - M. Mesu slumping in the carbonatic sequence and the landslide scarp on the M. Lachesos. During the Plio-pleistocene upflit the originally mesa is been involved by gravitational processes.

The particular structure of the drainage pattern, with a system of tributaries from the right side and all parallel to the main watercourse, produces a parallel-type of «pattern» that develops by selective erosion on the pumiceo-cineritic ouctrops. Rio S'Abba Salida flows along the fault line, in a S-N direction; along this alignment, in the upstream tract, we find the Pranu Mannu lava flow, which already flowed along the valley, now buried, in the Pliocenic age (2.9 M.y.b.p.). The system of tributaries has a *trellis-like* pattern with cataclinal and anticlinal incisions that run towards the main river after crossing the *gorges*, which suggests a reactivation of the fault line in the Quaternary.

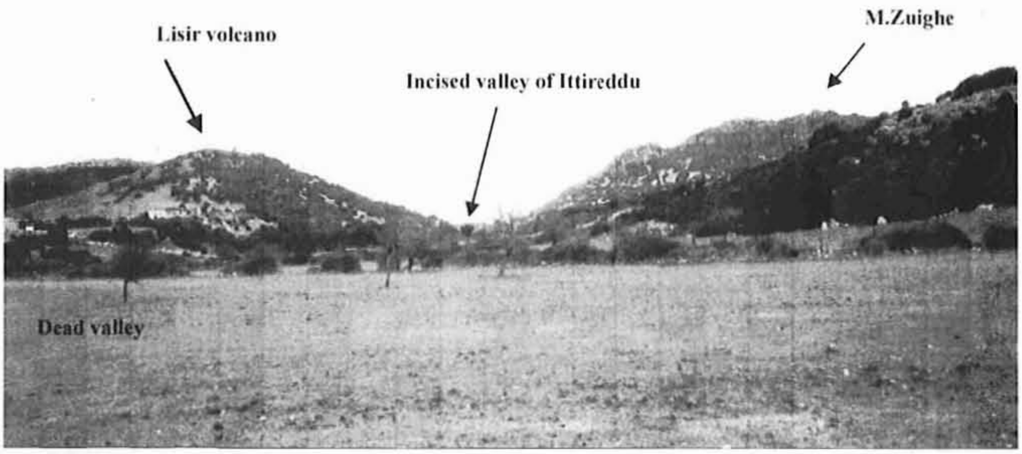
The same *trellis-like* geometry is observed in Rio Adisu-dei Padri, which flows in a S-N direction as an orthoclinal watercourse, into which a system of torrential (cataclinal) incisions flows from the right slope. Nevertheless, the evolutionary events, resulting from Pleistocene volcanic activity, have been the main influences on this watercourse. Even Rio Mannu di Mores develops a *trellis-shaped* geometry, though a morphostructural asymmetry of the valley occurs here, with a volcanitic slope on the right and a carbonaceous one on the left.

It is interesting to observe that in about 0.4 M.y., the erosive activity of this watercourse has led to a recession of the carbonaceous slope of about 500 m. Rio Sparghe Abba represents the only incision that re-ascends the slope of M. Lachesos; as to the origin of this watercourse, the presence of a fault line that caused the gravity phenomena observed in the survey can be hypothesised.

The fossilisation of large stretches of Rio Mannu di Mores, by the lava flows of M. Cujaru and M. Austidu, conditioned the evolution of the area upstream and downstream from the barrage. This can be deduced from the small-capacity, torrential flow rate of this watercourse despite its large storage lake. The solid load itself is discontinuous along the bed, where at certain points it is buried under an abundant gravelly deposit and at others is completely lacking. This situation is brought about by the secondary origin of the gravelly material which comes in part from the displacement of old fluvial terraces, and in part from the erosion of the arenaceous-conglomeratic level of the miocene cover.

In particular, the terraces present along the upland plain, between the lava flow fronts and the saddle of Ittireddu, indicate the existence of an old fluvial layout abandoned after the effusion of M. Cujaru and M. Austidu. With the effusion of M. Lisir (0.2 M.y.b.p.), the evolution of the old fluvial layout underwent a second phase of flooding, which determined the condition of dead valley in Rio Calarighes and the condition of deviation of Rio Chercucomida in the upstream tract (fig. 4). Before the deviation, this watercourse was the upstream tract of the Rio Adisu dei Padri-Rio Calarighes system; subsequent to the lava barrage of M. Lisir, this stretch of the river was taken up by Rio di Mores, as is seen in the 90° deviation at the locality of Nuraghe. With the resumption of erosional activity, the Riu Adisu dei Padri reconstructs its bed incising old alluvia, where it forms large swampy stretches at Sa

FIG. 4 - Dead valley of Rio Chercucomida. In the background the incised valley of Ittireddu.



Udulia place. This watercourse shows a regressive character towards the valley of Rio Calarighes, where it forms a step fault of about 3 metres along the saddle of Ittireddu.

The Terraces

The ancient alluvia of Rio Mannu di Mores are visible in the terraces situated along the ignimbritic upland plain, between the lava flow fronts of M. Austidu and M. Lisir, on the orographic right of the river, and along the valley incision of M. Zuighe-M. Ruju, at an altitude of between 260 and 290 metres. Terraced deposits are clearly visible on this surface along the edge of the roadworks, between the villages of Mores and Ittireddu, beyond P.te Edera (fig. 5). These deposits have been subdivided into 1st and the 2nd order terraces according to their altitude and stratigraphic characteristics. The first order of terraces is located near P.ta Petrosu, at an altitude of between 300 and 280 m along the Ittireddu-Mores road; here, the edge of the roadworks uncovered a stratigraphic sequence made up of conglomeratic and clayey-sandy levels in crossed stratification (fig. 6). The gravelly deposit presents a thickness of about 2 metres, where an alternation of pebbles with clayey-sandy levels can be seen.

The conglomerate horizon is made up mainly of very rounded elements of tertiary volcanites and of the Palaeozoic basement, and altered basaltic elements from the Plio-Pleistocene lava flows upstream from the basin. The elements present high sphericity with diameters ranging from 10 to 20 cm. The elements can be seen graded and their size decreases from bottom to top. The transition to the clayey level is highlighted by a clear-cut erosion surface, where pebbles of about 10-15 cm are found.

The clayey-sandy levels originate in the alteration of the ignimbritic substrate; the lower levels present evidence of pedogenesis. This condition indicates an alternation of humid and dry phases of the climate with torrential characteristics of the watercourse, subjected to prolonged low water periods. The sequence of levels presents the following order from bottom to top:

- clayey-sandy deposit about 40-50 cm thick at the contact with the tertiary volcanic substrate made up of cinerites; oxidation crusts and a few quartz elements of a few mm are present.
- Level of pebbles about 30 cm thick; it lies directly at the clayey-sandy level distinguished by a clear-cut erosive contact. It presents a graded texture with elements from the volcanic and Palaeozoic basement of the order of 30-40 cm, rich in manganese-bearing crusts. Between the lower level and this one, clear pedogenetic processes are evident.
- Sandy layer of the thickness of 10-15 cm of a lenticular aspect, it shows an erosive contact on the underlying level.
- Pebbly level 20-30 cm thick with elements in a crossed arrangement
- Sandy lenticular deposit about 10 cm thick.
- Slope deposit made up of pebbles in a chaotic arrangement, from the erosion of terraces located upstream.

The 2nd order terraces are found along the slopes of the tableland of M. Austidu, near the lava front at an altitude of about 265 metres along the road, beyond P.te Edera, towards Ittireddu (fig. 7). Along the ignimbritic upland plain, they are made up of pebbly deposits located at an altitude of between 270 and 260 metres. The elements are arranged chaotically, due to the discharge of debris-flow materials from upstream slopes during wetter climatic phases.

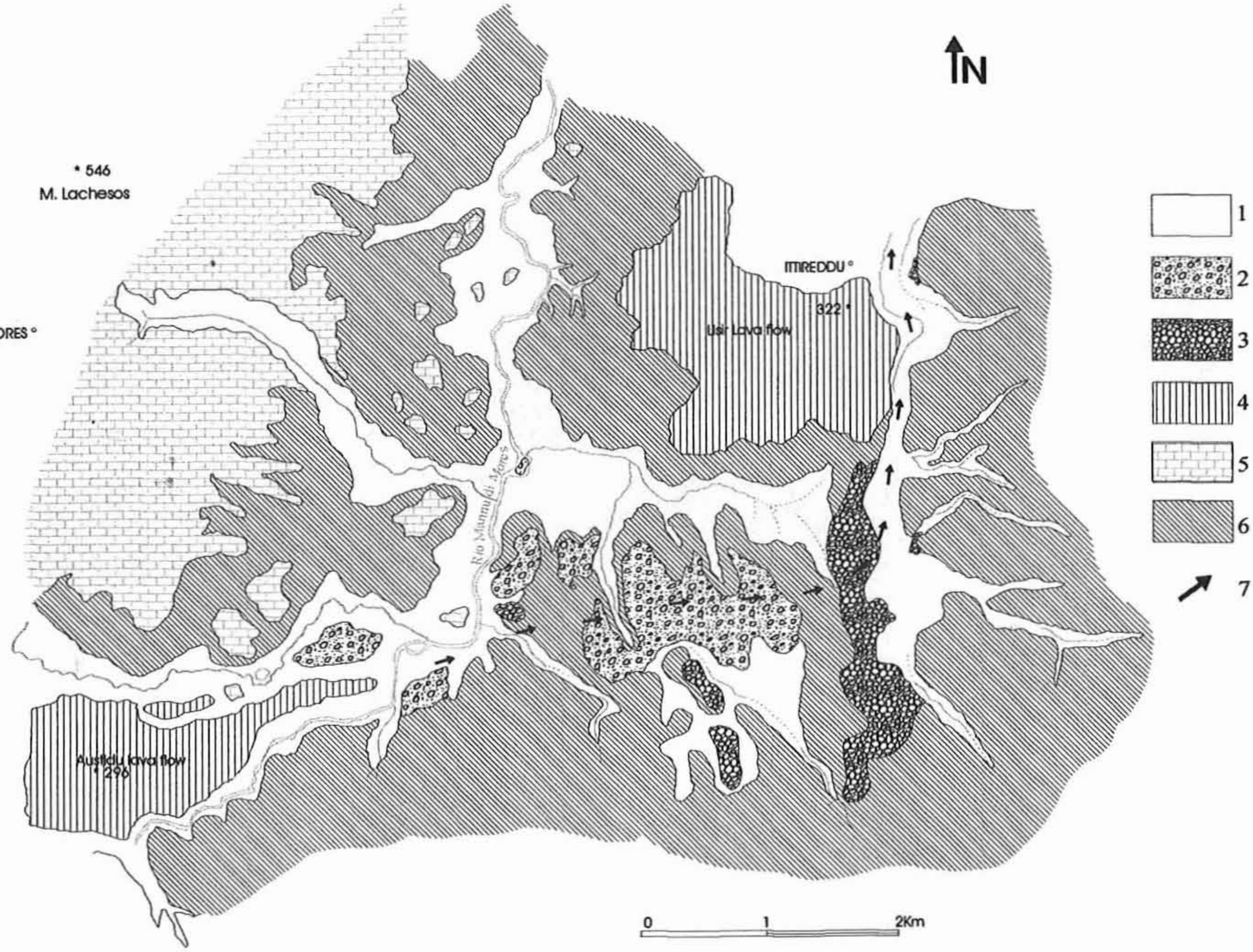


FIG. 5 - Terrace sketch map of Rio Mannu di Mores. 1) Pleistocenic sediments; 2) 2[ord] Terrace; 3) 1[ord] Terrace; 4) Basaltic lava flow; 5) Miocene sedimentary formation; 6) Oligo-Miocene volcanics; 7) Ancient direction of Rio Mannu di Mores.

The thickness of these terraces varies from a minimum of 60 cm to a maximum of 1 metre. In the thickest terrace the following three levels from bottom to top are distinguished:

- Pebbly level made up of elements of the Tertiary basement and of basalt supporting the substrate of tertiary volcanites marked by an erosive contact surface. The elements are rounded with sizes of about 4-5 cm.
- Sandy-pebbly level made up of Tertiary volcanic and Plio-Quaternary elements of a size of 3-4 cm. A few sand and pebble lenses are clearly visible.
- Level about 20 cm thick made up of pebbly elements in a chaotic arrangement from the slope due to displacement of the terraces located upstream from the deposit.

Moreover, near the Chilivani plain along the orographic right of Rio Mannu di Mores, at C. Basoli, terraces are found at an altitude of about 240-250 metres. It has not been possible to indicate a sequence for these terraces, since the material was spread over the surface suggesting remodelling and erosion of the terrace. Alluvial deposits are found at Monte Mariano at about 1 km from the previous site at 250-255 m above sea level. At this same altitude, but in the opposite position, pebbly deposits lying on the Miocenic sedimentary or ignimbritic substrate are found. At a higher altitude, about 265-270 metres, there are a few alluvial deposits at C. Torolò; these deposits could be included in the 2[nd] order terraces.

Alluvial deposits were located along Rio S'Abba Salida, at an altitude of about 300-280 m above sea level, at a height of about 30-20 metres above the present bed, partly buried under slope deposits and landslide bodies.

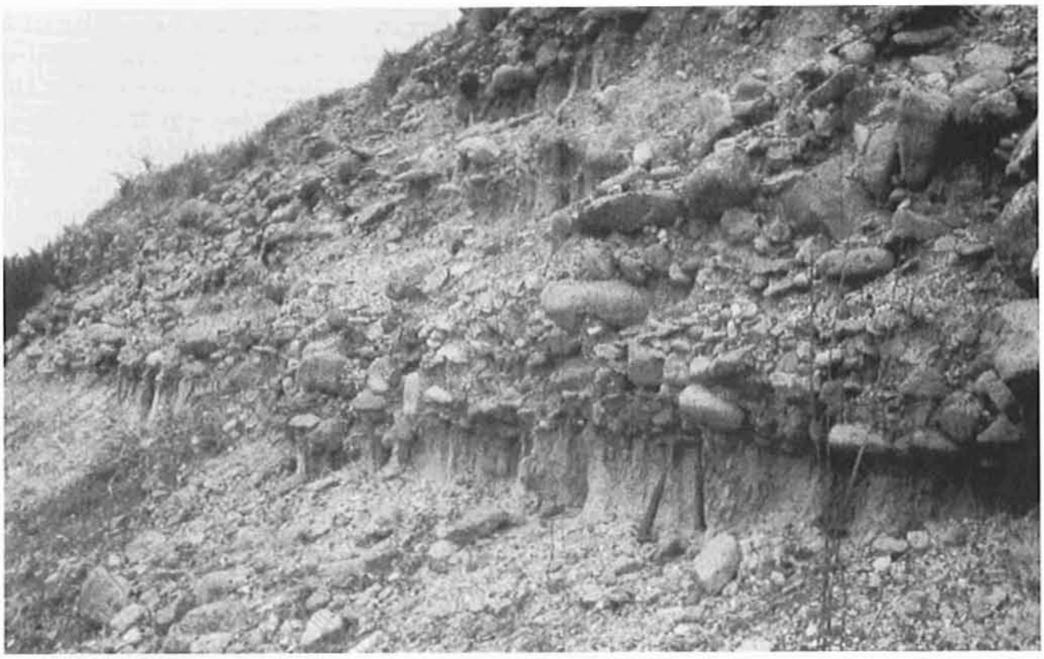


FIG. 6 - 1^{erd} Terrace. Sequence of alluvial sediment (the Ittireddu-Mores road).

FIG. 7 - 2^{erd} Terrace. Alluvial sediment caratterized by debris flow dinamics.

Erosive surfaces, classified as erosion terraces, are recognised along Rio Mannu di Mores at Padru Iddau near the confluence with Rio Butule, where terraces are situated at the same altitude, between 250 and 260 metres along Rio Mannu di Mores.

THE ORIGIN OF THE ALLUVIAL TERRACES

There are certain elements suggesting different streams from the present one for Rio Mannu di Mores only along the terraces found on the edges of road works between Mores and Ittireddu, where a stratigraphic sequence of clear fluvial origin is visible.

On the origin and age of these two terraces, a hypothesis was formulated concerning the sliding surfaces of M. Cujaru (0.8 M.y.b.p.) and M. Austidu (0.4 M.y.b.p.), which are only visible on the map in the terminal portions. After the effusion, first M. Cujaru and then M. Austidu, flooding phases occurred and consequently changes in the current direction of Rio di Mores.

The presence of a few basalt pebbles, in the lower order terrace, strengthens the hypothesis of a different age. This hypothesis is also confirmed by the position of the two terraces, which are about 3 km from the present talweg. This fact suggests that a migration towards the present position of the palaeo-Rio di Mores occurred. The position of the terraces according to a SSW-NNE orientation indicates the direction of the palaeo-Rio di Mores towards the opening of M. Zuighe-M. Ruju near the village of Ittireddu.

The valley incision, in this dike structure, is certainly produced by a watercourse of a greater flow rate and with a more extended basin than the present one. With the effusion of M. Lisir (0.2 M.y.b.p.), the valley of Rio Calarighes was definitively closed, resulting in overflooding, and its stream was fossilised.

The alluvial deposits found in different places, at different altitudes between 260 and 250 metres in the Mores-Chilivani plain are to be considered the product of the erosion of synsedimentary terraces during the upper burdigalian tectonic; these outcrop at altitudes of about 275 metres near Oppia Nuova, along the road between Mores and Ittireddu, and at Pedras Frittas. The alluvial deposits are made up of conglomerates and sands that have undergone diagenised (with a bright red colour, 7.5R5/8 Munsell coloration), with elements from the erosion of the Palaeozoic substrate and to a lesser extent of the tertiary volcanic substrate. A few remarks should be made about the terrace found near Fossadu locality, at 268 metres above sea level; here, the alluvial deposit made up mostly of elements of the Palaeozoic basement, less by elements of the tertiary volcanic basement, were brought to light in an excavation. What relates these deposits to the Oppia Nuova formation is the bright red coloration of the clayey-sandy component in which the pebbles are immersed. A few differences are to be noted: absence of diagenesis of the deposit, which is also easily cut; the presence of smaller elements and a greater clayey component, grey in colour, that predominates towards the upper part of the terrace.

Therefore the Fossadu alluvial deposit could be interpreted as a displacement of the Oppia Nuova formation, and the same alluvial deposits present in the Chilivani plain could be attributed to erosion of this formation by the slope, as a *glacis*, which would subsequently make up transportation material for the watercourse.

ANTHROPIC FORMS

The human impact on the territory is sporadic and diversified, almost showing its morphological adaptation to an entirely unviolated environment.

Sheep-farming is the prevailing activity along the eastern slopes of the valley, where there is an outcrop of Tertiary vulcanites, on which appropriate soils for herbaceous plants suitable as pastures develop. Along the same slopes, crossed by tracks, there are frequent reservoirs situated in the incisions and gorges that cross the eastern slope. In most cases, these artificial basins are located in the valleys, which present a colluvial clayey cover, derived from the weathering of the volcanites and favourable to the stagnation of meteoric waters. This is the case of the torrent that flows towards Rio di Mores, near C. Scaladeroccu, which is active only after meteoric events, and which crosses a valley over 4 km long and between 100 and 150 metres wide, and is overestimated with respect to its hydrological characteristics.

Two reservoirs are located along this torrent which presents several swampy areas. This situation is repeated with Rio Chercucomida, a tributary of Rio di Mores, at the level of the Roman bridge (P.te Ezzu), and with its right tributary, Rio Giuanne. Both of the situations described show the features of watercourses that have undergone a process of overflooding.

In the carbonaceous slope, anthropic activity is limited to sporadic cultivation and sheep-farming, which is widespread and is associated with intense deforestation to make place for the cultivation of herbaceous plants.

A few quarries for the extraction of inert materials, abandoned in the past few decades, are present near Ozieri on the Palaeozoic limestones, while they are still active at Ittireddu, where basaltic scoria is extracted. Medium-sized quarries, not large enough to be represented on the map, are found in various parts of the area and used as disposal sites for inert materials.

The Ittireddu quarries are visited by nature tourists, as they are a unique sight in an interesting geomorphological setting. Thanks to its rich volcanic forms, the entire area lends itself particularly to nature and cultural itineraries, being so rich in prehistoric and historic content that it has become an important land museum for the region (Sias, 93).

GEOMORPHOLOGICAL EVOLUTION

The evolution of the study area referred to the entire study area, which extends from the Campeda-Abbasanta plateau to the Chilivani plain. A wide basin is configured here with a NNE direction, whose southern boundary is the Campeda lava flow (3.5 M.y.b.p.), while it is bounded to the north by the volcanic reliefs of Anglona horst. The form of both the Campeda and the Pranu Mannu lava flows shows the existence of palaeo-incisions, though very weak, along the present direction of Rio Mannu. These incisions furrow the top-depositional surface of the Miocene.

These flows have prevented Rio Mannu from extending southwards; instead it has progressively lowered its altitude from 550-600 m (surfaces buried by the flows) to the present 350-300 m. This large erosive phase is attributed to a period between the Upper Pliocene and the Lower Pleistocene, as is deduced from the relief inversion of the Pliocene lava flows which are practically equal and at the same altitude, though produced in different effusion ages. This observation suggests that the uplift started about 2 million years ago, with the last effusive phase of the Pliocene.

The general uplifting of Logudoro led to an erosive phase that, in the Mores-Chilivani area, was controlled by the structural conditions of the basement. The erosive dynamics manifested itself with phases of vertical erosion, at first along the margin at the contact between the Marghine-Goceano palaeo-horst and the sedimentary cover. In this first phase, the watercourse will have eroded the Tertiary volcanic basement along M. Zuighe-M. Ruju up to the opening of the Ittireddu valley. Lateral incision phases alternated with vertical phases according to a scheme imposed by the monoclinal structure of the volcano-sedimentary cover.

Selective erosion, between the Tertiary volcanic basement and the Miocenic cover, led to a progressive recession of the carbonaceous levels with exhumation of the pre-miocene transgression surface. The changes in the flow direction of the watercourse are posterior to the exhumation of the pre-miocenic surface and are to be attributed to the effusion of M. Cujaru and subsequently of M. Austidu.

In their form and direction, these lava flows show that in the Middle Pleistocene (between 0.4 and 0.8 M.y.) Rio di Mores flowed in a NNE direction towards the valley of Ittireddu. In the phases following the effusion, the conditions occurred to deviate the watercourse as a result of the overflooding of the area upstream and downstream from the barrage. Resumption of erosion after the first effusion, the M. Cujaru effusion, will have led to the establishment of a drainage on the west side of the flow, which will have imposed a first phase of westward shifting of the watercourse.

With the effusion of M. Austidu, the occlusion of Rio di Mores and of the entire upstream basin was completed and the resumption of drainage on the western side, near the contact with the sedimentary cover, was prevented; today in fact it proceeds at the contact with the M. Cujaru flow and the eastern volcanic slope. Rio di Mores has taken on its present position in a period between 0.4 and 0.2 M.y., as is deduced from the M. Lisir lava flow, whose form shows the existence of a drainage in that direction. The vertical incision of Rio di Mores in the Tertiary substrate, with the formation of terraces, is attributable to palaeo-climatic causes, probably related to a humid phase of the Riss-Wurm.

Regressive erosion along the main lineations, visible in the presence of saddles and escarpments, probably resulted from the last glacial phase (Würm), which presumably determined a stable resumption of erosion during the cataglacial phase.

Moreover, the changes in the geometry of the drainage pattern of Rio di Mores have been distinguished and the evolutionary sequences defined as a function of the age of effusion of the lava flows, which have made possible the identification of alluvial terraces resulting from phenomena of deviation and fluvial capture.

Rio Mannu of Coghinas crosses different geo-morphological situations: including the plain of Chilivani, which is a structural basin, the half-graben of the Coghinas plain, the Tertiary volcano-sedimentary basin and the hercynian batholith. This geomorphological-evolutionary complexity makes it possible to deduce that the geometry of the drainage pattern is strictly connected to structural factors that conditioned their development.

The most interesting result is the evidence of an evolutionary pattern of denudation in the pre-miocene basins as a result of uplifting phases of the territory, which have been attributed an age referable to the Villafranchian and which provides the key to reading the entire territory of northern Sardinia. More in general, the study permitted a geomorphological-evolutionary reconstruction of the area from the Upper Pliocene onwards. These results once more confirm that the entire territory of Logudoro may constitute a regional point of reference in reconstructing the events that have deeply affected landscape evolution in Sardinia.

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