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THE RECENT EVOLUTION OF THE SINIS REGION (WESTERN COAST OF SARDINIA, ITALY) ON THE BASIS OF NEW RADIOMETRIC DATA OF THE PLIOCENIC VOLCANISM

ABSTRACT: DUNCAN R., GINESU S., SECCHI F. & SIAS S., *The recent evolution of the Sinis region (western coast of Sardinia, Italy) on the basis of new radiometric data of the pliocenic volcanism*. (IT ISSN 0391-9838, 2011).

The present paper focuses on the relationships between Pliocene volcanic activity and geomorphological evolution of Sinis region (western Sardinia, Italy). Plio-Pleistocene volcanic activity plays a key role in the recent landscape evolution. Morphological evolution has been reconstructed on the basis of chronological data obtained on different volcanic episodes.

In order to constrain the evolution model, Ar/Ar radiometric studies have been carried out on volcanic episodes of Sa Mulargia and Catalano island. The landscape is characterized by smooth morphologies and a poorly defined hydrographic network; volcanic relief shows relief inversion processes. These processes produced a roughly NS trending drainage in the western sector, favored by extensional faults that conditioned the geomorphological features commonly observed in the coastline. Several ponds in the eastern Sinis area are likely related to the interaction of morphogenetic processes favored by tectonic activity and sea level fluctuation and variation of Tirso river, the main river of Sardinia.

KEY WORDS: Geomorphological evolution, $^{40}Ar/^{39}Ar$ chronology, Recent tectonic activity, Sardinia, Italy.

RIASSUNTO: DUNCAN R., GINESU S., SECCHI F. & SIAS S., *Il vulcanismo pliocenico del Sinis (Sardegna occidentale) età e implicazioni geomorfologiche sull'evoluzione recente della linea di costa*

Il presente lavoro è dedicato alle relazioni fra l'attività vulcanica pliocenica e l'evoluzione geomorfologica della regione del Sinis (Sardegna occidentale). I dati raccolti mettono in evidenza il ruolo determinante assunto dall'attività vulcanica recente nella comprensione dei meccanismi evolutivi del paesaggio di questa regione resa particolarmente complessa dagli imponenti movimenti tettonici che la hanno caratterizzato dal Pliocene. I dati reperibili in letteratura, grazie soprattutto ai sondaggi profondi condotti dall'AGIP mineraria negli anni '60 nella parte settentrionale della fossa tettonica campidanese settentrionale mettono in luce gli indici significativi di sprofondamento dal Pliocene valutati intorno ai 600 m. La presenza di vulcaniti del ciclo plio-pleistocenico intercettate a quota 322 nel pozzo Oristano 1, favorisce il riscontro morfologico con quelle oggetto dello studio permettendo una possibile ricostruzione morfologica dell'evoluzione del Sinis considerato un blocco tettonico non disgiunto dai movimenti che hanno caratterizzato la fossa.

L'evoluzione morfologica dell'area investigata può essere ricostruita sulla base dei dati cronologici ottenuti sui differenti episodi vulcanici. Allo scopo di definire la ricostruzione recente della regione in studio, sono state condotte analisi radiometriche con le moderne tecniche Ar/Ar su campioni rappresentativi di rocce vulcaniche prelevate in località sa Mulargia e nell'isolotto del Catalano.

Il paesaggio del Sinis è caratterizzato da forme dolci interrotte da ben evidenti processi di inversione del rilievo e da un reticolo idrografico non ben definito. Nelle porzioni occidentali dell'area investigata, i processi di inversione hanno dato luogo ad un reticolo idrografico disposto grosso modo N/S, la cui origine è favorita da faglie estensionali che hanno sensibilmente condizionato i lineamenti geomorfologici comunemente osservabili lungo lo sviluppo costiero. Le analisi effettuate sull'attività vulcanica del Sinis hanno permesso di identificare per il neck del Catalano un'età di poco superiore ai 4.5 Ma, mentre per il plateau di Sa Mulargia, si ottengono valori sensibilmente più recenti attorno ai 3 Ma. L'intervallo tra le due attività vulcaniche riconosciute, consente di ipotizzare una evoluzione significativa del sistema idrografico dell'intera regione investigata e correlare la colata del promontorio di Capo S. Marco con quella osservata nella porzione sommersa del Catalano per analogia morfologica essendo entrambe impostate in un sistema idrografico maturo.

I movimenti recenti, la presenza e la posizione cronologica delle colate in affioramento e di quelle intersecate nei sondaggi all'interno della fossa ed il sistema di stagni costieri ad est della penisola del Sinis, hanno verosimilmente determinato una risposta morfologica del fiume Tirso con la migrazione del proprio corso verso sud, determinando l'abbandono di un'antica foce per giungere direttamente all'interno della fossa campidanese.

TERMINI CHIAVE: Evoluzione geomorfologica, Cronologia $^{40}Ar/^{39}Ar$, Neotettonica, Sardegna.

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INTRODUCTION

Researches carried out in northern Sardinia, allows a quite precise geomorphological reconstruction because of the wide distribution of basaltic lava-flows related to the Plio-Pleistocene anorogenic cycle (Sias, 2002). These volcanic episodes, in this part of Sardinia, have been chronologically defined mainly by K/Ar techniques (Beccaluva & *alii*, 1985). Recently, to better define the geomorphological reconstruction of middle to upper Pleistocene, new chronological analyses have been carried out by Ar/Ar techniques on selected samples of volcanic episodes from northern territories of the Island (Duncan & *alii*, 2002). These new data allow us to redefine the already published data, testyfing a younger age and supporting the hypothesis of human presence in the Island (Cordy & *alii*, 2001; Ginesu & *alii*, 2003; Cordy & *alii*, 2007). The chronological data used in the geomorphological reconstructions, is quite significant the Sinis region because of the documented recent tectonic movements related to the Campidano tectonic though, that moduled its evolution (Cherchi & *alii*, 1978). In addition, the volcanic activity related to the Plio-Pleistocene anorogenic cycle, still poorly chronologically constrained, give a contribution for geomorphological reconstruction of the whole Sinis peninsula and the nearby inland areas.

Published papers on the study area are mainly devoted to stratigraphy of sedimentary successions whereas the Plio-Pleistocene magmatic cycle is poorly constrained. Several lines of geological evidences such as the occurrence of a thick aeolian successions widespread along the western coast, the occurrence of terraces in the eastern Sinis and last, but not least, the thick recent deposits observed in submerged area (Lecca & *alii*, 1983; Forti & Orrù, 1995) corroborated the hypothesis that the whole hydrographic network was strongly conditioned in its evolution, producing a progressive southward migration of the rivers to the center of the northern Campidano tectonic though.

Radiometric data indicate values of about 3 Ma for neck and lava flows of sa Mulargia. Slightly older values of about 4.8 Ma are obtained for Catalano small island. On account of general geological and geomorphological context, these data are in good agreement with a different evolution of Sinis region and the Catalano-Mal di Ventre area where it appears that relief inversion processes are more pronounced, as well as the evolution of now submerged cliffs. [with respect to the submerged morphologies observed between islands and mainland.

GEOLOGICAL AND GEOMORPHOLOGICAL PICTURE

The Sinis region (western Sardinia) is a NS-trending narrow peninsula not exceeding 125 km^2, geologically dominated by Cainozoic sedimentary covers and subordinately by anorogenic volcanics referable to the so called Plio-Pleistocene magmatic cycle of Sardinia (fig. 1). In de-

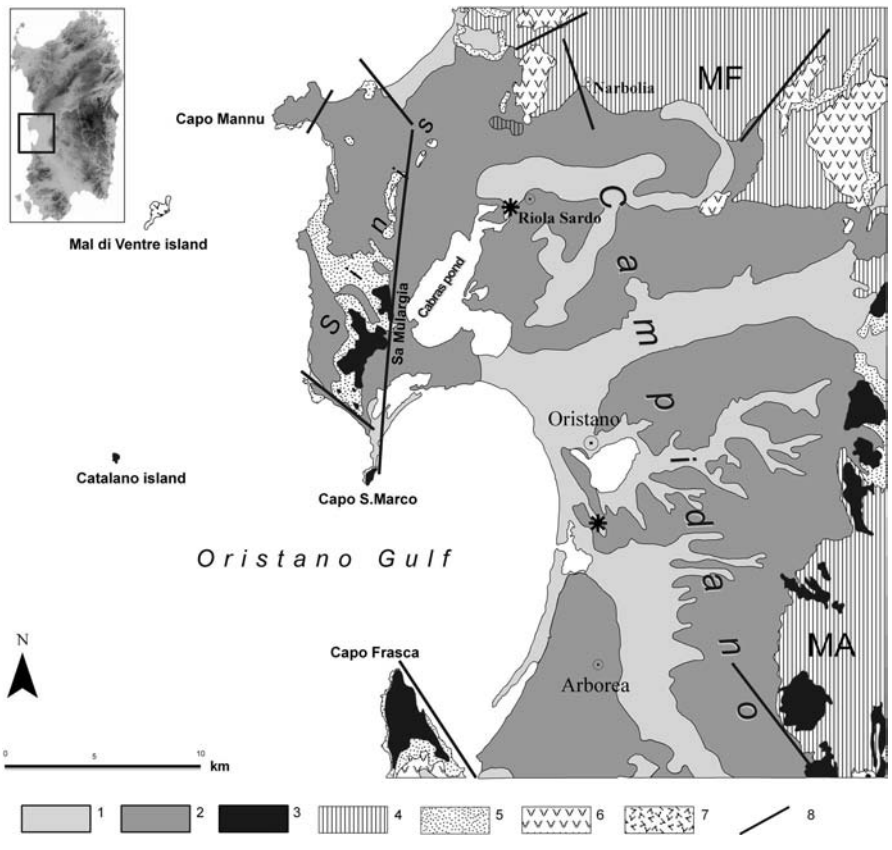

FIG. 1 - Simplified geological sketch map of central-western Sardinia (Italy). (1) recent covers; (2) Pleistocene continental to marine deposits; (3-4) Volcanics of Plio-Pleistocene anorogenic cycle: (3) basaltic lava-flows and necks; (4) central volcanic massifs of Montiferru (MF) and Monte Arci (MA); (5) sedimentary covers (middle-upper Miocene-Pliocene); (6) orogenic volcanics of Oligo-Miocene cycle; (7) Palaeozoic basement. Other symbols: main (certain, hypotized and buried) regional faults (8). Black stars refer to the localization of Oristano 1 (southward of Oristano town) and Oristano 2 (near Riola Sardo village) drillings. Fault pattern after Lecca & *alii* (1997).

tail, sedimentary covers are mainly limestones and marls of marine environment grading upward to evaporitic limestones (Messinien). Volcanic covers are represented by small and elongated basaltic lava-flows still observed in the surrounding submerged areas and reaching 15 m thick; sub-volcanic bodies (necks) are locally observed along focus (Catalano small island and sa Mulargia plateau).

More ancient rocks in the area, are small orogenic volcanics of Oligo-Miocene magmatic cycle observed in the north-east of the region and granitic rocks of Palaeozoic basement in the Mal di Ventre small island.

Recent covers are aeolian deposits diffusely observed along the western coastline of the region and reaching considerable thickness of 50 m along the Capo Mannu cliff, testifying continental conditions since the Pliocene (fig. 2). The most recentmost rocks are marine deposits widespread along the coastline, and stratified slope deposits unconformably overlying fossiliferous sandstones and conglomerates of upper Pleistocene age (Pecorini, & *alii*, 1974; Ulzega & Hearty, 1986; Forti & Orrù, 1995).

FIG. 2 - Aeolian thick succession in the Capo Mannu interrupted by several pedogenetic levels.

According to reconstructions of Lecca & *alii* (1997), the Sinis region is a tectonic block at the contact with Campidano tectonic though and blocks of northern Sardinia (fig. 3). The Sinis block is bordered by roughly NS trending extensional faults, likely actived during a Oligo-Miocene tectonic phase and re-activated during Plio-Pleistocene times. Evidences of recent activation of these NE/SW trending faults is offered by archaeological remnants of roman-punic age observed in nearly submerged areas (Cherchi & *alii*, 1978; Marini & Murru, 1983).

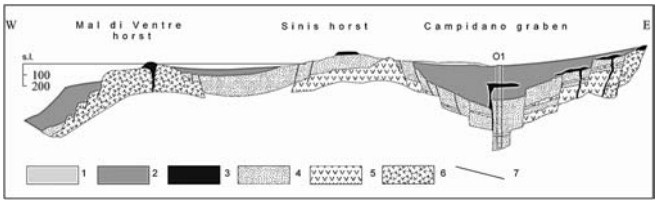

FIG. 3 - Schematic cross section for Sinis block and northern Campidano. Symbols as in fig. 1. O1 refer to the Oristano 1 drilling. Modified after Lecca & *alii*, 1983 and (eastern side) Tilia Zuccari, (1969).

The occurrence of Palaeozoic basement in Mal di Ventre island, as well as the asymmetric profile of submerged areas (fig. 3), suggests the Sinis region as a slight tilted block characterized by contrasting and complex mechanism in different times and bordering Miocene and Pliocene sedimentary basins to the west.

Geomorphological features of the investigated region, are mainly characterized by the relief inversion processes observed in the Pliocene anorogenic volcanics. These processes produce a slight pronounced valley system well exposed at Capo S. Marco and also recognizable in the submerged areas between western coastline of Sinis region and Catalano-Mal di Ventre small islands. Geomorphological features of the Sinis region show the close relationships between pre-basaltic morphologies and the sea level fluctuations during Pleistocene. Particularly in the eastern and western nearby submerged areas of Sinis region, lies a system of coastal ponds and swamps areas grading abruptly from the present coastline to an edge of 3-5 m, commonly observed along the whole Sinis coastline (Forti & Orrù, 1995; Ginesu & *alii*, 2009).

Forms and distribution of basaltic lava-flows well exposed at Capo S. Marco and sa Mulargia plateau (fig. 4), indicate a pre-volcanic, southward draining, hydrographic network and suggest the occurrence of a recently emerged and slightly smooth continental area mainly made up by Miocene and Pliocene deposits showing an scenario quite similar to that observed for northern Sardinia (Sias, 1994). In addition, this hydrographic network was constrained by the tectonic behaviour of Sinis block, located at the contact with Montiferru block and the Campidano tectonic though. Cartographic data available for submerged areas of nearly marine areas of Sinis indicate the occurrence of a wide continental shelf. Depths recorded between the Mal

FIG. 4 - The Capo S. Marco lava-flow. Courtesy of Sinis-Mal di Ventre A.M.P.

di Ventre-Catalano islands alignment and Sinis area, not exceed 40 m, being the upper limit of 50 m, observable 15 km offshore. Moreover, Mal di Ventre-Catalano islands represent the western culmination of Sinis block characterized by cliffs during Pliocene and Pleistocene time span and not recognizable southward because of the occurrence of Campidano tectonic movements.

It should be emphasized that recent tectonic movements played a kay role in the evolution of the investigated area. Reconstruction is constrained by the results obtained from two deep drillings carried out during the sixties by the italian company for petroleum researches (AGIP) in the northern Campidano, and named Oristano 1 (southward of Oristano town) and Oristano 2 (near Riola Sardo village; fig. 1). Geological data offered by Oristano 2 drilling, suggest that the northern Campidano is characterized by a relatively high subsidence rate of at least 200 m since Pliocene/Pleistocene as testified by basaltic lava flows (Tilia Zuccari, 1969; fig. 3). The same drilling indicates considerable subsidence rate of about 856 m to extend from the Pliocene present time span.

Consequently, the recent Plio-Pleistocene uplift movements redefined and changed the evolution of relief system of Sardinia; in this scenario the role played by Sinis region in the recent evolution of northern Campidano is especially interesting. Marine conditions in the Sinis region, end at lower middle Pliocene as testified by the above mentioned deposits while the nearby submerged areas, are characterized by opposite movements reaching a depth of 50 m.

THE CATALANO ISLAND AND THE PLIOCENE VOLCANIC ACTIVITY IN THE SINIS REGION

Located 13 km offshore west of Capo S. Marco and 10 km southward Mal di Ventre island, the very small island of Catalano show a sub-rounded form that not exceed the 125 m in diameter. This island is a neck made up of basaltic rocks referable to the Plio-Pleistocene cycle. Catalano rocks are commonly microgranular basalts, often affected by alteration processes and showing several mainly sub-vertical fracture systems. Locally, the magmatic body is crosscutted by sub-vertical basaltic porphyritic dykes, 1 m thick, containing greenish hornfelsed enclaves coming from Palaeozoic basement (figg. 5; 6). Sub-angular fragments of metamorphics, occur at the contact with host-rock. In the inner sides of the small island are centimetric peridotite nodules and sub-vertical cumulitic levels made up of olivines and Ca-rich pyroxenes.

Catalano islands are located at the western culmination of Sinis tectonic block. Geological survey of submerged areas near the Catalano island, indicates a N/S trending basaltic lava-flow extended for at least 5 km not far to Mal di Ventre island, 1.5 km northward of Catalano island, the submerged lava flow, rises gradually to a small sub-rounded mound about 5 m below sea level, likely representing a possible volcanic focus of observed lava flow.

Because of the key role played by the Plio-Pleistocene volcanic rocks in constraining the evolution of the Sinis area, selected samples of basaltic rocks outcropping in Catalano and in Sa Mulargia area, were sampled to obtain chronological data. Samples were dated by $^{40}Ar/^{39}Ar$ method at the Oregon State University. Samples were irradiated at OSU TRIGA reactor for 6 hours at 1MW power. Neutron

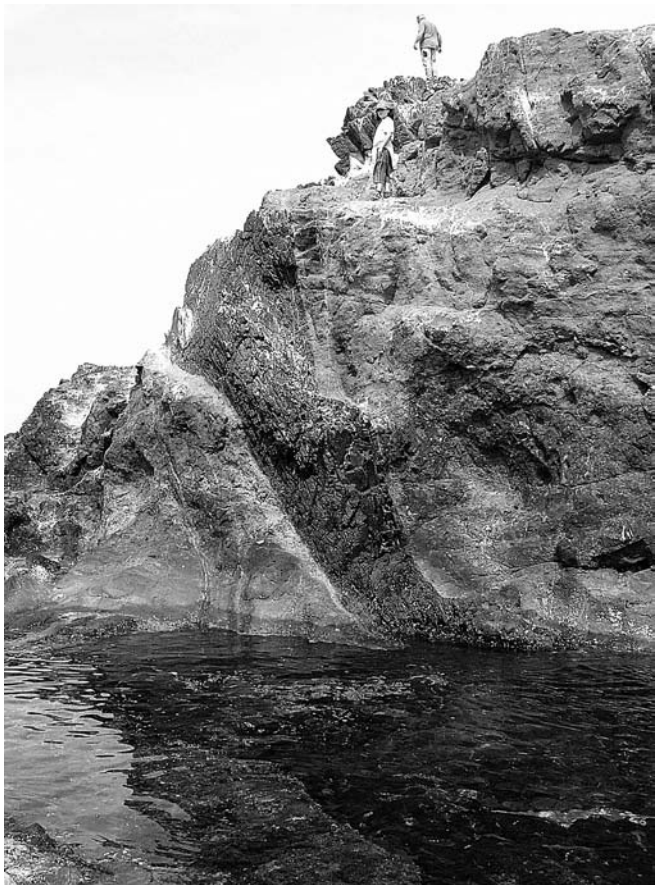

FIG. 5 - Sub-vertical basaltic dikes crosscutting the volcanic rocks of Catalano small island.

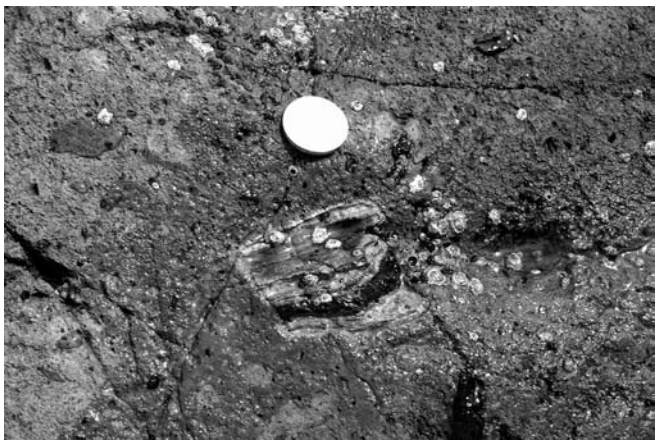

FIG. 6 - Hornfelses fragments in the porphyritic basaltic rocks of Catalano island.

flux was measured using FCT-3 biotite monitor (Renne & *alii*, 1994). Data were successively reduced by ArArCALC software for geochronology (Koppers, 2002).

Obtained radiometric data indicate values of about 4.7 Ma for Catalano basaltic rocks (tab. 1). In addition, Catalano rocks clearly predates basaltic lava flows characterizing the nearby Sinis area for which we obtained decidedly younger values of about 3.2 Ma.

TABLE 1
^{40}Ar /^{39}Ar whole rock age determinations for selected basaltic rocks of Sinis area (western Sardinia, Italy)

	Plateau				Normal isochron		Total fusion
	Age ± 2_	Steps	% ^{39}Ar	MSWD	Age ± 2_	$^{40}Ar/^{39}Ar$ ± 2_	Age ± 2_
MP1	**3.28 ± 0.12**	7/12	75.2	0.73	3.33 ± 0.27	294.4 ± 4.5	3.18 ± 0.24
MP2	**3.18 ± 0.08**	6/11	75.1	0.92	3.18 ± 0.12	295.0 ± 3.0	3.11 ± 0.16
CT1	**4.83 ± 0.18**	10/11	99.3	1.43	4.79 ± 0.29	296.1 ± 3.6	4.77 ± 0.37
CT2	**4.76 ± 0.16**	10/12	96.1	0.61	4.60 ± 0.20	294.6 ± 2.4	4.60 ± 0.74
CT3	**4.58 ± 0.06**	8/12	92.3	1.39	4.60 ± 0.12	293.6 ± 8.4	5.39 ± 0.20

All ages are expressed in Ma. In bold are reported preferred interpreted crystallization ages. Samples labeled «MP» and «CT» refer to basaltic rocks of Sa Mulargia and Catalano small island respectively. MSWD refer to the mean square of weighted deviates.

Stratigraphical (Cherchi & *alii*, 1978) and palaeontological data (Abbazzi & *alii*, 2008) available in the literature for Sinis region, suggest the occurrence of marine environment until middle Pliocene (3.5 Ma); the comparison between these data and those offered by geological survey and radiometric ages collected in the present paper, indicate a contrasting evolution between the Sinis area and the western portion of Sinis block constituted by Catalano and Mal di Ventre island and the nearby submerged area.

The correlation between basaltic lava flows of the Sinis area and those drilled in the northern Campidano, indicate the following. Forms of Plio-Pleistocene volcanic activity in the Sinis surrounding areas as Capo Frasca, Monte Arci and Montiferru massifs (fig. 1), suggest a common flow-direction of lava flows to the Campidano though.

The relationships between these volcanic episodes and those drilled in the northern Campidano, indicates considerable tectonic activity in this region in recent times prior and after the basaltic activity. Basaltic rocks observed in the Oristano 2 drilling near Riola Sardo, are located at 230 m of depth and cover about 500 m of sedimentary deposits referable to Pliocene (Cherchi & *alii*, 1978). Quite similar data are offered by Oristano 1 drilling near Oristano town where basalts occurred at 322 m, lying over 500 of sedimentary deposits of Pliocene age (fig. 3).

Good comparison between depth and thickness of Pliocene sedimentary covers, is in good agreement with a narrow time span separating the several volcanic episodes.

During this continental period the northern Campidano plain was characterized by a hydrographic network fossilized by basaltic lava flows erupted at the edges of tectonic though.

Data from Mortiferru are quite different. In general the southern portion of Montiferru volcanic activity shows western or south-western flow-direction (Narbolia and Riola Sardo). The volcanic episode found in the Oristano 2 drilling show a thickness of 25 m, implying the occurrence of a pronounced cañon rather than an alluvial plain.

The thickness of Pliocene volcanism in the Sinis region, plays a key-role in the geomorphological reconstructions.

THE RECENT GEOMORPHOLOGICAL EVOLUTION OF THE SINIS REGION

Schematically, Catalano Island testifies to the occurrence of a NS trending palaeo-hydrographic network, located in the western culmination of Sinis block, fossilized by subaerial volcanic activity. In particular, forms observed below sea level indicate the occurrence of a narrow and elongated hydrographical network in which inversion relief processes were active as suggested by local cañon forms. Moreover, Mal di Ventre-Catalano islands represents continental areas during volcanic activity, not invaded by the sea before middle Pliocene (about 4 Ma). In contrast, Sinis region was a submerged area limited northward by the Montiferru volcanic complex. The Sinis area contacted eastward with a continental area dominated by a hydrographical network draining to the northern Campidano tectonic though coming from northern massifs of Sardinia, [still testified by the occurrence of palaeo-hydrgraphical forms fossilized by subaerial lava flows of Plio-Pleistocene cycle].

Basalts in the Oristano 2 drilling, at about 230 m, implies the existence of a hydrographic network at the southern edge of Montiferru massif and a palaeo-mouth of Tirso river in the Is Arenas area, immediately north of Sinis region, as first argued by Seuffert (1970). On the other hand, the occurrence of a wide dune field system distributed along Is Arenas beach, implies the existence of an important basin offshore, as documented by some Authors (Lecca & *alii*, 1986). This hypothesis is corroborated by the occurrence of a fossil soil in the aeolian succession of the Capo S. Marco cliff, likely referable to the middle Pliocene (Pecorini & *alii*, 1974) as well as by the presence of marine levels of Thyrrenian age (Cherchi & *alii*, 1978), drilled at 33 m and 7 m in the Oristano 1 drilling, in the northern Campidano tectonic though.

At a large scale, fast subsidence characterized the Campidano though, indicated by thick Pliocene continental deposits on top of basaltic lava flows. Lava flows recognized in the Sinis region, about 3 Ma old, fossilized a poorly developed hydrographic network in a young continental area.

Basaltic lava flows, recognized in sa Mulargia area, documented the presence of a poorly defined hydrographic network developed in a younger continental area, as constrained by stratigraphical relationships offered by terrestrial fossil vertebrates (Abbazzi & *alii*, 2008).

Contemporaneously, the western sides of Sinis tectonic block were characterized by relief inversion processes. Particularly, the Catalano island is morphologically limited westward by a submerged cliff located along the main faults of Sinis block separating from the continental shelf.

To the east, a smooth submerged morphology had palaeoponds located now at a depth of 30 m (Forti & Orrù, 1995). Lava-flows in Sinis region, moreover, emplaced on a uniform landscape that could be extended at the inner part of northern Campidano. In contrast, Capo S. Marco lava flow is in a valley strongly incised in marine deposits of middle-upper Miocene. Contact field relationships basalts/sediments show pronounced scarps, locally still fossilized where the inversion of relief is less evident, as testified the occurrence of deep gravitational deformation (fig. 7).

On the basis of we feel that the Capo S. Marco lava-flow could be contemporaneous to the Catalano volcanic activity and linked to a hydrographical network influenced by tectonic movements that controlled the basalt form.

FIG. 7 - Active deep deformation processes, at the top of basaltic lava-flow (Capo S. Marco cape).

CONCLUSIONS

Radiometric ages on volcanic rocks, of Catalano small Island and sa Mulargia in the Sinis mainland, allow us to review the landscape evolution.

The time span of about 1 Ma between two dated episodes, allow us to hypothesize the change of preexisting hydrographic network began progressively less pronounced and characterized by rivers flowing in flat morphologies. Similar cañon morphology documented in lava flows of Capo S. Marco cape and in the submerged area nearly of Catalano lava-flow suggest a common evolution in the same time span during the early Piocene.

As in other areas of Sardinia such as the Logudoro basin (Sias, 2002), volcanic episodes played a key-role in landscape evolution, because they fossilize a hydrographic network and likely constrained the palaeo Tirso river to leave the ancient valley at the southern edges of Montiferru massif, in particular, the role played by basaltic lava flows in fossilizing the ancient landscape and in determining the variation to the south of the Tirso river. The Tirso river changes its course from a possible mouth located along the Is Arenas beach, southward of Montiferru massif, to the northern Campidano though in an area now occupied by Oristano gulf (fig. 8a; b). This morphological/volcanic feedback, conditioned the present morphologies and produced the wide ponds at the eastern side of Sinis region. The progressive migration, toward the northern Campidano tectonic though hypothesized for the Tirso river, is likely related to an increase of its subsidence rate, as testified by 730 m thick of Pliocene continental deposits recognized in the Oristano 1 drilling and more than 60 m with respect of Oristano 2 near Riola Sardo.

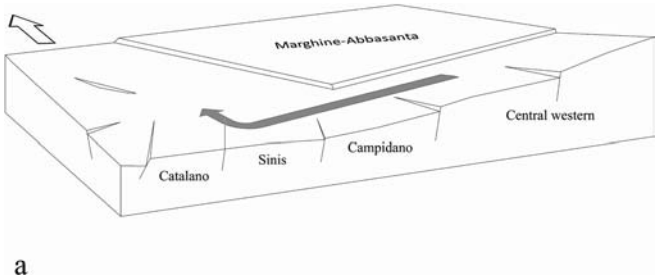

FIG. 8a - Schematic block-diagram for pre-basaltic evolution (early-middle Pliocene) of lower course of Tirso river. Grey arrow, refers to the river flow. Names refer to the tectonic blocks.

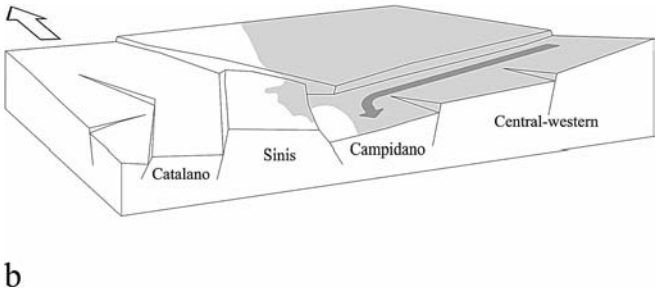

FIG. 8b - Schematic block-diagram for syn to post-basaltic evolution (early-middle Pleistocene) of lower course of Tirso river. Grey arrow, refers to the river flow. Names refer to the tectonic blocks. Note the evolution of Tirso course, constrained by the uplifting of Sinis block.

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