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A NEW LAKE IN ITALY (SOUTHWESTERN SARDINIA): A MAAR?

ABSTRACT: GINESU S., *A new lake in Italy (Southwestern Sardinia): a maar?* (IT ISSN 0391-9838, 2012).

This study of a small lake basin located near the southwestern coast of Sardinia has allowed individualisation of this morphology as this lake is linked to the volcanic outcrops of the Oligo-Miocene that constitute the basement of this territory. The historical, physical and geological characteristics of this lake, known as «Stagno'e Forru» («stagno» means «pond», so it has always been considered as such), allow us to hypothesise to a possible origin as a maar formed during the final activity of the calc-alkaline cycle in the Oligo-Miocene span. The possible genesis is examined and discussed within the recent evolution of the landscape. Its age, in accordance with the ancient shorelines individualised in the sea base and in the cords of the beach, cannot be established, making drilling of the lacustrine deposits necessary for further investigation. However, knowledge of this lake is significant because it is the confirmation of another lake existence in Sardinia; until now, Sardinia is known to have only one natural lake, which was formed by an aeolian obstruction.

KEY WORDS: Origin of lakes, Maar, Landscape evolution, Sardinia, Italy.

RIASSUNTO: GINESU S., *Un nuovo lago in Italia (Sardegna sud occidentale): un maar?* (IT ISSN 0391-9838, 2012).

Lo studio di un piccolo bacino lacustre situato in prossimità della costa sud-occidentale della Sardegna ha permesso di individuare tale morfologia come un lago legato all'attività vulcanica dell'oligo-miocene che costituisce il basamento del territorio interessato dall'indagine. I caratteri storici, fisici e geologici di questo lago, conosciuto come lo «Stagno'e Forru» e, come tale, sempre considerato uno stagno, consentono di ipotizzare la sua origine formata da un maar, quale morfologia relitta dell'ultima fase di attività del ciclo vulcanico calc-alcalino dell'Oligo-Miocene. La sua genesi viene esaminata e discussa nell'ambito dell'evoluzione recente del paesaggio. La sua età, in accordo anche con le antiche linee di riva individuate nella piattaforma a mare e nei cordoni di spiaggia, potrà essere riconosciuta con maggior precisione grazie alla campagna di sondaggi che si sta effettuando sui sedimenti del suo fondale. La sua conoscenza appare comunque significativa perché in Sardegna, finora, è noto un unico lago naturale la cui origine è legata ad uno sbarramento eolico.

TERMINI CHIAVE: Laghi, Maar, Evoluzione del paesaggio, Sardegna, Italia.

INTRODUCION

Sardinia is known to have only one natural lake, Baratz lake, which is located in the northwestern sector of the island near the city of Alghero. The origin of this lake is linked to the cold climate variations of the upper Pleistocene, when the accumulation of sand pushed by the Mistral wind (coming from NW) caused the obstruction of a small river, thus creating an aeolian obstruction lake.

The main aim of this study is to define this water body as a new lake and to investigate its possible origin. Therefore, it is important to remember what conditions are universally approved in defining the existence of a lake with certainty; it is especially useful to remember the definitions offered by the physical geology, physical geography and geography. Generally, this form is defined as a «Depression of the surface occupied by water generally isolated, not in direct communication with the sea»; and, according to geographical texts, the «water's basin is not immediately connected with the sea» (Palagiano, 1972). The definition is more exact in physical geography: «in physical terms, lakes can be defined as a mass of water, generally isolated, but sometimes brackish or also salty, located in natural depressions of the continental surface, without direct communication with the sea; the communication with the sea can happen through a river arm or it can be completely absent. The origin of the lakes can be reported to different causes of geologic, geomorphologic and also human nature» (Lupia Palmieri & Parotto, 2000). Also, specific texts on the origin of such forms offer the concept that a «lake is a water-filled hollow in the earth's surface, inland from the ocean» (Burgis & Morris, 1987).

A geomorphologic survey along the coast of southwestern Sardinia, with the purpose of reconstructing the recent

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This work was carried out during fieldwork in 2008-2010, and was made possibile by the collaboration of my multi-composed crew. I am grateful to Drs. S. Sias (Geomorphology), B. Tadolini (Biology), D. Carboni (Geography), M. Coppini (Sailing), F. Secchi and M. Marchi (Petrology) for their constant support and to Mr. G. Fonsa for providing support during the lake survey.

beachline evolution, has allowed a detailed three-year study of a small basin. This basin has been considered a pond, as underlined by its ancient name «Stagno'e Forru», which in the Sardinian language means «fire-bow pond» because of its circular form and the red colour of the volcanic rocks surrounding it.

The geographical analysis and the characteristics of the Stagno e'Forru adequately respond to the condition of a lake, and as will be seen subsequently, its physical characteristics and geographical context reveal that it is dissimilar from the only natural lake present on the island, the lake of Baratz, which is located along the same western coast of Sardinia (fig. 1); above all, their forms distinguish the two morphologies. The first, the lake of Baratz shows a lengthened and branched form, which is typical of obstruction lakes; the Stagno e'Forru, with its circular form, is generally attributable to a crater lake.

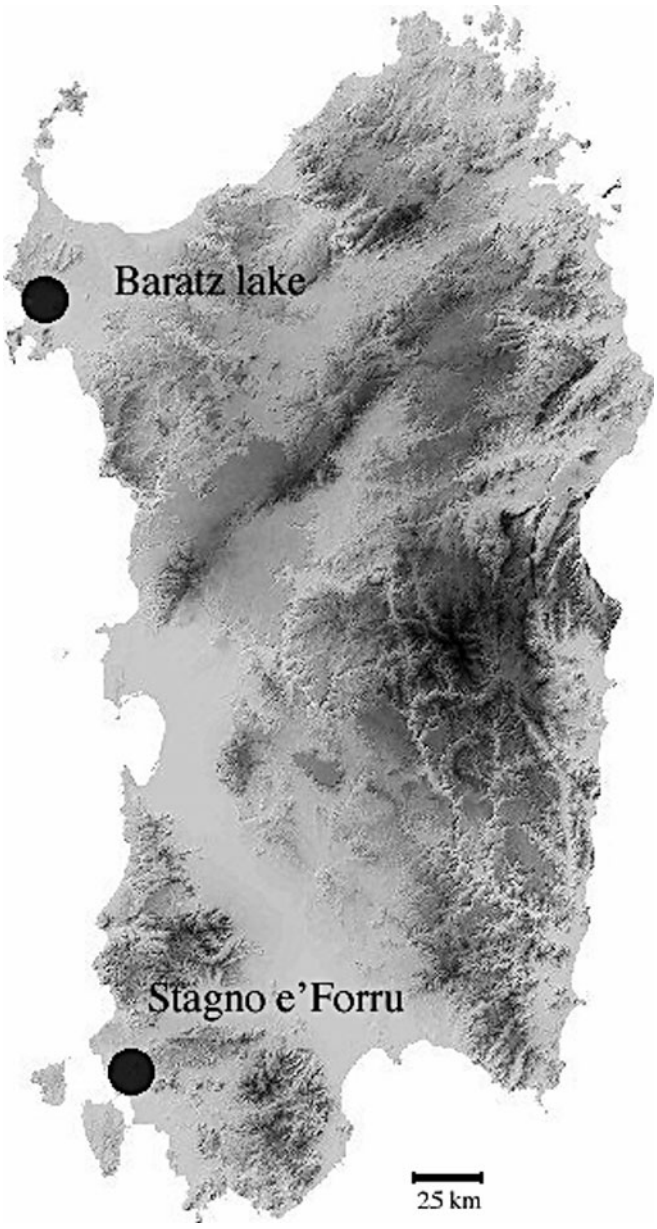

FIG. 1 - Studied area location (Stagno e'Forru) and position of the one lake present in the island (Baratz lake).

THE GEOLOGICAL AND GEOMORPHOLOGICAL ENVIRONMENT

The western Sulcis region of Sardinia, where the study area is located (fig. 2), is characterised by outcrops of a Palaeozoic basement of Cambro-Devonian age in discordance with the volcano-sedimentary coverage, which differs in age and geologic meaning. The more meaningful landscape line is represented by wide volcanic sequences referable to the Oligo-Miocenic orogenic magmatic cycle (Morra & *alii*, 1994). Under these, isolated calcareous edges referable to the Trias are recovered (Maladroxia in the island of S. Antioco). Sedimentary successions of a continental environment are present and are constituted by clastic deposits with coal layers and continental deposits intercalated (Paleogene) and referable to the Cixerri Formation of the lower Eocene-Oligocene. The studied coastal tract is widely covered by aeolian deposits referable to more climatic episodes of the Pleistocene, with calcareous horizons of a marshy environment that, altogether, reach over 15 meters, filling the ria morphology that characterised this territory up to the last cold climatic phases of the middle-upper Pleistocene (Biaggioli & *alii*, 2006).

The volcanic sequences appear diffused on the surface in the western portion of the investigated area, where they reach a thickness of approximately 1000 ms, referable to the time span of 27-15 My (Araña & *alii*, 1974; Morra & *alii*, 1994; Lecca & *alii*, 1997). These sequences are mostly represented by andesitic rocks and ignimbritic flows with different compositions, from dacitic to comenditic compositions (Biaggioli & *alii*, 2006).

Tectonically, the studied area is situated out of the principal branch of the Sardinian *Rift*, and it is articulated in different blocks that are tilted and small *half-graben* basins filled by Oligo-Miocenic volcanic successions (Lecca & *alii*, 1997).

Such sequences fill two different sub-basins: the trough of Carbonia in the southern portion and the trough of Cortoghiana in the northern portion. Away from the culmination of the tilted blocks, such tectonic system favoured the accumulation of aeolian and marine deposits for the whole Pleistocene in the sector between the Palaeozoic basement and the volcanic covers, according to a meridian direction. Recent morphological reconstructions (Biaggioli & *alii*, 2006) posit the existence of a deep ria morphology approximately 25-30 ms above the actual sea level. Such filling deposits constitute the most ancient sediments referable to the Pleistocene climatic fluctuations in this area (Biaggioli & *alii*, 2006), and they show reworked traces during the following climatic changes (buried soils and abandoned paleotalwegs).

Recent debris deposits are present that constitute the morphological link among the slopes of the ignimbrites

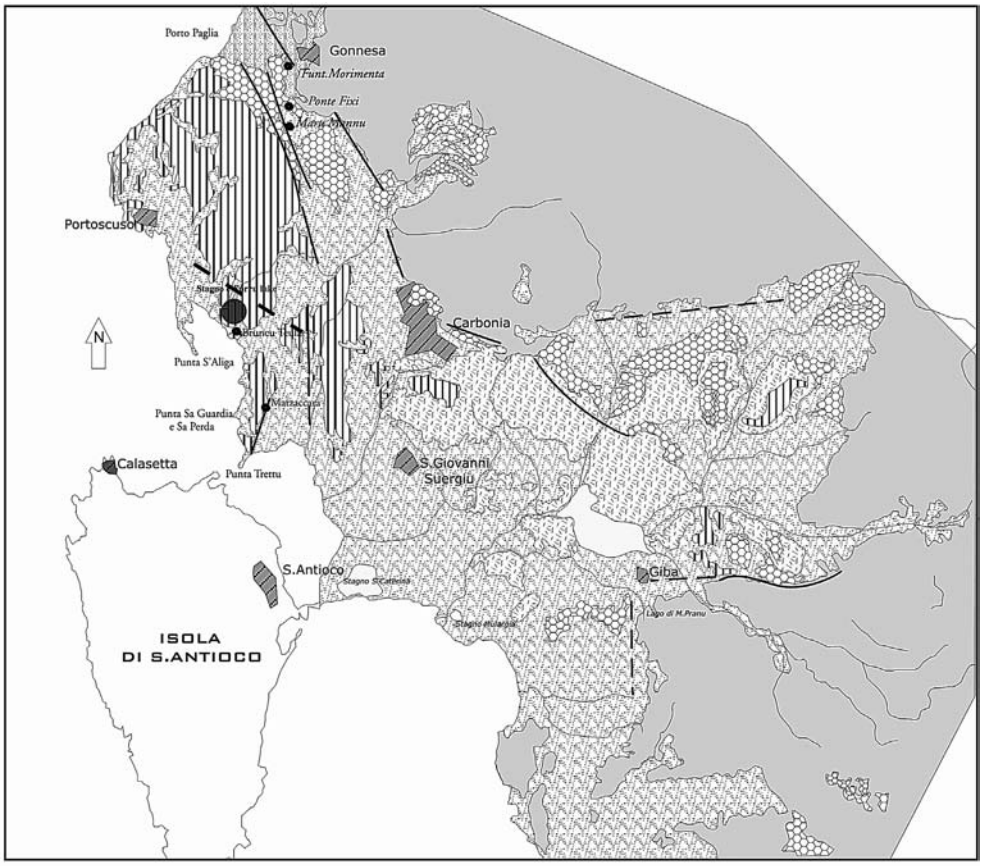

FIG. 2 - Semplified geological skeme of the south western sector of Sardigna. (1) Pleistocenic not differentied deposits; 2-3 orogenic volcanic episodes of the Oligo-miocenic cycle: ignimbrites (2), upper sequence, and andesites (3) lower sequence; (4) pre-miocenic sediment covers; (5) palaeozoic basement not differenzied; (6) main fault; (7) presumed fault. The grey circle indicates the Stagno e'Forru's localization (from Biaggioli & *alii*, 2006, partially modified).

that constitute the Bruncuteula basin, where the lake currently exists. Such deposits, which are not visible, are probably attributable to the existence of a coastal bar when the sea level reached more elevated altitudes than the actual one (12 ms), probably in the middle and middle-lower Pleistocene. The most recent terms of the actual sedimentation are represented by the wide sandy deposits of the beach along this coast, one of the most dynamic of all Sardinia. Of particular interest, finally, is the lake deposits of the Stagno e'Forru that constitute the progressive burial of this morphology, of which no reference exists in the literature.

DESCRIPTION OF THE LAKE

The position of the Stagno'e Forru appears peripheral for the whole southwestern sector located in a marginal land condition. The first historical cartographic document about the existence of this lake is possibly in a map of Sardinia dated to the first part of the XVIII century (Colombino, 1720), while a second possible reference is Captain W.H. Smyth's Map of 1827.

Another reference that appears to be a great deal more possible is the 1826 «Carte pour servir à l'intelligence. Ier Volume du Voyage en Sardaigne» (Della Marmora, 1826). A more recent cartographic reference can be attributed to the relief of the Map of Italy at a scale of 1:100,000 on Foglio (Sheet) 232 «Isola di San Pietro», which is dated 1903, compiled by 1897 surveyors and updated in general recognitions in 1940. The updating in 1983 was entirely on the administrative limits. Finally, in 1926, the lake appears on the Carta of the Italian Touring Club at a scale of 1:250,000 in Foglio (Sheet) 45 «Iglesias».

Today, the small lake is used as a reserve of fresh water for the industrial area; nevertheless, the evidence of aerial photos taken over the zone indicates the existence of fresh water in the lake since 1943 and the variability of the quantity of water contained in the lake (fig. 3 a/b). The sequence of the observed photos does not allow appraisal of the annual regime, but it can be deduced because the decreasing level of the water during the summer allows the emergence of a marshy island in the centre of the lake. These photos also confirm the existence of a natural lake exclusively fed by the regime of the rains before being in a steady state in the years '70/80.

DESCRIPTION OF THE PHYSICAL AND MORPHOLOGICAL CHARACTERISTICS

The Stagno e'Forru possesses numerous characteristics that make it unusual within the landscape of Sardinia. First, the lake has a perfectly circular form with a middle

FIG. 3 - The fig. 4a, a particular from a 1954 aerial photo, taken in summer period (june), show the Stagno e'Forru stil partially submerged by fresh waters while in fig. 4b, taken in the 1977 springtime, the activities of hydraulic organization can be observed round the lake full of fresh water.

diameter of approximately 450 ms. The lake represents a small morphology depressed in an area enclosed by tertiary volcanic outcrops that form a ring around the lake; the ring is open at two points where the recent changes of the coast have determined backshore aeolian deposits. The lake's extension is approximately 159 hectares, while its perimeter (calculated in May 2011) is 1,350 km. The extension of the morphological ring that surrounds it (a crater form) can be increased by approximately 30% in comparison with the reported measure to the level of the water of the lake. The Stagno e'Forru is approximately 600 ms from the sea and does not have any water from outside its basin; it is only fed by meteoric waters that revert into its basin directly.

The bottom profile is morphologically flat and covered by a thick blanket of thin sediments, predominantly sandy clays with abundant organic matter; it is possible to sample the first 80 cm in proximity of the deepest point. The depth quickly increases from the banks of the lake to conform to values up to 2 ms; the maximum depth is 2,70 ms in the oriental sector (fig. 4). The values of temperature, salinity and conductibility were taken on a particularly warm day in May 2011 (external temperature of 25°-26° from 11.00 at 16.00 hours). The values of salinity and conductibility do not have a particular meaning because of artificial mixing with the outside waters; nevertheless, the salinity was below 2‰, while the conductibility had low values (70σ), confirming a low degree of mineralisation.

The temperature in the most superficial layer was 21°. However, under the first meter of depth, it was 19°; the lowest value of 18° was recorded in the deepest point.

THE ORIGIN

The origin of this lake is unclear, and determining it requires lengthy preparation for conducting surveys and

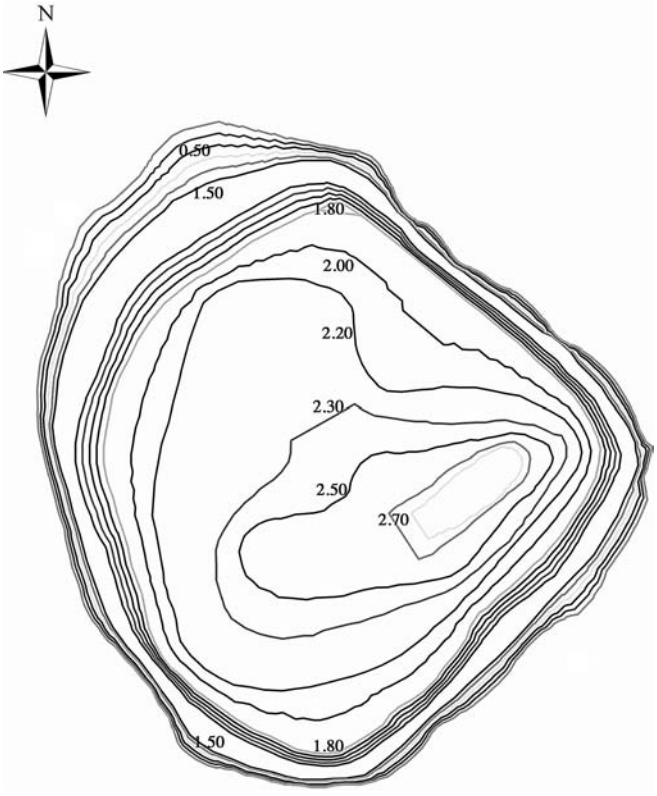

FIG. 4 - The batymetric map of the Stagno e'Forru shows its low deepness and its flat bottom morphology.

examining historical sources and the scarce literature of this area. A true definition does not exist on its origin but, in the technical relationships furnished by the various district administrations, it is considered a pond located in the sands of the Pleistocene or on a tectonic volcanic depression without any definition. The survey and the morphological, petrologic and geologic evidence have led us to propose an origin linked to a presence of a small volcanic crater.

THE MAAR HYPOTHESIS

As previously described, the Stagno e'Forru is placed within the Oligo-Miocenic volcanic context that characterises the entire surrounding area and produces the eastern and western closing of the basin by ignimbritic reliefs that are 34 m and 33 m above sea level, respectively, while the altitude rises to 38 m to the north. The divide of these reliefs determines an area that could coincide with an ancient volcanic crater (fig. 5); the rocks represented in these reliefs would have been arranged with an explosive episode. In fact, in the northern sector, pyroclastic levels with thin materials are also present (ashes and ejecta, fig. 6). The outcrops along the ring of the reliefs show a strong dip of the rocks towards the outside in the west reliefs (Bruncu Teula hill) in the reliefs set in the north (Sa Serra de Paringianu hill), while they appear smaller in the oriental reliefs (Nuraxi hill). The ring of tefra has a diameter of 600 m and, therefore, would be classified as a maar of average dimensions, considering that monogenetic maar-diatreme volcanoes are the second most common volcano type on continents and islands (Lorenz, 1986; Lorenz & *alii*, 1970). Nevertheless, the diameter of approximately 450 ms would indicate a «small» maar dimension, according to the used classification (Gevrek & Kazaner, 2000). The inner slope dips towards the interior of the crater at approximately 45° (not a natural angle of rest), and the outer slope dips outward, showing an angle of approximately 15°, often according to the ignimbrites' inclination (fig. 7). From the comparison between the activity span of the maars and their respective sizes (Lorenz, 1986; 1970), the large dimension of maars and the depths of their craters is linked to their activity for months or even years, and so, the maars grow in size the longer they are active. The small dimension of Stagno e'Forru lake suggests that it was produced by one brief volcanic episode at the end of the Oligo-Miocenic cycle, the younger is referable to 15 M.y. BP.

The lake is located along a fault oriented NW-SE, which is possibly responsible for the gentle morphologies between the ring hills.

LANDSCAPE RECONSTRUCTION PROBLEMS

The geomorphological evolution of the territory and its surroundings appears to be highly complicated due to substantial modification during the last million years. The morphological and chronological data in our possession (Orrù & Ulzega, 1989; Biaggioli & *alii*, 2006; Lecca & *alii*, 1997) show how much the territory has changed after the last effusive activity, which ceased approximately 15 M.y. Before Present (Araña & *alii*, 1974; Morra & *alii*, 1994; Lecca & *alii*, 1997). The post-volcanic tectonic movements produced a progressive subsidence of the western portion that favoured the modification of the coastline and the variations of the sea level over the whole coast of southern Sulcis. The southwestern tract of the coast is progressively lowered by the SE-NW trending faults up to an isobath of

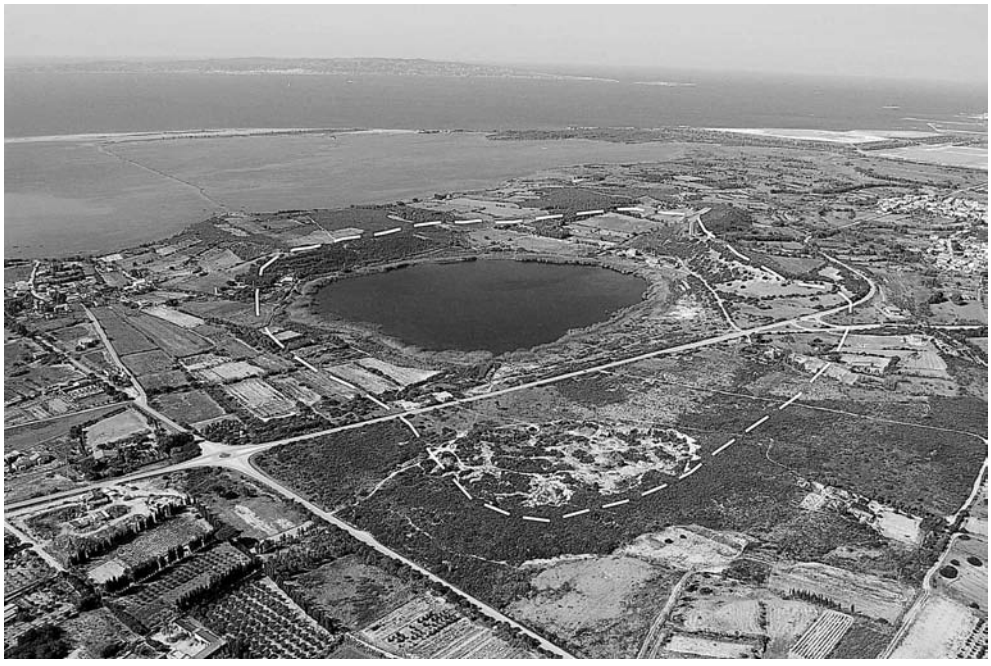

FIG. 5 - The elicopter view show the divide of the Stagno e'Forru lake (white dotted line) and its position regarding actual coastline.

FIG. 6 - Pyroclastic deposits round the Stagno e'Forru perimeter, they contribute the formation of the external ring.

over 100 m to few kilometres from the shore. The morphological difference between the coastal portion and the inner part is underlined by the process of relief inversion that brings the Oligo-Miocene volcanic outcrops to altitudes of more than 200 m, showing the morphologies as a plateaux. This process shows the elevated erosion capacity of the surfaces and the structures of the Tertiary one. Unfortunately, the great quantity of eolian sands that uniformly cover the inner area and the before backdrops have not allowed the identification of forms and deposits referable to the upper Pleistocene landscape to confirm a transgression of the sea inside the lake. The present altitudes of the divide on the morphological ring of the Stagno e'Forru do not disprove this hypothesis because the altitudes remain at 13 m on the western divide and 9 m on the southern divide (fig. 5). The existence, however, of a marine environment does not invalidate the idea of the existence of a maar; besides, on the walls of the morphological ring of the lake, forms attributable to a meteomarine dynamic are not present.

FIG. 7 - On the top of the ring, the ignimbrites show an evident dip to external slopes.

The hydrographic network of the area flows outside the ring to a few metres below the dividing line, although it flowed at a higher altitude during the upper Pleistocene (Biaggioli & *alii*, 2006). This study also examined the surveys undertaken in the surrounding territory during the end of the 1970s and the beginning of the 1980s (Casmez, 1980-82) produced during groundwater research in the graben of Sulcis. Within this study, the drillings nearest to the Stagno e'Forru (drillings PF, PD, PE, PB, PA in the cited study) were considered; all have underlined a notable thickness of the detritical superficial horizons constituted by sands, slimes and clay levels that, in some cases, exceed 60 metres. These data could support the idea of a possible «emptying» of the maar crater, preserving the deepest structure; nevertheless, it appears difficult to justify that a «fragile» morphology such as a maar could have been intact for over 10 million years, preserving an almost original situation. Besides, the ring constituted by the ignimbritic outcrops is not necessarily arranged with this morphology. After the eruption ended, the maar crater was filled by the groundwater and surface water, but only the youngest maar would still contain the lake (Lorenz & *alii*, 1970; Lorenz, 1986) because the depression would be filled over time by lacustrine deposits and would be destroyed by erosional processes. The most meaningful test to document the presence of a maar or a volcanic crater is the presence of the fault that cuts with a SE-NW direction through the area where the lake is located; nevertheless, we must remember that, in Sardinia, erosive activity would have eliminated the most part of referable volcanic morphologies of episodes older than 0.6/0.7 M.y. (Sias, 2002; Assorgia & *alii*, 1992).

From a geomorphological point of view, the hypothesis of a possible and quick formation of the crater can be shared because it corresponds better to the possible morphological reconstruction of the territory.

An important process immediately produced by the event after the explosion is the reducing partly the depth of the hollow. This process could also explain the particularly flat morphology of this morphology. By the dimensions of the ring (single ring) and by the characteristics of the flat bottom of the lake, it could be seen as the consequence of a small volcanic explosion during the last calcalkaline activity in the Miocene. A comparable example can be seen in the northern sector of the island where a similar miocenic volcanic crater is present. This morphology still preserve the volcanic complex and the crater in the top of the relief (fig. 8). The existence of this volcanic crater in the southwestern part of Sardinia may have played an important role in the shoreline variation during the Pleistocene. A further step in the investigation could be finalized to survey on lake sediments and deposits in the external sides, in order to document any ingression of the sea during the earliest phases of the Middle and Upper Pleis-

FIG. 8 - A panoramic view of Larenta Mount from east, in the central part of Sardinia. This relief is a volcano with a pseudo circular crater. The volcanic cycle is the same as Stagno e'Forru pond.

tocene and to reconstruct the geomorphologic evolution of the coastline.

DISCUSSION AND CONCLUSION

From a physical geography point of view, the most meaningful result of the work is to classify a new natural lake in Sardinia, which has, until now, only been documented and studied as a lake whose origin was due to a Pleistocene dune obstruction. The evident characteristics of the Stagno e'Forru allow defining it without some doubt as a lake, geographically describable as a coastal lake not otherwise from the existing Baratz lake (tab. 1). Its origin is still uncertain, and as previously described, it shows characteristics of volcanic morphology by explosive activity.

Although this hypothesis is reliable, other hypotheses cannot be excluded, such as the diapiric structures in the lava flows, which are more complex and rare phenomena but are present in the adjacent zones and in the same effusive complex, that recently signalled in very small forms (Mundula & *alii*, 2011) or as a particular form of volcanic explosion. However, today, the maar hypothesis is morphologically the most compatible with its origin, also on the basis of geomorphological reconstruction of the area; however, the question about the reasons that have preserved this morphology in the course of more than 10 million years remains. The presence, however, of volcanic forms similar in other parts of the island could comfort the idea that some areas of Sardinia were more protected from the strong areal erosion; especially in those parts of the volcanic areas where the plateaux or buttes morphologies forced the river system to a rapidly changing their course and induced a much more effective erosion.

The next steps are as follows: the search of its origin through a survey of the structures around the ring; the definition of its age through the analysis of the lake sediments and preliminary radiometric data and the search for a compatible model with the geomorphologic evolution of the Plio-Pleistocenic landscape in this part of Sardinia.

TABLE 1 - Comparison table between the two lakes. In the table the nuraghi, a particular Bronze Age megalithic buildings, are considered for a archaelogical comparison in the water utilization in historical period (comment not contained in the present work)

	Stagno e'Forru	**Baratz**
	m	m
North-South distance	461	810
East-West distance	435	914
NS-EW distance	445	581
SW-NE distance	385	1.170
Perimeter	1.350	5.000
Western threshold hight	13	67
Southern threshold hight	9	
Western threshold top distance	287	247
Southern threshold top distance	9	
Sea distance (W threshold)	590	1.260
Sea distance (S threshold)	577	
Medium depht	2	3
Maximum depht	2.70	14
Medium salinity	fresh water	fresh water
Nearest Nuraghe distance (historical monument II Mill.bC.)	964	2.35
Less than 5 Km Nuraghi number	6	3

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