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LANDSCAPE EVOLUTION IN THE TACCHI AREA (CENTRAL-EAST SARDINIA, ITALY) BASED ON KARST AND FLUVIAL MORPHOLOGY AND AGE OF CAVE SEDIMENTS

ABSTRACT: DE WAELE J., FERRARESE F., GRANGER D.E. & SAURO F., *Landscape evolution in the Tacchi area (Central-East Sardinia, Italy) based on karst and fluvial morphology and age of cave sediments*. (IT ISSN 0391-9838, 2012).

The east-central part of Sardinia (Italy) is characterised by Jurassic dolomitic mesas (Tacchi, or «table mountains») that overlie a Palaeozoic basement mainly composed of metavolcanics and phyllites. These mountains are the remnants of a continuous carbonate cover, dissected by faults and river erosion, and are now completely isolated hydrological systems. Most of these rivers have cut valleys more than 200 metres deep into the Palaeozoic basement rocks, whose slopes are often characterised by landslides, suggesting their recent oversteepening. Some valleys, on the contrary, have not reached the base of the carbonate sequence and appear to be suspended above the deeper incisions, apparently disconnected by them. Several subhorizontal surfaces can be distinguished on the table mountains, related to local base level stillstands. Also water table caves, scattered along the flanks of the mountains over an altitudinal range of about 200 m, show several stillstands in base level lowering. ^{26}Al and ^{10}Be burial dating of sediments in four caves located at different elevations on the flanks of the suspended Taquisara Valley show an Upper Pliocene or Lower Pleistocene age. Thus, this valley appears to be of Late Tertiary age. The deeper valleys, such as Riu Pardu, that dissect the Tacchi mountains completely, cutting deeply into the basement rocks, are much younger, as their unstable slopes suggest. Knickpoint retreat in Riu Pardu and estimated valley erosion rates suggest the capture of Riu Pardu by Rio Pelau to have occurred in the last 100 ky.

KEY WORDS: Cosmogenic burial dating, River erosion, Knickpoint retreat, River capture, Plio-Quaternary, Sardinia, Italy.

RIASSUNTO: DE WAELE J., FERRARESE F., GRANGER D.E. & SAURO F., *Evoluzione del paesaggio dei Tacchi (Sardegna centro-orientale) basato sulla morfologia carsica e fluviale e sull'età dei sedimenti di grotta*. (IT ISSN 0391-9838, 2012).

La Sardegna centro-orientale (Italia) è caratterizzata da altipiani dolomitici giurassici (Tacchi) che sovrastano un basamento paleozoico principalmente composto da metavulcaniti e scisti. Queste montagne sono quello che resta di una copertura continua, ora divisa da faglie e valli fluviali, e costituiscono attualmente dei sistemi idrogeologici completamente indipendenti. Molti di questi fiumi hanno tagliato delle valli profonde oltre 200 metri nelle rocce paleozoiche del basamento, ed i loro fianchi sono soggetti a frane, suggerendo una loro incisione abbastanza recente. Alcune valli, al contrario, non hanno ancora raggiunto la base della sequenza carbonatica e restano sospese sulle incisioni vallive più profonde, apparentemente decapitate da queste ultime.

Diverse superfici suborizzontali sono facilmente riconoscibili sulla sommità di questi tacchi, e la loro genesi è legata a livelli di base locali stabili. Anche grotte orizzontali, presenti lungo i fianchi delle montagne su un dislivello totale di circa 200 m, testimoniano diverse fasi di stabilità del livello di base locale. Età di seppellimento ottenute attraverso la datazione cosmogenica ^{26}Al e ^{10}Be di sedimenti in quattro di queste grotte, situate a diversi livelli sui bordi della valle sospesa di Taquisara, dimostrano che essi sono stati portati sottoterra tra il Pliocene superiore ed il Pleistocene inferiore. La Valle di Taquisara si è quindi formata verso le fine dell'era terziaria. Le valli più profonde, come il Riu Pardu, che tagliano i tacchi fino al basamento cristallino e oltre, sono invece molto più recenti, come suggerito dall'instabilità dei loro versanti. La recessione del *knickpoint* del Riu Pardu ed i tassi d'erosione della stessa valle consentono di stimare che la cattura del Pardu dal Rio Pelau sia avvenuta meno di 100 ka fa.

TERMINI CHIAVE: Datazione cosmogenica, Erosione fluviale, Arretramento del knickpoint, Cattura fluviale, Plio-Quaternario, Sardegna.

INTRODUCTION

Karst landscapes are important for studying past environments, because they can preserve landforms and sediments

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The first surveys and geomorphological investigations in the Taquisara area have been carried out with the help of R. Follesa. This work has benefited from the collaboration of S. Cabras, B. Ibba, A. Muntoni and L. Sanna. Many thanks to L. Sanna for having shared her cave pictures. Discussions with Vincenzo Picotti have been most helpful. This paper has benefitted substantially from the careful reviews of P. Häuselmann and A. Palmer.

that are otherwise difficult to find in surface deposits. Surface erosion, in fact, is limited in comparison to non karstic areas, since most of the surface waters penetrate easily underground, giving rise to the formation of an underground network of cave passages and enlarged fractures (Ford & Williams, 2007; Palmer, 2007). These underground voids are important repositories of old surface sediments that have washed in, often preserved in alcoves or under protecting flowstone deposits. These chemical and physical deposits, or the fossils they contain, can be dated and give minimum ages of the voids in which they occur.

Many caves are believed to have formed during the Quaternary, when climate and changing base levels (sea level, glacial erosion, etc.) were ideal for the development of karst systems. There is however increasing evidence that many important accessible and still-active cave systems developed before the onset of the Quaternary (e.g. Anthony & Granger, 2004; Häuselmann & Granger, 2005; De Waele & Granger, 2009; Wildberger & *alii*, 2010; Mocochain & *alii*, 2011). In east-central Sardinia several active cave systems are known to have started forming during the Tertiary, since well-developed conduits are filled with Pliocene basalts (De Waele, 2004).

The vertical arrangement of cave systems, composed of subhorizontal levels interconnected with vertical shafts, often reflects base level changes, in turn triggered by tectonic movements (Strasser & *alii*, 2009; Piccini, 2011) and/or landscape evolution (river or glacial erosion, sea level changes) (Marianelli & Piccini, 2011). These levels of karst development can be correlated to planation surfaces and river straths, giving a relatively good idea of the base level lowering over small areas (Anthony & Granger, 2007a).

In this research, the sediments of four inactive caves in the Taquisara Valley have been studied and were dated using cosmogenic nuclides. The Digital Terrain Model (DTM) of the area has highlighted some prominent geomorphological features, such as river captures, abandoned thalwegs, and planation surfaces. A 3D analysis of the caves and the planation surfaces has also been carried out to determine the local base level stillstands. This research allows some preliminary conclusions to be drawn on the geomorphological evolution of this part of Sardinia.

STUDY AREA

In Central-East Sardinia, Mesozoic carbonate mountains rest unconformably on a Palaeozoic basement complex composed of metasediments, metavolcanics and intrusive bodies. The Mesozoic transgression started in the Bathonian stage of the Jurassic with the fluvio-deltaic sediments and conglomerates of the Genna Selole Formation, containing marls, quartz conglomerates and coal seams, followed by marine dolostones and limestones. Surface and subsurface karst landforms are well developed in the largest of these carbonate areas.

The karstic Taquisara Valley is situated South of the Gennargentu Mountains in the east-central part of Sardinia. The river flows SW and is developed between 780-700 m a.s.l.. The valley dissects the Jurassic carbonate table mountains Tacco of Ulàssai and Taccu Isara and almost reaches the Palaeozoic basement (fig. 1). Towards the NE and SW of this area the drainage network, consisting of the Pardu and San Girolamo Rivers, has incised very deep and steep valleys into the Palaeozoic basement rocks. These channels are characterised by great variations in discharge, becoming dry during summer. The valleys are close to their treshhold angle, as their slopes are very unstable with a very large number of active landslides (Ulzega & Marini, 1977). At their confluence, Riu Pardu lies 210 m lower than Riu Taquisara, which now appears as a «hanging» valley, and steeply descends towards the SE flowing 600 m below the dolostone-basement contact at Ulassai, and reaching 125 m a.s.l. at Genna 'e Cresia, where it deviates abruptly towards the NE, flowing into the Tyrrhenian Sea near Cardedu. From an analysis of topographic maps it is obvious that Riu Pardu was captured by Riu Pelau. The drainage area of Riu Pardu upstream from the capture elbow is 44.78 km^2. An abrupt change in the river gradient, identifiable as a knickpoint, is located at 550 m a.s.l., around 10 km upstream from the capture point at 125 m a.s.l.. The palaeo Riu Pardu - named Riu Quirra - continues towards the SE 165 m higher, with a wind gap at Genna 'e Cresia, at 290 m a.s.l..

The evolution of the Taquisara Valley and of the deeply incised Riu Pardu and Rio San Girolamo Valleys, which separate the Tacco of Ulassai and Isara from the other table mountains, is reported to have occurred during Plio-Quaternary (De Waele & *alii*, 2005), based on geo-

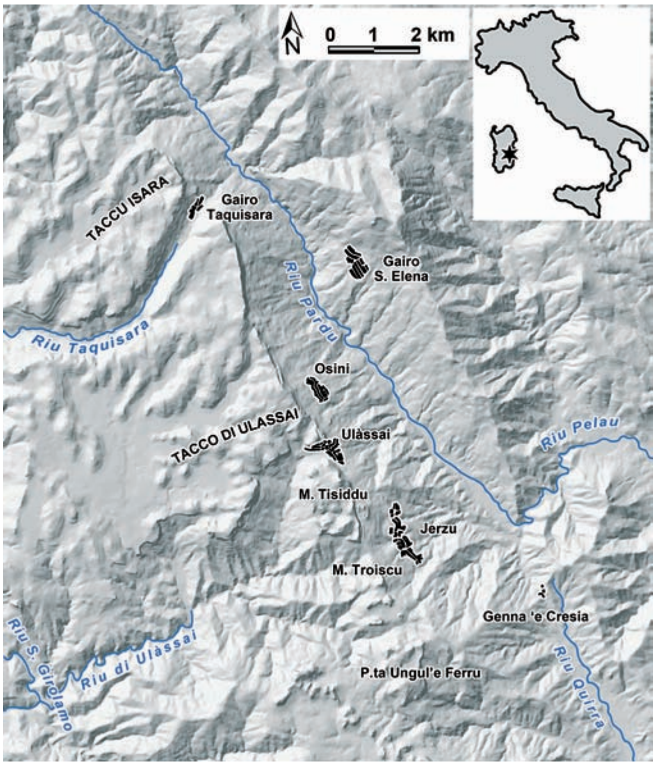
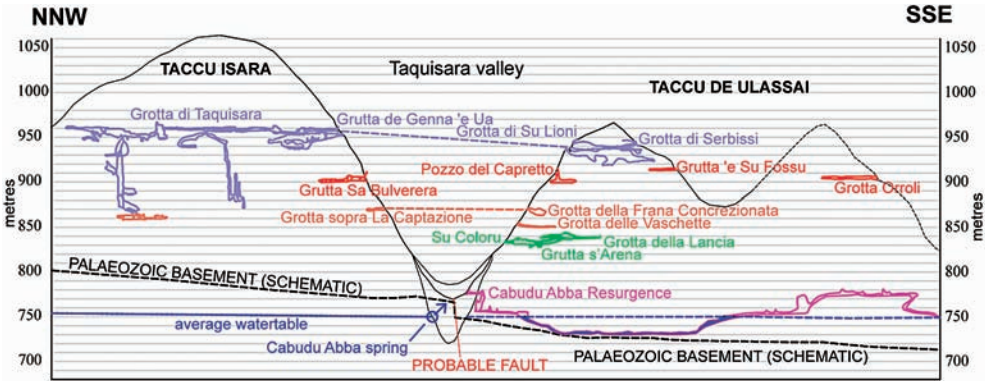


FIG. 1 - Location of the study area.

FIG. 2 - Generalised cross-section of Riu Taquisara with location of the main horizontal caves.



morphological observations, but there are no exact time constraints determined by dating methods.

Many caves are known along the borders of the Taquisara Valley, most are subhorizontal passages typically filled with stream sediments. Although their development follows more or less the almost horizontal bedding of the carbonate beds, they do not appear to be perched on resistant strata, but probably indicate former water table positions. These watertable caves are situated at different heights along the valley borders, especially at elevations of 775 m, 815-830 m, 850-870 m and 930-950 m a.s.l. on the SE side and 900 m and 950-955 m a.s.l. on the NW side (fig. 2).

CAVES AND THEIR SEDIMENTS

Taquisara Valley is one of the richest cave areas of Ogliastra (Central-East Sardinia) (Bartolo & *alii*, 1999). Six caves have been studied in detail and a total of eight quartzite pebble samples have been taken in four of these for Al-Be dating (two in each cave).

In Genna 'e Ua cave (952 m a.s.l.), on the NW flank of the valley, the impressive main passage has a length of 60 meters and is characterised by the presence of two underground collapse sinkholes that give access to an underlying cave level. The sinkholes cut through more than 4 metres of quartzite conglomerate layered with flowstone, overlying a 1 metre sequence of clayey sand (fig. 3C, fig. 4A-B). This sedimentary sequence is capped by an important flowstone (fig. 4C). In two places this flowstone shows a thickness of more than 2 metres and is extremely corroded. Samples were taken at the top and at the bottom of the conglomerate sequence.

At Taquisara cave (954 m a.s.l.), 500 metres SW of Genna 'e Ua, the underground river passage shows important cave sediments and a complex geomorphological history with an active cave level 70 metres below. Cave sediments are represented by quartz conglomerates with minor phyllite fragments, which in places occupy entire rooms. Some of these sediments have been intermittently eroded and transported to lower levels. No samples were taken in this cave.

On the opposite side of the valley the big Serbissi cave (938 m a.s.l.) also has an underground river passage, most probably related to the same karstic cycle that generated the Genna 'e Ua and Taquisara caves. The passage is near the surface, with rock thicknesses that may be less than 20 metres, which is not enough to shield the sediments completely from cosmic rays. Nevertheless, two samples were taken at different heights in the most internal part of the cave.

In the underground stream passage of the Sa Bulverera cave (901 m a.s.l.), located 50 metres below Genna 'e Ua, speleothems are corroded and sediment relics occur along the walls at heights of almost 2 metres, testifying that the passage was almost entirely filled with quartz conglomer-

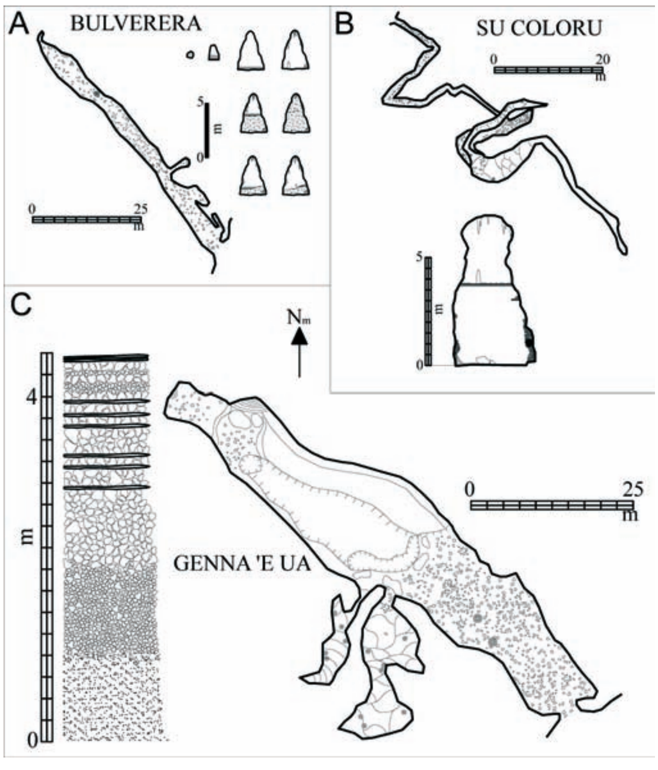


FIG. 3 - Schematic plan views of Bulverera, Coloru and Genna 'e Ua caves with sediment profiles and representative cross-sections.

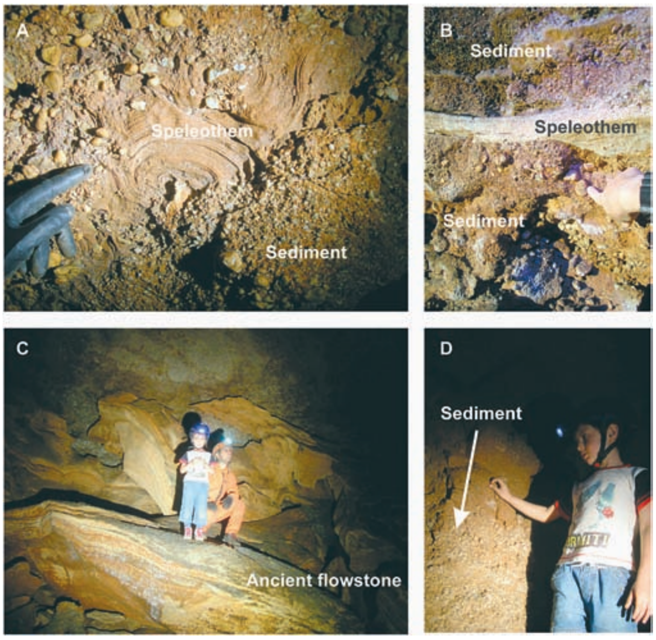


FIG. 4 - Samples: Genna 'e Ua cave, A) quartz sediment with old speleothem layers exposed on a cave roof; B) detail of the thick sediment showing a flowstone floor between quartz rich deposits; C) The large ancient flowstone that covers the entire quartz sediment sequence; D) quartz pebble sediments in carbonate cement attached to the wall of the river passage in Su Coloru cave. All photographs by Laura Sanna.

ates, that were successively removed during a reactivation period (fig. 3A). The dimensions of this cave are smaller and probably reflect a shorter period of formation than the one that was responsible for the huge passages of Genna 'e Ua, Taquisara and Serbissi. Samples were taken at 2 m and 0.5 m above the cave floor in the final part of the cave.

In the meandering Su Coloru cave (816 m a.s.l.), on the opposite side of the valley, the sedimentary sequence is more complete, with alternating quartz conglomerates and flowstones demonstrating cyclic erosion and depositional events (fig. 3B, fig. 4D). Dimensions are similar to those of Sa Bulverera, suggesting a comparable time span of formation. Two samples were also taken here, one at 0.5 m above cave floor, the second 3 m higher.

At almost the same altitude and in the immediate surroundings, several other interesting caves are known, which document a stable base level. One of these is the Lancia cave (825 m a.s.l.), which hosts more than 5 metres of fine grained, orange-brown-yellowish sediments, covered with old speleothems.

Twenty metres below, the active Cabudu Abba resurgence (800 m a.s.l.) descends very rapidly and hosts several sumps located 15 metres below the actual Taquisara Valley floor, containing sediments characterised by quartzite-carbonate sands derived from the Genna Selole Formation. No samples were taken here since the cave is believed to be of very recent origin.

Caves and their altitudes (highest and lowest points) are shown in table 1 and figure 2.

An analysis of valley morphology did not reveal distinct river terraces, but the cave floors testify to different base-level stillstands.

TABLE 1 - Caves in the Taquisara Valley and their entrance altitudes, locations, and vertical ranges from highest to lowest points. SA/NU are cave register identification numbers

Caves	Cave Number	Elevation a.s.l.	Coordinates UTM	Total length	Depth ranges
TAQUISARA VALLEY CAVES					
Genna 'e Ua grotta di	43 SA/NU	952 m	32 S NK 3967 1248	174 m	–12 m
Taquisara grotta di	86 SA/NU	954 m	32 S NK 3936 1211	1100 m	–100 m
Lioni Grotta di Su	222 SA/NU	935 m	32 S NK 3788 0905	120 m	–10 m
Serbissi grotta di	669 SA/NU	938 m	32 S NK 3954 1091	206 m	–8/+3 m
Orroli grutta 'e S'	671 SA/NU	940 m	32 S NK 3999 1135	173 m	–10 m
Munserra grutta 'e	672 SA/NU	940 m	32 S NK 3942 1079	108 m	–39 m
Lioni pozzo di Su	848 SA/NU	955 m	32 S NK 3857 0927	17 m	–8 m
Turlututu grotta	1004 SA/NU	950 m	32 S NK 3949 1073	65 m	–4/+5 m
Stelle pozzo delle	1005 SA/NU	935 m	32 S NK 4006 1132	128 m	–24 m
Lumache grotta delle	1007 SA/NU	935 m	32 S NK 4003 1128	22 m	–7 m
Bulverera grotta de	138 SA/NU	901 m	32 S NK 3975 1248	63 m	–2 m
Fossu grutta 'e Su	846 SA/NU	915 m	32 S NK 3985 1107	63 m	–3 m
Capretto pozzo del	1003 SA/NU	910 m	32 S NK 3940 1088	87 m	–16 m
Cocci grotticella dei	2075 SA/NU	900 m	32 S NK 4003 1196	8 m	0 m
Frana Concrezionata grotta N.2 della	2349 SA/NU	865 m	32 S NK 3968 1144	20 m	–4 m
Calleleddu grutta 'e Su	2351 SA/NU	870 m	32 S NK 3892 1092	15 m	–1 m
Vaschette grotta delle	2352 SA/NU	850 m	32 S NK 3963 1137	56 m	–5 m
Captazione grotta sopra la	2353 SA/NU	870 m	32 S NK 3894 1094	36 m	–4 m
Frana Concrezionata grotta N.1 della	2354 SA/NU	870 m	32 S NK 3968 1144	11 m	–5 m
Lasagna grotta della	2362 SA/NU	860 m	32 S NK 3897 1035	15 m	+3 m
Coloru grutta de Su	670 SA/NU	832 m	32 S NK 3939 1122	140 m	–3/+7 m
Arena grutta 'e S'	673 SA/NU	830 m	32 S NK 3963 1153	252 m	–10 m
Lancia grotta della	722 SA/NU	830 m	32 S NK 3939 1119	65 m	–5 m
Cardu grutta 'e Su	845 SA/NU	815 m	32 S NK 4098 0855	12 m	–8 m
Coloru grotta N.2 di	849 SA/NU	830 m	32 S NK 3939 1122	24 m	+5 m
Cabudu Abba gruttixedda	850 SA/NU	825 m	32 S NK 3939 1122	27 m	+4 m
Felci grotta delle	851 SA/NU	820 m	32 S NK 3961 1137	10 m	+2 m
Ossus grutta 'e Is	852 SA/NU	820 m	32 S NK 3984 1171	8 m	0 m
Pseudoscorpioni grotta degli	2350 SA/NU	830 m	32 S NK 3929 1100	49 m	–12 m
Rosmarino grotta del	2363 SA/NU	828 m	32 S NK 3918 1072	14 m	–5 m
Cabudu Abba risorgente di	718 SA/NU	778 m	32 S NK 3942 1131	640 m	–41 m
TACCO DI ULASSAI CAVES					
Marmuri grutta de Su	55 SA/NU	880 m	32 S NK 4172 0759	850 m	–25 m
Orroli grotta di	70 SA/NU	902 m	32 S NK 4097 0950	194 m	+2 m
Lianas grutta de Is	193 SA/NU	905 m	32 S NK 4108 0747	75 m	–10 m
Armidda grotta S'	549 SA/NU	890 m	32 S NK 4136 0864	370 m	–33/+10 m
San Giorgio grotta di	550 SA/NU	950 m	32 S NK 4150 0839	42 m	–10 m
Lecorci grotta di	660 SA/NU	800 m	32 S NK 4193 0741	190 m	–20 m
Trodori grotta di	674 SA/NU	793 m	32 S NK 3698 0486	100 m	–21 m
Terrena grotta	687 SA/NU	860 m	32 S NK 4375 0603	12 m	–2 m
Porcellino grotta del	692 SA/NU	855 m	32 S NK 4261 0593	45 m	–13 m
Janas grutta de Is	715 SA/NU	830 m	32 S NK 4242 0587	74 m	–7/+8 m
Nino Businco grotta	723 SA/NU	905 m	32 S NK 4183 0803	505 m	–82 m
Chillottis grutta de Is	727 SA/NU	855 m	32 S NK 4258 0593	134 m	–10 m
Abba Sa foxi 'e	728 SA/NU	875 m	32 S NK 4205 0772	142 m	–24/+10 m
Columbus brecca de Is	729 SA/NU	870 m	32 S NK 4158 0682	40 m	–22 m
Trodori funtana	730 SA/NU	745 m	32 S NK 3686 0495	128 m	+1 m
Matzeu grutta	808 SA/NU	910 m	32 S NK 4313 0637	53 m	–16 m
Baccas grutta de Is	2138 SA/NU	910 m	32 S NK 4081 0787	36 m	–2 m

COSMOGENIC DATING

Burial dating of cave sediments with ^{26}Al and ^{10}Be is one of the few radiometric methods that date Quaternary and Pliocene deposits ranging in age from about 100,000 years up to 5 Ma. Burial ages indicate the time sediment has been underground, often corresponding to the time in which the passage has developed or, in some cases, giving a minimum age of the passage. More details on the method are reported in Granger & *alii*, 2001 and Granger & Muzikar 2001. Cave sediments for this study have been carefully mapped and samples were taken in the summer of 2005 (see description of sediments above).

AMS measurements were made at PRIME Lab. Beryllium-10 was measured against a standard derived from NIST, but the values reported in table 2 have been adjusted to match the standard of Nishiizumi & *alii* (2007). The ^{10}Be meanlife used in calculating burial ages is 2.005 My (Korschinek & *alii*, 2010).

TABLE 2 - Cosmogenic ^{26}Al/^{10}Be burial ages of cave sediments

Cave	[^{26}Al] (10^3 at/g)	[^{10}Be] (10^3 at/g)	Burial date (My)
Genna 'e Ua	50.3 ± 10.2	27.9 ± 4.5	2.74 ± 0.47
Serbissi	60.8 ± 10.7	7.6 ± 0.8	insufficient depth
Sa Bulverera	23.3 ± 5.2	10.9 ± 1.7	2.40 ± 0.50
Su Coloru	38.0 ± 27.0	20.5 ± 2.7	2.70 ± 1.13

All of the cosmogenic nuclide concentrations in the sediments were very low, indicating relatively high erosion rates in the sediment source area. Uncertainties in the burial ages are thus quite large. Of the four caves of Taquisara, the sediments at Serbissi proved undatable due to insufficient burial depth below the surface. Resulting ages are shown in table 2. The cosmogenic results indicate that all of the cave sediments have similar ages, and their burial dates at least to the Late Pliocene. The nearly horizontal cave passages of the Taquisara caves have formed during relative stable periods during which the Taquisara river slowed its incision, but the cosmogenic nuclide dating did not achieve sufficient precision to distinguish these various stillstands. It is also possible that cave sediments have been transported underground from the upper levels to the lowest ones, without ever coming to the surface, but this hypothesis seems unlikely. In that case, the upper cave levels would be older than 2 Ma, while the lowest caves might be much younger.

PLANATION SURFACES, CAVE LEVELS AND VALLEY MORPHOLOGY

Topographic maps at the scale of 1:10,000 have been used to construct a DTM of the entire region enveloping the Tacchi of Isara, Ulassai, the minor ones of Tisiddu, Troiscu and Ungul'e Ferru from the upstream Riu Pardu Valley up to its capture by Riu Pelau and its ancient Rio Quirra Valley. Accuracy of this DTM is 10 m.

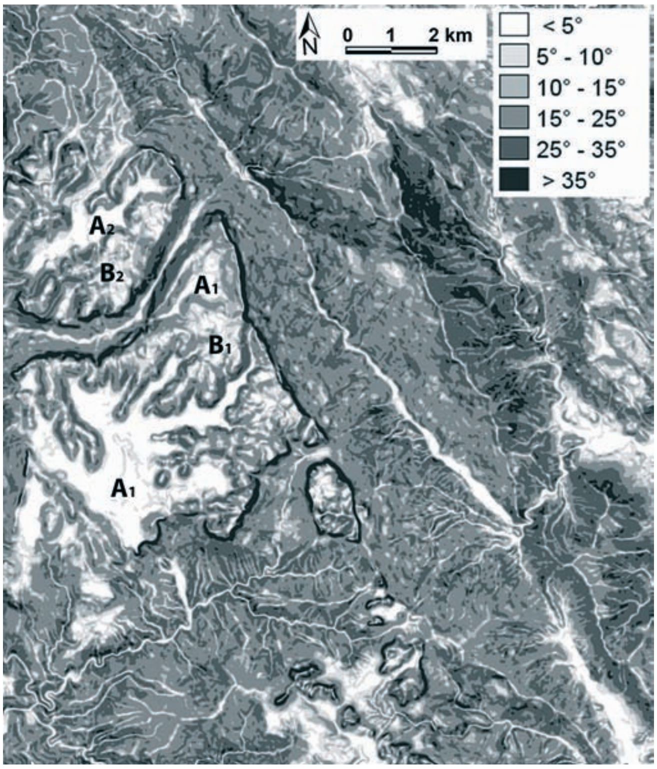


FIG. 5 - Slope map of the study area. A and B = largest planation surfaces of the lowest (A) and upper (B) levels.

The slope map (fig. 5) shows the main dolomite table mountains and their almost vertical outer cliffs, but also highlights the large planation surfaces on these plateaus (white areas in fig. 5). The most extensive of these surfaces (A1 in figure 5) on the biggest table mountain (Tacco of Ulassai) has a dendritic pattern and is probably related to an ancient drainage system flowing from the NE to the SW and draining the highest mountains of the Island (Gennargentu Mts.). It is developed between 810 and 750 m a.s.l. (see Taccu di Ulassai graph in fig. 6) and inclines toward the SW. This surface is clearly recognizable also in the Taccu Isara (A2), but here it develops between altitudes of 900 and 870 m a.s.l.. This surface is visible on the northern part of Taccu di Ulassai at the same altitude (A1 in figure 5). There is another altitude cluster at 975 m a.s.l. on Taccu Isara (B2 in figure 5), and another less visible at 955 m a.s.l. on Taccu di Ulassai (B1) (fig. 6). These constitute smaller remnants of an older planation surface located 100 m higher than the main one. The smaller table mountains also have typical planation surfaces, located at 875, 740 and 770 for Monte Tisiddu, Troiscu and Ungul'e Ferru respectively (fig. 6). A general 3D analysis of these surfaces confirms the general trend of decreasing altitude from NE to SW for both the upper and the lower one (fig. 7).

Also caves are developed at certain altitudes (see figure 2), with horizontal passages not related to lithological factors and almost certainly reflecting local base level stillstands. These levels are 935-955, 900-915, 850-870, 815-830, and around 750-775 m a.s.l. (table 1). Although there

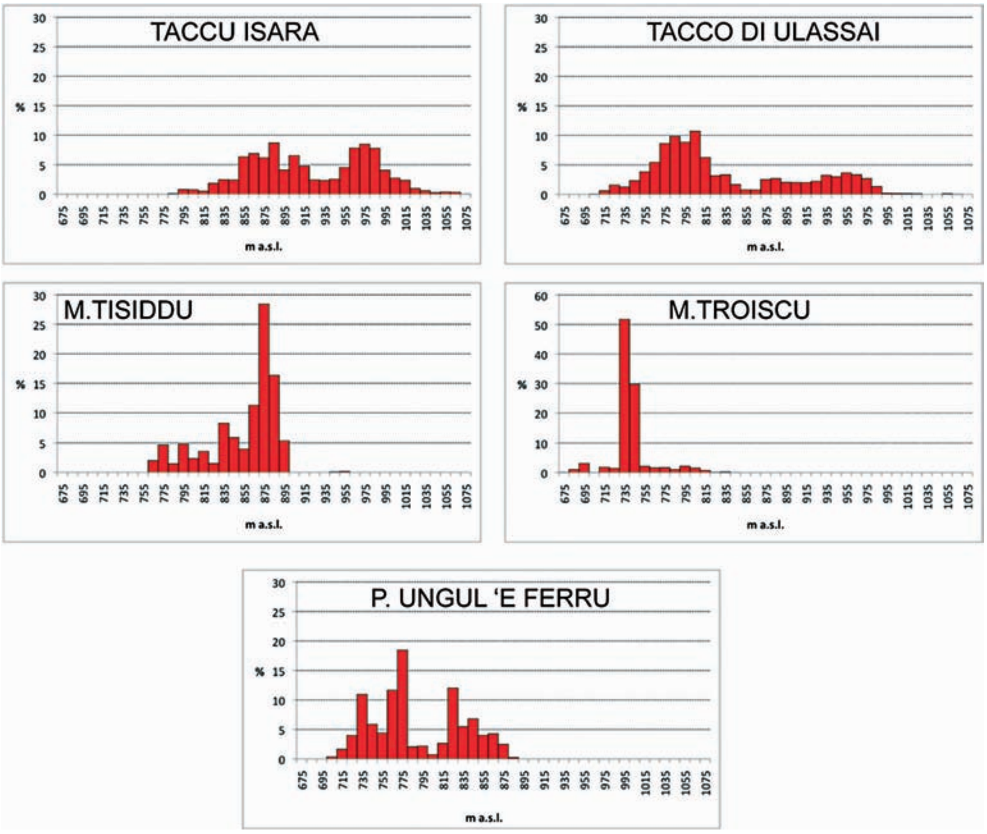


FIG. 6 - Altitude histograms for the five different «Tacchi».

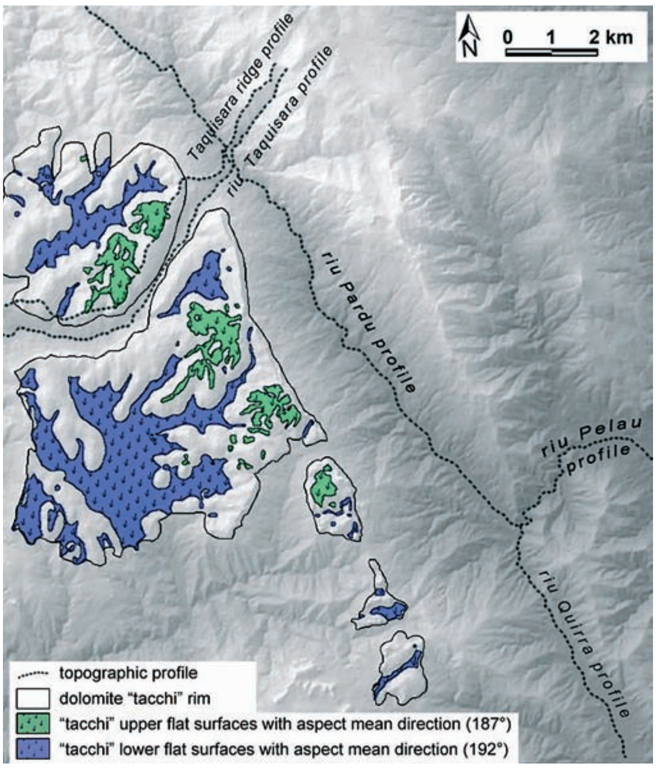
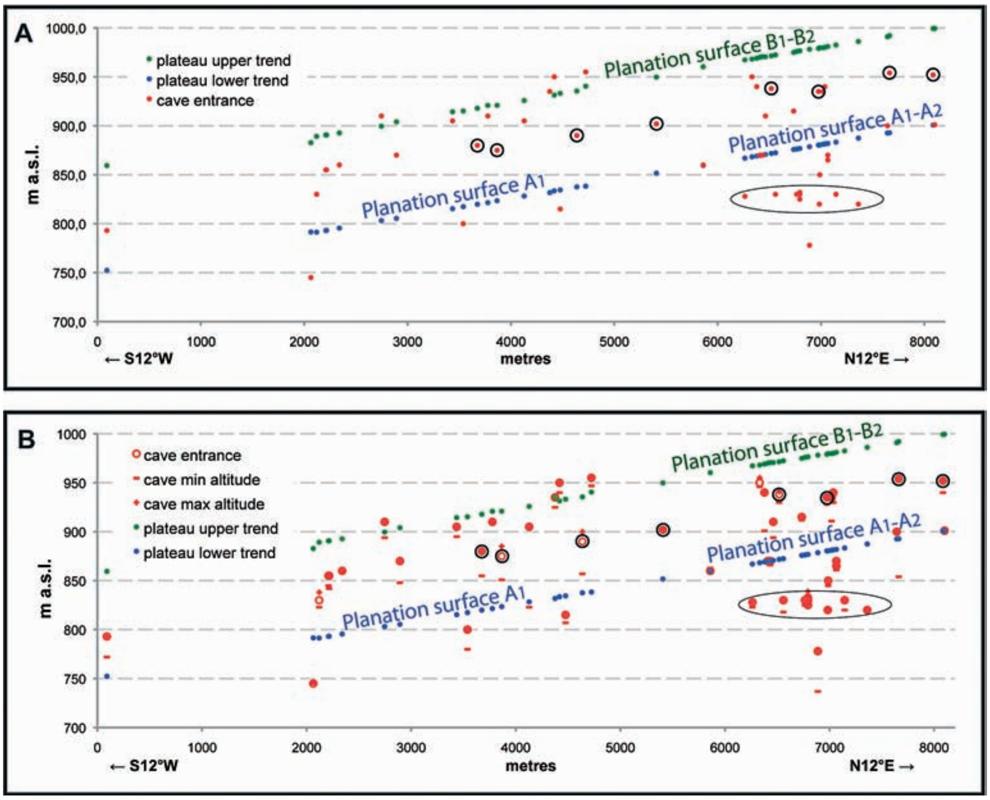


FIG. 7 - The two main planation surfaces and their generally decreasing elevation toward the SSW. Location of longitudinal river profiles is also shown (see figs. 9-10).

is no simple method for demonstrating a precise relationship with planation surfaces, cave altitudes cluster more or less below the two main planation surfaces identified on the table mountains (fig. 8). The six caves with very large passages (black circles in fig. 8) tend to be developed around 50 metres below the highest planation surface (green dots in fig. 8). Their distribution, although based only on six points, shows the same decreasing altitude in a SSW direction. The caves at around 830 m a.s.l. in Taquisara Valley cluster on a horizontal level (black ovals in fig. 8). The black oval (fig. 8) is horizontal while the cave and planation surfaces slope. This distribution is an indication of a water table level.

The Tacchi area is dissected by the deeply cut Riu Pardu Valley, which extends in a NNW-SSE direction following a major Tertiary fault (fig. 1). In its northeastern part, this tectonic feature has been uplifted several hundreds of metres, allowing the erosion of the Mesozoic cover that once overlaid the Palaeozoic rocks. Riu Pardu cuts its valley in porphyric rocks and phyllites, and has steep and unstable slopes. The villages on its flanks (Gairo, Osini) have been subjected to landslides, the most devastating of which has caused them to be abandoned and rebuilt in another location in the mid 1950s. These unstable slopes testify to a rather rapid incision of the river. No river straths can be distinguished along the flanks of the valley, suggesting erosion has been continuous without important interruptions. Downstream, the river has been captured and turns abruptly eastwards at Genna 'e Cresia, and changes name to Riu

FIG. 8 - Relationship between cave development and planation surfaces: A. Upper and Lower Plateaus and cave entrances; B. Upper and Lower Plateaus and caves, showing entrance, minimum and maximum altitudes of the caves. Black circles indicate caves of large size; black oval indicates the caves located at almost the same altitude.



Pelau, and then flows into the Tyrrhenian Sea close to the village of Cardedu. At Genna 'e Cresia the abandoned Riu Pardu Valley continues southward as Riu Quirra (fig. 1). It is clear that Riu Pardu at one time was captured by Riu Pelau, causing a rapid incision upstream at Genna 'e Cresia. Longitudinal profiles have been constructed for Riu Pardu, Riu Quirra, and Riu Pelau (fig. 9). These show evidence that the upstream Riu Pardu and Riu Quirra have equilibrated profiles (grey dashed line in fig. 9), while the knickpoint in Riu Pardu, at present located around 10 km upstream of the capture point, is rapidly receding upstream. Riu Pardu flows over 600 m below the dolostone contact near Ulassai, 4 km upstream from the capture, while 6 km more upstream, at the confluence of Riu Taquisara and Riu Pardu, the altitude difference reduces to 210 m.

Today the Taquisara Valley flows towards the southwest and hosts a temporary rather unimportant streamlet. Its size cannot be explained by the present day configuration. Caves along its flanks apparently drained important quantities of water towards the valley in the past, as testified by significant amounts of coarse fluvial sediments. Their petrographic signature, containing quartz and abundant fragments of metamorphic rocks, suggests that they were derived from the Palaeozoic basement rocks, and most probably were transported over rather long distances (given their maturity) from the mountainous region to the northeast. Taquisara's drainage basin almost certainly extended far beyond the present-day outcrop of Jurassic limestones, and comprised the Palaeozoic basement rocks of what is now the northeastern flank of Riu Pardu. Here, small remnants of an ancient drainage network have their knickpoints at an altitude of around 830 m a.s.l. (fig. 10), corresponding to the horizontal (water table) cave level found in Taquisara Valley.

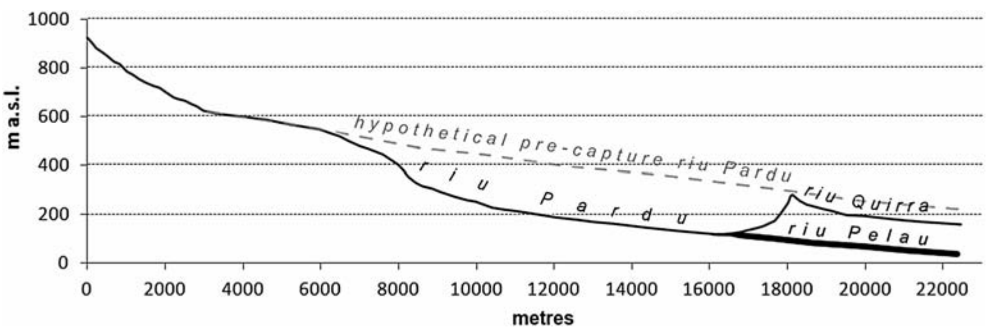


FIG. 9 - Longitudinal profile of the Riu Pardu-Riu Pelau and Riu Quirra Valleys (see fig. 7 for location)

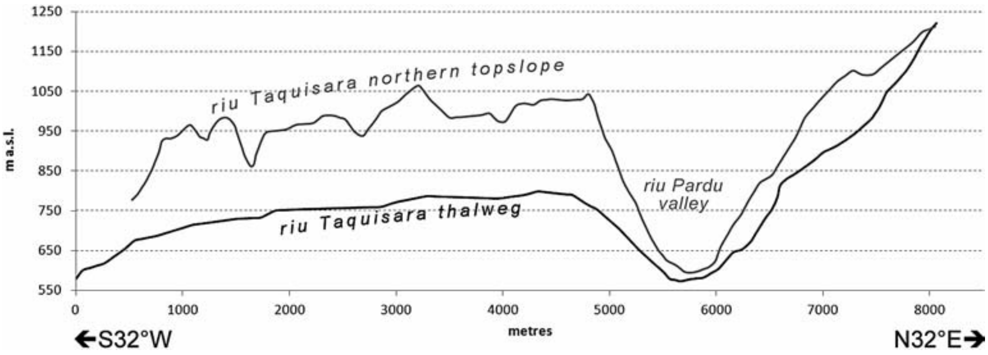


FIG. 10 - Longitudinal profile of Riu Taquisara valley and ridge (see fig. 7 for location)

DISCUSSION AND CONCLUSIONS

The presence of two planation surfaces with an altitude difference of around 100 m, and the clustering of horizontal cave levels at certain altitudes, allows us to draw a rather detailed landscape evolution scenario.

The upper planation surface (B1 and B2 in figure 5) corresponds to a phase in which no karstification nor sedimentation occurred. At this time the carbonate rocks were probably not yet completely exposed at the surface, and rivers drained from the high mountains to the North towards the South and East. Remnants of such valleys have been recognized in many parts of east central Sardinia (De Waele & *alii*, 2005). This early stage is much older than 2 My and might be Miocene or Pliocene in age.

An erosional phase lowered the local base level, abandoning the upper planation surface, and created the first level caves. The size and morphology of these highest-first level-caves (Serbissi, Genna 'e Ua, Lioni, Taquisara, etc.) suggests that they formed in a more humid climate, with higher rainfall values. The rivers, at least during floods, were able to transport cobbles of several cm in diameter. To these first level caves also belong Orroli, s'Armidda, Foxi 'e s'Abba, and Su Marmuri caves. These caves formed during a relatively long period of quiescence with a more or less stable base level, and were also gradually filled with sediments that were later washed out during the following incision period. The general slope of these caves (see figure 2) might indicate that they drained southward, in a time in which the present Taquisara Valley did not yet exist. This palaeo-Taquisara probably was carved along the same NE-SW lineament surely before 2 My.

Another incision period created the present Taquisara Valley, caused the formation of the second level caves and also started forming the large planation surfaces (A1 and A2 in figure 5). The beginning of formation of these planation surfaces must also be older than 2 My, since the caves below are older than 2.82 ± 0.5 My. After another period of quiescence, erosion continued, lowering and widening planation surfaces A_1 and A_2 (figure 5) and forming the third level caves at 830 m a.s.l. These caves and the final planation surface A might be as young as 1.6 My (2.76 - 1.17 My).

The second level (Bulverera) and third level caves (Coloru, Lancia etc.) are much smaller in size respect to the first level caves, and appear to have formed by smaller underground rivers, as confirmed by the much smaller grainsize of the transported sediments. The relatively extensive development of the third level of caves suggests this phase to have lasted longer, although the size of the caves is an indication of lower rainfall rates. Their development at a more or less constant level (around 830 m a.s.l.) is an indication of a local base level, almost surely the Taquisara Valley. Today active caves are located around 200 m below the highest level caves, more or less 20-30 m below the present thalweg.

Cosmogenic dating of cave sediments in the Taquisara Valley have shown all caves to be older than 2 My. Therefore, the Taquisara Valley appears to have achieved its present shape by the Late Pliocene (2-3 My ago). The Taquisara valley has witnessed four major incisions of 50, 30, 40 and 80 m respectively. Cosmogenic dating, however, was not able to resolve these incision periods, that must have happened before the onset of the Quaternary.

Also the large planation surfaces present on the Tacchi, relative to at least two main erosion stages, must be older than 2 My. The highest surface is surely much older, and so are most of the large-sized highest caves. This surface and these caves might well be Pliocene or even Miocene in age.

The deep valleys such as Rio San Girolamo and Rio Pardu, instead, are younger than the Taquisara incision, and have probably formed in the last 2 million years.

Riu Pardu has clearly been captured by Riu Pelau, and the altitude difference between the wind gap (today's Rio Quirra) and the present thalweg at the capture elbow is around 165 m. Considering a mean river erosion rate of 0.2-0.4 mm y^{-1}, based on studies carried out in Corsica (Fellin & *alii*, 2005; Kuhlemann & *alii*, 2008) this capture might have occurred in a period between 400-800 ky. Considering the weak nature of the incised bedrock (phyllites) and the sudden lowering of base level over more than 150 metres, erosion might have been faster by an order of magnitude (i.e. occurring during the last 100 ky).

Since the capture occurred, the knickpoint has retreated approximately 10 km upstream. With an average knickpoint retreat velocity of 0.1-0.2 m y^{-1}, similar to what has been measured in an Appalachian fluviokarst (Anthony & Granger, 2007b) or in Mediterranean rivers (Loget & Van Den Driessche, 2009) of similar size and with similar rainfall and hydrological behavior, this would suggest the capture to have occurred between 50 and 100 ky.

From these preliminary data the present landscape of Central-East Sardinia, with its isolated table mountains (*Tacchi*), resting on the Palaeozoic basement, seems to have started forming during the Late Tertiary, with a major incision rate during the last 2 My. This faster erosion might have been triggered by Quaternary climate variability with increased rainfall and erosion during ice ages and drier climate with aggradation during interglacials. The capture of Riu Pardu by Rio Pelau might have occurred around 100 ky ago, when climate got wetter and erosion increased. Further research is needed to confirm these dates and to relate these events to the incision of other main rivers of the region, that according to these preliminary data appear to be less than 2 My old.

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