Bulletin de la Société géographique de Liège, 29, 1993, 153-161.

Geometry of piezometric surfaces in a perched karst : Redondo valley, Cantabrian mountains, northern Spain

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Abstract

Redondo karst is developed in carboniferous limestones and is stratigraphically perched due to the existence of underlying impervious turbidites dipping 45-60° against the valley slope. Cobre cave system, with 12 km of passage, is up to date the most important drain of Redondo karst. This multilevel cave has a low gradient trunk developed just at the piezometric surface. Projected elevations of the stream profile reveals a roughly horizontal piezometric surface. Near the resurgence point, this surface drops 19 m in 450 m, and contains two short inflexions controlled by narrow dolomitized zones, which are interpreted to be the cause of local perching of 1.5 and 2 m thick (respectively), and gradient increments up to 7 degrees in the profile of the underground stream. Two paleopiezometric surfaces have been defined by bedrock tenaces (Ti and T2) with lower average gradients but with the same inflexions as the present one. Near the resurgence, Tl lies 6 m above the water table and makes onlap against the present piezo surface 1000 m upstream from the resurgence. It implies a Holocene fall of 6 m in the turbidite-limestone boundary, interpreted as the result of a glacial erosive removal of 8.5 m in the valley walls. The system is now adapting itself by means of headwards retrogressive entrenchment.

Résumé

Le karst de Redondo s'est développé dans des calcaires carbonifères; en pendage de 45 à 60° par rapport à l'inclinaison de la vallée, il est stratigraphiquement perché à cause de lutites imperméables sous-jacentes. Le système de la grotte de Cobre, qui totalise 12 km de passages, est le plus important drain de ce karst. La grotte, à plusieurs étages, a une artère en pente faible juste au-dessus de la surface piézométrique. Des projections du profil longitudinal du cours d'eau révèlent une surface piézométrique à peu près horizontale. Près de la résurgence, cette surface s'abaisse de 19 m en 450 m, et comprend deux courtes inflexions sous l'influence de zones dolomitiques étroites, que l'on interprète comme étant la cause d'augmentations, jusqu'à 7°, de pente dans le profil de la rivière souterraine.

Deux surfaces paléopiézométriques ont été définies par des terrasses dans la roche en place (Tl et 12), dont les pentes moyennes sont plus faibles que la présente, mais qui possèdent les mêmes inflexions. Près de la résurgence, T1 se trouve à 6 m plus haut que le niveau de la nappe, tandis qu'elle s'y raccorde à 1000 m en amont de cette résurgence. Ceci implique une chute de 6 m, pendant l'Holocène, de la limite lutite-calcaire, que l'on interprète comme le résultat d'un recul de 8,5 m, par érosion glaciaire, des parois de la vallée. Actuellement, le système s'adapte en s' enfonçant régressivement.

I. INTRODUCTION AND SETTING

In mountain karst areas, given the high irregularity and relief of the piezometric surfaces, and their wide range of seasonal fluctuation, it is usually assumed that these surfaces do not fossilize or they are only poorly defined (BÖGLI, 1980). In contrast, in stable karst areas with minor relief, the typical cave levels are found elsewhere, and, if lithological perching can be discarded, the paleo-piezometric surfaces can be accurately established using the "piezometric limit" concept (PALMER, 1987, 1989), despite the existence of relatively thick flood—water zones. The present paper deals with the recognition and geometry of paleo-water tables in a fairly common type of mountain karst: a karst stratigraphically perched by impervious rocks underlying the limestone aquifer.

Redondo Karst (province of Palencia, Cantabrian mountains, northern Spain; Fig. 1) lies within a narrow band (100-200 m) of Upper Carboniferous limestones (Agujas limestone Member; VAN DE GRAAF, 1971) sandwiched between thick impervious turbidites of the

Vapes and Covarrés Formations (VAN DE GRAAF, 1971). The carboniferous succession forms a NW-SE oriented syncline in Redondo valley. The Agujas Limestone Mb. crops out all along its northeastern inverted flank, dipping 45 to 60° against valley slope (Fig. 2). The existence of underlying impervious turbidites of the Covarrés Formation causes the karst aquifer to be stratigraphically perched. So, the topographically lower boundary between limestones and turbidites is marked by a level of resurgences. These resurgences are the outlets of different cave systems; two of them have been recently explored *(Cobre* and *Pesadilla* caves, Rossi *et al.,* 1990).

Triassic sandstones and conglomerates of the Labra Formation (MAAS, 1974) crop out in the upper part of the mountain ridges around the valley. These deposits unconformably overlie the Agujas Limestone, and they provide an allochtonous (but nearby) recharge area for the karst aquifers.

Cobre Cave System, with more than 12 km of known passageways, is the most important drain of Redondo Karst and at the same time the underground origin of the Pisuerga river (Fig. 3). This system comprises a complex multilevel cave *(Cobre* Cave) and two penetrable links *(Torc6n,* 800 m long and 140 m deep, and *Sel,* 600 m long and 115 m deep), both connected hydrologically, but not physically, with the main cave (Rossi *et al.,* 1990). Limestone containing the upstream half of the cave system is partially covered by till of the *Covarrés* and *Sel de la Fuente* fossil mountain glaciers, considered to be active at least during the Late Pleistocene (HERNÁNDEZ-PACHECO, 1944). Recent work suggests a strong influence of glacial processes upon cave development, as it is shown by widespread occurrence of glacial till injections in the paleo-sinks of the southernmost branch of the cave system *(Geológos* series). This branch became abandoned during a glacial advance, favouring the development of a new, parallel-oriented, and more northerly branch *(Torcón-Sel-Sifones* series), still active actually. Well defined piezometric limits (sensu PALMER, 1987) in this part of the system, suggest that this drainage shift took place when the local piezometric surface was 70 m higher than it is today (Rossi & ORTIZ, 1990).

Cobre Cave has its entrance at the resurgence point of the system, at 1600 m above sea level, in the middle part of the northeastern wall of the Redondo valley. This resurgence is located exactly at the intersection of two surfaces: (1) the topographically lower limestone/turbidite boundary, and (2) the present landscape (Fig. 4). This widespread perching allows the development of a true phreatic zone downdip the limestone. The downstream section of Cobre Cave has a low gradient active trunk, considered to be in broad equilibrium with the top of the limestone aquifer, as no important bedload sediments are present actually.

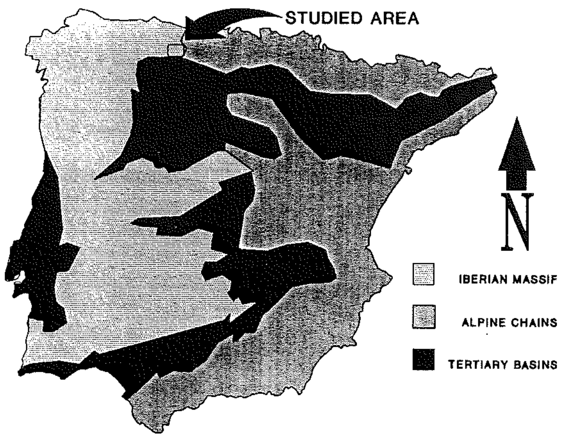

Figure 1: Location of Redondo valley (Cantabrian mountains, northern Palencia, Spain).

II. METHODS

As the whole cave system has been surveyed to BCRA grade 5b (standard classification of ELLis, 1988), unsuitable for our purposes, we have chosen a test area for more detailed work: the last downstream kilometre of the river cave, including the countless relict passages above it. The main survey line of this area has been resurveyed for morphometric purposes using KB-14 Suunto compasses and clinometers, and fibron fibreglass tapes graduated in metres and centimetres. Stations were fixed and discretely marked on protruding features of solid rock. Readings were taken forward and backward, not less than 4 times for every survey leg, by different operators with different devices. At each survey station (or at other points of interest), careful measurements were made, including geologic contacts, bedding planes, fractures, passage ceilings and floors, bedrock tenaces, and so on. Data computing has led to four different types of plotting: (1) 1:500 plan (2) Extended elevations (useful to determine true stream gradients and profiles) (3) Projected elevations (useful to see oriented sections of the piezometric surfaces) (4) Cross-sections correlation diagram (useful to summarize the relationship between all the conduits).

III. GEOMETRY OF THE PRESENT PIEZOMETRIC SURFACE

All along the main collector of Cobre cave, there is a low gradient subterranean stream. The combined evidence of (1) the absence of bedload sediments and (2)

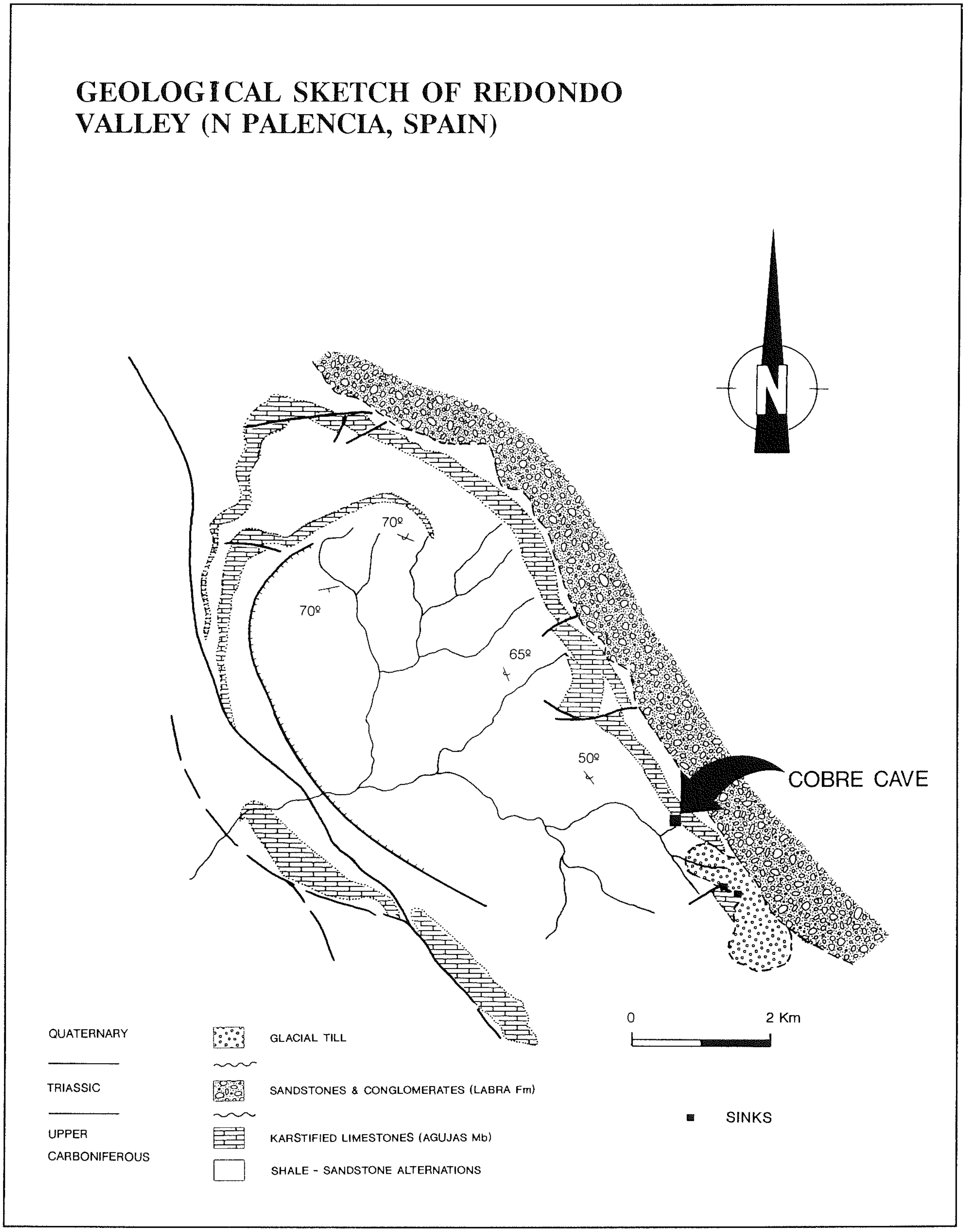

Figure 2 : Geological sketch map of Redondo valley, showing the locations of the caves. Karst developed in the limestone bands (Agujas Mb.) within the carboniferous overturned syncline, unconformably overlaid by the Triassic Labra Formation. The origin of almost every superficial river is just at the turbidite-limestone contact.

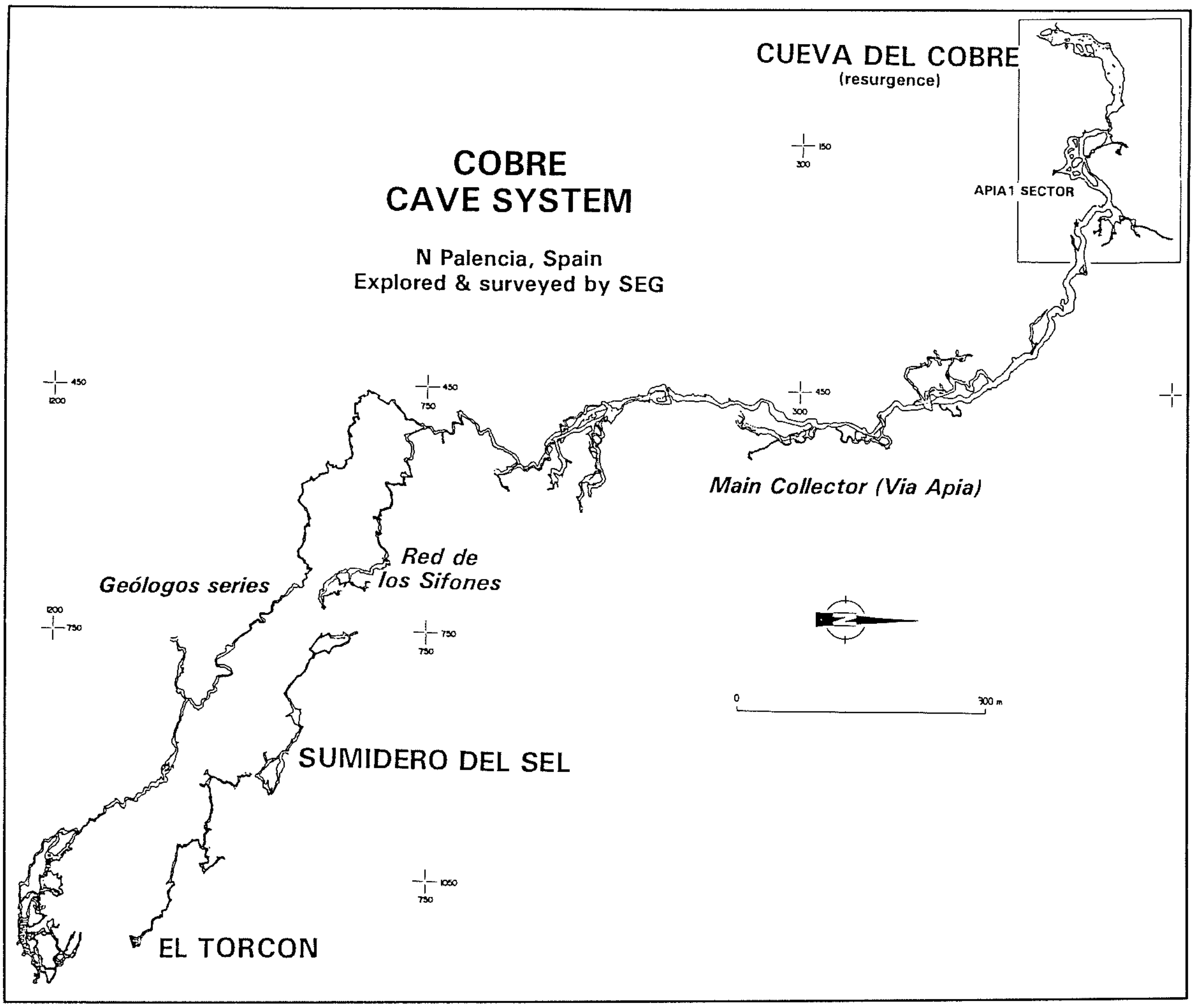

Figure 3 : Plan pattern of Cobre Cave System. The grid system has his origin in the cave entrance. The (rame indicates the position of the area studied in detail (Apia-1 sector).

the overall low-gradient nature of the trunk conduit, suggests that this stream is in broad equilibrium with the piezometric surface, controlled in turn by the outcrop elevation of the lower boundary of Agujas limestone Mb.

Apia-1 sector includes the 450 m of the main collector nearest the resurgence. In this sector, average gradient of the subterranean river approaches 2.5° (4.2 %), distributed in three different segments. These three segments are separated by two short ramps of 30 and 40 m, located 310 and 200 m away from the resurgence, respectively. Local gradients at this ramps go as far as 7° (Fig. 4). Upstream from Apia-1 sector, average gradient of the main collector does not exceed 1°.

Actual piezometric level geometry approaches an horizontal plane, except in Apia-1 sector, where it falls down 19 m along 450 m of profile. This decrease is not homogeneous: on the contrary, it presents the two above mentioned inflexions.

The most important inflexion is associated with an irregular resistant level of ferroan dolomites, which causes a 2 m local damming of the water table. Therefore, the top of the water table has a gentle stair-like geometry towards the resurgence (Fig. 4).

IV. BEDROCK TERRACES WITH STRONG BASAL WIDENING AS PALEOPIEZOMETRIC INDICATORS.

The main active trunk of Cobre cave *(Via Apia)* consists of a wide canyon, originated by the complex entrenchment history of several systems of looping phreatic tubes. Just above the level of the present active stream, there are two extensive levels of well developed bedrock terraces remnants (Tl and T2), both actually relia, as they have suffered canyon incision of variable

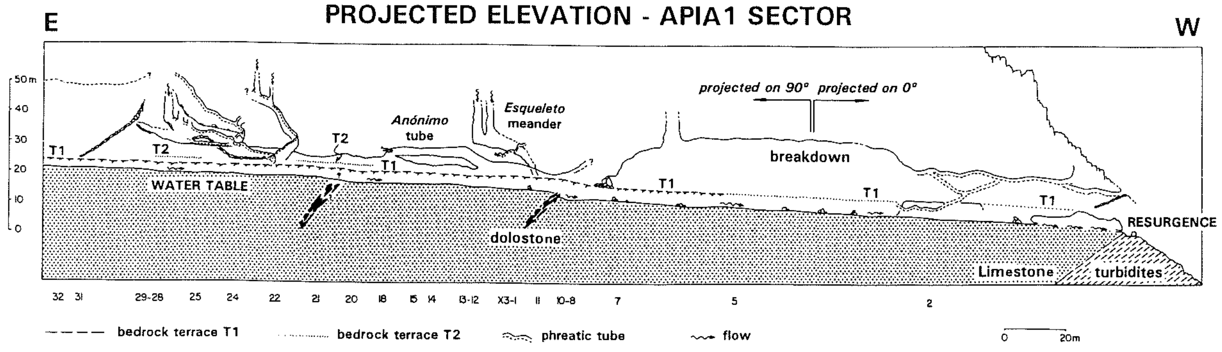

Figure 4 : Projected elevation along the main trunk conduit of Cobre cave in Apia1 sector. The plane projection direction is S-N until 0,100 of the grid system, and W-E for the rest of the projected elevation. See the geometry of the piezometric surface, with two steps controlled by narrow dolomite zones. The same steps are present also in the bedrock terrace T1. Numbers under elevation shown cross section positions of Fig. 5.

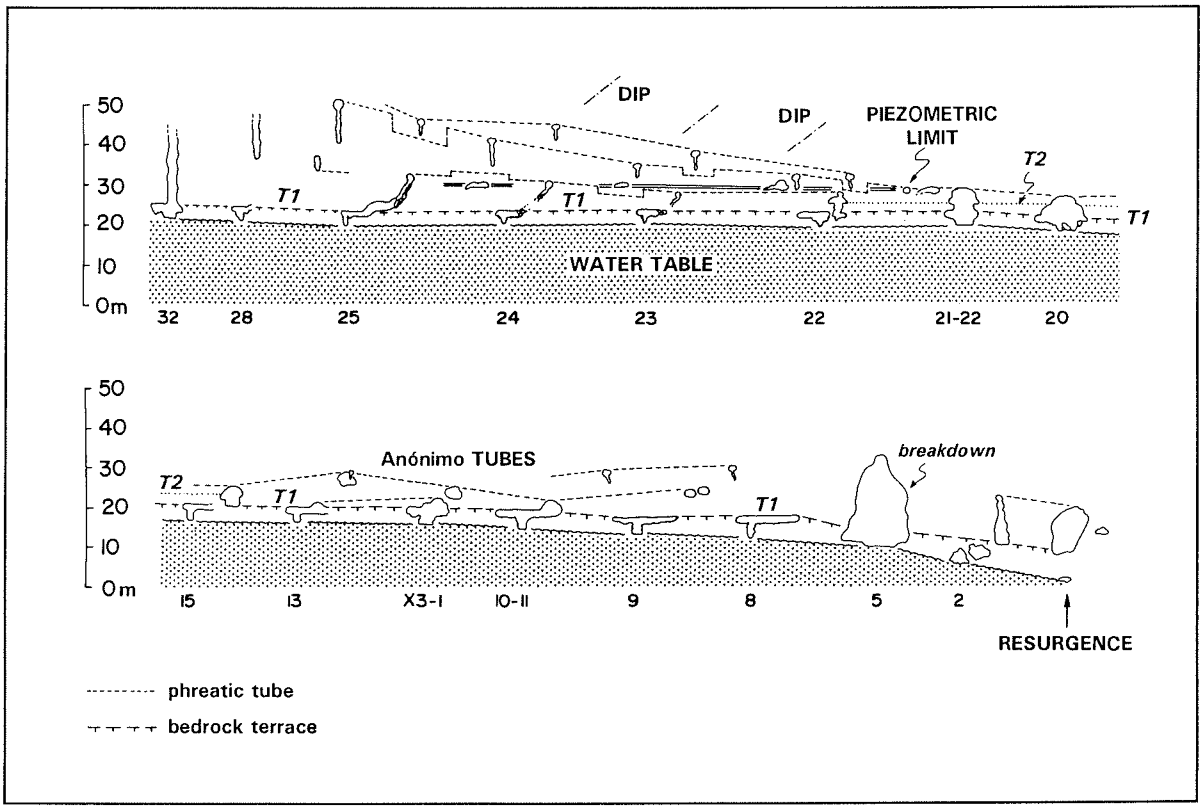

Figure 5 : Cross-sections correlation diagram. Cross-sections have been measured perpendicularly to the main collector, including all the passages above it. Cross-section numbers are the same as in Fig. 4. See text for discussion.

magnitude. If we don't take into account later incision, these tenaces have a characteristic cross-section, with flat solutional floors, flat solutional ceilings, high width/thickness ratios (above 10) and a rather constant thickness (1 m ± 0.2). (Fig. 5).

In the upstream direction, the height of T1 above the active stream progressively decreases: 300 m upstream from the resurgence point, its ceiling lies 3 m above the level of the present subterranean stream. At the cave entrance, its correlative level lies 6 m above the actual resurgence.

Cross-section width reaches a maximum near the resurgence (16 m) and decreases upstream (8 m measured 500 metres upstream from the resurgence). At the exposed sides of the tenace, there are widespread remnants of a fining-upwards, flowstone-cemented, sand and conglomerate succession. The original passage seems to have been filled to the ceiling with clastic sediment elsewhere, as suggested by the presence of isolated pebbles cemented to the roof.

Near the resurgence, Tl is partially obscured by breakdown. In this area, development of large wedge-like breakdown blocks is favoured by the concurrence of two factors: high width/thickness ratios of Ti, and a direction of basal widening perpendicular to fracture trends. In this case, the fault dips 42° towards 315°, and guides not only the entrance series, but also the resurgence position.

On Apia-1 sector (Fig. 4), the longitudinal profile of Tl has an average gradient of 2° (3.7%), slightly lower than that of the present underground river. However, the longitudinal profile of T1 is not homogeneous, and has two short inflexions with higher gradients (7Q) along 30-40 m. Surprisingly, these inflexions match exactly with similar gradient increases on profile of the subtenanean stream (Fig. 4). This remarkable fact is of considerable transcendence, as it demonstrates that relict tenaces and present stream profiles contain the same irregularities.

Additionally, it has been identified a higher bedrock tenace level (T2), also with strong basal widening and similar features to those in Tl. T2 has been mapped near the junction between *Tubo Rojo* (an ancient relict phreatic tributary) and the main collector *(Via Apia).* The flat solutional floor of T2 lies 2 m above Tl ceiling.

In the downstream direction, the correlative ledges of T2 can be traced along the downward part of a phreatic loop (the *Anonimo* wide phreatic tube). T2 disappears when Anonimo looping tube descends below the level of *Esqueleto* Meander. Near the system resurgence, T2 is not recognizable because of breakdown related to Tl.

The distinctive tenaces Ti and T2 apparently represent periods of relatively static position of the water table, when dissolution in the main stream was unable to progress downwards and being limited to the lateral direction. The steeply dipping bedding and fracture planes demonstrate that such extensive solutional flat floors and ceilings must be the result of a water table control, indicated also by the close geometric similitude between their profiles and that of the present stream (Fig. 4).

V. PIEZOMETRIC LIMITS AND HIGHER PHREATIC SYSTEMS

Above T2, another relict piezometric surface has been recognized with different criteria. 340 m upstream from the resurgence, this relict surface lies 5 m above the present active river (Fig. 6). Here, a narrow vadose rift (guided at its roof by a looping tube), grades into a phreatic unentrenched tube. The altitude of this change in character, from vadose to phreatic, represents a piezometric limit (sensu PALMER, 1987). Not far from here, there is a low-gradient passage with phreatic appearance, developed just at the same elevation as the piezometric limit, and characterized by an horizontally oriented, lenticular cross-section. As a result of the geological structure (bedding and fractures dipping more than 40°), almost every phreatic tube of Cobre has well developed loops. In contrast, the chape and gradient of the mentioned lenticular passage indicate the lack of stratigraphie or structural control, and must be the result of a direct water table control. The combined evidence of a piezometric limit and a epiphreatic tube, botte at the sanie elevation, argues in favour of the existence of a relict piezometric surface at this altitude, at least in Apia-1 sector. Further work is needed to identify this surface more inside the system.

At higher altitudes, Apia-1 sector contains several systems of phreatic tubes, whole profiles rise and fall along their lengths, with a vertical range of more than 30 m. As seen on Fig. 4, the whole system of tubes seems to be the downward portion of a multiphasic phreatic loop, with its upper branches being gradually abandoned as the water table dropped. After that, ail these tubes have been entrenched downward by vadose water, coming from shafts that reflect minor and still active recharge points. This late vadose incision has obscured ail possible evidence of the paleopiezometric surfaces linked to the genesis of the higher tubes in this sector.

VI. RECENT ENTRENCHMENT OF THE UNDERGROUND STREAM

Tl bedrock tenace level shows evidence of recent vadose incision, with a graduai upstream decrease in magnitude: 6 m deep in the resurgence point and disappearing 1 km away from the resurgence. As the entrenchment decreases, width/thickness ratios of Tl become reduced too. This pattern indicates that the system is still now adapting itself to an holocene base level fall, by mens of headwards retrogressive entrenchment (Fig. 7). The associated drop in the water table must have been rapid in comparison with previous rates, but not deep enough to cause the abandonment of the passage.

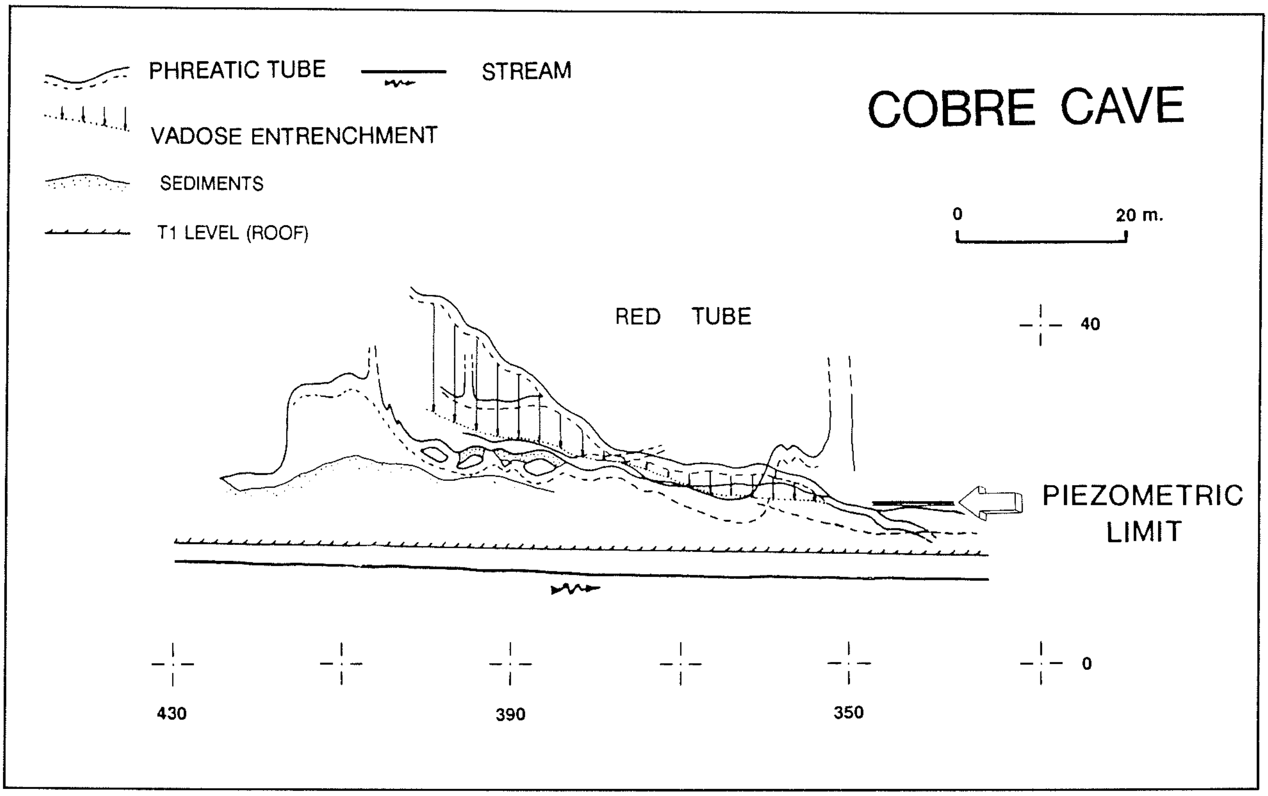

Figure 6 : Extended elevation of Tubo Rojo tributary with the exact location of a piezometric limit (P.L.). Here, a narrow vadose rift (vertical arrows) grades into a phreatic unentrenched tube. The altitude of this change in character, from vadose to phreatic, represents a piezometric limit. At the same altitude there is a low-gradient passage with lenticular cross-section, interpreted as an epiphreatic tube. See text for discussion.

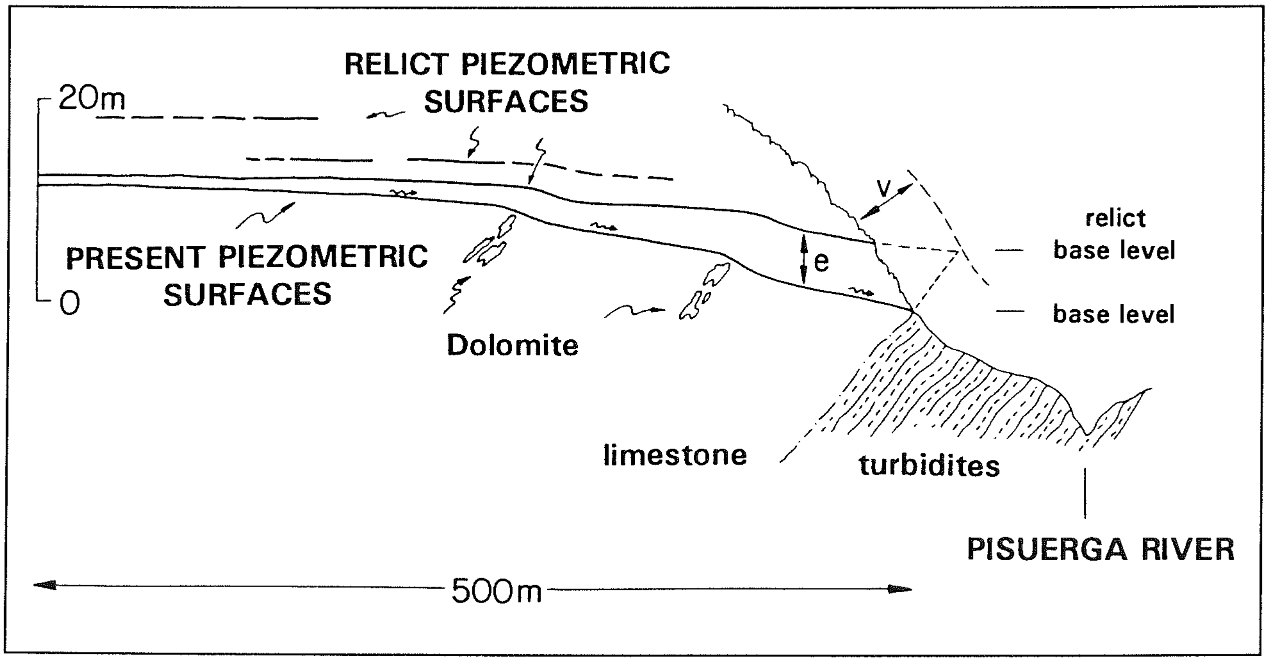

Figure 7 : Schematic diagram of Redondo Karst, showing the geometry of present and relict piezometric surfaces. E: Magnitude of holocene entrenchment near the resurgence. V: Holocene erosive retreat of the valley walls.

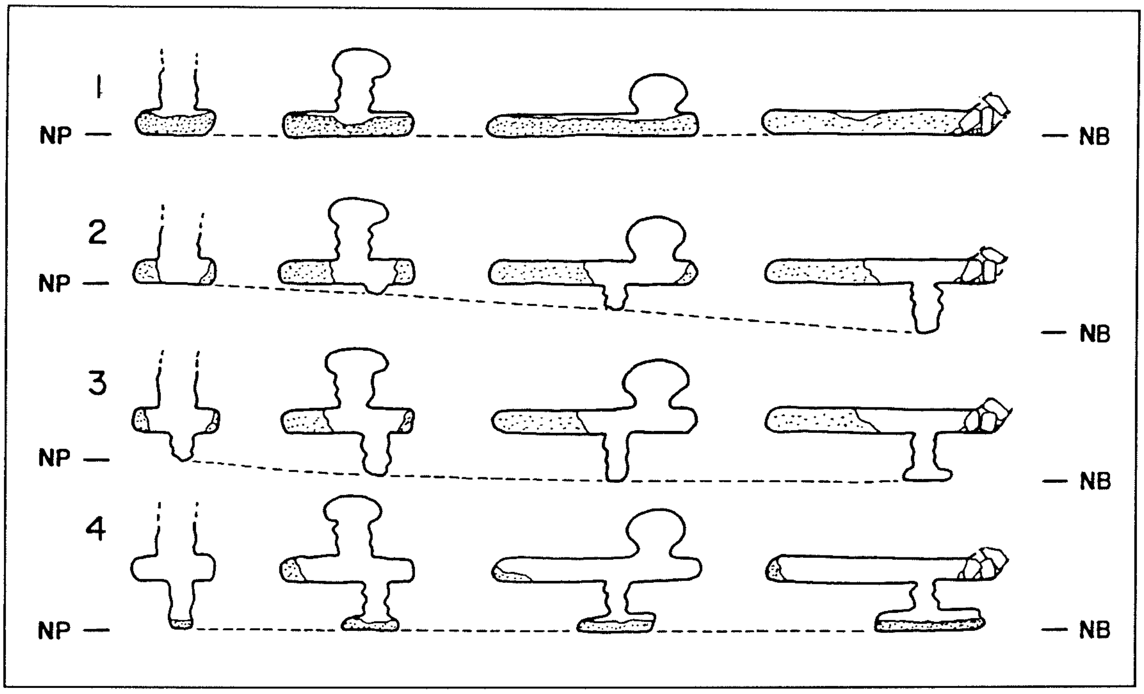

Figure 8 : Interpretive sketch of cross-section evolution along the main collector when base level falls. (1) Meandering channel with lateral widening during a period of base level (NB) stability: the piezometric surface (NP) approaches an horizontal plane. (2) Sudden base level fall and headwards entrenchment. (3) basal widening begins in the downstream part. (4) New period of base level stability: the magnitude of basal widening decreases upstream.

After a base level fall, it must be expected that the more downstream parts of the system will become in equilibrium with the new base level prior to the more proximal parts. When reach equilibrium, the distal part of the collector would Begin basal widening processes. Meanwhile, proximal parts could be yet under incision. This could be partly the cause of the upstream decreasing in width/thickness ratios for Ti: the stability period which represents Ti was not long enough to allow basal widening along the more proximal part of the main collector (Fig. 8).

VII. DISCUSSION

In Redondo karst, widespread perching precludes the possibility of direct fluvial base level control. Local base level is determined by resurgence altitude, i.e., the altitude of the lower limestone/turbidite boundary. If this altitude remains static, no water table drop should be expected. In contrast, Cobre Cave System has evidence of long periods of radier static base level interrupted by episodic entrenchment. As the only way to lower resurgence altitude is retreating valley walls, the recorded drops of the phreatic surface must represent episodes of accelerated erosion rates at surface. As an example, the youngest recorded base level fall implies a 6 m lowering in the resurgence position. In order to bring the limestone/turbidite boundary 6 m down, an erosive retreat of 8.5 m in the valley walls is necessary (Fig. 7).

Ti and T2 levels developed during periods of reduced erosion rates, and as a consequence, local base level remained ratier stable. These stable stages were interrupted by periods of high erosion rates. Without any doubt, there must be a close relationship between this periods of accelerated erosion and the activity of the nearby *Covarrés* and *Sel de la Fuente* mountain glaciers.

VIII. ACKNOWLEDGMENTS

We thank the members of the Sociedad de Espeleología geológicas for their friendship and cooperation in the survey. In particular, we appreciate the help of A. Cortel, O. Bernaldo and F. López Quintanilla in resurveying the main collector of Cobre Cave.

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