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Geology and Speleogenesis of the M2 Cave System, Western Massif, Picos de Europa, Northern Spain

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Abstract: The geological history of the Picos de Europa has been particularly favourable from a speleological point of view with 1200 metres of carbonates thickened by overthrusting in 2000 metres of relative relief. The M2 cave system, in the Western Massif, has been explored to a depth of -986 metres. The upper part of the M2 cave originated as a single small phreatic passage which descended steeply to the major phreatic conduits below. Two models of the early development of the cave are discussed. The first model has a bathyphreatic system modified by vadose entrenchment while the second proposes that passages in the upper cave are para-phreatic and formed within an extensive vadose zone. Inclined ramps in the upper cave are vadose features formed where the base of each pitch has retreated head wards and cut downwards. Glacial melt water is proposed as the erosive agent of the pitch-ramp systems. Sediments preserved within the lower passages strongly resemble 'Red Permian' materials and demonstrates the existence of a post-Carboniferous cover during the early development of the cave.

INTRODUCTION

The Picos de Europa mountains of northern Spain are divided into three massifs by spectacular gorges which dissect the range from south to north (Fig. 1). In the Eastern Massif several major cave systems have been discovered and explored by Lancaster University Speleological Society (LUSS) and the Seccin de Espeleologa Ingenieros Industriales (SEII) (Sefton, 1984), while in the Central Massif groups of French cavers have discovered major systems such as Torca de Urriello and Sima del Trave (Benoit, 1985). The Western Massif is divided into northern and southern sections by the ridge of the Picos de Cornion. Oxford University Caving Club (OUCC) have been working to the north of the ridge for many years where they discovered Pozu del Xitu (Singleton, 1981). However, the region to the south received relatively little attention from speleologists until 1983 when the area was explored by a combined team from York University Cave and Pothole Club (YUCPC) and the SEII from Madrid. The same group has returned to the area each summer since 1983 and has focused attention on the cave numbered 'M2' after it's discovery in 1984 in the Vega Huerta area to the south of Pena Santa.

GEOLOGY

The three massifs are composed almost entirely of limestones which were laid down during the Carboniferous Period of between 290 and 345 million years ago. In the Western Massif approximately 1200 metres of carbonates were deposited with very few impermeable horizons so that most formations are suitable for cave development (Fig. 2). The geological history of the Picos de Europa since the beginning of the Carboniferous resulted in a region with large speleological potential and the development of cave systems such ai M2 is intimately related to the geological structure and lithology.

The Carboniferous Period and Variscan Orogeny

During the Carboniferous Period the Picos de Europa occupied a palaeogeographic position which was favourable for carbonate deposition. While neighbouring regions experienced increasingly unstable conditions the Picos de Europa remained a relatively stable province in which carbonate deposition predominated for 55 million years. The Picos de Europa was located on the northeastern margin of the Cantabrian Zone, a palaeogeographic unit distinguished by Comte (1959). The province was bounded to the west by the Ponga Nappe

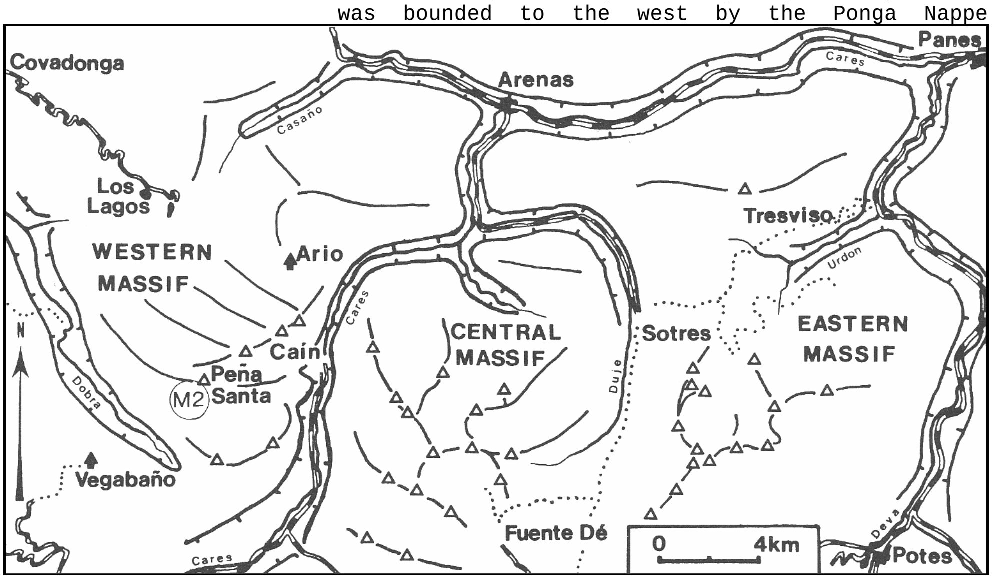
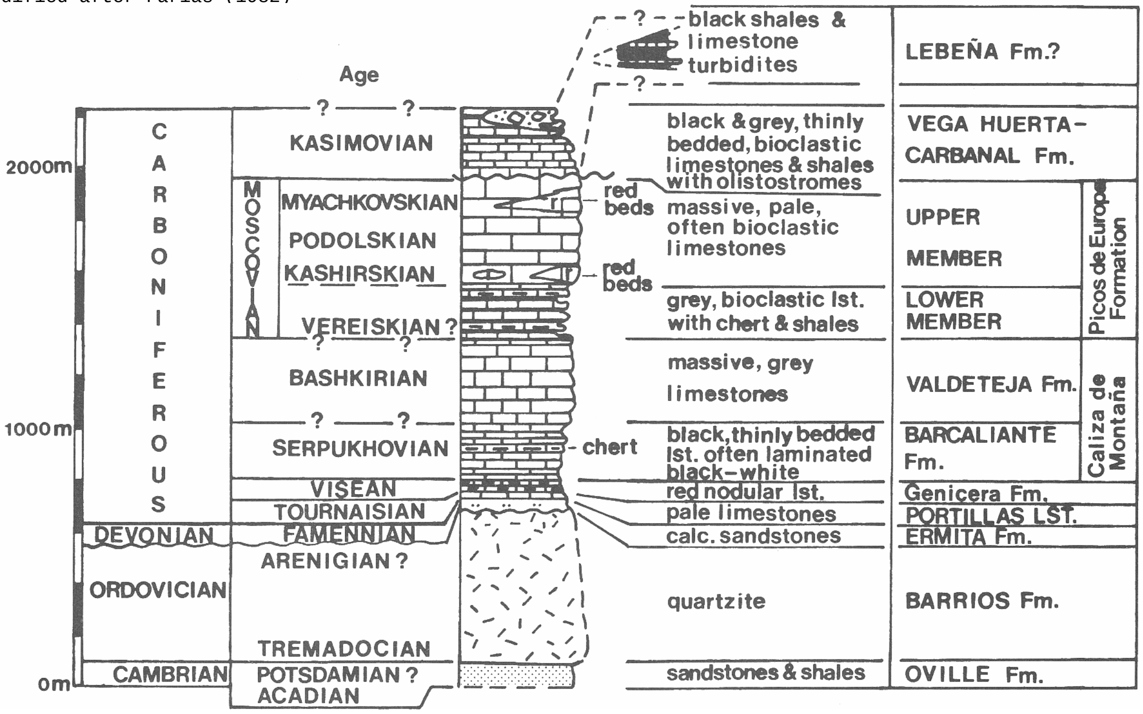


Figure 1 The three massifs of the Picos de Europa.

Province and to the south by the Pisuerga-Carrion

Figure 2 The general stratigraphy of the Western Massif. Modified after Farias (1982)



Province.

At the beginning of the Carboniferous Period uniform marine conditions existed throughout the Cantabrian Zone resulting in the widespread deposition of a sequence of red, nodular limestones with chert and thin shales, the Genicera Formation (Fig. 2). At the beginning of the Namurian the black, ‘Caliza de Nontana’ was deposited but in the Ponga Nappe and Pisuerga-Carrion Provinces sedimentation became increasingly dominated by terrigenous material. Carbonate deposition continued in the Picos de Europa Province however, with intraformational breccias and slump deposits the only indications of tectonic disturbances.

The cause of the instability was the north-western movement of the African continental plate towards the Eur-American plate. The Variscan orogenic belt developed along the line of collision. The details of the Variscan Orogeny are complicated and several models have been proposed (see Windley, 1984 for a review).

The main period of deformation in the Cantabrian Zone occurred during the Asturian Phase of the Variscan orogeny, at the end of the Moscovian (about 295 Ma). Sediments were thrust into the core of a developing arcuate mountain chain (i.e. into the Cantabrian Zone) from the northwest, west and southwest. The Picos de Europa Province was the last to be affected by deformation because of its position at the north-eastern margin of the Cantabrian Zone, away from the encroaching thrust sheets. The main phase af

View to the north from base camp at Vegabano. The escarpment on the right is the southern edge of the Frontal Nappe Unit. The main peak is Pena Santa and the entrance of M2 is located close to the imposing south face. The bottom of M2 is about 100 m below the level of base camp.

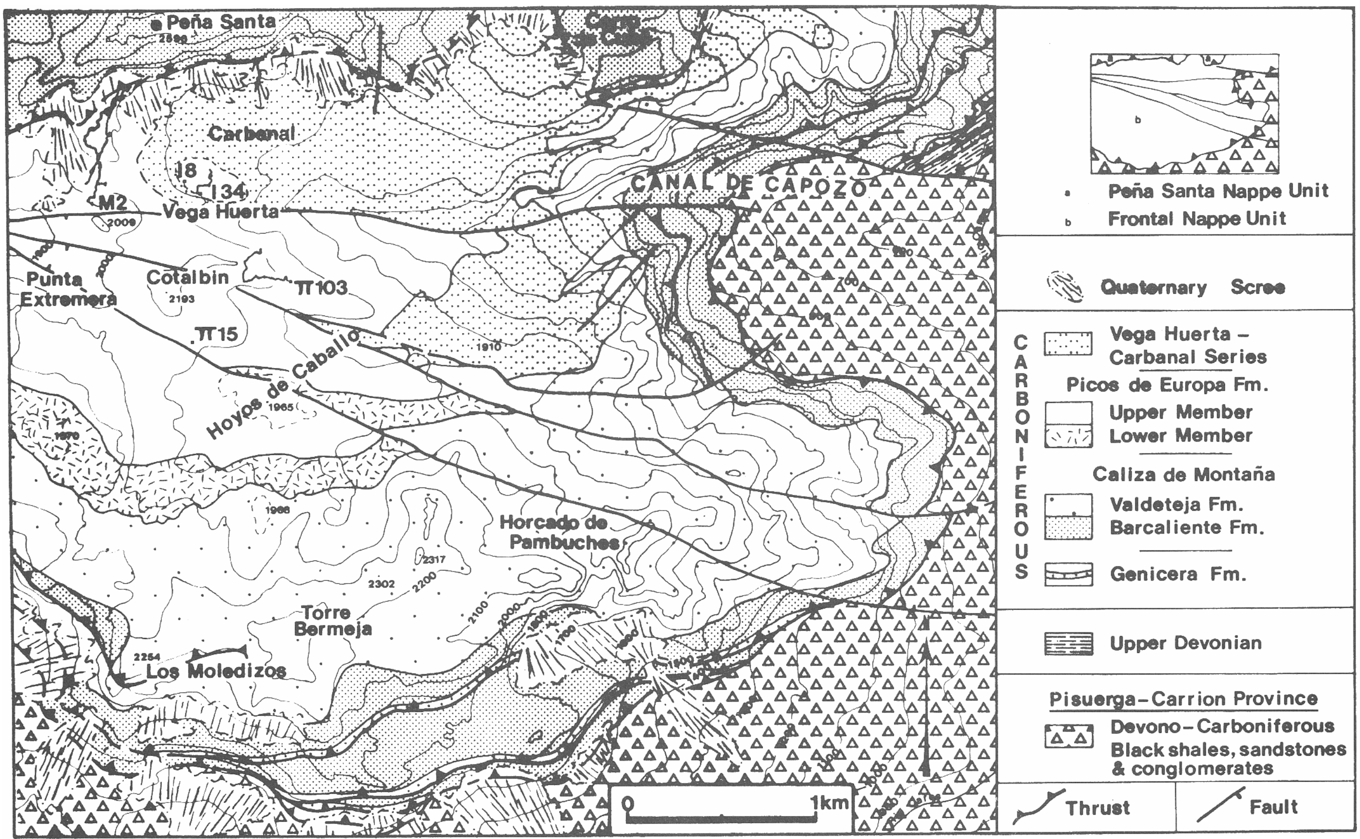


Figure 3 The Geology of Vega Huerta. Largely after Farias (1992). M2, I8, I34, Pi15 and Pi103 are the major caves discovered to date.

deformation within the Picos de Europa Province began in the Kasimovian and continued within down-faulted regions, as at Sotres until the Autunian (Martinez-Garcia, 1981). Palaeozoic sediments, predominantly Carboniferous carbonates, were thrust from the north-northeast to the south-southwest over the Pisuerga-Carrion Province (Naas, 1976; Marquinez, 1978; Farias, 1982). The massively bedded limestones moved as a series of competent sheets with very little internal folding. Each thrust sheet was pushed over the one emplaced immediately to the south which greatly increased the total thickness of the carbonate sequence. Naas, '(1976), estimated that the limestones moved at least 20km because the Pisuerga-Carrion facies is so different from that of the Picos de Europa.

Post-Variscan Events

During the Permian, Nesozoic and early Tertiary, a sedimentary sequence was deposited over the Picos de Europa limestones. This is inferred by the presence of Permian deposits within down-faulted regions, as at Sotres (Marquinez, 1978; Smart, 1984), and by the present drainage pattern which must have been superimposed on the Carboniferous limestones from a post-Variscan cover.

Post-Variscan deformation was extensional in character with fault-bounded basins controlling the pattern of sedimentation. In late Eocene and Miocene times, however, northern Spain experienced a further period of' north-south compression, this time related to the Pyrenean Orogeny. The compression ended about 38 Ma ago and probably: initiated the uplift of the Picos de Europa massifs (Le Pichon & Sibuet, 1971; Boillot & Depeuble 1982; Vegas & Banda, 1982). The Pyrenean deformation affected. the Carboniferous limestanes largely by re-activating existing Variscan and post-Variscan fractures, These are particularly important controls on cave development because they are less well 'sealed' by veining and provide the most open routes for water into the massif.

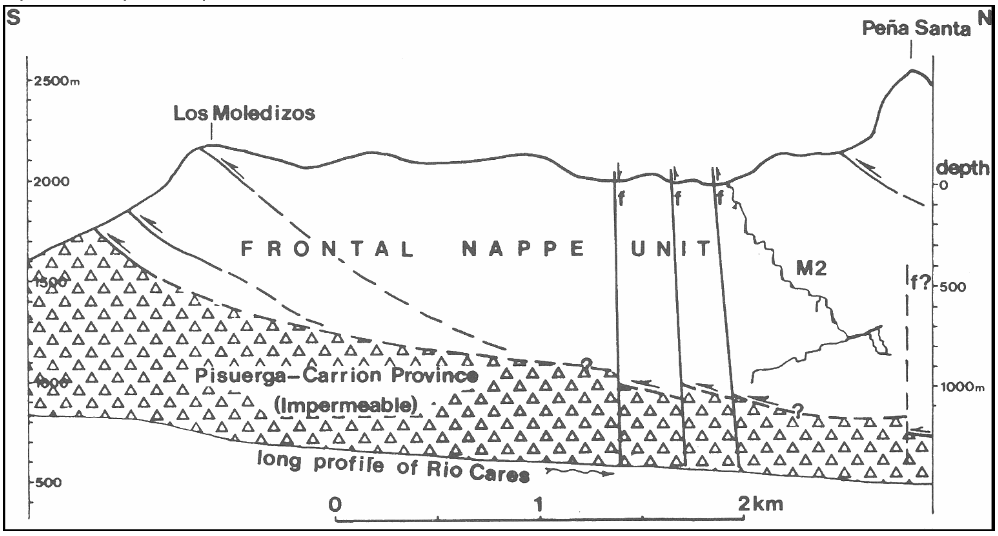


Figure 4 Diagramatic section through the Frontal Nappe Unit.

The Geology of Vega Huerta

The Western Nassif has been mapped hy Farias (1982) although only the eastern part of the range is covered (Figs. 3 and 4). Farias identified four major Variscan thrust sheets (or nappes). Each is overthrust on to the one immediately to the south so that the dip of the thrusts generally increases from south to north. Vega Huerta is located on the first (most southerly) nappe to be emplaced which is called the Frontal Nappe The highest mountain in the massif, Peña Santa, located at the front of the second nappe, the Peña Santa Nappe Unit. Within the Frontal Nappe Unit the dips of the beds are generally 0° to 20° although the dip reaches 30° at the southern escarpment and steeper dips occur near major faults. This contrasts with the area to the north and around Treviso where the dip is rarely less than 45°.

All the limestones of the Frontal Nappe Unit are potentially cavernous although the Vega Huerta-Carbanal Series which has a significant shale content, contains only callapsed shafts at the surface with no negotiable entrances found to date. Erosion of this - formation has produced 'windows' into the underlying Picos de Europa Limestone Formation within which the caves I8 and I34 are developed (Fig. 3).

Several major post-Variscan faults cut the Frontal Nappe Unit. These trend east-west and southeast-northwest and three come together just to the south of the entrance of M2. There are also many less persistent fractures, not shown in Fig. 3, but which are. clearly important controls on cave development.

CAVE DEVELOPMENT WITH SPECIAL REFERENCE TO M2

The Frontal Nappe Unit differs from the nappes emplaced later (in the region north of Peña Santa) in that the limestones rest on the rocks of the Pisuerga-Carrion Province. These are largely black shales, sandstones and conglomerates and therefore provide an impermeable basement to the limestones. The Rio Cares has cut completely through the Frontal Nappe and now flows some 300 metres below the base of the limestones. Therefore vadose conditions must have existed throughout the Frontal Nappe for a considerable period (Fig. 4). At the present time, water draining to the base of the Frontal Nappe can be expected to flow down the dip of the basal thrust, approximately towards 010°. In part of the area explored by OUCC, between Peña Santa and Ario, there appears to be a perched water-table which causes the caves to terminate in sumps at an altitude of about 1300 metres (Roberts, 1986). The existence, of the M2 cave system, which descends almost to the base of the limestones, demonstrate the absence of a water-table at 1300 metre4 in the Frontal Nappe.

As Smart (1984) commented, cave development would have been initiated with the exposure of the Carboniferous limestones from beneath the post-Variscan sedimentary cover. At present there is little information to date this event but erosion of the post-Variscan cover would have both accompanied and followed the uplift of the Picos de Europa. Major cave systems probably developed while the post-Variscan cover supported large drainage catchments and concentrated water into a few sinks. Such systems will be termed 'cover systems' in this paper. As the cover was eroded however, an increasing number of smaller catchments would have developed as new fractures were exploited. Many of the existing sinks and cave passages would have been abandoned.

The glaciation of the Picos de Europa during the quaternary had a number of important affects. Glacial periods are characterised by both erosion and deposition so many established depressions were undoubtedly choked with debris. However, cave systems were probably formed at this new time by glacial melt water sinking into the limestones as proposed by Smart (1986) for many caves in the Eastern Massif. Essentially .the glaciers provided large catchments and concentrated water into certain sinks. The Picos de Europa must have been a region of high relief before the quaternary glaciations, so the majority of the post-Variscan cover may have been eroded (and major caves developed) before the onset of glacial conditions.

Since the retreat of the glaciers the surface of the Frontal Nappe has probably changed very little except that most of the larger shafts have gradually choked with scree. At present there are hundreds of shafts developed in the surface of the Frontal Nappe but very few lead to negotiable cave passages. The large number of fractures means that each one has only a small catchment area, often receiving water only from the snow-plug within it. These flows are insufficient to keep cave passages

Top Camp below the south face of Pena Santa. The main face is composed of limestones from the Barcaliente Formation which are thrust over the disrupted Vega Huerta-Carbanal Series.

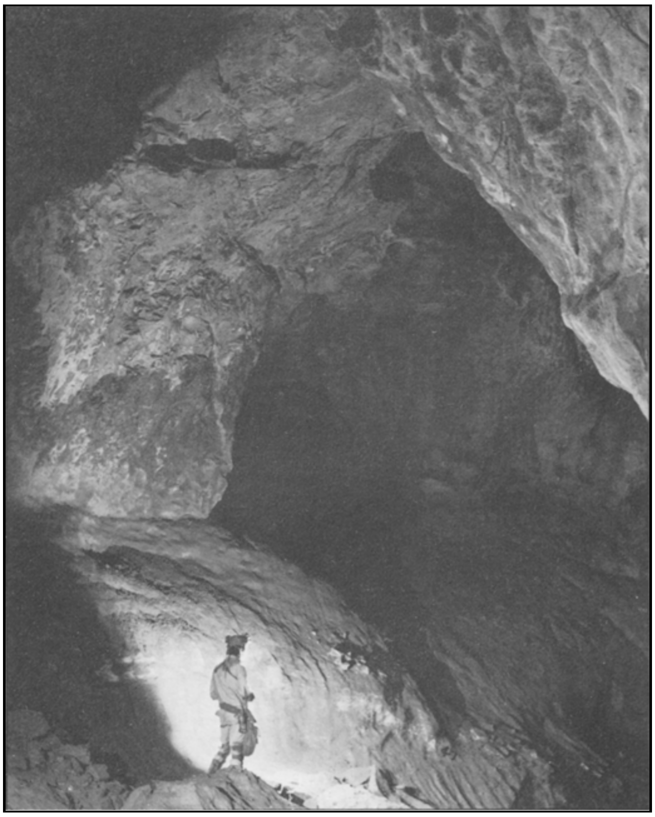
clear of the debris loosened by freeze-thaw action in the winter months. The entzances to the 'cover systems' are almost certainly eroded or buried, although deeper passages may have been preserved. The major cave systems discovered to date are usually those with entrance passages which have been created or enlarged by meltwater and which have then escaped infill because of a fortunate location or because they have high-level routes over the blockages created by debris from the surface (Laverty and Senior, 1981).

THE M2 CAVE SYSTEM

The entrance of M2 is located about 400 metres west of Vega Huerta beneath the imposing south face of Peña Santa. In this location ice accumulation was probably less extensive and less prolonged than on the north-facing slopes of the areas explored by OUCC and LUSS. Nevertheless, remnants of terminal moraines exist in the major depressions south of Peña Santa and glacial rounding is evident in the limestone ridge containing the entrance of M2. The entrance is on a minor fault dipping 65° to 020° which forms a linear depression along the long axis of the ridge. A possible explanation for this location is that crevassing occurred where the ice rode over the ridge so that supra-glacial and en-glacial melt water was directed to the base of the glacier, where it then sank into the M2 cave.

Within the cave individual passages can be seen to exploit various geological controls but by far the most important are faults. The term 'fault' is used in the following sections only where movement can be clearly detected. The term 'fracture' is used in a general sense to describe all planar fissures and includes faults, joints and major bedding planes. In general, the orientation of the cave passages (Fig. 5) suggests that the overall trend is controlled by two sets of fractures which strike approximately 020° and 140°. Fractures with this orientation are mostly related to the period of extensional deformation which followed the Variscan orogeny. These fractures are the most important controls be1ow Non-Stop Drop. Above this point the cave is developed down the dip of fractures striking approximately 280°.

Looking up the main phreatic conduit towards Road to Nowhere. The passage is about 15 metres in diameter and has a gradient of about 15°.



The phreatic tube just downstream from Ken Hill Gallery. Here it is mostly developed above a bedding plane within the Valdeteja Formation. Downward solution was limited by sediments.

The Upper Section of M2

The entrance fault runs into a more prominent reverse fault dipping 65° to 040° which is first encountered just beyond No Eighth (Fig. 5 and Fig. 6). This second fault defines the roof of the pitches between Watford Gap and Ivan's Other Orifice. The cave clearly developed down the dip of the fault plane and a small phreatic tube is preserved at the head of Watford Gap, its trend determined by a small phreatic tube which approximately follows the strike of another fracture. The Amapolo Series is probably a separate system which has been intersected by down-cutting of the canyon in the main cave. Scallops in the Amapolo Series indicate a direction from west to east.

The pitches developed along the second fault plane are linked by ramps which rise from the base of each pitch to the head of the next. Such ramps are common in M2 and are important features inmany Picos caves. Fig. 7 summarises the morphology of the ramps and shows that they are vadose features formed by pitch retreat. They are not lithologically controlled and are not of Phreatic

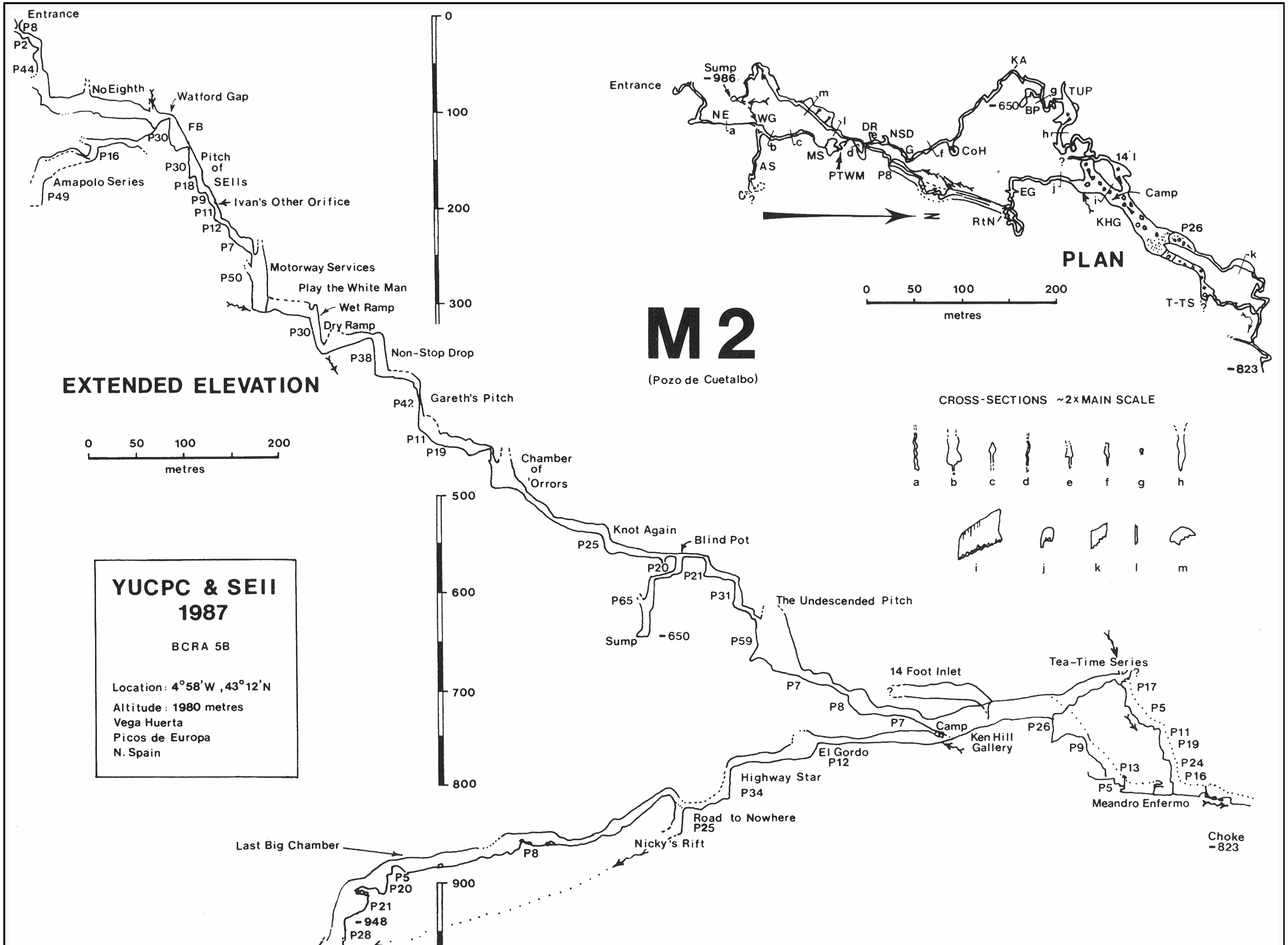


Figure 5 1987 Survey of M2. Multiple phreatic levels near Ken Hill Gallery have been omitted for clarity.

tubes intersected by vadose canyons. Each ramp marks the foot of a pitch where it retreated head wards and cut downwards. The gradual decrease in width of both the ramp and the canyon towards the base of the pitch may be evidence of a decrease in discharge over time. Measurements of ramps in two caves, M2 and M103, have revealed mean gradients varying between 30° and 34° which suggested that the head ward erosion rate is more than 1.5 times that of down cutting. The larger size of the pitches compared to the canyons demonstrates the greater erosive power of falling water compared to channel flow. The canyons are often too narrow to traverse so the only negotiable route through these ‘pitch-ramp’ systems is usually down the pitches then back up the ramps. The nature of erosion at pitches was studied by Brucker et al (1972) who measured a decrease in carbon-dioxide pressure in water as it fell down shafts. They attributed this change to de-gassing of dissolved carbon-dioxide from the thin film of water flowing down the walls. In M2 - at present, very little water falls through the pitch-ramp system. In normal summer flow conditions, only a thin film of water flows down the walls and the wetted area is restricted to a small section of the shaft below the inlet canyon. In the highest flows observed to date the inlet stream disperses into a fine spray as it falls which causes an increase in the wetted area on the shaft. If the erosion rate is equal over the whole wetted area, these observations infer that the length of a ramp depends on its age whereas the width of a ramp is related more closely to the mean discharge. A consequence of predominantly low flows is that the wetted area on a pitch approaches that of a canyon so that pitch-ramp systems tend to evolve into steep, narrow canyons (Fig. 7b, stage 3).

Further work is required to determine the significance of the ramp angle in particular with respect to the angle of the dipping surface, usually a fault plane, beneath which the ramps develop. Potholes commonly develop at the base of the pitches because the mechanical erosion of swirling sediment in the plunge pool ‘drills’ downwards at a greater rate than the exit canyon can cut down (Ford, 1965). The absence of potholes at the base of the pitches in ‘pitch-ramp’ systems infers that the exit canyon could always cut down at the same rate as the base of the pitch. The simplest explanation for this is that there was insufficient sediment to create potholes, a conclusion which supports the earlier suggestion that glacial melt water was probably involved in

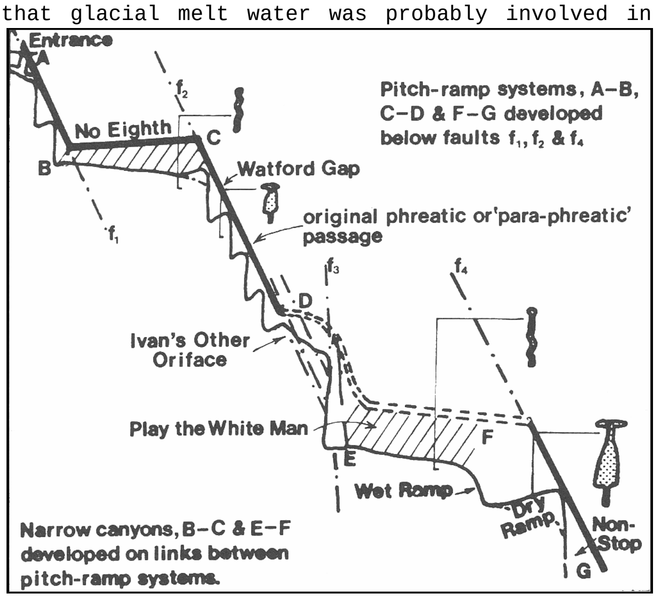


Figure 6 Diagramatic section of M2 between the entrance and the Dry Ramp.

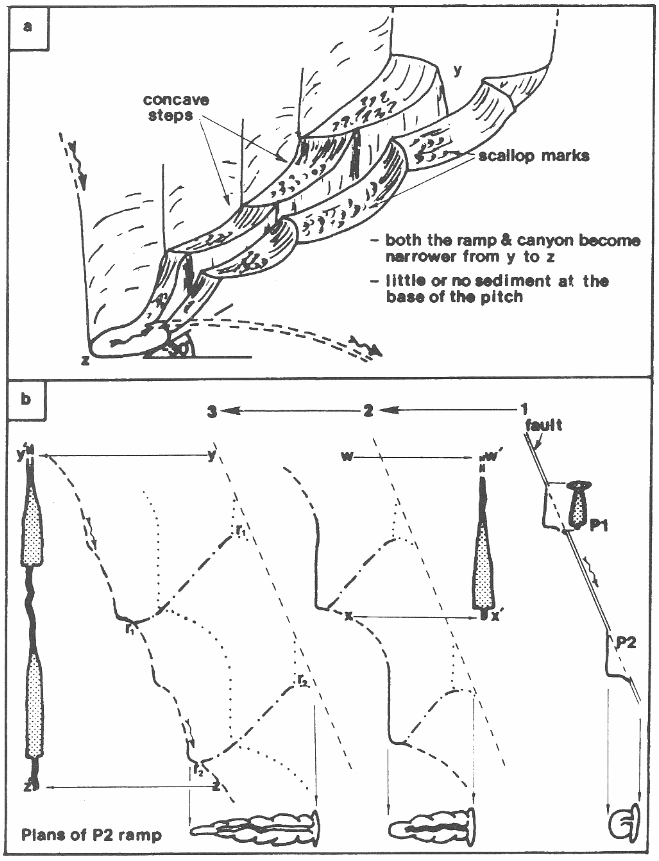


Figure 7 a) The general morphology of pitch-ramp systems. b) Schematic development of ramps r1 and r2 due to rre-treat of pitches P1 and P2.

the formation of the upper cave.

At Motorway Services a small stream enters and flows down the tortuous Play the White Man canyon. This passage is similar to No Eighth in that it cuts through massively bedded limestones to link one series of fault-guided pitches with another. On such links a narrow and meandering canyon has developed because it is solely the result of canyon incision. No pitch has retreated along it to form a ramp (Fig. 6).

The passage enlarges beyond Play the White Man as the stream cascades down the dip of a fault with calcite and dolomite veining (the Wet Ramp) to sink at the bottom in an immature rift. The way on is up the Dry Ramp, which is between 2 and 3 metres wide and rises approximately 25 metres to the head of Non-Stop Drop. The Dry Ramp has also formed as the result of pitch retreat beneath yet another fault (Fig. 6) but the ramp-forming pitch has been abandoned due to a capture down the Wet Ramp.

Below Gareth’s Pitch the cave changes direction towards the northwest. The new trend is determined by a phreatic tube which rises and falls along another fracture inclined at 70° to 040°. A deep vadose canyon is developed below the tube and there has been extensive modification by collapse. Near Chamber of ‘Orrors, for example, two parallel open fractures and one filled with ochre, dolomite and shale have contributed to a massive collapse.

Below Chamber of ‘Orrors, the tube continues in the roof of the passage and constantly changes direction and cross-section as it exploits successive fractures. There are several pitches along this section of the cave but only in the case of Blind Pot, an obvious capture, does the tube continue over the head of the pitch. At the other pitches the tube must have descended steeply down the dip of the controlling fracture. Subsequent modification of this dip segment under

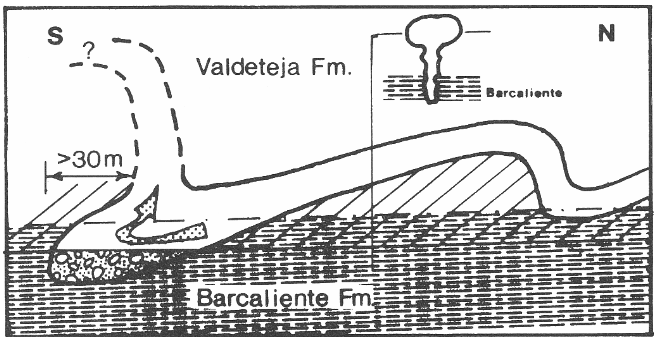


Figure 8 The relationship of the main phreatic conduit to the geology near Last Big Chamber showing how the chamber developed by solution at the bottom of a phreatic lift.

vadose conditions has removed signs of its original phreatic morphology; however the tube is always encountered again at the base of the pitch where it is developed along a suitable fracture.

The Lower Section of M2

At the Undescended Pitch the dimensions of the cave increase and a large meandering canyon leads to the junction with the lower section of M2 at Ken Hill Gallery. Remains of phreatic tubes more than 3 metres in diameter reveal the origin of this section of the cave although there has been substantial modification by collapse. Two major phreatic conduits meet at Ken Hill Gallery. One is the Tea-Time Series which has suffered two captures, one within Ken Hill Gallery where the Tea-Time Series enters and another at the limit of ‘upstream’ exploration. These two routes join and then choke at -823 metres. The second major phreatic inlet lies in the roof of the canyon between The Undescended Pitch and Ken Hill Gallery. Near the bottom of Ken Hill Gallery, below the camp, a stream joins the main gallery, flowing in a meandering canyon. A small phreatic tube in the roof diverges from the canyon in an upstream direction and terminates at a pair of perched sumps. In a downstream direction from Ken Hill Gallery, incision by the inlet stream gradually increases and eventually the large phreatic passage in the roof becomes inaccessible. The stream falls down some wet pitches (another relatively recent capture) and eventually disappears into Nicky’s Rift. Fortunately the phreatic passage can be regained above the Road to Nowhere after which it again descends, clearly developed down the dip near and at the base of the Valdeteja Formation (Fig. 8). The main phreatic conduit exploits both faults and bedding planes but it’s general trend seems to be controlled by the bedding of the massive Valdeteja Formation. In Ken Hill Gallery and adjoining passages there are considerable thicknesses of sediments which are of five main types:

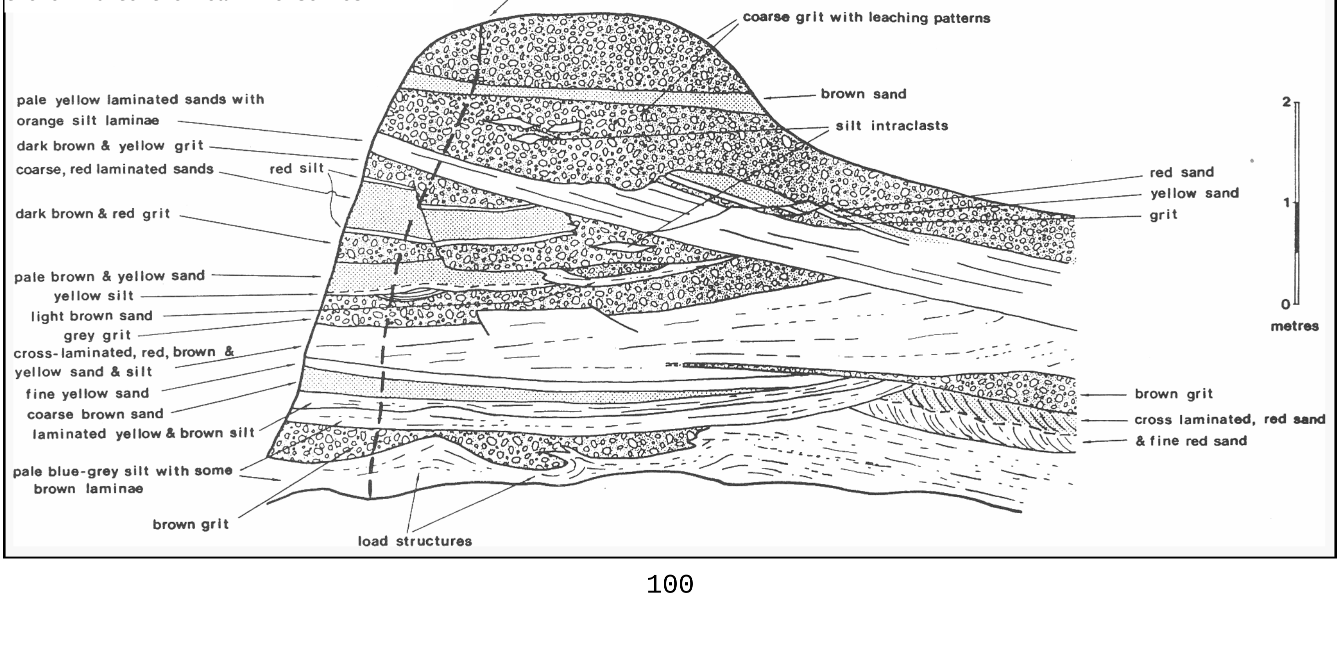
1. Unsorted, limestone boulder beds with rounded boulders up to 0.7 metres in length. These make up the largest volume of sediment.
2. Well sorted, well rounded, imbricated limestone pebhle beds.
3. Cross-laminated and cross bedded sands and silts of many colours with lenses of unsorted sandy gravels, the material loosely termed ‘grit’ in Fig. 9.
4. Well rounded, brown to red, gravels and sandy gravels. These are an equivalent lithology to the lenses of unsorted, sandy gravel (‘grit’) within the cross-bedded sequence, however they have a much wider distribution.
5. Dark brown clay. This is found on top of the cross-bedded sequence and is the material filling the fissure in Fig. 9.

The sandy gravels are remarkable sediments. They are extremely porous and water moving through the deposits has produced spectacular leaching patterns. Some beds are weakly cemented by calcite but most are unconsolidated and form extensive talus slopes in Ken Hill Gallery.

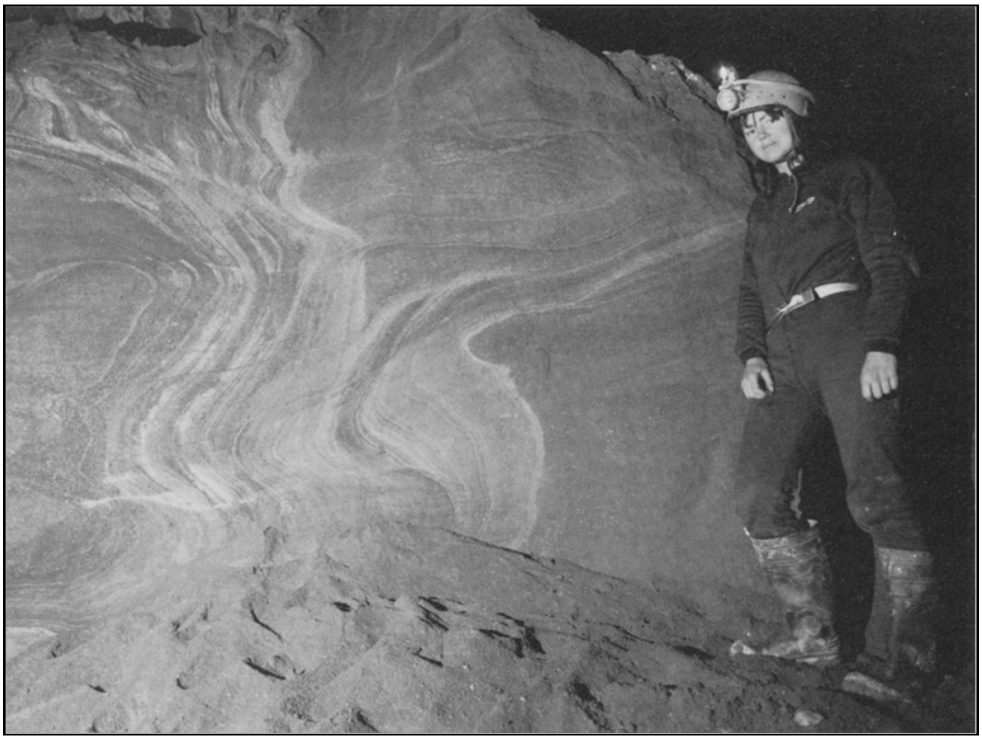
The cross-bedded sequence of silts, sands and sandy-gravels appears to be the oldest sediment preserved and represents alternating still and energetic periods. Most of the fine material, particularly the blue-grey silt, is found at the bottom of the sequence. The sandy gravels are found cutting across the beds beneath and become more extensive towards the top of the sequence. One lens has clearly been deposited in a channel with a steep bank showing that the phreatic conduit was at lest partly drained when the last of the coloured sediments were being deposited. The unsorted nature of the sandy gravels and the chaotic inclusion of silt intraclasts suggested that these materials were deposited suddenly at the confluence of a fast-flowing inlet (the Tea-Time Series?) with a relatively still river or lake within Ken Hill Gallery.

The Carboniferous succession in the Picos de Cornion (Fig. 2) contains no formation which could have provided these materials. They are most similar to the so-called ’Red Permian’ formations like the Sotres Formation of the Eastern Nassif (Marquines, 1978, Martinez-Garcia, 1981, Smart, 1984) or the Labra Formation (Maas, 1976). In the

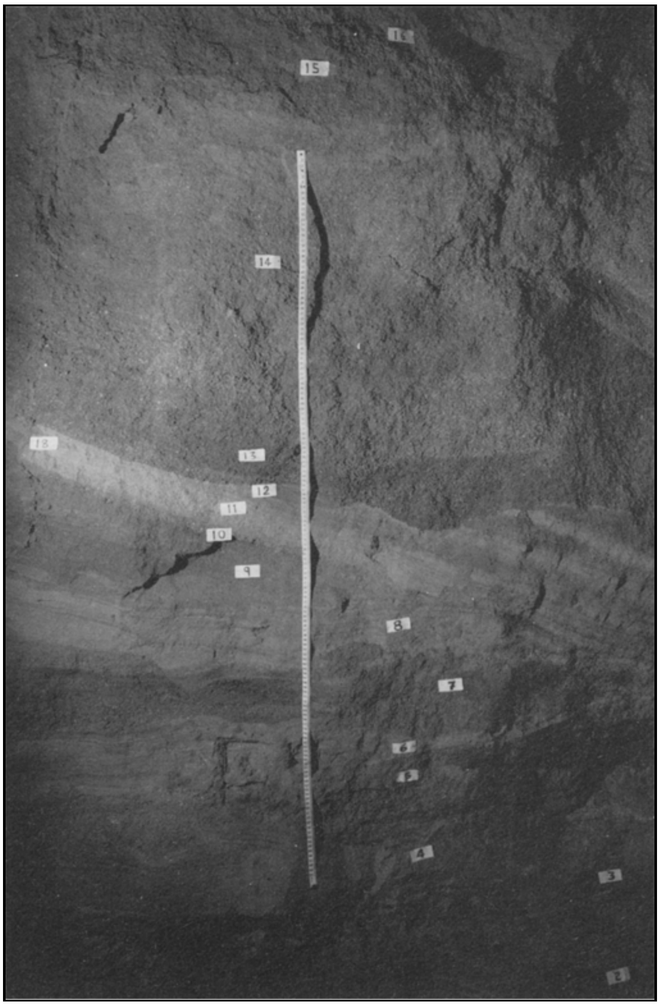
Figure 9 Sketch of the sediments below the climb to the Tea-Time Series.



Leaching patterns in unsorted sandy gravels, Ken Hill gallery.



western Massif, a small outcrop of 'Red Permian' is preserved to the north of a mountain called Valdepiño, about 2km west of Vegabaño, but at an altitude of only 1400 metres. The M2 cave



Cross-bedded sediments below the clib to the Tea-Time Sereis in Ken Hill Gallery. The photo covers part of the area shon in Fig. 9. Numbers indicate sediment sampling sites and the clay-filled fissure can be seen near no. 18. The tape is 1.5 metres long.

sediments provide the first direct evidence of a post-Variscan sedimentary cover at higher altitudes in the Western Massif. Since the lower section of N2 descends from north to south the source of the cave sediments may have been to the north of the Peña Santa ridge.

The dark brown clay which covers the coloured sediments in Ken Hill Gallery is also found between the sediments and the wall of the cave, and infilling fissures. This shows that the coloured sediment dried, shrank and cracked before being re-submerged at the time the dark-brown clay was deposited.

The rounded limestone pebble beds and the boulder beds appear to post-date the coloured arenaceous sediments. This relationship is most clearly seen in the Last Big Chamber where the pebble beds can be seen on top of parallel-bedded yellow silts and fine sands.

Discussion

Passages with a phreatic morphology occur at -100 metres (Watford Gap), -140 metres (Amapolo Series), between -425 metres and -575 metres (base of Gareth's Pitch to Undescended Pitch) and within the lower section of the cave (-700 to -986m). The relationship between these passages is not clear but, as mentioned previously, the Amapolo Series is probably a separate development. The small size of the high-level tubes suggests that the upper part of M2 did not originate as a 'cover system', If the highest phreatic passages are interpreted as having formed beneath a regional water-table then base level in the Rio Cares and Rio Dobra must have been some 1100 metres higher than it is today. Higher base levels have been proposed to explain the presence of phreatic passages at high altitudes within Pozu del Xitu (Laverty and Senior, 1981) and Sima 56 (Smart, 1984, and 1985). The fact that the phreatic tube in the upper section of M2 exploited fractures of various orientations en-route to the lower part of the cave shows that the local hydraulic gradient at the time was towards the lower cave and not towards either of the gorges. Therefore the lower part of M2 must be at least as old as the upper cave. If upper and lower cave originally formed as part of the same phreatic system, M2 is an example of a 'bathyphreatic' cave (Ford and Ewers, 1978). These authors describe such caves forming where groundwater hydraulic gradients are steep and the water table remains high because firstly the fissure network is immature and secondly the distance between point of influx and the resurgence is great. This interpretation implies that the main phreatic tube in the lower cave must rise again, perhaps by as much as 500 metres, to its former resurgence level. According to the model of Ford and Ewers (1978) bathyphreatic caves evolve towards 'deep-phreatic' then 'water-table' caves as the fissure network matures and shorter routes are exploited between the point of influx and the resurgence. Such passages are not seen in the upper part of M2 and the single phreatic tube which controls the trend of the upper cave shows no significant increase in size with depth. These observations suggest that phreatic conditions existed for about the same length of time throughout the whole of the upper cave. The upper cave was possibly abandoned at an early stage then re-activated some time later under vadose conditions.

However, the earliest vadose canyon in the upper cave is everywhere developed below the small phreatic tube. It has not exploited other routes so the period of abandonment was not long enough to allow a significant increase in the permeability of the fissure network by the time vadose conditions become established. Within the bathyphreatic model, a very rapid drop in base level seems to be required to explain these observations.

The phreatic morphology of the earliest passage in the upper section of M2 may, however, be an extreme example of a 'para-phreatic' passage (Tratman, 1957). A para-phreatic passage is one formed where large volumes of water drain through a network of low permeability fissures within the vadose zone. Local phreatic conditions would have existed as long as the volume of water exceeded the capacity of the passage. If an immature fissure network is assumed, such conditions may have existed long enough for phreatic tubes to have formed on the more horizontal sections of the immature cave. Vadose conditions would have become established first on the more vertical segments where capacity to transmit water was greater. This model is proposed because it would explain the morphology of the phreatic passage in the upper cave without invoking a sudden drop in base level.

Feldspathic conglomerates of the 'Red Permian' north of Valdpino. Rocks like these are the likely source for the coloured sediments in M2.

The regional water table could have been fairly stable, probably close to the level of Ken Hill Gallery, at the time the upper cave was initiated.

Both models require an immature fissure network but the conditions in the aquifer are quite different, phreatic in the case of the bathyphreatic model and vadose in the para-phreatic model. At present there is insufficient evidence to prove or disprove either of these interpretations. Further exploration may show whether the phreatic riser inferred by the 'bathyphreatic' model actually exists. The lower section of M2 was clearly a major phreatic conduit and acted as the 'focus' for several subterranean streams. The large passages and sediments in the lower cave may be remnants of a pre-glacial 'cover-system', formed within the phreatic zone, and exploited by caves initiated under glacial conditions. Torca de Urriello in the Central Massif appears to be similar to M2 although the author has no personal experience of the cave. From the published survey, the upper section of Torca de Urriello has developed down the general dip of the beds and major structures. This section of cave links into a much larger, and probably much older development oriented along the strike. It may not be coincidence that the lower sections of M2 and Torca de Urriello are both at similar altitudes.

The trend of the lower passages in M2 gives no clue to the location of the ancient river's resurgence but presumably it was in the Rio Cares or Rio Dobra. The stream which enters the lower cave at the bottom of Ken Hill Gallery sinks into Nicky's Rift and fluorescein dye has proved that the same water emerges again near the terminal sump. From there the water has been traced to the canal de Capozo some 4km to the east and approximately 350 metres lower than the terminal sump (Lloyd, pers. comm.). The major east-west fault located just to the south of M2 probably conducts the water to this resurgence and may prove to be a key feature controlling the trend of the unexplored continuation of the main phreatic passage. Further exploration is required to determine the destination of the ancient river which formed the main phreatic conduit.

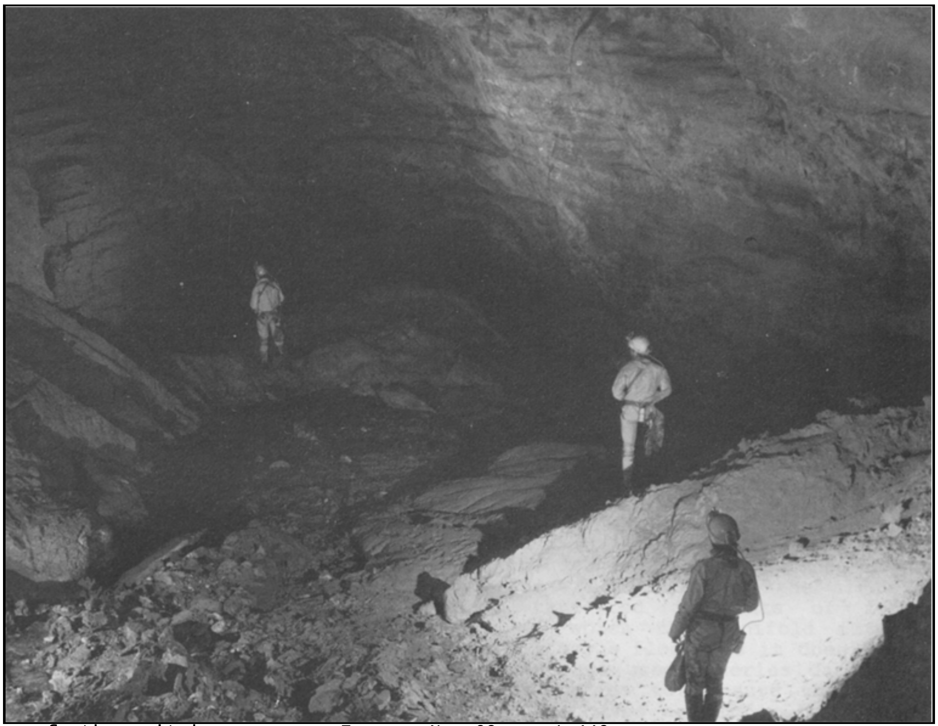
The geological section through the Frontal Nappe (Fig. 4) shows that perhaps 300 metres of 1imestone may exist beneath the sump at -986 metres. This interpretation is based on the fact that the top of the Barcaliente Formation is seen within the cave at an altitude of about 1100 metres (-900 metres depth) while along the strike to the east, in the Canal de Capozo, the Barcaliente Formation reaches 400 metres in thickness because of over thrusting (Fig. 3). The dip of the Barcaliente Formation in the lower passages is about 5° to the south and it is probable that the same resistant level is responsible for the termination of the cave at the -823 metre choke, in Nicky's Rift and at the final sump.

CONCLUSIONS

The discussion above and the conclusions summarised below are based on observations made during the 1986 and 1987 expeditions to M2. It is hoped that sediment analyses will be completed during 1988 which will identify the source rocks with more certainty and possibly provide a data for the deposits. The preliminary conclusions are:

1. The geology of the Frontal Nappe Unit provides different conditions for cave development compared to the other nappes because the limestones have an impermeable basement.
2. The ramps found in M2 and many other Picos caves are vadose features formed by pitch-retreat. Ramps form where sediment supply is low which

The Last Big Chamber. The thin beds visible in the far wall are within the top part of the Barcaliente Formation.



prevents potholing at the base of the pitches. Glacial melt water is proposed as the likely agent responsible for the erosion of the 'pitch-ramp' sections.

3. The phreatic tube in the upper part of M2 exploited various, low permeability fissures to transfer water down the local hydraulic gradient into the lower section of the cave. If the upper cave originates beneath the regional water table the whole of M2 is an example of a bathyphreatic cave. The phreatic tube in the upper cave may, however, be a para-phreatic passage formed within an extensive vadose zone.

4. The lower section of M2 acted as a major phreatic conduit and formed before post-Variscan sediments were completely eroded from the Carboniferous limestones.

5. The sediments in Ken Hill Gallery are probably derived from 'Red Permian' formations now eroded from most of the Western Massif.

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