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KARST PROCESSES AND LANDFORMS IN THE MATIENZO DEPRESSION, CANTABRIA NORTHERN SPAIN

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CHAPTER ONE

INTRODUCTION

Data obtained from all aspects of a karst landscape, as defined below, can be linked to help provide a general picture of the morphological evolution of that landscape. The karstic process is taken to mean the solutional removal of rock. This study aims to provide the framework for the development of such a model.

A karst terrain can be defined as a landscape combining a distinctive assemblage of landforms and hydrological network developed when a soluble rock with highly developed secondary porosity has been chemically denuded by the action of a suitable solvent. A karst terrain develops when the solutional process is concentrated in discrete areas of the main rock body, namely the cracks and fissures responsible for the secondary porosity. It follows that rocks with high primary porosities and insufficient mechanical strength to maintain discrete conduits within it's rock structure do not tend to develop karst landscapes. Furthermore very highly soluble rocks such as halites are generally unable to sustain karst development when they are exposed at the Earth's surface, as the entire rock mass is too readily removed by solution. The chemical enlargement of underground fissures by karst waters and the subsequent capture of surface waters is a key feature of a karst terrain. The most common rock type to bear karst features are limestones but they are not the only group of rocks to do so, other carbonate rocks, evaporites, silica cemented quartzites and siliceous sandstones all have developed examples of karst terrains. For the purpose of this report the terms karst and limestone landforms are regarded as synonymous. It most also be stated that although a prerequisite for karst development solutional weathering is not the sole process acting upon karst rocks. The normal weathering and erosion processes that shape other geological units also act alongside solution in shaping limestones.

The main solute responsible for karstic dissolution are acidified meteoric waters, weak carbonic acid. Relatively pure water in the form of precipitation can become acidified once in contact with carbon dioxide from the atmosphere or contained within soils. Organic acids present within the biomass can also mix with water to produce a solvent capable of dissolving karst rocks. Other sources of solvents that can produce karst features are connate, or deep ground, waters and brackish waters from sea water mixing zones.

Geomorphologists aim to gain an understanding of the processes and their rates of action that have acted to produce a landform that we see today. Generally we are restricted to measuring the type and rate of present day processes at work on a landscape. Landscapes are however often largely a relic feature of a dominant geomorphological process that has now ceased to act upon the region. The relative importance of certain geomorphic processes is altered as major climatic changes, such as those detected in the Quaternary, occur. The geomorphological effects of past glaciations, a process associated with cold phases, on the landscapes of some now temperate areas are a clear example of this. The process acting to produce features such as glacial troughs are no longer evident today. Secondary evidence must then be sort in order to explain landforms in such cases. Such evidence is often found in the form of a sedimentary record or process types and rates are inferred from the type, size and location of the fossil features that remain.

Significantly karst landscapes can retain a sequence of depositional records, representing the product of erosional events occurring upon that landscape, that can be accurately dated. These dating techniques, mainly the magnetic stratigraphy of cave sediments and uranium series dating of calcite deposits, will be discussed later. Furthermore if a landscape has developed under the dominance of one consistent group of processes a deeper understanding of that development can be achieved. Certain karst landscapes can provide such an opportunity.

One area that fits the criteria of uninterrupted development with an assiduous set of erosion processes is the Matienzo region of Cantabria, northern Spain. Work by Waltham(1981a) suggest that a minimum of 1.8 million years of uninterrupted karstic development have produced the landscape that can be seen at Matienzo today.

The purpose of this work is two fold. Initially an overview of the karstic processes that are acting to shape the Matienzo region is given. Secondly an investigation undertaken to determine preferential erotional paths, signified by groundwater movements in the area, is described. An overview of the geomorphological interest in karst terrain evolution is also given.

The karstic processes and features described in section A include the following: dissolution chemistry of limestone, karst hydrology, the development of cave systems, cave deposits, the development of karst depressions (dolines and poljes) and the development of surface solutional features karren). Section B describes the use of a technique which utilises the weight loss of gypsum blocks buried at the soil/bed-rock interface to determine water flow pathways.

Gypsum blocks will lose weight, by the solutional removal of gypsum, as water passes the block. The amount of weight loss is dependent on the discharge of water over the block. A number of sites were chosen in the Matienzo area and blocks emplaced for periods of up to twelve months in order to ascertain locational variations in weight loss, hence relative water flows, between the sites.

The findings of this and other recent studies concerning the magnetic properties of Matienzo's cave deposits could form the basis for continued research projects concerned with the development of a model describing the evolution of a karst landscape via the affiliation of surface and subsurface process and survey data.

CHAPTER TWO

THE DEVELOPMENT OF KARST TERRAINS

2:1 INTRODUCTION.

Powell (1975) summarised the aims of limestone geomorphologists as follows:

'The ultimate goal of karst and cavern research, so far as geomorphology is concerned, is to postulate, or perhaps even to prove, a scheme of landscape evolution.'

This goal is in accordance with the aims of researchers investigating other types of landforms. The likelihood of achieving this goal in the case of limestone research is however much enhanced by a combination of three principals that is exclusively related to karst processes:

1) The dominant erosion process involved in karstic evolution, the aqueous solution of limestone, is relatively simple and well understood.

2) 'Karst immunity' the concentration of the erosion process into conduits tends to leave the karst surface in a relatively stable relict state and is hence prone to longevity and the consequent easing of interpretation by geomorphologists.

3) The ability to determine absolute dates for some cave deposits and to place their deposition into a sequence of landscape development.

(adapted from Gunn (1986)).

In addition the solutional process is free of the thresholds that constrain other erosion processes (Ford 1980). If a rock mineral is capable of being dissolved it will be provided that there is a suitable solvent present. No critical limit need be exceeded before the solutional process begins. There are however limits to karstic evolution, the presence of suitable rock and solvent being the most basic. The karstic process is a series of chemical reactions that are free of thresholds and simply proceed until an equilibrium is achieved, section 3:2 describes these reactions. The effect of this is to smooth erosional events into one continuous episode. This is in comparison to the episodic erosion controls assigned to nonkarst landscape development. Schumm (1975) describes the geomorphic threshold that a fluvial system must pass before significant erosion occurs and the complex response of that system, once that threshold is passed, as a new equilibrium is sort, landscape evolution then progresses in a series of steps separated by periods of little activity.

The two main approaches to general landscape development can be applied to the specific problem of karstic evolution. The historic approach, as typified by the ideas of Davis(1899), Penck(1953) and King(1953), involve the development of a general model describing the origin and a series of evolutionary steps that shape a landscape. A general overview of the ideas of Davis, Penck and King is given by Summerfield(1991). A second approach is that of a 'denudation chronology' where a sequence of erosion and subsequent deposition is interpreted to give an account of the evolution of the landscape. The development of denudation chronologies was advocated by geomorphologists following Davis's model of landscape evolution. It was envisaged that earlier cycles of erosion would leave evidence of their action on the present day landscape which could be interpreted to yield a history of landscape development. The three principals listed above are of particular assistance when considering a denudation chronology for karst landforms.

2:2 GENERAL MODELS OF LANDSCAPE DEVELOPMENT.

The work of Grund(1914) and Cvijic(1918) typify the initial approach to karst landscape evolution. Grund based his ideas on his knowledge of the karst regions of Bosnia and Hercegovina and his impressions of the karst regions of tropical Jamaica and Java. He proposed a universally applicable sequence of evolution with karst depressions at increasing degree of development marking the intermediate stages: isolated dolines(solutional depressions) begin to enlarge and eventually unite growth continues and intervening ridges are removed ultimately all the hills are removed and a corrosional plain remains. The level of this corrosion plain would be controlled by the height of the regional water table and consistent with a 'Davisian' cycle of erosion subsequent uplift of the region would rejuvenate karstic development. Grund assumed an unlimited thickness of limestone for his evolutionary sequence and that underground drainage of water asserted no influence on general surface development.

Cvijic also envisage the successive expansion and coalescence of dolines into uvulas and eventually to large solutional depressions(poljes) in his model of development. Unlike Grund Cvijic's model applies only to the karst regions of Bosnia and Hercegovina with the consequent influence of geological structure, the limestone being sandwiched between non karst rock strata, taken into consideration. As the uppermost non karst rock is removed a normal fluvial regime is imposed onto the limestone until the solutional enlargement of fissures is sufficient to accommodate underground drainage. Dolines begin to develop at these solutional openings and at the maximum level of karstification dolines are found at all points of the land surface including interfluves. This multiple source of underground drainage matures into complex cave systems with combined outflows(resurgences) at suitable marginal sites. With the continued removal of limestone by solution dolines expand and eventually the impervious bed-rock is exposed the final stage of development is where only isolated residual hills of limestone(hums) remain and normal fluvial regimes are again dominant.

Later workers have tended to consider the development of exokarst (surface landforms)(Williams,1972; Jennings,1975) and endokarst (subterranean features)(Ford and Ewers ,1978; Waltham,1981b) separately.

Neither Grund's or Cvijic's conceptual models allow the initial heterogeneous geological, hydrogeological or geomorphological conditions of karst areas to be varied. Ford and Williams(1989) envisage karstification proceeding from any one of four rudimentary conditions given here with examples:

1) an uplifted unkarstified dense rock that is protected by an impervious horizontally or upstream bedded cover. The limestone regions of England's Yorkshire Dales and Peak District are an example of this situation. Here horizontally bedded Carboniferous limestones are overlaid by impervious beds of Upper Carboniferous Yordale and Millstone Grit rock strata. This impervious layer shields the underlying limestone from contact with surface water and allows streams to form. The karstic evolution of the limestone will begin however when these streams flow off the impervious beds and onto the exposed limestone.

2) an uplifted unkarstified dense rock that is protected by an impervious cover with a dip in the downstream direction (the Mammoth/Flint Ridge cave area of Kentucky, U.S.A.).

3) an uplifted unkarstified rock with low density (high primary porosity) (recently exposed coral reef as found in the Cook Islands, exposure can be caused by low eustatic sea levels).

4) an uplifted rock that has undergone a previous episode of karstification (peripheral areas of the Guizhou plateau, China).

2:3 DENUDATION CHRONOLOGIES.

Attempts to date landforms by means of a denudation chronology are generally problematic. Often only pieces of evidence can be used to assess the whole situation, only small sections of the stratigraphic record remain intact leaving only supposition to fill the gaps. As noted above however denudation chronologies are more viable in karst areas. The dominance of the solutional erosion process allows measured weathering rates to be extrapolated backwards to give an age for a landform. Waltham (1981a) used this technique in his estimation of 1.8 million years of evolution for the Matienzo depression. Studies of the weathering rates of limestone gravestones (Cann 1974) show that solution rates for karst rocks vary only with climate and the type of karst rock involved. The uncertainties of climatic changes and the poor quality of data for present day erosion rates however allows only rough estimates of development timescales to be given. Somewhat more exact estimates of evolutionary timescales can be gained from the absolute dating of cave deposits. Dating techniques and the resolution of geomorphological events have been established for both calcite precipitates and clastic sediments within cave environments.

2:4 PRECIPITATE DATING.

The age of calcite deposits found within a cave(speleothem) will give a minimum age for the development of that section of cave passage, a stalactite can not develop unless a cave exists. Further more as calcite can only be deposited under aerobic conditions a minimum age for the draining of cave passages formed under phreatic conditions can similarly be determined. Details of the various speleothem generally found in caves is given in section 3:5. The draining of phreatic passages is associated with the general lowering of the local 'water table' which is normally a result of valley floor lowering due to a fall in the base level. When a stable piezometric surface is again established phreatic cave development will ensue, if several such cycles of lowering and stability occur a sequence of landscape development can be determined from the altitude of phreatic cave passages and the dating of speleothem collected from these caves. Techniques for dating speleothem, uranium series disequilibrium and electron spin resonance, are described by Ford & Schwarcz (1990) and Miller(1990) respectively.

2:5 SEDIMENT ANALYSIS.

Clastic cave sediments derived from outside the cave environment, allogenic deposits, can also reveal significant palaeoenvironmental information and depositional timescales. Upon settling fine grained sediments orientate themselves parallel to the Earth's magnetic field once deposited their orientation remains fixed unless any outside disturbance occurs. The periodic variations and reversals in the Earth's magnetic field are reflected in the orientation of contemporary sediments. A core sample can reveal the pattern of variation of deposition alignments as they change down a sediment profile. This pattern of change can be compared to an overall chronology that has been determined for magnetic changes over the geological time scale and the dating of the core fixed. Butler (1992) provides detailed accounts of palaeomagnetic investigations of sediments. The variations in ferrous content of sediments can also be determined by measuring the changes in magnetic susceptibility, the degree to which a sediment can be magnetised, along a core sample. The ferrous content of sediments will vary either over time, as the sediment source area remains constant in space but changes in character, or through space, as a separate source area is responsible for the deposits. Comparative studies of cave sediment magnetic susceptibilities have been used to predict variations of source area for deposits from caves in the Matienzo area (Quin 1992).

CHAPTER THREE

THE MATIENZO KARST AND KARST PROCESSES

3:1 THE STUDY AREA

The Matienzo area lies 25km south east of the northern Spanish city of Santander, Cantabria, in the foothills of the Cantabrian mountains.(figure 3:1). The largest landform in the region is the massive enclosed karst depression that bears the name of the area. The Matienzo depression covers an area of 26.3km^2.(figure 3:2). The near horizontal floor, at an altitude of approximately 150m, is divided into three alluvium covered valleys each covering an area of approximately 1km^2. La Secada valley to the north contains the cave Cueva de Carcavueso which carries the river that drains the depression. The Ozano valley to the south east holds a small stream which joins the main Matienzo river at the confluence of the three valleys. The eastern valley, La Vega, is the site for the main river resurgence that feeds into the area, Cueva del Comelliante. Access to the valley can be gained from three cols, Fuente las Varas(alt.445m) to the north, Cruz Ozano(alt.347m) to the south east and Puerto de Alisas(alt.650m) to the west. The geology of the area is dominated by near horizontally dipping lower Cretaceous limestones. The limestone beds are occasionally interrupted by thin beds and isolated lenses of sandstones.(Mapa Geologico de Espana 1978). The geological sequence for the area is summarised below. (figure 3:3).

figure 3:3 GEOLOGICAL SEQUENCE FOR MATIENZO.

AGE	THICKNESS	DESCRIPTION
ALBIAN	300m	Thin bedded limestones, with some massive beds.
APTIAN	100m	Massive bedded Urgonian limestone, with thin marls.
APTIAN	200m	Thin bedded limestones with orbitalinas, also thin sandstones.
BARREMIAN	500m	Sandstones and marls.

(Source:- adapted from Mills and Waltham 1981.)

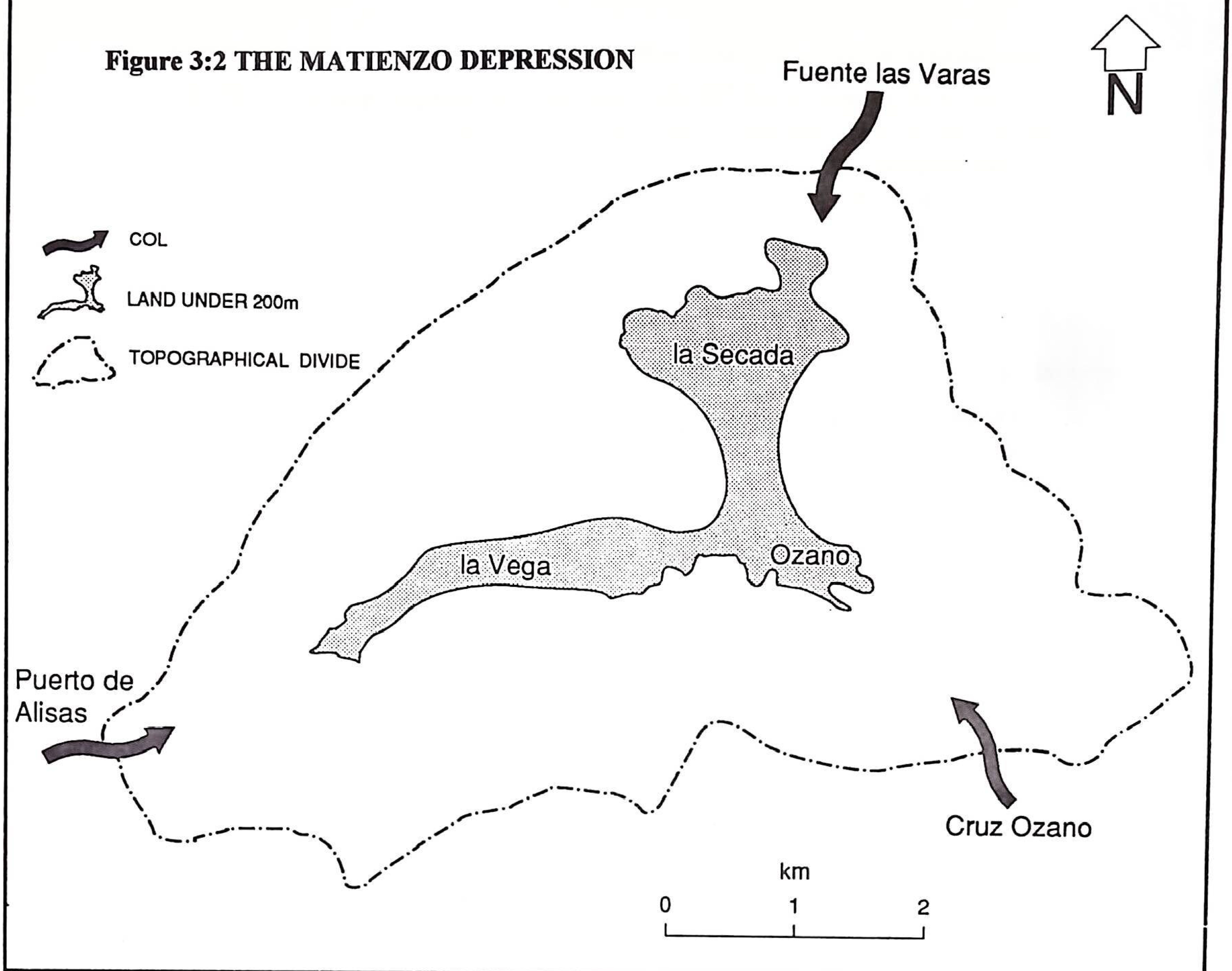
The main geological structure in the area is the regional anticline the axis of which runs from west to east along the line of La Vega valley. Beds dip gently away from this feature, to the north and south, at approximately 5^o. Other more localised faults are observed throughout the area and variations in the dip of the beds are related to the rotational nature of these structures.

The most obvious karstic feature of area is the depression itself but occurring at lesser scales are a considerable number of other karst landforms. 968 speleological(related to caves) sites have been recorded in the area by the Matienzo Caving Expedition. Of these a considerable number are extensively developed cave systems. Cave development has tended to be concentrated at various distinct levels resulting in the characteristic cave systems found in the area. Matienzo's caves are often multi-levelled with immature vertical connections between the near horizontal main cave galleries. The horizontal development appears almost exclusively phreatic in

Figure 3.1 MATIENZO LOCATION MAP.

CANTABRIA

Figure 3:2 THE MATIENZO DEPRESSION



nature (formed at or below the 'water table'). Cave deposits are common in the area. Both precipitates and clastic deposits are abundant in most sites. The topography of the main depression is peppered by a considerable number of smaller scale solutional hollows and a whole range of karren(small scale solutional) features. The chemistry of the karstic process and the evolution of landforms seen in the Matienzo area is discussed in the remainder of this chapter.

3:2 DISSOLUTION CHEMISTRY OF LIMESTONE

Essentially the chemistry involved in the solution of limestone is relatively simple but several controlling factors make the karstic process more complicated, initially I will review the basic chemistry.

For a calcium carbonate limestone only the calcite mineral is dissolved, it should be noted that the mineral dolomite behaves in a similar manner to calcite when considering calcium magnesium carbonates. With only de-ionized water present calcite is only very slightly soluble and even with the H^+ ion available from the dissociation of water calcite is no more soluble than other rock forming minerals such as quartz. However when significant quantities of the H^+ ion is present, as in the case of carbonic acid, calcite becomes increasingly more soluble. As noted in the introduction solvents other than carbonic acid are involved in karst development but the dominance of dissolved carbon dioxide in most limestone solutional processes leads to its prominence here. The dissolution of calcite can be viewed as a series of chemical steps beginning with CO_2 migrating into pure water and culminating in the removal in solution of carbonate material.

CO_2 is dissolved into water according to Henry's law, that is the solubility of CO_2 is proportional to its partial pressure it is also inversely proportional to temperature.

$$CO_2\text{gas} \overset{H_2O}{\Leftrightarrow} CO_2\text{aqueous} \quad \textbf{(3.1)}$$

The aqueous CO_2 is then hydrated to form carbonic acid.

$$CO_2 + H_2O \Leftrightarrow H_2CO_3 \quad \textbf{(3.2)}$$

The carbonic acid dissociates into hydrogen and hydrogen carbonate ions.

$$H_2CO_3 \Leftrightarrow H^+ + HCO_3^- \quad \textbf{(3.3)}$$

The bicarbonate ion can dissociate further.

$$HCO_3^- \Leftrightarrow H^+ + CO_3^{2-} \quad \textbf{(3.4)}$$

The preceding disassociations occur in any fresh water in contact with atmospheric CO_2 if calcite is present its solution will occur as follows.

$$CaCO_3 \Leftrightarrow Ca^{2+} + CO_3^{2-} \quad \textbf{(3.5)}$$

With the presence of hydrogen ions hydrogen carbonate is formed thus removing the carbonate ion from the mineral surface zone.

$$Ca^{2+} + CO_3^{2-} + H^+ \Leftrightarrow Ca^{2+} + HCO_3^- \quad \textbf{(3.6)}$$

All the above chemical processes are reversible and once the rates of forward and reverse reactions become equal the system is in equilibrium. This equilibrium can be disturbed however at several points throughout the system. The removal of the carbonate ion in equation 3.6 will push the reaction in a forward direction resulting in more calcite being dissolved to balance the equation. The reverse reaction in equation 3.3 will disturb the equilibrium in equations 3.2 and then 3.1 in turn culminating in extra CO_2 being dissolved from the atmosphere. The presence of the extra H+ ions associated with this newly dissolved CO2 or any other addition of an acid will disturb the equilibria in equations 3.3, 3.4 and 3.6 again resulting in more dissolution of calcite from the limestone.

It has been observed in laboratory conditions(Plummer et al 1978) that calcite dissolution occurs by two chemical reactions other than equation 3.6.

A direct reaction between calcite and carbonic acid.

$$CaCO_3 + H_2CO_3 \Rightarrow Ca^{2+} + 2HCO^{3-} \quad \textbf{(3.7)}$$

Dissolution with water.

$$CaCO_3 + H_2O \Rightarrow Ca^{2+} + HCO_3^- + OH^- \quad \textbf{(3.8)}$$

This whole range of equations are commonly shortened to:-

$$CaCO_3 + CO_2 + H_20\ (H_2CO_3) \Leftrightarrow Ca^{2+} + 2HCO_3^- \quad \textbf{(3.9)}$$

The lack of chemical thresholds, discussed in section 2:1, in this series of reactions allows the karstic process to proceed in a wide spectrum of aqueous conditions from static water to high velocity stream discharges. The solutional process will continue until the solution becomes saturated, that is an equilibrium is reached. The value of that equilibrium concentration is controlled by several factors, which act either to increase or reduce the amount of calcite dissolved.

Temperature and the partial pressure of CO_2 (Pco_2) are the main determinants. As noted above the amount of CO_2 dissolved in water, and by implication the amount of calcite dissolved, is inversely proportional to temperature so that at a Pco_2 of 0.03% the solubility of calcite in water at 25°C is 55mgl^{-1} and at 0°C is 75mgl^{-1}. It should be noted however that the availability of CO_2 to be dissolved often limits these values. As the PCO_2 increases the amount of CO_2 in solution increases. An increase in PCO_2 can be achieved in several ways. The turbulent waters of a flood can entrap air onto the roof of a submerged section of cave, increasing pressure upon the air bubble by as much as several atmospheres. The resultant increase in dissolved CO_2 as been associated with the development of solutional pockets on the roofs of phreatic passages. PCO_2 significantly higher than that found in atmospheric conditions can be detected in the biomass. Values up to 11% have been recorded in tropical soils (Smith and Atkinson 1976). The enhanced PCO_2 in soils are produced by the respiration of soil fauna and the expulsion of excess CO_2 by flora through their root systems. This activity in the biomass increases with temperature thus counteracting the decreasing solubility of CO_2 with increasing temperature. Moisture moving through the soil zone will then be able to absorb large amounts of CO_2 and become a potentially potent karst solvent. High CO_2 concentrations can also be found in caves and surface fissures due to the gas percolating downwards, due to its relatively high density, and then accumulating in suitable collection areas.

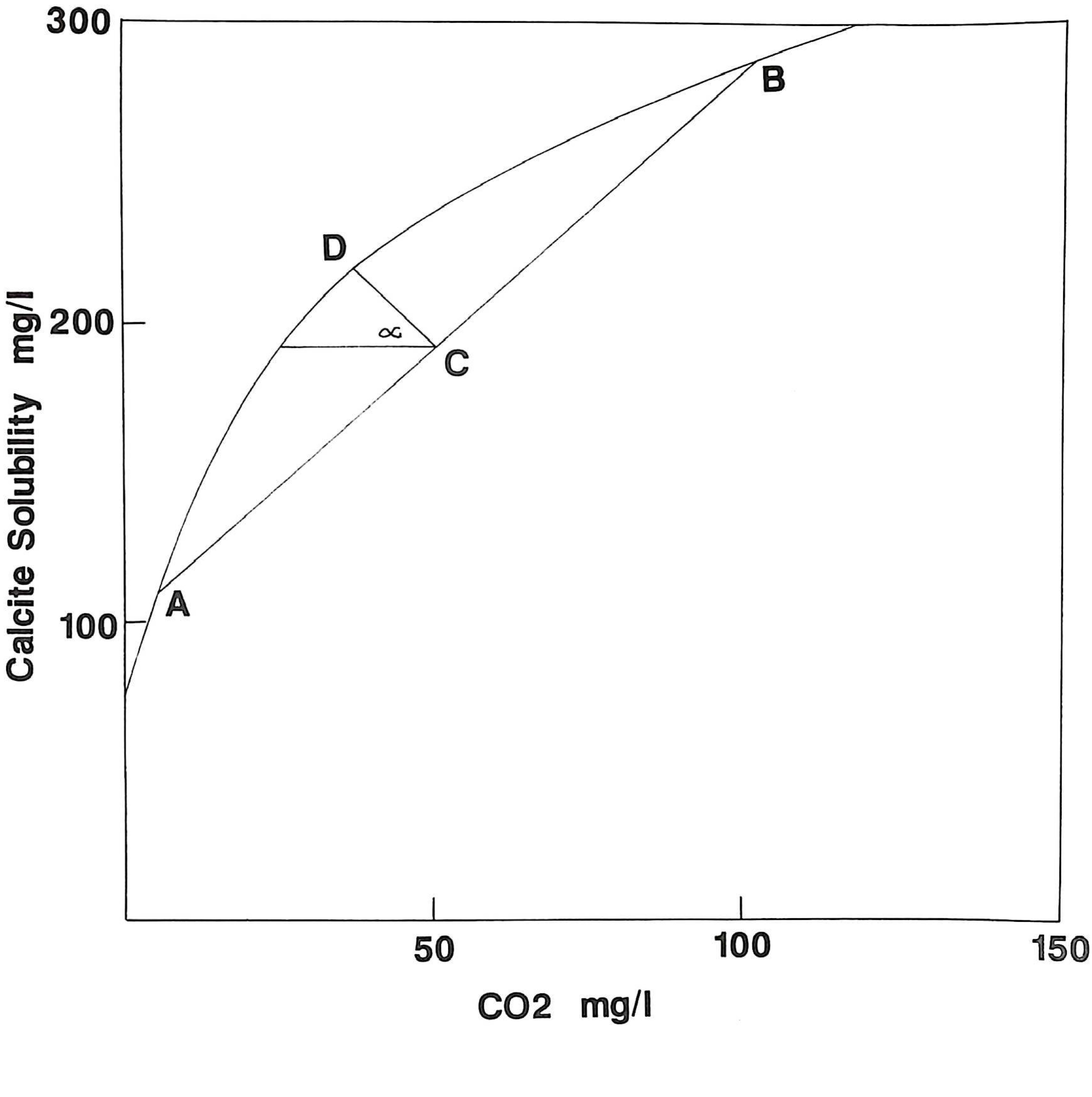
The relationship between PCO_2, temperature and aqueous CO_2 can be expressed as the following equation (after Ford & Williams 1989).

$$CO_2\text{aqueous} = \text{Cab} * PCO_2 * 1.963$$

CO_2 is in gl^{-1}, Cab is a absorption function dependent on temperature and 1.963 is the weight in grams of one litre of CO_2.

A final important phenomenon involved in karst solution, initially noted for karst waters by Bogli (1964)(translation in Bogli 1980), is mixing corrosion. Here two fully saturated karst waters from differing sources become aggressive again upon mixing. The relationship between PCO_2 and the equilibrium value of saturated calcium carbonate is non-linear, figure 3.4. Two saturated waters, one at point A on the equilibrium line and the other at point B will produce a water with a calcium carbonate concentration at point C when they mix. This point will always fall below the equilibrium line and will be chemically aggressive. The ratio of the distance AC:BC will be the same as the ratio of the calcium carbonate concentrations of the waters at points A and B. The final equilibrium concentration is shown at point D. The angle α is given also by the ratio of A:B.

figure 3.4 Mixing Corrosion.



3:3 POLJES, UVULAS and DOLINES.

Poljes, uvulas and dolines are closed depressions found in karst areas and formed by the solutional denudation of the land surface. Collapse can also play a part in their development. Dolines are the smallest of the features with a roughly circular morphometry ranging from a few meters wide and deep to one kilometre wide and several hundred meters deep. An uvula is a feature developed by the growth and coalescence of several dolines. When two or more dolines merge the interconnecting ridges are progressively removed. Neighbouring dolines may have their bases at different altitudes resulting in a feature with an irregular topography when they coalesce. The largest of the solutional depressions is a polje they are large flat floored features evolving with the aid of a throughput of water. Solutional dolines are common in the Matienzo area some of which have developed into uvulas and the Matienzo depression itself can be described as a polje.

In Matienzo dolines are present on an existing exposed karst surface indicating that the solvent input into the feature must be autogenic as surface streams tend not to develop on karst terrains. Rainfall onto the area of the doline moves through the overlying soil where it becomes acidified and then the solutional erosion occurs at the soil bedrock interface. The general bowl shape of dolines suggests that the solution process is being concentrated into the centre of the doline. Carbonate material from the bedrock is removed in solution. A throughput of water is maintained by new rainfall, soil moisture movements and drainage of the area through the fissures of the bedrock.

The envisaged stages of doline development are as follows. Groundwater is most chemically active in the top few meters of the bedrock resulting in a rapid narrowing of fissures with depth. This closing of the fissures acts to reduce the permeability of the rock mass to a sufficiently low value to allow groundwater to back up, especially after heavy rain. Continued solution will further enlarge fissures until one fissure becoming the dominant flow path for water leaving the area. Flow paths over the area of ponded water will then adjust to the path of least hydraulic resistance. A positive feedback system will become operational as increased water flow will cause more solutional widening with a corresponding reduction in hydraulic resistance hence capturing more water flow. Soil also tends to collect in the base of dolines again acting to concentrate the solutional activity to the centre of the feature. Extra soil can hold more moisture thus prolonging the contact time between the bedrock and groundwater and also provide more opportunity for acidification of that water due to greater biogenic activity. Dolines developed in this way are known as drawdown dolines. In several areas of Matienzo doline growth as developed to such an extent that neighbouring features have coalesced into uvulas. The largest doline in the Matienzo region is the 1km. across and 300m deep Hoya de la Luza, figure 3:5, figure 3:6 shows a uvula situated next to this larger feature.

Definitions of a polje are at times contradictory, writing about the Matienzo depression, Waltham (1981a), states that 'the valley lacks the sharply defined slope edges....and there is no guiding element in the structural geology, so the term (polje) can only be applied loosely.' Whilst agreeing that there is no structural geological control to the development of the valley sharp breaks in slope are readily apparent around the whole of the valley floor. Further to this Ford and Williams(1989) conclude that a baselevel polje being free of any geological controls can be considered as 'the purest kind of polje.'. In summarising the geomorphological literature on poljes Gams (1978) distinguishes three key geomorphic elements to be used in classifying a polje. It should have:-

Figure 3:5 LOOKING INTO THE 1km WIDE HOYA de la LUZA

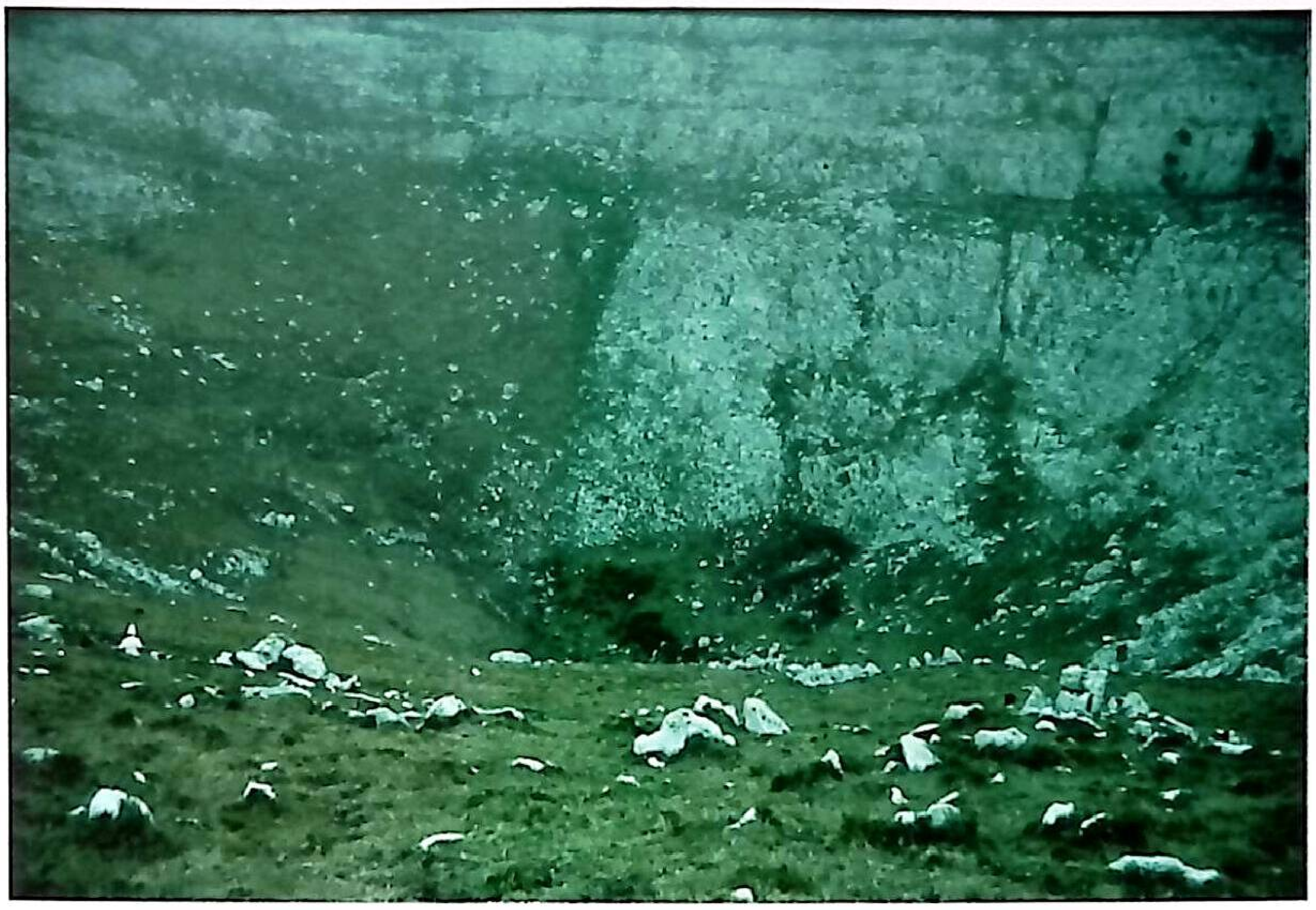


Figure 3:6 AN UVULA CLOSE TO THE HOYA de la LUZA

1) a flat rock or unconsolidated sediment floor.

2) a closed basin with a steep marginal slope rising on at least one side.

3) karstic drainage

Ford and Williams(1989) describe the geomorphic development of baselevel poljes in the epiphreatic zone. Here the solutional erosion of the depression occurs, primarily, between the upper and lower levels of the piezometric surface. Surface streams will provide lateral extension to the depression if the base level of the basin is denuded down to the level of the lower piezometric surface. Observations from the Matienzo area would suggest that the feature could best be described as a baselevel, or true, polje. All of Gams's conditions are met, the Matienzo basin has a flat alluvium covered floor with steep slopes rising, in all directions, to the topographical divide, figure 3:7. The whole valley is drained through a cave system. In addition the geomorphic conditions described by Ford and Williams are in evidence. Several caves at valley floor level become completely flooded near to their entrances, indicating that the piezometric surface is close to the valley floor level. A present day river crosses the valley floor and at times of high rainfall the valley floor has been seen to be inundated by flood waters.

3:4 CAVE SYSTEMS.

Cave development proceeds when micropores with a limestone bedrock are solutional enlarged to a diameter that allows turbulent water flow to develop. Flow in micropores is analogous to flows within a small tube which are described by Poiseuille's Law, equation 3.10. Once flow becomes turbulent the increased mixing and consequent increase in the volume of water coming into contact with the limestone walls of the tube allows the rate of solutional removal of carbonate material to increase dramatically and true cave development processes to ensue. Equation 3.13 denotes how velocity is proportional to the square of the tube radius. A diameter of 5-15mm is an effective minimum before turbulent flow can develop. The onset of turbulent flow occurs when a critical 'Reynolds number', around 500, is exceeded. Reynolds number increases with velocity, equation 3.11, which in turn is dependent upon the physical size of the tube, equation 3.12.

$$q = (\pi r^4 / 8 l \mu)\ \Delta h \qquad \textbf{(3.10)}\ \text{(Poiseuille's Law)}$$

where q is specific discharge; r is the radius of the tube; Δh is the loss of head due to friction along the length of the tube, l. ; μ is the dynamic viscosity of the water.

$$Re = \rho v y / \mu \qquad \textbf{(3.11)}\ \text{(Reynolds Number)}$$

where Re is the Reynolds number; ρ is the density of the water; v is velocity; y is the depth of water; μ is viscosity.

$$q = va \qquad \textbf{(3.12)}\ \text{(Specific Discharge)}$$

where q is the specific discharge; v is velocity; a is cross-sectional area(for a tube = πr^2)

$$q = v\pi r^2$$

combining equations 3.10 and 3.12:-

$$v\pi r^2 = (\pi r^4 / 8l\mu)\ \Delta h$$

$$v = (r^2 / 8l\mu)\ \Delta h \quad \textbf{(3.13)}$$

Substituting this value of v into equation 3.11 shows how higher Reynolds numbers, hence turbulent flow, can be achieved by an increase in the radius of the conduit.

The solutional enlargement of micro and macropores within a karst rock can be accelerated due the mixing corrosion phenomenon described in section 3:2. Once a cave exists its passage cross-section can evolve under either phreatic, water moving in response to a hydraulic gradient, or vadose, water moving under the influence of gravity, conditions.

Phreatic development takes place at or below the piezometric surface. With water filling the entire void space the solutional removal of the bedrock occurs at all points on the passage cross-section. If erosion is not concentrated on to particular planes of weakness, joints and beds, the classic phreatic circular cross-section will develop. Water, under hydraulic pressure, will however be forced into any open cracks and fissures which will become solutionally enlarged with a corresponding alteration to the shape of the cave passage. It should be noted that water moving in discrete conduits, such as cave passages, due to a hydraulic gradient can easily move upslope. The direction of water flow that created a phreatic passage can not be determined by the slope direction of the passage floor.

When a water filled passage partially or totally drains vadose cave development will follow. Here the solutional removal of material only occurs on the wetted perimeter of the cave and entrenchment will ensue. Stream velocities in the vadose zone are generally faster than those under phreatic conditions allowing a larger calibre bedload to be transported. The mechanical erosion of the floor due to the movement of this bedload will also enhance the entrenchment process. Water in the vadose zone will move downwards towards the new piezometric surface in response to gravity in a similar manner to a surface fluvial system. However unlike a surface river a cave stream is constrained to a pre-existing channel or group of channels that have developed in a previous phreatic phase, unless open fissures, such as faults lines, are exploited.

The Matienzo cave systems are a significant karst feature of the area. Several caves are in excess of 20km long including The Four Valleys System at 40.5km and Torca de Azpilicueta at 21.5km. Most caves in the area are similar in character. Extensive near horizontal cave passages with large cross-sections, up to 20m across and 30m high, are found at various altitudes throughout the valley. In the longer systems several of these horizontal developments are superimposed often with small immature vertical cave sections connecting the various levels. The shape and undulating nature of the major passage developments(figure 3:8) suggest that they are of phreatic origin whilst the interconnecting vertical sections are of a vadose nature. The lowest level of major development is within the present day active phreatic zone. The investigation of this level of development is limited to that undertaken by cave divers and is consequently relatively unknown compared to the rest of the areas caves. The amplitude of the undulations within the relic passages and the depth to which the active phreatic system has been penetrated suggests that cave development in the shallow phreatic zone is prevalent in the Matienzo area.

No evidence of vadose alteration of the main passages in Matienzo's caves has been recorded suggesting that they drained relatively rapidly. This suggestion is supported by the presence of large quantities of undisturbed fine sediment material, typical of phreatic caves, that remains in the relic passages. Any active vadose system would tend to rework fine material and it is often removed altogether in such circumstances. The sequence of successively lower levels of major phreatic passage development connected by immature vadose sections suggests that rapid changes in base levels were interspaced with periods of a stable piezometric surface coincident with the major phreatic cave development.

3:5 CAVE DEPOSITS

Several types of deposit are commonly found in the caves of the Matienzo area. Those derived from inside the cave, autogenic deposits, included calcite, aragonite and gypsum precipitates along with clastic deposits derived from the mechanical breakdown of the cave walls. The most abundant allogenic deposit, being derived from outside the cave environment, are of a fluvio clastic origin.

Calcite precipitates, collectively named speleothem, are deposited as CO_2 is degassed from water seeping into the cave from the surrounding rock. Water percolating down through fissures in the limestone from the surface will tend to have a high dissolved CO_2 / calcite equilibrium value. This is due to prolonged contact with soil and bedrock. The lower PCO_2 in the cave air will result in a disequilibrium with the percolating water as it enters the cave. CO_2 will degass from the water to restore the equilibrium leaving the water supersaturated with calcite. The precipitation of calcite crystals will ensue, onto the cave wall or existing calcite crystal, to restore the equilibrium. This reaction proceeds in the reverse direction of the carbonate dissolution reaction, equation 3.9.

calcite deposit

$$CaCO_3 + CO_2 + H_20\ (H_2CO_3) \Leftrightarrow Ca^{2+} + 2HCO_3^- \quad \textbf{(3.9)}$$

degassed

Two types of speleothem are deposited in this way, flowstones and dripstones(figure 3:8). Flowstones occur when calcite is precipitated from water flowing over the wall of the cave and dripstones from individual droplets of water. The most prevalent dripstones are stalactites, which extend downwards from a cave roof, and stalagmites

Figure 3:7 La VAGA ARM OF THE MATIENZO DEPRESSION (POLJE)

Figure 3:8 A SMALL PHREATIC PASSAGE IN ONE OF MATIENZO'S CAVES SHOWING DRIPSTONE AND FLOWSTONE CALCITE DEPOSITS

formed from the precipitation of calcite from water dripping onto the cave floor. The potential to establish the age of calcite precipitates and its geomorphological importance is discussed in section 2:4.

The meta-stable carbonate mineral aragonite is found in the form of groups of needle like growths from some calcite deposits in some caves in the Matienzo area. The mode of formation of these features is however unclear. Needles of gypsum are also common in the fine grained sediments that are found in some of the dryer areas of the caves.

The final autogenic deposit found in the caves is the result of the mechanical failure of cave walls and roofs. The load on a point within the rock mass (p) is a function of its density(ρ), thickness(h) and gravity(g) :-

$$p = \rho g h$$

Breakdown occurs when this load, in the form of stresses within the rock, becomes distorted around openings within the rock mass. Cave passages being examples of such voids. Tension develops above the cave passage resulting in additional stresses at the walls of the cave. The increasing stresses culminate in the eventual mechanical failure of the cave walls. The large angular blocks produced in this way often form partial blockages to cave passage that can hinder cave exploration. The draining of phreatic caves removes buoyancy forces that have acted to resist mechanical failure. This appears to be a likely contributory factor to much of the breakdown observed in the Matienzo caves.

The majority of allogenic deposits within the caves are fine grained silts and clays of terrigenous origin. These are carried into the caves as suspended sediments in the fluvial system and then deposited as stream velocities fall. Caves act as efficient traps for these sediments and the stable environment found in relic passages favours their preservation. The significance of these sediments in terms of palaeoenvironmental reconstructions is highlighted in section 2:5.

3:6 KARST HYDROLOGY

The hydrological processes within a karst region are significantly different from those found in areas of other lithologies. In non karst areas ground water flow is often described according to Darcy's law :-

$$Q = -K\,A\,dh/dx$$

where Q is discharge; K is the hydraulic conductivity; A is the cross-sectional area of the flow; dh/dx is the hydraulic gradient.

However some of the assumptions from which Darcy's law is derived are not applicable in karst areas. Darcian flow is seen as a discharge through a cross-sectional area in a isotropic homogenous porous media. Movement of karst water is significantly different from this model. Here water flows are contained within discrete conduits, the spatial arrangement of which is determined by fracture patterns and cave development within the bedrock. Further to this Darcy's law is only applicable to laminar flows but turbulent flows are common in karst hydrology. A more accurate description of water flows through conduits can be gained if Poiseuille's law (equation3.10) is applied. Another important feature associated with karst hydrology is the ongoing changes in the porosity of the media due to the solutional enlargement of the flow paths.

A basic areal unit in hydrology is the catchment, which is often delineated by the topographical divide around a river. Such a division is not easily defined in karst areas. Cave systems often transgress surface topographic features and hydraulic connections between several distinct valleys is not uncommon. Surface streams, a common feature of most catchments, are rare in karst landscapes. All of these factors must be taken into account when karst drainage systems are investigated.

The unknown factors and linkages within a karst hydrological system prompt Ford and Williams(1989) to advocate the adoption of a 'grey box' approach to their investigation with consideration given to the following nine attributes of the system:-

1) The areal and vertical extent of the system

2) Its boundary conditions

3) Input and output sites and volumes

4) The interior structure of linkages and stores

5) The capacities and characteristics of the stores

6) The relative importance of the stores

7) Throughput rates

8) The response of storage and output to recharge

9) The system's response under different flow conditions

Little is known of the hydrology of the Matienzo region. Discharge data is available for some karst springs and several underground rivers have been partially mapped but much more could be learned by any future hydrological study of the area. Potential avenues of study include: the constant recording of spring discharges and subsequent analysis of the resultant hydrograph; water tracing experiments to determine underground hydraulic connections and flow through times; and the continued mapping and exploration of the regions caves.

3:7 SMALL SURFACE SOLUTIONAL FEATURES (KARREN)

In addition to the larger scale solutional landforms described a variety of smaller scale features can be found in the Matienzo area. These small solutional features are collectively known as karren. They take the form of hollows, grooves and channels. Karren are formed on bedrock either below a soil cover or subaerially. A characteristically rounded form is produced on karren that develops beneath the soil due to the solutional process being maintained over the whole surface of the bedrock. Conversely a sharp profile develops in subaerial conditions as the dissolution of rock is concentrated into low points in the bedrock and developing karren feature.

Solution hollows develop on flat lying rock where water can preferentially accumulate, maybe in an existing hollow or due to soil or vegetation variations. The accretion of water will accelerate the solutional process in that particular location. A positive feedback mechanism will operate, with more water accumulating as the feature enlarges allowing more solutional removal of rock. Solution hollows can develop along the line of small fractures in the bedrock and their form will be elongated in the direction of the fissure.

Grooves and channels develop as water moves down the sloping surface of rock due to gravitational forces. The transformation of sheetflow into beaded flows has been cited as the inception point for the development of these features. They are found in groups aligned in the direction of the water flow.

CHAPTER FOUR

AN INVESTIGATION OF SOIL WATER FLOW PATHS IN THE MATIENZO DEPRESSION

4:1 INTRODUCTION

Knowledge of the water flow pathways in operation on the slopes of a karst depression would facilitate a greater understanding of the evolution of that feature. The bedrock of limestone slopes are solutionally denuded as soil water passes along the soil-bedrock interface. The rates of solutional erosion have been clearly linked to water chemistry, as described in section 3:2, and to the climatic variable, annual runoff(Smith and Atkinson, 1976; Gunn, 1981). There is then a clear link between hillslope hydrology, the movement of ground water, and geomorphology, the evolution of solutionally eroded hillslopes. Techniques for the measurement of the rate of solutional erosion in karst regions were developed by Chevalier(1953). The basis of the technique is to embed a small piece of native rock(normally a shaped rock tablet), of known weight, at the soil-bedrock interface. The sample is then retrieved after a given time period reweighed and the weight loss calculated. The change in weight over the time period that the rock was emplaced is then an indication of the rate of solutional loss of rock at that point on the hillslope. Whilst the use of rock tablets in this way can produce estimates of erosion rates the time scale for emplacement is beyond the scope of this project. However relative water flows can be determined by a similar but less time restricting technique.

Crabtree and Trudgill(1984a) demonstrate how the dissolution of gypsum(plaster of Paris) blocks is proportional to the amount of ground water passing the block emplacement site. If the gypsum blocks are used in a similar manner to the rock tablet technique described above a more rapid rate of weight loss would be observed. As a result of this shorter periods of emplacement are required and less accurate weighing techniques need to be employed. The dissolution of gypsum does not however imitate the solutional erosion of bedrock. As indicated above the rate of the solutional erosion of limestone is controlled by water chemistry(section 3:2 of this report) and runoff rates(Smith and Atkinson, 1976; Gunn, 1981). Only in extreme conditions, a pH value of less than 3.9, does water chemistry affect the rate of solution of gypsum(Crabtree and Trudgill(1984a). The technique will however allow comparisons of water flow conditions to be determined between sites over a given time period if several block emplacement sites are considered. In an area of relatively homogenous soils, hence similar ground water chemistry, the relative water flow conditions can be analogous to the relative solution erosion rates occurring beneath those soils. This comparison must however be applied with considerable caution as several other contributing factors are at work. However homogenous a soil may be it is likely that diverse biotic activity will be present throughout the area thus affecting soil CO_2 concentrations. Also gypsum blocks will only dissolve as water moves past them whereas the dissolution of limestone will proceed in static water conditions until an equilibrium is reached. The solutional activity of water temporally stored within the soil will not be recorded by the gypsum blocks.

The aim of this study is to investigate the spatial variations of water flow paths throughout the Matienzo depression over a twelve month period. Several variables that could affect the quantity of water moving past a site where compared. Ground water will tend to converge upon topographical features such as hollows and concavities and discharge will increase as the collection area grows. The importance of these points is recognised by the inclusion of significant topographic parameters in mathematical modeling of groundwater flows, in particular the $\ln(a/\tan\beta)$ parameter of Beven and Kirkby's TOPMODEL(Beven and Kirkby, 1979)(a is the area draining past a point and β is the mean slope angle). Whereas the TOPMODEL topographic parameter is derived using computer generated Digital Terrain Models an approximation of this factor was used in this study. The relationship between other potential parameters that could affect water flow rates such as aspect and altitude and the measured weight loss of gypsum blocks were also investigated.

4:2 RESEARCH DESIGN

Around sixty gypsum blocks were manufactured, in the laboratory in Lancaster, in advance of the departure to the study area. The recommendations of Crabtree and Trudgill (1984b) were followed in the manufacture of the gypsum blocks to be used in this project. The hemi-hydrate form of gypsum, commercially available plaster of Paris, forms the basis of the block material. Upon mixing with water the plaster of Paris reverts to dihydrate gypsum(equation 4.1) which hardens and takes the shape of the mould into which it is placed. The mould in this case being ice cube trays.

$$CaSO_4.1/2H_2O \quad + 4H_2O \quad \Rightarrow CaSO_4.2H_2O \quad (4.1)$$

A mixing ratio of 0.2kg of plaster of Paris to 0.125l of distiled water, as suggested by Crabtree and Trudgill (1984b), produces a mixture of such a consistency that it can be relatively easily poured into the moulds before the mixture begins to set. Care was taken when preparing the slurry to ensure that a consistent mixture was produced. Once set the blocks were dried in an oven for 96 hours at 45^{o}C to remove the excess water that remains within the blocks after their production. Immediately after drying the blocks were inspected and those with irregular surface features, due to air bubbles in their mixture, were rejected. The remaining blocks were then weighed to an accuracy of 0.01g and then each sealed in a water tight plastic bag which was labelled with the weight of the block. Prior to leaving for Spain three gypsum blocks were left, in a secure position but open to the atmosphere, as controls. This was in order to determine if any weight loss could be detected due to the solutional removal of gypsum by atmospheric moisture. Another set of control blocks were similarly left in Spain for the duration of the study.

Fourteen sites, within the Matienzo, depression were chosen for block emplacement. These sites were chosen in order to encompass the following variables: aspect; slope angle; altitude; ground cover; and distance from the topographical divide. Site positions are shown in figure 4.1.

At each site groups of three blocks were buried at the soil-bedrock interface. The hole was excavated in a manner least likely to disrupt the local soil water movements. An incision was made into the soil cover from below the block site, using a trowel, until bedrock was reached. The blocks were then emplaced and any disturbed soil replaced. Three blocks were buried together in order to reduce the possibility of erroneous weight loss data due to an individual block having a different solubility than any other. This may arise from undetected differences in the mixing of the plaster of Paris. The blocks were placed in a fine netting bag in order to keep them together over the twelve month period that they were in place, and to make their retrieval simpler. The exact location of the buried blocks was surveyed, using a tape measure, sighting compass and clinometer, utilising at least three permanent landmarks. Each site was also photographed in order to ease the recovery of the blocks, figure 4:2. The locational data along with block weights, the date of burial and ground conditions was recorded at each site. The blocks were emplaced between the 17/8/91 and the 21/8/91. Blocks from four sites were recovered and replaced by new blocks between the 30/12/91 and 1/1/92. All the blocks including the controls, but not those from site H, were recovered between 4/8/92 and 8/8/92. The blocks from site H proved impossible to relocate, this was caused partially by a lack of a site photograph due to an undetected camera failure at this location.

Upon return to Lancaster any loose soil was gently removed from the blocks by means of a soft brush. All the blocks were then re-dried for 96 hours at 45^{o}C and then cleaned further again using a soft brush. Care was taken not to disturb the fabric of the block material when they were being cleaned. Finally the blocks were weighed to the same accuracy as before using the same balance and the results recorded. A comparison between a new block and one that has been recovered and cleaned after being in place for twelve months is shown in figure 4:3.

4:2 RESULTS

SITE DESCRIPTIONS

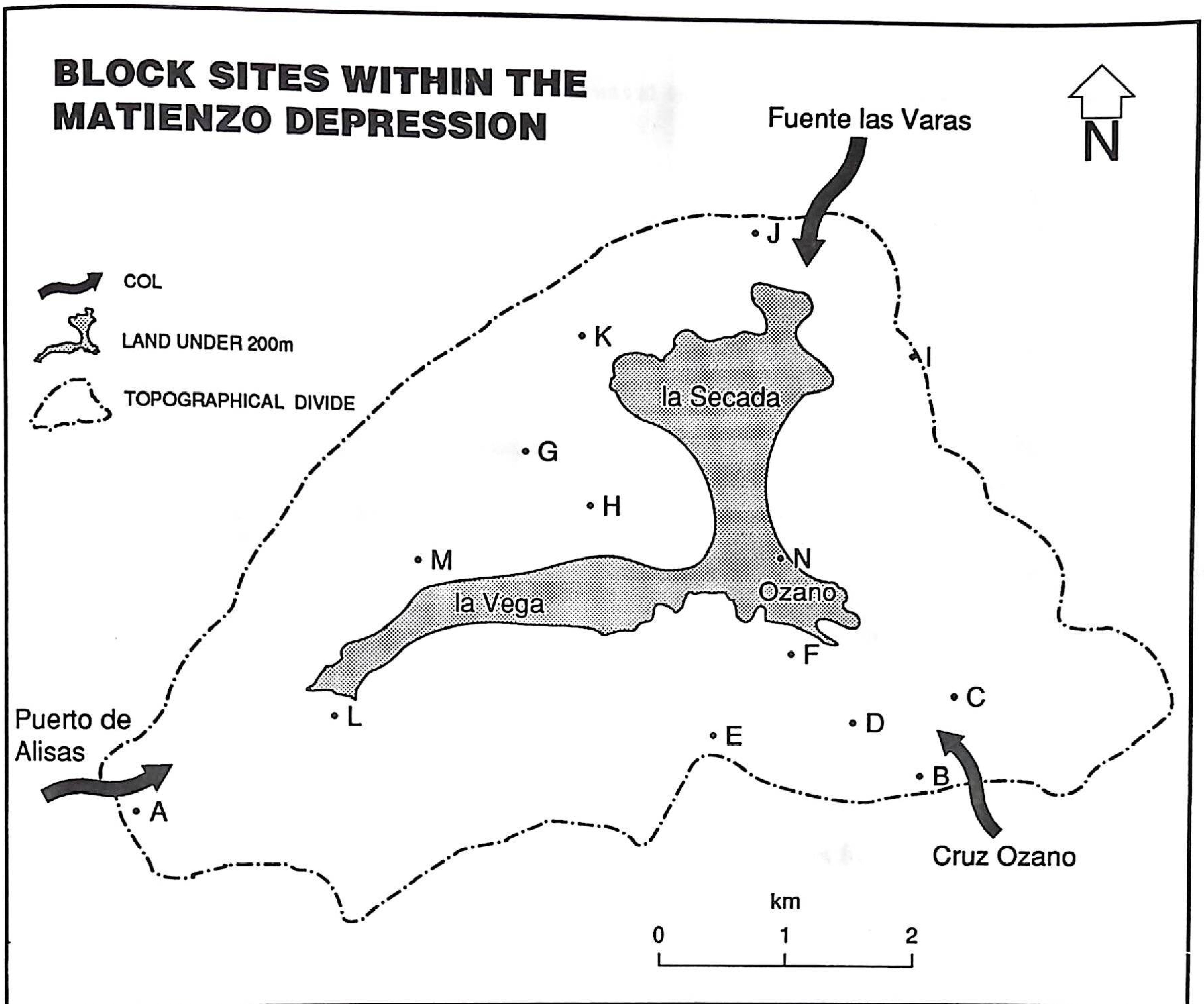
These descriptions should be read in conjunction to figure 4.1.

SITE A :- Located close to the topographic divide at the Puerto de Alisas col at an altitude of 695m with an easterly aspect. The soil cover was approximately 15cm deep with a grassy cover.

SITE B :- Situated on the topographic divide at the Cruz Uzano col at an altitude of 347m. The soil cover was 8cm deep under rough grass vegetation.

SITE C :- Sited midway between the topographic divide and the Ozano arm of the valley floor. Altitude 310m with a north northwesterly aspect. The site was amongst an oak plantation with a soil depth of 15cm.

SITE D :- Positioned 1.2km to the west of site C at an altitude of 280m. 400m from the topographic divide on a northeasterly facing grassy slope with a 8cm deep soil cover.



SITE E :- This location, 100m from the topographic divide, is at an altitude of 510m on a north facing slope. The bedrock was covered by 10cm of soil with a grassy covering.

SITE F :- Sited close to the Ozano valley floor at an altitude of 265m. with a northerly aspect. The soil cover was 10cm deep with a grassy covering.

SITE G :- Located on the northern slopes of la Vega valley at an altitude of 410m and 400m from the topographic divide. The slope has a south easterly aspect and the soil cover was 10cm deep with covering of gorse plants.

SITE H :- Positioned approximately 1km to the south east of site G at an altitude of 300m on a south westerly facing slope. The soil here is 5cm deep with a covering of rough grass.

SITE I :- Situated 120m from the topographic divide on the eastern slopes of la Secada valley at an altitude of 360m. The 5cm deep soil cover had a rough grass covering. The blocks at site I were recovered and replaced by new samples on the 30/12/91.

SITE J :- Located on the col at Fuente las Varas at an altitude of 450m. The soil cover was 4cm deep with a grassy cover.

SITE K :- Is midway between the topographic divide and the floor of la Secada valley on a south easterly facing slope at an altitude of 360m. The 10cm deep soil had a grassy covering. The blocks here were retrieved and replaced on the 1/1/92.

SITE L :- Situated at the western end of la Vega valley. The site was 3.8km from the topographic divide at Puerto de Alisas. The area is wooded and has soils 10cm deep. The blocks were reprieved and replaced on the 1/1/92.

SITE M :- Is found on the northern slopes of la Vega valley 1.8km from the topographic divide at an altitude of 230m. 15cm deep soils had a grassy covering. The blocks were again retrieved and replaced on the 1/1/92.

SITE N :- Located at valley floor level, 175m, at the confluence of the three arms of the depression. The site has a westerly aspect and soils 18cm deep with a grassy covering. This site is just above the break of slope between the alluvium covered floor of the depression and the thinly covered side slopes.

EC :- Are the control blocks left in England.

SC :- Are the Spanish control blocks left in the Matienzo area.

The original weights and details of the weight loss for the blocks from these sites is given in figure 4:4.

Figure 4:4 The Weight Loss From The Gypsum Blocks.

SITE	ORIGINAL WEIGHT (g	FINAL WEIGHT (g)	WEIGHT LOSS (g)	% WEIGHT LOSS
A	58.28	52.33	5.95	10.21
B	65.1	57.02	8.08	12.41
C	57.76	43.75	14.01	24.26
D	59.31	44.18	15.13	25.51
E	66.82	42.17	24.65	36.89
F	64.94	26.43	38.51	59.83
G	63.36	32.54	30.82	48.64
H	60.2	/	NOT RETRIEVED	/
I	64.64	57.07	7.57	11.71
I(2)	62.86	58.04	4.82	7.67
J	62.9	51.3	11.6	18.44
K	63.93	45.11	18.82	29.44
K(2)	62.56	26.05	36.51	58.36
L	64.89	60.44	4.45	6.86
L(2)	63.13	53.58	9.55	15.13
M	61.85	56.12	5.73	9.26
M(2)	62.05	48.62	13.43	21.64
N	65	35.87	29.13	60.2
EC	42.82	42.72	0.1	0.23
SC	64.17	63.4	0.77	1.2

Figure 4:2 SURVEYING A BLOCK SITE.

Figure 4:3 WEATHERED AND UNWEATHERED GYPSUM BLOCKS

A negligible weight loss was detected for the control blocks especially, the 0.23% loss recorded for the Spanish set. In the case of the main set of blocks weight loss appears to be independent of the location of the block site. No significant relationship was detected between the weight loss of gypsum blocks and any of the parameters investigated. Sites A, B and J located on the topographic divide recorded relatively low percentage weight losses as would be expected from their situation. Even this observation is not appreciably different from the weight loss recorded from other sites such as site L, located close to the valley floor. Sites K and N at or close to the valley floor had the high percentage weight losses, around 60%, but site K situated midway between valley floor and the dividing ridge recorded a comparable weight loss, 58%. The lack of correlation between weight losses and distance from the topographic divide is reflected in a similar lack of dependence on weight loss and catchment contributing area. Aspect appears equally unrelated to weight loss with sites on opposite facing slopes recording similar weight losses, site C facing north northwest 24% weight loss and the south facing site M, 22% weight loss. Similarly vegetation cover appears not to influence flow paths with sites in wooded areas, C(24% loss) recording equivalent weight losses to those in grassy areas, site D(25% loss). At three of the four block sites that were replaced after six months, sites K, L and M, much higher percentage weight losses were detected for the second half of the study. At site I however a lower weight loss is indicated for the last six months of the study period.

4:3 DISCUSSION

The inconclusive nature of the weight loss data derived from this study highlight the difficulties in monitoring soil water movements. Point sources of data, the block sites, are expected to yield information that can be extrapolated over a much wider spatial area, in this case the Matienzo depression. Many factors may however influence the water flow conditions at a particular site and affect the validity of the resultant data. The act of emplacing the blocks may significantly influence the flow regime in that locality. The heterogeneous nature of soils may result in discrete flow paths through the medium that may either by-pass or intersect the sample site. Small, undetected, variations in the slope profile above the sample site can channel water flows either away or towards the site. All of these factors can lead to discrepancies in the results and emphasis the dangers involved in extrapolating point data over a larger area.

The spatial organisation of the sample points may also be of concern. More significant results may have been achieved if a smaller study area had been investigated. One or more sections of a hillslope within the depression with a high density of block sites would furnish a more detailed picture of soil water movements. Whilst acknowledging the limitations of this particular study the technique of using gypsum blocks to investigate water movements within soils appears to be a useful geomorphological tool. The use of this technique, to determine surface water flow paths, could be allied with data concerning subterranean flow routes to gain a fuller understanding of the regional karst hydrological system. Considering the strong link between hydrology and geomorphology in karst regions this knowledge if integrated with sedimentary evidence of past hydrological processes could form the basis of further research into the evolution of karst landscapes.

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