

KARST AND ITS BEARING ON CONDITIONS
IN BAHRAIN

by

Despina Costa Al-Samahiji



A dissertation submitted in partial fulfillment
of the requirements for the degree of Master of Science
in Engineering Geology of the University of London
and for the Diploma of Membership of the Imperial
College of Science and Technology

Engineering Geology Section
Royal School of Mines
Department of Geology
Prince Consort Road
Imperial College of Science and Technology
London SW7 2BP

August 1988

ABSTRACT



Soluble rocks are divided into two major groups, the soluble carbonate rocks and the soluble non-carbonate rocks. Main representatives of the soluble carbonate group are limestones, dolomites and chalk. They are dissolved principally by aggressive water, aided by erosion, to form surface and subsurface solution landforms. The surface landforms include a variety of solution and collapse dolines, swallow holes and other enclosed depressions such as polje and uvala. The subsurface landforms are represented by cave systems which provide drainage corridors for ground water.

Soluble non carbonate rocks are principally gypsum, anhydrite and halite genetically weaker rocks than those of the soluble carbonate group. They are also dissolved by aggressive water and may produce surface features such as collapse and gash brecciation of the overlying strata.

Soluble rocks represent a hidden engineering hazard, as illustrated by case histories, expressed in the reduction of bearing capacity and differential settlement of the ground and increased secondary permeability.

A number of methods exist for the detection of solution features but no one method has yet been successfully applied to all existing variable rock

regions.

The carbonate rocks in Bahrain display limited solution landforms. In view of the seriousness of the engineering problems associated with soluble rocks a study is proposed to verify the extent of presence of solution landforms on the island.

ACKNOWLEDGEMENTS

The author is most grateful for the advise
given by Dr. M.M. de Freitas and Dr. P.R. Bush
during the preparation of this dissertation

CONTENTS

	<u>page</u>
INTRODUCTION	3
1.1 SOLUBLE CARBONATE ROCKS	4
1.1.1 Limestones	4
1.1.2 Dolomites	4
1.1.3 Chalk	5
1.2 DISSOLUTION PROCESS AND INFLUENTIAL FACTORS	7
1.2.1 pH	10
1.2.2 Carbon dioxide	12
1.2.3 Mineralogy and effect of impurities	15
1.2.4 Lithology and structure	15
1.2.5 Turbulence	16
1.2.6 Rates of dissolution	17
1.3 CREATION OF KARST LANDFORMS	19
25 CHARACTER OF KARST	
2.1 SURFACE LANDFORMS	25
2.1.1 Dolines	25
2.1.2 Cockpits	32
2.1.3 Uvala	32
2.1.4 Polje	32
2.1.5 Swallow holes	33
2.2 SUBSURFACE FEATURES	38
2.2.1 Phreatic caves	39
2.2.2 Vadose caves	43
2.2.3 Vertical caves	47
2.2.4 Inlet caves	48
2.2.5 Outlet caves	48
2.3 CAVE DEPOSITS	50

	<u>page</u>
2.3.1 Non-Calcareous deposits	50
2.3.2 Calcareous deposits	51
2.4 KARST LANDFORM EVOLUTION	55
3 SOLUBLE NON CARBONATE ROCKS	58
3.1 Introduction	58
3.2 GYPSUM AND ANHYDRITE	58
3.3 HALITE (ROCK SALT)	63
4 METHODS FOR THE DETECTION OF SOLUTION FEATURES	66
4.1 REMOTE SENSING	67
4.1.1 Aerial photographs	67
4.1.2 Scanning systems - Infra red imagery	69
4.2 GEOPHYSICAL METHODS	71
4.2.1 Electrical resistivity survey	71
4.2.2 Magnetic survey	75
4.2.3 Electromagnetic survey	77
4.2.4 Gravity survey	79
4.2.5 Seismic survey	80
4.3 GRID PATTERN	81
4.4 SHRIMP METHOD	83
4.5 COMPACTION METHODS	84
5. ENGINEERING PROBLEMS ASSOCIATED WITH KARST	86
6. POTENTIAL FOR KARST IN BAHRAIN	94
6.1 THE PHYSICAL SETTING	94
6.2 SEDIMENTS IN THE GULF	96
6.3 LITHOSTRATIGRAPHY	99
6.3.1 Eocene	100
6.3.1.1 Rus group	100

	<u>page</u>
6.3.1.2 Dammam group	104
6.3.2 Miocene	108
6.3.3 Pleistocene	109
6.4 GROUND WATER	110
6.5 OLD CLIMATE WITH EMPHASIS ON SEA-LEVEL CHANGES	113
6.6 PRESENCE OF KARST WEATHERING	116
6.6.1 Caverns	118
6.6.2 Dayas	119
6.6.3 Discussion	121
7. A BASIS FOR STUDYING KARST IN BAHRAIN	125
8. CONCLUSIONS	129
REFERENCES	132

LIST OF FIGURES

Figure	<u>page</u>
1.1.1.1 The classification of carbonate rocks	6
1.2.1 The dissolution process in four phases, after Bugli (Sweeting)	11
1.2.1.1 The Bayliss Lime deficiency curve and the Langelier Saturation Index	11
1.2.2.1 Comparison between Equilibrium solubility and Anaerobic solubility	14
1.2.5.1 Solution of a solid controlled by diffusion	18
1.2.5.2 Rate of solution of Portland Stone and its dependence on flow velocity	18
1.2.7.1 Graph to illustrate mixture corrosion mechanism of Bogli	22
2.1.1.1 Types of doline	31
2.2.1.1 Ideal paths of ground water movement (after King)	41
2.2.1.2(a) Network cave pattern	44
(b) An example of network cave pattern	44
2.2.2.1(a) Characteristic forms of phreatic caves	46
(b) Development of vadose caves from phreatic caves	46
2.2.3.1 Vertical cave development sequence	49
4.2.1.1 Electrode configurations for electrical resistivity traversing	73
4.2.1.2 Postulated solution features from resistivity survey with plotted depth contours below finished floor level	76
4.2.1.3 Mapped extent of fissures after excavation	76
4.2.2.1 Comparison of electrical resistivity and magnetic profiles across a clayfilled sinkhole at Upper Enham, Hampshire	78

		<u>page</u>
Figure		
6.1.1	The location of Bahrain in the Arabian Gulf	95
6.1.2	The location of Bahrain Islands	95
6.1.3	Relief and physiographical subdivisions of Bahrain	97
6.2.1.1	Generalized geological outcrops	103
6.5.1	Summary of the main geomorphological controls, sea level and climate which have affected the evolution of landforms of the Arabian Gulf area	111
6.5.2	Temperatures, sea levels and terrace heights in the Arabian Gulf area during the last 18,000 years	112
6.6.1	The location of caverns and dayas on Bahrain	117

LIST OF TABLES

		<u>page</u>
Table 1.2.1	Dissolution rates	19
Table 4.1	Summary of detection methods	68
Table 6.3.1	A correlation between the Eocene divisions used by Willis and the later survey	100
Table 6.3.2	Lithostratigraphic correlation of the Eocene and Miocene of Bahrain with neighbouring areas	101

LIST OF PLATES

- Plate No. I Jabel ad - Dukhan :
Highest altitude on Bahrain Island
- Plate No. II Dil' Rafah Carbonate formation
- Plate No. III Foraminiferal Carbonate formation capped
by the Al-Buhayr Carbonate formation
- Plate No. IV Al-Buhayr Carbonate formation
Green clay filling Karstic solution
depressions.
- Plate No. V West Rafah Flint formation
- Plate No. VI Dil' Rafah Carbonate formation in the
foreground. Foraminiferal Carbonate
formation at the middle of the sequence.
Al-Buhayr Carbonate formation capping
the outcrop.
- Plate No. VII Saucer-shaped Dayas.

INTRODUCTION

There has been very little research connected with the presence of Karst landforms in Bahrain. In the quest for land to satisfy the continuous urban and industrial development of the island it is unavoidable that this development will have to extend to presently virgin areas. Carbonate rocks are known to be associated with engineering problems caused by the presence of Karst landforms. This study will assimilate the current knowledge of the carbonate rocks and their engineering significance from the literature together with case histories for the illustration of relevant problems. It will then concentrate on evaluating the Bahrain carbonate rocks and their potential for Karst landforms and will propose a study for their investigation.

Soluble carbonate and soluble non carbonate rocks, the mode of the dissolution process and the resulting landforms in both cases are discussed separately.

The first chapter deals with the genesis of Karst highlighting the characteristics of carbonate rocks susceptible to the dissolution process, the factors influencing the process and its mode of occurrence.

In the second chapter the various types of Karst landforms as expressed on the surface and subsurface and an overview of their occurrence is presented. The first two chapters are deliberately longer than the

others as the author was seeking to present in detail the dissolution process and the formation of Karst landforms; it is felt that this elaboration becomes important in the attempt to explain the set up in Bahrain and the limited existence of solution features on the island.

Details of the methods for detecting solution features together with examples of where these methods have been successful are outlined. Often anomalies obtained from a certain investigation are ambiguous and more than one interpretation is possible. The methods outweigh the alternative extensive drilling programme in time and expense, but no one method is, as yet, applicable and successful to all field conditions.

The engineering problems associated with soluble rocks are discussed with reference to case histories and other situations where problems have arisen in Karst areas. The factors that need to be considered when engineering projects are to be developed in areas of soluble rocks and some measures that can be used to improve ground conditions are referred to.

In concluding the study, an overview of the Bahrain carbonate rocks and the palaeoclimate is set up. A discussion outlines the possible reasons for the up-to-date known, restricted presence of solution features on the island. A basis for detecting solution features and their importance in the future development of the country is suggested.

Introduction

The word Karst is the German form of the Slovene word "Kras" and the Italian "carso". The word itself is probably of pre-Indo-European origin, denoting bare, stony ground. The characteristic karst landforms were initially described in the regions of Slovenia between Trieste and Ljubljana, now considered the "Classical Karst" area and for sometime the focus of much attention by scientists from all over the world.

All areas of Karst regions are areas of massive limestones and dolomites where the essential characteristic is the presence of vertical and underground drainage.

The susceptibility of carbonate rocks to solution in ordinary atmospheric water and their distinct way of weathering, by the combination of erosional and solutional processes, results in the formation of Karst landforms.

The following chapter will describe the soluble carbonate rocks as well as the solution process, and the other factors influencing the formation of the surface and subsurface solution features and their characteristic morphologies.

1.1 SOLUBLE CARBONATE ROCKS

The principal soluble carbonate rocks are limestones, dolomites and chalk.

1.1.1 Limestones:

A vast variety of rocks is included under the name limestones and any rock consisting of more than 50 per cent carbonate is considered to be a limestone. The carbonate minerals which form the greater part of limestones are calcite, aragonite and dolomite. Fig. No. 1 shows clearly the most important distinctions between the carbonate rocks. There are several classifications of limestones based on their genetic and textural differences. Of most importance to the study of Karst landforms are the latest attempts to classify the limestones from a textural point of view where a justified importance is given to the porosity. Hence limestones can be considered as compact with little pore space, fine-grained with feeble pore space and porous with variable interstices and high porosity. Porosity in limestones is also affected by the presence of stylolites which are irregular structures usually parallel to bedding and along which solution has taken place.

1.1.2 Dolomites:

Although they closely resemble limestones they are different in many aspects. Mainly in mineralogic

composition (see Fig. 1.1.1.1). The presence sometimes of remains of fossils and intraclasts implies that they are formed secondarily by dolomitization of limestone although some very fine grained dolomites are thought to be of primary origin, especially if they are associated with evaporites. Dolomites are closely related with limestones in the field with which they may be interbedded but the distribution of dolomites is frequently controlled by faults and folds. Dolomites that form the core of coral reefs are highly porous as they contain many voids despite the fact that they are well cemented. Dolomitization, which involves large scale recrystallisation, generally destroys the original structures and has an important effect on porosity and permeability. Power, suggests that in any given textual group, porosity and permeability progressively decreases as dolomite increases from 10 to 80 per cent, increases where dolomite forms 80-90 per cent of the rock and again decreases as dolomite exceeds 90 per cent.

1.1.3 Chalk:

It is a fine-grained, porous and friable variety of limestone and is believed to be an almost unaltered deposit which has failed to become a dense, hard rock and thus does not give rise to typical Karst landforms.

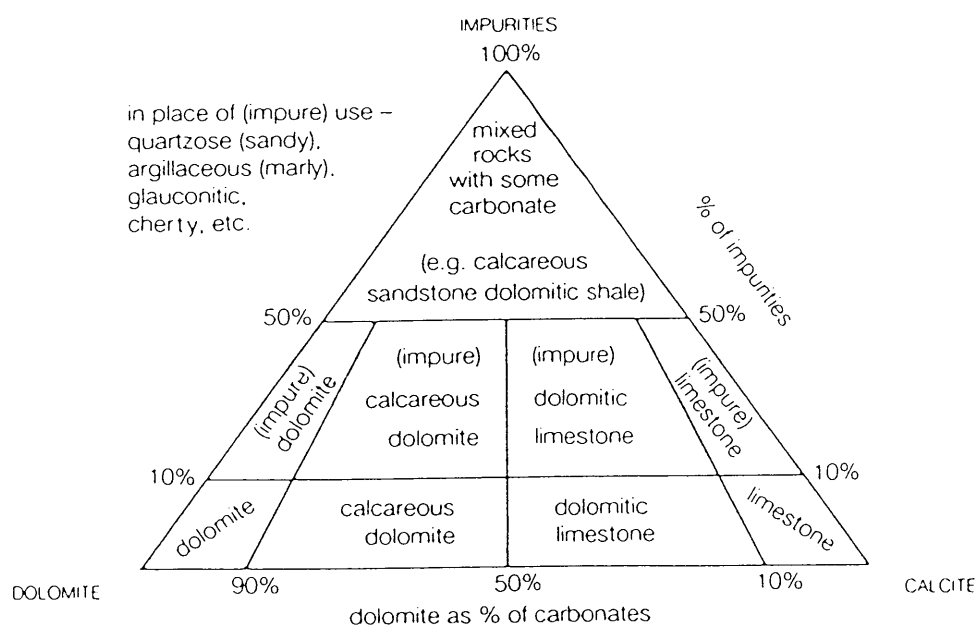
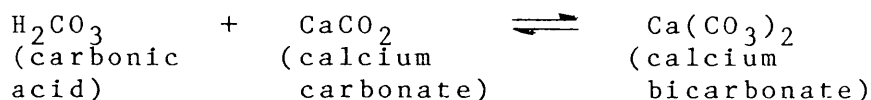
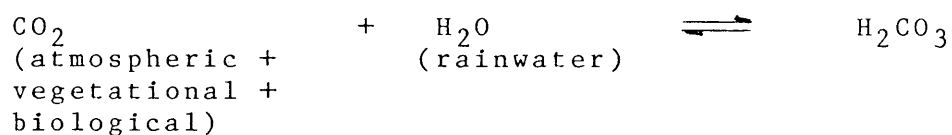


Fig. 1.1.1.1 The classification of carbonate rocks

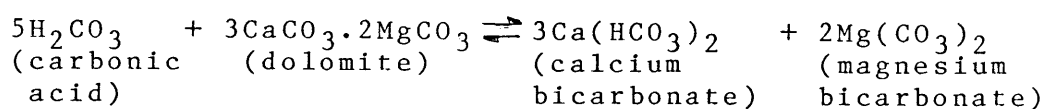
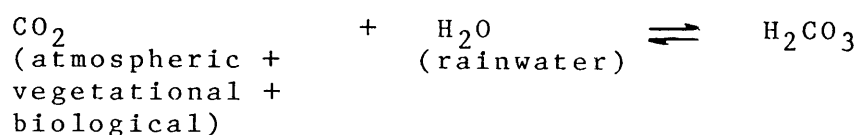
1.2 DISSOLUTION PROCESS AND INFLUENTIAL FACTORS

A differentiation between the words solution and dissolution should be made before we proceed; throughout the text the word solution will refer to solution features as part of Karst landforms used to denote their shape and form, i.e. surface features (dolines), subsurface features (caves). The word dissolution will be used to describe the process whereby particles of the soluble rock-mass are released by chemical reaction from the rock and transferred into the water in contact with it to be carried away.

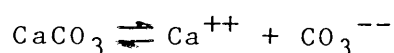
Although most of the scientific investigations about the dissolution have been done on limestones and to a lesser degree on dolomite and chalk the findings equally apply to all the carbonate rocks. The solubility of calcium carbonate is given by the general equation:



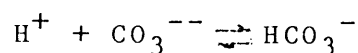
and of dolomite by:



A more detailed insight of the dissolution process is given schematically by A. Bogli in Fig. 2. He states that the dissolution process in limestone is controlled by four chemical phases. Calcium carbonate is slightly soluble in pure water, so in the first phase the limestone dissolves directly without any of the carbonic acid contained in the water being involved. The amounts involved tend towards solution equilibrium.

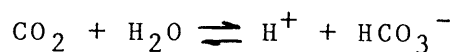


During the second and third phases the dissolved carbon dioxide takes part in the reaction and at 4°C only 0.7 per cent is in the form of carbonic acid, the rest being physically dissolved. In the second phase the H^+ ion of the carbonic acid reacts with the CO_3^{--} ion of the first phase



As a result of the association of the two ions, CO_3^{--} is thrown out of solution equilibrium and must be replaced until a new equilibrium is reached; this is achieved by further solution of limestone. The balance between the physically and chemically dissolved carbon

dioxide is also disturbed and in phase 3 the physically dissolved carbon dioxide is changed into carbonic acid and its ions.



This is the beginning of a series of reactions, at the end of which a further solution of limestones occurs.

Bogli also examined the rate at which limestone passes into solution in relation to the four phases of the solution process discussed above. He claims that solution during the first two phases is rapid and as shown from Fig. 1.2.1 more limestone passes into solution in the first second of a fixed set of conditions than it does all the rest of the time that the same conditions prevailed, but the equilibrium may take as much as sixty hours to be reached.

All these reactions are reversible and their direction depends upon the saturation of CaCO_3 . The equilibrium of CaCO_3 is regulated by the CO_2 dissolved in water and called the carbon dioxide of equilibrium. If the pressure of the CO_2 dissolved in water is greater than that of the atmosphere then the water is termed as aggressive and it will dissolve more calcium carbonate but in the reverse case CaCO_3 will be precipitated. Magnesium carbonate is found to be more soluble than calcium carbonate at all temperatures and all pressures of CO_2 . The solution rate of dolomite though is not well understood and it seems that the double carbonate is less soluble than either calcite or

magnesite as confirmed by Gerstenhauer and Pfeiffer and by Preisnitz.

1.2.1 pH

The range of pH of rainwater varies from 4.5 to 7.1 with very low acidic values occurring with increasing content of carbon dioxide, chlorides and sulphates. The most acidic rain occurs in industrial areas where CO_2 and SO_2 are abundant in the atmosphere due to burning of fossil fuels and ejection of other components. The presence of CO_2 forms carbonic acid which attacks and dissolves carbonates as discussed earlier, while the presence of SO_2 is responsible for the occurrence of sulphuric acid which attacks the carbonates and converts them into easily soluble gypsum. Along the coast enrichment of rainwater in chlorides takes place from the sea spray with some of the chloride forming HCl .

If water is undersaturated in respect to CaCO_3 , it is capable of attacking and dissolving limestone until saturation is reached. Such water is termed "aggressive" or "corrosive" and the degree of its aggressiveness can be found by measuring its pH. The corrosiveness of water is presented by the Bayliss Lime Deficiency curve and the Langelier Saturation Index (L.S.I.). (Fig. 3). The L.S.I. is a number combining together the chemical equilibria of water with CaCO_3 quantitatively in regard to calcite, at a given temperature, pH of the solvent, carbonate hardness and

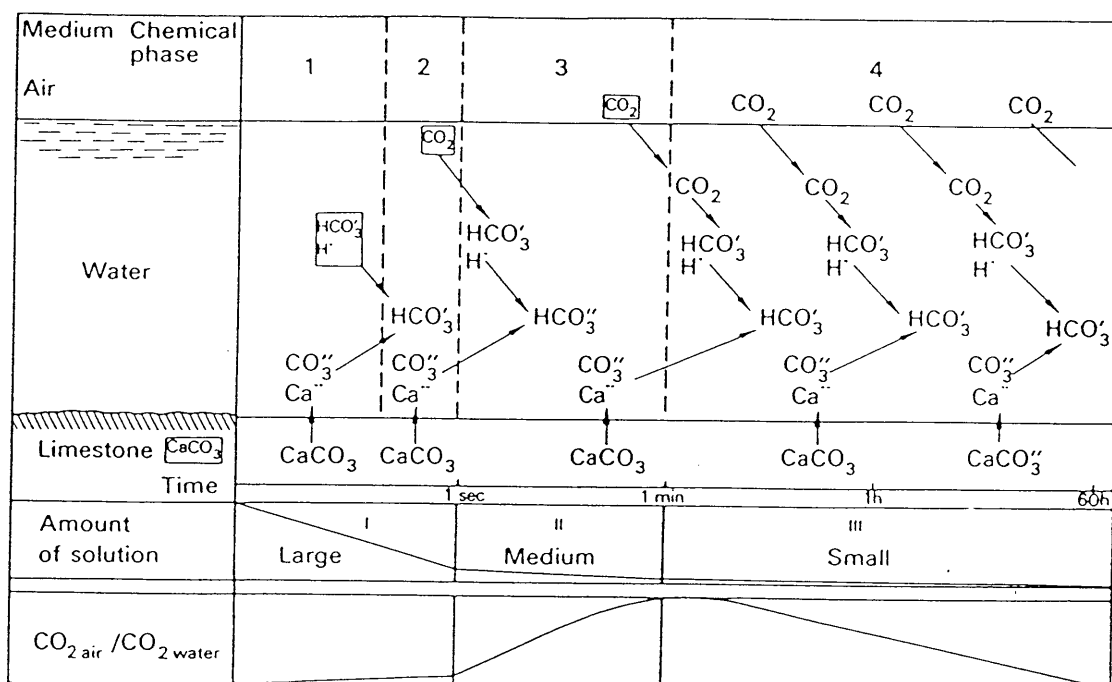


Fig. (1.2.1) The dissolution process in four phases after Bogli (Sweeting)

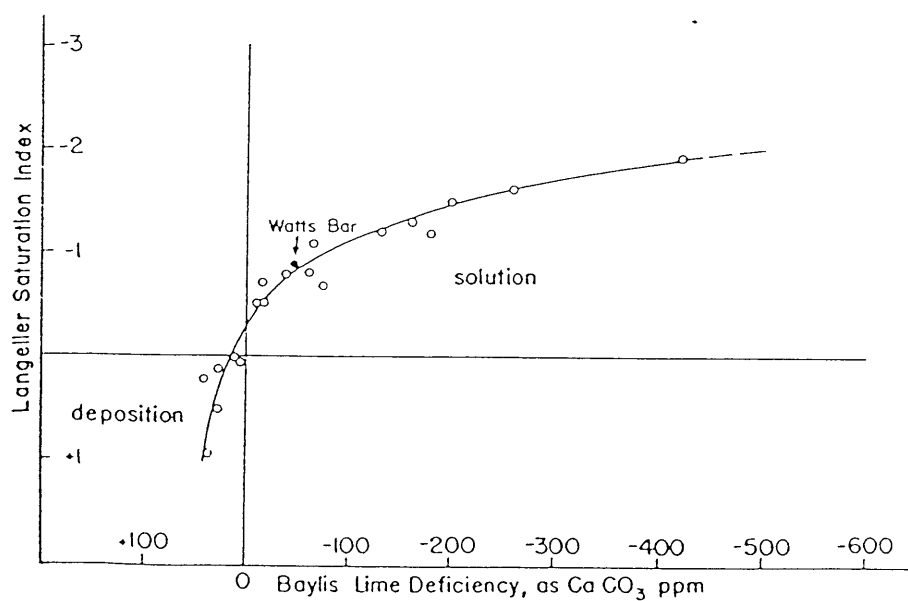


Fig. (1.2.1.1) Relationship of the Langelier Saturation Index with the Baylis Lime Deficiency curve

total hardness. At 0 the water is in equilibrium with calcite.

1.2.2 Carbon dioxide

Calcium carbonate is slightly soluble in pure water reaching only 12-14 p.p.m., but its solubility increases in rainwater and groundwater due to the presence in them of CO_2 . The temperature effect on the quantity of CO_2 dissolved in water is inversely proportional i.e. the lower the temperature the more CO_2 may be dissolved and vice versa. Whereas the abundance of CO_2 in the air is in direct relationship with the amount of CO_2 that can go into solution until a balance is reached between the molecules of CO_2 going from the air into water and those coming out from the water into the air.

Two types of solubility are concerned with carbon dioxide. The "equilibrium solubility", based on the condition that the water dissolving the limestone is continuously exposed to air from which it draws supplies of CO_2 until equilibrium is reached. In such an open system the equilibrium may take hours or days to be reached as discussed earlier. The second type is "anaerobic solubility" where the water comes into an initial equilibrium with the air but where the CO_2 is cut off during the dissolution process i.e. it is transformed into a closed system by the water passing down into joint planes or phreatic zone. The equilibrium is reached sooner but at lower

concentrations (Fig. 1.2.2.1).

A most important factor in the solution process is the CO_2 pressure. The CO_2 in the atmosphere has 0.00033 atms pressure or is 0.033 per cent by volume but air in the soil exhibits 10 to 100 times greater CO_2 pressure. This increase is clearly related to the vegetational and bacterial decomposition. Biological activity within the soil, at least in tropical and temperate regions, shows a seasonal rhythm and is greatest during spring and summer. There is supportive evidence to the above, where distinctly higher values of CaCO_3 were reported during the summer than in the winter when this effect was studied i.e. in the Peak District, Derbyshire, Malham Tarn, Yorkshire and river Mellte, South Wales. In addition, it has been demonstrated that the dissolution process is far more active in tropical and subtropical climates than in the Alpine and Arctic regions despite the fact that the solubility of carbon dioxide is higher at lower temperatures. However, there are cold environments where the CO_2 pressure is increased and these are areas covered by snow banks and drifts. As previously discussed the CO_2 is more soluble in colder than in warmer water and it is suggested that the daily freezing and thawing of the snow surface leads to higher concentrations of CO_2 in the air contained within the snow banks. As the CO_2 is heavier than the air it concentrates close to the base of the snow and any meltwater or rainwater passing down into the ground

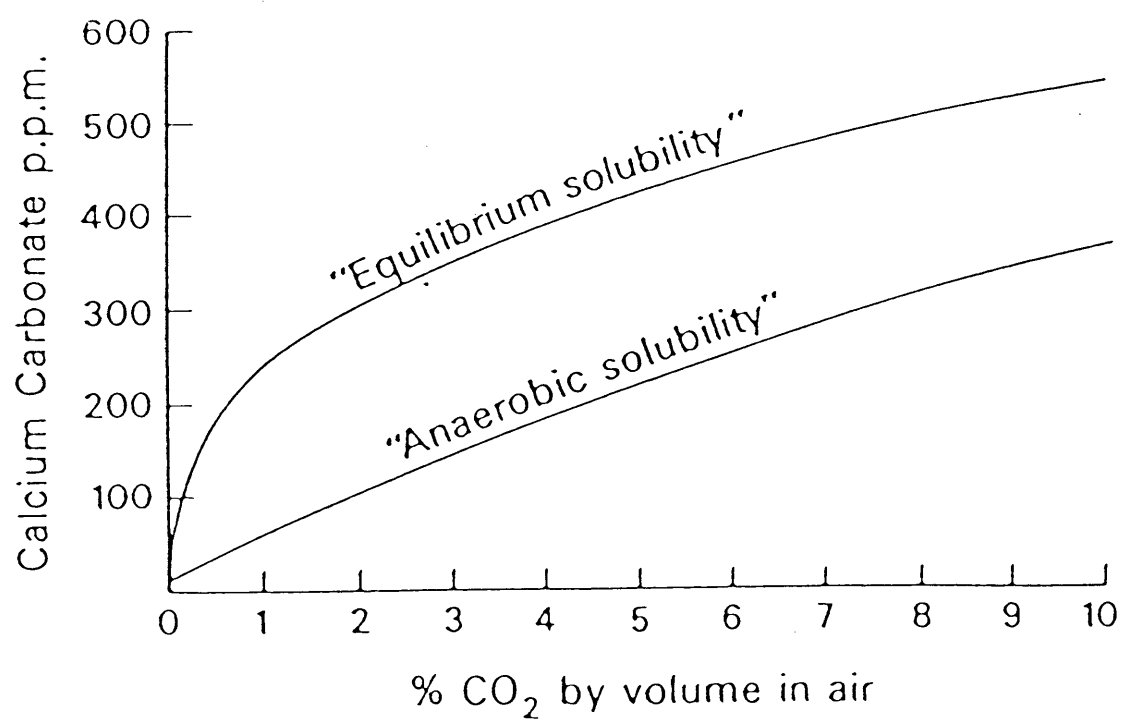


Fig. 1.2.2.1 Comparison between Equilibrium solubility and anaerobic solubility

becomes highly charged. Although the conditions described above are characteristic of snow it is not yet established if glaciers and glacier waters demonstrate the same aggressivity, a subject on which conflicting evidence has been provided.

1.2.3 Mineralogy and effect of impurities

It has been mentioned earlier that carbonate minerals have differential solubilities with claims that the speed of leaching of limestones is five times greater than that of dolomites. Other mineralogical impurities such as the presence of quartz or sulphide minerals influence the dissolution process. Any quartz grains or secondary silica present increase the resistance to weathering, whereas the presence of lead or iron sulphides increase the solubility of limestones. This happens as the oxidation of the above mentioned minerals leads to the formation of sulphuric acid which in turn converts the calcium carbonate into easily soluble gypsum. Sodium and potassium are also considered to increase the solubility of calcite while recent studies by Terjesen and others indicated that small traces of heavy metals such as lead, scandium, copper and manganese have an inhibiting effect on the solubility of calcite.

1.2.4 Lithology and structure

Dissolution rates depend not only on chemical parameters but characteristics such as the texture and

structure of limestones themselves. The porosity of the limestones determines the amount of the aggressive water which will permeate the rock and the permeability determines the ease with which this water will circulate in the limestone and so highly porous and permeable limestones will be more susceptible to dissolution than the ones with very low porosity and permeability. These two properties are greatly influenced by the type of calcite making up the Karst limestone and the way of their initial formation.

Circulation of solutional waters is to a large degree assisted by the presence of joints, bedding and faults. However, there are instances where joints are rewelded by the precipitation of CaCO_3 or where chalk is injected along a fault plane and thus forms a partial barrier to ground water flow. In general though the presence of fissures in the limestones is crucially favourable to the development of Karst landforms. Rough, irregular surfaces are more soluble than smooth surfaces presumably because they expose larger areas to the dissolutional process and because they induce some turbulence with their irregularities.

1.2.5 Turbulence

Turbulence or agitation of water in contact with carbonate bedrock is believed to increase the rate of dissolution. It has been shown that whereas stagnant water becomes supersaturated, a flowing stream causes rapid dissolution. When the products of reaction that

are present at the solid-liquid interphase are removed by a high velocity stream, more particles are readily diffused from the crystal face, hence the rapid dissolution rate (Fig. 1.2.5.1 and 1.2.5.2). This has been confirmed by field observations, where very high values of CaCO_3 in waters collected as they fell upon bare rock were reported and by the higher amounts of the same, held in suspension during floods than at any other time.

1.2.6 Rates of dissolution

There have been many attempts to estimate the loss of limestone by dissolution and the lowering of limestone areas in terms of mm/1000 years. Mathematical formulae which take into account many variables, some of which are difficult to measure, do not inspire a high degree of confidence. A fact that imposes additional complications to the efforts of measuring the rate of dissolution, is the pitted nature of the topographic relief which causes the non-uniform process of dissolution of limestones. Table No. 1 gives an indication of the non-uniformity and the range of the rate of the dissolution process measured by various researchers in many parts of the world. (Sweeting, 1972).

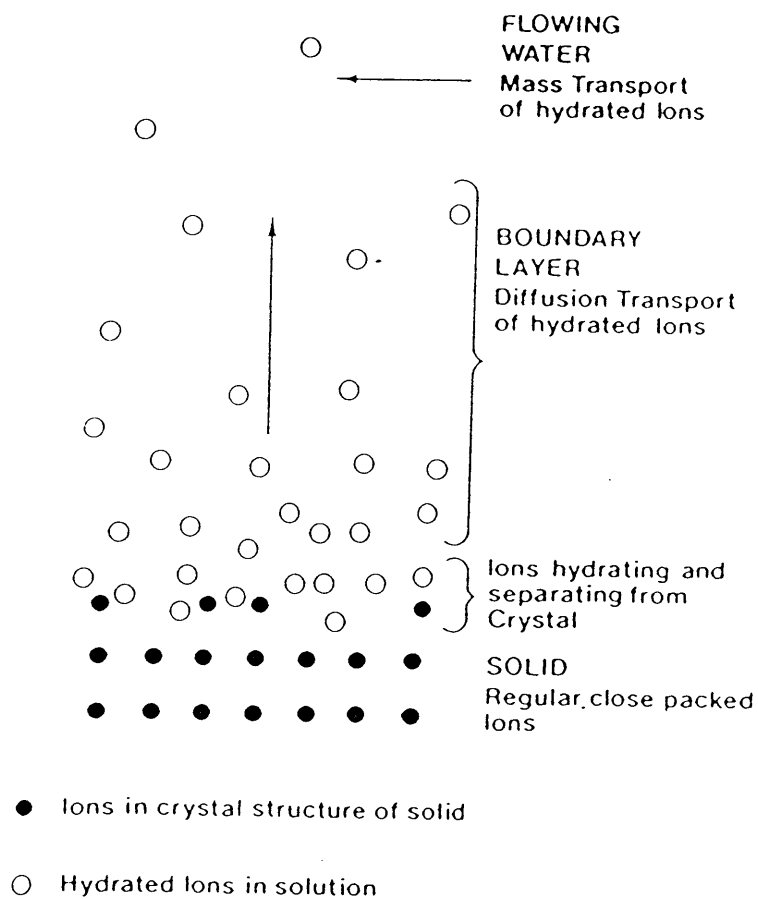


Fig. 1.2.5.1 Solution of a solid controlled by diffusion

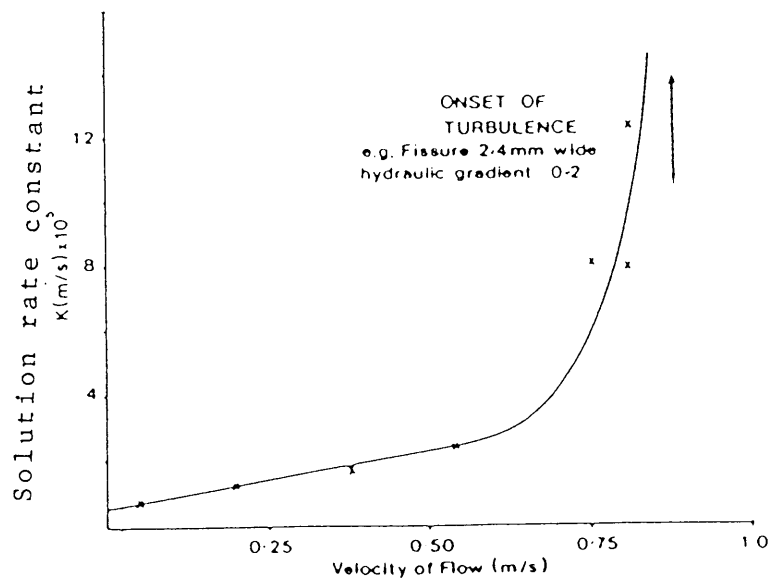


Fig. 1.2.5.2 Rate of solution of Portland Stone and its dependence on flow velocity

Table No. 1.2.1

<u>Author</u>	<u>Location</u>	<u>Rates of dissolution mm/1000 yrs</u>
V. Williams	S. Wales	18
P.W. Williams	Co. Clare, Ireland	55
Sweeting	N.W. Yorkshire	49-50
Gams	Slovenia	77-80
Pigott	Derbyshire	55-100
Bogli	Glattalp, Lucerne	15.1
Bingelli	S. Alps	250-333
Perrin	E. Anglia (chalk)	25
Versey	White limestone Jamaica	72
Pitty	Peak District, Derbyshire	75-83

1.2.7 Creation of Karst landforms

The dissolution process is dependent upon many factors and the objective is to apply the information from the above discussion in an attempt to explain the formation of Karst landforms.

In order for an underground network of solution features to develop, one requires a surface inlet for water, a subterranean flow regime and a point of resurgence. The water must initially develop surface paths for downward passage. This can be done by the

widening of bedding planes and joints by dissolution.

Let us consider a completely sound stratum of limestone which is subjected to a normal surface drainage. The limestone will accept water to fill-up the pores and any open joints and bedding planes. The degree of openness of the joints depends largely on the regional tectonic history and the degree to which the limestone was subjected to folding and faulting deformations and the subsequent stress relief. As discussed earlier the role of CO_2 content in water, provided by air, continuously incoming water and organic matter, is vital to the dissolution of limestone. If the water levels in pores and joints are fairly static the two first mentioned sources of CO_2 become unavailable. The water soon becomes saturated with CaCO_3 and the dissolution of CaCO_3 ceases. It is believed though that in cases like this one either biogenic CO_2 is provided by the bacterial oxidation of the organic matter present in the groundwater or CO_2 is formed by the presence of sulphide minerals. In principle these are valid explanations but when one considers the sizes and volumes of underground cave systems and passages is likely to seek additional mechanisms for their formation.

One such mechanism was put forward by Bogli, called "mixture corrosion". He effectively says that water held in capillary fissures, gradually loses its corrosive power and ceases to dissolve the rock unless

it meets with another stream with a different dissolution potential. Fig. 2.2.1.1 illustrates the mechanism. The upper line is the equilibrium curve that separates the precipitation zone from that of aggressive water in relation to limestone. A straight line joining two points on this curve, W_1 and W_2 representing two saturated solutions, always crosses the zone of aggressive water. The resultant solution is represented by point D; the position of point D on the line depends on the volumes of the two saturated solutions W_1 and W_2 . The figure shows that the resulting solution is capable of dissolving a further quantity of limestone (per unit volume) represented by the length of line CD. Bogli applies this only to underground corrosion but "there seems to be no reason to deny its activity in surface streams and rivers". (Sweeting).

Another explanation about the solution of limestone was put forward by Renault and is the corrosion caused by fall in temperature. He suggested that in winter the ground surface zone of limestone is cold and becomes warmer the deeper one goes. Rainwater arriving on the cold surface dissolves the limestone until it reaches saturation but when it permeates the surface and meets the warmer zone it loses some CO_2 and precipitates $CaCO_3$ thus becoming aggressive again and dissolving limestone at depth, forming underground voids and eventually caves. Some critical thoughts

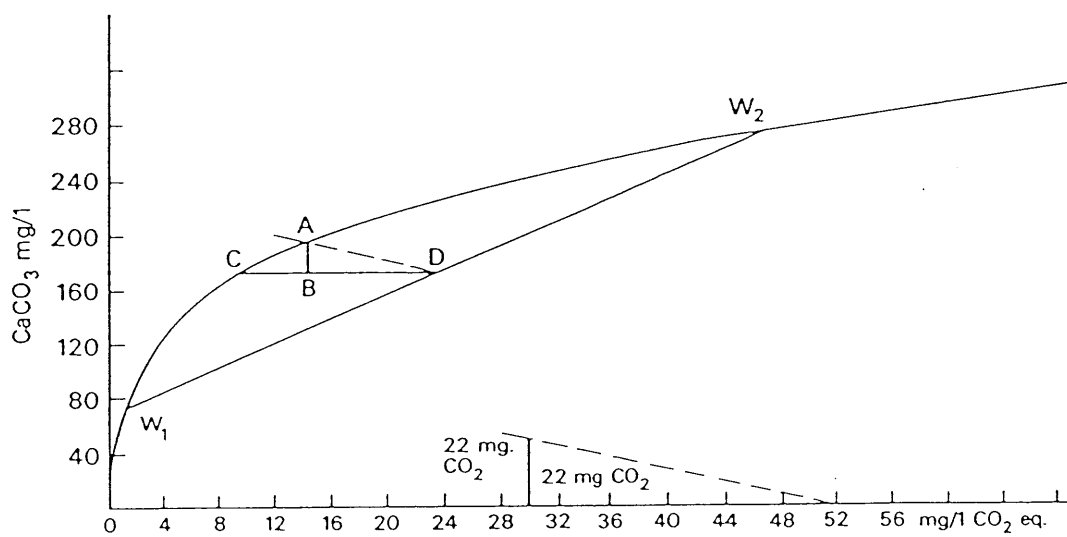


Fig. 1.2.7.1 Graph to illustrate mixture corrosion mechanism of Bogli

should accompany this explanation as this type of corrosion is restricted to a fairly narrow zone close to the surface. Furthermore it is found only in climates with wide differences of daily or seasonal differences.

To explain the mode of formation of caves, is often difficult to do, using field evidence since the present condition of caves may be one in several cycles of erosion and deposition. Returning to the hypothetical stratum of limestone which was initially considered after the mechanisms of dissolution have been explained, an attempt can be made to include other aspects of development of caves. The limestone may contain discontinuities but only a few will ever develop to become caves. Those which are more open may be preferentially enlarged by dissolution and once the diameter of the passage exceeds the critical 2.4 mm then the flow, if sufficient discharge is available, will change from laminar to turbulent with the corresponding advantage of increased dissolution rate. Mixture corrosion may also play its role, if more than one water sources meet at intersecting passages. The anastomosing channels formed at gently inclined bedding planes in the phreatic zone may act as a primitive cave system which can be further developed. In steeply bedded limestones linear tubes oriented down dip may widen, partly due to dissolution partly due to erosion to accomodate larger water flows and also eventually

develop to underground voids.

Although more emphasis has been placed in explaining the formation of caves, the surface solution features are created based on the same dissolution principle but aided to a greater degree by surficial erosional processes.

Introduction

In this chapter the landforms formed by the dissolution of soluble carbonate rocks will be discussed. They will be examined under two major headings, the surface landforms and subsurface landforms. An attempt will be made to clearly explain the creation of the most characteristic features encountered in Karst regions.

2.1 SURFACE LANDFORMS

2.1.1 Dolines

Dolines are tub-shaped depressions, small, roughly circular, of not very significant depth, hollowed out in limestone. They are restricted to flat or gently sloping landscape where the water can seep through to the permeable limestone. They have also been known as sinkholes, potholes, shakeholes and solution pipes. Their diameter varies from 10 to 100 metres and depth can be anything from 2 to 100 metres. Many of these formations lead to caves, underground passages and watercourses. Cvijic distinguished three main morphological types of dolines:

(i) Bow-shaped dolines:

These are very shallow in relation to their diameter; in this category all dolines whose diameter is approximately 10 times their depth are included. The slope of the sides is between 10° - 12° and they have a relatively broad base.

(ii) Funnel-shaped dolines:

In this group all depressions whose diameter is two or three times their depth are included. The angle of the sides is 30° - 45° and the area of the base becomes less, as depth increases.

(iii) The well-shaped dolines:

These are holes with steep almost vertical sides that either descend perpendicular and unbroken all the way or are sheer at the bottom; the latter case is a transitional form between a funnel-shaped and a well-shaped doline. The diameter of the well-shaped dolines is usually less their depth. Since Crijić's work many studies of dolines and many attempts have been made for their classification. The following is a classification by Cramer (1941).

a) Normal solutional doline

This type of doline is formed by water infiltrating through fissures and joints in limestone and gradually dissolving the rock along them. As a result of this dissolution the discontinuities enlarge so the surface materials settle and a distinct localized depression is formed on the surface (Fig.

2.1.1.1a); this causes the runoff water to become concentrated into the depression, assisting further the dissolution process. Residual clay and alluvial material may collect in the depression as it enlarges and as this may contain additional CO₂, aids the dissolution. Vegetation and particularly trees also assist doline formation; the mechanical and chemical action of their roots, the accumulation of organic debris and the increased growth of fungi and other plants, all mean that the soil is enriched in CO₂, a factor of speeding the dissolution and subsequently doline formation. The velocity of surface runoff is critically helpful to the formation of dolines. If it is less than a certain value, then water permeates downwards to the carbonate rock and starts the dissolution process along discontinuities.

As the dolines enlarge with continuing dissolution, their slopes may be subjected to slope wash and fluvial action during periods of high intensity rainfall. Depressions, at times are covered with impermeable material which does not allow free percolation of water through to the limestone thus on one hand slowing dissolution and on the other hand forming pools of water during wet seasons.

b) Alluvial doline

As the name suggests these are depressions where the carbonate rock is overlain by alluvium or other superficial material, i.e. glacial drift. They are

usually funnel-shaped and develop best where the thickness of the alluvium is 2-6 metres and rarely occur where the thickness exceeds 10-11 metres. Solution of limestone takes place along joints and cracks beneath the alluvial cover (Fig. 2.1.1.1b) As these discontinuities enlarge the superficial material subsides into them forming water-like hollows on the surface. The slopes of alluvial dolines tend to be unstable and full of small landslips particularly as the dissolution process continues and more alluvial material subsides into the enlarged joints. The aggressive water in these depressions, with the additional CO₂ provided by the alluvial mantle, speeds the dissolution process. The active development of alluvial dolines is visible from tears in the vegetation covering their inner slopes.

Their size and depth is controlled by the following factors: (i) width and depth of the joints in the underlying limestone; (ii) thickness of the overlying drift deposits; (iii) amount of surface drainage entering the discontinuities and; (iv) slope of the land surface. Their side slopes are steep and in time if they become lined with fine impermeable material, drainage is hindered and ponding or marshing develops during rainy seasons.

c) Solution subsidence:

These enclosed hollows are formed in a similar manner to the alluvial dolines but the difference in

this case is that the limestones are succeeded by shales or sandstones. (Fig. 2.1.1.1c) Enlargement of discontinuities, and formation of cavities due to solution and subsequent collapse of the sedimentary formation into them, forms crater-like hollows on the surface. Where the rock overlying the limestone is of clay or fine grained material the sides of the subsidence hollows are forming gentle slopes as the collapse of the material into the solution cavities below is slow and smooth. Where the overlying material is strong, competent rock as are sandstones for instance the subsidence is more sudden and uneven forming hollows with near-vertical joint-faced walls which are irregular in plan as opposed to the more circular and oval plan shapes of the subsidence hollows of finer grained material. This kind of doline may extend to great depths and it has been suggested with supporting evidence that the mechanism of subsidence of large sandstone blocks involves partial collapse in large underground systems of caverns and caves. Similar solution subsidence occur in sandstones underlain by limestones and gypsum beds.

d) Collapse doline

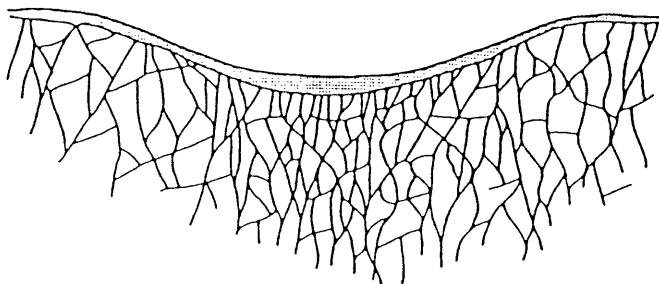
These are formed by large scale collapses of limestone caverns at depth and transmitted to the surface limestone in the shape of small closed depressions. The most characteristic collapse dolines have oval or near circular shapes and steep-cliffed

walls. (Fig. 2.1.1.1d) The depressions may be small but the whole solution feature possesses a high depth to diameter ratio. Collapse dolines are more characteristic of areas with well established underground drainage and usually in wetter than drier Karstlands; they are also important in regions with distinct variation of rainfall as this causes variations in the volume of underground water levels which exert enormously different hydraulic pressures on to the supporting cavern roofs leading to their weakening and collapse.

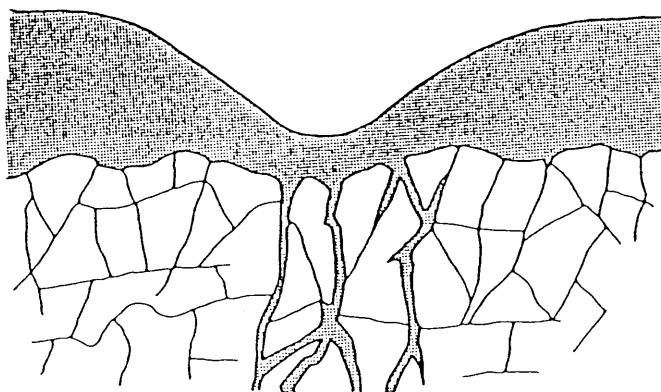
Cvijic recognised two types of collapse dolines: Firstly the ones leading into short "blind-ended" cave passages eroded along joints and cracks, normally having a funnel-shape. Secondly, the ones that are associated with underground river systems where a steep-sided collapse doline either exposes the underground river or is indirectly involved by many intervening passages and caverns with it.

Dolines are in general structurally controlled but as discussed above with the four types many other factors can also be influential. As the sizes of dolines increase and their sides weather it becomes very problematic to differentiate one type of doline from another. The only real method in deciding about the origin of a doline is to view it in section as exposed in cuttings or to excavate the base to define the character of the infill of the structure. In tropical climate the normal, more or less circular type

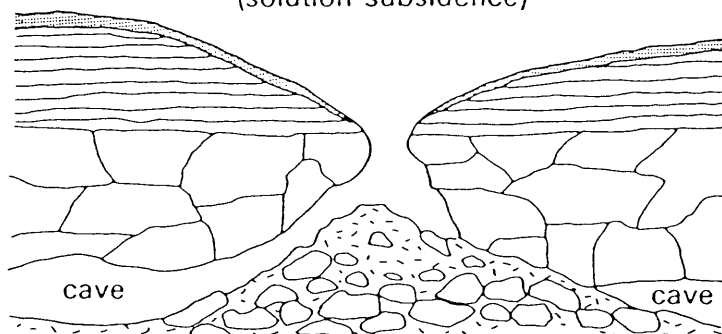
(a) Solution doline



(b) Alluvial doline



(c) Collapse doline in rock overlying limestone (solution subsidence)



(d) Collapse doline

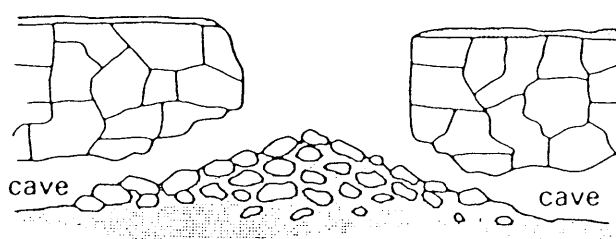


Fig. 2.1.1.1 Types of doline

of doline that we have described above is replaced by irregular star-shaped hollows called cockpits (described below).

2.1.2 Cockpits

These are sinuous, angular, star-shaped depressions, set between regularly spaced residual hills. Their sides are lobed convexly inwards with gullies carrying streams after heavy rains. Many cockpits have bedrock shafts at or near their lowest points, formed by surface solution which are used as drainage paths for the rainfall; in wet seasons the bases of cockpits may be transformed into puddled muddy areas by the ground water level becoming higher and by the thin clayey mantle provided during drier seasons.

2.1.3 Uvala

This term refers to complex depressions, having uneven floors and more than one low points but no extensive flat areas. It is believed that often are due to the coalescing of several dolines or to the formation of smaller dolines within a large one.

2.1.4 Polje:

A term used for closed depressions with flat floors at least 400m across. Usually they are elongated along the strike of the rocks and can be compact and irregular in plan. Parts of their sides may be in impervious rocks from which streams flow down

on to the floors. Along the margins with limestone springs arise. The streams flow over alluvial fans or plains where they sink; these streamsinks are called ponors and may vary from cave entrances to alluvial dolines.

2.1.5 Swallow holes

This term is used to describe a solution feature where a watercourse partly or wholly disappears from the surface to flow underground. These solution features are also sometimes referred to as swallets, water or stream sinks. It is worth mentioning that both the British Standard Institute CP2004: 1972 and BS5930: 1981 incorrectly define the term swallow hole; they consider it to be synonymous to sink hole but as we have discussed above (2.1.1) one can appreciate that these two terms do not have the same meaning.

According to Sweeting (1972) there are two types of swallow holes, as described below:

a) Swallow holes with little or no topographical expression

These are places at the bed of a stream where it disappears slowly into the limestone through bedding planes and joints. There are no visible cavities and the gradient of the valley changes very little if at all to accomodate the sinking of the water beneath the surface. This is a youthful stage and with time the stream entering the limestone will both erode and corrode visible swallow holes in the rocky bed.

b) Swallow holes which form a relief feature

There are three types:

(i) Swallow holes associated with caves:

These are formed in two ways, either by the enlargement of bedding planes by solution and erosion to form a cave into which the river is absorbed or they may develop to provide a link between the river and a pre-existing underground cave. This type of swallow holes tend to develop in horizontally bedded or gently dipping limestones.

(ii) Swallow holes with vertical or steeply sloping shafts:

They are particularly influenced by faulting and develop in steep dipping hard, sparry limestones which do not have the tendency to shattering or collapse, by dissolution along a joint or along a small fault plane and are therefore deep and narrow. The walls of the shafts may be relatively straight but often the falling streams cause the formation of fluted and rounded walls and columns resembling a form of Karren. Although lithological and structural considerations are very important this type of swallow holes develop best in regions of recent and present glaciation. In non-glacial environments, they develop to a much lesser extent where lithological, structural and relief conditions are suitable.

(iii) Swallow holes formed in alluvium or drift:

They occur in limestone as solution widened fissures but are covered with much alluvium. The hole into

which the stream sinks is neither of a cave nor of a shaft type because of the drift cover, they are usually muddy depressions in the flat floor of a valley and if drainage is impeded they are prone to ponding during wet seasons. They are especially connected with polje which are areas of flat, planed alluvium covered limestone (2.1.4).

Swallow holes are present along dry valleys which were recently the surface water courses of the present subterranean streams. Generally they cope satisfactorily with the water flow but occasionally during wet seasons when much higher flows and flooding occurs, the dry valleys are rejuvenated. Over a period of time the active swallow holes enlarge and migrate upstream i.e. those further upstream develop and replace the ones downstream. The downstream swallow holes may be required occasionally during periods of heavy rainfall but often become infilled and eventually impermeable.

2.1.3 KARST VALLEYS

There have been many discussions on whether valleys in limestones are part of typical Karst landforms but as they are the most important of the landforms not produced by true Karst processes they will be mentioned. According to Sweeting (1972) they can be divided into the following groups:

- a) Allogenic or through valleys - formed by rivers

which rise on the impermeable rocks surrounding the limestone area and are always canyon-like. Only rivers with large amounts of water are able to traverse the limestone without succumbing to the intensive Karstification process by permeating through joints into the bedrock. The river incision is favoured by the readiness with which the bedrock can be dissolved and abraded, the signs of which actions are found in the fine potholes in the limestone. The valleys may become wider due to lateral collapse of limestone blocks. The shapes of allogenic gorges depend partly upon the nature of limestones through which the rivers traverse, whereas dolomite usually forms V-shape valleys as it weathers easier than thick bedded limestone which forms steep-sided walled gorges under the same circumstances. A combination of widening of joints by solution and collapse, leaves the limestone in the form of natural bridges and arches and unusual scenic features very characteristic of some Karstic regions. Some allogenic valleys contain large scale depositions of calcium carbonate in the form of tufa and travertine which are even in greater proportions in warmer regions where evaporation is faster and CO₂ more.

b) Blind valleys.

These are river valleys, closed at their lower ends by disappearing streams; this happens as the widened by solution joints and bedding in the limestone, in time are capable of absorbing all the

water from the stream causing the river to dry up.

c) Pocket valleys, also referred to as steepheads.

These features are the reverse of blind valleys, occurring in association with the large springs resurging at the foot of a limestone massive. They consist of flat bottomed U-shaped valleys with steep walls and a steep headward cliff from the foot of which normally a spring issues.

d) Dry valleys.

Originally developed as the surface path of a river. With time the surface flow is swallowed through solution widened joints and captured underground. The flow initially is partially swallowed, but as the joints enlarge and can cope with larger volumes it disappears totally underground. This is done by the migration of swallow holes, i.e. by the formation of new swallow holes upstream so that they can capture all the flow. Earlier holes become inactive and in many cases filled with debris. Large stretches of these valleys become dry when the underground flow piracy is fully developed. The floors may be rather flat and the valley of either U-shape or more V-shape.

It will be an omission if before concluding our description of the surface Karst landforms we do not briefly mention the superficial features of limestones Karren or Lapies. These are small scale solutional and other weathering features, commonly formed directly on bare limestone or on limestone under a vegetational cover. These features resemble chiselling of the rock

with grooves and ridges of which the depth and width vary considerably from one type to another. Several factors affect the formation of Karren such as the amount, distribution and nature of precipitation, and presence or absence of vegetational cover.

2.2 SUBSURFACE FEATURES

The definition of Karstification involves the development of underground drainage and consequently the formation and development of underground landforms becomes a vital part of any study on Karstlands.

Caves develop by various processes but the most effective geomorphic process is the one associated with Karst processes. It will be misleading to suggest however that caves develop everywhere in Karst regions as there are some requirements for their development regarding the quality of Karst rock and the water. In reference to the Karst rock, this should be pure enough not to yield insoluble residues in big enough quantities to block incipient cave passages, strong enough to support cave roofs and should contain planes of weakness necessary to promote secondary permeability but not too close together for cave development to be favoured. In reference to the water this should be present in liquid state and some relief must be available to provide hydraulic gradient for its movement. As a general rule the water for this purpose is meteoric but locally hydrothermal water may form

caves or connate water from considerable depths.

The variety of caves in Karst is immense, both in size and in nature. The current depth record is 1494 metres in Gouffre St Bernard in the French Alps, while the largest cave chamber is the Sarawak Chamber in Good Luck Cave (Lubang Nasib Bagus) Sarawak which is 700 metres long, 400 metres wide and 280 metres high. In complexity caves vary from single rooms, short passages and open shafts to intricate three dimensional systems of passages, linking rooms, shafts, chambers and halls of all kinds of shapes and sizes. Caves are found all the way from the tops of mountains to valley bottoms and coastal plains, even well beneath the sea. They may be completely dry or completely filled with water and their entrance vary from vertical shafts to lateral openings in hilltops and cliffs. Bedrock is exposed over the total area of some caves but most of them are partially covered with deposits; if the deposits fill up a cave completely then it becomes a fossil cave.

The following section aims to present the current understanding of cave formation as it has accumulated by pioneers of cave investigation during the last two and half centuries

2.2.1 Phreatic caves

Phreatic caves are formed below the water table where the water flow is confined and under hydrostatic pressure.

The dissolution process takes place along joints

and bedding planes in the carbonate rock in a slow but steady manner under unchanged conditions. The movement of water below the water table is downward in areas of greater hydrostatic pressure and upward in areas of less pressure, the two movements being connected by a curved lateral one (King, 1899). (Fig. 2.2.1.1) The water flows are likely to be faster directly below the water table than at greater depths and similarly the dissolution rates will be greater just below the water table than at deeper levels.

Observations made by Moneymaker (1941) suggest that at present the process of dissolution is taking place with the development of unconnected and inaccessible water filled cavities in thick limestone regions. He has discovered solution cavities up to 30 metres below the water table in the Tennessee Valley but most are within the first 12 metres from the water table.

Phreatic flows create circular or elliptical forms, them being the ones offering the least resistance to the infiltrating waters and guided by pre-existing fissures, either bedding planes or joints. The developed passages may also have upward gradients. It has been suggested that the circular shape is developed first and as more ground water, resulting in mixture corrosion and increased dissolution rates, flows in the elliptical form is produced.

Bretz described the cave features characteristic of phreatic flow as follows:

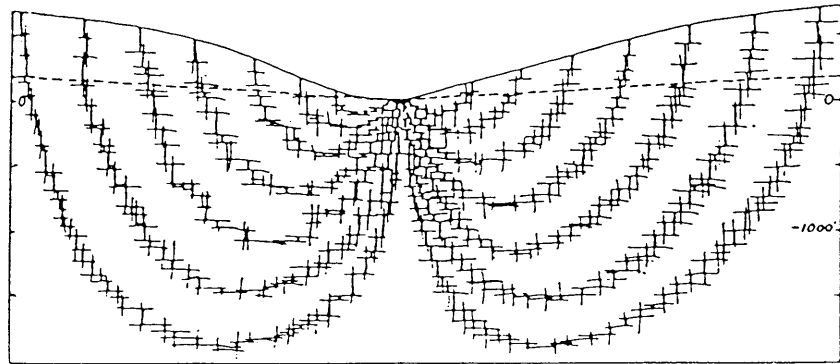


Fig. 2.2.1.1 Ideal path of ground water movement

(i) Spongework.

A complicated pattern of minor cavities and separating partitions, a few cm to 0.5 m in depth and present on cave walls and ceilings. This phenomenon is the result of differential solubility of the limestones when submerged in groundwater.

(ii) Pockets.

These are larger than spongework cavities and commonly are separated by stretches of unaffected wall. Usually they are deeper than they are wide.

(iii) Bedding, and joint-plane anastomoses.

This is a multitude of small, sinuous passages along a bedding plane rarely large enough to crawl into. It seems to be the earliest attempt at cave-making in formation which for various reasons did not develop further. Individual holes commonly have a bulbous cross-section. They are unknown in solutional ceilings, occurring only on those produced by the falling-off of slabs.

(iv) Joint determined wall and ceiling cavities.

These are deep and narrow slots on the walls and ceilings of cave chambers some of which extend several feet in depth. It is believed that they have developed by differential solution process along joints, sometimes by water penetrating upwards from the cave passage and sometimes by mixture corrosion.

(v) Network or maze patterns.

A development of a network pattern by which many "blocks" are completely surrounded by linear passages.

It is thought that the development of this characteristic pattern is due to solution along controlling joints in completely saturated rock. (Fig. 2.2.1.2a and b).

(vi) Rock pendants.

They occur on the roofs of many caves and resemble stalactites but are part of native limestone formed as a result of differential solution under ground water.

(vii) Scallops and flutes.

Both are solutional forms but are the results of the character of water flow. They are similar to the wave phenomena occurring in sand ripples and water waves. Scallops may be described as "interrupted concavities" covering a surface in an irregular pattern which appears largely at random. Flutes occur more rarely and as described by Curl are forms where the crests are nearly parallel to one another for distances greater than the distance between them. The form of scallops and flutes can be used as an indication for the direction of flow.

2.2.2 Vadose caves

Vadose caves develop above the water table where there is free movement of water. Water infiltrates into the limestone and soon preferential seepage develops along joints and bedding planes. Initially the water flow is laminar but as its route widens the flow becomes turbulent. Due to the dissolution process joints and bedding planes are enlarged initiating the

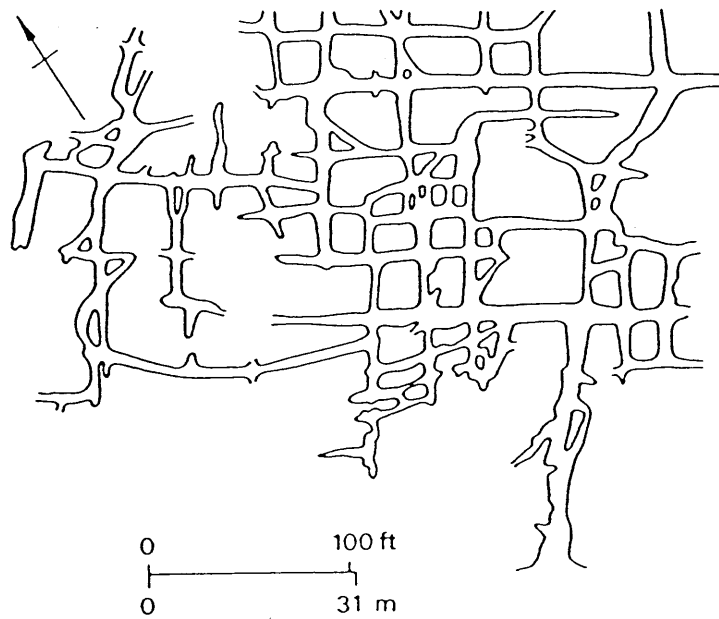


Fig. 2.2.1.2(a) Network cave pattern

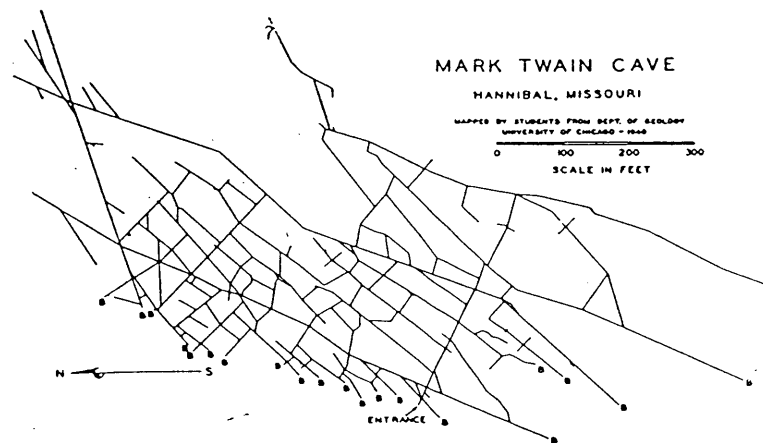


Fig. 2.2.1.2(b) An example of network cave pattern

vadose cave formation. Vadose caves either totally develop in the zone above the water table as described above or develop from the phreatic state, after they have been uplifted or after a lowering of the water table below their level. The characteristic circular or elliptical phreatic shape changes by the formation of a deep cut by a vadose stream at the lower part as illustrated by Fig. 2.2.2.1a and b. It is frequently difficult to decide upon the phreatic origin of a vadose cave as the process of dissolution and stream erosion soon modify and may even eradicate completely former phreatic features.

The vadose passages often possess a triangular shape with a broad base at the bottom due to lateral cutting and solution of the cave stream. In plan vadose caves exhibit a branching, dendritic shape the result of the underground behaviour of streams, very similar to that of the surficial river flows. Cave passages and galleries tend to form at different levels.

Certain features are also characteristic of the vadose caves; these are horizontal grooves and niches which become very thin and wide resembling shelves eventually collapsing under their own weight. They are formed by a meandering vadose stream by differential solubility of cave walls discontinuously, and only at places where the outer part of the meander comes in contact with the walls. Vertical groovings are present on steeply inclined or vertical passages carved out by

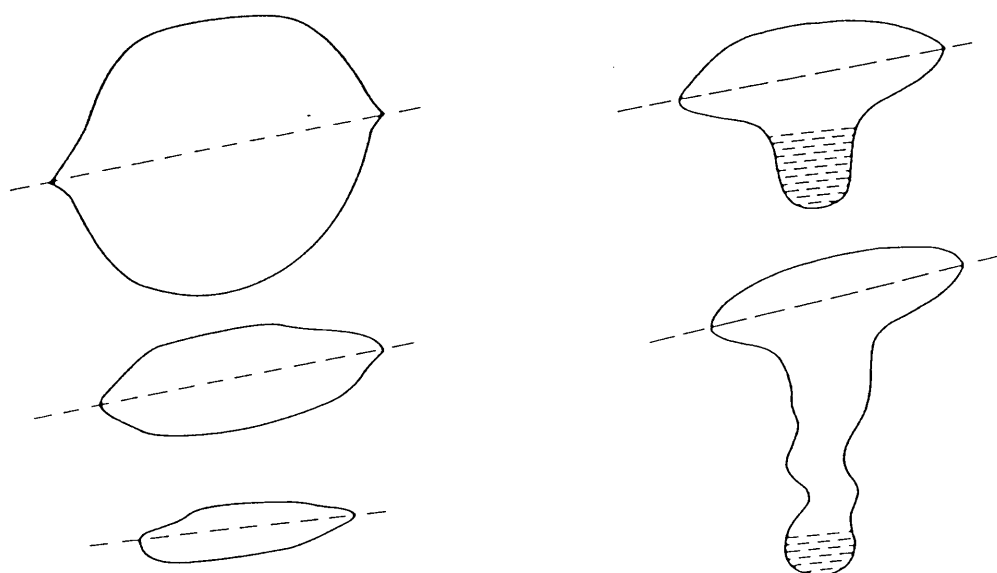


Fig. 2.2.2.1(a) Characteristic forms of phreatic caves

(b) Development of vadose caves from phreatic caves

descending streams. Sometimes enlarged blind passages are present leading for a short distance from the main passage; they are usually joint controlled and mixture corrosion is thought to be the cause of their formation as water from a different source seeps out of the joint to join with the main vadose stream.

Phreatic caves are smaller than vadose caves and this is thought to be due to the erosional input of the genetic stream. It is obvious that a stream carrying sediment coupled with its kinetic energy possesses a certain erosional strength for the enlargement of its passages. Additionally we must point out that block collapse where jointing is favourable is another factor for the enlargement of vadose passages.

2.2.3 Vertical Caves

Also referred to as "domepits" or "pitches". They are deep cylindrical shafts with fluted walls, lithologically and structurally controlled, developing along joints and faults. They occur where stream flows descend from an upper bedding plane to a lower one and their development is a joint function of dissolution and erosional processes. With the enlargement of vertical passages the water descends down the shaft as a water fall with spray and dips producing the characteristic fluted walls of the shafts.

Vertical caves also form by dissolution of limestone beneath an impermeable caprock. Water with low pH seeps through cross-joints downwards forming

shafts with dome-shaped roofs and vertically fluted walls caused by films of flowing water. The water dripping from the roof of the cave with an impact forms a cup-shaped basin on the floor. Their development depends upon the nature of limestone and quantity of seepage and is illustrated in Fig 2.2.3.1.

The most favoured positions for the development of vertical shafts are near escarpments and on valley sides but never near dolines. They have very little surface expression. The deepest vertical caves develop in thick deep limestones and a single vertical shaft 200 metres in depth has been reported by Eyre in Greece. They also occur in association with modern glaciers and near the sides of former ones like in the Alps where the highly faulted and folded limestones possess not only favourable relief and tectonics but are also supplied with plentiful quantities of meltwater.

2.2.4 Inlet caves

These develop where water passes underground into swallow holes and often are close to the contact between the limestone and the overlying rock cover.

2.2.5 Outlet caves:

They form where springs issue water at or near the base of the limestone outcrop. They may have uphill or downhill gradients and if these are a series of springs more than one cave may occur. Active ones are mostly

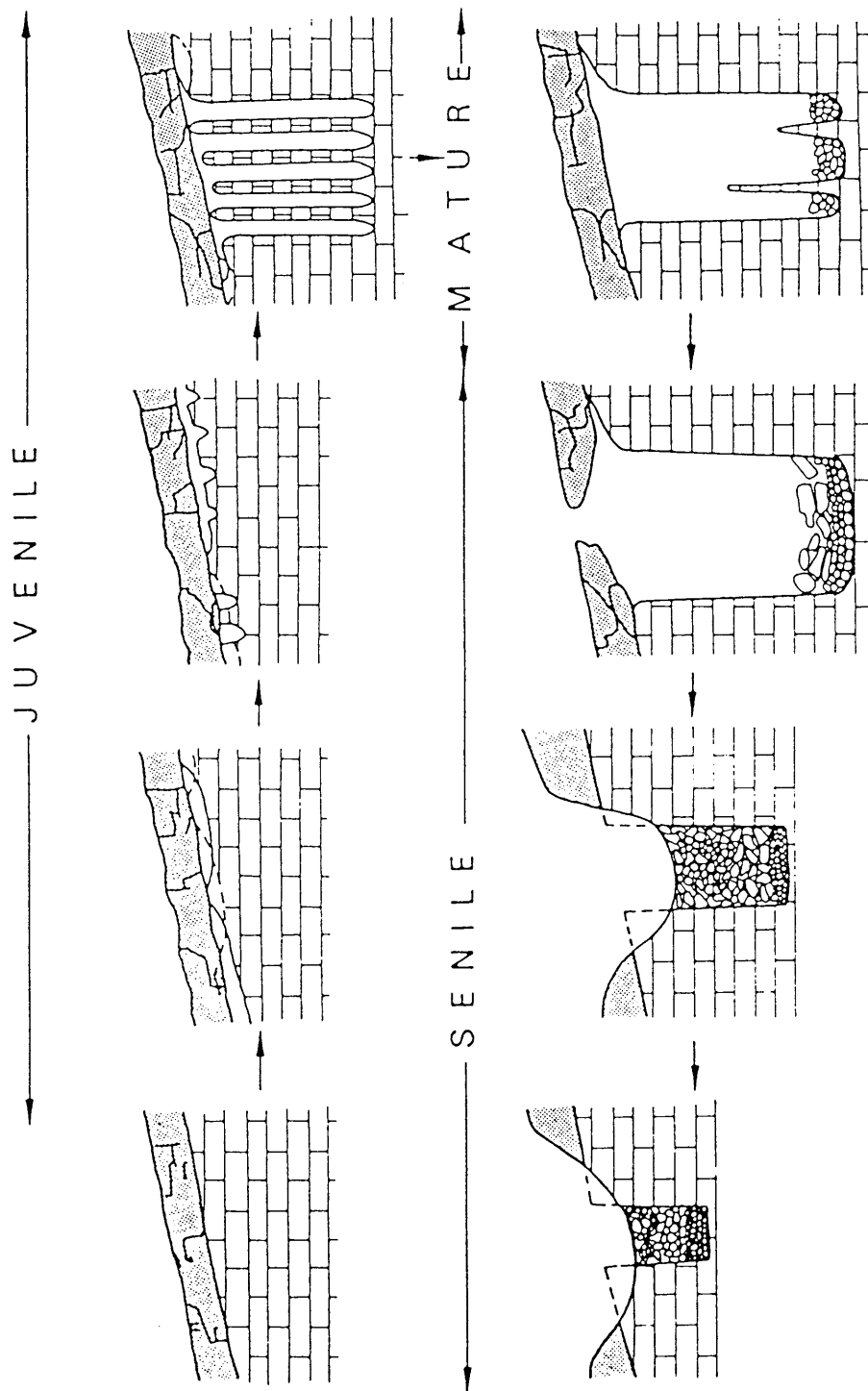


Fig. 2.2.3.1 Vertical cave development sequence

flooded and inaccessible but fossil ones are more accessible.

2.3 CAVE DEPOSITS

The study of cave deposits forms an intrinsic part of the study of caves in general. The importance of this study lies with the fact that the underground preserved deposits enable the reconstruction of past weathering phases through their examination, whereas many of the same features would have been weathered and eroded away, had they been on the surface..

Cave deposits can be divided into "autochthonous" which include deposits resulting from the solution of limestone and its subsequent redeposition but also collapse material and fine clays also resulting from the dissolution process, and to "allochthonous" which include all the "foreign" material brought into the caves by the phreatic or vadose water.

2.3.1 Non-calcareous deposits

The most important non-calcareous deposit is a form of clay as this is the only fine sized material able to pass through the relatively fine cracks of limestone and the quiet flow of underground caves enables it to settle. Due to their fine size clay particles are transported into suspension to great distances into the recesses of caves before they are deposited. The clay is resistant to CO_2 and if it is lining the bedrock it prevents further dissolution of

limestone. The most abundant clay mineral in caves is illite although kaolinite and sepiolite are also found. Clays are reddish or grey if they contain iron. In temperate regions depositions of varved clays are found due to the different size particles deposited during the summer and the winter seasons.

The other important non-calcareous cave deposits are sands and gravels laid down in terraces by vadose streams. They seem to have entered the caves through large and open passages. The pebbles are flatter and more rounded than the ones derived from non-cave environments. In high gradient caves the sands and gravels act as scouring agents enlarging the void space. All the non-calcareous deposits tend to become cemented by CaCO_3 a process that makes them harder and more indurated and consequently important in the stratigraphic record.

In descending caves, at high altitudes, ice formations are developing such as drips of water freeze, ice stalagmites and large glacial formations.

2.3.2 CALCAREOUS DEPOSITS

This section will deal with the significant aspects of calcite deposition as it affects the interpretation of the caves and their history as landforms. The principal mineral in calcareous deposits is calcite occurring widely in the more stable rhombohedral form of the same name and less often in the less stable orthorombic form of the mineral

aragonite. Gypsum deposits also occur. A delicate balance exists between solution and deposition in cave waters and even minor changes are able to shift the balance to the one or other side of the reaction.

Although it is still widely believed that evaporation of water is the main factor for the precipitation of CaCO_3 , cave atmospheres of 100% humidity strongly suggest that there should be another more viable factor. As shown by Holland and others a reduction in CO_2 pressure is the overriding factor for the CaCO_3 deposition. Only rarely the CO_2 pressure drops so abnormally low that evaporation of water or temperature changes become effective in the depositional process.

Calcareous deposits are related to cave environments and can be divided to those formed by: a) dripping water, b) running water, c) seepage water and d) under water each of which will be very briefly described below.

a) Dripping and running water flows

These are the best known and include the stalactites and stalagmites. Stalactites are caused by the dripping of water from cave roofs. As the solutinal water from joints enter the cave, it loses some of its CO_2 as it mixes with the cave atmosphere and CaCO_3 is deposited in the shape of a tiny ring at the place of contact of the water drop and the cave roof. Consequent drops enlarge the stalactite, some of

which reach considerable lengths. Sometimes the flow of water is rapid and there is no time for the deposit of calcite to form before the drop falls on to the ground and no stalactite is formed.

Instead a stalagmite will start growing. These are simple explanations about the occurrence of stalactites and stalagmites, processes controlled by the chemistry of water and gravity; but many things may interfere and interrupt their simple growth, and then their shapes and sizes change to reflect these interferences and their effects hence the spectacular shapes, colours and sizes of these two basic depositional calcite forms.

b) Flowstone and rimstone deposits

These are forms created by flowing or running water down the walls of caves or over the floor. Flowstone is an even, normally crystalline, hard, frequently layered or bedded deposit in which the crystals are perpendicular to the surface of deposition. Where flowstone forms unevenly in the shape of barriers, when water flows over irregularities on the rock floor and where eddies or riffles provoke evaporation of CO_2 it is called rimstone. Frequently each barrier encloses a pool or a dam and they are then known as rimstone pools.

c) Seepage deposits

Helictites - Delicate, worm-like depositions of

calcite and sometimes aragonite. They are formed by water seeping through minute openings but as the seepage is so slow a drop does not form and precipitation of calcite crystals is not affected by gravity. Their eccentric form is obtained by each crystal being deposited not exactly over the previous one.

Cave shields or palettes - These are semicircular sheets of calcite which average about one inch in thickness and may be several feet in diameter. They form by water seeping through a joint that is why every shield or palette is separated to two parallel plates by a fracture which is an extension of the joint in the rock wall.

Cave corals - Another form of deposition through seepage on the cave walls. These are knobby clusters of calcite, generally smooth with each individual knob 1-2 cm in diameter and 2-3 cm high.

d) Deposits formed in or under water

In dry caves calcite crystals are formed on the surface of standing pools, and are very thin and easily disturbed. Calcite crystals can also grow under water on the walls and floor.

The importance of the study of cave deposits cannot be overestimated and it is so far in its infancy. Cave deposits suggest that the processes of dissolution and deposition occur simultaneously. On a

scientific note cave deposits are already being used to identify the warm and cold, and wet and dry phases of the Pleistocene. The occurrence of cave breccias is believed to be associated with a wet and frosty climate in the Mediterranean. Stalagmites and flowstones are associated with wet conditions. But as this study is still at its dawn and correlations of cave deposits over wide areas are not yet possible the future benefits are believed to yet come and be of great value.

2.4 Karst Landform Evolution

Since the 19th century various workers have been proposing models to explain the evolution of Karst landforms

Some misunderstanding was introduced by the use of cyclic concept by W.M. Davis although his work has constituted an important reference work for many years after its publication. With his cyclic concept Davis has influenced the work of others like Cvijic, Penck and Grund. The cyclic concept explains the development of surface landforms as well as the development of cave systems. In reference to the evolution of cave systems Davis proposed that caves were produced either in two cycles i.e. initiated by dissolution in the phreatic zone and further developed and enlarged by dissolution and erosion in the vadose zone after they have been uplifted, or that they were wholly developed in the vadose zone by dissolution and erosion (one cycle

theory).

Swinerton (1932) considered that caves formed only in the vadose zone especially at about the water table. In a later work Gardner (1935) showed that some of his field studies agreed with the two cycle theory of Davis and some agreed with Swinerton's proposals. To accomodate his ideas though he put forward his own theory of "static water zone". This theory states that static water fills porous zones in limestone areas which of course cannot dissolve the limestones unless circulation of water is possible; this is done when the limestones are intersected by a valley thus providing the possibility of water movement and the following solution features. The water from the saturated limestone areas is drained away through springs or other outlets, allowing the limestone to become less saturated and thus subjected to recharge provided by rainfall and causing development of solution features by dissolution and erosion.

Bretz (1942) who exhaustively reviewed "Vadose and phreatic features of limestone caverns " basically agreed with Davis' two cycle theory. Glennie (1954) in his studies about the origin of caves in limestones based on his knowledge of the British cave systems agreed with both Davis and Swinerton. Coleman and Baldwin (1959) after carrying on studies into solution features in the Mendip hills presented a cyclic theory of evolution of the features in this area.

However, modern research into Karst landforms and

better understanding of their formation changed the whole concept of cyclic evolution and made it unacceptable. M.M. Sweeting (1972) categorically states that "Neither caves nor dolines nor poljes occur at any particular stage in the development of a Karst landscape but only when the conditions which favour their development exist. Karst can exist without dolines, they can also exist without caves ... Karsts are also particularly sensitive to climatic and vegetational changes. There is therefore no cycle of landforms."

Introduction

Soluble non-carbonate rocks are evaporitic sedimentary rocks formed by precipitation from inland saline seas or lakes in arid areas. Quantitatively they constitute a small part of the sedimentary rocks. Members of this group of rocks are gypsum, anhydrite and halite. Because of its high solubility halite does not occur on the surface whilst gypsum and anhydrite outcrop in thick beds. This chapter will discuss gypsum anhydrite and halite, their character and engineering problems associated with them.

3.1 Gypsum and anhydrite

These two rocks will be discussed together as genetically they are closely related. The chemical formulae for gypsum and anhydrite are $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ and CaSO_4 respectively. Work carried out by Hardie (1967) on the gypsum anhydrite equilibrium showed that although anhydrite could be formed by dehydration under a given set of temperature, pressure and activity of water in a geologically reasonable time, primary precipitation of anhydrite could not be achieved. It is therefore generally accepted that anhydrite is formed by evaporation of water from gypsum at increased rates of temperature and pressure present at great

depths of burial. This transformation of gypsum to anhydrite is accompanied by a reduction in volume and consequently material from above subsides to accomodate the change. The transformation of gypsum to anhydrite is reversible. When erosion plays its role in reducing the temperature and pressure induced by the overburden, and ground-water is able to percolate through to anhydrite, hydration takes place. This hydration though is not a peaceful event but is associated with ground uplift often explosive as an increase in volume in the region of 38 to 60 per cent accompanies this reconversion of anhydrite to gypsum.

Gypsum can also form as a secondary product from sulphate which results from the oxidation of sulphide minerals and carbonate supplied by limestones and marls. This kind of gypsum infills fractures in country rocks and is present as thin veins or veinlets.

Gypsum is far more soluble than limestone, 2100 p.p.m. of gypsum can be dissolved in non-saline waters as compared with 400 p.p.m. of calcium carbonate. The solution rate of gypsum and anhydrite is principally controlled by the surface area in contact with water and the flow velocity of the water associated with a unit area of the rock. Hence, the amount of fissuring in a stratum composed of gypsum or anhydrite and whether it is enclosed by permeable or impermeable rocks is extremely important. Beds and veins of gypsum tend to be more easily dissolved and leached away if

bordering with permeable horizons. It is noticed that the leaching process may result into a zone, sometimes many tens of metres deep, where the gypsum has been entirely removed from a succession of rocks previously containing many gypsum horizons. Other gypsum horizons continue to exist at greater depths unleached until below a critical point gypsum is replaced by anhydrite. Such vertical succession is known at a site at Heysham, Lancashire. Solution also depends on the degree of saturation of CaSO_4 in the ground water. According to James and Lupton (1978) the concentration dependence for gypsum is linear whilst that for anhydrite is a square law. The chemical composition of the water is also influential as the rates of solution of gypsum and anhydrite are proportional to the concentration of sodium chloride, carbonate and carbon dioxide in water.

Massive deposits of gypsum are less dangerous than similar ones of anhydrite because of the way that gypsum tends to dissolve. Gypsum dissolves in a steady manner forming caverns or causing progressive settlements. If small fissures occur at less than 1 m intervals solution usually takes place by removal of gypsum as a front, moving downwards at a rate of 0.01 m/year. However, this is not always the case as James and Lupton (1968) have shown. They suggest that if the rock temperature is 10°C , the water contains no dissolved salts and a hydraulic gradient of 0.2 is imposed, then a fissure which is 0.2 mm wide and 100 m

long will widen by solution in 100 years to form a cavern. If the initial width of the fissure is 0.6 mm then a runaway situation will occur in very short time. In long fissures, where the hydraulic gradient is low and the rate of flow is reduced, the water becomes so saturated that little or no material is removed by dissolution. A flow rate of 10^{-3} m/s is suggested as a critical value in that if it is exceeded, extensive solution of gypsum will occur. Grouting to reduce seepage velocities lower than the critical value protects foundations from an accelerating deterioration of gypsum.

Massive anhydrite can be dissolved to produce uncontrollable runaway situations where seepage flow rate increases rapidly. Even small fissures in massive anhydrite can prove dangerous. If dissolution takes place under increased flow rates not only caverns may form but the fissures may enlarge to long tapering sections. However, if the fissures are 0.1 mm wide then the water becomes supersaturated and precipitation of CaSO_4 follows sealing the outlet of the fissure.

Sinkholes and caverns can develop in thick beds of gypsum more rapidly than they do in limestone. Indeed in the United States such features are known to have been formed within a few years where beds of gypsum exist beneath dams. Extensive surface cracking and subsidence has occurred in certain areas of Oklahoma

and New Mexico due to the collapse of cavernous gypsum. The problem is amplified by the fact that gypsum is weaker and softer than limestone. In the United Kingdom where gypsum occurs in relatively thin beds and is interbedded with marls, collapses are common, over large plan areas where a bed of gypsum has been leached and are called "solution breccias" or "collapse breccias". The effect of these features decreases upward grading to undisturbed beds. "Gash breccias" are features most closely related to collapse dolines. These are narrow steep sided pipes with parallel sides or widening upwards, infilled with brecciated material which is not restricted only to the strata roofing the former solution but extending to ground level.

Soluble mineral particles formed in the ground may be removed by dissolution causing settlement. In such situations the width of the solution zone and the rate of progress are important. Another point which should be borne in mind is the reduction in strength of conglomerates induced by the removal of the soluble cementing material. A classic example illustrating this is the failure associated with the St. Francis Dam in California in 1928. One of the abutments of the dam was founded on conglomerates cemented by gypsiferous material. As the gypsum was removed by dissolution the rock started losing strength until failure took place. Hawkins (1979) noted the presence of voids in Kemper deposits in the Severn Estuary region. These voids

were formed as a result of gypsum being removed by dissolution. In the Dolomitic conglomerate not only the cement and some of the clasts are soluble but it is believed that some of the semi-spherical shape hollows resulted from the dissolution of mammilated gypsum nodules. The effect of dissolution of gypsum in dolomitic rock was noted during the construction of the airport road stormwater interceptor near Bristol. When voids were discovered an X-ray diffraction analysis was undertaken where traces of mineral fragments found within the voids were analysed. The results showed that the main mineral present was celestine, one that as a result of diagenetic processes replaces accumulations of gypsum - anhydrite.

3.2 Halite (Rock salt)

Considerable solubility of rock salt in the region of 1000 to 30000 p.p.m. in natural ground waters means that it does not outcrop on the surface. In areas where salt deposits exist ground water circulation produces considerable dissolution of salt creating solution surfaces at depths of several tens or even hundreds of metres. Regions beneath surfaces which are subjected to groundwater circulation are called wet rockhead. Where beds of rock salt are beyond the reach of ground water their original thickness is preserved and these regions are called dry rockhead. In areas where rock salt dissolves, the overlying strata produce collapse breccias similar to those occurring above

gypsiferous beds where dissolution has taken place.

Bell (1975) gives an account of the extraction of salt in Cheshire, England by brine pumping and describes some characteristic landforms produced as a result of dissolution of salt beds at depth. These are the Cheshire Meres some of which are floored by peat deposits probably of pre-Pleistocene age. This type of subsidence extends over large areas and it takes place extremely slowly, beyond the context of historic time. These collapses produce linear subsidence depressions at the surface. When brine is extracted beneath glacial deposits the latter collapse to form rather circular hollows at the ground surface.

It is generally believed that sizeable subsidence does not occur in areas underlain by saliferous beds probably because an equilibrium has been reached between the salt available for dissolution and the supply of unsaturated ground water. However serious subsidence occurs as a result of brine pumping or direct rock salt mining. In the Cheshire Basin brine pumping was uncontrollable until the last 40 years when controlled pumping was introduced. At present the only salt mine in the area is at Winsford, run by I.C.I. (Imperial Chemical Industries) and the method used is that of controlled solution mining. By this method the cavities created are in dry rock head and the shape is controlled so that sufficiently large pillars are left between them to support themselves and prevent

collapse. The cavity roof is supported by a cushion of air or oil and the borehole to the cavity is cased and grouted once the maximum size of the cavity is reached. With this method only negligible subsidence has been reported so far.

Soluble non carbonate rocks while possessing some similarities with the soluble carbonate rocks they display some basic differences in their landforms. They do not develop stable underground cave systems or underground drainage but produce collapse and gash breccias. On the surface, landforms above gash breccias and areas of salt dissolution resemble collapse dolines. This information is not adequate for the detection of solution features but provides basic guidelines on which to assess areas containing such rocks with regard to subsidence risk.

METHODS USED FOR THE DETECTION OF SOLUTION FEATURES

Introduction

Solution features represent a subsidence hazard to engineering structures if they are undetected, during site investigation and subsequently provided for. There is also a danger to the public and lives have been lost due to unexpected ground collapse. Therefore the detection of such dissolution features before construction of an engineering structure is of extreme importance.

Solution features may be on the surface or subsurface. They exhibit a variety of parameters, shape, lateral extend, depth and infill. Detection relies on contrast shown by the solution feature and its surroundings. Solution features may be filled with air, water, soil, rock, covered with vegetation or a combination of any of the above; therefore the exhibited anomaly is not always distinct and varies between different locations, situations and methods used. Hence, a method used successfully for the detection of a solution feature under a certain set of parameters does not necessarily mean that it will always be successful in any given situation. In the following section the principles and merits of the

methods used for the detection of solution features are more fully discussed. A summary is given in Table No. 4.1.

4.1 REMOTE SENSING

4.1.1 Aerial photographs

i) Air photographs are a useful supplement to maps as they provide a more detailed information than is given by maps. They are taken from an aeroplane along traverse lines and in such a way that each photograph overlaps the previous one by 60 per cent. Vertical air photographs are taken with the camera pointing vertically downwards and those taken with the camera at an oblique angle are called oblique. Generally panchromatic black-and-white film is used but colour or infra-red may also be used for special occasions.

For the solution factor to be detected they must have some surface expression. Collapse dolines for example may be seen as circular or elliptical depressions when viewed stereoscopically. A major problem arises where thick vegetation or forestation may mask the surface expression, characteristic of depressions, though sometimes a difference in the vegetation in a soluble rock area may give away positions of swallow holes or collapse dolines. In the "Road Research Laboratory" report Dumbleton and G. West deal with aerial photograph interpretation and some of the photographs used show the characteristic

Table No. 4.1

<u>Method</u>	<u>Advantages</u>	<u>Disadvantages</u>
1 Remote sensing) (i) Aerial photography (B/W)) (ii) Aerial photography) Infra red) i. Scanning systems (i) Thermal infra-red imagery) (ii) Satellite imagery)	Inexpensive and quick if photographs already available. Otherwise expensive. Solution features with or without expression can be detected. Easily obtained.	Difficulties if no surface expression of solution features or covered by vegetation but infra red successful if no relief present. Scale problems.
2 Geophysical methods (1) Electrical resistivity survey (2) Magnetic survey (3) Electromagnetic survey (4) Gravity survey (5) Seismic survey	Quick, portable Accurate, quick Portable, quick, inexpensive. Portable Surface or down the hole surveying possible Possible direct viewing of cavities by down-the-hole-camera	Difficulty in interpretation of anomalies sensitivity decreases with increasing thickness of overburden. Magnetic free area. Decrease of anomaly with increase in depth. Difficulty in interpretation results not totally reliable. Difficulty in interpretation and computation of results allowing for corrections is time consuming. Very expensive.
3 Grid Pattern drilling		Time consuming, expensive
4 SHRIMP method	Surface or down-the-hole surveying possible and quick	Expensive. Sophisticated anomaly interpretation, cannot rent or buy equipment

depressions associated with dolines and swallow holes. A point to bear in mind is that collapse features may be man made, i.e. small borrow pits, quarries, so it is highly advisable to check the interpreted features with a follow-up field survey.

ii) Infra-red aerial photographs

Infra-red photography is most useful in vegetated or forested areas when searching for collapse dolines. Water totally absorbs infra-red radiation and differences in reflectivity between plant species are most pronounced in the infra-red part of the spectrum, making colour infra-red photography particularly useful when studying drainage and vegetation. An assumed interpretation will then be, that healthy plants are concentrated at places better supplied with water. In soluble rock areas these places may be swallow holes, solution dolines, resurgence points or solution widened joints. At a comparison of the same dolomitic area by using black-and-white and infra-red photographs where water bearing zones were sought after, the infra-red aerial photography gave better results by clearly showing the solution widened fractures along which ground water flow was concentrated.

Scanning systems

(i) Thermal infra-red imagery

These systems can operate both in the day and at night and they are obtained in as much the same way as

aerial photographs but are built on the basis of emitted thermal radiation from the surface. This is done using a multispectral scanner which receives thermal emissions from the ground. After processing, an image is obtained either in black-and-white or colour coded but in both cases the range of tones corresponds to thermal contrasts at the ground surface and is in effect a kind of a thermal map. The advantage of using this kind of imagery in contrast to aerial photographs is that solution features with or without surface expression can be detected. If a doline in a soluble rock is present and is filled with clay, then the infill is likely to have different temperatures than the bedrock, giving two different thermal emissions. This method works better where the overburden above the soluble rock is not thick. If the overburden is thick it shows very dark and the subsurface information is blotted out. Such imagery can and is used complementary with aerial photographs and other forms of remotely sensed data providing information not obtainable otherwise by any other survey method.

ii) Satellite Imagery

The multispectral scanner (MSS) imagery is the most accessible currently. Since their inception in 1972 the Landsat satellites have acquired some 250,000 images of the earth's surface so that at present good, cloud-free imagery of over 90 per cent of land areas is

readily available. Data acquired by the satellite sensors in four spectral bands is recorded on magnetic tape and subsequently telemetered to a receiving station. All the imagery acquired by Landsat is available from the EROS Data Centre in U.S.A. either in the form of computer compatible magnetic tapes (CCTs) or photographic products at extremely low cost. The interpretation of the data may be carried out by visual inspection of the films or prints, by automated methods using the digital data directly or by a combination of the two, utilizing interactive computer facilities with visual display devices. Among other valuable information which these images may provide is information about moisture conditions and drainage characteristics, of great significance, as highlighted above, for the detection of collapse features. The only setback considered in the use of the information obtained in such a manner is concerned with scale; if collapse features are of small size they may not be clearly visible on the processed images.

4.2 GEOPHYSICAL METHODS

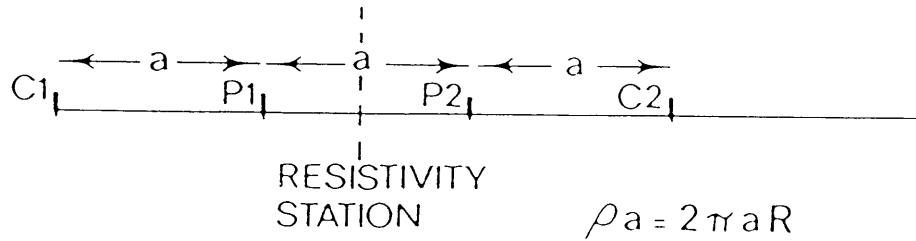
4.2.1 Electrical resistivity survey

Several electrical methods for investigation exist but the electrical resistivity traversing is the most commonly used. It provides a measure of lateral resistivity variations in the ground at a depth which depends on the electrode array configuration used.

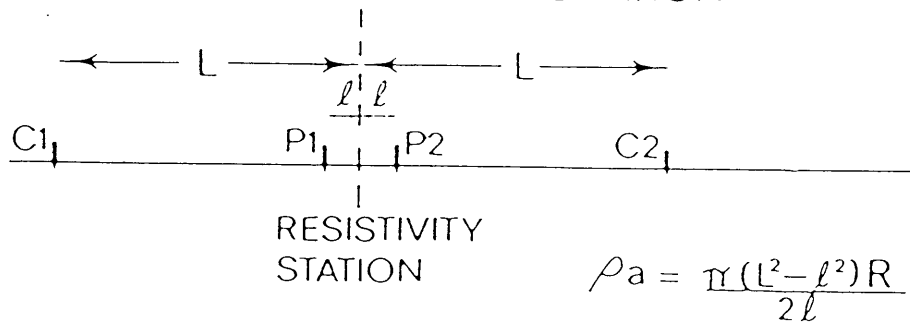
The field procedure involves four electrodes placed in line. Alternating current is passed into the ground through the two outer electrodes and the potential drop is measured between the inner two. Most resistivity meters provide a value for the ground resistance (R) directly and this is multiplied by the appropriate electrode distance () to give the apparent resistivity (). The whole configuration is moved along the line of resistivity traverse which ideally should be perpendicular to the expected strike of elongated features being detected. This is possible if the solution feature under consideration is a widened linear joint. In case of circular or subcircular in plan features the traverse spacing should equal the station interval and the distance between successive stations should be smaller than the radius of the feature being detected, in order to clearly show the anomalies. The results are presented either in traverse form or as iso-resistivity maps. Areas displaying low resistivity indicate clay infilled sinkholes.

McDowell (1975) used the three configurations shown on Fig. 4.2.1.1 to detect a clay infill sinkhole in chalk overlain by clay-with-flints and compared the results. The Wenner configuration uses a constant electrode separation which may successfully be used to detect clay filled fissures in Karstic bedrock. It has the disadvantage though of not being able to detect

WENNER CONFIGURATION



SCHLUMBERGER CONFIGURATION



CENTRAL ELECTRODE CONFIGURATION

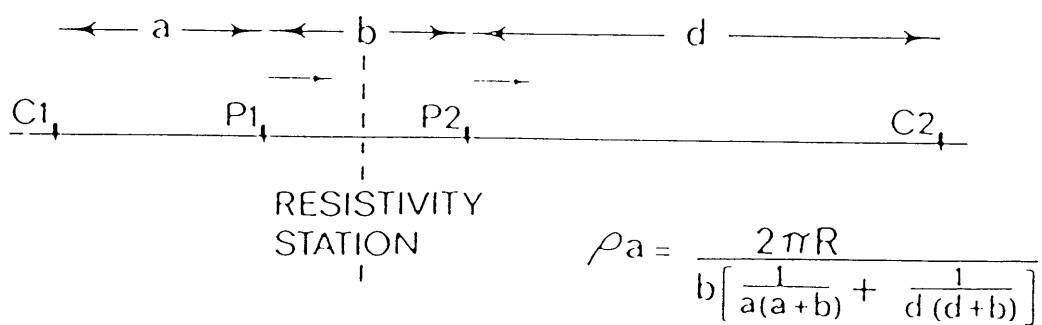


Fig. 4.2.1.1 Electrode configurations for electrical resistivity survey

narrow features with steeply inclined margins. Traversing with a larger ratio of current to potential electrode distance, as the Schlumberger configuration does, enhances the anomaly but it is a much slower field process. The Central Electrode configuration seems the most appropriate as only the potential electrodes are moved, hence the traversing is more rapid than with the two above mentioned configurations. The profile is usually smoother and the resistivity anomaly larger in amplitude.

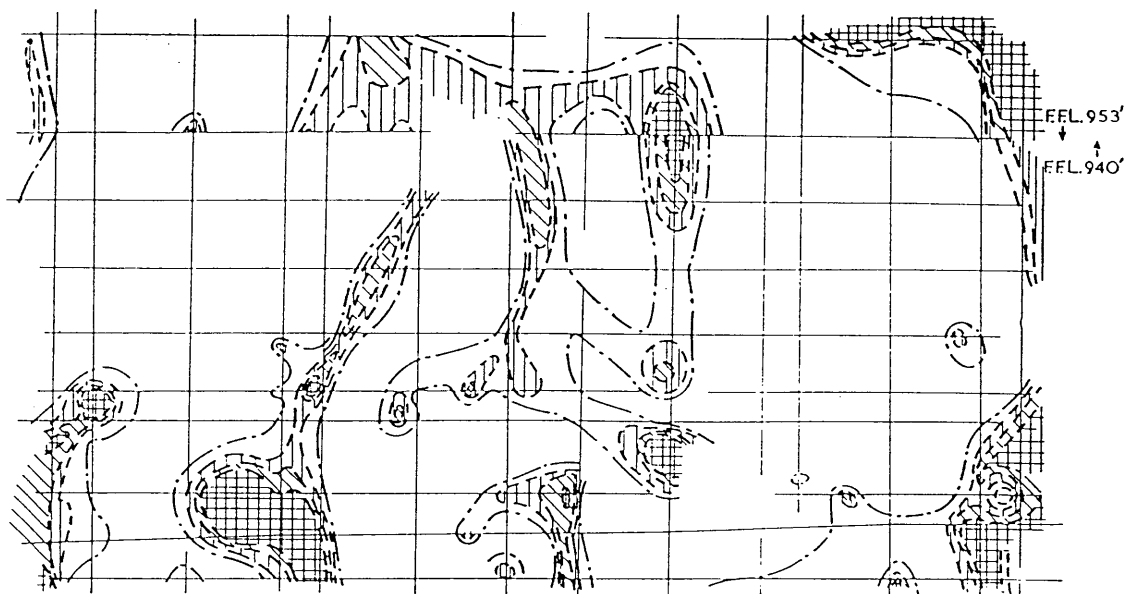
Early and Dyer (1964) used the Wenner configuration to locate clay infilled fissures in Karstic dolomite at a site near Hopton, Derbyshire. The site was initially investigated by bore holes which revealed the presence of solution features. A trial test was conducted to establish the good resistivity contrast between the dolomite and the clay infilled fissures. Once the success of the test was established the survey was extended to cover the area under question on a grid pattern. High resistivity values in the region of 4,000 ohm ft were taken to represent dolomite and low values of about 200 ohm ft were considered representative of clay. Many of the traverse readings coincided with borehole positions where actual depths of fissures were obtained. These results together with those of the apparent resistivity were utilized to produce a map shown on Fig. 4.2.1.2 where the position, trends and depth of fissures is

shown. After the site was excavated to finished floor level, the fissures were mapped and several pits were dug to verify the results of the resistivity survey. Fig. 4.2.1.3 shows the visible fissures. By comparing Fig. 15 and Fig. 16 it is seen that the resistivity survey was effective in this case and its use led to substantial savings in time and money over the alternative method of using a bigger number of boreholes.

4.2.2 Magnetic survey

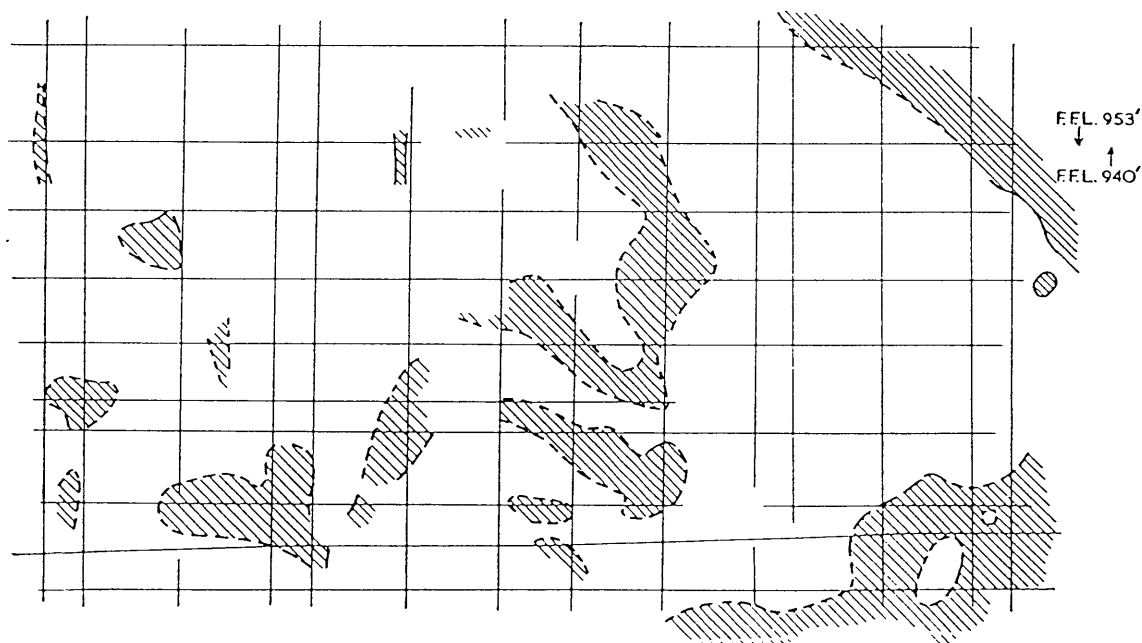
This method uses proton precession magnetometers to measure the total earth's magnetic field. The measurements are fast, as these magnetometers do not require accurate levelling and orientation and corrections only need to be applied for diurnal and secular variations in the earth's magnetic field. The results are expressed to an accuracy of one gamma or less. McDowell compared this method with resistivity surveying, described above and concluded that magnetic anomalies of small amplitude and width associated with clay infilled sinks, can be rapidly and accurately located. (Fig. 4.2.2.1) The magnetic survey is based on taking readings over a grid pattern. High magnetic values are expected from clay filled sinkholes, while chalk exhibits less magnetic susceptibility.

Unfortunatley there are some limitations to the use of magnetic methods. A magnetically clean site, free from metal and ferrous objects is essential for



Scale 1 in to 80 ft

Fig. 4.2.1.2 Postulated solution features from resistivity survey with plotted depth contours below finished floor level



Scale 1 in to 80 ft

Fig. 4.2.1.3 Mapped extent of fissures after excavation

success as the magnetic anomalies produced by the clay infill sinkholes are small. Also the magnetic anomaly decreases rapidly with increasing depth of cover.

4.2.3 Electromagnetic survey

An instrument called the Geonics EM31 is used in this survey method for the detection of solution features. It consists of a transmitting and receiving coil positioned at each end of a four metre boom, with a direct conductivity reading meter at the centre of the apparatus. The transmitting coil induces an alternating current in the earth generating a magnetic field and the solution cavity should in principle, generate a secondary magnetic field. The resultant of these two fields is detected by the receiving coil.

The instrument is light and portable and can be held at hip level by a shoulder strap. This makes the survey method quick, simple and inexpensive. One person walks over a set grid pattern from station to station taking readings. Errors due to changes in coil alignment are removed as the coil positions are fixed. The penetration capacity of the instrument is 6 metres depth which causes detection problems if solution features are present deeper than 6 m or if their dimensions are less than their depth.

The method was checked against a resistivity survey using a Wenner configuration. It was found that some corrections had to be applied to compensate for nonlinearities in the instrument and if the instrument

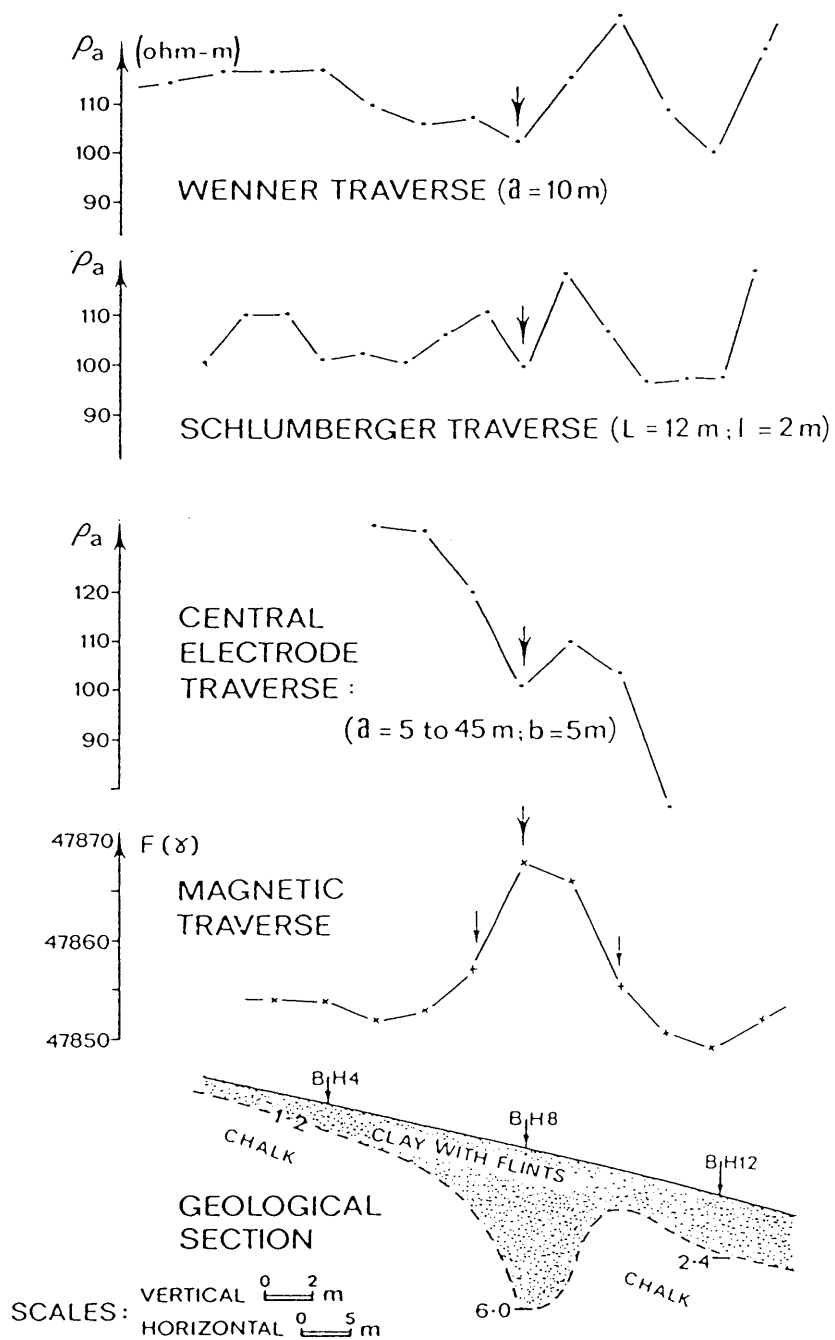


Fig. 4.2.2.1 Comparison of electrical resistivity and magnetic profiles across a clayfilled sinkhole at Upper Enham, Hampshire

was used while set up on the ground. The results obtained by the two methods were comparable and it was concluded that the Geonics EM31 may be very useful in a preliminary site investigation at shallow depths where one person can survey a given area much quicker than by a resistivity survey.

4.2.4 Gravity survey

The principle of this method is to detect underground solution features by means of the local disturbance of the earth's gravitational field which is caused by them on the surface. The anomalies are very small and so highly sensitive instruments, called gravimeters, are used. The variations in the gravity field depend on variations in density of the materials in the bedrock and the infill. The anomalies detected are called "Bouguer Anomalies" to which corrections have to be made considering the change in gravity due to latitude, height and attraction of topography. The order of accuracy of the gravimeter is 0.01 to 0.02 mgal depending on its type. The instruments are portable and readings are quick to obtain but it is necessary to return to the base stations periodically to monitor the instrument's drift. The survey stations themselves require accurate surveying and levelling as well as a topographic survey of the area. The corrected data are used to produce contour maps of equal Bouguer anomaly; the contours are called isogals.

Brink (1979) reports that the above method is

successfully being used in South Africa to detect solution features. The bedrock is dolomite with chert rubble and other unconsolidated debris infilling the cavities. The dolomite isogals obtained by the survey are interpreted relative to the water table; positive isogals indicate to solid dolomite above the water table and negative where the bedrock is below the water table. If a closed spaced grid of observation stations is used then a reasonably accurate delineation of the presence and form of underground solution features may be expected.

In the UK this method is not widely used for the detection of solution features. A brief mention by Bristow and Burton (1976) was made where this method was used to detect air and water filled cavities.

4.2.5 Seismic survey

Theoretically this method of surveying may work in detecting solution features. The difference of the seismic velocity between the bedrock and solution infill is measured but the detection of the cavity depends on the magnitude of this difference which is not significant in most cases.

Dresen (1973) reports using diffracted seismic wave amplitudes to locate circular cavities. The detection of these cavities is done with the help of two boreholes, positioned opposite each other on each side of the suspected cavity. One borehole accomodates the source of the seismic waves and the other the

receiver. While the source remains stationary the receiver is moved up and down inside the other borehole. The geometrical shadow boundary of the waves received, due to the presence of the cavity, is used to define its size and position.

In comparison with the other geographical methods mentioned, the seismic surveying requires a sophisticated field set up, making it uneconomical to use in most cases. Another disadvantage is that geometrically irregular cavities may not be detected.

4.3 GRID PATTERN DRILLING

Drilling on a grid pattern may be adopted where an important engineering structure is to be placed on ground suspected of containing solution features. This method may prove to be very expensive for two reasons. Firstly because of the big number of bore holes that has to be drilled and secondly because they have to be cored. As coring each bore hole is extremely expensive some of them are cored and the rest are drilled by percussion while resistance to penetration is measured. The interpretation of resistance to penetration is the following: if no resistance is recorded it is likely that a cavity is present, and if the resistance is low in comparison with what is expected according to stratigraphy an assumption can be made that the bore hole is penetrating a less consolidated infill material within a solution cavity. Probing with precise measurements was employed very effectively and at a low

cost during the site investigation for the Remouchamps Viaduct in Belgium. Probes were drilled to 6 m depth on a 2 m grid, and to 30-50 m on a 10 m grid. Voids filled with young unconsolidated sediments were successfully detected. A few zones of small cavities in softer materials may indicate the existence of arching soil conditions, a dangerous metastable subsurface situation.

Whenever cavities are thought to have been encountered they should be further investigated with a down-the-hole camera. The camera can be mounted in such a way to be forward looking, i.e. downwards along the axis of the borehole or sideward looking, i.e. perpendicular to the borehole axis. The camera can be orientated to take photographs in a specific direction or take a series of photographs covering the perimeter of the borehole in a full 360° circle. This is ideal for studying the size of solution features and presence of infill. However, it has some problems like resolution of camera lens for clear focussing, adequate lighting and the presence of muddy water.

Grid pattern drilling often has proven to be successful in locating solution features but in many instances also has been known to have provided limited information regarding the amount and shape of solution features. Also, according to the grid spacing and the area it covers this method of investigation may be an expensive and time consuming task.

4.4 SHRIMP METHOD

The Savage and Heierli Resonant Investigation Method - Patented (SHRIMP) technique is designed to be used together with drilling. The objective is to detect and map subsurface solution features. The principle of the method is to apply a vibrating compression wave of variable frequency to the ground. When the wave encounters a solution cavity at a predetermined resonant frequency, the cavity walls will vibrate and propagate a compression wave up to the surface. At the surface this response is picked up by sensors, called accelerometers; the signals are recorded, processed and interpreted to define the depth and plan area of the cavity. When required the accelerometer may be placed in the borehole to provide a depth profile of the deduced cavity.

The vibrating compression wave is provided by a 3000 pounds eletrohydraulic vibrator which is vibrated through a frequency range of DC 200 Hz and maintains a constant force output. The sensors' output is recorded by fibre-optic oscilloscope. A swept-frequency function generator allows a variety of waveforms, frequency ranges and sweep times to be recorded.

The technique is used with a 20 m grid pattern which may be expanded for larger areas. It can penetrate up to 60 m in depth depending on ground conditions and is much cheaper than grid pattern drilling.

The method was used in an attempt to detect

sinkholes and solution cavities in limestone but the results were inconclusive with an overall limited success.

4.5 COMPACTION METHODS

These are not methods for detecting solution features but methods for ground treatment. During ground treatment by compaction methods underground cavities may be detected and hence treated.

a) Dynamic compaction

A heavy weight is dropped on the ground at specific points determined by a grid pattern. This is done, normally to densify the ground to improve its bearing capacity. If near surface solution features exist then the dropping weight may cause them to collapse. Once collapsed they will be exposed to the surface and subsequently treated, preventing the danger of collapse after a structure has been built on the ground.

b) Vibrocompaction

A vibrating weight is used, again for the improvement of bearing capacity of the ground. The vibrations could trigger liquefaction of doline infill material causing it to collapse, hence detection of the solution feature and treatment before a structure is erected.

In recognition of the hazardous presence of solution features underground, continuous research and

development is going on to enhance methods for their investigation.

A research project carried out by Edmonds, Green and Higginbottom is suggesting hazard mapping as a cost-effective measure to be used in advance of planning and site investigation. The research was focussed on the English Chalk outcrop and led to the development of two models used to predict the subsidence hazard for both natural and man-made cavities. A range of geological, geomorphological and hydrogeological factors have been evaluated to identify significant relationships with subsidence. These factors are incorporated into two quantitative subsidence hazard models formulae which can be applied to perform hazard mapping. It is believed that the models have important implications for all types of limestone rocks.

Introduction:

Karst regions pose serious problems associated with various engineering structures, the most dominant of which is related to subsidence. Subsidence may be defined as the movement of the ground resulting from the underground removal of minerals or rock by natural processes or human activity. In this chapter subsidence caused by the natural process of dissolution of carbonate rocks and problems associated with it are going to be highlighted.

Surface Karst landforms pose a greater hazard than subsurface features. Underground caves are generally located at such depths that surficial loading will not affect them to a degree that will cause problems. In contrast, surface landforms such as dolines, swallow holes and solution widened joints represent a greater hazard, in relation to stability of engineering structures built in areas where they are present, more so because they are not always visible as they are mostly concealed by thick younger deposits. This metastability is expressed in two ways. Firstly, as loss of bearing capacity due to collapse and secondly as differential settlement. The latter occurs in structures partially founded on dolines where

consolidation of the infill may lead to extensive damage. The subsidence of the infill may occur either by collapse of small scale voids present within the infill, or by consolidation of the unconsolidated younger sediments of the infill. In thinly bedded strata large voids migrate upwards due to the collapse of successive roofing beds which degrade with time. In massive rocks the collapse is more likely to be caused by loss of frictional resistance on bounding joints, followed by the fall of a rock-block into the void.

The hazards in Karst regions will be discussed as encountered during the construction of dams and reservoirs, motorways, bridges and during the lowering of ground water as illustrated by case histories in the UK.

When construction of hydraulic structures, such as dams and reservoirs is considered the rocks in the area are of primary importance. Any soluble rock should be looked upon with suspicion as bedding planes, joints and other discontinuities will enlarge if subjected to substantial hydraulic gradients, resulting in seepage which may reach unacceptable levels. The high hydraulic gradients may be induced by the water table in the reservoir or dam and the local ground water table. The water may then flow under great pressures under the dam foundations through infilled discontinuities. During its flow the water will erode the fill material enlarging the discontinuities leading to excess seepage. This may make the structure

unstable and liable to sliding or toppling failure. The increased flow of water will induce a faster dissolution rate since, as discussed in 1.2.5, the boundary layer at the soluble rock interface becomes thinner and the saturated water is continuously replaced by fresh undersaturated water to continue the dissolution and remove the dissolved ions. In addition, as the discontinuities become wider and the critical width of 2.4 mm is exceeded, turbulent flow replaces the laminar one also increasing the dissolution rate.

Despite the above discussion dams and reservoirs have successfully been built in fissured and Karstic limestones in many parts of the world such as in Yugoslavia, France, Turkey and the United Kingdom. Knill (1972) argues that the leakage in reservoirs is controlled greatly by the in situ ground water pressures. If the piezometric level of the ground water in the area of the reservoir is higher than the top water level of the reservoir, then water will drain into the reservoir and will not be affected by the natural and developed permeability of the rocks present at the base and flanks of the reservoir. This was demonstrated by the example of Cow Green Reservoir, built at the border between Durham and Cumbria, a site which was initially rejected as having a high leakage potential because of the existence of Karstic limestone and old mine workings.

It is obvious that Karst regions should not be

automaticallly rejected as future dam or reservoir sites because of the possible catastrophic leakage consequences but should be critically examined in view of ground water pressures which may change a hazardous site to a quite safe one as practice has proved.

Collapse of pre-existing solutions features may be caused by surface water inflows but also by lowering of the groundwater table. The groundwater may be lowered either by pumping from a mine at depth or by pumping from water wells for water supply. Price (1971) gives an example where he discusses the link between collapse and ground water lowering. At a proposed housing site, the Panshanger Housing Estate, Welwyn Garden City Hertfordshire, water injection tests were used to detect pipe-like dolines in the chalk. The principle was to recharge locally the ground water by injection and then stop pumping as to allow the water to fall to its original level. In doing so settlement was induced in the unconsolidated doline infill. Alternatively the fines from the infill were washed downwards by the water movement inducing subsidence and hence consolidation. The experiment provided a twofold effect, delineating previously unknown dolines and improving the bearing capacity of the infill by consolidation.

The permeability of soluble rocks is an encouraging factor in sinking wells to be used as a source for water supply. However, it must be borne in

mind that soluble rocks possess two types of permeability, the mass permeability, an inherent qualitative characteristic of the rock itself and the secondary permeability developed by cavitation and solution widened discontinuities present in the rock. The sinking of a well into a soluble rock aquifer is not necessarily successful in providing satisfactory amounts of water but the rate of success can be higher if the well is sunk in fractured zones of the soluble rock aquifers, as a study by Lattman and Parizek (1964) showed. The groundwater flow is concentrated in the fractured zone aquifers, thus providing large amounts of water and making the extraction more economical.

Another potential hazard associated with the open nature of solution widened discontinuities in Karst landscapes, is the danger of contamination of water supplies. Inflows of water into open fissures and swallow holes rapidly become part of the underground drainage system without much chance of filtration. Atkinson and Smith (1974) carried out studies to determine if springs in the Havant area Hampshire could be contaminated. The idea was to locate the soakaways beside a major road close to swallow holes which were established to communicate with the springs via underground drainage channels. The study concluded that accidental pollution, for example spillage of a toxic chemical by a tanker on the road, would produce severe contamination of the water supplies at the

springs in Havant within 2-3 days as water flows through fissures in the chalk.

Route construction through regions of soluble carbonate rocks represents a major exercise associated with ground subsidence. Hazards are represented by covered surface solutions which may collapse due to disturbances of the natural ground conditions in the vicinity i.e. excavations, additional ground loading and vibrations. It was stated that cave systems located at depth do not represent an immediate problem of subsidence. Nevertheless, during the design of a route the necessity arises to locate possible shallow individual caverns. In this connection the post glacial history may be important and particular attention should be given to limestone outcrops. Evidence for the possible existence of shallow caverns should be sought above known large systems as signs of their earlier development. Indications such as old sinkholes, dry valleys, swallow holes, sinking streams and points of resurgence should be carefully investigated. Considering the sporadic nature of occurrence of solution features and the length of routes one can appreciate the sizeable problem of site investigation. As discussed in Chapter 4 detecting the solution features in advance is not always successful.

Where bridges are built in cavitated rock, foundation ground is made safe either by infilling the cavities and fissures or by distributing the load on

either side of the cavity on sound rock. Higginbottom (1965) records the open-jointed conditions in chalk during the construction of the Medway bridge on the M2 motorway. A system of fissures was found up to 2 in wide and 18 in apart during excavations for the pier foundations. They were treated by grouting the chalk. West and Dumbleton (1972) and Higginbottom give an account of the construction of A24 near Dorking where it had to cross the Mole Valley at Burford Bridge. The site investigation revealed swallow holes infilled with alluvium, obviously unstable for foundations. The position of underground drainage in the valley invalidated the excavation and backfilling of swallow holes. To protect the road and bridge embankment it was decided to apply the load to the surrounding the swallow holes sound chalk. This was done by covering each swallow hole by a concrete dome, the largest of which was 58 feet in diameter. Each dome was provided with a manhole for periodical inspections and monitoring to ensure no dangerous subsidence was taking place. West and Dumbleton also record problems faced during the construction of M40 also on chalk. Here the problem of near the foundations swallow holes was solved by grouting the ground and by building a reinforced concrete raft. The same authors stress the careful consideration which should be given to drainage measures along motorways and the positioning of soakways. They reckon that a pipe-like doline 1 m deep can be formed in 10 years if concentrated flows of

water from the motorway enter the chalk at the same point. This is explained by the undersaturation of rainwater in CaCO_3 coupled with the erosional power of concentrated flow.

This chapter dealt with problems which may arise in Karst regions. It is by no means a complete account of situations that may arise in constructing engineering structures in areas of soluble carbonate rocks but an attempt has been made to highlight major problems. The remedial measures can be summarised in one sentence. "Improve ground conditions." This can be done in a variety of ways such as infilling and compacting cavities, grouting, bridging cavities to locate foundations load on the adjacent sound part of the stratum. In dealing with situations arising from the problematic Karst landscapes one should, above all, use his or her geological judgement in combination with other parameters to successfully resolve problems.

POTENTIAL FOR KARST IN BAHRAIN

Introduction

6.1 THE PHYSICAL SETTING

The state of Bahrain is located at approximately latitude 26°N and longitude $50^{\circ} 30' \text{ E}$. (Fig. 6.1.1). It consists of a group of low lying islands the principal of which are Bahrain, Al-Muharraaq, Sitrah, Umm Na'asan and Hawar the rest being only shoals and patches of coral reef. (Fig. 6.1.2). The island of Bahrain is the largest measuring 48.3 km by 16.1 km with a maximum altitude of 134.1 m at Jabel Ad-Dukhan (Plate I). The islands occur in the Gulf of Salwa which is a shallow arm of the Arabian Gulf between the Qatar peninsula and Saudi Arabia. The whole group of islands lie towards the Southern margin of the Arabian Gulf. The Arabian Gulf is linked to the Indian Ocean in the east by the strait of Hormuz. The sea in the vicinity of Bahrain rarely exceeds 18 m in depth as the Gulf of Salwa is underlain by part of the Shelf area of Saudi Arabia. Bahrain is located in the core of an extensive arid zone extending from the Sahara north-eastwards across Arabia and Afghanistan to the Gobi Desert. Physiographically Bahrain can be divided into five regions which occur as concentric units of variable

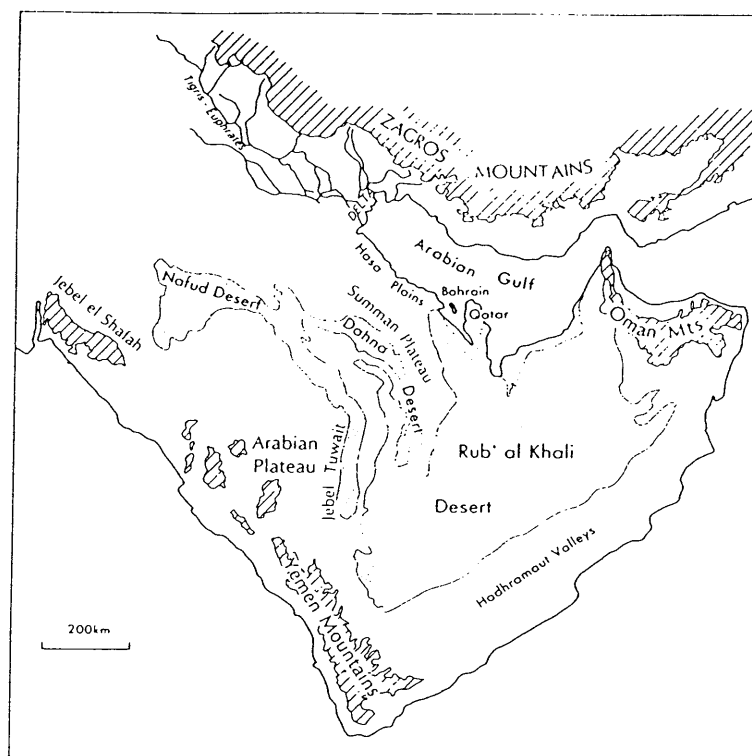


Fig. 6.1.1. The location of Bahrain in the Arabian Gulf

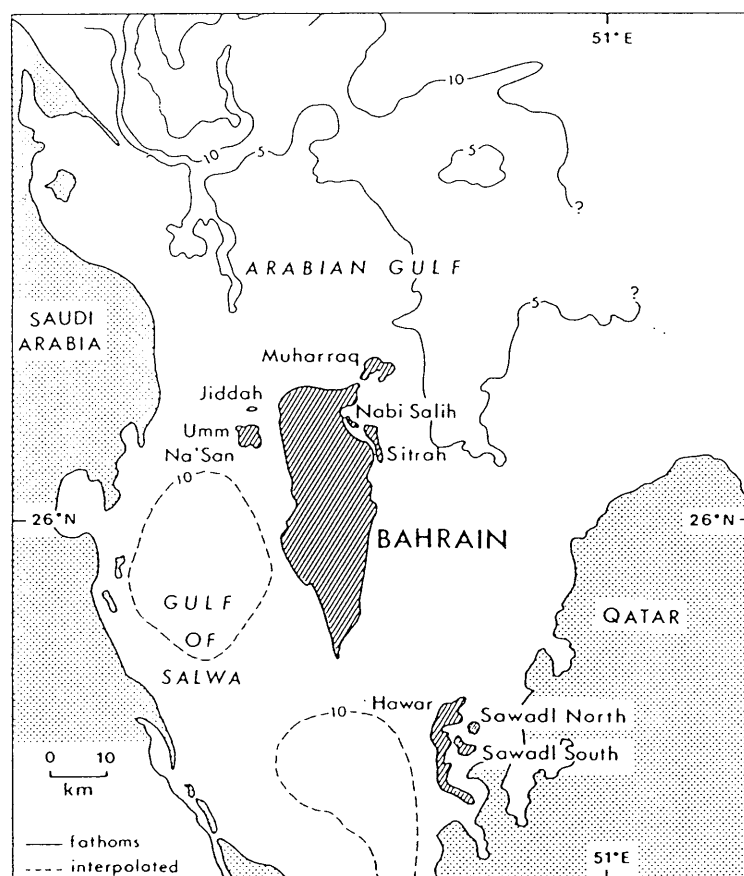


Fig. 6.1.2 The location of Bahrain Islands.

width (Fig. 6.3).

In this chapter the lithologies of the rocks at outcrop and the Pleistocene and recent climatic changes will be examined. Then an examination of the presence of Karst features and their potential will be attempted.

1.1 SEDIMENTS IN THE GULF

The Arabian Gulf has since long been a major region of carbonate sedimentation. These carbonates are not evenly distributed but can be considered in three not strongly defined belts. On the Iranian side the annual rains of 200-250 mm transport enough clay to produce marls. Roughly parallel to the axis of the Gulf a shallow shelf begins called the Arabian Homocline; on this shelf carbonate sands or muddy sands are only 5-20 cm thick and between ripples and sand patches there are often exposures of Neogene limestones and dolomites. Many of the sediments are surfaced by hard-grounds. The third region the Arabian coastal belt which includes Bahrain is an irregular belt adjoining the Arabian coast to the shelf and is about 50-150 km wide.

6.2 SEDIMENTS OF THE ARABIAN COASTAL BELT:

The coastal belt sediments consist of carbonate muds and sands built of foraminifera, algae, corals, gastropods, pellets and ooids in various proportions. Many of these are loose sediments which show normal

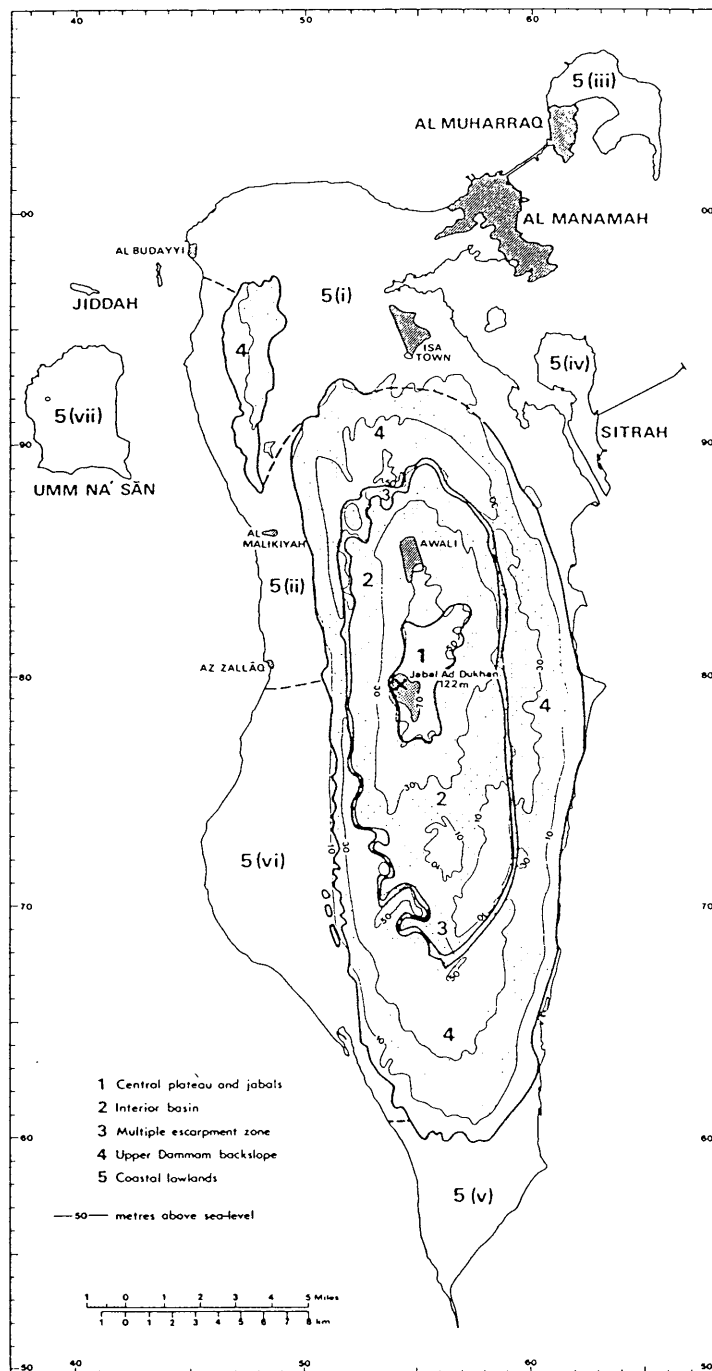


Fig. 6.1.3 Relief and physiographical subdivisions of Bahrain

structures of current deposition and others are immensely burrowed by crabs. Some are bound by the black mangrove or by seagrass. The high temperature and high salinities, normally 40‰ and reaching 70‰ in the inner part of the Gulf of Salwa and 100‰ in some isolated lagoons, means as the coast is approached the components making up the sediments become less biogenic and more inorganic. At times the surface waters become so saturated with calcium carbonate that clouds of aragonite needles precipitate as whittings. (Wells and Illing, 1964). In some regions as the intertidal areas are crossed with sabkhas the developments of a variety of evaporitic minerals particularly gypsum and anhydrite but also dolomite, magnesite, celestite and halite are distinct. (Curtis, Evans, Kinsman and Shearman, 1963; Evans and Shearman, 1964). Since the early 1960s there has been much further work on these evaporites (Kinsman, 1966, 1969, 1976; De Groot, 1969; Bush, 1970; Butler, 1969, 1970, 1971; and in Purser, 1973 (De Groot; Bush, Hsii and Schneider; Butler). The area constitutes a classic region for the discovery of evaporite crystallisation in sabkhas and for the early description of contemporaneous dolomitization. The conditions associated with these facies are the high temperatures, the low rainfall, the prevailing winds during the winter, the shallow sea and the minimal oceanic influences.

The significance of the present day sedimentary

setting is enormous. There are impressive similarities between the sediments forming today and those of the Eocene period in Bahrain. If this interpretation is correct it implies that the special conditions prevailing today have existed for the last 50 million years. Sea levels have risen and fallen so that at times Bahrain was under the sea and while the individual environments migrated laterally, the existence of the Arabian Gulf in a predominantly arid climate seems to date back to Cenozoic when the rise of Oman mountains nearly cut off the Gulf from the Indian Ocean.

6.3 LITHOSTRATIGRAPHY

The centre of Bahrain islands is composed of Eocene sediments except for a small cap to the Jabal ad Dukhan (Miocene?). They form an oval outcrop around which there is a border of largely unconsolidated to weakly cemented Pleistocene and recent sediments. The latter two series also cover Umm Na'san Island and Al-Muharraaq.

The divisions of the Eocene sediments in Bahrain were proposed by Willis R.P., and used widely. In the book "Geology Geomorphology and Pedology of Bahrain" which resulted from the work of the Bahrain Surface Material Resources Survey a more detailed classification is proposed and is the one that will be followed. In Table (6.3.1) a comparison of the Eocene divisions proposed by Willis and those suggested by the

aforementioned group permits a correlation between the two classifications while Table (6.3.2) outlines the corresponding lithostratigraphy of the area with that of Bahrain.

6.3.1 EOCENE

6.3.1.1 Rus Group

Consists of the Awali Carbonate Formation and the Hafirah Carbonate formation

a) Awali Carbonate formation: This is the oldest outcropping formation (Fig. 6.3.1.1). It occupies the

Table 6.3.2

Willis (1967)	Later Survey
White Limestone	Jabal Hisai Carbonate formation
Orange Marl	West Rifa Flint formation
Brown Crystalline limestone	Al Bukkayr Carbonate formation
Shark's Tooth shale	Foraminiferal Carbonate formation
	Dil'Rafah Carbonate formation
Rus	Hafirah Carbonate formation
	Awali Carbonate formation

	DAMMAM Powers <i>et al.</i> 1966; Tleel 1973	BAHRAIN (this work)	QATAR Cavelier 1975
MIOCENE	Dam Formation	Jabal Cap Formation	(Lower Fars Formation)
		Jabal Hisai Carbonate West Rifa Flint	
	Alat Member	Al Buhayr Carbonate	Abarug Member
	Khobar Member	Foraminiferal Carbonate	{ Umm Bab Member
	Alveolina Limestone		{ Dukhan <i>Alveolina</i> Limestone Member
	Saila Shale		Midra (and Saila) Shales Member
	Midra Shale	Dil 'Rafah Carbonate	Rujm Al'd <i>Velates</i> Limestone Member
Dammam Group			
	Limestone (member)	Hafirah Carbonate	
	Marl and Limestone (member)	Awali Carbonate	
	Limestone (member)		Rus Formation
Rus Group			
	Umm er Radhuma Formation	(not present at surface)	Umm er Radhuma Formation
EOCENE			

Table 6.3.2 Lithostratigraphic correlation of the Eocene and Miocene of Bahrain with neighbouring areas

central part of the interior basin and reaches 17 m in thickness. The top of the formation is marked by a half-metre hard-ground riddled with vertical borings called the Lithophaga band. Below this band 4 to 8 m of homogeneous dolomite is present. Much of the Awali carbonate is very thick to thick bedded with occasional medium thickness beds. The colour is variable. The porosity is not consistent and many of the pore spaces may be due to superficial alteration. Weathering has been moderate and there is some iron-staining. The rocks in this formation are almost exclusively dolosiltites consisting of dolomite crystals with small and variable amounts of quartz and clay minerals. Relatively harder bands occur at intervals of a quarter to several metres showing indurated infillings of crustacean burrows. At several horizons there are bands of globular concretions of chalcedonic quartz (geodes) ranging up to 0.25 m across. At another horizon dense black flinty cherts are found. Sometimes these siliceous concretions are seen partially to replace circular brecciated zones within the dolocarbonate stone. Although they occur at several levels within the Awali formation neither the geodes or the black flint is sufficiently persistent to be used as a mapping horizon. The presence of geodes indicates to the original evaporitic nature of the beds, since the siliceous concretions replace anhydrite.

b) Hafirah Carbonate formation

This formation forms a belt around the margins of

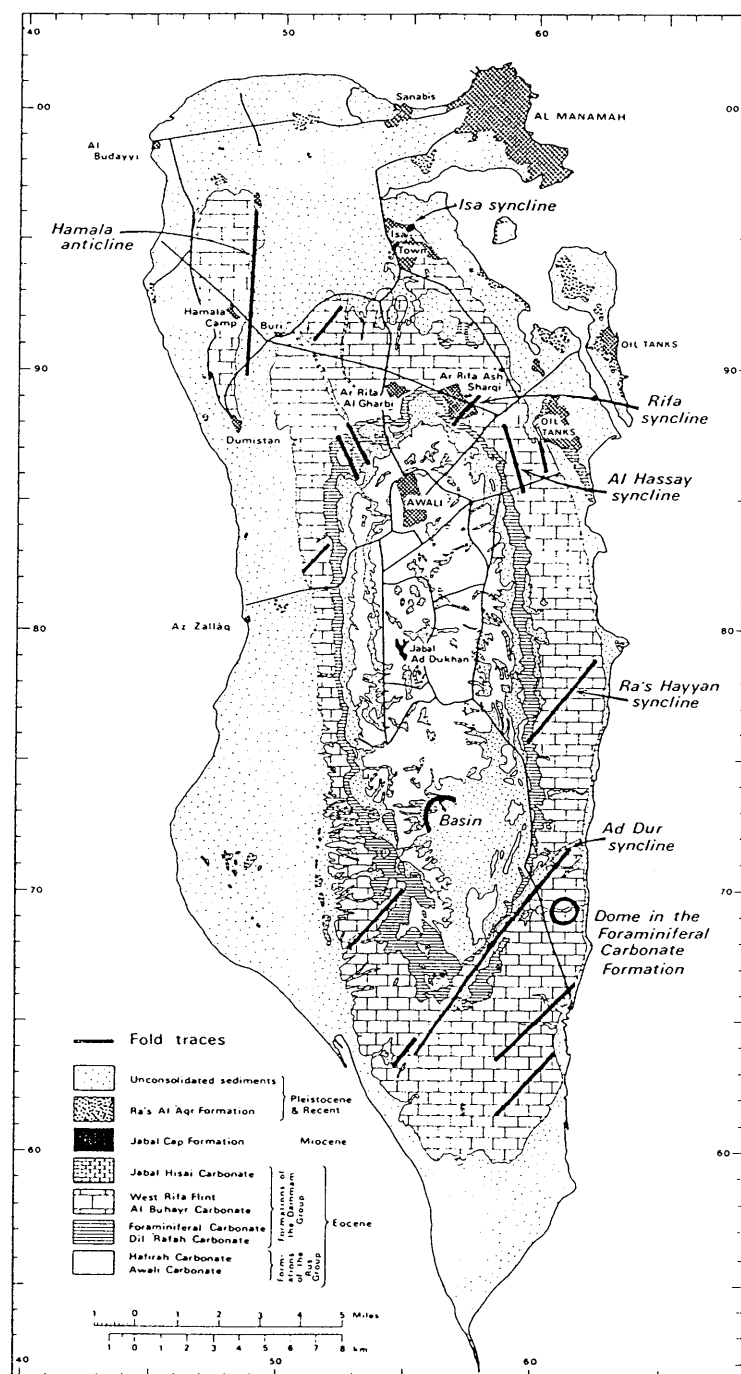


Fig. 6.3.1.1 Generalised geological outcrops

the interior basin about one kilometre wide (Fig. 6.3.1.1). The rocks are medium to thick bedded with very thick beds towards the top of the sequence. White colour predominates but pale orange and pale greenish yellow are also present. Dominantly dolosiltites, very often cavernous they consist of dolomite crystals; whilst the upper part of the formation is pure dolomite, near the base there is an admixture of clay and quartz. The lower part of the formation is a continuation of the Awali Carbonates with irregular weathered surfaces. Globular concretions with chalcedonic quartz, nodules and hollow geodes are also common in this formation as in the lower one; there are also secondary and represent replaced anhydrite. These concretions may litter the surface after weathering while they leave hollows in the limestone. The upper part of the formation is similar to the lower part of the Awali Carbonate formation with massive white dolosiltites interrupted by horizons with concentrations of crustacean burrows; these burrows are filled with coarser-grained dolomite, more resistant to weathering than the finer-grained matrix.

6.3.1.2 Dammam group

The Dammam group consists of five formations.

a) Dil'Rafah Carbonate formation

This unit forms much of the complex escarpment enclosing the interior basin as well as the cliffs that bound the minor depressions north west of Awali. (Fig.

6.3.1.1). The exposed thickness varies from 14 m to 29 m. The formation consists of an alternating series of dolosiltites and shales and clays, at intervals of up to 3 metres with the carbonate units being dominant. The carbonate beds are thin to medium bedded, occasionally thick to very thick while the clay beds by contrast are thin to very thin. Both units are moderately weathered. The carbonate units are fine-grained with occasional beds and patches of medium-grained material. They are composed of equigranular aggregates of dolomite crystals. The beds generally coarsen upwards from dolomitized chalky limestones to slightly quartzose limestone. Bands of chert, chalcedony and quartz occur in the lower part of the formation. The shale and limestone of the Dil'Rafah formation form a rhythmic sequence of sedimentary units repeated through the whole formation (Plate II). Each shale unit is followed by a featureless massive dolosiltite which in turn is capped by finely bedded or laminated dolostones.

b) Foraminiferal Carbonate formation

It usually forms the upper part of the escarpment-zone enclosing the interior basin (Fig. 6.3.1.1). Its maximum exposed thickness is 8.5 m but is as little as 5 metres at some outcrops. It outcrops at various places on Bahrain island and has also been recognised on the Hawar islands. The unit is thickly to very thickly bedded, the lower few metres consisting of 0.5 to 1.0 m bands of massive dolostone separated by

impersistent beds of softer friable dolostone. The colour is variable from white at the top of the formation to very pale orange. (Plate III). The rocks are dolosiltites and dolosands. The dolomite is granular and fine-grained. The dolomite crystals display a bigger variation in size than in older rocks reflecting the variable nature of the primary material that has been dolomitised. The rocks are slightly weathered.

Dolomitised foraminifera are common throughout the formation. The basal dolostone bed contains tests of *Alveolina* and is distinguished as the *Alveolina* limestone member and provides an excellent mapping horizon. The importance of this horizon is that together with the oyster-bed below the Foraminiferal Carbonate formation they mark the commencement of a new sedimentological regime in the Eocene of Bahrain. At this level the thin-bedded, variable limestones are replaced by the more massive uniform limestone beds.

c) Al-Buhayr Carbonate formation

The rocks of this formation form cliffs in the depression south of Isa Town and reach thickness of about 15 metres (Fig. 6.3.1.1). The base of this formation is characterised by a prominent laminated, misty yellow orange argillaceous dolosiltite, sometimes containing clay pockets. Its thickness is variable reaching up to 2 m and tends to weather more rapidly than the more massive limestone above and below. It also outcrops on top of the main escarpment around the

Interior Basin, around the northern fringe of the dipslope between Buri and A'ali and on the coast between Sanad and Jardab. At the latter locality gypsiferous laminations and ripple markings suggest very shallow highly saline water conditions. The main limestone unit of Bahrain overlies this yellow marker band. Although the Al-Buhayr carbonate is a limestone some metres below the surface it is dolomitized. At some locations it has also been partially silicified to a hard saccharoidal dolostone with a concretionary and carious structure. Altered limestones of this type is locally known as "blue askar". At the same locations removal of superficial material (Plate IV) has exposed patches of green clay filling Karstic solution depressions in the limestone. The sediments above the yellow marker band are generally white to very pale orange dolosiltite. They are fine-grained and granular with occasional layers of medium-grained material. The limestones are characteristically thickly bedded. The whole sequence was extensively burrowed by crustaceans but the sediment has not been totally homogenised. The upper few metres of the formation are more thinly bedded. Chert occurs irregularly at a number of different stratigraphic levels.

d) West Rifa Flint formation

This formation outcrops on the dipslope of the main dome structure (Plate V). In areas where the superficial material has not been removed, the outcrop is conspicuous and can be distinguished from that of

the similar underlying formation by the abundance of brown weathered flints lying at the surface. The W.R.F.F. does not always rest comfortably on the underlying formation. The thin to medium-bedded dolostones of this formation contain layers of brown or black tabular flints arranged parallel to the bedding at intervals of 0.2 to 0.3 m. The carbonate compound is white to very pale orange. It is a fine granular compact dolosiltite with few obvious pore spaces and very few scattered microfossils. Where the superficial materials have been stripped away, the limestones of W.R.F.F. are seen to have been transformed to "blue askar" and patches of greenish clay occupy solution features in the surface as in the underlying formation.

e) Jabal Hisai Carbonte formation

This formation forms a prominent escarpment extending southwards from the Refinery to Ra's Juqayyid on the coast and some other locations (Fig. 6.3.1.1). The formation consists of white or grey slightly quartzose dolosiltites containing darker crustacean burrows which are more prominent upwards where they become infilled with dolosand from the overlying member.

6.3.2 Miocene

Jabal Cap formation

This is a massive caprock (Plate I) which forms the top of the Jabal ad Dukhan and has protected the underlying sediments from erosion. It consists of

massive dolomititic limestone (Fig. 6.3.1.1) For the major part it has a fine laminated structure, sometimes flat-lying but more often rising into rounded cauliflower structures formed by fossil canals and algae. Frequent molluscan borings are noticeable and some of the sediments are coated with later travertine. All the facies of the Jabal Cap Formation are indicative of deposition under very shallow water regimes. The assemblage of lithologies in this formation is unlike any other one of the rim escarpment. The deposit is clearly much younger than the underlying Eocene on which it lies unconformably.

6.3.3 Ra's al 'Aqr Formation

Details of this succession vary from one location to another but three facies are widely spread; they are briefly described in an upward order.

a) Caprock limestone: it consists of very pale orange, medium to fine-grained, thinly-bedded, moderately weathered, slightly leached, quartzose shelly oolitic limestone.

b) Mudflood deposits: this is a very pale orange to a distinctive pale olive green, soft, massive dolosiltite, often conglomeratic.

c) Calcisiltites: these are thinly-bedded, very pale orange, fine to very fine-grained dolomitised calcisiltites with locally interbedded coarser dolosands.

From the above detailed description of the rock sequence in Bahrain it is clear that pre-Pleioscene rocks can be divided into two broad groups. Firstly, the rocks of the Rus formation consisting of homogeneous, massive, thick-bedded dolomites which contain a horizon of concretionary chalcedonic quartz and some flints. The massive dolomites of the Miocene Cap formation may also be included in this group. Secondly, the thinly to medium-bedded dolomitised limestones, interbedded with thin clays, argillaceous, easily weathered limestones or friable dolostones. The main mass of rocks of this group consists of the rocks of the Damman group.

6.4 GROUND WATER

Three main aquifers exist in Bahrain, although on a regional scale they all form part of a single hydraulic unit known as the Eocene Aquifer system. The deepest one, known as the "C" aquifer, contains highly saline water typically 12,000 p.p.m. NaCl. Above, aquifers "B" and "A" are less saline with 700 p.p.m. general salinity.

These aquifers carry water originating in Saudi Arabia and contribute important quantities of sulphate and other ions to the surface waters of Bahrain as they are found near the surface. They also emerge as springs at several locations in the North of the island and offshore. In Bahrain these springs have been famous for several millenia for they have made the

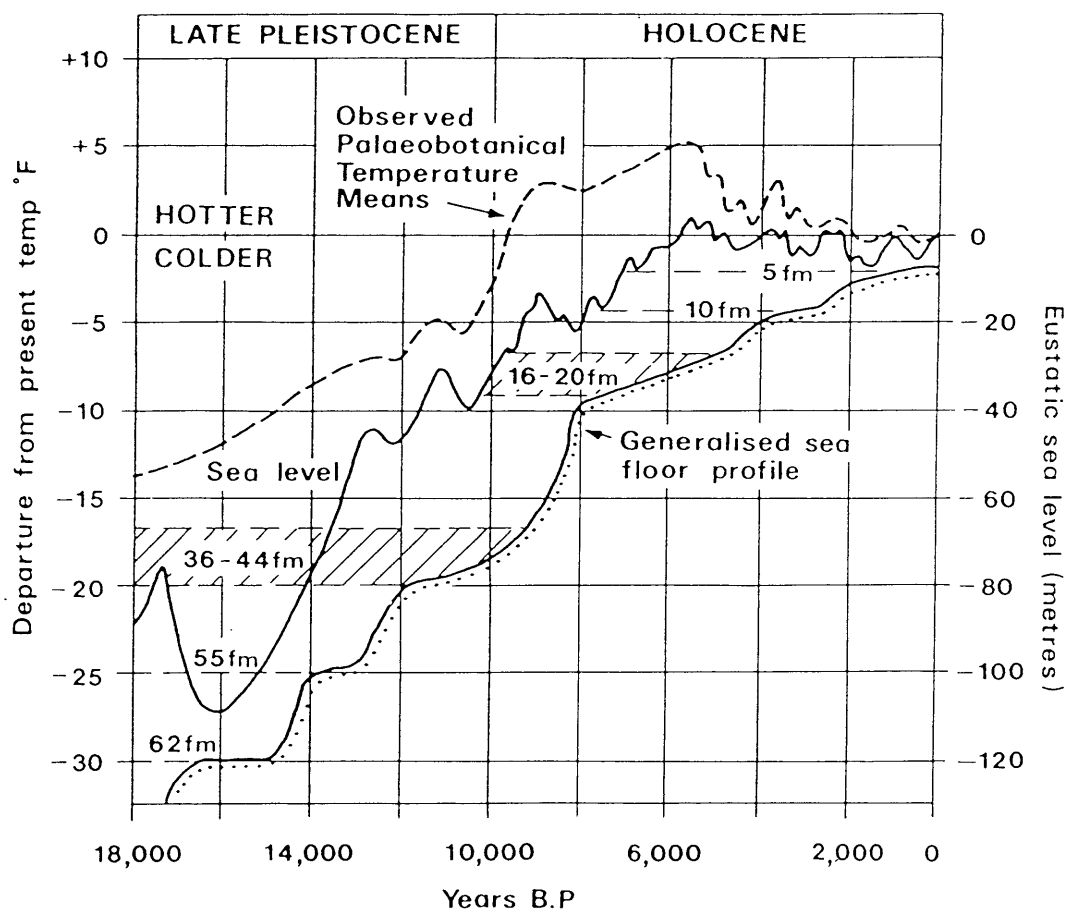


Fig. 6.5.2 Temperatures, sea levels and terrace heights in the Arabian Gulf area during the last 18,000 years

island the sea-based kingdom of Dilmun. Therefore a deducible assumption can be made about the presence of water aquifers similar to today's on the island since several thousand years. Modern exploitation has reduced the level of the groundwater profoundly.

6.5 LATE PLEISTOCENE AND HOLOCENE CLIMATE WITH EMPHASIS ON SEA LEVEL CHANGES

The effects of both climate and sea-level changes have had a profound influence on the geomorphological development of the area. Of particular importance is the fact that between 100,000 and 5000 B.P. sea-levels were much lower than at present and extensive areas of the Arabian Gulf floor were exposed as dry land or converted into shoal areas of evaporite deposition. During most of this period Bahrain island was connected to Arabia and Qatar by the emergent land area of the Hasa Terrace. At these times aeolian quartz sand movement was widely spread and great sheets of sand spread from Hasa plains of Arabia across the present Gulf of Salwa onto and over parts of Bahrain, Qatar and the Great Pearl Bank.

The impact of these events on Bahrain was very great and is expressed in the introduction of quartz sand into the area and resulted in profound topographic changes due to sand blasting, dune development and more recently coastal deposition. The details of base level changes in the Gulf are not perfectly well known especially with regard to the evolution of Bahrain

topography. The evidence available may be summarised as follows: (Fig. 6.5.1)

(i) There is scattered evidence in Oman, Qatar and Bahrain of a high sea level in the early Pleistocene. Erosion surfaces of possible marine origin suggest a sea level of +150 m in the Oman mountains, Saudi Arabia coast and Qatar.

(ii) Sea-level then appears to have fallen in stages resulting in the formation of terraces and inland sabkhas on the Arabian shore. The present sea level is thought to have been attained approximately 100,000 years ago.

(iii) At some stage during this period of rather higher sea level, more pluvial climatic conditions probably led to increased stream erosion and wadi development, a sheet of coarse alluvial gravel being laid down in a north-eastward oriented belt across what is now the Gulf of Salwa, just to the South of Bahrain. This deposit is thought to have been graded to a sea-level at +90 m.

(iv) Following the deposition of these gravels, the present Gulf of Salwa suffered fault guided tectonic subsidence, except for the Bahrain Ridge, a NW-SE oriented Iranian structure crossing the northern part of Bahrain Island, which appears to have continued to rise until recently.

(v) Sea level then fell during the later Pleistocene to -110 and -120 m. Thus between 70,000 and 17,000 B.P. continental conditions existed over much of the

Arabian Gulf and the Tigris-Euphrates river system extended as far to the east as the present straits of Hormuz. The courses of these drainage lines now form drowned valleys in the floor of the Gulf. It was during this period of low sea level that the main movements of Saudi Arabian sand affecting Bahrain took place.

(vi) The exact timing and events of the late Pleistocene and post-glacial (Holocene) rise in sea level are incompletely known; there is some agreement that sea level began to rise between 20,000 and 17,000 B.P. reaching its present level at approximately 5000 B.P. The advance seems to have been intermittent with oscillations and standstills which resulted in the production of marine erosion platforms and deposits at depths from -9 m of the Arabian coast (Hasa Terrace) to -120 m of the Gulf of Oman, Hormuz Strait.

The transgressive sea reached -18 m level near Bahrain about 8000 B.P. and entered the Gulf of Salwa to isolate the island of Bahrain at about -7.2 m level some 6,000 years ago. The importance of this event lies in the prevention of further ingress of Saudi Arabian quartz sand and the initiation of the extensive coastal deposits including the sabkhas and beach ridges which fringe the present rock outcrops.

The late Pleistocene and Recent sea levels were also associated with dramatic climatic changes. The evidence of cemented slope deposits and the relict drainage systems reported from elsewhere in the Middle

East (Chapman, 1971) support the idea that pluvials may have also occurred before 20,000 B.P. McClure (1976) reports evidence of a pluvial phase from the Rub'al Khali dated between 36,000-17,000 B.P. with the highest concentration of dates between 21,000-30,000 B.P. Since that time there is evidence of a profound change in climate which became steadily hotter and drier with occasional humid phases (Kassler, 1973). A humid phase was also reported between 9,000-6,000 years B.P. (McClure, 1976). A general rise in temperature reaching approximately present levels by 10,000 years B.P. is suggested by palaeobotanical evidence. (Fairbridge, 1961; Kassler, 1973). Temperatures continued to rise above present levels until 6,000 years B.P. and then falling irregularly to the present temperatures. Thus, there is a broad coincidence between the deduced sea level and temperature curves as shown in Fig. 6.5.2.

6.6 PRESENCE OF KARST WEATHERING

There is little evidence of Karst weathering on Bahrain despite the fact that the majority of exposed rocks are dolomites and limestones. The presence of solution features is expressed in four small caverns on the Upper Dammam backslope, a number of dayas (Fig. 6.6.1), some localised signs of surface solution and a limited number of intermittent streams. In this section the Karst landforms will be described and then the possible reasons for their limited presence will be

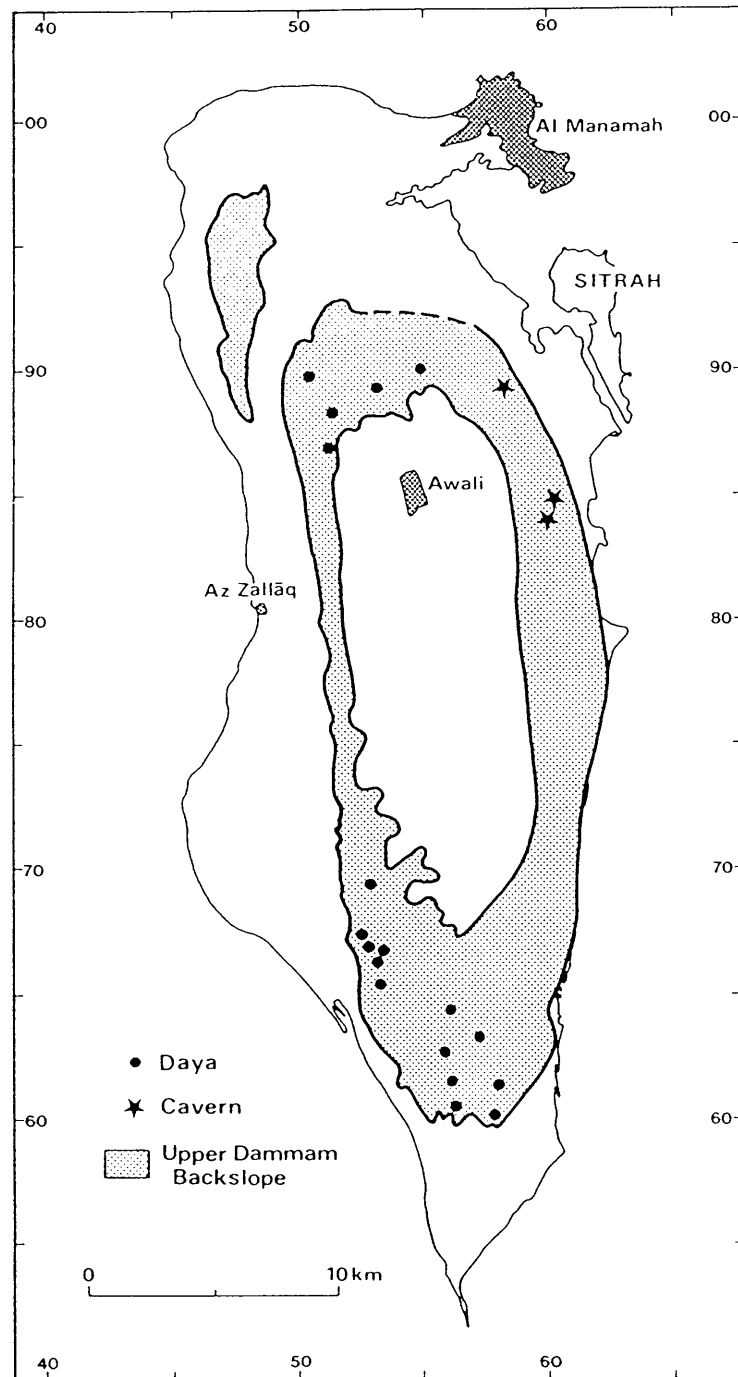


Fig. 6.6.1 The location of caverns and dayas on Bahrain

discussed.

6.6.1 Caverns

The four caverns have been detected on the upper Damman backslope and only due to the recent stripping of the pavement surface for desert fill (Plate III). Two of them are very close together (Fig. 6.6.1). One is 3 m wide and approximately 5-6 m deep and the other is 7 m across. The subsidence of surface material revealed that the interior of the caves are lined with flow-stone. The only evidence for surface solution is the occurrence of few isolated patches of rillestein. To the south of the latter two caves, a very small entrance, approximately 15-20 cm in diameter, leads to a small vertical cave of unknown dimensions. The fourth can be approached by a slit entrance approximately 30 cm high and 1 to 5 m wide and is 3.5 m deep and 1 m wide. The caves display a number of common features. They are small and they occur in the Al-Buhayr Formation which provides massive beds suitable to support cave roofs. They all occur near the surface but towards the base of the backslope and have not been exposed to the surface.

In addition to the latter caverns few minor bedding plane caves were discovered in the Multiple Escarpment zone where subterranean water flows towards the Interior Basin have washed out the shale partings beneath the massive calcisiltstones. This probably involves minimal dissolution if any, the formation of

the bedding-plane caves is due more to water weathering and erosion.

6.6.2 Dayas

Generally these landforms are depressions in limestone, chalk or gypsum bedrock in desert areas. They are usually only a few metres deep, while they extend up to kilometres in diameter. They roughly possess saucer-shapes (Plate VII) with flat floors and abrupt edges. Usually they have a soil infill, act as basins for runoff, have more natural vegetation than the surrounding areas, exhibit occasional ponding and in many parts of the world are used for cultivation. They resemble true Karst depressions such as dolines or poljes, therefore a solution or collapse hypothesis is often put forward to explain their occurrence. However, there is locally always evidence of deflation.

Dayas are not common landforms in Bahrain and their distribution can be seen on (Fig. 6.6.1). They are enclosed basins of more than one hectare in area and they form distinctive flat-floored hollows within the Damman Group outcrop. Several are totally enclosed. Smaller silt patches may be regarded as incipient dayas. All dayas on Bahrain have a sedimentary infill which is predominantly silt size. Quartz and carbonate in the form of calcite and dolomite are predominant constituents of the infill silt. The presence of mica and feldspar in measurable quantities together with the quartz indicate to a

source of fine material from outside Bahrain.

Some investigations were carried out regarding the origin of these dayas. In two places the daya silt was penetrated and a predominantly green clay was found and appeared to be resting on the bedrock. X-ray diffraction analysis showed that this green clay was very similar mineralogically to the green marl which was collected from the backslope near Az-Zallaq. The green clays are mineralogically different from the underlying Al-Buhayr beds and so they are not derived from them. As shown by the analysis the clay is characterised by a high dolomite and calcite content which makes it an unlikely solutional residue.

Three hypotheses were put forward which might satisfactorily explain the observed form and deposit relationship in dayas:

(i) Formed by wind erosion and deposition as deflation dayas. There are clear indications of aeolian deposition and evidence of wind abrasion of both silt and bedrock in the northern dayas. The southern dayas exhibit little of this evidence and in addition they interrupt the orientation of aeolian sculptured topography and are believed not to have been produced by wind action.

(ii) Surface solution accompanied by the development of insoluble residue may be the factor of the creation of this localised depressions. The impermeable floor would be relatively damp and would tend to collect aeolian silt. At present the

information available is not sufficient to deny or substantiate this hypothesis but the absence of other solutional features in the carbonate rocks makes this hypothesis seem unlikely.

(iii) Subterranean solution could create caverns which subsequently collapsed to form collapse dayas. These collapse dayas create small depressions preserving the material which once formed the cover of the original surface (i.e. green clay) and provide a locus for aeolian deposition. This hypothesis can be substantiated by the following observations:

- a) The occurrence of caverns on the backslope.
- b) The aeolian origin of the silt.
- c) The fact that the green clay is very similar to the green clay/marl found in overlying deposits.

Further work is required to acquire supporting evidence for any of the above hypotheses. Meanwhile, the fact is that dayas are moister areas which lead to the entrapment of airborne sediments and might promote both limestone dissolution at the limestone/silt boundary and salt weathering.

6.6.3 Discussion on the reasons for the limited presence of Karst landforms on Bahrain

The dissolution process is subjected to many variables the most important of which are the presence and quality of water and the character of soluble carbonates.

The very restricted occurrence of solution

features on Bahrain reflects primarily the lack of water. A hot and dry climate similar to the present one existed during the last 10,000 years on the island. Despite the recorded existence of pluvial phases during this period of dry climate, the precipitation events were marked by rapid channel flows, not allowing the slow infiltration into the carbonate which would assist dissolution. As discussed previously (1.2.2) the amount of dissolved CO_2 and pH of water are vital factors for the reaction to take place. The amount of dissolved CO_2 regulates the equilibrium of CaCO_3 in the water, i.e. the more dissolved CO_2 the more aggressive the water may be. Increased solubility of CO_2 may be achieved at lower water temperatures and by percolation through soils where microbiological activity is high, for example in areas mantled with vegetation. Conditions that have been limited or maybe completely non-existent on the island during the last ten thousand years. Lower pH also contributes to the aggressiveness of water and therefore to the rate of dissolution process.

A secondary reason for the limited Karst features on Bahrain may be associated with the quality and structure of the carbonate rocks.

In principle the dissolution process applies to both limestones and dolomites. However, from literature on Karstic regions it appears that massive and pure limestones are more susceptible to the process

than dolomites. On Bahrain the majority of exposed rocks are dolomites, some of which are thinly bedded and interbedded with clays.

As discussed in 1.2.5 turbulence is a very important factor in the dissolution process as it enables flowing water to remove dissolved products present at the solid-liquid interface and expose fresh faces available for dissolution. Layers of dolomites and clays may act as aquifers and aquicludes respectively. Water enters the pores of the dolomite stratum and may dissolve a certain amount of dolomitic rock. It soon becomes saturated and if enclosed within the clay aquicludes its flow is restricted which means it soon becomes stagnant, saturated and unable to act as a solvent. Layers of overlying clays may also prevent the limited rain water enriched with atmospheric CO_2 , another positive factor for dissolution of carbonates, to enter the dolomitic layers.

The intensity of jointing in Karst rocks is known to positively influence dissolution rates. The Bahrain carbonates do not exhibit this characteristic which normally results from faulting and folding.

Impurities in the carbonates are seen to alter dissolution rates. Mineralogical analyses on the Bahrain rocks revealed that in their majority they contain impurities most of which are quartz which is known to play a retarding role to the dissolution process as it is less easily weathered.

It appears that solution features in Bahrain are very limited, nevertheless a survey may be contacted to verify this impression.

Introduction:

To the author's knowledge no extensive study has yet been conducted on the islands of Bahrain for the investigation of the presence of Karst features. Therefore a basis for such a study will be outlined.

Initially the study should be concentrated on outcrops where solution features are already known to exist, i.e. at the Upper Damman backslope (Fig. 6.6.1) Later it may be extended to cover the whole area of outcropping soluble carbonate rocks.

The study may consist of:

7.1 Collection of local records

Every available information from construction companies and quarries related to solution features (cavitated rocks, collapse features, presence of caves) obtained during their activities should be collected, evaluated and filed. The Bahrain National Oil Company may be approached to supply any information about reported incidents which occurred during drilling operations where cavities were suspected, i.e. accelerated rate of drilling, loss of drilling fluid, and the records should be checked for such possibility.

7.2 Remote Sensing

(i) Use of B/W aerial photographs

Black and white aerial photographs which are readily available may be examined for the presence of any collapse features. As discussed in 4.1.1 the disadvantage of B/W aerial photographs lies in the fact that only features expressing topographic relief may be detected. Therefore hidden subsurface solution features may be investigated by employing other methods.

(ii) Infra-red thermal imagery

This method like the B/W aerial photographs can be used for a greater areal cover. The method as discussed in 4.1.2 involves the interpretation of a thermal map created by the different thermal emissions from the ground. Therefore, if a location seems to have different thermal radiation characteristics from the surrounding bedrock should be further investigated as it may represent infill of an underground collapse feature. The generally thin overburden in Bahrain is a favourable point for this method of investigation.

The two above described methods are expected to provide some information about subsurface solution features although their limitations are recognised. At this stage a more sophisticated and expensive phase may be introduced where magnetic and gravity survey methods may be used in delineating buried solution features. These two methods are suggested in preference to others because they have the advantage of being quick, easy

and require only one or two persons for the operation of instruments.

7.3 GEOPHYSICAL METHODS

(i) Magnetic survey

This method measures variations in the total earth's magnetic field with an accurate magnetometer (4.2.2) to cover a large area and delineate areal anomalies readings may be taken over a grid pattern.

(ii) Gravity survey

This method is based on the detection of local anomalies introduced by underground cavities, within the earth's gravitational field (4.2.4). This can be done with highly sensitive and portable gravimeters. The method is reported to have been successfully used in South Africa on dolomite bedrock with chert rubble and unconsolidated debris infilling sinkholes, a situation which resembles the Bahrain bedrocks and superficial deposits.

Depending on the success and number of results which will be obtained from these investigations, locations favourable for the presence of buried solution features may be identified and if need be further explored. A number of methods exist (Table 4.1) from which the most suitable for local conditions may be explored for further detailed investigations for Karst landforms in Bahrain. The methods chosen should be economically justified in comparison with the

project sizes and risks involved.

As stressed in Chapter 4 no one method of investigation exists which can be successfully applied to all situations at all times. Therefore, the methods suggested as a basis for detecting Karst features on the island are quick, easy and not very expensive which constitute a favourable beginning for a potential study but their success for the local conditions has yet to be evaluated.

It is known that the island has enormously developed in the last years since the discovery of oil in 1932. However, the development and expansion continues with the introduction of new industries and the demand for land for industrial development and housing is continuously increasing. It is unavoidable that in the future the road network and new town dwellings will have to be extended to areas presently uninhabited to satisfy the ever-growing needs of the country.

The impact of underground solution features, if undetected and untreated, on engineering structures may prove catastrophic or very expensive to rectify. Several such problems were highlighted in Chapter 5. The possibility and extent of such a problem on the island is worth investigating, in conjunction with further development.

Conclusions:

This study has examined the various soluble rocks. Initially the dissolution process, rates of dissolution and influential factors were considered, followed by the description and formation of a number of surface and subsurface landforms. The volume of available literature on the subject is vast and so a summary from selected publications was presented.

A variety of engineering problems that have been encountered in many engineering projects associated with soluble rocks were discussed. From this, it is appreciated, how valuable the detection of solution features at the early stages of site investigation could be. Ground improvement techniques may have to be applied prior to construction of projects. The methods used currently for the detection of solution features are tabulated with an indication of their advantages and disadvantages. However, as discussed earlier no universally successful method for all field conditions exists yet. The method chosen for each site will be the best under local circumstances, factors of reliability and cost effectiveness considered.

Urbanization and agricultural developments in Bahrain are concentrated mainly on the northern and western regions and the northern part of the Interior Basin mainly because of the existence of ground water.

As the nature of aquifer changes because of overextraction and sea-water intrusion, the country's water needs are satisfied to an ever increasing degree by desalination plants. In the future, as the population continues to increase and expansion in industrial and agricultural development becomes vital in making the country self sufficient, the need for land will have to extend to presently uninhabited parts of the island. These uninhabited areas have not yet been surveyed for their suitability in engineering projects. Having highlighted the problems associated with solution features, the importance of the detection of solution features, in advance of any development, can be appreciated. Hence, the outlined study in Chapter 7 which may serve as the initial stage for delineating subsurface solution features on the island. The study may be extended if there are positive results about the presence of solution features to cover all potential areas. The extent of the undeveloped potential areas permits this coverage in terms of cost. A map may be created based on the results of this study. Regions which can be identified as possible locations which may represent problems should be further carefully investigated prior to the design and execution of any engineering project.

As land is scarce one must always remember that sites may not be abandoned on the basis of their engineering unsuitability. Sites can improve to become suitable and this can be done only if the ground is

investigated and understood.

REFERENCES

- AL-ASFUR, T.A. 1982. Changing Sea-level along the North Coast of Kuwait Bay
- AL-SAYANI and ZOTL, J.G. (eds). Quaternary period in Saudi Arabia
- ATTEWELL and FARMER. 1982 Principles of Engineering Geology
- BEAUMONT, T.E. 1979. Remote sensing survey techniques. The journal of the Institution of Highway Engineers, April, pp. 2-14
- BELL, F.G. 1983. Fundamentals of Engineering Geology
- BELL, F.G. 1975. Salt and subsidence in Cheshire, England. Engineering Geology, Vol. 9, pp. 237-247
- BELL, F.G. 1977. A note on the physical properties of chalk. Engineering Geology 11, pp. 217-225
- BRETZ, J.H. 1942. Vadose and phreatic features of limestone caverns. Journal of Geology, Vo. 50, pp. 675-811
- BRISTOW, G.M. and BURTON, P. 1976. Some case histories of geophysical surveys to locate air-filled cavities. Proceedings of the Geological Society of London. Summary of paper read at the Regional Meetings: Exeter. 13-16 September 1976. Methods of investigation in Engineering Geology

- BRITISH STANDARDS INSTITUTE: 1972: CP2004 Code of
Practice for Foundations
- BRITISH STANDARDS INSTITUTE: 1981: BS5930. Code of
Practice for Site Investigation
- BRUNE, G. 1965. Anhydrite and Gypsum problems in
engineering Geology. Association of Engineering
Geologists, Vol. 2, pp. 26-33
- CAWSEY, D.C. 1977. The measurement of fracture
patterns in the chalk of Southern England.
Engineering Geology, Vol. 11, pp. 201-205
- DAVIS, W.M. 1930. Origin of limestone caverns.
Bulletin of the Geological Society of America.
Vol. 41, pp. 475-628
- DRESEN, L. 1973. Investigation of diffracted seismic
wave amplitudes as a method for locating circular
cylindrical cavities in solid rock. Proceedings
of the International Association of Engineering
Geology Symposium, Hanover. Sink holes and
Subsidence - Engineering geological problems
associated with soluble rocks, pp. T3-A1-T3-A8
- DOORNKAMP, J.C., BRUNSDEN, D. and JONES, D.K. (eds).
Geology, Geomorphology and Pedology of Bahrain
- DUMBLETON, M.J. and WEST, G. 1970. Air photograph
interpretation for road engineers in Britain.
Road Research Laboratory Report LR369
- EARLY, K.P. and DYER, K.R. 1964. The use of a
resistivity survey on a foundation site underlain
by Karst dolomite. Geotechnique, Vol. 14, pp.
341-348

EDMONDS, C.N., GREEN, C.P. and HIGGINBOTTOM, I.E.

Subsidence hazard prediction for limestone terrains, as applied to the English Cretaceous Chalk. In: BELL, F.G., GRIPPS, J.C., GULSHAW, M.G., O'HARA, M. (eds) "Planning in Engineering Geology" Proceedings of the 22nd Annual Conference of the Engineering Group of the Geological Society

EDMONDS, C.N. Towards the prediction of subsidence risk upon the chalk outcrop. Quarterly Journal of Engineering Geology, Vol. 16, No. 4, pp. 261-266

FORD, D.C. 1964. Origin of closed depressions in the central Mendip Hills. Abstract papers of the 20th International Geographical Congress, London, pp. 105-106

GARDNER, J.H. 1935. The origin and development of limestone caverns. Bulletin of the Geological Society of America. Vol. 46, pp. 1235-1274

GLENNIE, E.A. 1954. The origin and development of cave systems in limestone. The Transactions of the Cave Research Group, Vol. 3, No. 2, pp. 75-83

HAWKINS, A.B. 1979. Case histories of some effects of solution/dissolution in the Kemper Marl of the Severn Estuary region. Quarterly Journal of Engineering Geology. Vol. 12, No. 1, pp. 31-40

- HIGGINBOTTOM, I.E. 1965. The engineering geology of chalk. Session A. Paper 1. Proceedings of the Institution of the Civil Engineers Symposium on Chalk in earthworks and foundations, pp. 1-13
- HIGGINBOTTOM, I.E. and FOOKES, P.G. 1970. Engineering aspects of periglacial features in Britain. Quarterly Journal of Engineering Geology. Vol. 3, pp. 85-117
- JACUCS, L. 1977. Morphogenetics of Karst regions
- JAMES, A.N. and KIRKPATRICK, I.M. 1980. Design of foundations of dams containing soluble rocks and soils. Quarterly Journal of Engineering Geology. Vol. 13, pp. 189-198
- JENNINGS, J.N. 1985. Karst Geomorphology
- KENNARD, M.F. and KNILL, J.L. 1969. Reservoirs on limestone with particular reference to the Cow Green Scheme. Journal of the Institution of Water Engineering, Vol. 23, pp. 87-113
- KNILL, J.L. 1972. Assessment of reservoir feasibility. Quarterly Journal of Engineering Geology, Vol. 4, pp. 355-372
- LATTMAN, L.H. and PARIZEK, R.R. 1964. Relationship between fracture traces and the occurrence of ground water in carbonate rocks. Journal of Hydrology, Vol. 2, pp. 73-91
- MALKIN, A.B. and WOOD, J.C. 1972. Subsidence problems in route design and construction. Quarterly Journal of Engineering Geology, Vol. 5, pp. 179-194

- MARINOS, P., DIMADI, A.A., XIDAKIS, G.S. 1987. Ground Water hydraulics of a large Karst conduit - Sinkhole drainage and spring discharge in Drama area, Greece. Proceedings of the second multidisciplinary conference on Sinkholes and the environmental lapses of Karst. Orlando/Florida
- McDOWELL, P.W. 1975. Detection of clay infilled sinkholes in the chalk by geophysical methods. Quarterly Journal of Engineering Geology, Vol. 8, No. 4, pp. 303-310
- MEIGH, A.C. 1976. The Triassic rocks, with particular reference to predicted and observed performance of some major foundations. Geotechnique, Vol. 76 pp. 391-452
- MITCHELL, J.K. In-place treatment of Foundation Soils Journal of the Soil Mechanics and Foundation Division. Proceedings of the American Society of Civil Engineers
- MONEYMAKER, B.C. 1941. Subriver solution cavities in the Tennessee Valley. Journal of Geology, Vol. 49, pp. 74-86
- NEWMAN, G.H. 1981. The effect of water chemistry on the Laboratory Compression and Permeability Characteristics of Some North Sea Chalks. 56th annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers held in San Antonio Texas. Oct. 5-7

- PILGRIM, G.E. Memoirs of the Geological Survey of India. The geology of the Persian Gulf and the adjoining portions of Persia and Arabia.
- PRICE, D.C. 1971. Engineering Geology in the Urban Environment. Quarterly Journal of Engineering Geology, Vol. 4, No. 3
- PURSER, B.H. (ed.) 1973. The Persian Gulf
- SMART, P. 1977. Engineering problems of Karst landscapes - an overview. Abstract paper in: Engineering Geology of Soluble Rocks. Engineering Group of the Geological Society Regional Meeting, Cardiff
- SMITS, R.M.M., de WAAL, A., van KOOTEN, 1986. Prediction of Abrupt Reservoir Compaction and Surface Subsidence due to pore collapse in Carbonates. 61st Annual Technical Conference and Exhibition of the Society of Petroleum Engineers held in New Orleans LA October 5-8
- SWEETING, M.M. 1972. Karst Landforms
- SWEETING, M.M. (ed) Karst geomorphology
- THOMAS, T.M. 1954a. Swallow holes on the Millstone Grit and Carboniferous Limestone of the South Wales Coalfield. Geographical Journal. Vol. 120, pp. 468-475
- THOMAS, T.M. 1954b. Solution subsidence outliers of Millstone Grit on the Carboniferous Limestone of the north crop of the South Wales Coalfield. Geological Magazine. Vol. 91, pp. 220-226

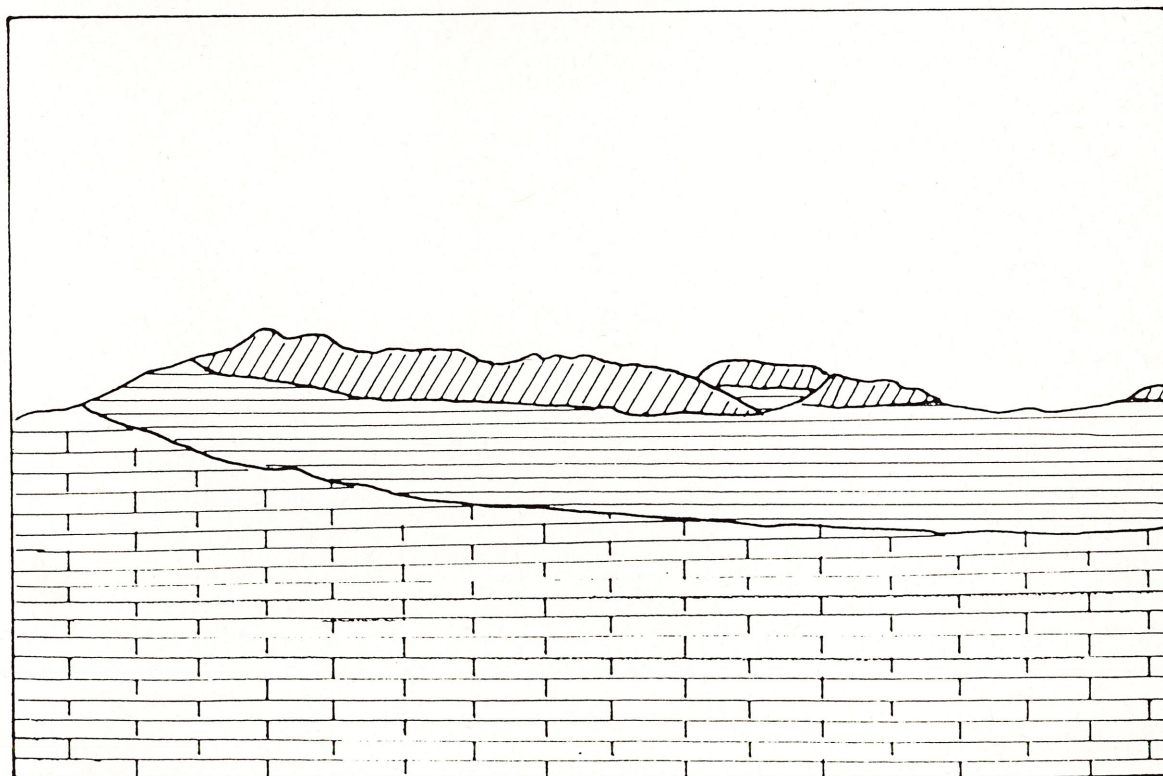
- WEST, G. and DUMBLETON, M.J. 1972. Some observations
on swallow holes and mines in the chalk.
Quarterly Journal of Engineering Geology.
Vol. 5, pp. 171-178
- WILLIS, R.P. 1963. Geology of the Arabian Peninsula -
Bahrain. United States Geological Survey,
Professional paper 560-E
- WINKLER, E.M. 1966. Corrosion rates of carbonate
rocks for construction. Engineering Geology
(A.E.G.). Vol. 3, pp. 52-58

Plate I



Jabal al-Dukhan highest altitude on Bahrain

A sketch of the above location where the whole sequence of the exposed rocks may be seen



 Jabal Cap Formation

 Dummam Group

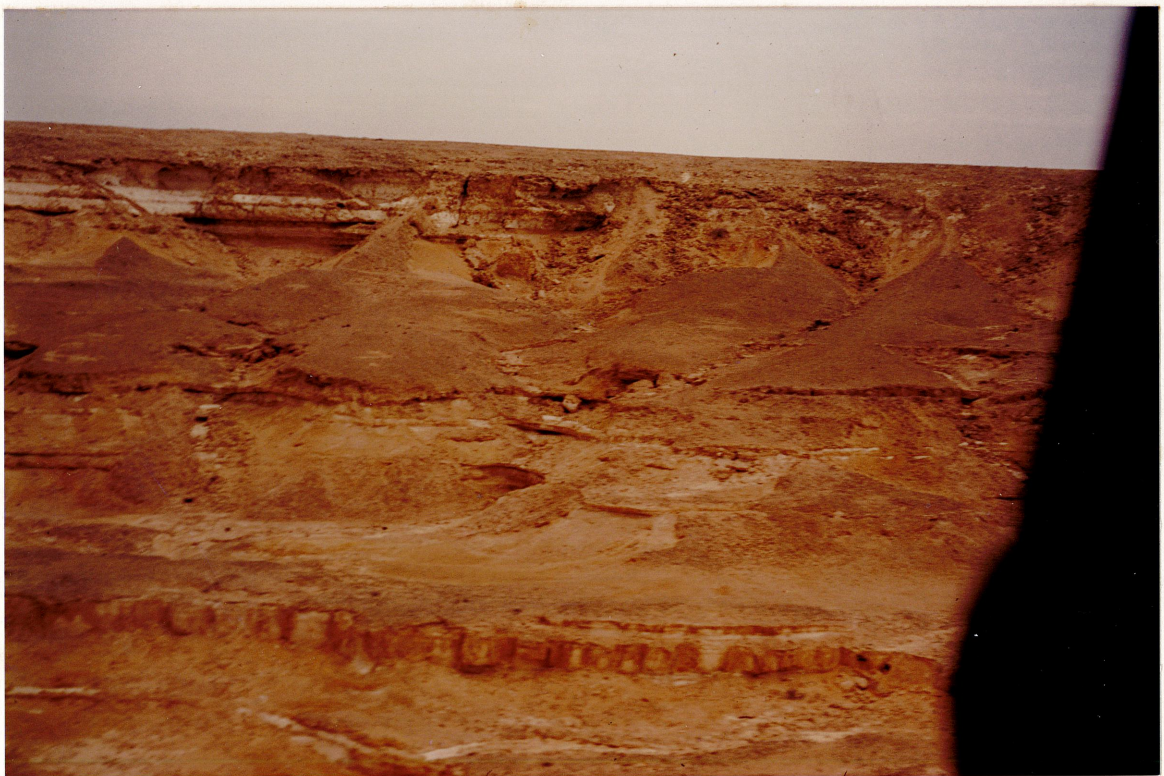
 Rus Group

Plate II



Dil Rafah Carbonate Formation

Plate III



Foraminiferal Carbonate formation capped by the
Al-Buhayr Carbonate formation

Plate IV



Al-Buhayr Carbonate formation. Green clay filling
Kurstic solution depressions

Plate V



West Rafah Flint formation

Plate VI



Dil-Radfah Carbonate formation at the foreground
Foraminiferal Carbonate formation at the middle of
the sequence. Al-Buhayr Carbonate formation capping
the outcrop

Plate VII



Saucer-shaped Dayas