THE MORPHOLOGY OF A
GYPSUM KARST

THE MORPHOLOGY AND HYDRO-CHEMISTRY OF A GYPSUM KARST, CODROY, NEWFOUNDLAND

by

Geraldine Ann Sweet, B.A.

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AUTHOR: Geraldine Ann Sweet, B.A. (University of Western Ontario)

SUPERVISOR: Dr. D.C. Ford

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ABSTRACT

In the summer of 1976 a study was undertaken of the Woodville/Codroy gypsum karst plain, an area of about 4 km^2 in southwest Newfoundland. Geology of the gypsum is revised and the general geomorphology described. Sinkholes were surveyed and classifications based on several criteria are presented. Hydro-chemistry is reported in some detail from field and laboratory analyses. It is shown that the gypsum karst system evolves in much the same way as that of limestone but at a greater rate, permitting comprehensive study of morphologic evolution within post-glacial karst areas. Processes at work in the gypsum may be initially simpler than those in carbonates but complexities of rock characteristics complicate the picture. Some water measurements indicate diffuse flow conditions in the aquifer, while others suggest conduit flow; it is demonstrated that both diffuse and conduit flow systems may operate in conjunction.

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CHAPTER 1

INTRODUCTION

It has been established that the dominant erosion process in all karst areas is solution. The dominant karst rocks are dolomites and limestones; consequently most karst research has been conducted upon them. Other karst-forming rocks are chalk, gypsum/anhydrite and halite. The geomorphic process of solution is dependent on several parameters. Obviously lithology and structure will be factors as will the chemical composition of the rock. Few surface features are seen in salt because it dissolves too quickly for lasting land forms to occur; massive dolomite may show little underground effect from solution because there are few joints and bedding planes along which water can pass.

The factor controlling solution rate is the availability of CO_2 to the water which comes in contact with the rock. It is the admixture of the water and gas which creates the solvent. Various factors, such as temperature, vegetation cover, soil type etc., alter the amount and pressure of the gas. The process of carbonate solution may be represented as:

$$Ca\ CO_3 + H_2O + CO_2 \rightleftharpoons Ca^{++} + 2HCO_3^-$$

This is the system involved in limestone and dolomite.

Gypsum, a sulphate, reacts in a similar but simpler way. In this case the solution takes place by simple dissocation of the molecule as follows:

$$Ca\ SO_4\ 2H_2O. + x\ H_2O \rightleftharpoons Ca^{++} + SO_4 + y\ H_2O$$

In this case reagents other than gypsum and water do not have to be included; however the solutional process in anhydrite can be retarded by the hydration of the rock, and this would have to be considered when rates of solution are being estimated in any area where both forms of the sulphate rock are present.

Most of the past work on karst processes and forms has been limited to carbonates. Recently however some work in the southern U.S.A. and western Canada has marked a geographical interest in the land forms associated with gypsum. At the same time, in the Soviet Union and eastern Europe considerable work has been done, particularly on the chemical and hydrologic aspects of gypsum solution. Gypsum is most soluble at 37°C which is much warmer than most groundwaters. Temperature then will play a major role in determining rates of solution and at lower temperatures there may even be some precipitation.

Anhydrite is defined as anhydrous calcium sulphate ($Ca\ SO_4$) and is frequently found below gypsum. Many authors suggest that most gypsum has been dehydrated by pressure or heat after deposition to form anhydrite and is subsequently hydrated as a result of sub-arid exposure to re-form gypsum. As the hydration takes place there is an increase in volume of up to 50% (Jennings 1971). This can have retarding effects on solution, particularly along joints and fissures where the expansion would close the cavity, thus sealing off the anhydrite below. Ultimately this seal may be dissolved but it has acted as a severe retardant. In areas where large deposits of anhydrite have been altered to gypsum, masses of gypsum are found with relict nodules of anhydrite.

Many of the conclusions concerning karst generally are applicable to gypsum and similarly those concerning gypsum may be of help in defining carbonate karst. Drake (1970) suggests that since gypsum is at least ten times more soluble than the much studied carbonates, its karst should evolve more rapidly both in time and space. Therefore, it would be possible to study more of the evolution of both process and form. This in turn may help to explain similar forms in the more slowly evolving carbonate rocks. There are, however, some properties of gypsum which make it unique and trends observed in the more commonly discussed karst forms may be too simple to explain those in gypsum. Because of its plasticity this rock deforms very easily and tends to flow, after formation, into zones of least resistance. This plasticity also means it will be found in a great variety of thicknesses and forms. This is especially true in areas of great tectonic activity like Newfoundland, where the gypsum strata become discontinuous and often extremely complex in structure. Thus there tends to be a complex pattern to the distribution of the resultant landforms. In addition the hydration of anhydrite causes expansion which in turn seals large masses, drastically reducing the fissure frequency and solvent penetrability compared with carbonate rocks. It is the existence of these two unique characteristics that Jakucs (1974) uses as an explaination for the lack of large-scale, widespread and lasting land forms in sulphate karst. This study shows that surface features at least are both as large as those found in carbonates and as varied in type.

CHAPTER 2

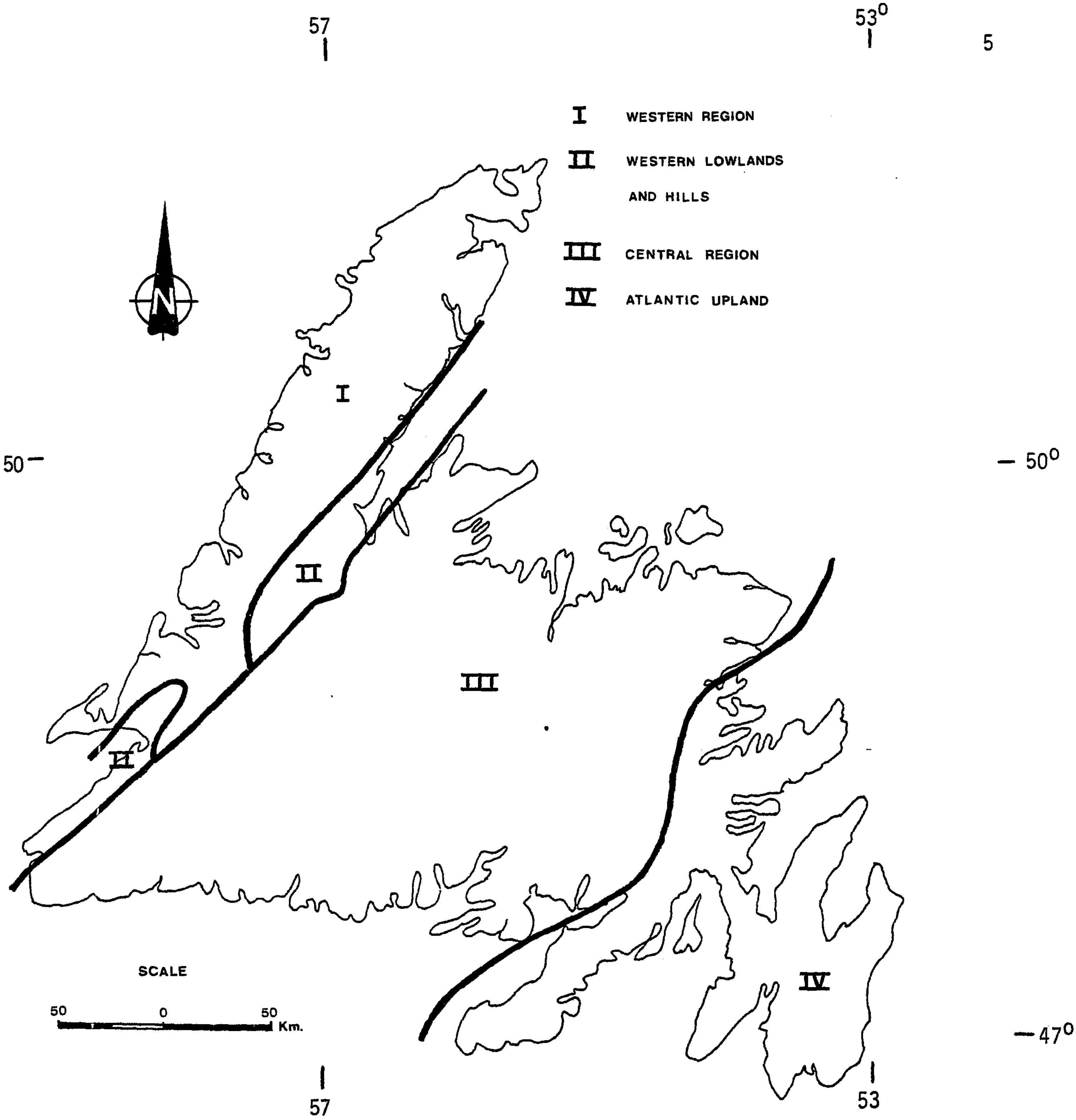
GENERAL GEOLOGY

The island of Newfoundland forms the north-east terminus of the Appalachian geological and physiographical region and it is suggested that this section was adjacent to Europe before the continents drifted apart Bird (1972). As a result of movement during the orogenies the landforms of the island exhibit a dominant northeast-southwest trend; a major fault zone effectively cuts off the extreme west and the northern peninsula, while the rest of the island can be further divided into three zones (Fig. I). These four units, based on structural controls, divide the island into its four main physiographic regions.

In the far east, the Atlantic Upland is strongly controlled by Precambrian structures, where the bays correspond to downfolds. The area has been levelled and subsequently uplifted, a process which is still continuing today.

The Central Upland is an elongated synclinal basin of greywackes, volcanics, shales and sandstones surrounded by granitic intrusions. There are numerous lakes and the generally flat topography is relieved by isolated hills and ridges, particularly in the granite. The western margin of this upland is a fault-guided slope in the southern part along the western side of the Long Range Mountains.

Between this fault and the Western Region is a narrow belt which can be correlated with the Fundy Geosyncline and represents the last of the



PHYSIOGRAPHIC REGIONS OF NEWFOUNDLAND. BIRD, 1972.

FIGURE 1.

major tectonic movements affecting the island. The rocks in this region, between Codroy Valley and White Bay, include sandstones, conglomerate and gypsum which have been rapidly denuded to form a gentle vale divided by a massif of the Grenville basement. The southern section is dominated by the Anguille Mountain, a fault-guided block of limestone which has been folded into an extended arch. Short, steep sided valleys are deeply entrenched along the sides, and the undulating surface of the summit reaches over 550 m.

The Western Region is made up of several distinct features. A tilted plateau block of Precambrian rock north of Bonne Bay forms the basis of the Northern Peninsula. In the central area, to the immediate west and south of Corner Brook, there are a series of klippen massifs or plateaux surrounded by uplands of clastic and carbonate rocks. In addition to the south, there are a series of coastal plains including the Port au Port Peninsula and the West Coast Plain. This produces a very varied landscape including wide U-shaped valleys, possible peneplain surfaces, short steep river valleys, cliffs and rugged fjord-like shorelines (Plate 1 & 2).

Plate 1. Fault guided front - Long Range Mtns.

Plate 2. Summit of the Anguille Mtns.

CHAPTER 3

GYPSUM GEOLOGY

There are a number of gypsum outcrops in the southwest of Newfoundland, all within the area formed by the Fundy Geosyncline. These outcrops are contained within the Codroy Series of Carboniferous age. There is some controversy over the precise stratigraphic position of these beds which lie on the border between the Pennsylvanian and Mississippian (Hayes and Johnson 1938 , Bell 1948 , McArthur and Knight 1974), (Table 1). It has been difficult to comprehensively understand the stratigraphy of the area because of the complex folding and faulting which has occurred. The most recent work, by McArthur and Knight, suggests that in fact only the lower members of the Codroy Series, previously determined, should be included. Thus according to the different authors the upper horizon of the Codroy series belongs in different geologic times. The base of the series is now generally accepted to be the Ship Cove Limestone; this is a fine-grained, grey, unfossiliferous limestone with considerable quantities of interbedded anhydrite and some layers of sandstone and shale. This is succeeded by red shales and siltstones ranging from a few metres to about 35 metres in thickness. In some places however the main or basal gypsum/anhydrite bed rests directly on top of the limestone. This unit is from one hundred to at least 350 metres thick, and consists of massive anhydrite in the deeply buried sections and gypsum in those areas which have long been exposed to surface or subsurface moisture. There are in addition two or possibly three other gypsum zones which are separated from this bed and each other by red shales.

TABLE 1

STRATEGRAPHIC SEQUENCE OF CODROY SERIES, NEWFOUNDLAND. AFTER McArthur and Knight 1974.

Age	Time Unit	Hayes & Johnson 1938	Bell 1948	Baird 1949	Baird & Cote 1964	McArthur & Knight 1971	
Pennsyl-vanian	Rivers-dalian	Barachois Series	Barachois Series	Barachois Series	Barachois Group	Upper Searston Beds	
	Cansoan	Mapped var-iously as Barachois or Codroy	Searston Beds	Searston Beds	Searston Beds	Disconformity	
Mississi-ppian	Windsor	Codroy Series	Codroy Series	Codroy Series		Lower Searston Beds	
		Woody Point Sandstone	Woody Head Beds	Woody Point Beds	Codroy Group		
		Woody Cove Shale	Woody Cove Beds	Woody Cove Beds	Upper Codroy		Fault
		Black Point LLSTN Codroy Shale	Gypsum Beds Black Point LLSTN Codroy Breccias	Codroy Beds inc. Black Pt. LLSTN	Lower Codroy	Lower Red Bed & Gypsum Series inc. Black Pt.LLST, Other LLSTN Units, Codroy Breccia Ship Cove LLSTN	
		Variously Mapped with Codroy & Anguille Ser.	Ship Cove LLSTN.	Ship Cove LLSTN.			
		Anguille Ser. inc.Codroy S. Snakes Bright Shale.Cape Anguille SST.	Anguille Series undifferent-iated	Anguille Ser. Seacliffs SST. Snakes Bright Shale. Anguille SST.	Anguille GP. Seacliffs FM. Snakes Bright FM. Cape John FM.	Anguille Seacliffs FM. inc. Woody Head. Woody Cove Beds Snakes Bright FM. Cape John FM.	
Pre-Carboni-ferous							

siltstones and limestones. Above this thin layers of gypsum alternate locally with shales and siltstones.

The whole gypsum section is overlain by more than 1000 metres of clastic rocks including shallow water limestones, grey and khaki sandstones, shales and some conglomerate. The continental-type sandstones and conglomerates are banded with coal. These are the youngest rocks found in Newfoundland. Altogether the series ranges between 1500 and 3000 metres in thickness, but it is divided into two sections or even different series, by different authors (Table 1).

Bell (1948) suggests that the series were laid down in three stages. The gypsum was part of the first stage when the deposition was mainly of marine type. Gypsum is an indicator of shallow coastal water or a lagoonal environment. Other factors indicating shallow water deposition are ripple marks and cross bedding in the Ship Cove limestone as well as beds of beach sandstones, (Plate 3). The two later stages included the deposition of the Upper Codroy Series. This early work was supported by Baird (1959) but the recent work of McArthur and Knight, especially in the Codroy section relocates the Upper Codroy series below the Ship Cove Limestone; this as the result of the discovery of a previously overlooked syncline.

On the Port au Port Peninsula and in the Romaines Brook area the gypsum beds lie as small basins of flat or gently dipping strata in Precambrian depressions (Plate 4). In the St. George-Riverbrook area open folds are characteristic and the gypsum/anhydrite zones outcrop in sweeping lines following an anticline on the north end of the Cape Anguille Mountains. In the southern part of the belt the rocks have been massively folded and faulted. The gypsum/anhydrite beds therefore occur irregularly and because

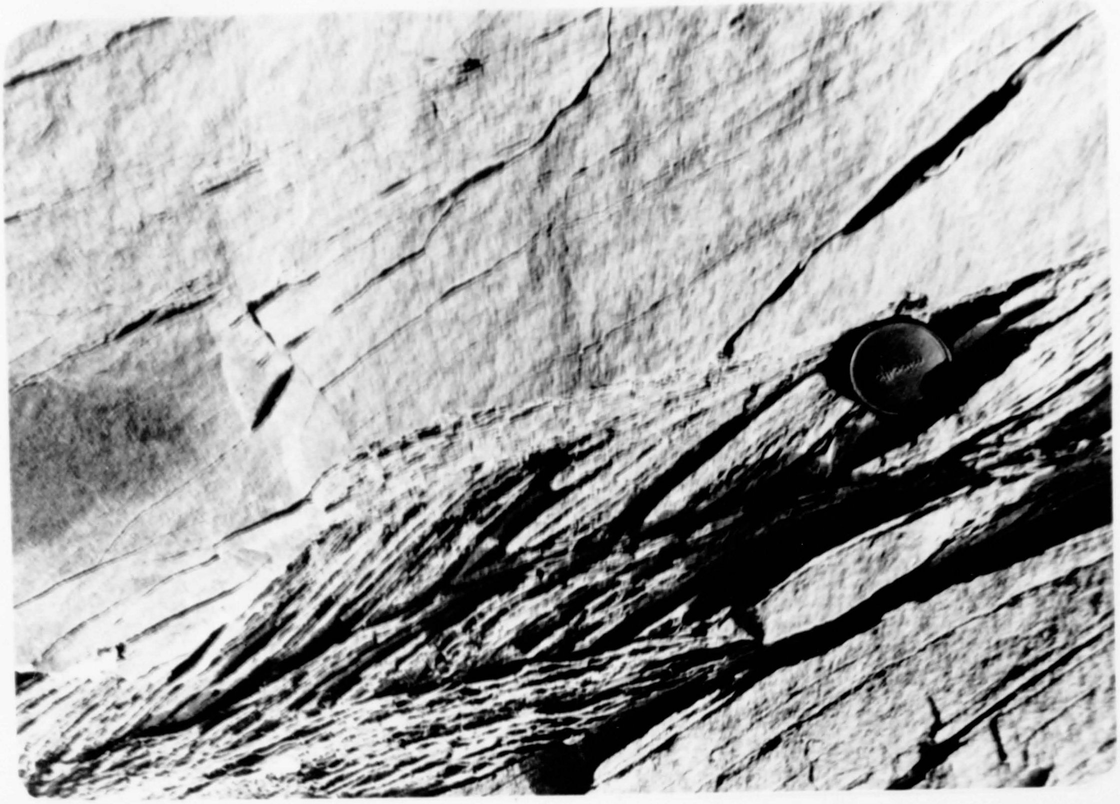
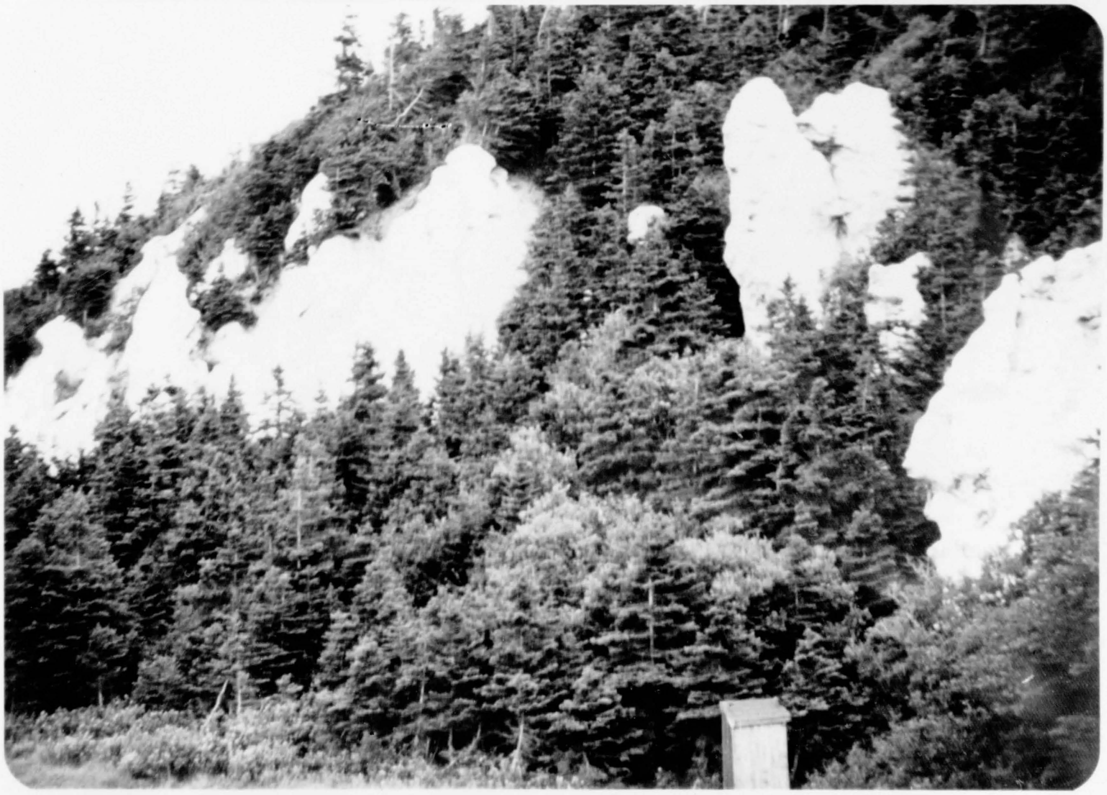


Plate 3. Cross bedding in sandstone of Codroy beds.

Plate 4. Gypsum cliffs, Romaines Brook, Nfld.



plastic flowage has taken place some masses have pseudo-intrusive boundaries or contacts with the adjacent sedimentary rocks (Plate 5).

It is the lower massive beds of the gypsum/anhydrite which are exposed and mined in the Bay St. George area, but in the south, along the coast at Codroy all three gypsum units are seen.

"The rocks of the [Codroy] area constitute a full section of the Codroy series. They are greatly faulted and are in some places isoclinally folded. The structure is known in broad aspect but much of the detail is obscure. Gypsum which occurs at many places along the shore is not generally conformable with the adjacent strata. Gouge, breccia, slickensides and crumpling within the mass show that deformation has taken place on all sides. The gypsum as the shore zone suggests, occurs as deformed lenses and bulbous masses which are only broadly conformable with the adjacent strata." Baird (1951), (Plate 6).

In fact there are sixteen outcrops along this coastal section of about six kilometres and in many of them the belts of gypsum, shale and siltstone are set almost perpendicular (Plate 7). In addition the gypsum appears to have flowed in some sections and the result is a series of intrusions along zones of weakness in other rocks where "the bodies are cut by fibrous gypsum veins and thick veins of selenite crystals", McArthur and Knight (1974), (Plate 8).

The gypsum of the Codroy beds is of all colours and textures and within the cliff section at Codroy five different types are exposed. These range from fine alabaster to grey sugary gypsum, the latter being most common. The most striking is probably the fine crystal banding of selenite with cleavage plates as much as a foot in diameter. Included also are small

Plate 5. Gypsum intrusions in siltstone and shale.

Plate 6. Bulbous gypsum lenses.

Plate 7. Perpendicular beds of shale.

Plate 8. Selenite veins in the Codroy Cliffs.

outcrops of very large veins of colourless (white) gypsum intruded along cracks in the Black Point Limestone. In addition there are samples of very fine pinkish-white massive gypsum in which no apparent bedding or jointing is present (Plates 9-12). All of these indicate the complexity of the system.

The cliffs in this section are being rapidly undermined by wave erosion and show anhydrite below with gypsum in the upper parts (Baird 1959). Some of the cliff faces show jointing of anhydrite with hydration apparently having moved outward from the joints. These outcrops appear to have boulders of anhydrite surrounded by gypsum. When these break off they produce a form of spheroidal weathering along the shore. The strange shape of some of the residual masses, forming the bluffs, is due to differential weathering of the two associated rocks.

These bluffs are the seaward expression of the gypsum but as Baird points out these cannot be used, without other evidence, to indicate the landward extension of the gypsum beds. The indentations between them are formed by less consolidated siltstones and shales. While the beds have been very much contorted it is possible to see a general pattern of tectonic movement. There seem to have been at least three stages of folding which may or may not have occurred at the same time. The beds are intensively folded at right angles to the shore and within this folding secondary folding has occurred. There is also evidence of more gentle folding more or less parallel to the shoreline and to the line of contact with the Anguille Series, which is found close by. McArthur and Knight (1974) indicate the presence of a syncline, hitherto overlooked, which adds complication to the stratographic sequence in the area. They suggest, as a result, an inversion

Plate 9.

Plate 10.

Plates 9-12. Various gypsum types in the Codroy section.

Plate 11.

Plate 12.

of sequence, putting the Woody Head and Woody Cove beds before instead of later than the gypsum beds.

The overall movement in this zone is a strike-slip movement of unknown direction. This is inferred from the folded nature of the shales and gypsum and is supported by the fold trends of the Anguille group below. In the Codroy coast section the so-called gypsum plain is in contact with the underlying Anguille Series along a predominantly strike slip fault, indicated by a break in slope at the foot of the Anguille Mountains (Plate 13).

The complexity of the area is indicated by the following sequence of events which appear to have occurred:

1) strike slip faulting

2) normal faulting

3) thrusting perpendicular to the faulting (Fig. 2).

Plate 13. Break of slope - Anguille Mtns - Woodville Plain.

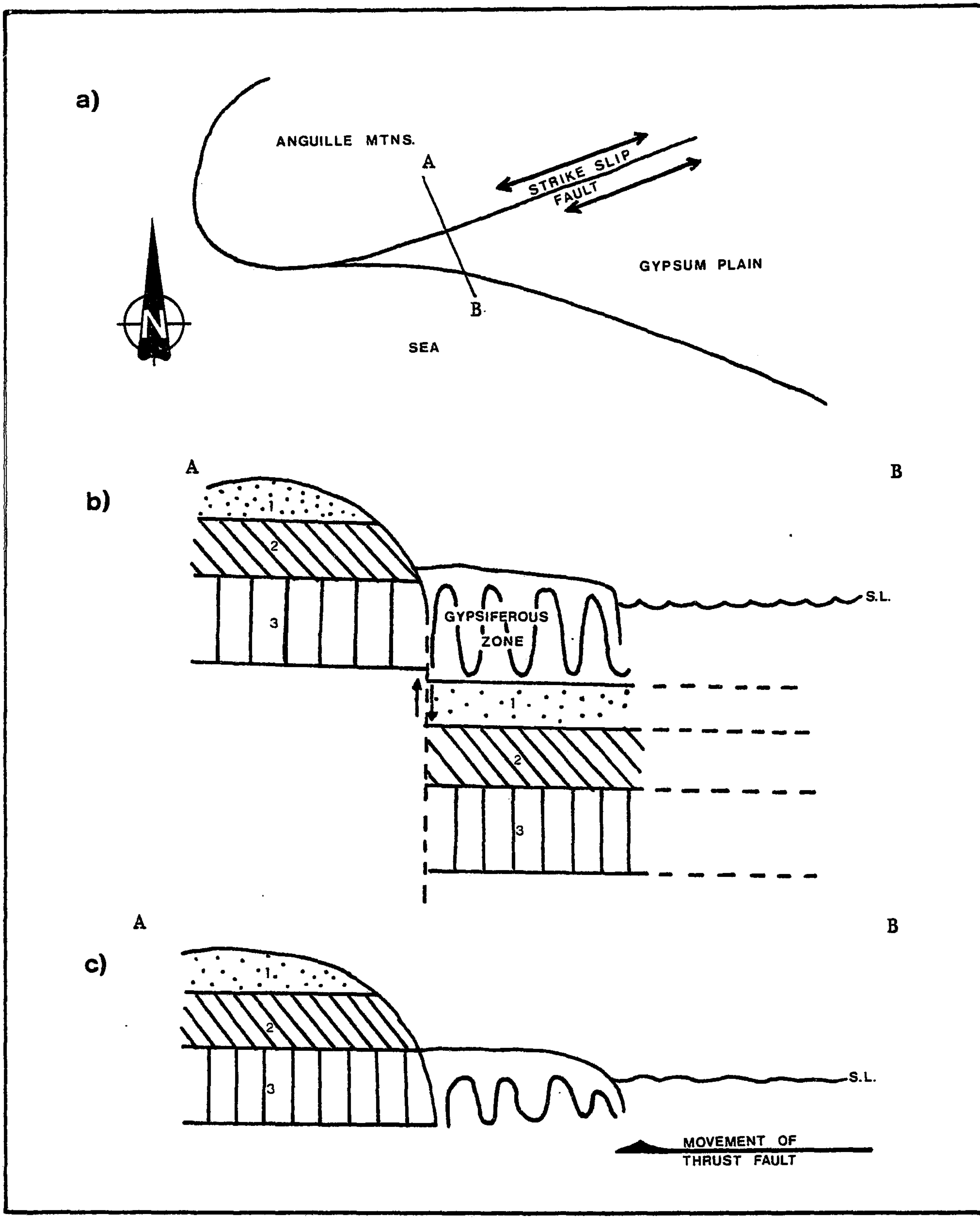


FIGURE 2.

SCHEMATIC REPRESENTATION OF POSSIBLE TECTONIC MOVEMENT IN CODROY AREA

CHAPTER 4

GEOMORPHOLOGY

To the south of the Anguille Mountains the Codroy beds outcrop along the coast and up the valley of Grand Codroy River. There are exposures of gypsum along the coast south of Codroy village (Plate 14) and in the valleys of Brooms and Ryans Brooks. This paper is concerned with the first of these (Fig. 3). Southeast of Codroy Village the beds form a wedge-shaped plain divided by a probable strike slip fault from the Anguille Mountains and bounded about 1.6 km to the south by a somewhat tenuous fault zone. The whole section slopes gently towards the sea with a gradient of 1:19 and is being rapidly eroded away by the sea.

The area is covered by a glacial till mantle of variable thickness. With the exception of three small gypsum pillars about 150 m from the shore, in the main stream valley, there are no outcrops of gypsum inland. Because of this mantle, produced during the Wisconsin glaciation which retreated from this area about 13,000 B.P., it is difficult to put accurate limits on the gypsum beds. Along the coast the till cover varies from five to fifteen metres in thickness (Plate 15) and some of the inland depressions are at least 18 metres deep with no apparent contact with the gypsum or gypsiferous shales at their bases. The glacial material ranges widely in size from boulders to fine clay. Rocks found in the till include a predominance of sandstone, siltstone and shale with some limestones plus granite, conglomerate, amphibolite and selenite in very small quantities. There are no

Plate 14. Gypsum Bluffs, Codroy.

Plate 15. Varying till depths at the Coast.

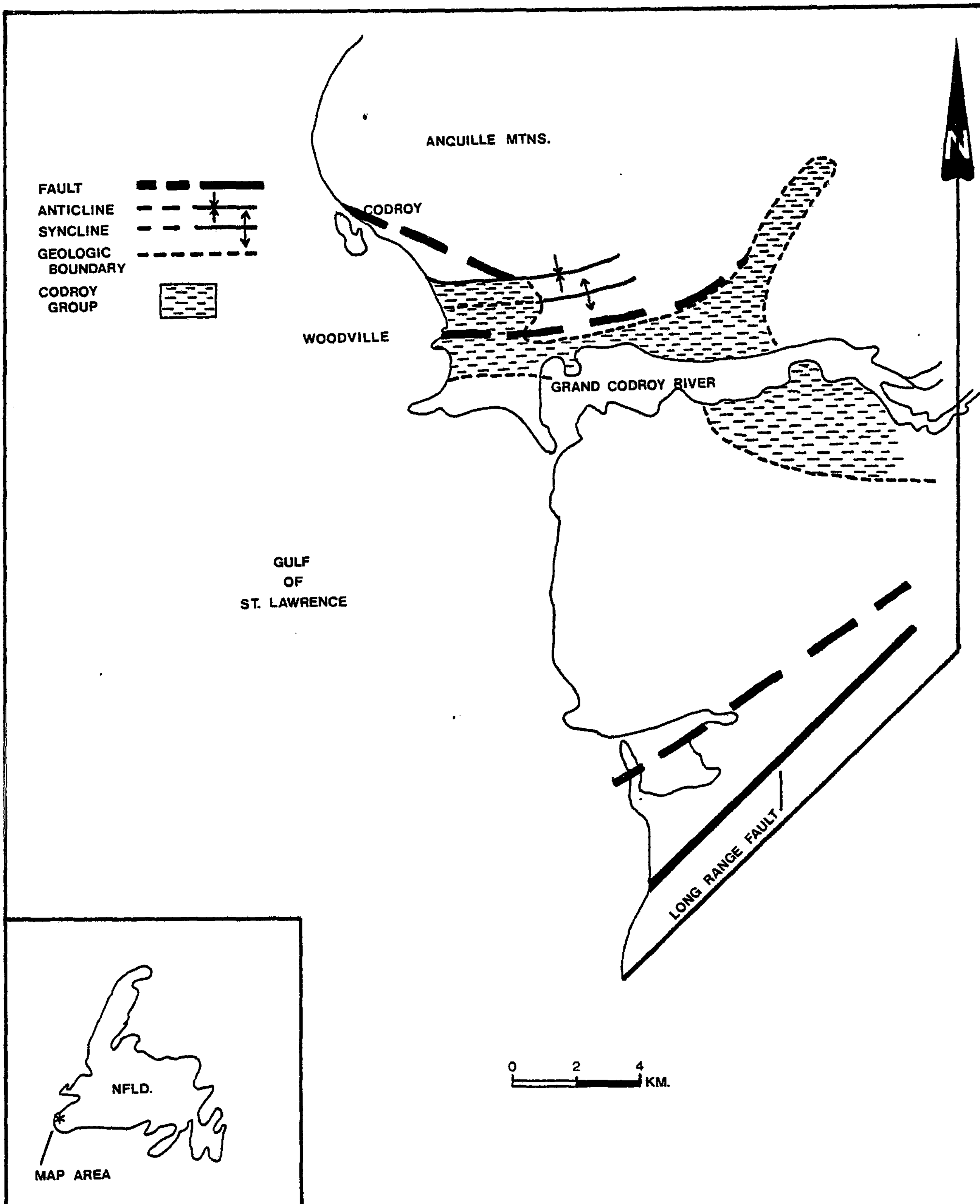


FIGURE 3.

STRUCTURE OF S.W. NEWFOUNDLAND.

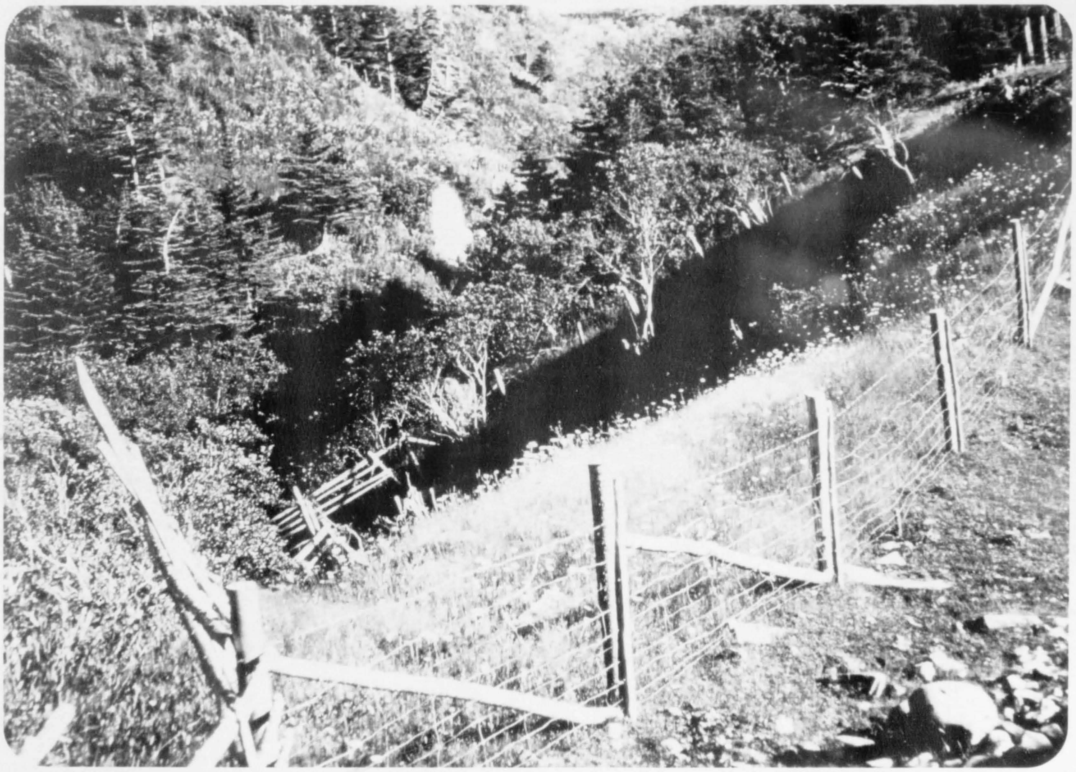
gypsum pebbles. Samples analysed showed that close to the coast some of the fines had been removed completely, while the soluble content of the fines is approximately 7% of which 3% is sulphate; obviously the sulphate has been dissolved and washed out in the water passing through the tills.

Within the area there are several surface streams, the most important of which is about 1.7 km long. All these streams are to some extent entrenched in their lower reaches (Plate 16). Only the main one appears to flow its full length pereniально. Two smaller ones are certainly seasonal in their upper sections where the stream channels become difficult to follow in marshy terrain (Fig. 4). The main stream, Darnis Brook, is fed from a very small spring and a sinkhole and flows in a straight shallow channel, lined with boulders at the head. It then meanders for over a third of its length through a boggy section, where it passes through several shallow collapse features and where a tributary stream joins it. Some 600 metres from the mouth the stream reaches a knickpoint and from here it flows through two relatively large sinks past the gypsum pillars, between steep banks to the shore (Plate 17). The entrenchment appears to be entirely post-glacial, apparently it is still in till rather than bedrock and it is certainly active today, for signs of headward erosion are obvious. This is however only a local base level.

Downstream of the knickpoint river capture has occurred, where the development of a large doline, close to the original post-glacial stream channel has created a lower hydraulic gradient for the water flow. The stream has been diverted through this new route leaving an abandoned valley lined with boulders and pebbles (Fig. 5). That the capture took place fairly early in the post-glacial development seems evident since the valley through

Plate 16. Entrenched valley of Darnis Brook.

Plate 17. Inland gypsum outcrop.



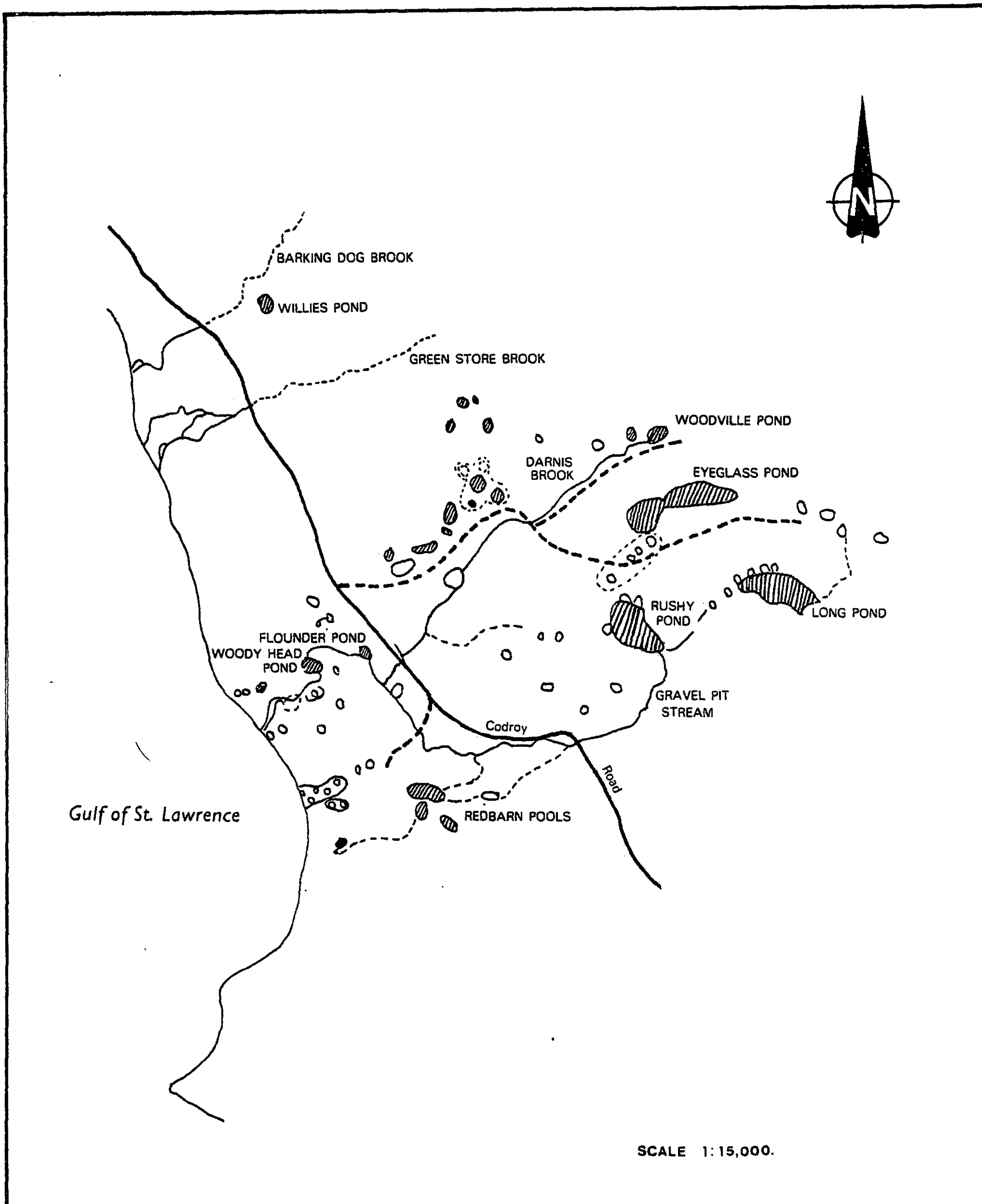


FIGURE 4. GEOGRAPHICAL AND RESEARCH NAMES OF CODROY AREA.

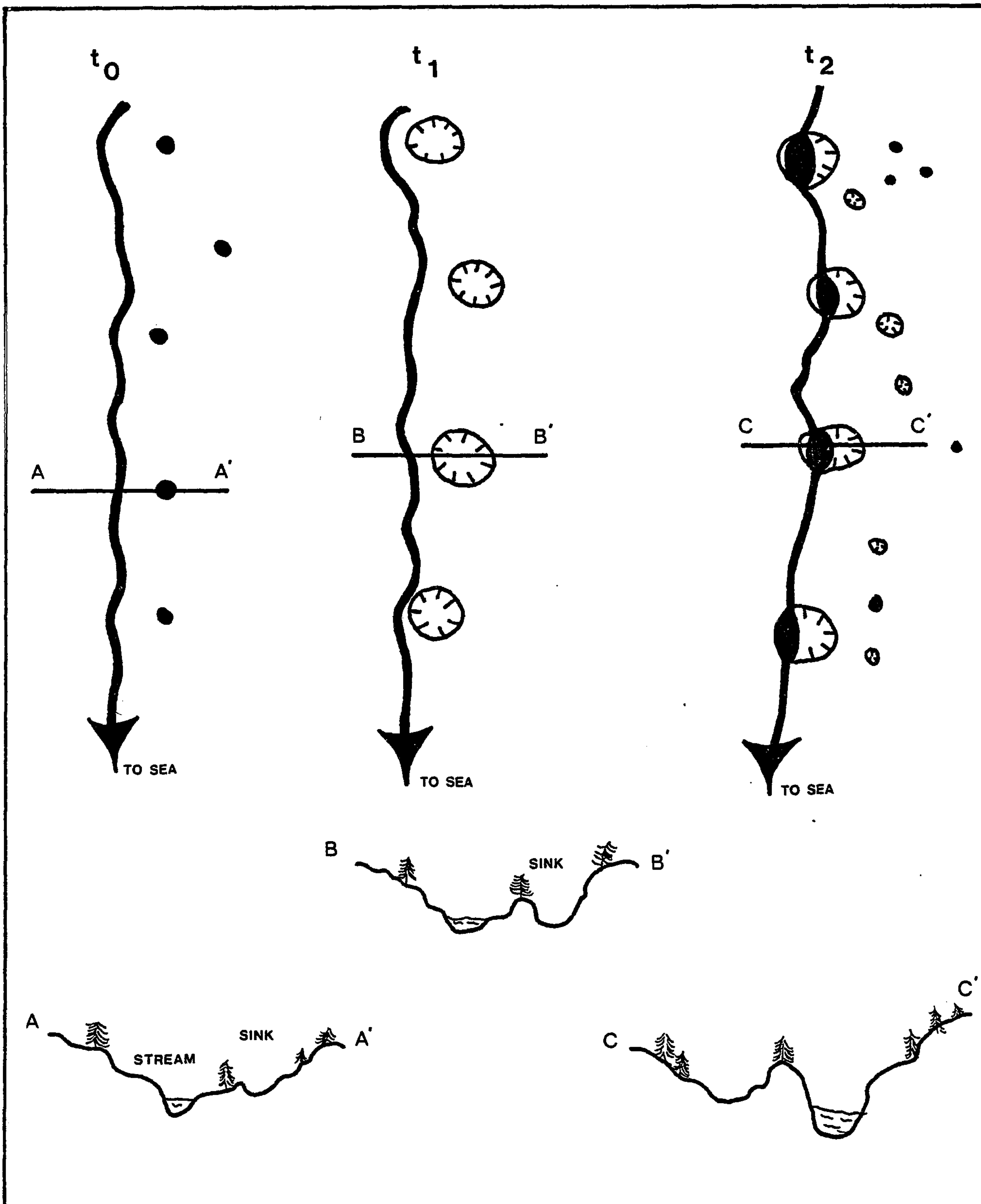


FIGURE 5

DEVELOPMENT OF STREAM SINKS AND STREAM PIRACY.

sinkholes is much more fully developed than the now dry valley. But as a result a secondary stage of down-cutting can be seen at the downstream end of the pond where the overflow channel is cutting down to grade itself to sea level. This cutting down is enhanced by a narrowing of the valley sides at stream level (Fig. 6). This may well be the result of a till bedrock contact, for it is here that the only inland gypsum shows; in the form of two isolated pillars of rock (Plate 18).

From here to the sea (about 150 m) the stream flows through a wide V-shaped assymetrical valley with a gradient of about 1:20. At the mouth of the valley the water flows over and through beach boulders to the sea. There is evidence along the banks of the stream of water entering the system from underground. At least two springs could be seen actively contributing downstream of Woody Head Pond, although the only surface water above them was in a small sink on the edge of the cliff. The main tributary, Gravel Pit Stream, flowed constantly in the lower reaches, but was dry at the source and seemed to have been that way for some time. The stream valley was clearly visible but the bed was entirely overgrown. There was evidence of a short flow season due to spring runoff.

An attempt was made to correlate the amount of knickpoint recession with the catchment area of this and several other streams in the area. It was extremely difficult to determine the actual catchment area because of the lack of surface drainage, or fossil drainage features and the arbitrary boundaries drawn up did not indicate any relationship between the two variables.

There are three other streams in the area, all rather different in form. South of Darnis Brook a series of shallow cliff-top sinks are joined

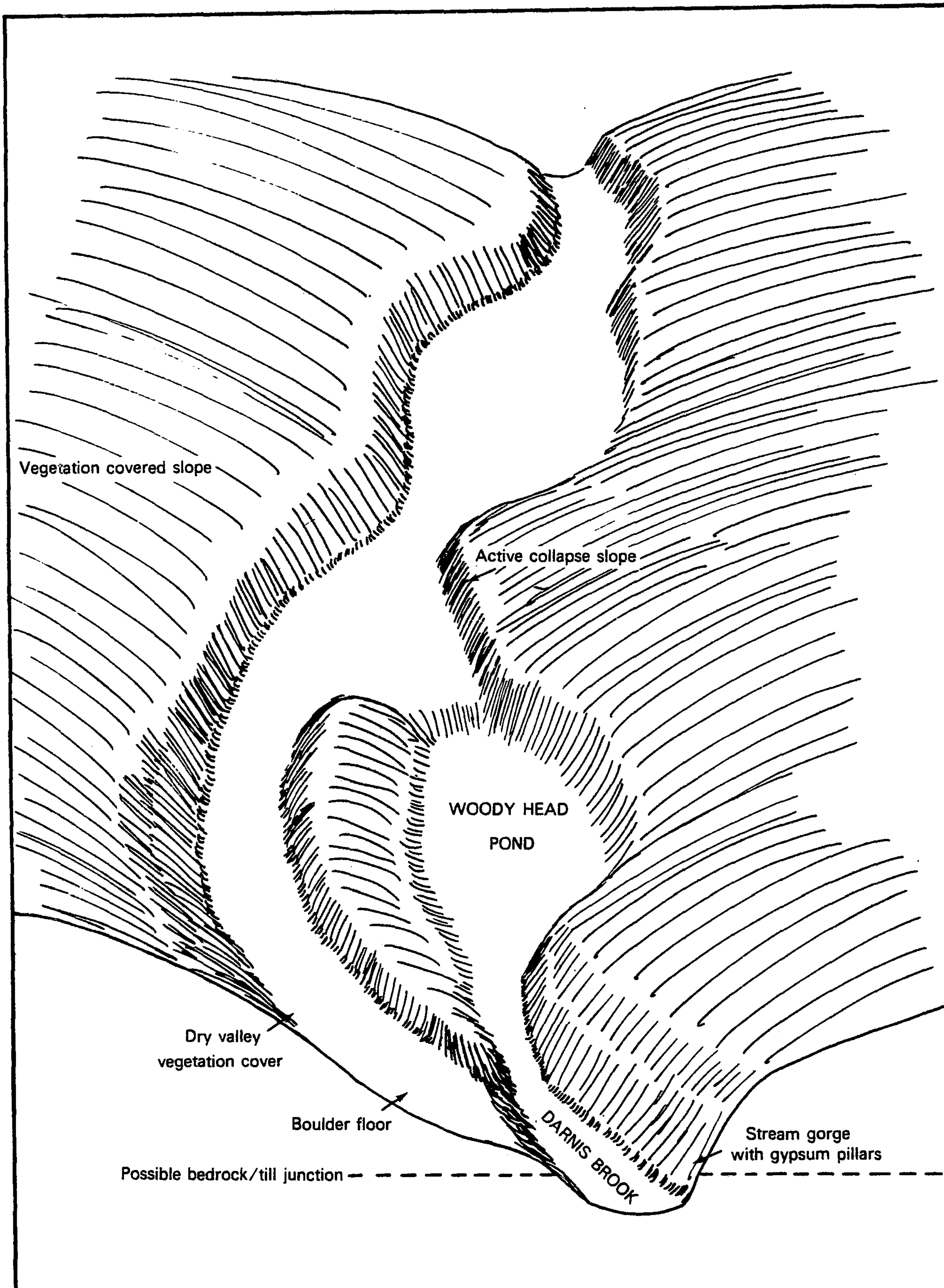


FIGURE 6 BLOCK DIAGRAM OF WOODY HEAD GORGE, DARNIS BROOK

Plate 18. Stream piracy, Darnis Brook.

Plate 19. Cliff top sinks - seasonal dry valley.

by a valley, dry in the summer (Plate 19). The water from this goes underground before reaching the cliffs and possibly re-emerges from Mud Cave and along the till/bedrock boundary close by. As a result the stream is ephemeral and the valley does not grade down to sea level. Greenstore Brook to the north is a short stream fluctuating considerably in volume, which cuts a wide deep valley that is totally in till between the road and the sea, a distance of about 200 m. Landwards of this break of slope it rapidly flattens out and disappears in a marshy depression on the hillslope.

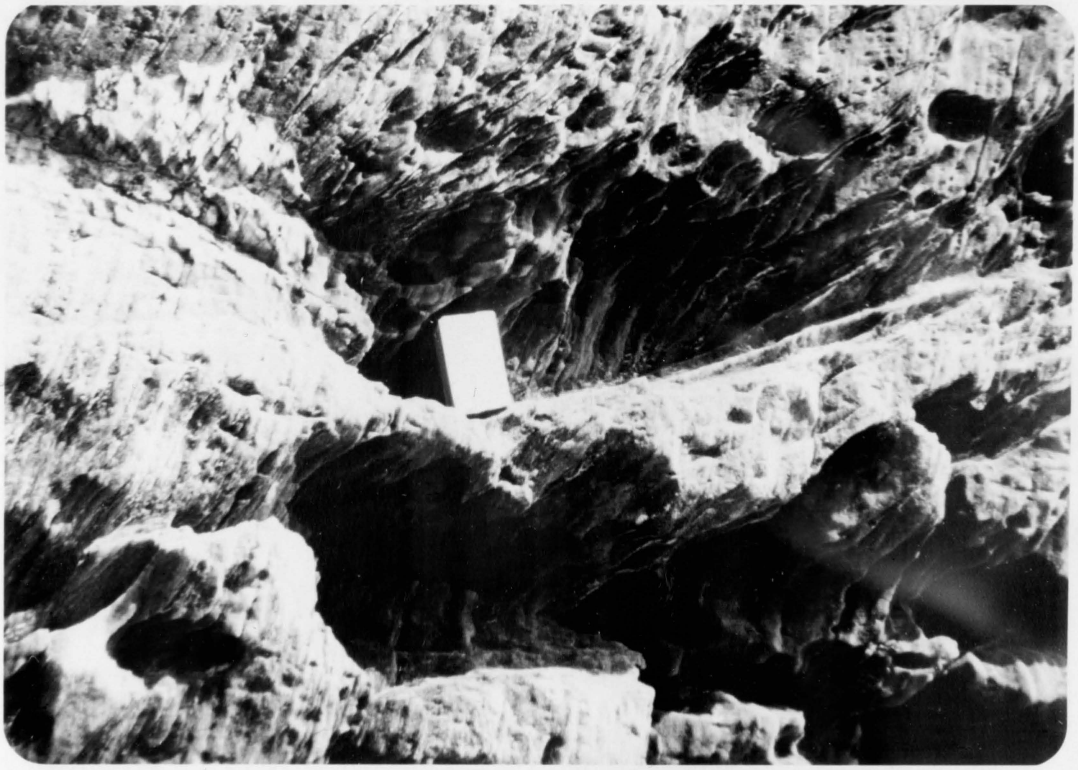
Barking Dog Creek has two sources, one stream drains overland from an indeterminate area just seaward of the road. This has a very small channel falling steeply towards the sea. It appears to flow all the year round, from the marshy area to a confluence with the second channel about 100 metres from the sea. The second branch is larger and is entrenched for much of the 2000 metres from the road to the confluence. There are several areas of active collapse along its banks and the water flows underground in some sections during the drier seasons. The material in the valley floor indicates active and large waterflows at least part of the year, probably during the spring runoff. This branch of the stream also becomes a mere trickle landward of the road, but the dry valley can be traced for some distance (Plate 20). Where the two branches meet there is a shelf about 25 metres wide above a knickpoint. Below this the stream is entrenched for the last 100 metres to the sea. The entrenched valley drops steeply to the sea and the water washes over large boulders of limestone and sandstone, as well as breakdown gypsum; more evidence of greater water flows than those seen during the field season.

Plate 20. Codroy-Woodville sinkhole plain.

There are a number of karst landforms in the area. Dry valleys are caused by river capture, or where water disappears underground, only flowing over the surface during spring runoff. Along the cliffs are several small sea caves and some small conduits higher up the cliff face (Plate 21). In addition some fine examples of karren are found, for the most part, on the underside of a wave cut notch at the high tide mark (Plate 22). These are however of minor importance: it is the sinkhole which is the most significant type of karst feature of this and other gypsum areas of Newfoundland. In this area the sinkholes reach a density of well over 100 per sq km, compared with 70 per sq km on limestone in the Mendips of Great Britain or more than 1200 per sq km in the remarkable gypsum karst at Romaines Brook, Newfoundland.

Plate 21. Sea Caves.

Plate 22. Sea formed Karren.

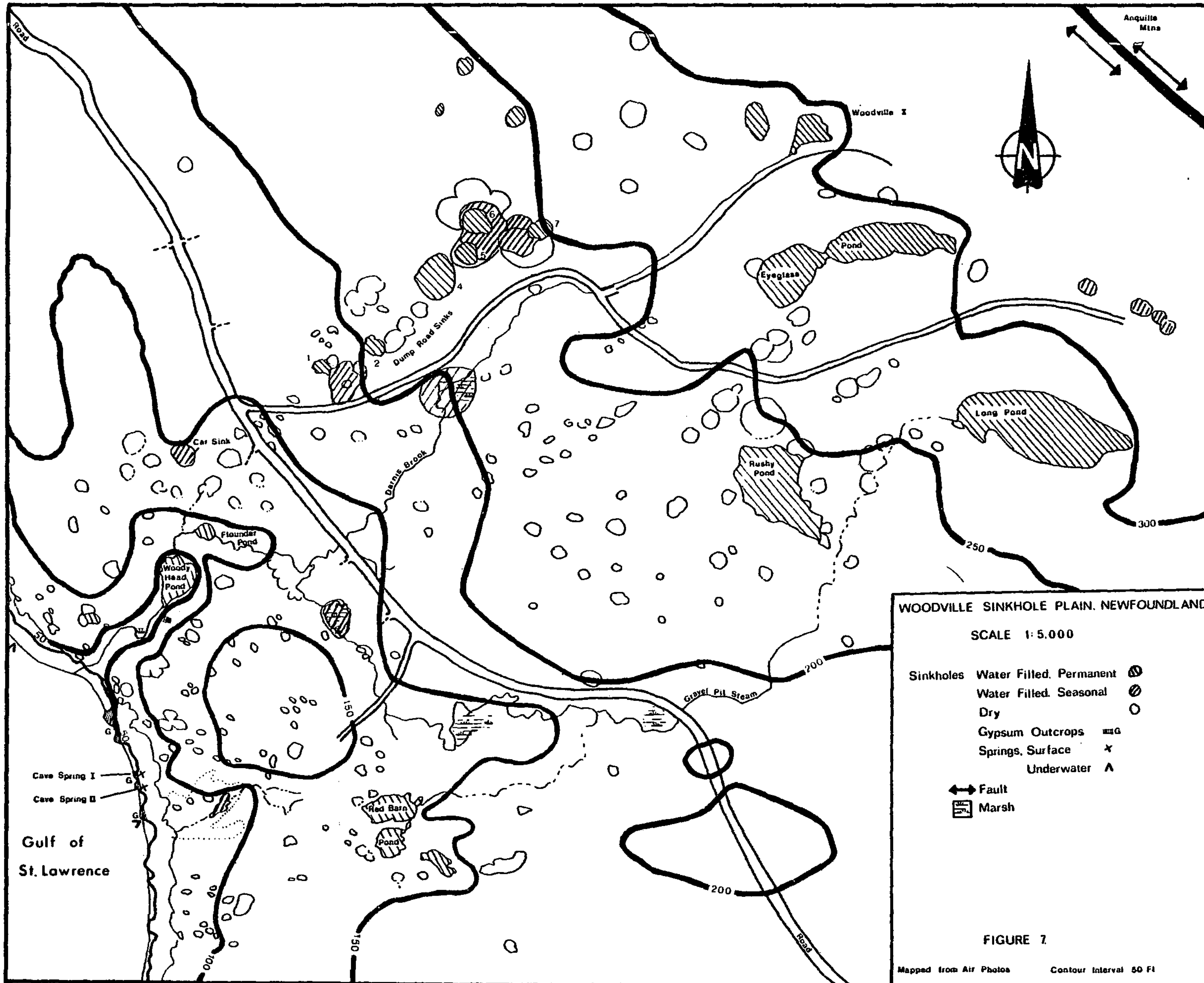


CHAPTER 5

SINKHOLE DISTRIBUTION AND CLASSIFICATION

By studying the distribution, nature and evolution of specific sinkholes more can be learned about the materials and processes operating underground. A special study was made of the sinkhole plain at Woodville, Codroy. Within an area of about 4 sq. km., approximately 250 sinkholes were mapped, (Fig. 7). Some are simply shallow grassy depressions and others are large deep ponds. While these depressions range from less than 1 metre to at least 18 metres in diameter, they are several types and can be divided into three distinct size categories. The 250 dolines shown on the map represent only the large and medium sized classes of depression, those that can be detected on the largest aerial photographs available. (July-September 1974, 1:12500 taken at 7890'). In many cases these have very small shallow depressions associated with them, often round their edges. These constitute the smallest size category. While some sinkholes have more subsidiary depressions than others, the average would be 4 to 5. There are large and medium sinkholes which have no auxiliary depressions; but over the whole area the total number of sinkholes must reach more than 1000.

In addition to the wide range of sizes the dolines display a considerable variation in shape. Many are perfect funnels, while others show a distinct bowl-like shape. Some, particularly the more recently developed ones, are simply collapse cylinders with near-vertical walls. It would appear at first reconnaissance that size and shape may be correlated in some cases but, particularly in the case of small sinkholes there is a complete range of



WOODVILLE SINKHOLE PLAIN, NEWFOUNDLAND
SCALE 1:5,000
Sinkholes Water Filled, Permanent
Water Filled, Seasonal
Dry
Gypsum Outcrops
Springs, Surface
Underwater
Fault
Marsh
FIGURE 7
Mapped from Air Photos
Contour Interval 50 Ft
Road
Anguille Mtns
Woodville I
Dump Road Sinks
Eyeglass
Pond
Long Pond
Rushy Pond
Car Sink
Flounder Pond
Woody Head Pond
Dennis Brook
Gravel Pit Stream
Red Barn
Pond
Cave Spring I
Cave Spring II
Gulf of St. Lawrence
300
250
200
150
100
50

shapes.

Similarly some are water filled, while others remain dry. This factor too seems to have no true dependency on size or shape with one exception - there are no very small water-filled sinks.

Considerable work has been done on a world-wide scale concerning the classification of sinkholes. The most comprehensive works in English are those of Jennings and Sweeting. These authors concentrate on dolines in carbonate rocks with no mention of gypsum features. They are primarily concerned with those features directly associated with bedrock. Thus they are of limited value when considering the study areas. Almost all the Codroy sinkholes are in till and are therefore contemporary with or later than the recession of the ice 13,000 yrs. B.P. The rapidity of their formation enables these gypsum karst features to be studied more fully than the forms in limestone and dolomite. Because of this, this study can perhaps enhance knowledge or genesis in other areas.

Quinlan's classification 1971 (pers. comm.) suggests a generic division into four categories and includes the problem of depressions in over burden (Table 2). With this and the previously mentioned schemes in mind an attempt has been made to classify the sinkholes of the Codroy gypsum karst.

The till mantle here ranges from about 3 metres to at least 20 metres in thickness. Even the deeper waterfilled sinks do not appear to be in direct contact with the underlying gypsum. This non-contact means that the sinks as surface expressions cannot be considered as solutional features. They are all of the collapse type; but as Quinlan suggests there may be more than one category within the broad type.

TABLE

GENETIC CLASSIFICATION OF MAJOR TYPES

Major Morphogenetic Processes	Major Surface or Near-Surface Material that is Lowered
Collapse (and sometimes subsidence)	Rock
	A. Into cavity at shallow depth[2]
	B. Into deep-seated cavity[3]
	Soil (or other clastic mantle)
Solution	Rock (and, in some instances, including soil)
	A. Subaerial[5], corroded by:
	1. Rain Water or snowmelt water, with
	a. Direct infiltration and rill flow
	b. Fluvial flow
	2. Icemelt, with subglacial flow
	B. Subsoil (or sub-alluvium, etc.
	C. Interstratas
Suffosion (El uviation)	Soil (or other clastic mantle)
Solution + suffosion + repeated step-like collapse of soil (or other clastic mantle)	Soil (or other clastic mantle)
Consolidation	Soil (other clastic mantle)

English Name for Doline Type	Description of Major Processes Causing Doline Development[1]
Collapse doline	Collapse of bedrock because of:
Shallow collapse doline	Denudation of surface and loss of stability of span Weakening of rock arch by solution Stoping of cave roof
Deep-seated collapse doline	Continued stoping because stable dome is not developed Solution by artesian water and continued stoping
Soil-collapse doline[4]	Collapse of soil because of: Lowering of water table, with consequent surcharge and collapse of soil arches Raising of water table, with consequent loss of cohesion of soil Flooding of surface, with consequent cohesion loss, suffosion, and surcharge
Solution doline	Lowering of bedrock surface because of:
Sunaerial solution doline	Subaerial solution of bedrock
Rock doline, solution pit, or karren well, depending upon size and shape[6]	
Ponor doline or swallet	
Sub-glacial doline	
Subsoil doline (or sub-alluvium doline, etc.)	Subsoil (or sub-alluvial) solution of bedrock accompanied by concomitant lowering of surface; availability of soil-CO_2 may favor relatively rapid corrosion of bedrock
Subsidence doline, structural sink (with rock-fill_, or geological organ with sediment fill)[7]	Interstratal solution of relatively soluble rock and concomitant subsidence of overlying relatively insoluble rock or sediment
Suffosional doline	Washing of soil (or other sediment) into underlying cracks and caves
Slumpage doline	Solution of rock fragments and bedrock plus down-washing on sediment into cracks; loss of cohesion by wetted soil causes local collapse of small arches over voids produced by solution and suffosion
Compaction-subsidence depression	Lowering of water table, with consequent reduction of void space and differential settlement of surface as water drains from sediment

James Quinlan, Nov.1971.

EXPLANATORY NOTES FOR CLASSIFICATION OF MAJOR TYPES OF DOLINES AND RELATED STRUCTURES

1. With the exception of the solution dolines, the occurrence of almost any of these doline types can be accelerated or triggered by earthquakes, other seismic activity, or faulting. Some might be triggered by mining subsidence.

2. Usually the collapse is through karstifiable rock that is similar to that of the subjacent cavity. Such dolines commonly allow access to an underlying cave.

3. Usually the collapse is through non-karstifiable rock or rock that is different from that of the subjacent karst cavity.

4. Soil-collapse dolines and compaction-subsidence depressions are the most common type of sinkhole in urban areas. They are anthropogenic because their development is triggered or accelerated by the works of man.

5. Some may have a very thin mantle of soil. Subaerial solution dolines are transitional to subsoil dolines.

6. If any of these develop chiefly beneath a snow cover they may be known as any of several types of snow-dolines such as: rock snow-doline, solution snow-pit, or karren snow-well, depending upon the size and shape of the depression. Advocacy of a specific name for these is not intended.

7. Structural sinks and geological organis generally do not have any topographic expression as a depression.

J.F. Quinlan.

In 1970 John Drake made a study of drift-covered gypsum in Wood Buffalo National Park, N.W.T. and Canal Flats, B.C. The study is primarily concerned with the hydrology of the area and he was working in an area with a limited number of sinkholes. His work does, however, suggest that there are two types, collapse and suffosion. The distinction between the two is the underground activity (Fig. 8). In the first case a major pipe system develops in the bedrock causing one or a few eventual catastrophic subsidences from above. This would suggest that water is moving rapidly and directly through the system. In the second case the movement of water through the system is by way of many cavities, often small in diameter, and frequently close together, all usually permitting a diffuse flow path through the bedrock. In this case collapse occurs more gently as the unconsolidated material is washed through the system - in the same way that sugar flows through a funnel. In both cases there has to be preferential solution along some lines of movement and in the case of gypsum/anhydrite where the solution by water expands and seals the cavities this preferential solution does not occur quickly. In Drake's study areas the gypsum beds were fairly continuous and almost flat. This is not the case at Codroy, where the complex structure will add further complications. The problem here is to see if one or both systems of genesis are present; then to determine any real distinction of form between the features formed by these processes. It is therefore necessary to look first at the apparent genetic sequence of the sinkholes' development.

Ideally one might expect the following sequence of events. If major pipe flow is the process, in the early stages of collapse a roughly cylindrical form would result with steep unstable sides and a fairly shallow flat bottom

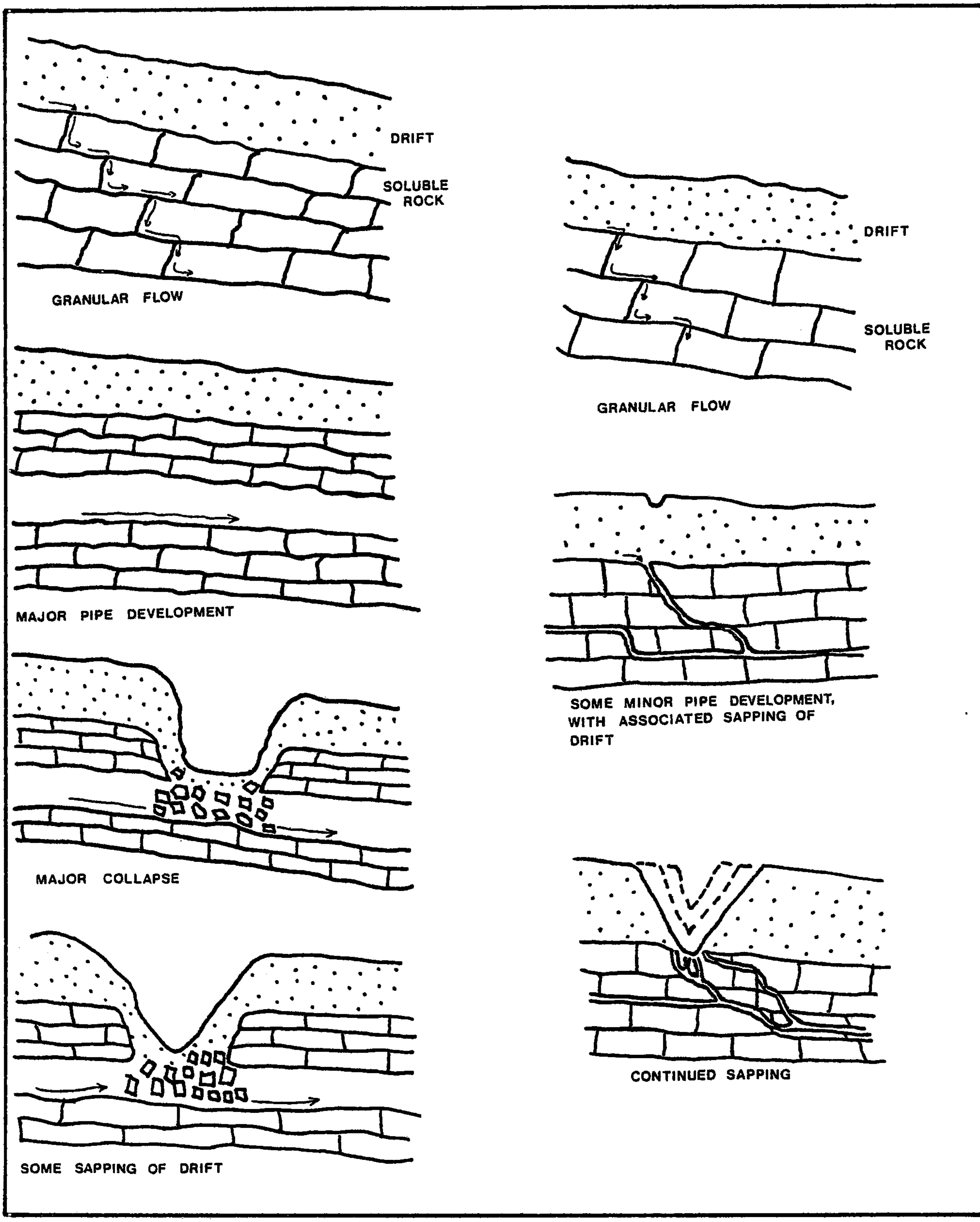


FIGURE 8. MODES OF SINKHOLE DEVELOPMENT AFTER DRAKE 1970.

to the depression. As this now totally displaced material is washed through the system and stabilization begins, the steep-sided cylinder will develop into a funnel shape, as more material is removed from the sides and falls to an angle of repose. Depending on the composition of the material and its hydrologic characteristics, the feature may then simply become a larger and larger funnel until some external factor limits further growth. This may be a change of composition, amalgamation with another feature, or a change in hydrologic conditions. The feature may, however, be modified further to form a basin shaped feature with steep sides and a flat base. This is likely to be the case for example if a high clay content causes a lining effect in the depression and water is able to accumulate. In time amalgamation is likely to take place creating uvalas or compound sinks (Fig. 9). The best example of this is the Dump Road Sink System. Here a set of bowl shaped sinkholes form a somewhat clustered formation in which the main sinks are water filled. In this case the water levels change rapidly and partially independently. Evidence shows that these are frequently one large pond, with permanently dry sinks along one side. All of these are part of the same uvala. They appear to be fossil features or are eroding so slowly that the vegetation cover is abundant (Plates 23 & 24).

A primary examination of the sinks in the area merely divided the depressions into those which are or are not water filled (Table III). It might be assumed that all water filled sinks would be somewhat similar in size or shape, or that those depressions close together would all have water levels at the same elevation. This is not the case. Certainly the largest sinkholes are water filled, but other sinks at the same elevation or adjacent but lower are dry. Similarly, at some sites relatively small sinks are water filled

Plates 23 & 24. Sinks amalgamating to form uvalas.

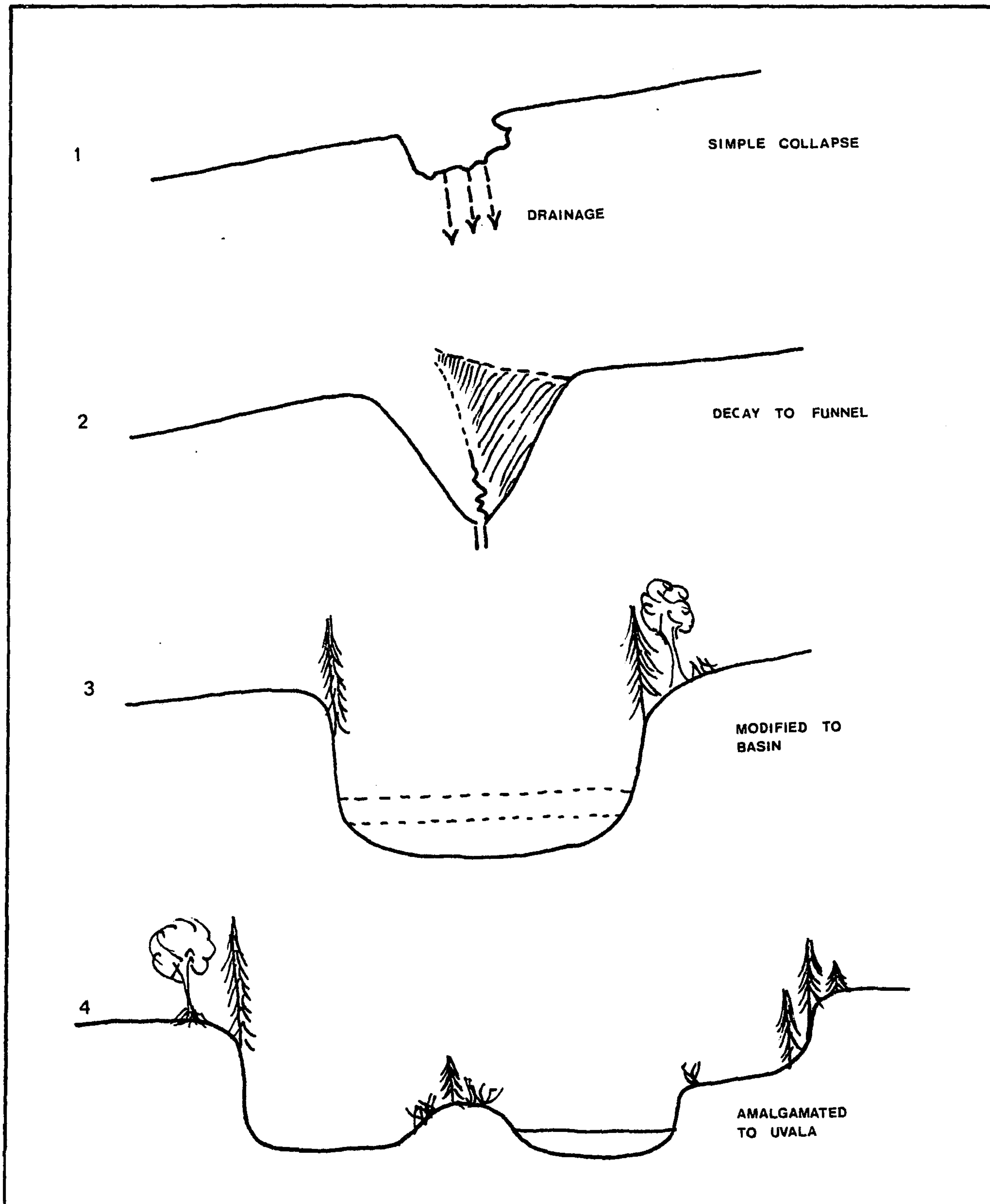


FIGURE 9 SCHEMATIC DIAGRAM OF SINKHOLE DEVELOPMENT IN GYPSUM

TABLE III

HYDROLOGIC CLASSIFICATION OF SINKS

Ponded		
	Permanent Static	17
	Permanent Flowing	3
	Seasonal Static	7
	Seasonal Flowing	2
	Flushing	1
Dry		>100

while larger ones are dry. If one accepts the conventional idea of a water table, in this area there must be very steep and irregular hydraulic gradients. This inconsistency in height of a water table could of course be a reflection of the extremely contorted nature of the rock beneath the till. The soluble gypsum and the insoluble shale and sandstone are all in contact with the base of the till in different areas, due to both the general tectonic contortion of the region and to the specific plasticity of the sulphate rock. Where the till base and the gypsum are in contact water will pass through the system more quickly. Where non-soluble rock is present, ponding is more likely to occur.

An alternate and more likely explanation for the ponding is local perching of water as a result of a clay sealer formed at the base of the sink when fines settle on the bottom. This perching seems to be randomly distributed throughout the area, with perhaps a greater tendency to greater frequency among the bigger sinkholes where there is a greater amount of clay to act as a sealant. In addition an analysis of particle size in the till did show a greater amount of fines progressing inland: most of the water filled sinkholes are away from the coast. (Fig. 9a).

That some of these water filled sinks are seasonal is easily explained as there is a much greater availability of water in the spring, and over the summer much of the water drains gradually through the system. This effect is further enhanced by the evapotranspiration rate in the dry summer weather. Thus some closely spaced dolines, such as Dump Road Sinks 5, 6 and 7, appeared to be three separate water filled entities in the summer of 1976. However, in winter time the water rises enough to join all three into one large pond.

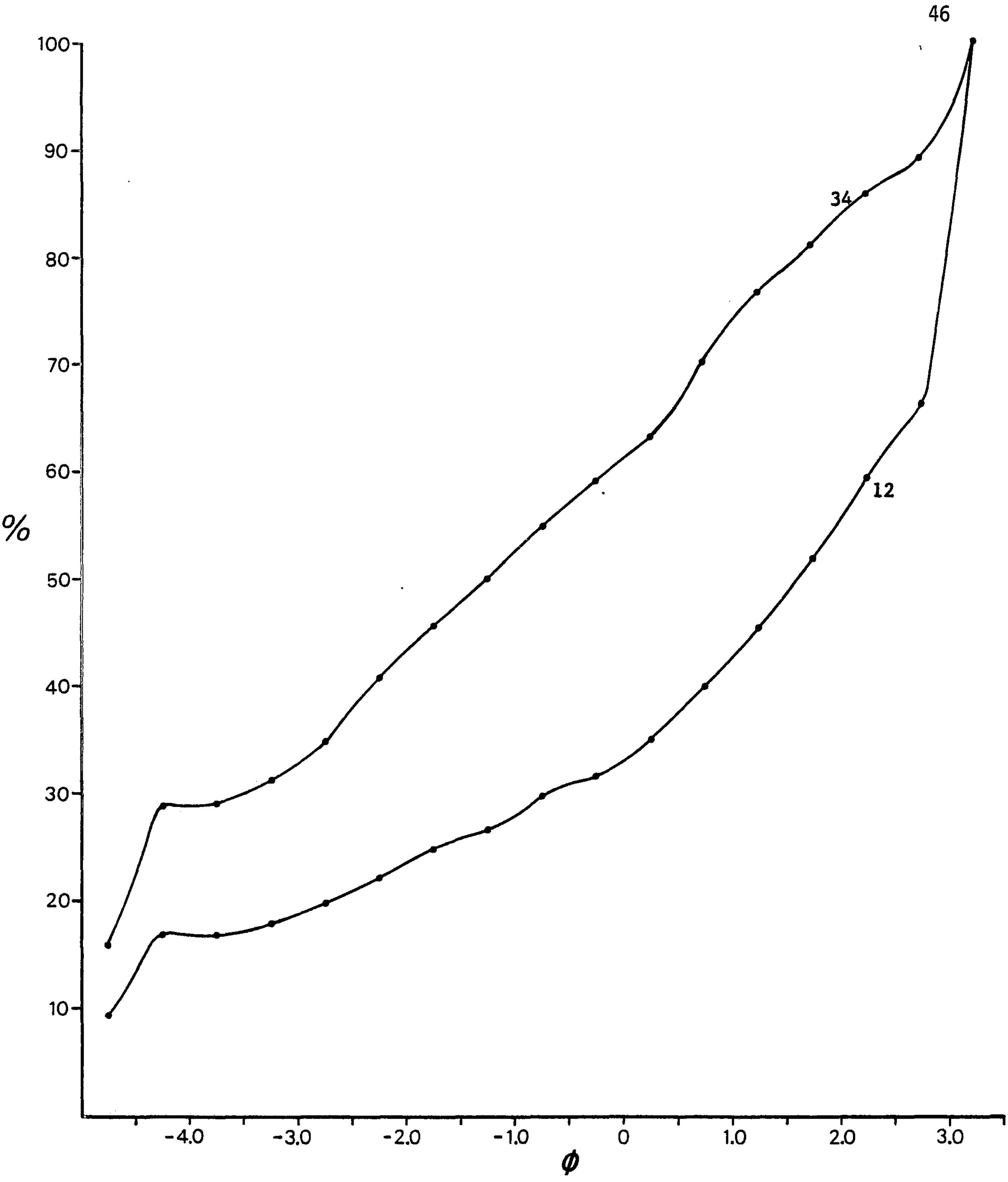


FIGURE 9a CUMULATIVE CURVE TO COMPARE COASTAL (12) AND INLAND (34) TILL SAMPLES

One large doline, Car Sink, (Plate 25) exhibited a unique cycle, water filling gradually over several years, then flushing dry in a space of hours before beginning the process again. This sinkhole, about 45 metres in diameter, was formed catastrophically some 12 years ago. It has been artificially infilled with rubbish twice but collapsed again, getting slightly bigger each time. It appears to be reasonably stable at present and the owner is once more trying to fill it. It flushes into Darnis Brook which is about 200 metres away and approximately 15 metres below the sink's current water line. It is possible that the pipe draining this funnel-shaped sinkhole is plugged with fines from the till. Water accumulates until some critical stress threshold is reached and the weight of water (and cars) breaks through the seal and flushes out the system. Once the water has drained, the water-logged sides of the doline slide slowly into the centre, reblocking the pipe.

Shape cannot be correlated directly with wet or dry states as both funnel and bowl shaped sinks contain water, but it would appear that the bowl-shaped ones are older and the flatter base is a result of the settling out of fine material. Funnel-shaped water filled sinkholes, such as Eyeglass and Woody Head Ponds appear to be lined with boulders rather than fines, although the latter may be beneath the former.

Two further methods of classifying the sinkholes were considered: by size and by shape. To supplement these the distribution pattern was studied by nearest neighbour analysis and quadrat analysis. Nearset neighbour analysis was attempted on the large and medium classes of sinkholes, which are visible on the air photographs. Measurements were taken to the fourth order. Results are quoted in Table 4.

At the first order the distribution of sinkholes is close to random with a slight tendency towards clustering; while at the second order the

Plate 25. Car sink - Woodville, Nfld.

TABLE IV

NEAREST NEIGHBOUR ANALYSIS

R_1 = 0.796 R_2 = 1.076 R_3 = 1.446 R_4 = 1.527

R_1 R_2 R_3 R_4

Clustered Random Uniform

system is almost ideally random. By the third and fourth order a tendency towards uniformity has developed. The fact that clustering is not more pronounced can be explained partly by the absence of measurements for the class of small sinkholes. Personal reconnaissance shows that many of the medium and large dolines do have much smaller ones associated with them, as noted. These surround the greater sinkhole at fairly regular intervals and at similar distances from its rim. Drake and Ford (1972) put forward a theory of clustered sinkhole development and distribution, in which the major feature is the dependence of one sink upon another. The small sinkholes develop round a larger one when the large sinkhole causes a depression in the local water table level. As a result of this the hydraulic gradient is steepened immediately surrounding the depression. The presence of this drawdown cone will cause more depressions to form within its perimeter. If the system were to continue to its limit a whole series of daughters would develop, getting shallower and shallower with increasing distance from the parent doline (Fig. 10). In the study area there are some sets that have developed into a two order cluster, but no farther (Plate 26).

There is also a linear clustering pattern which may well have a geological or geomorphic basis. There is for example a distinct line of sinks from Long Pond, following the course of Gravel Pit Stream (Fig. 10a). While it is difficult in this area to be sure that the stream was present before the sinkholes, it is probable. This would influence the development from the streambed and causes preferred development of sinks along or adjacent to the stream channel. These sinkholes in turn have slightly deflected the original path of the stream. Sections of now dry valley, close to the present water course indicate that this type of stream piracy has occurred (Fig. 11).

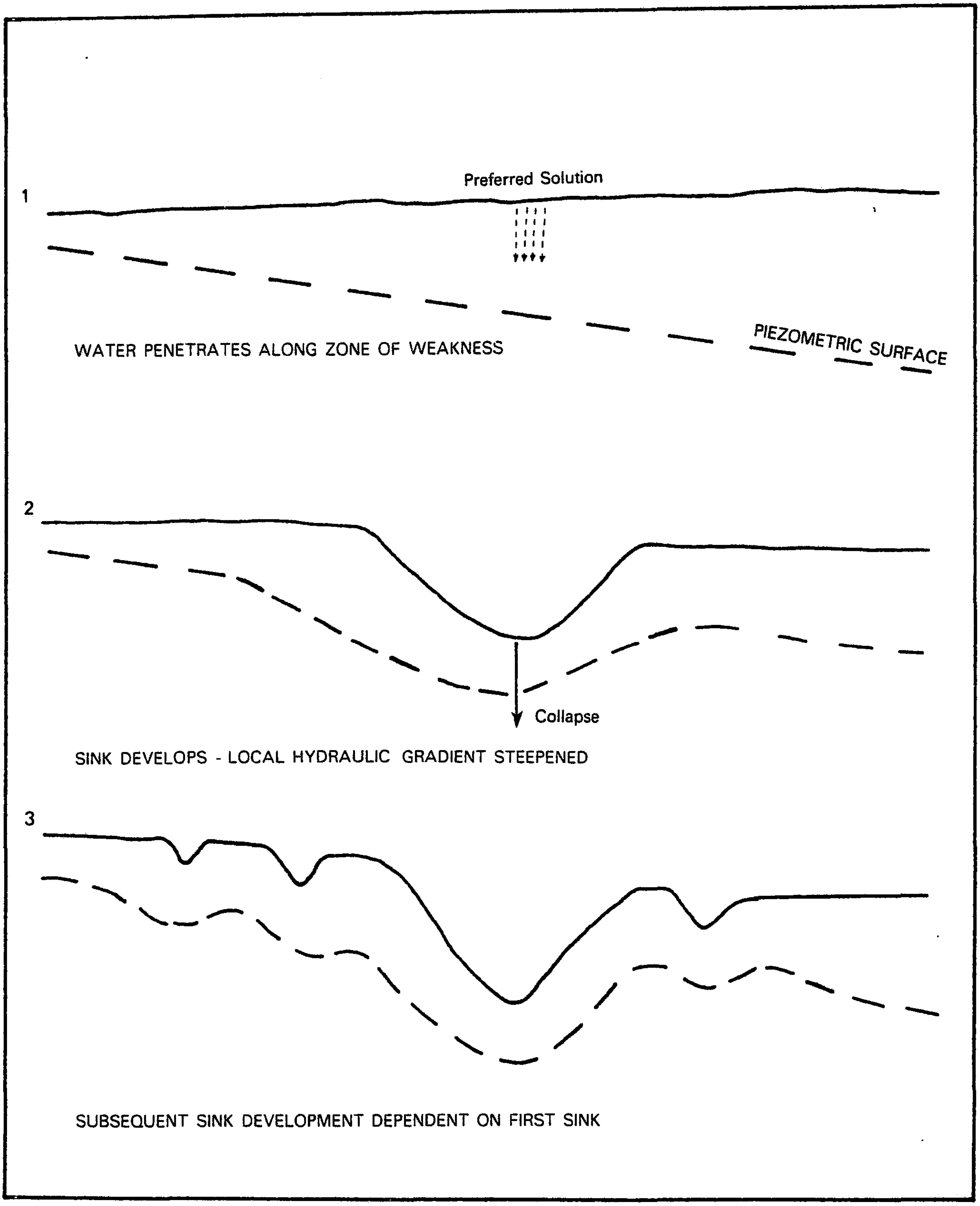


FIGURE 10 PARENT-DAUGHTER SINKHOLE DEVELOPMENT (after Drake and Ford)

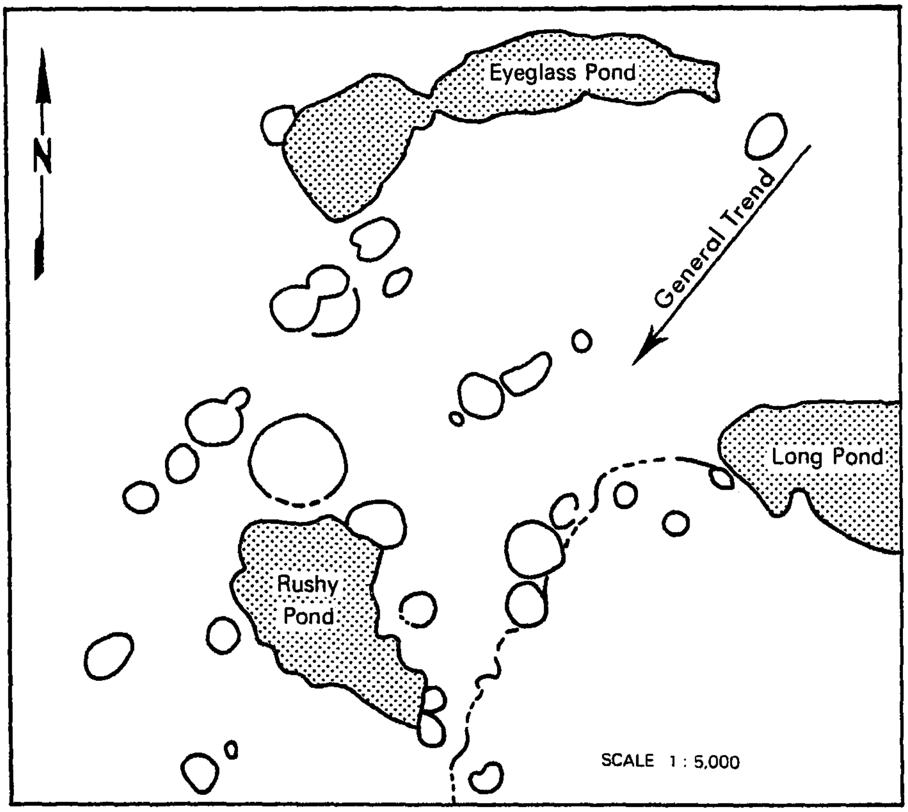


FIGURE 10a LINES OF SINKS FOLLOWING A GENERAL TREND FROM LONG POND AND EYEGLASS POND

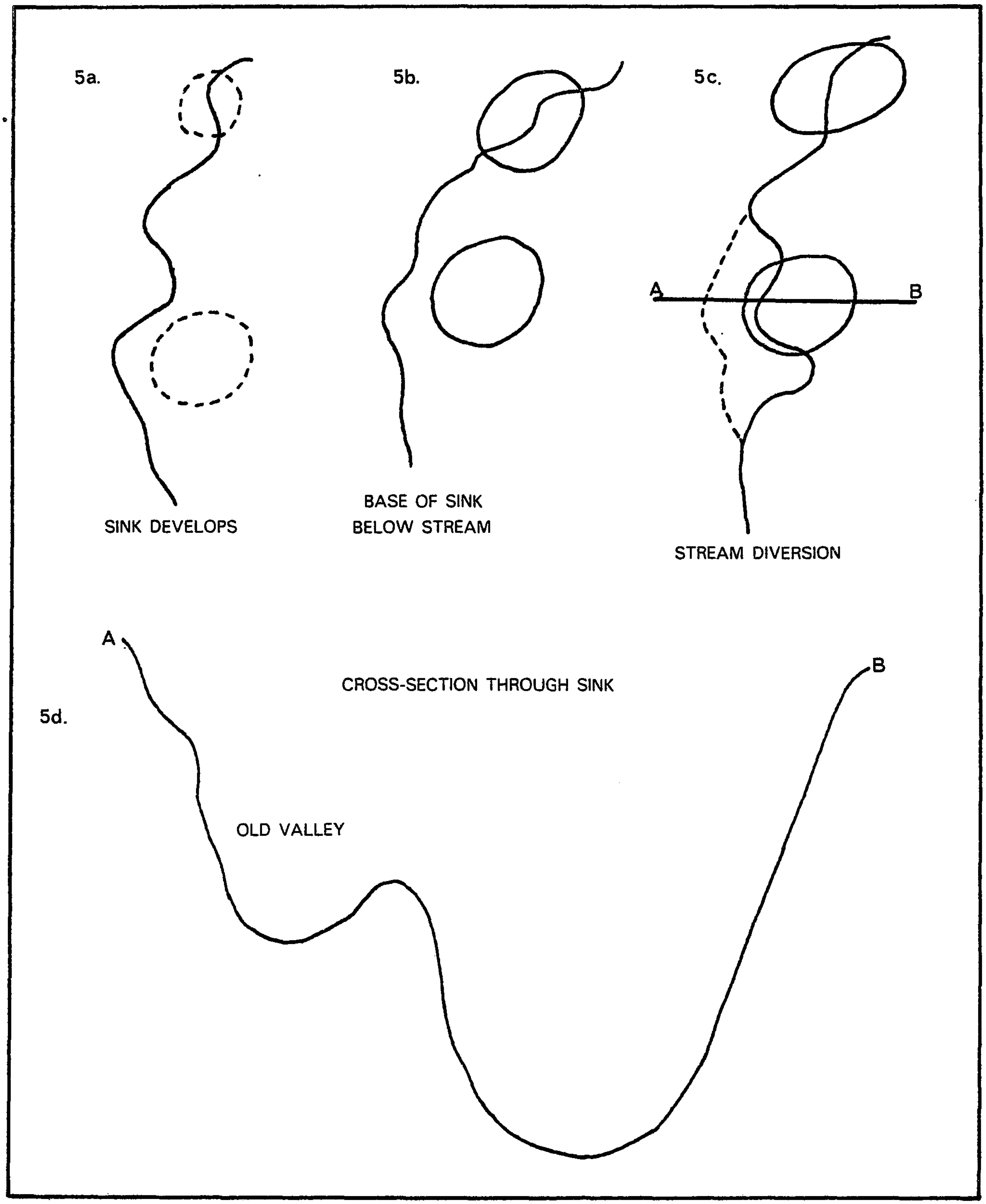


FIGURE 11 STAGES OF RIVER CAPTURE ON DARNIS BROOK

An almost straight line of at least ten sinks has developed southwest from Eyeglass Pond. Most of them are more than ten metres deep and there is no evidence of a stream valley linking them. Nor is there any evidence that they are ever water filled. It is of course possible that there is a direct association between these and a gypsum 'belt' below the till. It might also be that the till layer is very thin at this point. A third example of a linear relationship is that of the Dump Road Sinks. In this case several medium-sized sinkholes, some water filled, some dry, form a chain. This is quite separate from but parallel to Darnis Brook, the principal surface stream. Here the clustering effect has developed into a series of coalescing sinks or an uvala. This process of coalescence is still active today, as the walls of the individual depressions slump inwards and the fine material is washed out by spring melt. Other amalgamations show a series of dry sinkholes, for example extending inland at right angles to the cliffs. Here each sink is separated from its neighbour by a low col and the whole series of five or six sinks are themselves in a depression. While this linearity may indicate geologic control in these instances, it is not indicative of the whole area.

It is probable that the linear clustering does not show in this statistical analysis. One of the limitations of the test is the fact that particular patterns tend to obliterate its significance. Thus clustering will show up if it is circular and several points are the nearest neighbour of others. If the cluster is linear this does not show.

Second order analysis confirms the randomness of the sample, suggesting that there is no one predominant control on the sinkhole distribution. Possibly the till cover effectively masks the expected controls.

Third and fourth orders suggest a more uniform pattern. This might imply that the gypsum is uniformly distributed throughout the area at the scale of third order-plus separation. The evidence at the coast does not support this idea and also the effects of the varying depth of the till mantle must not be ignored. These would tend to mask the direct influence of the gypsum. It is also possible that extending the analysis to the fourth order is too much. If this is the case then the nearest neighbour analysis indicates a random pattern, with some tendency towards clustering.

To check this, quadrat analysis was applied. Quadrat size was determined by the formula (2a/n), each square being twice the mean area round each point in the pattern (L.J. King, 1969). Expected and observed frequencies were tabulated and a chi-square test performed to test the significance. In this situation the expected and the observed frequency should be the same if the area has a uniform distribution of sinkholes, as indicated at third order in the nearest neighbour analysis. The nul hypothesis is therefore that the expected frequency and the observed frequency are the same. The results of the χ^2 and the quadrat analysis show this to be incorrect. The observed and expected frequencies differ greatly, therefore the distribution is not uniform.

Thus from two independent statistical tests it would appear that the large and medium classes of sinkholes are randomly distributed over the plain. There are of course the above mentioned exceptions to this, but these findings are further backed up by the size distribution analysis of the features.

Although the depressions have a considerable size range they fall into three main categories. Small ones are less than 2.5 metres in diameter and very shallow in most cases. With very few exceptions these all appear to have developed by gradual sinking, not by collapse, i.e. they are of suffosion type.

Medium sinks are 5-30 metres in diameter and range from 3 - 4 to 15 metres deep. They vary in shape and may or may not be water filled. Large sinks e.g. Rushy Pond are almost 150 metres across and are water filled.

These large ones are somewhat different from the rest, and in fact from each other. Eyeglass Pond is definitely a series of three or may be more sinks which have amalgamated. It has steep sides which are still actively slumping in places. The deepest of the sinks is funnel shaped, reaching at lease 20 metres in depth. The rest of the pond is somewhat shallower with a bowl-like form. There is evidence that water seeps into this doline through an underground route or routes. It also appears to have an underground outlet. Rushy Pond and Long Pond are more difficult to define. There are also sinks around the edges of both these ponds and Long Pond exhibits sinkhole characteristics such as steep, actively slumping sides. It does have an overland flow although this is almost always dry. There is also evidence of groundwater flow reaching it. Rushy Pond is very shallow, has gently sloping sides and a very intermittent overland flow outlet. It also receives some underground flow. The evidence for underground flow to all the ponds was established by dye tracing. These ponds are much larger than anything else in the area and I suggest that sinkhole genesis cannot totally account for their development.

There is no sharp size division between the medium and small sinks, nor do they appear to be in any progressive sort of order. One would expect, all other things being equal, that the sinks closest to the cliffs would be the largest. Here the hydraulic gradient at initiation of karst development would be steepest and the features therefore should be in a more advanced state of development. This is not the case: there are numerous small sinkholes as well as large ones along the coast, while the Dump Road sinks which

which are far inland are larger than most coastal sinks. The sinks are not therefore developing in relation to any simple zonal hydraulic model.

There is, however, an indication that small sinkholes in many cases are directly associated with larger ones and some of the medium ones are directly associated with the large ones. This suggests the parent/daughter relationship (Drake and Ford 1972) discussed previously.

The next consideration was that of shape. Most of the sinks which have developed within living memory formed by catastrophically swift collapse, some as recently as spring 1975, and the initial shape of the features was cylindrical. These catastrophic events apparently occur in springtime when there is an excess of water in the till due to snowmelt and runoff. Instability may also be due to the effects of cold and frost action in loosening the till. While it is possible that the dissolved gypsum below the till has created a particular shape, there is nothing to suggest that the surface feature must be a direct reflection of this. It is possible that the material is being removed through a series of pipes. When a large enough cavity exists below, the surface collapses into it. The subsequent variations in shape are then a product of evolution away from the cylinder. From a shallow, perpendicular-sided feature evolution in this area produces four basic shapes.

The most common, (one that is found in all sizes of dolines) is the simple funnel with an underground outlet at the base. One would expect this shape to evolve quickly from the cylinder when material from the edges is washed down the sides, or slumps like sand in a funnel. If this was the case one would expect them to be the smallest also. They would gradually enlarge with age, filling out at the base and widening at the rim, to create a second shape, the bowl. There are a number of bowl-shaped sinkholes in the area and the overall gradient of their sides tends to be shallower than those of the funnel-shaped depressions. The sides of these features are generally stable and vegetated. The bases are covered with fine sediment which acts as a liner to the doline, usually preventing water from escaping. These bowl-shaped depressions are all water filled; however, they are not the only water filled type. Thus everything indicates that these bowl-shaped dolines are more mature than the funnels and appear to have reached a state of equilibrium, for there is little or no sign of mass wasting at present. This state of apparent equilibrium is not confined to the bowl-shaped features. There are also a number of the funnels which do not appear to be actively denuding at present. Nor does this state of equilibrium appear to be a function of size, for there are small funnel shaped sinkholes (diam. 2 metres, depth 1 metre) as well as large ones which are apparently static. The sides are grass or shrub covered and the larger ones even have dense base growth, often of trees. The shallow funnels are basically circular but the deeper ones are often steeper on the upslope and it is this side that is more heavily vegetated.

It has been suggested that all the sinkholes in the area are essentially collapse features, since the solution is in the gypsum below the surface. Till then collapses into the solutionally formed cavity. It seems possible that some of the very shallow depressions may be an expression of the rock being closer to the surface. In this case the amount of solution would be proportionally less before collapse occurred, than in the areas of thicker overburden. In some cases the larger funnel-shaped dolines are deeper than they are wide; 15 metres deep, diameter 10 metres, while others of similar diameter have a depth of only 5 metres maximum. This too suggests that the shallower ones are either newer or that they have developed where there is less till beneath. That there are funnel shaped sinks of various depths and widths does suggest that they do not all develop into bowl shapes as they mature, although many apparently do.

While bowl-shaped sinkholes are generally symmetrical, assymetry is a predominant characteristic of the funnel-shaped depressions. Many of them are slightly elongated in a down slope direction and they are also steeper on the upslope side. This is particularly noticeable in the larger ones which have preferred vegetation cover (Plate 26). The pattern is further emphasised at the bases where there are accumulations of small boulders. These are apparently kept free of sediment by water which collects periodically, then drains through the sinkhole. In almost all cases the boulder mats are also elongated downslope (Fig. 12). During the field season 1976, there was no evidence of standing water in these sinkholes. It is suggested that the only time there may be ponding is at the end of the winter during snowmelt. This would also explain why the sides of the sink are not active, or at least not visibly so. In the smaller sinkholes there is no predominant drain, but water can percolate through the till at any point. The effect of gravity will concentrate this percolation at the lowest part of the depression.

While the elongation is partially a function of slope it is probably also a function of depth. This elongation is certainly more pronounced in the larger deeper sinkholes. None of the water-filled sinks is elongate, suggesting that the process of continual draining with short or non-existent periods of ponding is the main reason for the elongation. Drainage will always be in a downslope direction as well as gravitationally inward. Once the feature is initiated the process will be self-perpetuating. As the slope becomes more pronounced, the more the water falling in the sinkhole will collect and drain on the downslope continually sapping into the downslope bank: this will make the downstream bank more unstable and

Plate 26. Elongate funnel shaped sink.

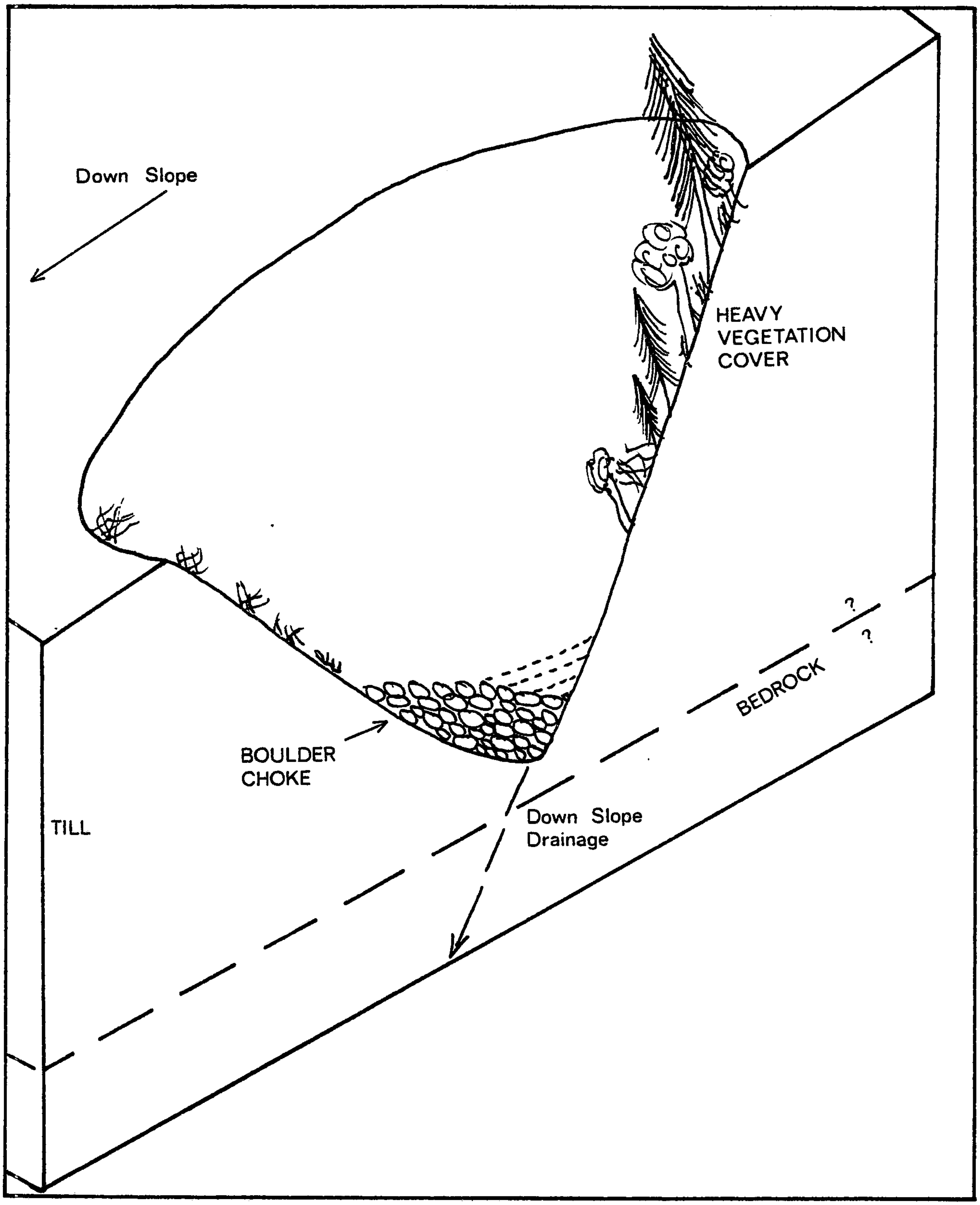


FIGURE 12 EXAMPLE OF AN ELONGATED SINKHOLE ON THE WOODVILLE SINKHOLE PLAIN

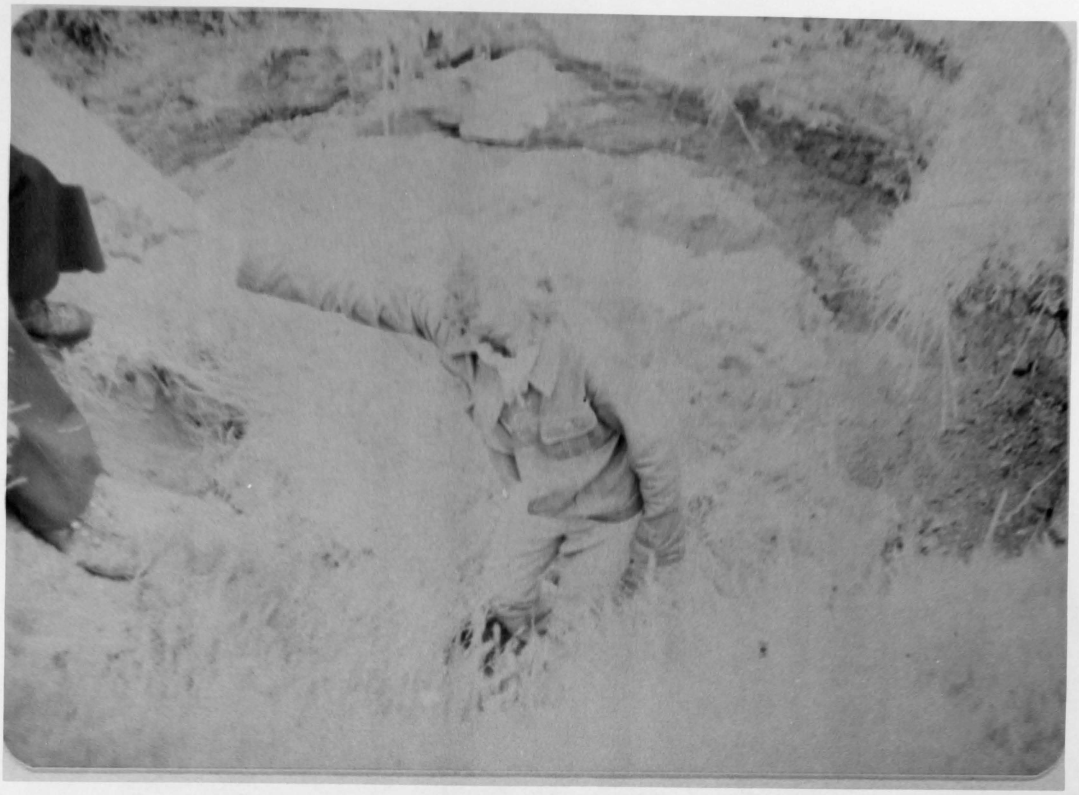


Plate 27. Recent collapse feature.

Plate 28. Shallow surface depressions.

susceptible to slumping.

Despite the stability of most of the features, there is some evidence of recent collapse. Some of the sinkholes do display shear faces and new depressions do appear; both in conjunction with existing sinkholes and in previously unpitted ground. Examples of catastrophic events are recounted by many of the local inhabitants and at least one major sink flushes on a regular basis (see Plate 25). The numerous examples of collapse features and gently subsiding features lends support to the concept that more than one evolutionary process is in progress. (Plates 27, 28). It appears that both methods suggested by Drake are likely. There are indications that conduit flow exists (page 81) but the conduits seem to be poorly developed. It is probable that they are formed along the contact zone between gypsum and other rock. It is here that water might accumulate and therefore dissolve more gypsum. These contact zones are unlikely to be of any great length or continuity because of the distorted nature of the rock. It would follow then that conduit development would also be disjointed. In addition, the heavy till mantle will tend to spread the available water before it reaches the bedrock areas. Despite these apparent drawbacks catastrophic events do occur. How are these catastrophic features created? Those which have developed recently are all within 100 metres of the cliffs or close to the incised stream valley. The hydraulic gradients are the highest of the karst region and would appear to encourage conduit development. The recent sinks then appear to be examples of collapse over an area of major pipe development.

For the area as a whole the general flow pattern suggests a more diffuse movement. This would be associated with the second system shown in Fig. 8. Sink development under such conditions would be of different rates. This would depend on factors such as the amount of unsaturated water in the system, the depth of till cover and the amount and nature of the gypsum underlying the area. That there appears to be no well defined size pattern as a result of this process is probably due to the contorted and sporadic nature of the gypsum bedrock.

It seems relevant to add a corollary to Drake's findings. In either hydrologic state sinks of varying sizes may develop in the initial stages of the process. In the case of catastrophic collapse this is particularly pronounced. There is evidence in the study area of recent, catastrophically formed, depressions ranging from about 1 metre in diameter to approximately 40 metres in diameter. Obviously an event producing a depression 45 metres wide and at least 20 metres deep would be somewhat earth shattering. (In the land owner's words, "I thought me time 'ud come. The 'ole 'house shook").

There must be some stress factor in play here. The gypsum below the till is gradually dissolved away leaving a series of widened cavities. At some point the combination of water in the mantle, the depth and nature of mantle material and cavity size lead to a collapse of that mantle into the cavity. It is possible that the roof of gypsum cannot support the mass above, or the gypsum may have been entirely removed and the unconsolidated material collapses, (Fig. 13). Jennings (1972) discusses similar events in shallow limestone caves.

The evolution described so far may answer the questions of type and size. It also explains in part the overall pattern of distribution. It does not satisfactorily explain the randomness of distribution of size and type. There are all sizes and all types spread over the whole area; even within

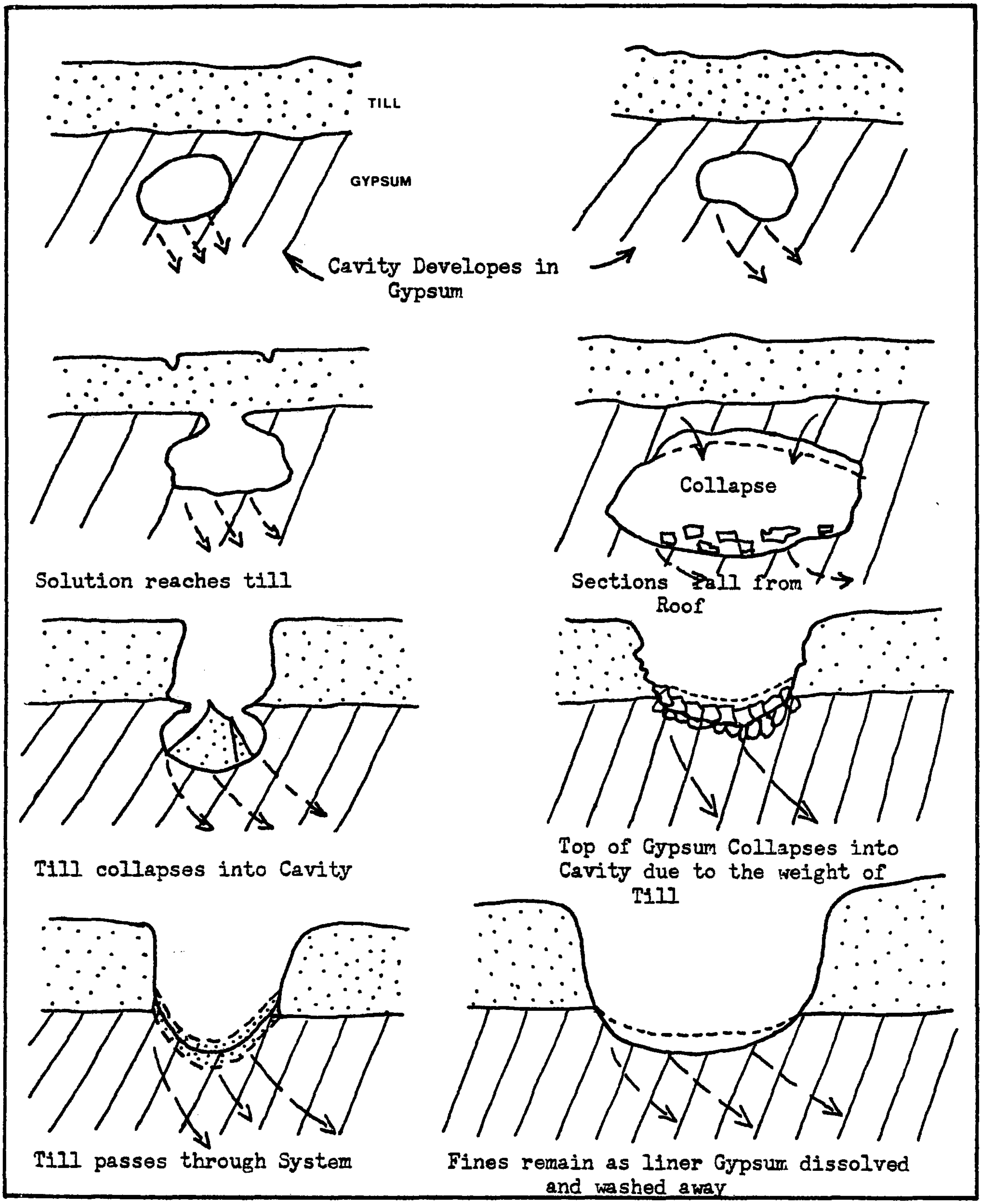


FIGURE 13 STAGES OF DEVELOPMENT OF SINKS BY STRESS COLLAPSE

an uyala there may be bowl and funnel-shaped sinks. The fact that there are large waterfilled sinks inland, and dry ones on the coast, as well as waterfilled and dry sinks side by side needs more explanation.

Although the greatest features, Long Pond and Rushy Pond, do have underground water supplies and smaller sinkholes associated with them, they do not appear to be true sinkholes themselves. They are neither rounded in planview, nor do they have any symmetry in cross-section. They do not appear to be amalgamations of several smaller depressions and one is considerably shallower than the other. The lack of soluble material in water suggests little contact with gypsum, despite their size. This is probably because they are 'lined' with till. It is suggested that they are basically glacial or possibly preglacial depressions which have been modified by karst processes in postglacial times.

Sinks such as Flounder and Woody Head have developed in direct relation to the stream and the gypsum which is exposed because of its entrenchment. Many of the small sinks have developed as daughters of earlier larger depressions. In several cases sinks have coalesced. Apart from these associations there is a randomness which is so far unexplained.

There is ample evidence to show that the till is not the same thickness throughout the area. In fact it ranges from 5-20 metres at least. It is possible that this is a result of differential movement of ice when the material was deposited but this seems too extreme a difference in such a small area. Also if this were the case one would expect substantial glacial topography, moraines, drumlins, etc. This is not so, for the area has a gentle slope from the mountains to the sea cliffs. There must be another reason for depth differences. It is probable that the preglacial surface of the area was not flat. In an earlier chapter (page 15) it was suggested that there were three directions of tectonic movement in the area. All of these occurred before glaciation and the surface must have undergone considerable weathering. Although the glaciation may have effectively smoothed away much of the earlier surface it is probable that the till has filled in the main depressions and created a reasonably uniform surface (Fig. 14).

In addition to this the preglacial tectonic activity has reorganized the original geology to such an extent that in different areas the gypsum will be at different depths below the present surface. Thus, available soluble material is at different depths.

Even if all the gypsum erodes at the same rate these different depths will mean that different stresses are needed to cause the formation of sinks above. It is unlikely that all the gypsum would erode at the same rate, for there are several different types of gypsum in the section. This too will effect the type and size of sink that will develop. Another consideration is that of adjoining material and the direction and type of folding which has occurred.

So it might be expected that most sinks would develop where the gypsum is closer to the surface, or where concentrations of water allow more rapid dissolution. Anticlinal folds will erode more rapidly than synclinal ones and might be expected to be closer to the surface, and many sinks would develop there. It is also possible that the deeper gypsum would be able to support more stress, therefore the underground cavities would be larger before the initial surface collapse occurs.

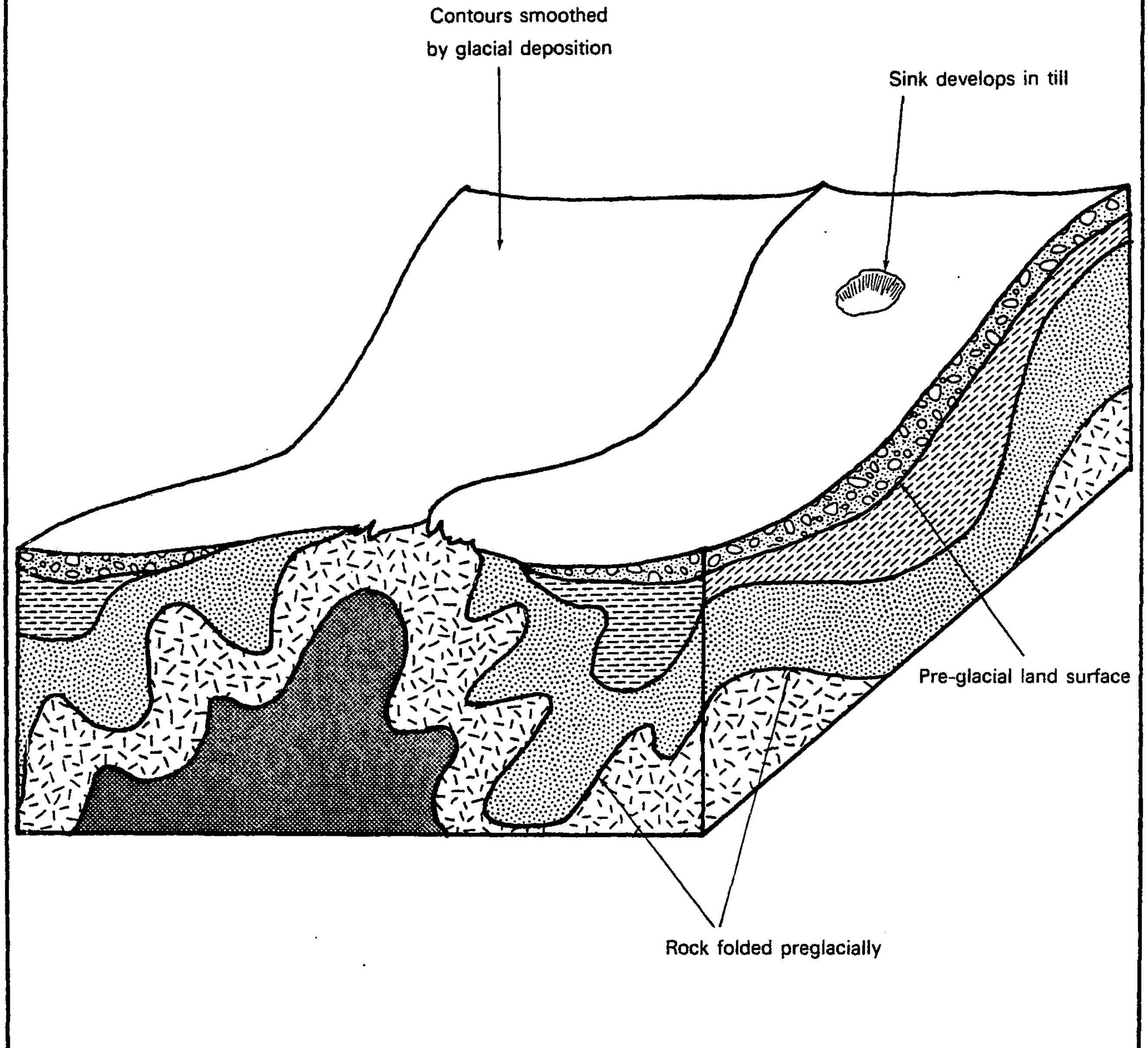


FIGURE 14 POSSIBLE GRADING OF PREGLACIAL SURFACE BY DEPOSITION OF TILL

Most of the area gets approximately the same amount of water, all from local precipitation. The only exceptions are Darnis Brook and lower Gravel Pit Stream, which flow all the year round. That there is not more sinkhole activity associated with the upper parts of the former must mean that the stream bed is effectively armoured with insoluble sediments.

As there are no surface streams flowing off the mountains onto the sinkhole plain there would appear to be no large amounts of water for concentrated solution. All areas receive groundwater recharge at approximately the same time and at the same rate. The varying depth of the till means that this water reaches the bedrock at different times. If it happens that it reached the shales first, it may be concentrated before it reaches the gypsum. Then preferred solution may take place along the contact zones (Fig. 15).

In the past the extent of the gypsum has been mapped from the coastal outcrops and the position of the sinks. This is much too simple and general to be accurate. If Drake's propositions are correct and this study seems to indicate that they are, then the sinkholes are not necessarily only immediately above the gypsum. Water will be concentrated along the junction with other rocks and maximum solution would then take place there, and the sinkhole develop adjacent to, but not directly above the gypsum band. It seems probable that both processes are at work here. Those sinkholes which develop to an ultimate bowl-shape are the result of major pipe development, with some rock collapse. Those sinks retaining a funnel shape are the result of minor pipe development and the removal of the till through that pipe system.

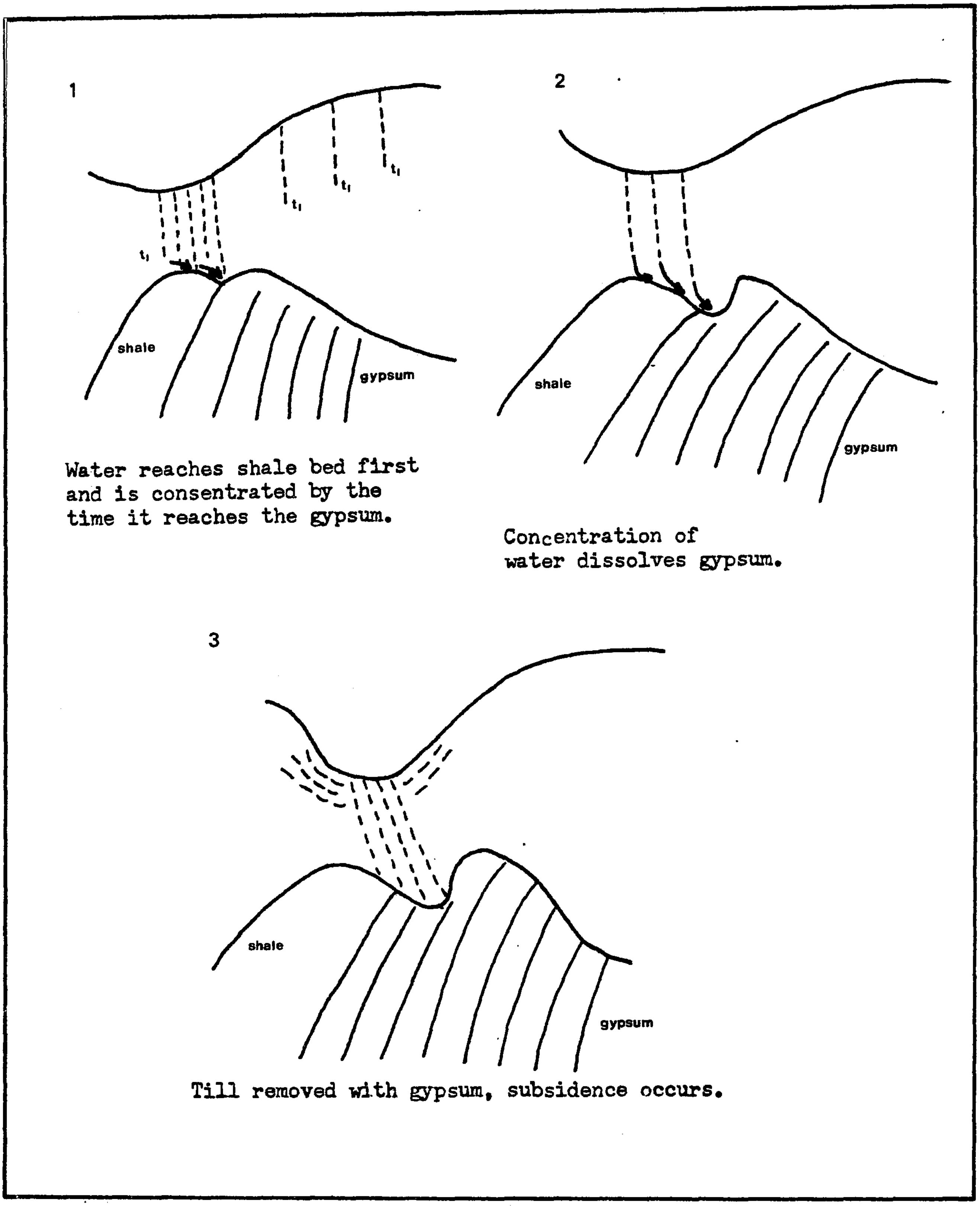


FIGURE 15 SIDEWAYS SOLUTION AND SUBSIDENCE BESIDE GYPSUM

The sinkholes of the area are varied in shape, size and process of formation (Fig. 16). Even Quinlan's classification needs some modification when being applied to this study. It does not consider the effect of a thick overburden; apart from this all the sinks in the Codroy area fit two major categories, collapse and suffosion; indicated at the beginning of the chapter. The first of these Quinlan subdivides into shallow and deepseated collapse dolines and soil collapse dolines. The first two of these refer to rock collapse in his definition, but the processes causing their development are those discussed herein, suggesting that he could extend these categories to include soil collapse dolines. In fact according to Quinlan's classification the sinks at Codroy could not be considered soil collapse features.

Obviously the process of development of gypsum sinkholes is made more complex by the lack of structure in the rock, the more simple and rapid solution process and, in this case, the varying thickness of the till mantle as well as the sporadic nature of the rock masses. However the features do have many of the same characteristics as depressions found in carbonate rocks and they do develop in a similar way. Therefore, it is not without justification that this author suggests that any attempt to classify dolines without including those found in gypsum, would be incomplete. That these surface indications of underground solution are considered by some authors to be transitory features also seems unjust. These dolines have been developing for hundreds or thousands of years and show no indication of degenerating any more quickly than they formed. In fact evidence suggests that many of them have reached a more or less permanent state. The general complexity of form and process is echoed in the complexity of sinkhole distribution.

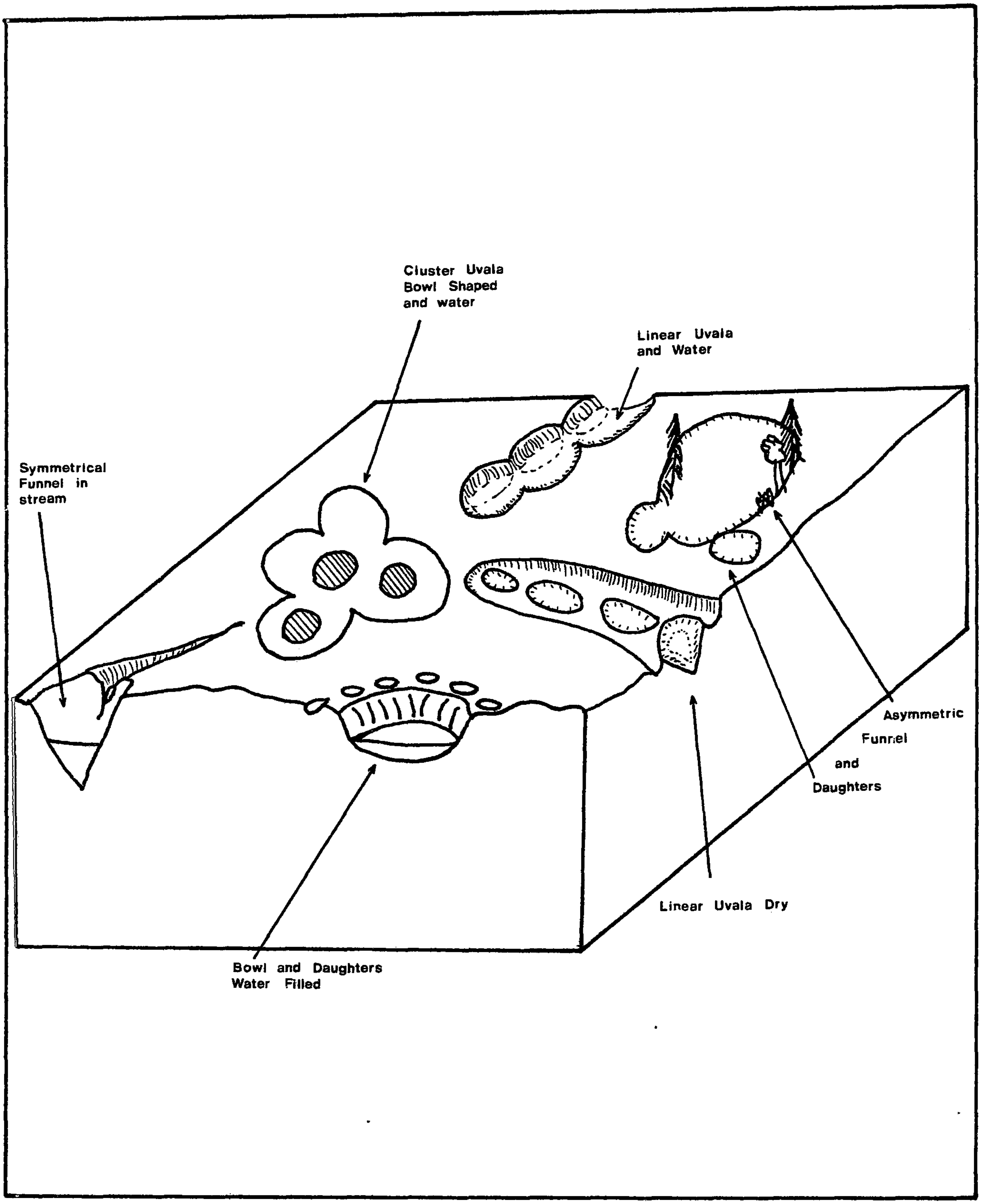


FIGURE 16 BLOCK DIAGRAM OF SINKHOLE TYPES IN WOODVILLE SINKHOLE PLAIN

CHAPTER 6

HYDROLOGY

In an area where solution is a major process of erosion, the status of water is a major factor. The amount of solution that can be achieved, in any karst, will depend amongst other things on the quantity of water available for solution and the temperature of that water. Precipitation figures for the immediate area are not available, but Stephenville, 110 kms north has about 500 cms of snow and 80 cms of rain per annum; while Port Aux Basques to the south has over 2000 cms of snow and 112.8 cms of rain per annum. Codroy therefore may be estimated at something between these two. (It is geographically closer in location and climate zones to the latter.) The proximity of the coast may lead to winds which would aid evaporation but the sea moderates the climate, keeping the temperature range narrow (less than 20°) and the maximum temperatures low (14.8°C). There is a considerable amount of snowfall from November to April but the temperatures are such that some of what falls in one storm in melted by the next. With minimum temperatures of only -6°C the ground will not be frozen for long periods allowing relatively free passage of water all the year round. Moderate rainfall during the summer months with few thunder storms and moderate temperatures complete the picture. These would seem to be almost ideal conditions for the maximum absorbtion of water into the system. The evidence of few surface streams or dry stream valleys would support the idea that there is little surface run-off and thence maximum absorbtion of terrestrial water. In addition the large number of depressions spread over the plain certainly act as catchments for both main types of precipitation. The till cover is such that water in these depressions may remain permanently, or for a considerable time into the summer adding water to the system even in dry seasons as in the summer of 1976. At this time the area received only 16 cms of precipitation.[1]

Assuming that this system has therefore an adequate supply of water for the solution processes it is necessary to look at those processes. It has been mentioned frequently in the literature that the actual rate of solution is very difficult to measure in concrete quantities. Water hardness is however a measure of the amount of karst mineral being carried by the water. Using the programmes initiated by Drake and Wigley (1970) it is possible to discover the effectiveness of various waters in the solution process. With this in mind a schedule of water sampling was carried out.

Water quality data for the Codroy area can be divided into two parts. An intensive study was made of particular waters from each major type and an overall pattern of spot sampling was undertaken from every available water source in the area. In addition waters from outside the study area but within the Codroy Valley geological area were sampled for comparison. All of these comparison samples were found to be almost totally lacking in carbonate or sulphate. Dye tracing was used to follow the path of underground water movement.

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1. These figures are for June, July and August at Port Aux Basques, where there is generally much more precipitation than in Codroy.

The waters of the area can be immediately divided into two main types. Pond water, as described in the previous chapter, is the first of these. The second, running water is divided into surface streams and coastal springs (Fig. 17).

The water sources of the ponds are several. Those such as Woody Head and Flounder have developed in direct association with the main surface stream. Woody Head developed adjacent to the stream, probably catastrophically and provided a lower valley for the stream to follow. Stream piracy resulted as the waters were diverted from the original valley. Flounder Pond represents a probable post-glacial knickpoint and thus a local base level. It is possible but not proven that a junction between the bedrock and the till is found here. The stream has not yet cut its channel down to the base of these sinkholes, so ponding occurs. The new profile between Woody Head and the sea is still being formed and it is likely that the cutting back has reached the narrow gorge just below the pond (Fig. 6, page 29).

Most of the ponds are permanently or seasonally filled sinkholes with no surface inflow. They must therefore gain all their water from precipitation and/or underground input. The study period was very dry; evaporation from these ponds was probably considerable and yet the water levels in many cases did not drop appreciably. This suggests that groundwater inflow is likely. This also suggests that there is some sort of water table. If perching were solely responsible for the water filled sinkholes, in a dry season there would be little source water and pond levels would drop. Water will maintain a particular level if there is a watertable, unless there is a change in the state of the system.

There are other indications of underground flow. A series of sinks

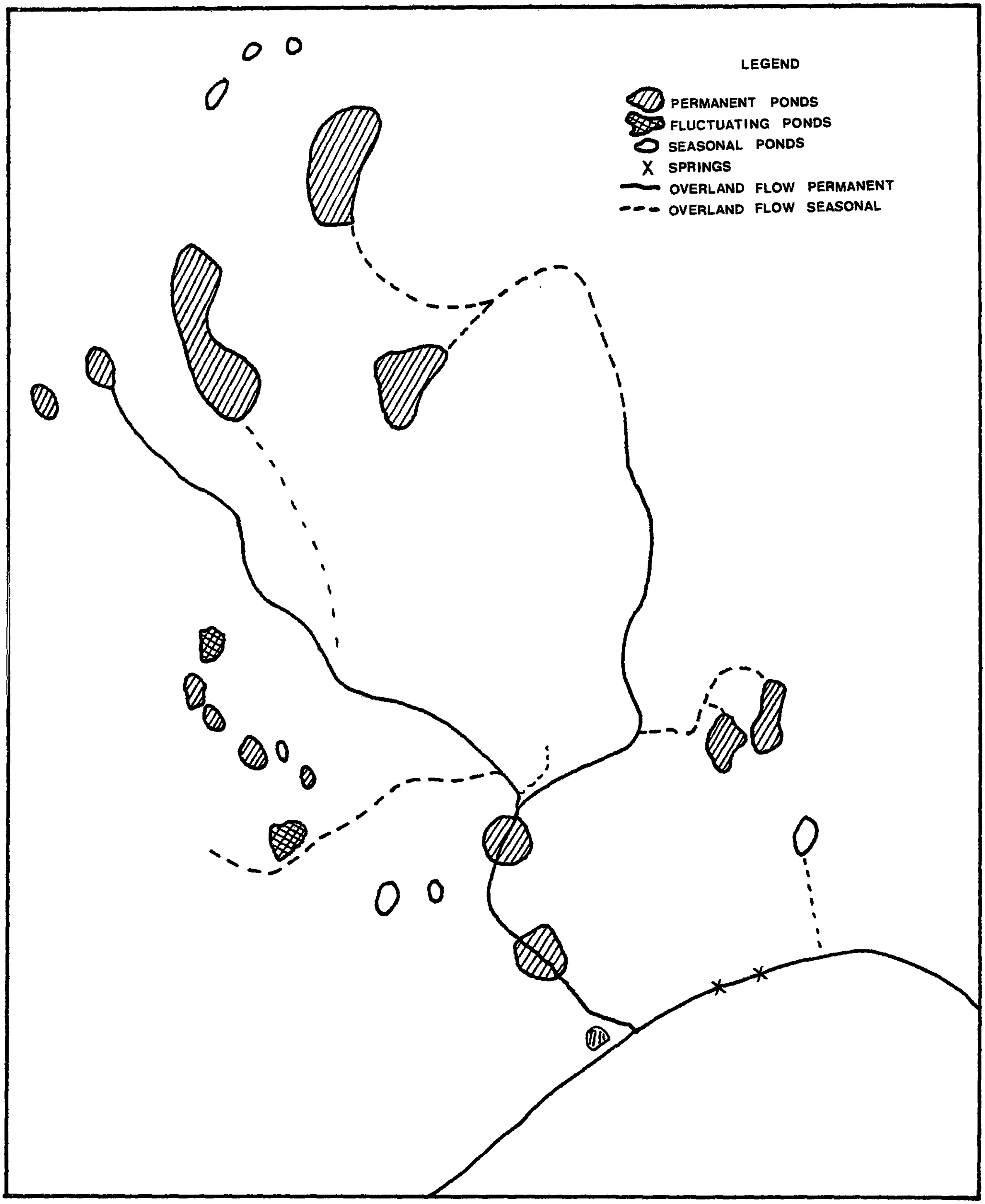

FIGURE 17 TYPES OF SURFACE WATER, WOODVILLE

such as Dump Road Sinks #4 - #7 fill up considerably higher in the fall and winter to make one large pond instead of four separate ones. By the end of the study period, mid-August 1976, #7 was almost completely dry, suggesting that water is escaping underground,(Fig. 18). That the other ponds in the complex did not lose an appreciable amount of water at the same time might defeat the argument for a local water table. The bases of the sinks are covered with very fine sediments and these act as a sealer, preventing the escape of water. As Figure 18, shows the emptying sink does have a deeper section at the upstream end of the uvala. The bottom of this is certainly lower than those sinks in the immediate vicinity.

Many of the dolines are seasonal pools as a result of heavy precipitation in the fall and winter and an accumulation of surface moisture during the winter. This is accompanied by heavy runnoff in the spring, which flows into the sinks and cannot be drained as fast as it ponds. As the season progresses the water drains away leaving dry depressions. Water obviously enters the ponds both from the surface and from ground seepage around the sides. That some sinks such as Dump Road Sink #7 and Car Sink have outward underground flow is obvious. The fact that dye traces were picked up in several places a very short time after dye was poured into the Dump Sinks proves that they too have underground pipes. None of these standing water filled sinks showed a total hardness of more than about 200 ppm of $CaCO_3$, suggesting a marked absence of contact with the gypsum.

The second source of surface water is found in the channelled streams which are fed from sinks or marshy areas where springs seep onto the surface. All the flowing surface water in the area was analysed close to the source and at several points along the length of the stream. Darnis

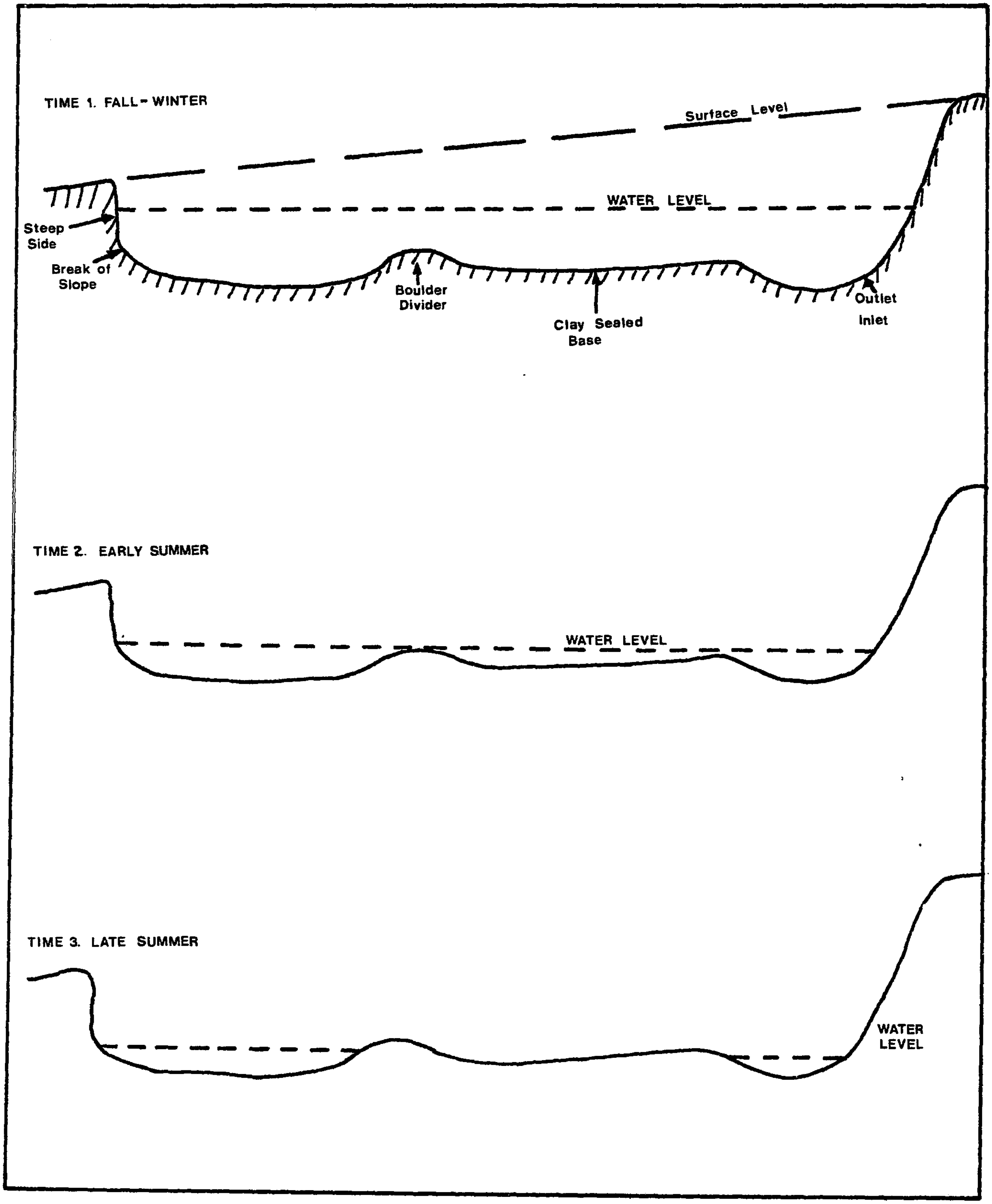

FIGURE 18 CROSS SECTION OF DUMP ROAD SINKS 6-7.

Brook, the only permanently flowing stream, has its source in a spring on the side of a sink. At that point the average total hardness value was only 94 ppm (total hardness values inside the gypsum area range from 50 - 900 ppm. 240 ppm average), suggesting little contact with carbonate or sulphate material. The most sulphate measured at this point was less than 30 ppm, which is approximately the same as the average for the non-gypsum area. Total hardness and sulphate values rise gradually down stream; Dump Road Bridge = 110 ppm, less than 30 ppm $CaSO_4$, Darnis Brook at the road 170 ppm, less than 60 ppm $CaSO_4$, but are still well below average. Gravel Pit Stream, while it is a tributary of the main brook has much higher values, (total hardness over 300 average, 200 ppm $CaCO_3$) and downstream of the junction of the two streams the values rise sharply. Flounder Pond has a sulphate value of 340 ppm, Woody Head over 360 and at the mouth of Darnis Brook the sulphate value is over 900 ppm. It would appear that there is no contact at all with gypsiferous rocks for at least half of the stream length. The till cover is evidently too thick. Once the stream reaches a lower level where water from the deeper sinks and the underlying bedrock can drain to it, the sulphate values go up. A small spring in the streambed below Woody Head has a specific conductivity of more than 1400 and its temperature remained constant all summer. This would indicate a deep supply of water which is in contact with calcium sulphate.

Darnis Brook is essentially in the youthful stage of development. As such it carried relatively small quantities of water along its course. It is remarkable then that it remains on the surface for its full length through an area of such high sinkhole density. This would lead one to suggest that the stream is perched on the till which covers the bedrock.

This would of course explain why the waters are not strongly enriched in gypsum. It is only in the lower reaches, below Flounder Pond, that the stream has cut through the till to the bedrock and here the sulphate values rise sharply. That Gravel Pit Stream has a much higher sulphate content may be due to some interference from man. The stream was so named because it flows along the edge of a gravel pit, where much of the till has been removed. Thus the stream may be in contact with, or closer to, the bedrock.

Darnis Brook gains water from springs at several places along its course. This may be assumed as the volume of water increases downstream before any surface streams join it. Those in the upper reaches must flow only through the till because they add almost no sulphate to the system. In the lower part of the stream these springs are large enough to be seen. There are also several surface tributary channels of seasonal nature joining the stream (Fig. 4 Page 26).

The third type of water is from independent springs which apparently flow underground for some distance to emerge along the coastal cliffs. The two main springs in the study area remained at an almost constant temperature and constant flow rate throughout the study period, (Table V). It is presently accepted that a relationship exists between the chemical properties of discharge waters and the type of underground water movement. Schuster and White (1972) working in the Appalachians suggest that on the basis of temperature a difference can be seen between deep diffuse-flow water and direct conduit-flow waters. The time it takes the water to pass through the system will also indicate the type of flow. Water showing diurnal or seasonal fluctuations in temperature and discharge has usually passed quickly through the system and is travelling in discrete conduits by the most direct route.

TABLE V

FLOW RATE AND TEMPERATURE OF THE CAVE SPRINGS, WOODVILLE

	CAVE SPRING 1		CAVE SPRING 2		Cumulative precipitation from June 1
Date	Temp.	Flow	Temp.	Flow	(mm)
Jul. 9	7 C	5/8 lts./sec.	7.5		43.5
10	7		8	5/6	43.5
11	7	5/7	8	5/6	43.5
14	7	5/8	7	5/6	46.3
18	7	6/8	7.5	5/5	51.1
21	7.2		7		Storm 24.4
22	8	5/8	7.5	5/6	79.6
25	7.5	5/8	7.5	5/6	79.6
29	8		8		Storm 16.0 99.7
Aug. 5	7.5	5/8	8	5/6	101.8
22	8	5/9	9	5/5	142.7

These flow values equal approximately 1.6 litres per second and 1.2 litres per second respectively.

This situation would generally be found in an area where the hydraulic gradient is high. Waters passing by a more diffuse route usually take a long time to reach the discharge point and discharge at a steady rate, with little change in temperature (Fig. 19). The Florida Aquifer is a good example of this latter type and Harrisonburg, W. Virginia, exhibits the characteristics of direct flow. Both of these areas studied by Schuster and White are limestone regions. The situation in the study area appears to be somewhat more complex.

That the two springs in the study area exhibit little fluctuation in discharge and temperature suggests diffuse flow, but in both cases at least modified conduit flow is present at the discharge point (Plate 29). The waters of both springs are very high in sulphate content and have high total hardness values. This shows that they are in contact with the gypsum, which in this area does not reach any great depth, nor does it extend over a very large area. The sporadic nature of the gypsum masses would make it a poor water holding reservoir yet the waters discharging from it have dissolved large quantities of sulphate. With water temperature of only 8^{o}C it would have to be in contact with a lot of gypsum or be in contact for a long time to be able to dissolve such quantities.

In an effort to see where the water might go in the system and how long it would take to pass through the system, dye was placed in the farthest inland/upstream of the sinkholes just before a heavy rainfall, (Plate 30). From that one injection traces of dye were picked up at a number of points in a very short time, suggesting that the water is flowing at least 0.5 m min. This fits more closely the rates of conduit flow according to Schuster and White (1971). The geographical divergence of

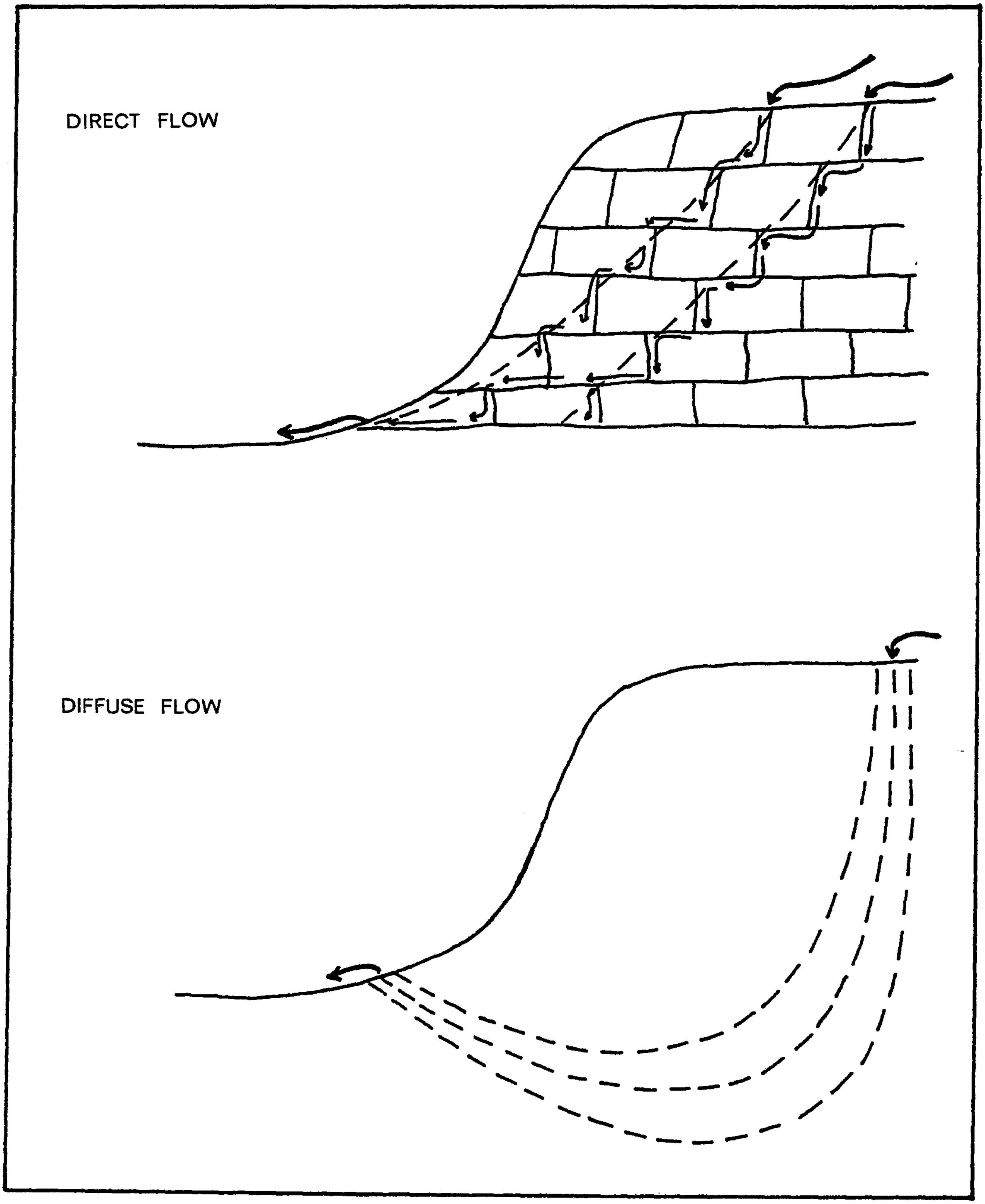

FIGURE 19 DIRECT AND DIFFUSE FLOW.

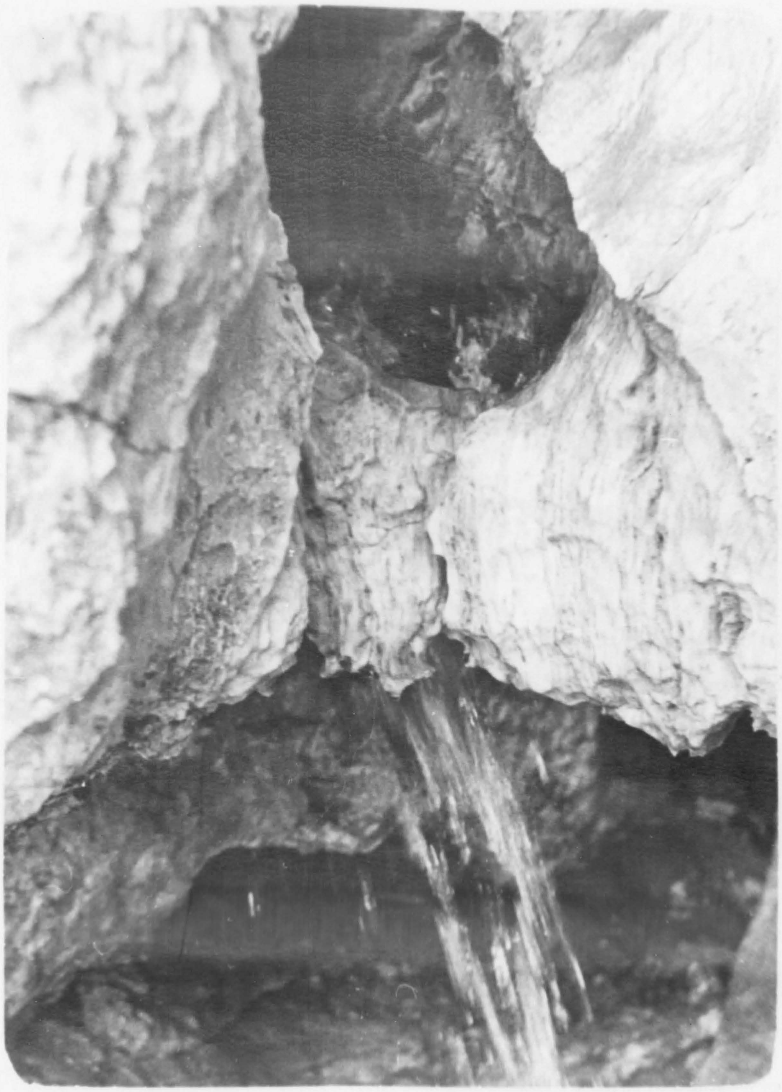

Plate 29. Conduit flow spring water.

Plate 30. Dye placed in water filled sink.

pick up points however indicates a more diffuse situation (Fig. 20).

So it would appear that there are elements of both direct and diffuse flow in the system and this over a very small area. Several explanations are possible. There is little flowing water on the gypsum plain and there is definite evidence that the water is not only passing through the till to the bedrock but also re-emerging through the coastal springs. The results of the dye tracing (Table 6) show that there is direct conduit flow through the system at this level. Water entering the system from precipitation directly onto the till plain passes quickly underground through the sinks and from wider seepage. It then reaches the interface of till and bedrock, where it is concentrated along the gypsum shale junction. Three conduits have developed and water passes rapidly along these channels often to re-emerge in sinkholes or along the entrenched streams at lower elevations. How much of the water entering the system this way re-emerges and how much leaks downwards into the diffuse system is not known. Some of the water must also be emerging from the coastal springs, which have very high sulphate values. However the spring water appears to remain about 8°C all the year round, for these springs do not freeze in winter. This water must be in the system for the temperatures to be this low, even in the middle of summer when the input temperatures are as high as 20°C. Water from the plain, especially during the periods of prolonged precipitation, pass into the lower parts of the Codroy Series and even into the Anguille Series below. There are no surface streams on the south facing slopes of the Anguille Mountains adjacent to the gypsum plain. These mountains do contain some limestone and calcareous breccias and it would appear that the water must be going underground. In time this water

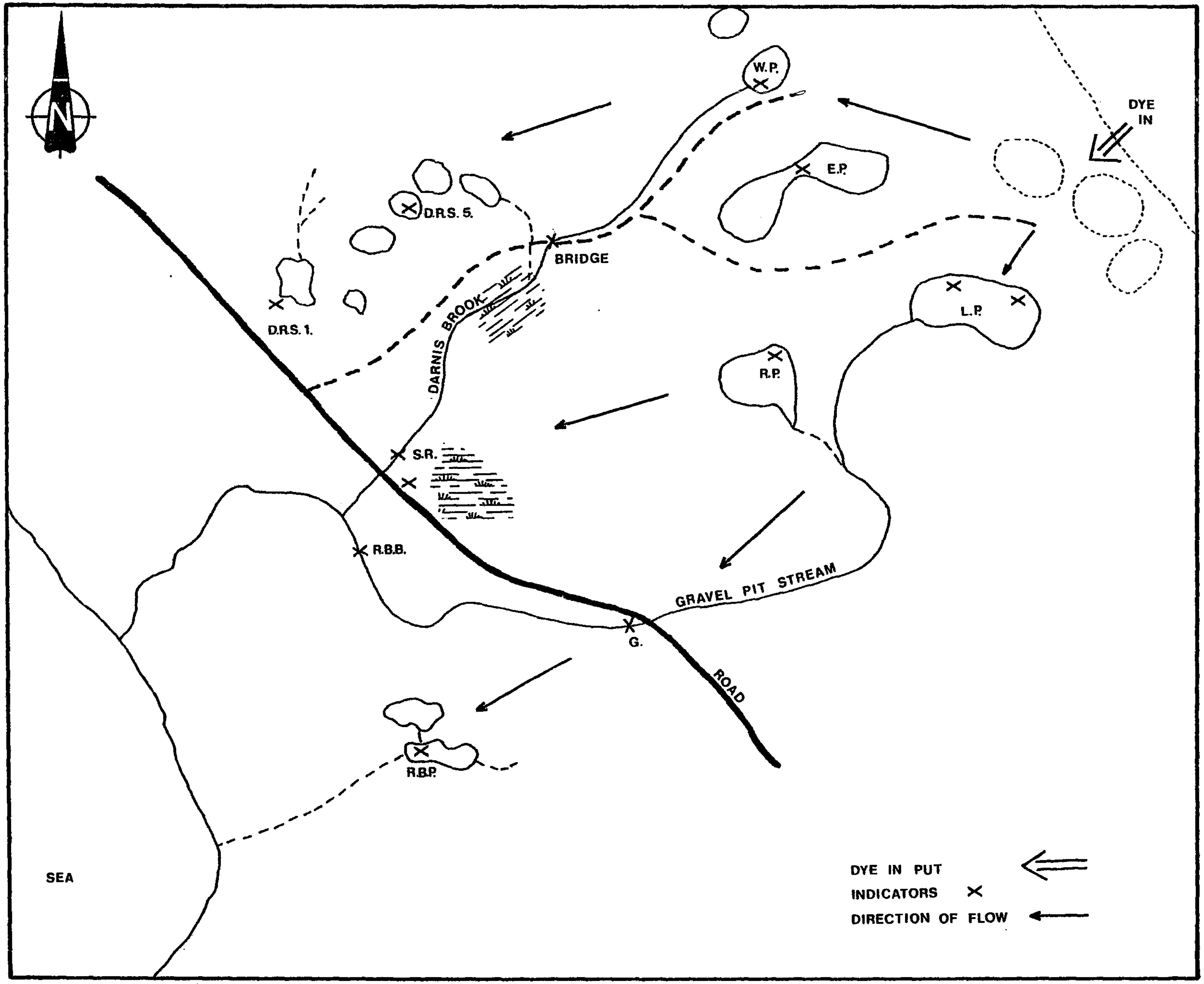

FIGURE 20 MAP OF DYE TRACING

TABLE VI

DYE TRACE DATA

July-Aug.	24	25	26	27	28	29	30	31	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	19	20	21	22
Long Pond				>100		>100							60																		100
Eyeglass				>100																											>100
Rushy Pond				>100																											>100
Woodville				>100									>100																		
Dump Bridge						>100																									>100
GravelPit St.						>100																									>100
													18																		
Dump Sink 5				>100																											
													>100																		
Stream #1 Row				>100																											>100
Dump Sink 1						>100																									>100
Red Barn Brook						55																									>100
Red Barn Pools				>100									80																		
Amt. of Rain Port Aux Basques	3.1	16.0			1.0			0.5	0.8	0.8				11.4		1.8			2.0			11.7	8.4	5.3	0.8						
Due In.	X					X																									
Standard Check		<20	48 hours + background																												
		18																													

must reach the surface somewhere. It would have a lot of head and would be able to emerge through the coastal springs or even through the springs which can be seen offshore. The fact that the coastal springs do contain calcium carbonate could be evidence for this. Water from the limestone and gypsum mixes and circulates through the lower system over a longer period of time to emerge through the upper system at the springs where the hydraulic gradient is the least. In addition to the two samples cave springs, which are only about 1½ metres above sea level, several springs are seen to emerge below the high water mark (Plates 31 and 32) and it is possible that there are yet others farther offshore. All of this water is moving through the system in a diffuse manner close to the Codroy/Anguille boundary. Conduits are developing headward from the springs in the way described by Rhoades and Sinnacori (1941). This mixing would account for the steady temperatures, hardness values and discharge rates.

It seems entirely possible that both processes of ground water flow can operate in conjunction with each other. Obviously more work has to be done on this aspect of karst hydrology.

There is apparent evidence for both isolated perching and some sort of water table. The main stream appears to be perched in some way for the water passes easily through the till all around it. In this case it may be that fine material has armoured the bed thus providing an impermeable base.

Some of the ponds appear to be perched; e.g. Rushy Pond, Long Pond and Eyeglass, three of the largest permanently water-filled depressions are immediately upslope of a number of dry sinks. If there was a continuous water table there would be some movement of water from one set to the other.

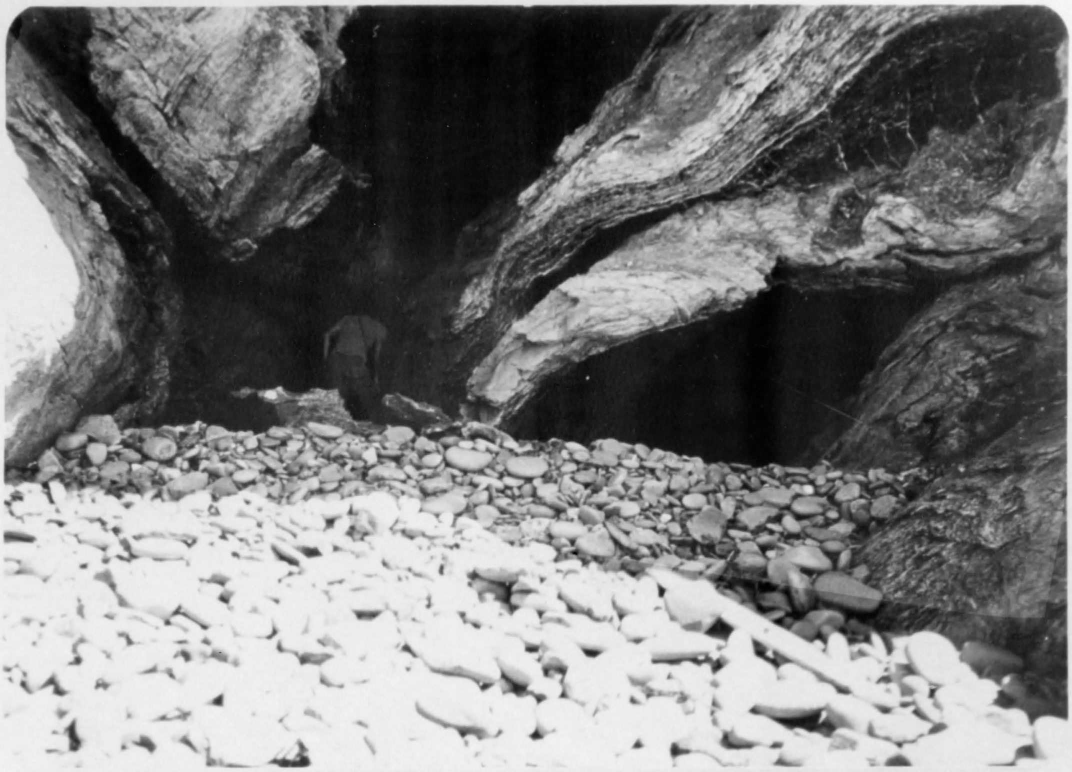

Plate 31. Entrance to Cave Spring 1.

Plate 32. Underwater springs.

It is the term "continuous" water table which is the key here. Considering this study so far, it is a reasonable assumption to say that the bed rock is very contorted. The plain-like appearance of the area is the result of masking by a till mantle. The water table would echo to some extent this unconformity. The configuration of the water table will depend on several things. Where the till layer is thick the water table will be farther from the surface, than where the cover is thin. If the shales are the dominant bedrock at a certain point, the till above will retain water for a longer period than it will over the more pervious gypsum. The contact zones between the gypsum and the shale will lose water much more rapidly because it is here that water will concentrate and in time remove more soluble material.

Where the hydraulic gradient is greatest the head will force water through the system rapidly, taking all washload with it. Where the gradient is less and water filters more slowly there is time forthe fines to settle and create a sealer in the base of the ponds. This will cause the water to seep away even more slowly. This may account for the general lack of ponding close to the coast and greater ponding inland.

It is evident from the information here that the flow systems are complex and that both diffuse and direct flow can operate together, or at least in close conjunction. If the amount of water entering the Anguille system is great enough there is surely enough head to produce more springs than those seen along the cliffs and just below the water level. It is not possible to assess the percentage of input water passing out of the two systems through the sampled Cave Springs. Some of the water may be evicted through undersea springs, and some may even remain within the system for prolonged periods. The relative importance of each may be estimated by temperature.

Obviously some water does not pass through the system at all, it is perched on the clay sealers and lost by evaporation. Some water passes through the system rapidly along the conduits, probably retaining high temperatures, but possibly mixing with colder, long-resident water before it leaves. If all the water was diffuse the temperature should be close to the mean annual air temperature, which would be considerably less than 8 °C. Some water from the Anguille system may also be flowing northwards out of the area of study. That water is stored in the system is obvious; the constant flow of the springs is not a reflection of short-term inputs.

What has been shown thus far is that some water entering through the sinks or the till plain is simply passing through the till and re-emerging in sinkholes closer to the sea level. Some of that same input is reaching the local bedrock and follows probable conduits to re-emerge in the local springs. Similarly, some of the water entering the Anguille rocks emerges through springs like the one above Woodville pond. Further water from both till plain and Anguille zones finds its way into lower rock levels where it mixes rogether in a diffuse flow system, before being expelled through local and probably more distant springs. To support the possibilities indicated here it is necessary to analyse the hydro-chemistry of these waters. This has been attempted and the findings are discussed in the following chapter.

CHAPTER 7

HYDROCHEMISTRY OF A GYPSUM KARST

A great deal has been written during the last few years about the geochemistry of karst waters. Authors such as Drake, Harmon, et al, 1973, Schuster and White, 1971, examine the effect of regionalism on hydrochemistry and discuss the value of chemistry as a distinguishing factor in flow types. Drake 1974, furthers this work. He explains that different chemical variables in waters help to determine the sources of various waters within a limited zone.

All these studies by implication limit karst to carbonate rocks, where the solution process is dependent on a particular chemical reaction, brought about by the mixing of two chemical components. Thus the availability of CO_2 and the partial pressure of that CO_2, moderated by temperature, become key factors. That solution processes of much the same type, creating the same sort of surface morphology exist in sulphate rocks is apparent. But there is a major difference between the solution processes of carbonates and sulphates. In the latter the process is a simple one of dissociation. This chapter will consider this process as it applies to the gypsum in the Codroy area. Included too are such aspects of the water chemistry as the effectiveness of solution, response of underground water to surface input; relative quantities of dissolved minerals and an investigation of the possibility of waters of different systems being found in the same areas.

Although the solution process in gypsum is a simple one there are associated factors which complicate the system. The first of these which would be encountered in any zone of gypsum, in temperate latitudes at least, is the duality of the gypsum itself. It has been established that in Codroy, as in most gypsum areas, there is associated anhydrite. Although water may reach the anhydrite along cracks and fissures the rates of solution will be severely retarded by the fact that the anhydrite may expand up to 50% during the alteration to gypsum. Thus water passing through the fissures will encourage the change from the anhydrous state, and the subsequent expansion will prevent further passage of water at least until new solvent from outside can re-establish the passage. The amount of retardant effect is not discussed here.

That solution in limestone creates caves and enlarges fissures is an effect of the jointing of the rock to begin with. Gypsum is a much more plastic rock and will yield to a considerable degree. It will, because of its 'plasticity' flow into cracks etc. As a direct result of this the incidence of jointing is much less in this rock, therefore there will be less opportunity for cave passage excavation. There will instead be a tendency for the rock to be removed in random patterns whenever unsaturated water reaches it, or has prolonged access to it. This latter would occur most frequently along the boundary of the gypsum with other rocks.

In the Codroy section the process is further complicated by the amount of tectonic activity which has occurred. There is massive folding in all dimensions and faulting has occurred in the more brittle rocks allowing flow of gypsum along these lines of weakness. Unlike the karst studied by Drake 1970, where the gypsum is known to be in a somewhat more regular and uniform pattern, Codroy exhibits several bands of gypsum in a number of forms within a small area. It is suggested that this factor at least partially explains some of the anomalies in the water chemistry of the area.

Codroy is primarily underlain by gypsum with bands of shale and sandstone. Only the gypsum is subject to solution. It would appear however, from the sampling results that the system is not as simple as might be expected. Therefore, there must be something else to explain this complexity. In close proximity to the gypsum to the north are limestone conglomerates and underlying the small gypsum outcrops, there are large masses of Blackpoint limestone and Ship Cove Limestone. Almost certainly some of the waters from these limestones are mixing with the gypsum rich waters before they are exposed in the coastal springs. Thus, surface runoff and shallow water in the area has a low calcite value gained only from the calcium carbonate in the till. Water passing into the deeper system from the gypsum plain cannot be separated from the water reaching this deeper system by underground routes from the limestone. Because of this a somewhat less simple process of solution is involved than that found solely in the gypsum at Canal Flats (Drake 1975) or that found in the Appalachian limestones studied by Schuster and White: (see also the work by Pitty 1974 and Gascoyne 1974). Here we have two solute minerals interacting with each other, and apparently using at least some of the same water.

This would be particularly true of any water flow in the diffuse system where water must be resident for some appreciable time and passes through a widespread section (Fig. 21).

What then happens to waters containing more than one solute mineral? A theoretical study of the chemical evolution of calcite/gypsum water has been completed by Wigley, (1972). He suggests that water which is saturated with respect to one of the minerals may still continue to dissolve the other; and under given circumstances precipitation of one may occur while the other is still being taken into solution. This may explain the very high total

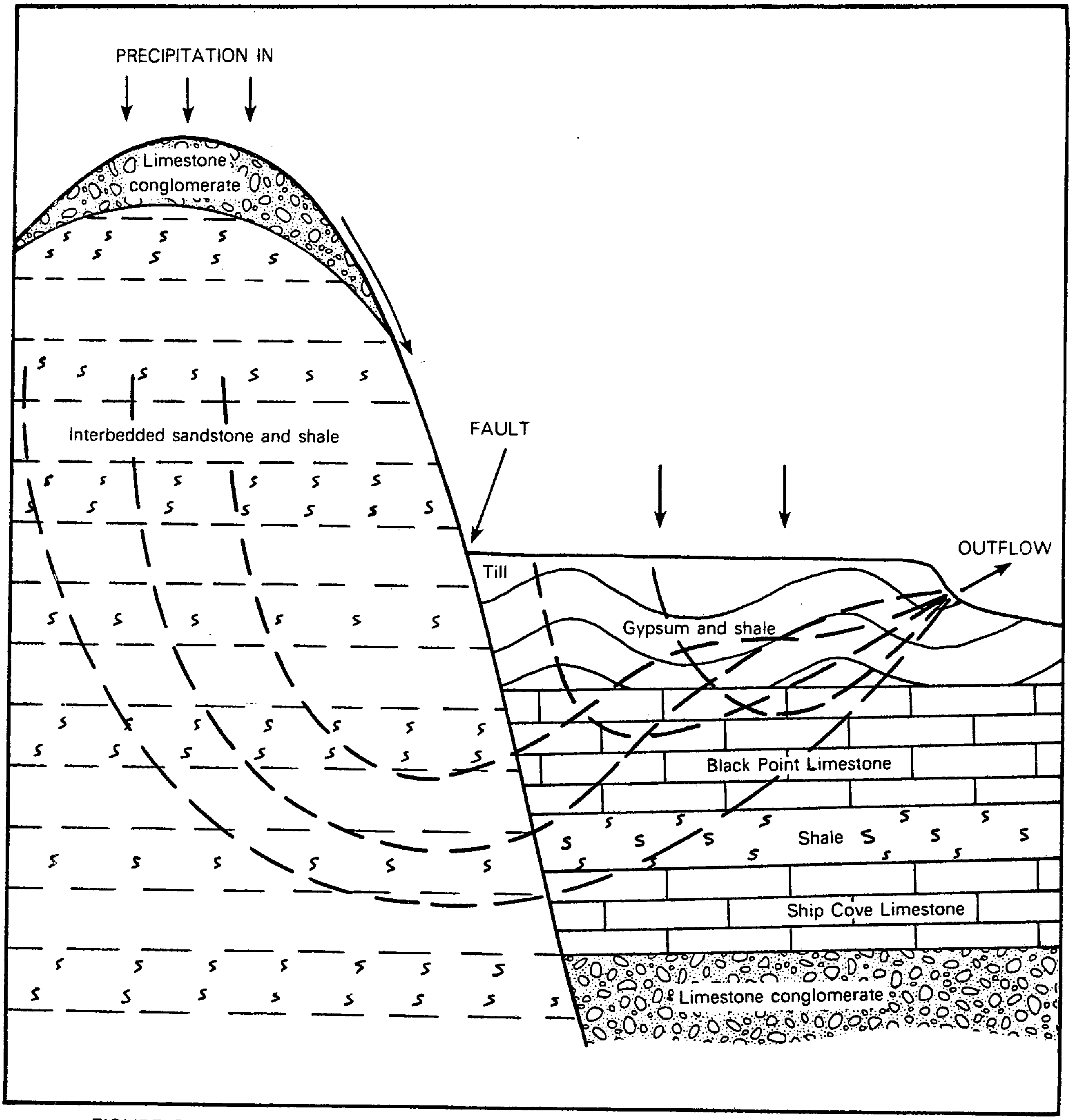

FIGURE 21 SCHEMATIC DIAGRAM TO SHOW THE POSSIBLE PASSAGE OF WATER IN A DIFFUSE FLOW PATTERN IN THE CODROY AREA

hardness values in the coastal springs and some of their anomalies in the calcium/magnesium values.

Because of this complex process regional rates of solution will be even more difficult to gauge and with the information gathered to date, this cannot be done with any accuracy. The present study can only be considered as a reconnaissance and any ideas can only be hypotheses.

Field measurements included temperature, pH, Ca^{++}, Mg^{++}, HCO_3^-, and SO_4^-. Further laboratory tests were conducted on samples with particularly high hardness values and finally a selected group of samples were tested through a mass spectrometer, to be used as a control. In the field measurements for Ca^{++} and Mg^{++} were obtained with SCHWARZENBACH E.D.T.A. titrants using British Drug Houses standard reagents (Appendix 1). Potentiometric titration with HCl was used to obtain HCl_3 values, whilst relative sulphate values were obtained by comparing field samples with pre-prepared standards (Appendix 1). Chloride testing was also attempted in the field but accuracy was poor so the results are not included. Specific conductivity, temperature and salinity were measured for every sample with a YSI Model 33 S.C.T. conductivity metre and temperature was checked with a simple mercury thermometer. pH values were measured with a portable Metrohm metre, calibrated between pH7 and pH10. The accuracy of this metre is accounted to be ± 0.05 units. These latter measurements were made at the site,and all other tests were conducted within 12 hours of sampling.

Later laboratory analysis of sealed sampled for magnesium and calcium give comparative results. Further analysis for sulphate followed the method described by Rainwater and Thatcher (1960) (Appendix 1). Chloride values were also obtained in the lab. and for purposes of this study it is assumed that Na (needed for ion equations) is measured as the same value. Those samples measured on the spectrometer, as controls, gave values in the same ranges as the field and lab. measurements.

Because of the high sulphate values there were some problems with the initial titrations in the field. In some samples total hardness was very difficult to determine because the titration initially attained the blue end-point at a lower value than that of the calcium hardness. After about 1-1½ minutes the solution reverted to pink. This could happen several times before a permanent blue was attained. In many of these samples a precipitate formed when indicator was added to the original water sample.

In the field the initial 50 ml samples were cut in half, primarily to conserve titrant. In the laboratory, samples were further diluted and gave slightly, but consistently higher values than those recorded in the field. This indicates that complex ion effects are present in the hardest waters.

The TOMCHEM programme, written originally by Tom Wigley and John Drake (1972) organizes the analysis of temperature, pH values, calcium, magnesium and sulphate values, as well as alkalinity and proceses an index of saturation for the sample waters. It was composed to look at carbonate solution, but was later adapted to include sulphate. Using the TOMCHEM index an attempt has been made in the following section to analyse and explain the chemistry of the waters in the gypsum plain.

Analysis of Results

The Codroy waters have already been tentatively divided into three categories, using the raw data of physical type, temperature and hardness. Figures 22-23 are graphic representations of the saturation indices of

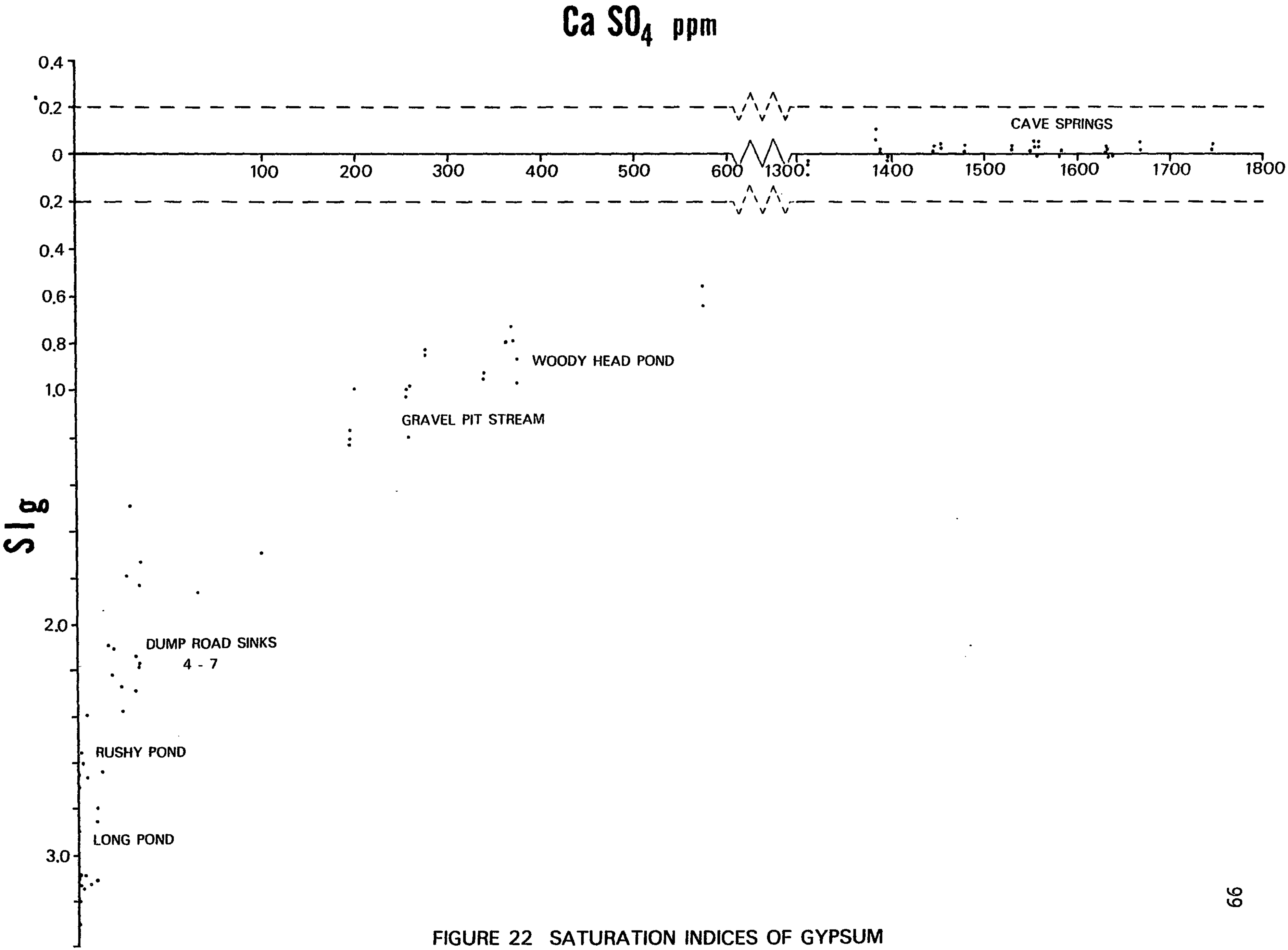

FIGURE 22 SATURATION INDICES OF GYPSUM

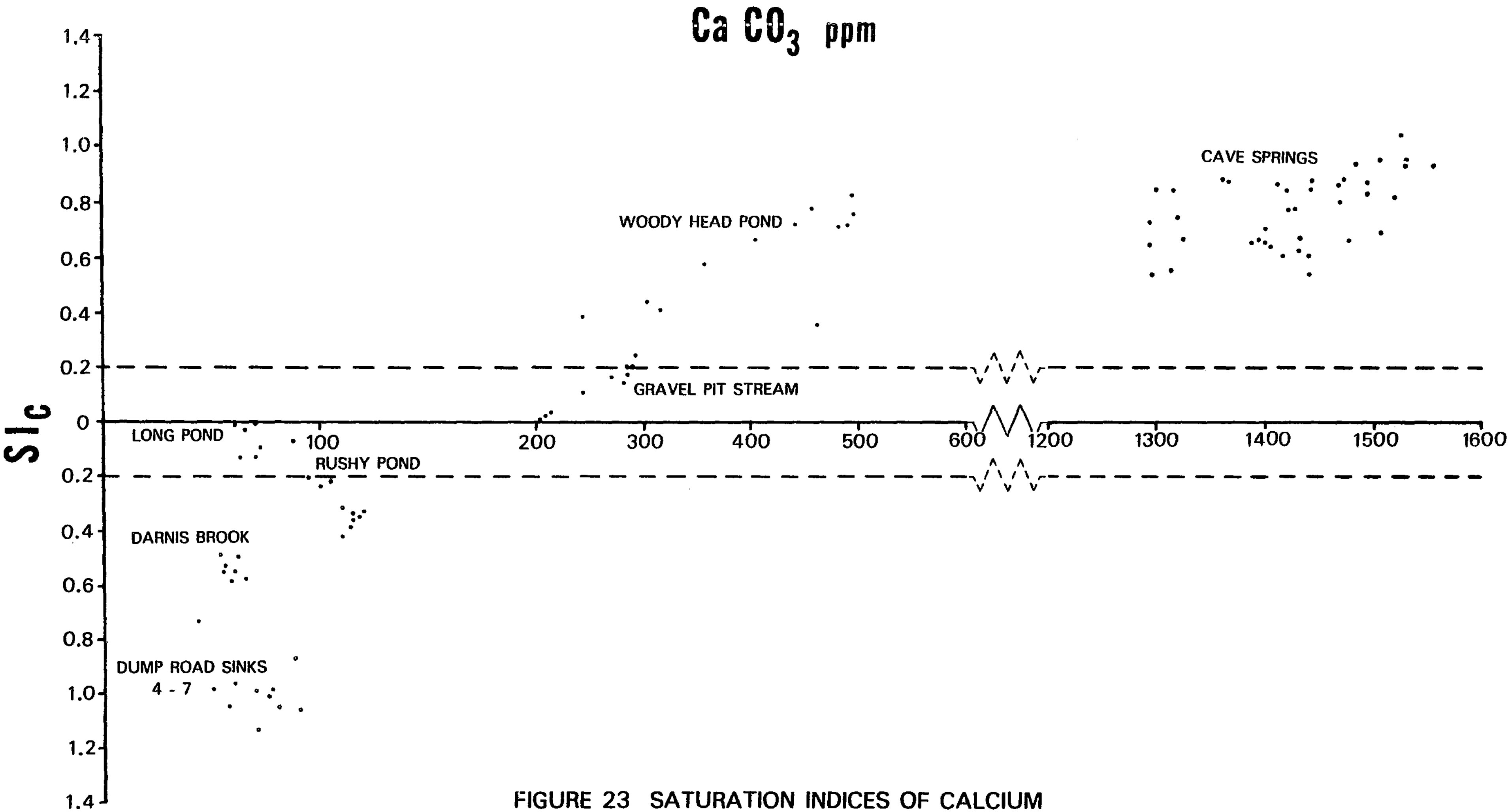

FIGURE 23 SATURATION INDICES OF CALCIUM

these waters. It is immediately obvious that there is a strong separation into underground spring, surface running and surface standing waters. In both SATCAL and SATGYP there are distinct levels of saturation or under-saturation. These levels show a distinct and similar trend for both minerals. Underground spring waters have a much greater degree of saturation than running surface water, which in turn shows a generally lower potential for more mineral absorption than the standing waters. Spring waters exhibit high hardness values for both calcite and sulphate; the waters are super-saturated with calcite, but only just saturated with sulphate. Although super-saturation with one mineral does not prevent more solution of the other it may possibly retard the process. It is obvious that these underground waters are effectively contacting both forms of calcium.

At the opposite end of the scale, all standing waters are aggressive. On both graphs the large ponds show more saturation than the small ones and this is probably a function of the greater water/rock interface. However, the level of under-saturation, or conversely the potential for solution is much greater in the gypsum measurements. In that case the values of under-saturation reach - 3.7, indicating water with a scarcely utilized potential for dissolution. All this standing water is protected from the gypsum by the till, which apparently retains only miniscule amounts of sulphate. This might be expected as the mineral dissolves so easily that any traces would be easily washed out. The amount of calcium carbonate in the till would be greater despite the limited source material, because it is less soluble.

The link between the saturated spring waters and the under-saturated standing waters is surface channel flow. In the case of SATGYP the surface flow is under-saturated from the sources of both streams, through their confluence and to the stream mouth. As might be expected the sources are more under-saturated, and the values closer to saturation down-stream. In the case of SATCAL the waters follow the source trend, but move from under-saturation to over-saturation progressively down-stream, as the waters have a longer contact with the calcite in the till.

In both SATCAL and SATGYP there is a great separation in values between underground and surface waters. This is an indication that the ground-water solute potential is being exploited more effectively than that on the surface.

Standing pond waters can be divided into three types. Clifftop Sink and Red Barn Pools, both close to the edge of the cliff, appear to be well below saturation level, not only wrt gypsum but also in carbonate minerals. This suggests that the sinks are in till only, without contact with any gypsum. It also suggests that they are isolated from the underlying limestone and no water from that system reaches them. Generally any till in the area would be expected to contain calcium carbonate; some of this may have been leached from the system since the end of the last Ice Age. One would still expect the waters to contain some calcium carbonate unless they are from direct precipitation and have been protected from till by an organic insulator on the floor of the ponds. This would certainly seem to be a feasible explanation of the chemistry of Clifftop Sink. This is a very shallow, almost ephemeral, pool with a great deal of swampy grass around it and a thick layer of organic muck on the bottom.

Red Barn Pools are at a slightly higher elevation than the cliff edge and the surface stream at the same location. This may help to explain why little underground water is entering them; therefore, little calcium carbonate will be dissolved.

Much the same situation seems to exist in the bigger inland ponds. Long Pond and Rushy Pond are both very large but apparently not very deep. Considerable changes in water temperatures over the summer, reflecting the daily changes in air temperature, substantiate this. In neither pond was there any evidence of direct contact with the bedrock and the bases were covered with a blanket of light coloured, fine till/clay. The chemical analyses show the waters to be generally below saturation wrt all three minerals, although on two occasions Long Pond appears to be just saturated with respect to calcium carbonate and magnesium. These were toward the end of August, when the air temperatures were consistently high and there had been no rain for several weeks. In these ponds, too, it seems likely that the only carbonate available to the waters is that from the till.

The pattern of saturation for the small water-filled sinks parallel to the stream is much the same. They are all, except in one case, undersaturated with respect to all three minerals, but have picked up some calcium carbonate from the calcareous till (Fig. 24).

While temperature does have an effect on the relative saturation of waters, the changes over the study period were not generally very great and in these ponds with very undersaturated waters there seems to be negligible response. In Eyeglass Pond there is an interesting relationship where the waters seem to be more saturated when the temperatures are lower. The reason for this is unclear.

There are two surface streams in the immediate study area, which meet and flow to the sea together. One might expect the two to display similar chemical patterns as they are flowing over similar terrain. This is not the case. Darnis Brook flows from Woodville pond and the small intermittent

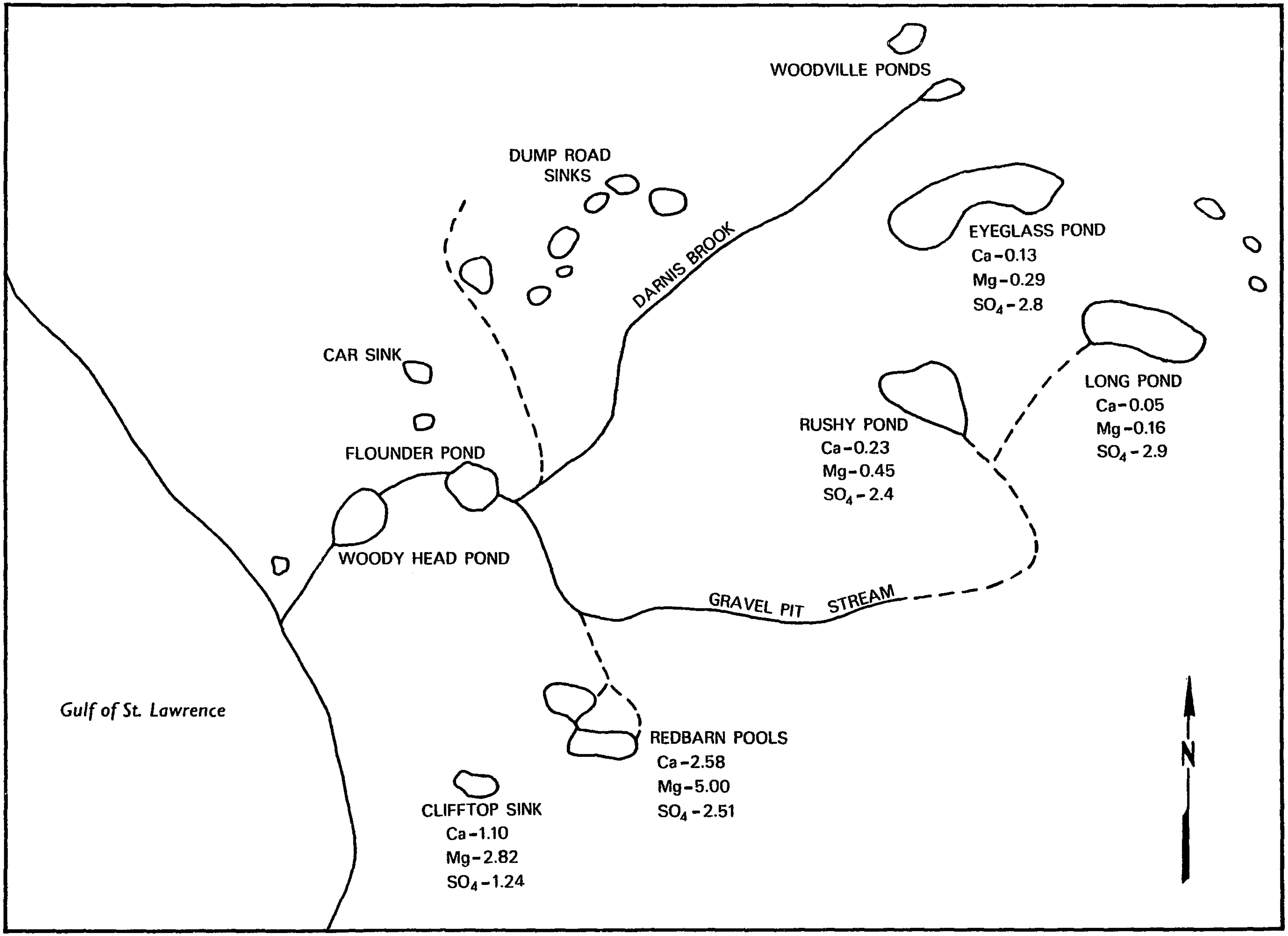

FIGURE 24 SATURATION VALUES FOR STANDING WATER

spring above it, almost at the junction with the Anguille Mountains. One might expect the spring water at least to be partially from the mountains as the fault line is in close proximity, dividing the Anguille and the Codroy series. But this stream is very undersaturated or at least to its confluence with Gravel Pit Stream, and remains undersaturated with respect to gypsum for its entire length. Gravel Pit Stream exhibits an interesting phenomenon; it is saturated with calcite, but not magnesium or sulphate.

By the time the newly united streams reach Flounder Pond the water is approximately saturated with calcite and magnesium, so it must have gained some minerals from the till since the confluence. The water still contains little gypsum, which suggests that any rock outcrop at this knick-point does not occur within the pond, or if it does it is efficiently masked. Woody Head Pond is supersaturated with both calcium and magnesium, but despite the amount of sulphate in the sample is still well below saturation level in that mineral. Between this point and the mouth of the stream, springs entering the system must be undersaturated for the waters are undersaturated wrt all three minerals when they enter the sea. That these springs are simply from till and intermittently-filled sinks on the adjacent hillside would complement this last statement. The amounts of sulphate in parts per million for both Woody Head Pond and for the stream mouth are very high and yet the waters do not come close to being saturated wrt gypsum, demonstrating that very large amounts can be carried in the water before a saturation level is reached (Fig. 25).

The third type of water in the area is that from the cave springs along the shore. In addition to those which gush from the rock, there were sometimes trickles flowing from the junction of the till and the bedrock.

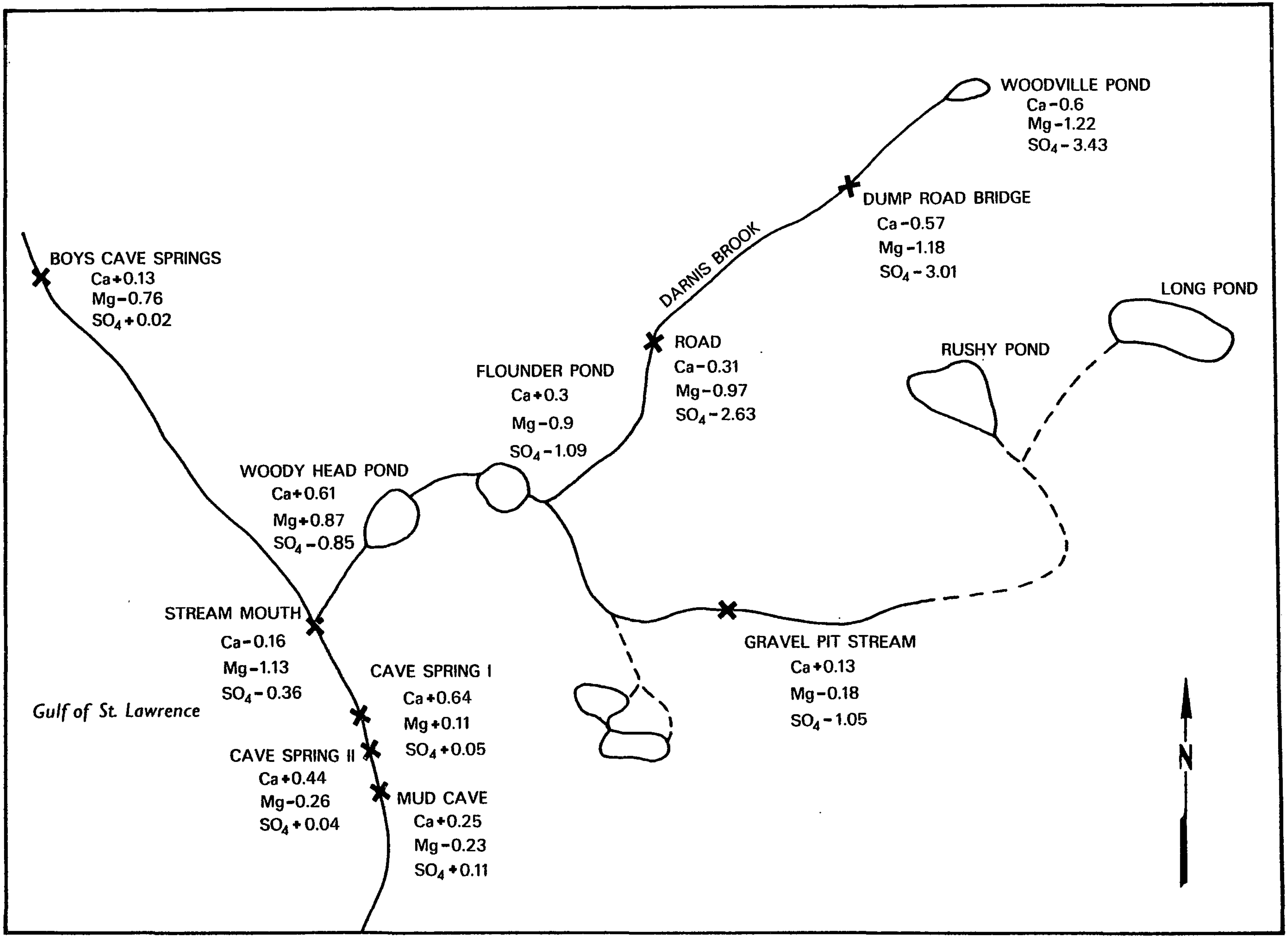

FIGURE 25 SATURATION VALUES FOR FLOWING WATER

These were generally so slight it was impossible to measure them. There was also evidence of underwater springs in the sea and in Darnis Brook downstream of Woody Head. It was not possible to separate and measure these waters.

Spring samples were taken from Mud Cave within the Gypsum/Shale boundary zone, from Boys Cave Springs 1a and 2 where the sediment load was always considerable, and from the Cave Springs in the Gypsum Bluffs. The results from the first three are rather surprising and will be mentioned first.

Throughout this very dry summer of 1976, Mud Cave contained only a small trickle of water which eventually dried up completely. Local authorities however explained that in Spring the whole cave fills with water which gushes out, usually for several days at a time. Total hardness values for this water were always very high (approx. 1500 ppm) and the sulphate values averaged 2009 ppm. These samples exhibited supersaturation in calcite and well above saturation in sulphate, but were undersaturated with respect to magnesium. Other samples in which this sulphate/dolomite relationship exists are Gravel Pit Stream, Flounder Pond, Boys Cave Spring 2 and Cave Spring 2. It is possible that there is physical linkage between all of these except Boys Cave Spring, which is some distance along the shore and beyond two stream valleys. Mud Cave is high in the cliff near the till boundary and is excavated in a very muddy and impure gypsum; it also contains considerable amounts of shale, etc. The waters passing through this cavity must have considerable contact with gypsum. It seems probable that a small quantity of water in prolonged contact with the gypsum will become saturated more readily than large quantities of water which are dissolving rock at a greater bulk rate.

The evidence from Boys Cave 2 would appear to support this. Although the waters here were consistently cloudy with gypsum particles in suspension, the total hardness values are only in the 1300s and the sulphate values averaged 1570 ppm. The waters are certainly saturated with calcium carbonate, but not with magnesium and the sulphate content only just reaches saturation. The quantity of water here was comparatively great and the movement swift; obviously a great deal of solution was occurring quickly and water appeared to be passing through the system rapidly. Dye injected into a sink less than 1 km from the spring was monitored in the spring waters less than 48 hours later. However, the water temperatures were almost constant and there was little fluctuation in the total hardness values. At first it would appear that the two sets of evidence contradict each other. But water from the sink would have considerable head and this may allow it to pass into deeper areas where mixing with waters from further inland may occur, before the two flow out at the spring. This might account for the constant temperatures. Using the field methods available it was not possible to see how much the dye had been diluted in its passage, so the previous statement cannot be proven by that means. The apparent speed of the water movement in the system may mean that it has little time to absorb the sulphate, although it is mechanically removing it. In this case a rider must be added; the spring must be gaining water from sources other than ground water of the gypsum plain. The flow was considerable and continuous and that much water could not have been supplied from the known sink above. That sink was partially filled after heavy rain but quickly dried up again.

If there is water from other sources as the evidence suggests, this may already be saturated with calcium when it reaches the gypsum. It then mixes with the gypsum-rich, but calcite-poor, waters and flows through gypsum rock thereby adding more sulphate to its load. The time spent by this mixed water actually in the gypsum is short; therefore, it has not reached a saturation limit. However, much of it has been underground for a considerable length of time accounting for the constant temperatures and the hardness values.

Both of the Cave Springs display constant temperatures and constantly high hardness values (1400 ppm), have high sulphate values (1500 ppm) and exhibit yet another combination of saturation and undersaturation. The water is always supersaturated wrt calcite and generally saturated wrt sulphate. This latter changed when the temperature rose slightly towards the end of the summer from an average 8°C to 10°C. Then the waters became slightly undersaturated. The values for dolomite range from supersaturated to greatly undersaturated, for an as yet undiscovered reason. In these springs the sulphate saturation is only just reached and this may again have something to do with the rate at which water flows through the system, as well as the temperature of that water. I suspect also that the general lack of water entering the gypsum system, because of the unusually dry summer, would also be a factor.

Thus the three categories of water established first by eye, then by preliminary analysis, are substantiated by more detailed analysis. However, it is necessary to explain more fully why some waters appear to be capable of dissolving more material than others, before saturation is reached. To do this several more aspects must be considered.

What does not seem to have been investigated in earlier studies of solution in gypsum is the nature of the gypsum itself. That is the case in this study too; but the difference in saturation values of the different samples which are obviously in contact with gypsum, give rise to speculation. It would seem quite possible for gypsum with different physical properties to be disaggregated and dissolved at different rates and for some to be more susceptible to solutional absorption in the waters flowing through them. It is further possible that the foreign minerals in the various gypsums may act as retardants or accelerators of the solution. With these considerations in mind it is possible that the total hardness for several waters could be similar and the saturation levels different. Conversely, the hardness values could be different for waters in a similar state of saturation.

It is known that the solution process in gypsum is slowed down in cold waters and that the maximum efficiency temperature for solution is 36°C. Obviously, the waters in Newfoundland or any other temperate region would never reach this maximum. The fact that these waters are cold (8°C) all the year round must have an important effect on their chemical efficiency. It is possible to see, from the samples of high sulphate value, that the potential solution level is greater when the water is warmer. In Cave Spring 2 the late August water temperatures rose about 2°C. The hardness values did not change significantly but the waters became slightly undersaturated.

If the waters were flowing only through the gypsum/shale, then this discussion need go no further, but this is unlikely to be the case. Almost certainly, waters emitted from the springs have come from calcite-rich material as well as the gypsum. This being the case the problem is compounded. In all instances the measured input temperatures were reflective of air temperatures, but the output at the springs remained almost constant throughout the season and were practically equal to each other. This suggests considerable time underground between input and outflow, therefore a major component of diffuse flow. Dye tracing results and the conduit nature of the spring point to direct flow. If indeed the gypsum waters are mixing with the carbonate waters from the adjacent rocks, this could be the source of the cold water. There would be a greater volume of the latter because the area of input is greater as is the storage time. The saturation of the spring waters with calcite does seem to add substance to this idea.

The relative contribution of the water from the two systems may be estimated approximately from thermal data. The average input temperature of the gypsum plain waters in summer is 18^{o}C; the emerging mixed waters have a temperature of 8^{o}C. The mean annual temperature of the area is 4.4^{o}C and it is assumed that long resident underground waters (i.e. Anguille will equilibrate to this value). Because the area is tectonically 'warm' an estimate of 5^{o}C is adopted forthe deeply circulating waters. The mixing ratio is therefore approximately 3:1 calcite: sulphate water; 75% of the spring waters are of deep origin and long residence time.

It is then necessary to consider how the water passes through and mixes within the system. Does the solution of the system take place as the water passes through the gypsum into the underlying limestones? If this is the case, is some of that gypsum precipitated in the limestone cavities, while solution of calcite is enhanced by the new water source and does that account for the undersaturation of some gypsum rich waters? What is equally possible, is that the saturated gypsum waters are mixed with waters from the limestone, which then pass through the gypsum on their way to the outflow, but the time and/or distance passed through, is not sufficient for solution to reach a new saturation level. Perhaps the input on the gypsum plain never leaves the gypsum system, but is mixed with carbonate waters very close to the springs and within the gypsum system. This latter suggestion would seem to be the best explanation for several of the anomalies which have appeared up to now. If the gypsum waters are only mixing with the carbonate waters just before they emerge from the springs, it would explain why dye tracing shows fast water flow and the temperature and hardness values indicate diffuse flow. (Fig. 26).

Certainly the water entering the system from the Anguille Mountains would have enough head to re-emerge through the gypsum beds and there is evidence of other springs along the coast, beneath the sea. The gypsum beds are not very thick nor very extensive and much of the water may bypass the gypsum entirely. The evidence of these undersea springs adds yet a further complication, in that any measurement of amounts of water or their chemical components cannot be assessed and it is therefore impossible to say how much of the water entering the system either on the gypsum plain or in the mountains, is in fact being expelled through the coastal springs.

At first the presence of a major fault between the two geological series was thought to be a deterrent to flow from one zone to the other. On closer consideration that does not seem to be the case. If the faulting brought only insoluble rocks against the surface, then the fault line would also be a spring line. In fact there is very little surface water anywhere along the fault; therefore, the water must be able to make its way through the fault zone into the gypsum or below.

What is the origin of the calcium rich waters? The Anguille Series does contain some limestone conglomerate but the main source must be the Ships Cove and Black Point limestones, which form part of the Codroy Series just below the gypsum. These have not been so contorted as the more plastic gypsum beds, but is thought that most of them must be below sea level. Thus to provide the head necessary for the processes discussed earlier there must be a

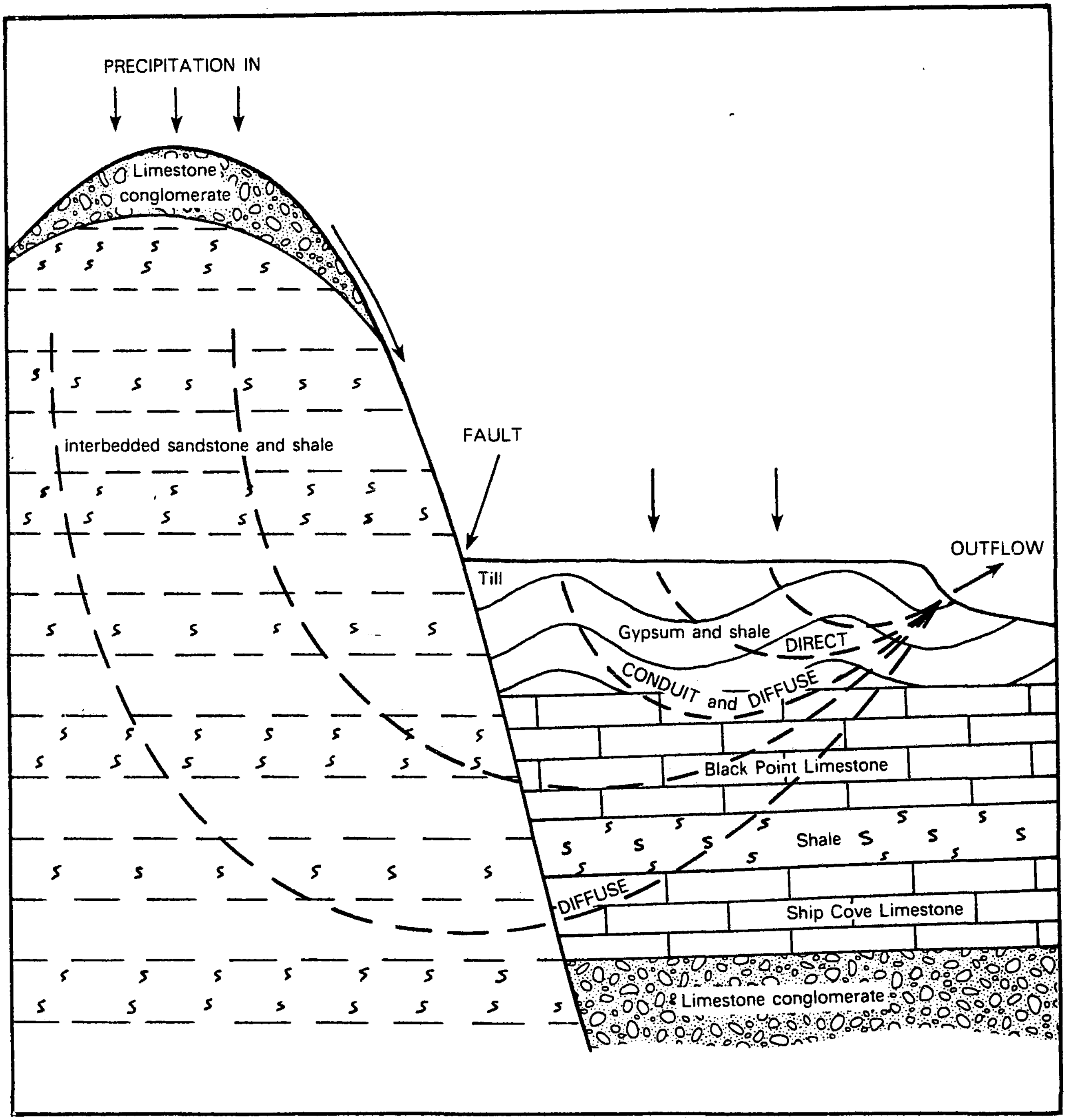

FIGURE 26 SCHEMATIC DIAGRAM TO SHOW ISOLATION OF TWO WATERS MIXING ONLY CLOSE TO THE SPRING

considerable height for the water to drop. This is provided by water entering from the mountains.

No attempt has been made to explain the undersaturation of magnesium in some of the samples and supersaturation in others, because no true investigation was made of the limestone stratigraphy. There is however a positive correlation between the calcite and sulphate values, particularly in the spring waters.

The ratio of calcium to sulphate is an interesting one and follows a definite pattern. In every case where the waters are sulphate-saturated the Ca/SO_4 ratio is less than one. In every case where undersaturation of sulphate is found, the Ca/SO_4 is more than one. Drake quotes the work of Zverev (1965), who discussed the carbonate-sulphate equilibrium. He suggests that the ratio might yield information on the ground water regime, Table VII. The following is an attempt to use this with the high sulphate waters of the Codroy area. Carbonate will be greater than the sulphate if sulphate is removed and/or calcium is added. If, as suggested above, the warm waters pass deep into the underlying rocks they will cool and may also come in contact with cooler water from the carbonate system. They will, therefore, be capable of holding less sulphate, and precipitation may occur. Those same waters may be capable of dissolving more calcium because they are cold. The system may be considered a closed one as the cavities must be small and the till prevents air from reaching the bedrock. Of course, as the waters resurge through the gypsum the second time re-solution may take place. If this is the case in the two cave spring where both $Ca>SO_4$ and $Ca<SO_4$ occur, the velocity of the water may be the determining factor. On average these two springs have a ratio close to unity caused (according to Zverev) by simultaneous entry of

TABLE VII. States of the sulfate-calcium equilibrium - after Zverev.

Equation determining the sulfate-calcium equilibrium	$\gamma_{caso4}[Ca^{++}][SO_4^{--}] = K_{caso4}$		
Quantities influencing the equilibrium as a whole	Temperature and pressure for K_{caso4} and γ_{caso4} Total ionic strength of solution, , and γ_{caso4}		
Kind of equilibrium	$Ca^{++} > SO_4^{--}$	$Ca^{++} \sim SO_4^{--}$	$Ca^{++} < SO_4^{--}$
Type of Ca^{++} and SO_4^{--} dynamics in solution	Removal of SO_4^{--} from solution and entry of Ca^{++} into solution	Simultaneous entry of Ca^{++} and CO_4^{--} into solution	Removal of Ca^{++} from solution and entry of SO_4^{--} into solution
Hydrogeologic condition governing kind of equilibrium	Sluggish water exchange in hydrogeologically closed structures	Intense water exchange in areas of gypsum and anhydrite	Sluggish water exchage in hydrogeologically open structures
Processes determining the kind of equilibrium	Microbiologic activity Reduction of organic matter. Cation exchange	Solution of gypsum and anhydrite	Oxidation of sulfides Precipitation of gypsum High CO_3^{--} content
Type of oxidising - reducing of environment and solution alkalinity	Acid reducing environment	Neutral oxidising environment	Neutral and alkaline oxidising-reducing environment

the two minerals into solution. This is certainly not the situation at Codroy but there may well be equal entry and there could certainly be intense water exchange in the gypsum/anhydrite, as he suggests.

Mud Cave has more SO_4 than Ca but this can surely be explained by a lack of calcium to begin with. The water is flowing from high in the cliff and is unlikely to have any contact with underlying limestone. It is therefore difficult to use Zverev's conclusions because the limestone and gypsum are not found in equal amounts, nor are all waters in contact with both.

So far no mention has been made about the influence of any organic material. Water must first pass through the soil layer to reach the till and then the rock below. In the carbonate system the type of organic material has an effect on the amount of CO_2 available. In this case where the water/sulphate process is one of simple solution and all the limestone is well underground, any influence of organic material will be minimal.

Many factors have to be considered in the last analysis, but it seems that the complexity of the geology is the key to the different waters within such a small area. Water flow is almost certainly both diffuse and of conduit type. Different waters are in contact with different solutes. The result is a series of waters with different characteristics.

CONCLUSIONS

The work of Drake (1972) in Canal Flats and Wood Buffalo National Park concludes that the index of gypsum saturation shows strong correlation with discharge. In the samples from Codroy the discharge varied very little in each of the spring waters, but it does appear that the length of time the water is in contact with the gypsum is significant. Thus it is suggested that both or either of these conditions are significant to saturation.

There is a second factor which must be added to this and may also be significant to the level of saturation. If the flow is vadose, the water passing through the rock would not be used to its potential and would therefore be under-saturated. There would surely be more chance of saturation if the flow were phreatic and the water completely surrounded by gypsum. In the sporadic gypsum/shale beds this would not always be the case. Thus those waters which are saturated with gypsum are also those which are in greatest contact with the rock. In this case the water is being used to its greatest potential both as a physical and chemical agent.

Gypsum is 183 times as soluble as limestone in distilled water at 20°C. The area studied had an average input water temperature of about 18°C from the standing ponds and about 10°C from precipitation during the study period. It is therefore possible that considerable amounts of calcium sulphate could be dissolved rapidly close to the surface, before that ground water cools at depth. Despite the sporadic nature of the gypsum subcrop, surface features as an expression of the solution form rapidly and frequently. One may consider all but the very largest sinks to have formed since the end of the last Ice Age. Even the largest are probably postglacial.

Even the retarding effect of the hydration process on anhydrite has not prevented the development of a considerable ground water flow regime. This is not consistent with the findings of L. Jakucs (1977) who maintains that no deep passage for water can form by widening in gypsum. It is suggested by this author such passages will form, the hydration process merely slows the rate of formation down a little. As the gypsum/anhydrite is so much more soluble than limestone to begin with, the solution process will still be more rapid in sulphate rocks that in carbonate rocks.

Jakucs further states that gypsum karst never attains the dimension of limestone karst despite its greater solubility. Instead, that solubility may prevent permanent features. However, the dolines in this small area of Newfoundland reach considerable proportions as do those in Wood Buffalo and Canal Flats. They are certainly larger than postglacial limestone dolines in Canada. The lack of extensive caves in the Codroy section may be attributed to the sporadic nature of the gypsum masses and to the plasticity of the rock. Caves in limestone are partially a function of the jointing of the rock. Gypsum flows and bends rather than fracturing even when subjected to the type of intensive tectonic movement found in Newfoundland. Thus there are few extensive, accessible cavities here. As this study shows gypsum masses are often sporadically placed and vary greatly in confirmation, making any form of erosion less or more effective within comparatively small areas. Where gypsum is found more evenly and extensively caves do form, for example, Texas (McGregor et al. 1963) and Germany (Hensler, 1968).

The apparently simple solution process of gypsum is shown, by this work, to be somewhat more complex than it at first appears. This study backs up with field evidence the work done by Wigley on the carbonate/sulphate solution relationship. It also examines the relationship between surface features and that solution process.

A work of this nature would not be complete, however, without some speculation about the future pattern of development in this small area. To do this it is necessary to consider the role of man in the past and now. The gypsum at least in this section of Newfoundland is not extensive nor accessible enough to be of commercial value. It was apparent that many companies had at various times visited the area, but all the surveys have produced nothing of value for the local population.

Although the area has been settled for about 100-120 years man has had little effect until now. Most of the original population moved here from Nova Scotia, where they had practiced some fishing and a little subsistence agriculture. Today little has changed except that the farm lots have become small, due to the practice of dividing land for succeeding generations. Because of economic pressure there is little economic fishing today, and the population of about twenty families is largely dependent on subsistence farming and welfare.

The properties of the rock are something of a hindrance to agriculture and it has been difficult for farming to expand. It has been hard for farmers to use modern equipment, both financially and physically. The land is so badly indented with sinkholes that for most people the use of a tractor would be an impossibility (Plate 33). Many of the farmers have tried, with limited success, to fill the sinks. Several of the deeper ones have been filled more than once. Car Sink, which is some 25 m in diameter, originally foundered catastrophically about 12 years ago. The owner has been progressively filling it with old cars, rocks and garbage ever since, (Plate 34).

Plate 33. Series of sinks forming uvala, poor farmland.

Plate 34. National and international use of sinkholes.

He has had it filled twice, but on both occasions, after the winter, it has flushed. All the soil and dissolvable garbage sinks and passes through the system into Flounder Pond, a doline on the nearby stream. This flushing has occurred several times to a lesser extent and the debris must pass very quickly through the system, as Flounder turns muddy brown on those occasions.

Many other sinks are used by the landowners as garbage dumps, where everything from tin cans to cars are dumped. Periodically the garbage is covered with a layer of soil in an attempt to make the land usable. Some farmers have been reasonably successful and the filled depressions are used as vegetable patches. Some of the naturally shallow depressions are idea for this because they tend to be floored with a richer organic base than the rest of the till (Plate 35). The larger waterfilled sinks have some fish because they have been stocked, and of course they are used by cattle for water (Plate 36).

The local water supply comes both from the main surface stream Darnis Brook, and from a spring about 100 m seawards of the Dump Road Sinks. Upslope of this water supply the three large, seasonally water filled sinks are the township garbage dump. In light of the information on groundwater flow in this study, it seems reasonable to suggest that the people are using contaminated water. On receipt of this information, the Newfoundland Department of Health and Welfare initiated a series of tests and the water was found to be polluted (Appendix 3). The level of contamination is not considered critical, and presumably people using that water all the time have built up an immunity to its impurities. That the people are living on land which may collapse at any time does not seem to affect the location of buildings. One recently built house is actually in a sinkhole and it is

Plate 35. Good soils in base of sinks.

Plate 36. Ponds for fishing, and watering cattle.

a common sight to see farmers scything by hand from the sides of the sinks. Apparently the grass is lush here and makes better hay.

None of this has made much difference to the natural flow of water, and the natural development of the gypsum karst. This may however, be changing. Gypsum, as explained above, is very soluble in water, particularly if that water is warm. Since the arrival of man in the area and particularly since the advent of modern home amenities, the amount of water passing from the surface in concentrated amounts in particular zones, has increased substantially.

During the study period there was always more surface runoff in seasonal streams and gullies on Mondays, the traditional washday. Modern plumbing and use of water means much more must be removed from the underground springs to be passed away on the surface. Over time this must have some effect on the system as a whole. Not only is more water passing through concentrated parts of the system, it is moving through more quickly and had been enriched by household chemicals. This water has been artificially removed from the system and then is artificially returned therefore altering the natural development.

There is presently a local proposition to bring water for domestic use from the nearby Anguille Mountains. If this is followed up relatively large amounts of water will be added to the present system in artificially concentrated amounts. This water, while partially saturated in carbonates, will be able to dissolve gypsum, especially if it has been 'warmed' by household storage and use.

Thus while man is limited by the local environment in the type and scale of agriculture which can be attempted, domestic use of the land may be affecting its overall condition and may also be speeding up the process of denudation. The future development of sinkholes may be escalated; this and the receding coastline may lead to the destruction of the sinkhole plain progressively more rapidly in the future.

APPENDIX (1)

METHODS OF ANALYSIS USED

Total Hardness, Calcium Hardness.

Add enough distilled water to one premeasured vial of E.D.T.A., to give a solution of 500 ml. The titratant is then measured into the water sample from a burette. 50 ml of sample water is pipetted into a 125 ml conical flask. 1 ml of concentrated ammonia buffer and a crushed total hardness tablet is added, E.D.T.A. is added until there is a permanent colour change from pink to blue. The amount of titratant used x 20 gives the total hardness as a value of ppm of calcium carbonate.

The calcium hardness is the same, substituting hydroxy napthal blue for the total hardness tablet and 1 ml of sodium hydroxil N4 for the ammonia. For a complete description and and bibliography see Douglas (1968).

Alkalinity determination.

This method, depending on a colour change is more accurate if the same person always administers the test. This was the case for the Codroy samples.

2-3 drops of British Drug Houses 4066 indicator are added to 50 ml of sample water. Then a solution of HCl .05N was added until a colour change from yellow to pink was reached; the amount of titratant x 20 gives the ppm alkalinity.

Using a concentrated solution of silver nitrate make up a litre of solution. Add 1-2 ml of potassium chromate to 50 ml of sample water. Add titratant of silver nitrate until an orange precipitate appears. Each ml of titratant used represents 1 mg of chloride and 1 mg of chloride in 50 ml of water equals 20 ppm. This was used with some success only on the samples brought back to the lab for testing.

Sulphate tests.

A set of standard solutions of calcium sulphate were made up in the lab. at values of 5, 10, 20 and 30 ppm. It was later realised that in the gypsum rich waters, these were much too small. It did give a measure of accuracy for the waters containing very small quantities of gypsum.

For the actual comparison tests; pour 5 ml of each standard into test tubes, add 1 ml of 5N HCl, shake it well then add 1 ml of saturated barium chloride. Do the same with sample waters then compare the cloudiness.

To get a more accurate value for the sulphate a second test was used on several controls and all the high sulphate samples.

To 100 ml of sample water is added 10 ml of HCl then 10 ml saturated barium chloride. This mixture must be stirred up well. Leave it to stand for 1 hour. 10 cm filter papers are dried and weighed, then the solution filtered through them. Precipitate must be washed out of the flask with distilled water. All the precipitate must be included. The filters are then dried at 110°C for at least 12 hours then reweighed. They have to be dried and reweighed until the weight stabilizes. Deduct the weight of the filter papers from the total then use the following formula to find the amount of sulphate. Difference between the weight of the $BaSO_4$ and SO_4 =

$$\frac{\text{Molecular weight } SO_4}{\text{Molecular weight } BaSO_4} \times \text{Weight of } BaSO_4$$

APPENDIX (2)

COMPUTER PROGRAMME

132

```
PROGRAM     TOMCHEM     73/73     TS                                FTN 4.6+428        04/26/77  1
--VARIABLE MAP--

C14         R              17B /TOMZ/               C2          R          3B /TOMZ/
C3          R               4B /TOMZ/               C4          R          5B /TOMZ/
C5          R               6B /TOMZ/               C6          R          7B /TOMZ/
C7          R              10B /TOMZ/               C8          R         11B /TOMZ/
C9          R              12B /TOMZ/               D           R       1353B
E           R           1354B                       EOF         R             FUNCTION
EQUCON      R                  SUBROUTINE           ERROR       R       1507B
FMT         R           1420B              8        FTNRPV.     -             EXTERNAL.
FX          R           1355B              19       G           R       1511B
GOTOER.     -                  EXTERNAL.            H           R       1400B
I           I   U       1401B                       INPCI.      -             EXTERNAL.
INPCR.      -                  EXTERNAL.            INPUT=      -         3B ENTRY
J           I   U       1513B                       K           I        20B /TOMZ/     10
KK          I   U       1467B              11       L           I  U    1502B
M           I              55B /TOMZ/      8        OUTCI.      -             EXTERNAL.
OUTPUT=     -              43B ENTRY                PH          R       1417B
PPCO2       R           1512B                       PUNCH=      -       103B ENTRY
R           R           1430B              19       S           R       1505B
SEQ         R           1465B                       STOP.       -             EXTERNAL.
SUMAN       R           1415B                       SUMCAT      R       1506B
T           R              65B /TOMZ/               TAPE5=      -         3B ENTRY
TAPE6=      -              43B ENTRY                TAPE7=      -       103B ENTRY
TDS         R              67B /TOMZ/               TOMCHEM     -       154B ENTRY
TT          R              66B /TOMZ/               U           R       1453B
UNITS       R                  SUBROUTINE           W           R       1454B
WW          R           1416B                       X           R        32B /TOMZ/     19
XTOY.       -                  EXTERNAL.            Z           R       1455B           8
ZZ          R   U       1402B              11

 7706B  PROGRAM-UNIT LENGTH            92 SYMBOLS
  44000B CM STORAGE USED            1.628 SECONDS
```

```
          103-  SULF   SO4--   CL-   NO3-
       11 FORMAT (1H1,*SAMPLE ID           TEMP        SAMPLE ID*)
         1CO2PPM SUMCAT  SUMAN   ERRCR CA/SO4  CA/MG   ION STR.*)  STGYP  PPCO2
       12 FORMAT(* *,2F7.2,11F6.2,7X,A10)
       13 FORMAT (1H ,A10,2X,F5.1,F6.2,5F7.2,2F7.4,F7.1,2F7.2,F9.5)
       14 FORMAT(//10X*SAMPLE IDENTIFICATICN   *A10//9X*I*12X*C A T I O N S*1
         1+X*I*12X*A N I O N S*27X*I*/10X*CALCIUM    MAGNESIUM SODIUM     POTA
         2SSIUM BICARB      CARBONATE SULFATE   NITRATE   CHLORIDE  I SATCAL
         3=*F6.2* IONSTR =*F6.5/1X*TOTAL         *4(F6.3,2X)* (ALKALINITY =*F6.2*)
         4*3(F8.3,2X)*I SATDOL   =*F6.2/1X*FREE          *9(F8.3,2X)*I SATGYP  =*F
         56.2/1X*SULFATE   *4(F8.3,2X)*I*16(3H  -)* I PCO2         =*F6.2/1X*BICAR
         6B      *3(F8.3,2X)*   NEGLECT I      TEMP   = *F6.2* DEG C    I     CA/MG
         7= *F6.2*   I CO2 PPM =*F6.2/1X*CARB          *3(F8.3,2X)*  NEGLECT I
         8ERROR = *F6.2* PERCENT I       CA/SO4 = *F6.2*   I PH          =*F6.2///1X
         9,44(3H*   ))
WARNING  *F CONVERSION CODE FIELD WIDTH IS LESS THAN MINIMUM REQUIRED
       15 FORMAT(1H1)
       99 FORMAT (A10,11F6.2)
C
          READ (5,100) (K(I),I=1,10),(KK(I),I=1,11),FMT
          IF (K(9).EQ.2) GO TO 4
          WRITE (6,10)
          GO TC 20
        4 WRITE (6,11)
C
C
C  READ IN ID, TEMPERATURE, PH, CA, MG, HCO3 AND SO4
       20 READ (5,FMT) SEQ,T,PH,X(1),X(2),X(3),X(4)
          IF (EOF(5)) 500,25
       25 DO 9 L=5,19
        9 X(L)=0.
C
          TDS=0.
C  CONVERSION TC APPROPRIATE UNITS AND STORE INTC ARRAY Z
          CALL UNITS
          DO31 I=1,8
       31 Z(I)=X(I)
C
          A=.4921+(T-5.)*.00079
          B=.3249+(T-5.)*.00016
C  FIND ABSOLUTE TEMPERATURE AND CONCENTRATION OF HYDROGEN ICNS
          TT=T+273.15
          H=10.**(-PH)
C  OBTAIN EQUILIBRIUM CONSTANTS
          CALL EQUCCN
C  U IS IONIC STRENGTH, U=0.5*(SUM OF M(I)*Z(I)**2)  FOR ALL I
C  WHERE M IS MOLARITY IN MOLES/LITRE,  Z IS CHARGE
C  ACCURACY IN SUSPECT WHEN U GREATLY EXCEED 0.01
        5 U=(4.*(X(1)+X(2)+X(4)+X(11))+(X(3)+X(5)+X(6)+X(7)+X(8)+X(9)+
         1X(10)+X(12)+X(13)+X(14)+X(15)))/2.
C
C  COMPUTE ACTIVITY COEFFICIENTS  FX
          DO 2 I=1,15
        2 FX(I)=10.**(-A*(U**(.5))/(1.+B*(U**(.5))*R(I)))
          FX(1)=FX(1)**4.
          FX(2)=FX(2)**4.
          FX(4)=FX(4)**4.
```

```
      FX(11)=FX(11)**4.
      DO 3 I=1,15
    3 AX(I)=X(I)*FX(I)
      S=X(1)
C  CA++ AFFECTED BY HCO3,SO4 AND CAHCO3 IN THE BALANCE
      X(1)=Z(1)/(1.+FX(1)*(AX(3)/(FX(9)*C3)+AX(3)*C2/(H*C4)+AX(4)/C5))
C  CHECK
      IF(ABS((X(1)-S)/X(1)).LT.E) GO TO 6
      AX(1)=X(1)*FX(1)
      X(2)=Z(2)/(1.+FX(2)*(AX(3)/(FX(10)*C6)+AX(3)*C2/(H*C7)+AX(4)/C8))
      AX(2)=X(2)*FX(2)
      X(3)=Z(3)/(1.+FX(3)*(AX(1)/(FX(9)*C3)+AX(2)/(FX(10)*C6)+AX(5)/
     1(C14*FX(15))+2.*C2*(1./FX(11)+AX(1)/C4+AX(2)/C7+AX(5)/(FX(12)*C11
     2))/H))
      AX(3)=X(3)*FX(3)
      X(4)=Z(4)/(1.+FX(4)*(AX(1)/C5+AX(2)/C8+AX(5)/(FX(13)*C12)+AX(6)/
     1(FX(14)*C13)))
      AX(4)=X(4)*FX(4)
      X(5)=Z(5)/(1.+FX(5)*(C2*AX(2)/(FX(12)*C11*H)+AX(4)/(FX(13)*C12)+
     1AX(3)/(FX(15)*C14)))
      X(6)=Z(6)/(1.+FX(6)*AX(4)/(FX(14)*C13))
      X(9)=AX(1)*AX(3)/(FX(9)*C3)
      X(10)=AX(2)*AX(3)/(FX(10)*C6)
      X(11)=C2*AX(3)/(FX(11)*H)
      X(12)=X(5)*FX(5)*X(11)*FX(11)/(C11*FX(12))
      X(13)=X(5)*FX(5)*AX(4)/(FX(13)*C12)
      X(14)=X(6)*FX(6)*AX(4)/(FX(14)*C13)
      X(15)=X(5)*FX(5)*AX(3)/(FX(15)*C14)
      X(16)=AX(2)*AX(4)/C8
      X(17)=AX(1)*X(11)*FX(11)/C4
      X(18)=AX(2)*X(11)*FX(11)/C7
      X(19)=AX(1)*AX(4)/C5
      GO TO 5
C
    6 SUMCAT=2.*(X(1)+X(2))+X(5)+X(6)+X(9)+X(10)+X(15)
      SUMAN=2.*(X(4)+X(11))+X(3)+X(7)+X(8)+X(12)+X(13)+X(14)
C  ERROR IS PERCENTAGE OF (SUM CATION - SUM ANION)/(SUM CATION + SUM AN)
      ERROR=100.*(SUMCAT-SUMAN)/(SUMCAT+SUMAN)
      W=999.
      IF(X(4).NE.0.) W=X(1)/X(4)
      WW=999.
      IF(X(2).NE.0.) WW=X(1)/X(2)
C  C IS SATCAL,D IS SATDOL, G IS SATGYP
      C=ALOG10(AX(1)*AX(3)*C2/(C1*H))
      D=-9.99
      IF(X(2).NE.0.)D=ALOG10(AX(1)*AX(2)*AX(3)*AX(3)*C2*C2/(C9*H*H))
      G=-9.99
      IF(X(4).NE.0.) G=ALOG10(AX(1)*AX(4)/C10)
      PPCO2= ALOG10(H*AX(3)/(10.**(-B1-B2)))
      CO2=44010.*(10.**(PPCO2-B1))
      DO 1  I=1,19
    1 X(I)=X(I)*1000.
      DO  8 I=1,8
    8 Z(I)=Z(I)*1000.
C
C  OUTPUT
      GO TO (70,80,90) K(9)
```

```
      70 WRITE (6,12) Z(1),X(1),Z(2),X(2),Z(5),X(5),Z(7),Z(3),X(3),
        1 Z(4),X(4),X(7),X(8),SEQ
         GO TO 20
      80 WRITE (6,13) SEQ,T,PH,C,C,G,PPCO2,CO2,SUMCAT,SUMAN,ERROR,W,WW,U
         WRITE (7,99) SEQ,T,PH,X(1),X(2),X(3),PPCO2,C,D,Z(1),Z(2),Z(3)
C
         GO TO 20
      90 WRITE (6,14) SEQ,C,U,Z(1),Z(2),Z(5),Z(6),Z(3),Z(4),Z(8),Z(7),
        1 D,X(1),X(2),X(5),X(6),X(3),X(11),X(4),X(8),X(7),
        1 G,X(19),X(16),X(13),X(14),PPCO2,X(9),X(10),X(15),T,WW,CO2,
        1 X(17),X(18),X(12),ERROR,W,PH
         IF ( ((J/4)*4-J) .NE. 0) GO TO 20
         WRITE (6,15)
         GO TO 20
C
C
     500 STOP
         END
```

```
--COMMON BLOCKS--
         70B  /TOMZ/

--ENTRY POINTS--
          3B  INPUT=              43B  OUTPUT=             103B  PUNCH=
         43B  TAPE6=             103B  TAPE7=              154B  TOMCHEM

--EXTERNALS--
   ALOG10.   EOF     EQUCON   FTNRPV.   GOTOER.   INPCI.   INPCR.   OUTCI.
   STOP.     UNITS   XTOY.

--STATEMENT LABELS--
   .1    ID        0B      .2    ID        0B      .3    ID       0B
   .5            257B      .6            544B      .8    ID       0B
   .10   F       760B      .11   F       774B      .12   F     1011B
   .14   F      1023B      .15   F      1126B      .20          211B
   .31   ID        0B      .70           712B      .80          716B
   .99   F      1130B      .100  F       755B      .500         737B

--VARIABLE MAP--                                           INTRINSIC
   A          R   1503B                  ABS     R   1330B
   ALOG10.    R          B.E.F.          AX      R     0B  /TOMZ/
   B          R   1504B                  B1      R   1510B
   B2         R     1B  /TOMZ/           C       R     2B  /TOMZ/
   CO2        R   1466B                  C1      R    14B  /TOMZ/
   C10        R    13B  /TOMZ/           C11     R    16B  /TOMZ/
   C12        R    15B  /TOMZ/           C13     R
```

```
      SUBROUTINE UNITS
C  ALL RESULTS RETURNED IN MOLES/LITRE UNIT
C
      REAL M
      COMMON/TOMZ/B1,B2,C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,
     1K(10),X(19),M(8),T,TT,TDS
C  NO CONVERSION WHEN UNITS ARE IN MOLES/1000 GM OF SOLUTION
      DO 1 J=1,8
C  PPM FOR K=2
      IF(K(J).EQ.2)  X(J)=X(J)/M(J)
C  EQUIVALENT CACO3 CONC. IN PPM FOR K=3
C  NOTE THAT MOLECULAR WEIGHT IS MULTIPLIED BY 1000 IN THE MAIN PROG.
C    HENCE, END RESULT IS X(I)/100.098, THE DENOMINATOR BEING CACO3
      IF(K(J).EQ.3)  X(J)=X(J)/100098.
C  MILLIMOLES/LITRE FOR K=4
      IF(K(J).EQ.4)  X(J)=X(J)/1000.
C  SUM TOTAL DISSOLVED SOLID IN PPM/1000
    1 TDS=TDS+X(J)*M(J)/1000.
      DO 2 J=1,8
    2 X(J)=X(J)*1000./(1000.+TDS)
      RETURN
      END
```

--COMMON BLOCKS--

```
          70B  /TOMZ/
```

--STATEMENT LABELS--

```
       .1    ID        0B              .2    ID        0B
```

--VARIABLE MAP--

```
  B1       R         0B /TOMZ/                 B2      R        1B /TOMZ/
  C1       R         2B /TOMZ/                 C10     R       13B /TOMZ/
  C11      R        14B /TOMZ/                 C12     R       15B /TOMZ/
  C13      R        16B /TOMZ/                 C14     R       17B /TOMZ/
  C2       R         3B /TOMZ/                 C3      R        4B /TOMZ/
  C4       R         5B /TOMZ/                 C5      R        6B /TOMZ/
  C6       R         7B /TOMZ/                 C7      R       10B /TOMZ/
  C8       R        11B /TOMZ/                 C9      R       12B /TOMZ/
  J        I   U    56B                        K       I       20B /TOMZ/     10
  M        R        55B /TOMZ/      8          T       R       65B /TOMZ/
  TDS      R        67B /TOMZ/                 TT      R       66B /TOMZ/
  UNITS    -        46B ENTRY                  X       R       32B /TOMZ/     19
```

```
   147B  PROGRAM-UNIT LENGTH          26 SYMBOLS

   44000B CM STORAGE USED           .146 SECONDS
```

```
      SUBROUTINE EQUCON
C  IN THIS SUBROUTINE B1 IS THE HENRYS LAW CONSTANT, B2 IS THE
C  EQUIL CCNST FOR (CO2 + H2CO3).   C1 TO C14 ARE EQUIL CONSTS IN THE
C  ORDER :  CALCITE, HCO3-, CAHCO3+, CACO3 UNDISSOC, CASO4 UNDISSOC,
C  MGHCO3+, MGCO3 UNDISSOC, MGSO4 UNDISSOC, DOLOMITE, GYPSUM,
C  NACO3-, NASO4-, KSO4-, AND NAHCO3.
      COMMON/TOMZ/B1,B2,C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,
     1K(10),X(19),M(8),T,TT,TDS
      C1=10.**(-8.0797997-.013328484*T+.25490188*T*T*10.**(-4.))
      C2=EXP(-(1000./(1.98719*TT))*(-3.596025*TT*TT/(10.**4.)
     1+5.35355*TT*TT*TT/(10.**7.)+.106897*TT))
      C5=10.**(-2.2-.0025166*T-.0000433*T*T)
      C8=10.**(-160.46267+62.90562*ALOG10(TT)+4871.03/TT-.046721*TT)
      DELF=-10.5304-.047122*TT*ALOG(TT)+1.94848*TT*TT/(10.**(4.))
     1-2.75001*TT*TT*TT/(10.**(9.))+620./TT+.3158096*TT
      C9=10.**(-1000.*DELF/(TT*4.575673))
      C10=10.**(-4.6406896+.00248775*T-.592158*T*T*10.**(-4.))
      C3 = 10.**(-1.26)
      C4 = 10.**(-3.1)
      C6 = 10.**(-.95)
      C7 = 4.0*(10.**(-4.))
      C11=10.**(-1.27)
      C12=10.**(-.72)
      C13=10.**(-.96)
      C14=10.**(.25)
      B1=1.12+.014*T
      B2=6.577-.01264*T+.144*T*T/1000.
      IF(K(10).NE.1) RETURN
      C3=10000.
      C1=10.**(-8.3389285-.0012357*T-.00005*T*T)
      C9=10.**(-16.5614285-.0124857*T-.0001999*T*T)
      RETURN
      END
```

--COMMON BLOCKS--

708 /TOMZ/

--EXTERNALS--

ALOG10. ALOG. EXP. XTOY.

--VARIABLE MAP--

		B.E.F.				B.E.F.
ALOG10.	R			ALOG.	R	
B1	R	0B /TOMZ/		B2	R	1B /TOMZ/
C1	R	2B /TOMZ/		C10	R	13B /TOMZ/
C11	R	14B /TOMZ/		C12	R	15B /TOMZ/
C13	R	16B /TOMZ/		C14	R	17B /TOMZ/
C2	R	3B /TOMZ/		C3	R	4B /TOMZ/
C4	R	5B /TOMZ/		C5	R	6B /TOMZ/
C6	R	7B /TOMZ/		C7	R	10B /TOMZ/
C8	R	11B /TOMZ/		C9	R	12B /TOMZ/
DELF	R	323B		EQUCON	-	206B ENTRY

```
          SUBROUTINE EQUCON      73/73    TS                                    FTN 4.6+428        04/26/77
--VARIABLE MAP--

        EXP.          R              B.E.F.                       K              I          20B /TOMZ/        10
        M             I          55B /TOMZ/        8              T              R          65B /TOMZ/
        TDS           R          67B /TOMZ/                       TT             R          66B /TOMZ/
135     X             P          32B /TOMZ/        19             XTOY.          -              EXTERNAL.


   414B  PROGRAM-UNIT LENGTH           28 SYMBOLS

   44000B CM STORAGE USED            .462 SECONDS
```

APPENDIX (3)

GOVERNMENT OF NEWFOUNDLAND AND LABRADOR
DEPARTMENT OF CONSUMER AFFAIRS AND ENVIRONMENT

ST. JOHN'S

1978 03 22

Ms. Geraldine Sweet
Lecturer
Dept. of Geography
The University of Winnipeg
Winnipeg, Manitoba

Dear Ms. Sweet:

Thank you for your letter of February 22, 1978 concerning the results of the dye test done by you in the vicinity of the Woodville-Millville waste disposal site.

We also conducted a preliminary investigation of the area which indicated that groundwater in the three sink-holes, used for dumping garbage, is part of the same ground-water system which discharges into various ponds, brooks and springs in the area. The results of physical and chemical analyses surprisingly provide no indication of pollution of the water in the area. All the parameters tested had concentrations much below the Canadian Drinking Water Standards. As expected, relatively higher concentrations of calcium (5-63 mg/l) and sulphate (5-138 mg/l) and higher values of pH (6.46-8.05) were observed. It is most probable that leachates produced at the dump site are diluted by the receiving waters thus keeping the concentrations much below permissible limits.

The results of bacteriological analysis conducted by the Department of Health indicated higher bacteria counts at some locations. It is felt that further monitoring of water for bacteria counts is required to identify the source of pollution.

Once again, thank you for your help.

Yours sincerely,

Wasi Ullah, Ph.D.
Hydrologist
Water Resources Branch

WU/mcf

"LET'S KEEP IT CLEAN"

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