SIMULATION OF CONDUIT NETWORK DEVELOPMENT ON BEDDING PLANES

By

STUART E. WATERMAN, B.SC.

A Thesis
Submitted to the School of Graduate Studies
in Partial Fulfilment of the Requirements
for the Degree
Master of Science

McMaster University
May 1975

SIMULATION OF CONDUIT NETWORK DEVELOPMENT ON BEDDING PLANES

MASTER OF SCIENCE (1975)
(Geography)

McMASTER UNIVERSITY
Hamilton, Ontario

TITLE: Simulation of Conduit Network Development on Bedding Planes

AUTHOR: Stuart E. Waterman, B.Sc. (McMaster University)

SUPERVISOR: Dr. D.C. Ford

NUMBER OF PAGES: viii, 116

ABSTRACT

The development of conduit networks on bedding plane surfaces has been simulated in a series of laboratory analogue experiments. Two types of hardware models were used to study the influence of various hydraulic and structural boundary conditions on the pattern of these networks.

Network pattern was found to be directly related to the pattern of fluid flow in the bedding plane, as determined by the configuration of input and output areas.

Bedding plane inclination did not directly affect network pattern. However, the relationship between stratal dip and the accumulation of sediment within the network may indirectly affect network pattern.

The shape of conduits in cross section was found to depend on their mode of origin. Discrete tubes maintained a circular cross section throughout their growth. However, anastomotic bands of tubes tended to develop into a single tube of elliptical cross section.

ACKNOWLEDGEMENTS

The author is indebted to his supervisor, Dr. D.C. Ford, who gave freely of his time and direction and whose continued support in the face of repeated failure made this study possible.

Particular thanks are due Mr. R.O. Ewers, whose mechanical wizardry contributed immeasurably to the success of the investigation.

Finally, the author wishes to thank his wife, Janet, for her patience and understanding and for typing the bibliography.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF PLATES

CHAPTER I

INTRODUCTION

The nature of limestone caverns has been a subject of considerable speculation during the past century. Numerous conflicting theories have been advanced to explain the origin and development of such features. These theories may be divided into three general categories, vadose, deep phreatic, or watertable, on the basis of the proposed spatial relationship between the zone of speleogenetic activity and the hypothetical location of a watertable.

The vadose theory of cavern genesis, typified by the work of Gardner (1935) and Mallott (1938), proposes cave formation in the vadose zone (above the watertable). The vadose theory has fallen into disfavour in the light of more recent investigations (e.g. Bretz, 1942). The pattern of many cave systems and the morphology of most cave passages suggests that, perhaps, a majority of caves were formed under phreatic conditions.

Davis (1930) and Bretz (1942) proposed that speleogenesis occurs at essentially random depths beneath the watertable, following deeply curving paths of groundwater movement in the phreatic zone. However, it is the watertable, or "shallow phreatic", theory which has enjoyed the greatest popularity in the recent literature. Many authors, including Swinnerton (1932), Rhoades and Sinacori (1941), Davies (1960), White (1960), and Thrailkill (1968), have associated speleogenetic activity with the position of a watertable. Indeed, G.W. Moore summarized the presentations of the National Speleological Society symposium on the origin of limestone caves by stating, "The network pattern of many cave passages strongly suggests that most caves formed in a zone of saturation . . . A local or regional piezometric surface appears to provide [this] horizontal control, and most caves have evidently been formed directly below such a surface." (Moore, 1960; p. 4)

The general theme of most discussions of speleogenesis seems to be that it is possible to explain the genesis of the majority of limestone caves with a single, "universal" theory, whether vadose, deep phreatic, or watertable/shallow phreatic in nature. However, several authors, notably Halliday (1960) and Ford (1971), have recently suggested that none of the three "classical" theories are universally applicable. In his discussion of the major theories of speleogenesis, Halliday states, "Only in the broadest terms can it be said that all limestone caves develop in the same way, and terminology which suggests that this is true should be replaced by descriptions of individual speleogenetic sequences." (Halliday, 1960; p. 23).

Ford (1971) points out that most theories of speleogenesis either disregard the effects of geological structure, or consider only the special case of horizontally bedded limestone. Ford further suggests that while none of the vadose, deep phreatic, or shallow phreatic theories are universal in nature, any one of these genetic sequences may apply in a given area, depending on the influence of such local factors as geological structure, and the hydraulic boundary conditions of the cave system.

An additional problem common to most speleogenetic speculation is a bias introduced by the nature of the morphological data available for cave networks. Curl (1964) points out that "The possibility remains that many clues to cave origin reside where we cannot observe them . . . . Students of cave origin may be willing to extrapolate with confidence from their observations in the available sections of caves to the remainder, but nature usually does not divulge her secrets to limited observation, and it is more likely that our present concepts are considerably biassed." (Curl, 1964; p. 102). Many theories of speleogenesis appear to disregard this possibility.

In fact, the concept of cave origin has been equated, in many instances, with the concept of cave enlargement. This is an unavoidable consequence of the tendency to identify a cave on the basis of the dimensions of the human body, i.e. "A solution cavity in limestone is a cave if we can get into it." (Curl, 1960; p. 68). The pattern and morphology of these explorable passages are, to a great extent, predetermined by the nature of the primitive network of smaller conduits developed in the early stages of groundwater circulation. Any discussion of speleogenesis must therefore take into account the processes which result in the development of this primary passage network.

Initially, groundwater circulation in a limestone mass is generally confined to planes of structural discontinuity, i.e. joints, bedding planes, faults and fractures, due to the low primary permeability of limestone. The pattern of the initial circulation is determined not only by the magnitude and spatial organization of the microporosity provided by these features, but also by the spatial relation of the primary penetrable void spaces and the hydraulic boundary conditions as determined by the surface topography in existence during the early stages of groundwater circulation. During this period, it is highly unlikely that the hydraulic conductivity of the limestone mass will be such that all available surface water drains underground. Thus, all available penetrable void spaces will be filled, and the primitive cave elements must inevitably develop in a phreatic or fully saturated environment.

The initiation of groundwater circulation in carbonate rocks results in solutional alteration of the surfaces along which the flow of unsaturated water takes place. Quantitatively, the most important avenues of groundwater flow in limestone appear to be bedding planes. Field observations (Ford, 1971) indicate that the ratio of the length of cave passage developed along bedding planes to the passage length developed along joints ranges from 10:1 to 100:1 in those caves where the solution of bedding planes is at all significant.

When the flow of unsaturated water follows bedding plane surfaces, solutional modification initially takes the form of networks of small diameter conduits. Continued solutional activity throughout the rock mass produces a complex three dimensional network composed of bedding plane and joint elements oriented along the paths of groundwater movement. As the conduit network becomes more efficient, the overall hydraulic conductivity of the rock mass increases to the point where the primitive network is able to accomodate most of the available runoff input. The network of small conduits which exists at this time is the precursor of the system of much larger "cave" passages accessible to speleologists. The development of larger scale, explorable passages is a result of the selective enlargement of certain elements of this complex, primitive network. Enlarging processes may here be defined as those which operate to increase the diameter of certain network elements, rather than the overall complexity of the network.

The processes involved in the selection of a main drainage path within the framework of phreatic elements and its subsequent enlargement may be affected by such factors as: the spatial variation of hydraulic conductivity within the network; the hydraulic gradient established across the network; the geological structure of the limestone mass; the infilling of network segments by allochthonous or autochthonous sediments.

The phenomenon of speleogenesis may therefore be divided into two distinct "phases" (Ewers, 1972): the primary phase of solutional modification of subsurface flow paths, resulting in the formation of a complex, three dimensional network of small diameter conduits; and the secondary phase involving selective enlargement of certain segments of the primary conduit network.

Since the enlarging processes involved in the second phase of cave development operate within the conduit framework of the first phase, the proper understanding of the Phase 1 genetic sequence is a necessary prerequisite to the study of larger scale passages amenable to human exploration. Many authors have attempted to formulate a "universal" theory of cavern genesis solely on the basis of observations of Phase 2 passage systems (for example: Rhoades and Sinacori, 1941; Bretz, 1942; Thrailkill; 1968). Since the processes operative in the second phase of speleogenesis are subject to pronounced spatial variation on both local and regional scales, it is not surprising that such attempts to construct a "universal" theory to explain the genesis of explorable passages have been largely unsuccessful.

Despite the acknowledged importance of the early stages of cave development (Ewers, 1966; Ford, 1971), relatively little is known about the formation of primary conduit systems. This problem is subjected to detailed investigation in the remainder of this paper. A series of laboratory analogue experiments have been conducted to study the evolution of Phase 1 conduit systems in a bedding plane environment under various structural and hydraulic boundary conditions.

CHAPTER II

THE SIMULATION OF SPELEOGENETIC PROCESSES

A. THE HARDWARE MODEL APPROACH

It is an unfortunate fact that the early stages of speleogenesis are, to all intents and purposes, impossible to observe. No means exist at the present time which could provide sufficiently detailed information concerning the initial stages of groundwater circulation within a limestone mass and the subsequent channelization of groundwater flow by the action of solution processes. In addition to the problems imposed by inaccessability, the nature of the chemical reactions involved in the dissolution of limestone in water is such that the evolution of these systems proceeds very slowly. The abandoned remnants of the primary or Phase 1 conduit networks which may be observed by speleologists are often either of unexplorable dimensions, or greatly modified by later processes unrelated to the speleogenetic circumstances under investigation. It is for these reasons that the decision was made to investigate the problem by employing hardware modelling techniques in a series of laboratory experiments.

The use of hardware models in geomorphology and geology is well established. Morgan (1967) cites many instructive examples. In general, the hardware model approach allows the experimenter to study individually the variables which may be involved in the phenomenon under investigation. The scaling of the operative boundary conditions from the prototype to the model permits the manipulation of both spatial and temporal factors for convenient study. This attribute is of particular value in studies of limestone solution processes, where the temporal scale of the phenomenon under investigation may be orders of magnitude greater than the lifespan of the investigator.

Hardware models have been used in several instances in karst studies. Goodchild and Ford (1971) simulated the formation of scallops or "flutes" on limestone surfaces. Stable scallop patterns were successfully generated on calcium sulphate surfaces set in a small flume operating under closely controlled conditions.

Howard and Howard (1967) conducted a series of laboratory experiments to study the kinetics of the carbonate solution process in a rock fracture environment. In this case, artificial "joint" openings were constructed by laminating rectangular blocks of limestone. Distilled water charged with a known amount of carbon dioxide was repeatedly circulated through the fracture opening. Samples were taken at intervals to determine the dependence of the amount and rate of solution upon the total length of flow. The authors were able to investigate the effects of rock type, fracture dimensions, and carbon dioxide partial pressures on the reactions in question. Although this system is, in effect, a full scale reproduction of the prototype, controlled laboratory conditions were necessary to yield the required levels of precision.

Patterns of groundwater circulation have been successfully simulated with various types of electrical analogues. The discrete or network electrical analogue replaces the continuous field of groundwater flow with an electrical circuit of lumped resistance and capacitance elements (for examples, see: Bear et al, 1968, pp 381-390). The equivalence between electrical conductance and hydraulic conductivity allows the analogy to be drawn between voltage values at nodal points in the electrical network, and volumes of flow at equivalent (or homologous) points in the groundwater flow field. Similarly, the capacitance elements of an electrical circuit may be used to simulate the storage of water in an aquifer. Bedinger (1966) utilized a discrete electrical analogue to simulate groundwater circulation patterns in limestone terrain. He employed a simple network of resistance elements, each of which simulated either a bedding plane or joint unit. The discrete electrical analogue, however, is suitable only for studies of generalized patterns of groundwater flow, due to unavoidable approximations involved in the reduction of a continuous flow field to discrete elements.

Ewers (1966, 1972) simulated the process of solution in a horizontal bedding plane element with a hardware model in which salt blocks were substituted for limestone strata. By injecting unsaturated solvent into the interface of a salt block and an insoluble plastic surface, he was able to observe the growth of simple conduit systems on bedding plane surfaces.

In a conceptually similar study, Reams (1963) simulated the evolution of domepits in a model system in which limestone was retained as the solute, while dilute hydrochloric acid was substituted as the solvent. In both instances, the substitution of chemical systems produced, in a short period of time, small scale solution features which were found to be morphologically analogous to much larger features observed in limestone caves. This type of model has been criticized (Watson, 1965) on the grounds that the substitution of one chemical reaction for another is not theoretically justified. This question will be dealt with in following sections.

B. THEORY OF HYDRAULIC MODELS

B.1 Similarity

"A model is a man-made system by whose operation the characteristics of natural systems can be predicted or tested." (Allen, 1968, p 200)

If a model system is to correctly simulate the operation of the prototype system, then certain requirements of similarity between model and prototype must be met.

Similarities involved in fluid mechanics are geometric similarity, kinematic similarity, and dynamic similarity (Yalin, 1971, Chapter 1). Geometric similarity exists between prototype and model if the parts of the model have the same shape as the corresponding parts of the prototype. Geometric similarity thus requires that the length ratios of all corresponding lengths in the model and prototype be the same, i.e.

$$L_r = L_1p/L_1m = L_2p/L_2m = L_3p/L_3m = \text{etc.}$$

where Lp is a length in the prototype system and Lm is the corresponding length in the model. L_r is the length ratio or scale factor.

If model and prototype are to be kinematically similar, then the streamline paths of fluid flow in both systems must be the same. Homologous points within the model and prototype flow will then possess the same velocity ratio, V_r, and the same acceleration ratio, A_r. Thus,

$$V_r = V_1p/V_1m = V_2p/V_2m = V_3p/V_3m$$

and $$A_r = A_1p/A_1m = A_2p/A_2m = A_3p/A_3m.$$

Dynamic similarity requires that equivalent parts of the prototype and model systems experience similar net forces. In the case of fluid flow, the systems are dynamically similar if the shear ratio, the pressure ratio, and the force ratios are the same at homologous points in the flow system. In most fluid flow situations, the force of inertia is involved (Albertson et al, 1960, p 491), and four standard ratios of fluid forces have been devised to characterize fluid flow, each of which incorporates the force of inertia. The four dimensionless parameters (i.e. independent of scale) are as follows:

$$\text{Reynolds number } (R_e) = \frac{\text{inertia force/unit area}}{\text{viscous force/unit area}}$$

$$\text{Froude number } (F_r) = \frac{\text{inertia force/unit area}}{\text{gravitational force/unit area}}$$

$$\text{Mach number } (M_a) = \frac{\text{inertia force/unit area}}{\text{elastic force/unit area}}$$

$$\text{Weber number } (W_e) = \frac{\text{inertia force/unit area}}{\text{surface energy force/unit area}}$$

Complete dynamic similarity between model and prototype requires that the value of each parameter is the same in both the prototype and the model systems. Because of the low velocities involved in groundwater flow, only the Reynolds number is important in the case of groundwater flow models.

Many phenomena are strongly influenced by additional factors for which an exact law of similarity cannot be determined; for example the mechanical properties of rocks and sediments. When this the case, empirical interpretations of model data are required (Lanhaar, 1951, p 74). In most such instances, tests are run in the model during which certain natural events are reproduced as accurately as possible. Various scale factors are then adjusted until the behaviour of the model satisfactorily duplicates that of the prototype. When the model has been verified in this manner, it may then be used to predict the outcome of events in the prototype. This approach to model studies is frequently adopted in engineering analyses where quantitative results are required (Albertson et al, 1960, pp 501-507 give several examples). This procedure is inapplicable in the present study, because no suitable data exist for groundwater flow in limestone, either in unmodified fractures or in solutionally formed conduits. Consequently, scaling a model of this system with verification techniques is impractical.

Hooke (1968) points out that model verification techniques are of little use in studies concerned with determining general relationships applicable to a population of systems, as opposed to a particular member of that population. He suggests that modelling in such instances should follow a "similarity of process" procedure. In this type of study, the model is considered to be a separate system in its own right, rather than a smaller scale version of the prototype. Hooke proposes three basic conditions which should be satisfied for simulation of a geomorphic problem using the similarity of process technique:

1) General scaling relationships must be met.

2) The model should reproduce a morphological characteristic of the prototype.

3) The processes producing this characteristic in the model can logically be assumed to operate in the same fashion in the prototype.

Hooke successfully employed this type of model in a study of alluvial fans. Although he states "...absolute certainty is practically impossible to achieve when the real phenomenon can't be observed." (i.e. the formation of alluvial fans), the laboratory experiments suggested a logical explanation for field observations and furnished support for the explanation. Another example of a process similarity approach to modelling is the glacier model of Lewis and Miller (1955), in which a mixture of kaolin and water flowing in an inclined treugh was found to simulate certain flow characteristics of valley glaciers.

The similarity of process approach is particularly applicable to the present study, in which an attempt is made to describe the evolution of a population of geomorphic features in general terms. This type of model allows the delineation of the most significant processes operative in the first phase of speleogenesis, while avoiding what Hooke terms a "dubious quantitative extrapolation from a model to a prototype" (Hooke, 1968). The modelling of the first phase of speleogenesis using a similarity of process model requires the delineation of those hydraulic and chemical factors which most strongly influence the pattern of fluid flow through a limestone medium and the processes of mass transfer along the paths of solvent movement. If these factors are adequately reproduced in the model system, then the behaviour of the model may reasonably be assumed to approximate that of the prototype.

B.2 Fluid Flow in Limestone

The first phase of speleogenesis involves two distinct types of groundwater circulation, planar flow and conduit flow. Initially, groundwater flow is constrained to a system of interconnected planar void spaces, primarily bedding planes and joints. Solutional modification of these planar flow paths during the first phase of speleogenesis gradually transforms the initial network of planar elements to one in which groundwater circulates primarily through an integrated system of conduits. Subsequent solutional activity selectively enlarges certain elements of this network, thereby increasing its hydraulic efficiency. Thus the initial pattern of groundwater circulation through the network of planar void spaces in the limestone mass can be seen to influence the subsequent development of the Phase 1 conduit network.

Groundwater circulation is fundamentally caused by a difference in hydrostatic head between the recharge (input) and discharge (output) areas of the system. The rate at which water may be transmitted from recharge to discharge is a function of the overall hydraulic gradient of the system and the hydraulic conductivity of the medium.

Because the unmodified fracture system is most probably incapable of accomodating the entire input in the recharge area (Ewers, 1972), the hydrostatic head (and the location of the watertable) is defined by the surface of the rock mass. Consequently, the initial hydraulic gradient of the flow system is strictly a function of the surface topography existing at the onset of groundwater flow.

The hydraulic conductivity of the rock mass is determined by two structural factors: the density of fissuration; and to a lesser degree, the transmissivity of the fissures themselves. Because the primary permeability of limestone can be considered negligible, the nature of the fissure network which provides secondary permeability is the most important factor controlling the initial resistance to groundwater flow. The density and spatial distribution of penetrable fissures (i.e. the spatial variation of hydraulic conductivity) has a great effect on the location of speleogenetic activity in a limestone mass. For example, folding produces joints and may cause enlargement of bedding plane openings. Flexural slip folding, a type frequently found in the cavern areas of the Appalachians (Egemeier, 1969), causes slippage along bedding planes at the flanks of folds and the formation of tensional joints which are often concentrated near the fold crest. As a result, the hydraulic conductivity of the limestone may be significantly enhanced near the fold crest, possibly leading to a concentration of groundwater flow and solutional activity in this area. Similarly, the presence of faults, which in some instances possess higher transmissivity than either bedding planes or joints, may provide a low resistance path for groundwater flow. In a study of caves in New York state, Egemeier (1969) found that "...faults seem to have controlled the development of nearly all the largest cavern passages..." (Egemeier, 1969, p 100).

While local variations in hydraulic conductivity induced by tectonic activity may influence the pattern of cave networks in plan, the average value of the hydraulic conductivity in a given region (derived from the fissuration density) may affect the nature of cave networks in the vertical dimension. Ford (1971) suggests that the "watertable" type of cave, typified by a concentration of passage development along a single gently sloping plane, may develop in those areas where the fissuration density, and consequently the regional hydraulic conductivity, is sufficient to establish a watertable at depth during an early stage of speleogenesis.

The characteristics of groundwater movement during the early stages of speleogenesis may thus be considered a function of the hydraulic boundary conditions (hydraulic gradient and hydrostatic head) imposed by the surface topography, and the resistance of the limestone medium to the flow of groundwater (represented by the hydraulic conductivity). Since the magnitude and direction of groundwater flow at various points in the limestone mass during this period strongly influences the subsequent development of the Phase 1 conduit network, the nature of the groundwater circulation resulting from these conditions is of great importance in any discussion of speleogenesis.

In a porous medium such as sandstone, the pattern of groundwater flow may be described by Darcy's law and the Laplace equations derived from it. Many authors have applied these relationships to the problem of groundwater circulation in fractured rocks, including limestones. Davis (1930) for example, based a deep phreatic theory of speleogenesis on flow theory developed for porous media.

In brief, Darcy's law postulates a linear relationship between the velocity of groundwater flow and the hydraulic gradient. Darcy's law may be written:

$$Q = k\,A\,\frac{dh}{dl} \qquad \text{B.2(1)}$$

or

$$v = \frac{Q}{A} = k\,\frac{dh}{dl} = k\,i \qquad \text{B.2(2)}$$

where Q is the discharge, k is the hydraulic conductivity of the medium, i is the hydraulic gradient or the headloss (h) over a distance (l) in the direction of flow, and v is an apparent flow velocity, often referred to as the specific discharge.

The linear relationship between Q and i is valid only when inertial forces in the flow are not important, i.e. under conditions of laminar flow. When groundwater flow becomes turbulent, equation B.2(2) becomes:

$$v = ki^{\phi} \qquad \text{B.2(3)}$$

where ϕ is the exponent of turbulence. The change from laminar to turbulent conditions is described by the Reynolds number. In porous media, the Reynolds number is defined as:

$$Re = \frac{vD}{\nu} \qquad B.2(4)$$

where ν is the kinematic viscosity of the fluid, and D is a characteristic length given by a representative particle diameter. For water flowing in completly filled conduits, the transition from laminar to turbulent flow occurs at a Reynolds number of approximately 2100. In filtration flow, however, inertial forces become significant at much lower values of Re. Investigations have shown that groundwater flow deviates from Darcy's linear relationship for values of Re ranging from 1 to 10. Hubbert (1940), for example, suggests that the critical point is reached at a Reynolds number of 4, while Yalin (1971) proposes a value of approximately 1.

In those instances where the linear Darcy flow law applies, it is possible to determine the groundwater flow vector at any point in the aquifer, and thus the general pattern of groundwater circulation.

Within an orthogonal coordinate system, the velocity of groundwater flow may be expressed as the vector sum of three component velocities given by:

$$v_x = k_x \frac{\partial h}{\partial x}, \; v_y = k_y \frac{\partial h}{\partial y}, \; v_z = k_z \frac{\partial h}{\partial z} \qquad B.2(5)$$

where k_x, k_y and k_z are the magnitudes of the hydraulic conductivity of the medium in the x, y, and z directions respectively. If the magnitude of the hydraulic conductivity is a function of the flow direction, the medium is said to be anisotropic. Conversely, if the hydraulic conductivity of the medium is the ame in all directions, the medium is isotropic. When the values of k_x, k_y and k_z are independent of the coordinates of the point in question, the aquifer is said to be homogeneous. If this is not the case, the aquifer is heterogeneous. In the simplest case of an isotropic and homogeneous aquifer, Equation B.2(5) may be written:

$$v_x = k\frac{\partial h}{\partial x}, \quad v_y = k\frac{\partial h}{\partial y}, \quad v_z = k\frac{\partial h}{\partial z} \qquad \text{B.2(6)}$$

Todd (1959) defines a "velocity potential" (ϕ) for groundwater flow, such that:

$$\phi = -kh \ . \qquad \text{B.2(7)}$$

The negative derivative of the velocity potential with respect to any given direction represents the fluid velocity in that direction.

Equation B.2(6) may be expressed in terms of ϕ in the form:

$$v_x = \frac{\partial \phi}{\partial x}, \quad v_y = \frac{\partial \phi}{\partial y}, \quad v_z = \frac{\partial \phi}{\partial z} \ . \qquad \text{B.2(8)}$$

All groundwater flow must satisfy the equation of continuity (representing the principle of mass conservation), given by:

$$-\left[\frac{\partial(\rho v_x)}{\partial x} + \frac{\partial(\rho v_y)}{\partial y} + \frac{\partial(\rho v_z)}{\partial z}\right] = \frac{\partial \rho}{\partial t} \qquad \text{B.2(9)}$$

where ρ is fluid density and t is time. If the void spaces remain constant in size and the fluid is considered to be incompressible. Equation B.2(9) reduces to:

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0 \ . \qquad \text{B.2(10)}$$

Substituting the values for v_x, v_y and v_z given by Equation B.2(8) leads to the expressionknown as the Laplace equation:

$$\frac{\partial^2 \phi}{\partial x} + \frac{\partial^2 \phi}{\partial y} + \frac{\partial^2 \phi}{\partial z} = 0 \quad . \qquad \text{B.2(11)}$$

Equation B.2(11) may be represented in a two dimensional graph by two families of curves that intersect at right angles. The members of one set of curves are called flowlines, while the other curves are known as equipotentials. The flowlines represent the paths along which water particles move in the flow field, the velocity vector at a given point being tangent to a flowline drawn through that point. The equipotentials connect points of equal velocity potential (ϕ).

It is most difficult to determine the extent to which such a flow net describes the circulation of groundwater in a limestone medium, which must be considered both anisotropic and heterogeneous. In spite of these conditions, Darcy flow laws are frequently used as a first approximation to groundwater flow in cavernous limestones (DeWiest, 1965, p 161). In such instances, the pattern of penetrable fissures is often considered to be regular and homogeneous (e.g. Rhoades and Sinacori, 1941; Rofail, 1965). Since groundwater flow in limestone is constrained to a network of linear bedding plane and joint elements, the curved trajectories described by Darcy flow theory are, at best, an approximate representation of the actual paths of groundwater flow. Figure 2.1 represents a possible modification of Darcy - type flowlines in a limestone medium.

The importance of the relationship between geological structure and the hydraulic boundary conditions of ground-

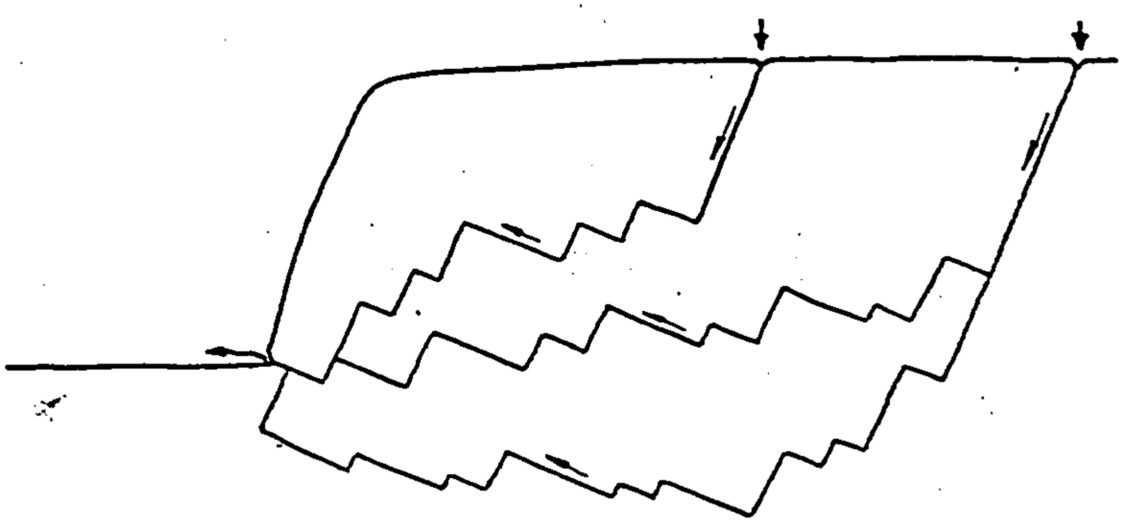

Figure 2.1 Darcy type flow in a fractured medium (after Ford, 1971)

-water flow has been stressed by several authors (for example: Ford, 1971; Waltham, 1971; and Jennings, 1971). Various aspects of geological structure may cause a significant deviation from theoretical flow paths. In general, bedding planes are more effective routes for groundwater flow than joints, due to their greater areal extent. Consequently, the dip of bedding plane surfaces may control the depth at which major speleogenetic activity occurs. In horizontally bedded limestones, for example, cavern development at depth may be inhibited by the presence of shallow bedding plane routes which provide a virtually direct connection between sink and resurgence areas. Conversely, deep phreatic caves are frequently found in steeply dipping limestones, where continuous bedding planes may conduct water to great depths (Ford, 1971). Waltham (1971) has proposed that the proportion of joint to bedding controlled passages is a function of the difference between the angle of dip and the overall hydraulic gradient of the system, such that the proportion of joint controlled passages becomes greater as the dip exceeds the hydraulic gradient.

The pattern of groundwater circulation and cave development may be further disturbed by lithological variations in a limestone mass. Thin beds of insoluble chert or shale may inhibit deeper penetration of groundwater, thus causing cave passages to be perched on such obstructions (Jennings, 1971).

In summary, it appears that the heterogeneous and anisotropic nature of limestone, combined with the influence of various structural and lithological variables, severely restricts the applicability of Darcy flow laws to groundwater flow in limestone aquifers. Only in the most general sense can Darcy flow nets be said to describe the patterns of groundwater flow in limestone areas. The spatial variability of such important factors as stratigraphic dip, fissuration density, and lithology renders suspect any general theory of speleogenesis which postulates a preferred zone of cavern development on the basis of Darcy flow theory. Regional patterns of speleogenesis are so strongly influenced by local variables, that any attempt to synthesize a specific speleogenetic sequence from field observations in widely separated areas must, of necessity, involve considerable generalization. It would appear to be more profitable to investigate those speleogenetic processes which operate to produce the smaller scale speleogenetic units common to all cave networks; those units which together comprise the primitive Phase 1 cave network.

B.3 Fluid Flow During the First Phase of Speleogenesis

The basic units of the Phase 1 network are the small conduit systems which form along individual planar voids in the limestone mass. The network may be viewed as a modular structure composed of interconnected planar units. Although the regional flow field, and thus the pattern of the entire network structure, may be controlled by the local boundary conditions, the nature of the individual modular elements should be largely independent of large scale patterns of groundwater movement.

The importance of the modular or "building block" concept has been recognized by Ford (1971). He proposed that where the ratio of penetrable bedding plane to joint length is large, the basic speleogenetic unit consists of bedding plane networks ranging from discrete "dip tubes" in high dip situations, to anastomotic bands of tubes in near horizontal situations. Since bedding planes are quantitatively the most important avenues for groundwater flow during the early stages of speleogenesis (Ford, 1971), the cave units which form in such environments were chosen as the subject of the model experiments.

The examination of speleogenesis at the level of such basic cave units greatly reduces the problems of model simulation. If a "similarity of process" approach is followed, it is then sufficient to reproduce the paths of groundwater flow in a bedding plane environment and the chemical processes which result in the removal of soluble material along these flow paths.

The pattern of groundwater movement across a bedding plane surface will be determined by two factors, the nature of the bedding plane and the hydraulic boundary conditions governing fluid flow. Quantitative information concerning the nature of unmodified bedding planes in limestone, and particularly the ability of individual bedding planes to transmit water, is unfortunately unavailable. The presence of bedding planes may be due to any one of a variety of phenomena such as an interruption in sedimentation, the presence of non-carbonate material (e.g. shale), or a change in sediment size. Consequently, the nature of these surfaces is highly variable. In general, the discontinuity which develops is characterized by a permeability much greater than the primary permeability of the surrounding strata. This enhanced permeability is apparently caused by the presence of numerous small openings whose dimensions are determined primarily by the coarseness of the sediments composing the surface of the rock units. The size and density of these openings varies over the bedding plane surface. In addition, certain areas of the bedding plane may be disturbed by the presence of fossil fragments, stylolites, chert nodules, and argillaceous material. Thus, a "typical" bedding plane may be considered to be a planar zone of enhanced permeability provided by a multitude of interconnected, irregular voids of varying size and areal distribution. In effect, a bedding plane acts as a two dimensional porous medium for groundwater movement. At a sufficiently large scale, the bedding plane may be considered as isotropic and homogeneous, allowing two dimensional versions of the flow equations presented earlier to be used to describe the movement of groundwater across it. For example, the components of the fluid velocity vector at any point are given by Equation B.2(6):

$$v_x = k\frac{\partial h}{\partial x},\ v_y = k\frac{\partial h}{\partial y},\ (v_z = k\frac{\partial h}{\partial z}),$$

where $\frac{\partial h}{\partial z} = 0$. Similarly, the Laplace equation (Equation B.2(11)) may be written:

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0 \qquad \text{B.3(1)}$$

and the flow net produced by a graphical solution of the equation may be used to determine the paths of fluid flow and the distribution of the velocity potential (ϕ) across the bedding plane. However, these equations are strictly applicable only under conditions of laminar flow when the Reynolds number is below the critical value.

While it appears reasonable to represent bedding planes as two dimensional porous media, many authors (for example: White and Longyear, 1962; Howard and Howard, 1967) have depicted bedding planes as uniform planar openings bounded by parallel strata. Laminar flow between parallel boundaries may be described by the same differential equation (and consequently the same flow net) describing laminar flow in a two dimensional porous medium. The proof of this analogy may be found in many texts (for example: DeWiest, 1965; Bear et al, 1968). In brief, it may be demonstrated that the components of the fluid velocity vector are given by:

$$v_x = K\frac{\partial h}{\partial x},\quad v_y = K\frac{\partial h}{\partial y} \qquad \text{B.3(2)}$$

where K, the hydraulic conductivity, is proportional to the square of the distance between the boundaries of flow. The upper limit for laminar flow in this instance is defined by a Reynolds number of approximately 1000 (DeWiest, 1965, p 325).

Although the general pattern of fluid flow as defined by a graphical solution of the Laplace equation is the same in both instances, the characteristics of fluid flow at a small scale are quite different. If a bedding plane is considered analogous to a uniform planar opening, then groundwater must be distributed continuously across the plane. However, in a porous medium analogy, groundwater flow is confined to a system of interconnected capillary tubes whose boundaries are defined by individual granular elements of the limestone surfaces. In essence, a "conduit" network precedes the onset of speleogenesis.

While the generalized pattern of fluid flow is identical in both cases, the environment in which solution of the limestone strata must take place is fundamentally different. Since the model experiments required duplication not only of the patterns of groundwater movement but also of the processes of limestone solution, a (two dimensional) porous medium analogue was selected as most closely duplicating the bedding plane environment.

C. LIMESTONE SOLUTION PROCESSES

C.1 Solution Kinetics

The dissolution of limestone (calcite) in water involves three equilibrium reactions:

$$CO_2(g) + H_2O \rightleftharpoons H_2CO_3$$

$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$$

$$CaCO_3 \rightleftharpoons Ca^{+2} + CO_3^{-2}$$

The rates of these reactions are determined primarily by the rates at which the chemical species diffuse through the solution, in particular the rate at which certain species diffuse across a saturated boundary layer. In addition, the process of limestone solution may be accelerated or retarded by the effects of temperature, pressure, solution mixing, and other chemical reactions (Thrailkill, 1968).

Weyl (1958) determined experimentally that the diffusion of solute across the boundary layer effectively determines the rate of calcite solution. Applying the experimental results to the flow of groundwater in capillaries and fractures, Weyl found that the solvent approached saturation asymptotically, such that solution virtually ceased after a finite distance of flow, which he termed the penetration distance. He defined the penetration distance, l, as the distance to 90% saturation, given by:

$$l = \frac{0.572\bar{v}a^2}{D} \text{, for a capillary environment}$$

or $l = \frac{0.304\bar{v}d^2}{D}$, for a fracture environment,

where $\bar{v}$ is the average fluid velocity, a is the capillary radius, d is the fracture width, and D is the diffusion constant for calcite in water. Although subsequent investigation by Howard and Howard (1967) and Curl (1965) suggest that Weyl's formulation may be incorrect, in general it appears that water flowing through small capillaries or fractures becomes saturated a short distance from the input point. Consequently, the rate at which limestone is removed from a given point is a function of the rate at which the saturated solvent is replaced (Ewers, 1972). In a bedding plane environment, the rate of solvent renewal at any point (given by the fluid velocity vector) is solely determined by the bedding plane flow field, and therefore the hydraulic boundary conditions governing groundwater movement. Therefore, a model which reproduces the pattern of solvent movement will reproduce the initial pattern of limestone solution in a bedding plane environment.

The kinetics of the solution process also exert an influence upon the later stages of bedding plane solution, as groundwater flow becomes confined to individual conduits. Kaye (1957) determined experimentally that the rate at which limestone dissolves in a conduit environment is directly dependent on solvent velocity. If this is the case, then in a developing conduit network that conduit which possesses the greatest flow velocity (i.e. the greatest diameter) will enlarge at the greatest rate. As this conduit enlarges, flow velocity and therefore the rate of solution continues to increase, with the net result being the establishment of a single dominant conduit.

White and Longyear (1962) proposed that the rate of solution increased dramatically as conduit flow becomes turbulent. They termed this phenomenon the "hydraulic jump", and calculated that the rate of solution should increase by a factor of seven at the transition point. Consequently, the acceleration of solution in the first conduit of a tube system to achieve turbulent flow would result in that conduit growing at such a rate that the development of alternate routes would cease.

The conditions of divergent conduit competition suggested by Kaye (1957) and White and Longyear (1962) would be extremely difficult to reproduce in a model situation. However, recent work by R. Curl (1965, 1974), based on the theory of diffusion processes, has conclusively shown that all conduits in a given system are convergently competitive, i.e. tending to the same diameter, in contrast to the hypotheses of Kaye (1957) and White and Longyear (1962). Curl found that the transition from laminar to turbulent flow temporarily delays, rather than prevents, conduit convergence. Therefore, the pattern of network development is essentially independent of flow conditions within individual elements.

C.2 Simulating Limestone Solution

In order to reduce the time required for the generation of conduit networks in the laboratory models, it is necessary to accelerate the dissolution process. This is most easily accomplished by substituting a more rapid chemical reaction for the calcite/carbonic acid system of the prototype. Watson (1965) has strongly criticized such substitutions on the grounds that the relationship between this type of model and its prototype is uncertain. Moreover, the scaling problems inherent in such a model preclude accurate comparison of the model and the prototype in those instances where the chemical reaction itself is of prime importance to the operation of the prototype system. In the case of limestone solution, however, it has been demonstrated that the element of the dissolution process which actually controls both the pattern of the conduit network and the enlargement of individual conduit elements is the diffusion of the chemical species across a saturated boundary layer. If quantitative comparisons of the model and prototype are not required (i.e. when a "similarity of process" model is employed), it is then possible to model limestone solution with any mass transfer process which is diffusion limited, as shown by Goodchild and Ford (1971).

The rapidity of a diffusion process is represented by the value of the diffusion constant, D. Weyl (1958) determined that the value of D in a calcite/water system is approximately $0.2 \times 10^{-4}\ cm^2 sec^{-1}$. The diffusion process selected for the laboratory experiments was the dissolution of calcium sulphate (plaster of paris) in water. This system is also diffusion limited, with a D value of approximately 0.78 x 10^{-3} $cm^2 sec^{-1}$ (Frank-Kamenetskii, 1955). Since the penetration distance is inversely proportional to D, solvent flowing in the model environment becomes effectively saturated at a comparatively short distance from an input point. Consequently, the geometry of solution features produced in such a model may be expected to be considerably smaller than the geometry of similar features in the prototype (Ewers, 1972).

D. EXPERIMENT DESIGN

A series of model experiments simulating the first phase of speleogenesis in a bedding plane have been performed, adopting the "similarity of process" approach. This approach was selected for two reasons: the lack of detailed information concerning the first phase of speleogenesis; and the highly variable nature of the prototype environment. The similarity of process approach simplifies the model design and allows the application of the experimental results to the general case of conduit development on bedding plane surfaces.

The models were designed to simulate both the pattern of fluid flow in a bedding plane environment and the mass transfer processes which result in the formation of conduit systems.

The pattern of fluid flow is determined by the distribution of a velocity potential across the bedding plane surface. This distribution may be determined by solving the Laplace equation (Equation B.3(1)) for the given boundary conditions. The direction of fluid movement at any point is given by the Darcy flow net, a graphical representation of the Laplace equation. For a given set of boundary conditions. the flow net will be the same for any type of potential flow, such as flow in a two dimensional porous medium or viscous flow between parallel boundaries. The porous medium analogy as most closely simulating the micro-scale characteristics of fluid flow in a bedding plane environment. Since the linear Darcy flow laws on which the flow net is based apply solely to laminar flow, fluid flow in the model must take place below the critical value of the Reynolds number ($Re_{crit.}$ ranges from 1 to 10).

The simulation of limestone solution requires duplication of both the mass transfer process itself, and the pattern of solvent movement and renewal. Since solvent renewal is governed by the flow field, the similarity requirement will be satisfied if linear Darcy flow conditions exist. The limestone solution process may be satisfactorily simulated by any diffusion limited mass transfer system. In this instance the prototype process was simulated by the dissolution of calcium sulphate in water. Whilst this reaction is diffusion limited, the value of the diffusion constant is much greater than in the prototype system. Consequently, the model process takes place at a greater rate and with a shorter penetration distance. In addition, plaster of paris may be readily standardized and easily moulded into a variety of bedding plane configurations.

Two types of models have been employed in this study. In the first, described in Chapter III, a bedding plane is simulated by a planar discontinuity moulded into a plaster of paris block. Solvent under a hydrostatic head is introduced to a point on the edge of the bedding plane and a hydraulic gradient is set up across the surface.

In the second type of model, a bedding plane surface is represented by the interface between a granular plaster of paris surface and an insoluble, transparent plastic sheet. This arrangement allows study of conduit systems at various stages in development. This model was employed in a series of experiments to study the affect of geological structure on the pattern of conduit development. The results of these experiments are presented in Chapter IV.

CHAPTER III

TWO SURFACE EXPERIMENTS

A. INTRODUCTION

The experiments described in this chapter were designed to provide data on the growth of solution conduits in a bedding plane. In order to realistically simulate the prototype situation, a bedding plane surface was represented in the models by a planar discontinuity within a block of plaster of paris. This "two surface" type of model (i.e. with soluble material on both sides of the model plane) was selected as the one most closely duplicating the chemical-hydrodynamic environment of the prototype.

A number of experiments were conducted with this type of model over an eight month period. Unfortunately, technical problems associated with the design of the model system led to the failure of these experiments. Repeated attempts to resolve these problems were unsuccessful. As a result, the two surface model was abandoned in favour of the single surface-model described in Chapter IV. However, the two surface models supplied some limited information concerning the initial growth of bedding plane conduits.

B. MODEL PREPARATION

A bedding plane was represented in the model by a planar discontinuity within a plaster of paris block.

Construction grade plaster, manufactured by Domtar, (Canada) Ltd. ("Quick Set" type) was used in all the experiments.

A plywood mold was constructed to the desired dimensions of the model. The mold was constructed in such a way as to facilitate disassembly on completion of the casting process.

Input areas were formed by casting short lengths of pipe, 5 cm in diameter, into the edge of the model at the level of the bedding plane surface.

Prior to casting, all joints in the mold were temporarily sealed with tape and the input pipe closed with a large rubber stopper. The assembled mold was then filled to the level of the bedding plane with a standardized mixture of liquid plaster. The mold was periodically vibrated to release any air bubbles trapped within the plaster.

The first layer of plaster was allowed to set for 15 to 20 minutes, at which time a second quantity of liquid plaster was added to form the upper layer (i.e. rock stratum) of the model. The completed model was allowed to harden in the mold for a period of 8 to 12 hours. The mold was then disassembled.

Because of the high primary permeability of the plaster of paris, it was necessary to seal the surface of the model to prevent the undesired seepage of solvent from within the plaster block. A combination of shellac and epoxy glue was used for this purpose. In order to obtain proper adhesion of these substances to the model, it proved necessary to thoroughly dry the plaster block. The edges of the bedding plane, with the exception of the input and output areas, were sealed with epoxy glue. Epoxy was also applied to the surface of the model in the area of the input pipe. The epoxy was allowed to cure for 24 hours. The surface of the model was then sealed with 6 to 10 coats of thin shellac. The shellac was allowed to dry for a further 24 hours.

C. APPARATUS

The apparatus is shown schematically in figure 3.1.

To ensure that the phreatic conditions of theprototype environment were maintained during the experiment, the model was placed underwater in a large tank fabricated of reinforced plywood. The models were securely fastened to a plywood mounting board with padded clamps. This assembly was then placed in the tank in the desired position. Due to the combined weight of the model and the mounting board, a mobile hoist fitted with a 3:1 block and tackle was constructed to lift the models into position. The tank and mounting board were sufficiently large to accomodate a single model 1 m square, or several smaller models.

The input system consisted of a constant head reservoir connected to the model input(s) with flexible tubing, as shown in figure 3.1.

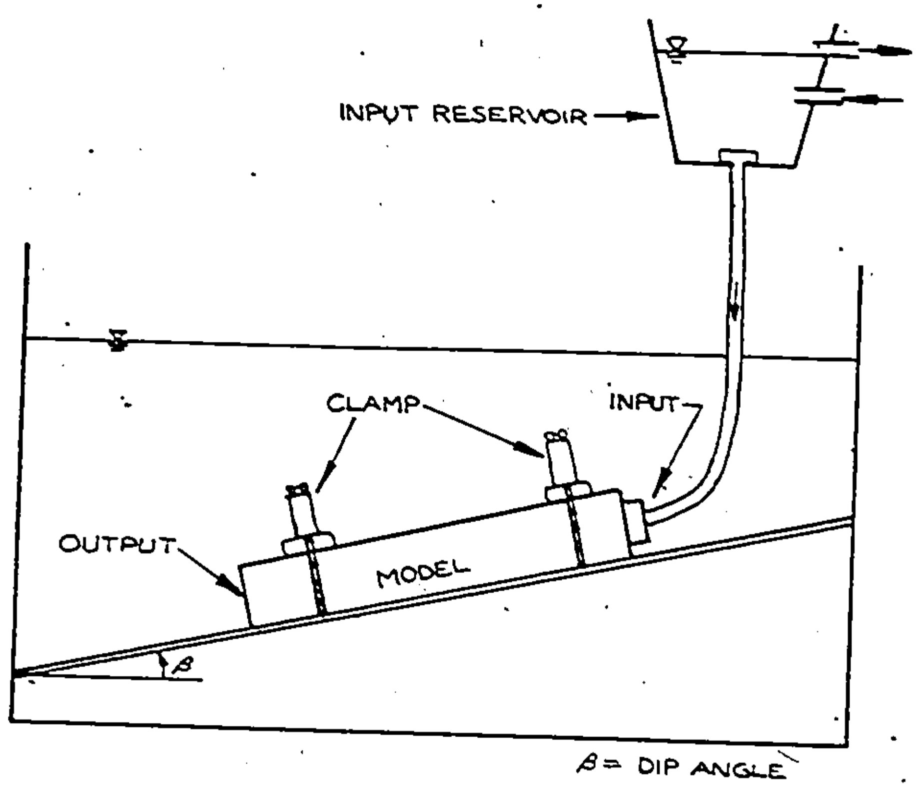

Figure 3.1

D. OBSERVATIONS

A series of experiments were conducted using models with a horizontal bedding plane and a single input area (figure 3.2). Technical problems inherent in the model design caused the failure of these experiments. Conduit development in the models was impeded to such an extent that it proved impossible to create systems of sufficient length that the input and output were connected.

The two most serious problems encountered during these experiments were: the failure of the sealant materials to confine the solvent within the model; and the slow rate of conduit formation.

The introduction to the model input of solvent under a hydrostatic head established a pressure gradient at the surface of the plaster. As a result, the sealing materials were subjected to considerable stress, particularly in the vicinity of the input. In addition, prolonged immersion of the model caused the bond between sealant and plaster to deteriorate. These factors combined to cause frequent rupturing of the epoxy and/or shellac layers, usually in the vicinity of the input. Solvent was then able to escape from the interior of the model. Because the primary permeability of plaster of paris is quite high, solvent escaped even in those instances when the area of sealant failure was not located on the edge of the bedding plane.

The problem of sealant failure was exacerbated by the

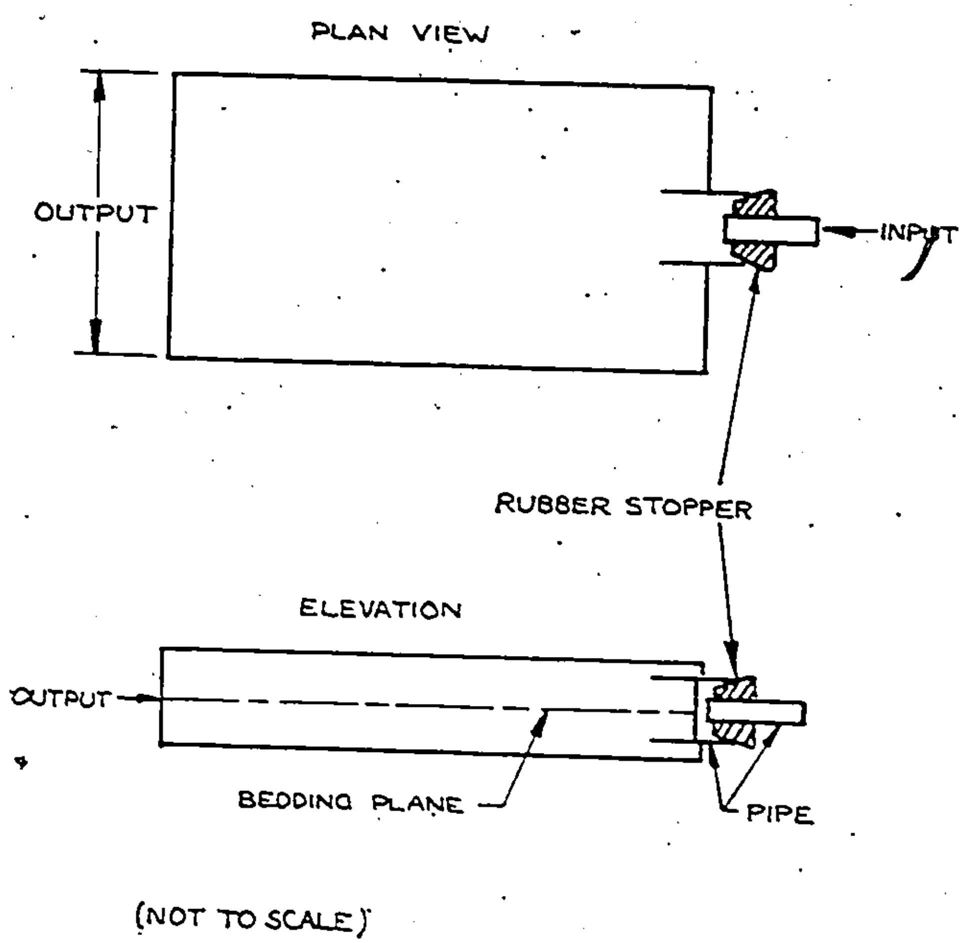
PLAN VIEW
OUTPUT
INPUT
RUBBER STOPPER
ELEVATION
OUTPUT
BEDDING PLANE
PIPE
(NOT TO SCALE)

Figure 3.2

slow rate of conduit formation. For example, the largest network produced required over 44 hours to reach an overall length of 13 cm, at which time the sealant ruptured and conduit growth (in the direction of the output) ceased. Two interrelated factors apparently retarded conduit growth: the low hydraulic conductivity of the bedding plane; and the retention of air in the pore spaces of the plaster.

The model bedding plane produced by the two stage casting process does not provide a measurable opening for fluid flow. The bedding plane is actually a planar concentration of void spaces within an otherwise homogeneous plaster block. The low rate of conduit growth suggests that the hydraulic conductivity of this surface is relatively low.

The drying process required for proper adhesion of the sealant inevitably trapped air in the pore spaces of the plaster. Fluid flow required that this air be displaced, further increasing resistance along the bedding plane.

These factors resulted in the failure of 17 experiments during the period of the investigation.

E. RESULTS

The two surface models failed to generate the complete networks required for the investigation. However, it is possible to make certain general observation concerning the formation of bedding plane conduits.

Plate 3.1 shows a typical set of conduit networks.

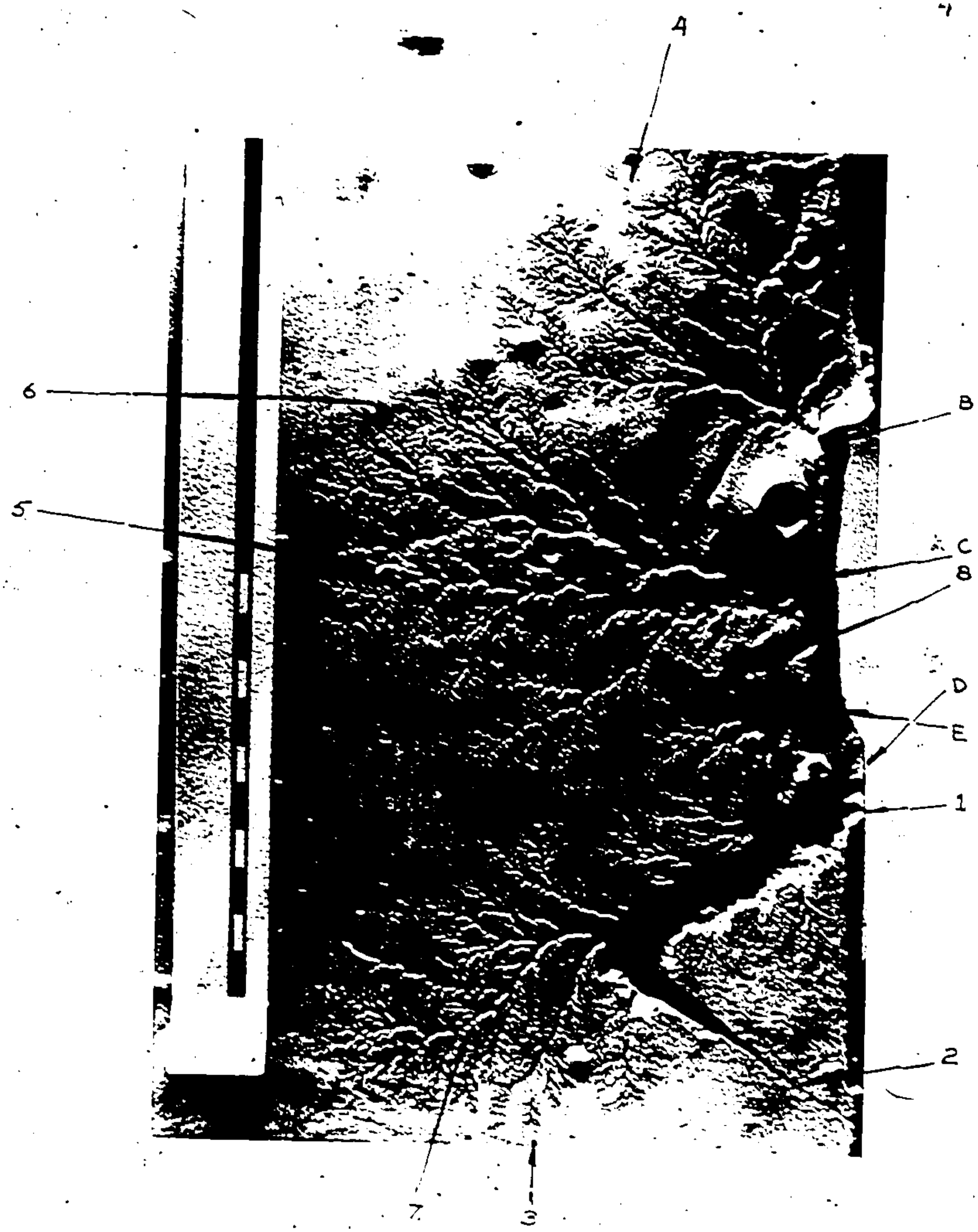

Plate 3.1 Lower surface of bedding plane. Scale in cm.

In this instance, solvent was introduced along a 7 cm section at the edge of a horizontal bedding plane. The net hydrostatic head of the input system was 45 cm.

Conduit systems formed at points B, C, D and E on the exposed edge of the bedding plane. These points apparently offered less resistance to fluid flow than the remainder of the area, thus favouring conduit development. The individual networks are predominantly dendritic in pattern. The long axes of the networks are roughly oriented in the direction of the output.

The large conduit segment at (1) connects the input to the fracture visible at (2). This fracture formed near the corner of the block, probably during the drying process. As the network grew from point D, it apparently breached the fracture. The full hydrostatic head of the input system was then transmitted along the fracture to the surface of the block. The stress thus created ruptured the sealant layer at this point, establishing a direct connection between network D and the exterior of the model. The central conduit enlarged rapidly, incorporating most of the original dendritic network. This conduit soon captured all the available input. The scallops visible on the walls of the large conduit are characteristic of turbulent flow over soluble surfaces (Goodchild and Ford, 1971).

The low hydraulic conductivity of the model bedding plane is evidenced by the "blind" conduit sections visible at several points (e.g. points 3 and 4, Plate 3.1) in the networks. At these points the enlarging network has abandoned the bedding plane, travelling for a short distance within the plaster stratum before returning to the bedding plane. This phenomenon suggests that the hydraulic conductivity of the bedding plane is often less than that of the solid plaster which surrounds it. Examination of the bedding plane at these points revealed no visible irregularities. The existence of such areas implies that elsewhere the difference in the hydraulic conductivity of the model bedding plane and the surrounding plaster is also quite small. This is in marked contrast to the prototype situation, where the primary permeability of limestone is negligible in comparison to the secondary permeability provided by bedding planes.

Despite the apparently slight increase in hydraulic conductivity afforded by the model bedding plane (in comparison to the hydraulic conductivity of the surrounding plaster), conduit development was essentially restricted to the bedding plane surface. Fluid flow in the zone of enhanced porosity provided by the bedding plane was sufficient to initiate conduit formation, which suggests that a separation between limestone strata is not a prerequisite for the formation of solution conduits in the prototype. This supports the previously postulated analogy between prototype bedding planes and two dimensional porous media.

E.1 Conduit Network Development

The predominantly dendritic conduit pattern visible in Plate 3.1 is in marked contrast to the Phase 1 networks commonly observed on near horizontal bedding planes in natural caverns. The model network has branched outward in several directions from the input, apparently seeking to fully occupy the entire bedding plane surface. Similar conditions in the prototype commonly result in the formation of parallel, anastomotic bands of conduits, separated by unmodified sections of the bedding plane (Ford, 1971). However, a small amount of interconnection is evident between individual dendrites (Plate 3.1, points 5 and 6). In addition, the primary conduits of the networks are anastomotic in some areas (Plate 3.1, points 7 and 8).

The low hydraulic conductivity of the model bedding plane may have influenced the pattern of conduit growth. Dye injected into conduit systems similar to those shown in Plate 3.1, failed to penetrate the bedding plane further than 6 to 8 mm beyond the limit of fingertip conduit formation. Scuh could not be the case had a continuous flow field been established between the input and output. In the apparent absence of fluid flow across the bedding plane to the output, the solvent renewal required for conduit growth may have been, in part, the result of the diffusion of solute species from the conduit network to the input system. Since the hydraulic conductivity of the bedding plane was evidently low, the rate at which saturated solvent was removed from the network by fluid flow across the bedding plane may have been sufficiently slow to permit the diffusion process to significantly influence the pattern of network formation. However, insufficient data exist to evaluate this hypothesis.

The slow rate of conduit generation associated with the low hydraulic conductivity of the bedding plane may have contributed to the dendritic pattern of conduit growth. The networks appear to be most elaborate near the limit of conduit formation, particularly in those instances where conduit formation ceased as the result of sealant failure near the input. The large number of small distributaries observed at the network margins may have developed during the subsequent stagnation of the networks. The comparative lack of these features near the input appears to support such an hypothesis.

Small quantities of insoluble material, presumably derived from dissolved plaster, were frequently observed in the distributary conduits of the networks. It is possible that the accumulation of this material may have inhibited solution in the fingertip conduits, causing bifurcation. The accumulation of insoluble material may be of great significance in the prototype, where large quantities of surface derived sediments are often introduced into subsurface drainage systems. Because the early stages of conduit development are associated with low flow velocities, fine sediments (e.g. clays) are those most likely to be transported through the network to the fingertip conduits. Thus, the effect of sediment on the pattern of prototype network development will depend on both the type and quantity of sediment input.

E.2 Conduit Cross-Section

The two surface models allowed the study of conduit growth in cross-section. Prototype conduits frequently exhibit a roughly elliptical cross-section, often with a greater degree of incision in the upper surface of the bedding plane (figure 3.3). White and Longyear (1962) suggest that the development of an elliptical cross-section is linked to the transition between laminar and turbulent flow in the conduit. They propose that the increased solution rate in the turbulent zone leads to the eventual development of an elliptical conduit, as shown in figure 3.4. However, their sequence of conduit forms was not observed in the experimental conduits. These conduits were roughly circular in cross-section, ranging in diameter from 0.1 mm to 4.0 mm. In addition. the conduits were approximately centred on the bedding plane. Because fluid flow in the networks was laminar, White and Longyear's hypothesis predicted the development of a non-elliptical cross-section. However, the experimental conduits are quite different from the initial stages of conduit development envisaged by White and Longyear.

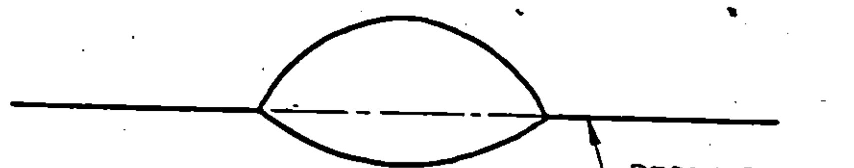

Figure 3.3 Hypothetical cross-section showing the elliptical form of many prototype conduits.

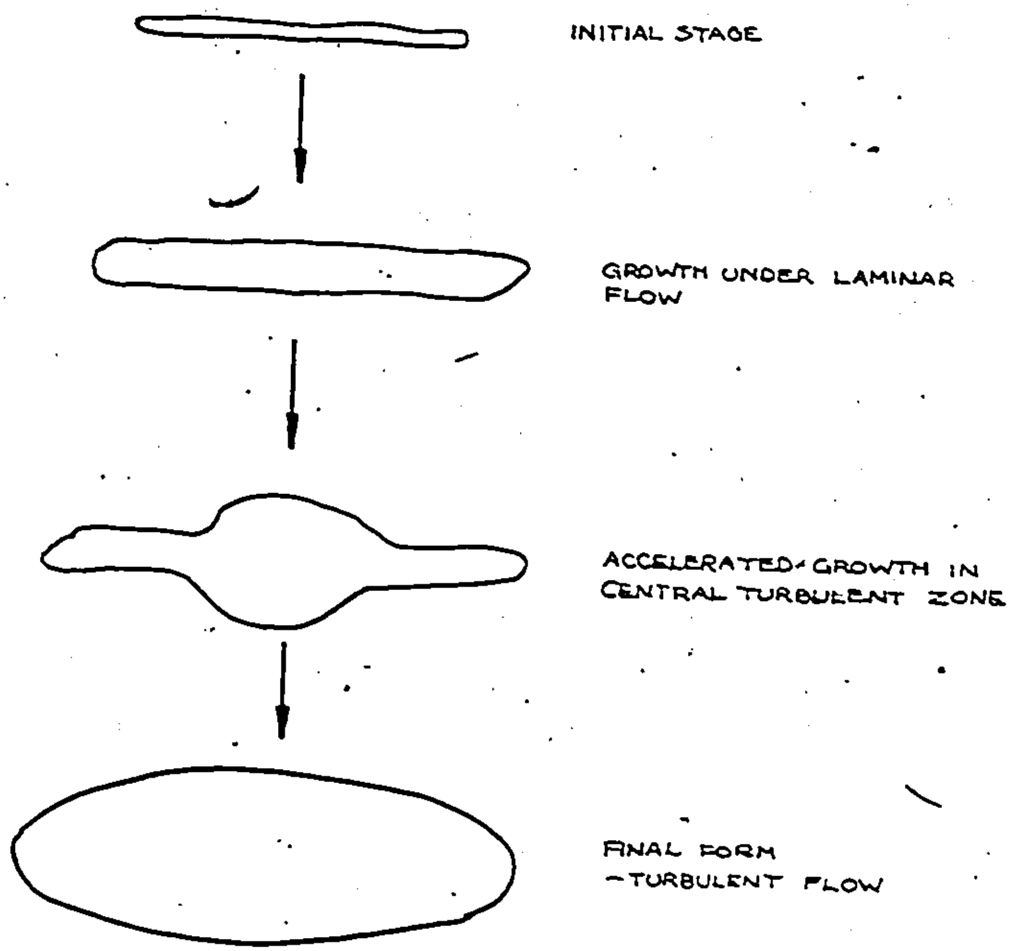

Figure 3.4 Hypothetical sequence of conduit forms resulting in an elliptical cross-section (after White and Longyear, 1962)

The much larger conduits (approximately 13 mm in diameter) which formed between the input and areas of sealant failure are also approximately circular in cross-section. Since the scalloped sides of such passages indicate that fluid flow was turbulent, it is apparent that the flow regime has not affected conduit shape in this instance.

Because the model is chemically similar to the prototype, the development of elliptical prototype conduits cannot be explained solely on the basis of hydrodynamic factors, as suggested by White and Longyear (1962).

The development of elliptical conduits has also been suggested to be a consequence of such factors as the shielding effects of sediment (Lange, 1963) and the action of mischungs korrosion along the exposed bedding plane (Bögli,). Conduits formed in environments which are unfavourable for these processes frequently exhibit a circular cross-section. Ford (1968) observed dip tubes of circular cross-section in steeply dipping strata, where sediment accumulation is inhibited. In addition, the early stages of speleogenesis, during which such passages evolve, are characterized by relatively low bedding plane hydraulic conductivity, which inhibits the mischungs korrosion process. This is analogous to the model situation, in which the quantity of sediment accumulation is small, and the mischungs korrosion phenomenon is inoperative. In effect, the models appear to duplicate the prototype conditions least favourable for the development of elliptical conduits.

F. CONCLUSIONS

The technical problems associated with this type of model precluded the study of conduit formation under various boundary conditions, since it proved impossible to isolate the systematic effects from the variables under study. Consequently, the two surface type of model was abandoned in favour of the single surface models described in Chapter IV.

Despite the failure of the experiments to provide data adequate for the purposes of the investigation, several conclusions may be drawn concerning the early stages of speleogenesis.

1) The model bedding plane closely resembles the two dimensional porous medium analogue previously postulated. The hydraulic conductivity of the model bedding plane appeared to be only slightly greater than the hydraulic conductivity of the solid plaster. The resultant low contrast in hydraulic conductivity between the bedding plane and its bounding strata establishes less favourable conditions for concentrated solvent flow than exist in the prototype, where the solute strata are relatively impermeable. Despite these comparatively unfavourable conditions, conduit formation was essentially confined to the bedding plane surface. This suggests that a two dimensional porous medium is a valid analogue to the prototype environment for solvent flow and

conduit formation.

2) The pattern of the experimental conduit systems was primarily dendritic, in contrast to the anastomotic conduit networks observed on low gradient bedding planes in the prototype by Ford (1971) and Ewers (1972). This dendritic pattern may be the result of several factors, primarily the low hydraulic conductivity of the model bedding plane.

Conduit growth requires the replacement of saturated solvent at the solute/solvent interface. The pattern of conduit growth is thus a function of the pattern of solvent flow within the conduit network. In the prototype situation, saturated solvent is removed from the conduit network by fluid flow across the unmodified bedding plane. Study of fluid flow in the model networks indicated that a continuous flow field did not exist between the conduit network and the output area of the bedding plane. Consequently, solvent renewal by the process of diffusion between the conduit environment and the input system may have been an important factor in conduit formation.

The effect of the diffusion process on the pattern of conduit growth is uncertain. However, it is reasonable to assume that this process will be most significant in this type of environment, i.e. where solvent velocity is low and the rate of diffusion of solute species is high.

The increased elaboration of the conduit networks near the limit of conduit formation may be linked to the stagnation of the network as fluid flow is diverted to other routes. This suggests that the branching nature of these conduits is in some way a function of the rate of solvent flow in the network.

The accumulation of insoluble sediment in the distributary conduits of the networks may have inhibited the growth of these conduits, thus stimulating the bifurcation process and hence the development of a dendritic conduit system during the early stages of speleogenesis.

3) The circular cross-section typical of the model conduits is in contrast with the elliptical cross-section common to prototype conduits. The similarity between conduits formed in conditions of laminar flow and those subjected to turbulent flow indicates that solvent velocity does not influence conduit shape in this instance. This in turn suggests that the elliptical shape of some prototype conduits may be caused by a factor (or factors) not simulated in the models, such as the mischungs korrosion phenomenon or the shielding effect of insoluble sediments.

CHAPTER IV

SINGLE SURFACE EXPERIMENTS

A. INTRODUCTION

In the following experiments, a bedding plane has been simulated by the contact between a plaster block and an insoluble plastic surface. This "single surface" type of model (so-called because only one of the bounding strata of the bedding plane is soluble) was used to study the effect of hydraulic gradient and stratigraphic dip on the development of bedding plane conduit systems.

The single surface model has three advantages compared to the two surface model used in the preceding experiments. First, conduit growth and network development may be observed directly through the transparent lower surface of the bedding plane. Second, the injection of dyed fluid into the bedding plane permits visualization of the fluid flow pattern. Third, a model design has been developed by Ewers (1972) which avoids the sealant problems of the two surface models. However, single surface models provide limited data on conduit growth in cross-section, because solution is unrealistically restricted to one surface of the bedding plane.

The plaster surface of the bedding plane was molded with a granular texture. When this surface was placed in contact with the plastic surface, the resulting intergranular

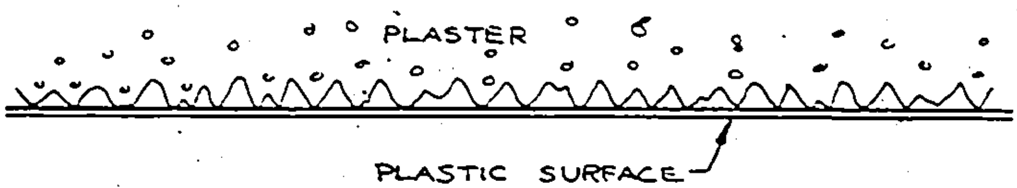

Figure 4.1 Cross-section of model bedding plane (Series 1: regular plaster surface)

spaces provided an avenue for fluid flow (figure 4.1). The model bedding plane thus possessed the fluid flow characteristics of a two dimensional porous medium. Consequently, the pattern of fluid flow in the bedding plane could be accurately determined given the hydraulic boundary conditions of the experiment. Because the hydraulic conductivity of the bedding plane far exceeded that of solid plaster, the single surface models provided a more favourable environment for conduit formation than existed in the two surface models.

B. MODEL PREPARATION

The models consisted of plaster of paris blocks, sealed on five of the six sides. The remaining side (28.5 cm x 40 cm) formed one surface of the model bedding plane. Solvent flow between the plaster block and the plastic surface upon which it rested resulted in the formation of conduit networks in the plaster surface. The texture of this surface was determined by the nature of the mold used in the casting process. Two different molds were used for the experiments, both being constructed of a latex rubber compound manufactured by General Latex and Chemicals, Ltd.

The first mold formed a bedding plane surface of a uniform, fine granular texture (figure 4.1). The bedding plane surface of the mold was the image of a sandpaper surface (120 grade, "open coat" type). A series of experiments conducted with this surface suggested that bedding plane morphology played an important rôle in determining the pattern of conduit formation. Consequently, a second mold was constructed which produced a more irregular bedding plane surface. This mold was formed on a surface of medium grade emery cloth which had been sealed with a thin layer of polyester resin. Small droplets of polyester resin were then applied to the surface in a random pattern. The droplets spread into the surrounding intergranular spaces, forming circular obstructions ranging in diameter from 1 mm to 4 mm (figure 4.2).

A typical model is shown in figure 4.3. The models were made as follows. The mold was placed on a level surface and "00" rubber stoppers set on the mold in the desired input-output configuration. 1500 cc of reagent grade $CaSO_4$ was mixed with 900 ml of distilled water in a large vaccum vessel. The liquid plaster was then subjected to a vaccum of 20 inches of mercury. This removed some of the air introduced into the plaster during mixing. The plaster was then poured into the mold and allowed to set under a thin layer of water for 2 to 3 hours. The model was kept saturated at all stages of the experiment to prevent the absorption of air by the plaster.

After the plaster had set, a layer of waterproof material was cast around the top and sides of the block. A concrete patching compound, "Quick Plug" brand, manufactured by Bondex (Canada) ltd., was selected as the sealant because

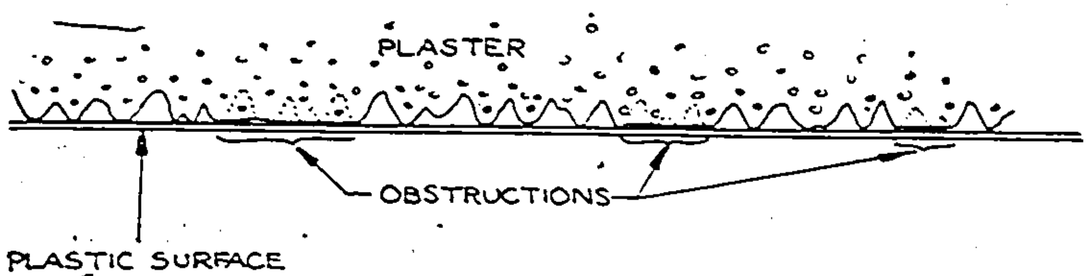

Figure 4.2 Cross-section of model bedding plane (Series 2: irregular plaster surface)

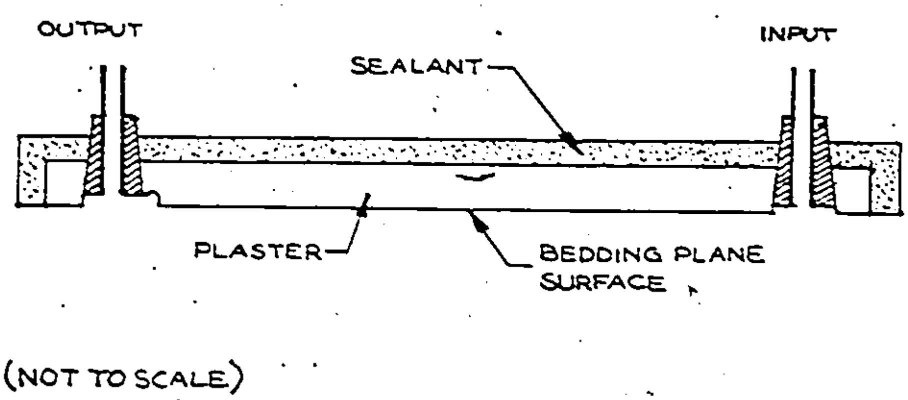

Figure 4.3. Vertical cross-section of model showing placement of input and output areas

of its ability to bond to wet surfaces. The sealant was cast around a reinforcing layer of 1/4 inch mesh wire screen. The completed model was allowed to set for a minimum of 4 hours under a thin film of water.

After the sealant had hardened, the model was removed from the mold and immersed in a saturated solution of $CaSO_4$ within an airtight container. The container was repeatedly evacuated to extract air which might have become trapped near the surface of the plaster.

C. APPARATUS

The construction of the apparatus is shown in figure 4.4.

The completed model was placed on a transparent, water-filled plastic pillow, which in turn rested in a glass-bottomed tank. A separate plastic sheet was placed between the model and the pillow to protect the pillow surface. The edges of the bedding plane were sealed to the plastic sheet with a thin layer of grease, thus confining the solvent to the interior of the model. During the installation of the model in the apparatus, the tank was filled with a saturated solution of $CaSO_4$, ensuring that air was excluded from the bedding plane. After the model was sealed to the plastic surface, the clamp was tightened, compressing the pillow until the block was in firm contact with the plastic sheet over the entire bedding plane. The overflow vent fitted to the pillow was adjusted so that the hydrostatic head applied

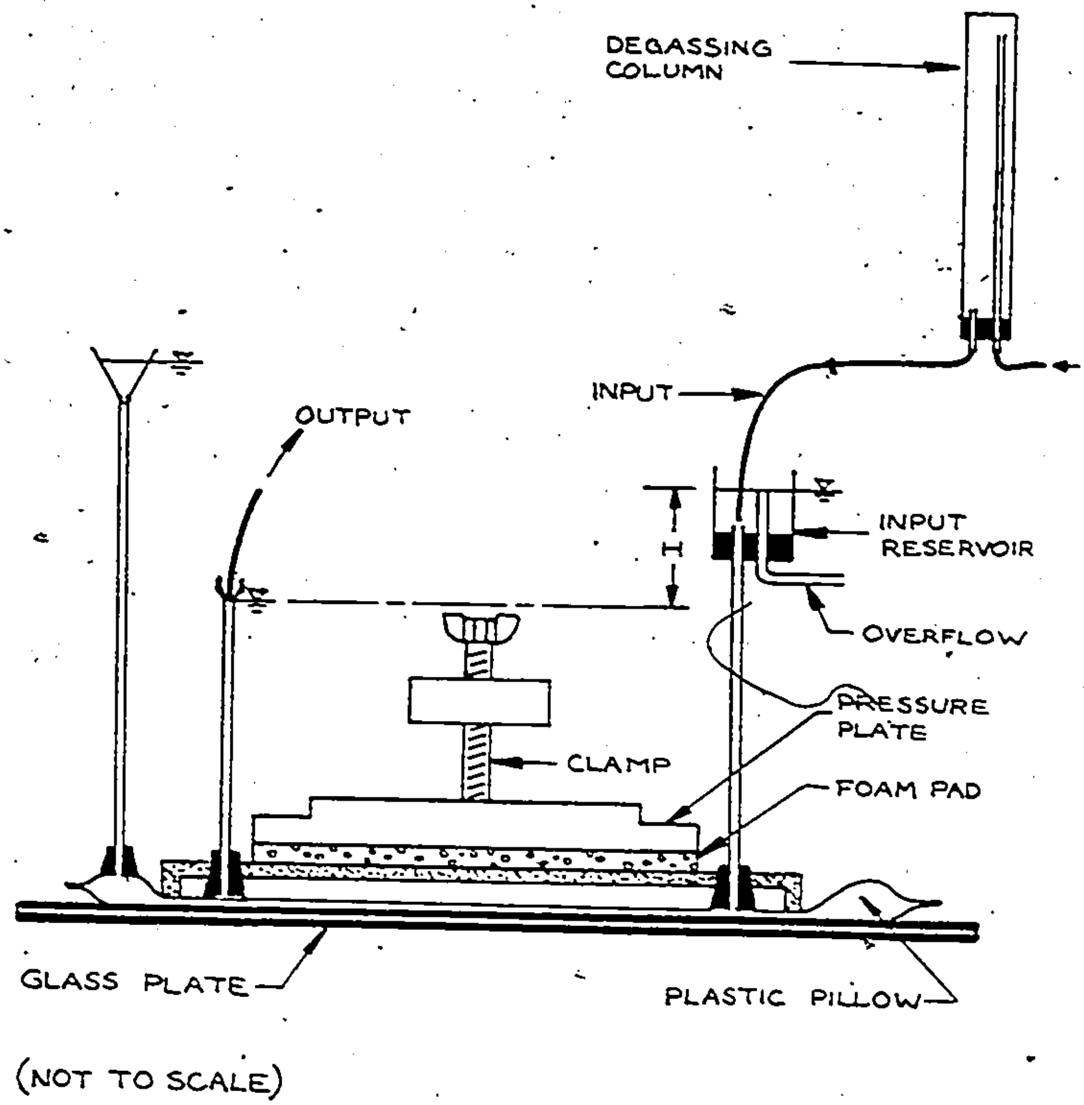

Figure 4.4 Cross-section of model apparatus. H represents the net hydrostatic head of the input system.

to the pillow exceeded that of the input system, ensuring that the plastic surface remained in firm contact with the model.

The input system supplied distilled water to the model input under a constant hydrostatic head. Electric metering pumps supplied solvent to the overflow reservoir through a degassing column as shown in figure 4.4. The column served to collect air bubbles from the input line before the solvent reached the bedding plane. The maximum capacity of the input system was approximately 14.2 ml min^{-1}.

The model discharge was collected in a column of 3/16 inch diameter flexible tubing. Fluid was extracted from this column through a small suction tube leading to a collecting bottle. Suction was maintained by an aspirator connected to the bottle. The difference in height between the extraction point in the output tube and the overflow level in the input reservoir represents the net hydrostatic head of the input system.

D. OBSERVATIONS

D.1 Fluid Flow

A series of 17 experiments was undertaken to determine the effects of hydraulic gradient and stratal dip on the formation of Phase 1 conduit systems.

The input-output system selected for these experiments is shown in figure 4.5. Since the model bedding plane was designed as a two dimensional porous medium, it is possible

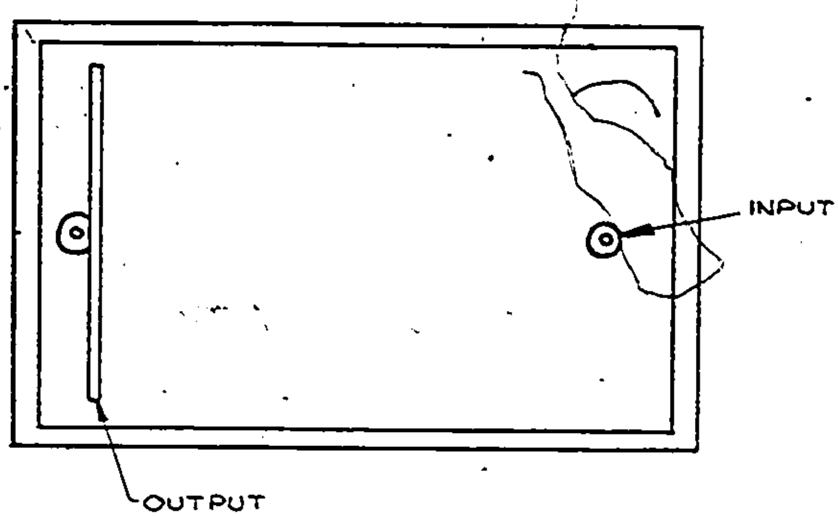

Figure 4.5 Plan view of model bedding plane showing placement of input and output areas.

to determine the pattern of fluid flow across the bedding plane given the geometric relationship between input and output areas and the net hydrostatic head of the system. A generalized flow field corresponding to the experimental boundary conditions is shown in figure 4.6. This flow net is strictly correct only for fluid velocities satisfying the requirements of linear Darcy flow.

The position of the flow lines and equipotentials shown in figure 4.6 remain unchanged regardless of the hydraulic gradient of the system. A change in the potential applied to the input will change only Δh, the difference in potential between adjacent equipotential lines. Thus, the pattern of fluid flow shown in figure 4.6 was common to all the experiments.

Although hydraulic gradient does not affect the pattern of fluid flow, it does determine the magnitude of the fluid velocity vector at a given point. Consequently, the hydraulic gradient of the system may influence the relative growth rates of individual conduits in a developing network.

When dye was injected into the bedding plane, the fluid was observed to flow across the bedding plane in the pattern predicted by the Darcy flow net. Calculations of the Reynolds number based on the velocity of the advancing dye front yielded values ranging from 0.8 to 3.0. Thus the condition existing in the unmodified bedding plane is

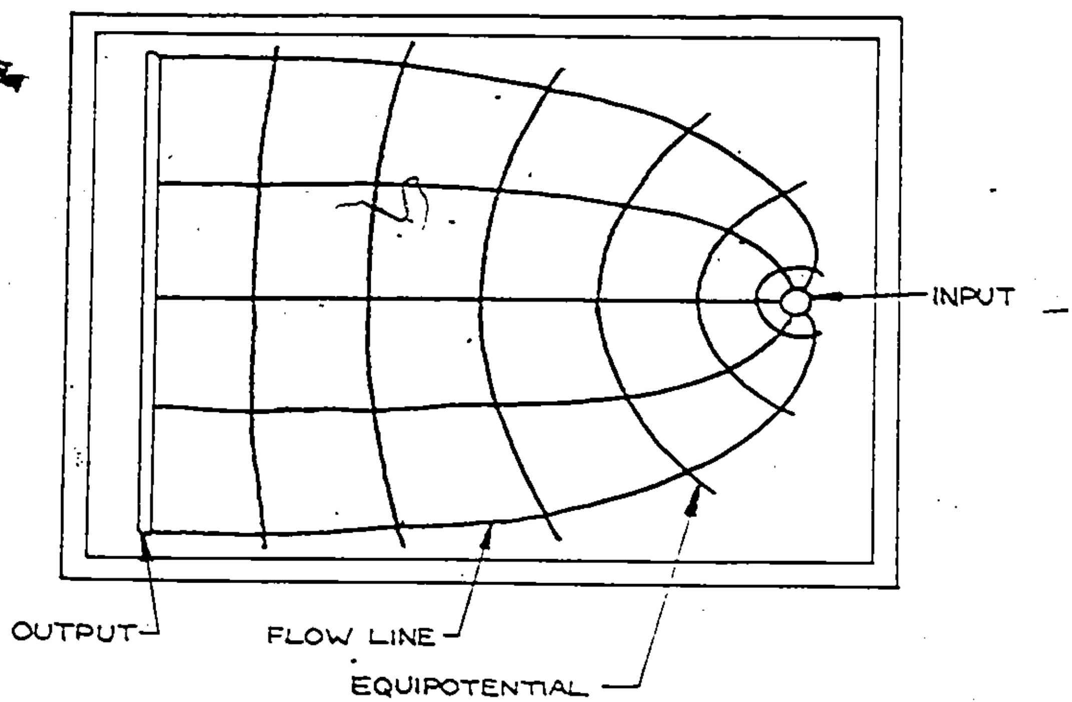

Figure 4.6 Bedding plane flow net

apparently one of linear Darcy flow. However, small deviations were observed between the flow net and the actual pattern of fluid flow. Local variations in the hydraulic conductivity of the bedding plane allowed more rapid flow in some areás than in others. This phenomenon caused the dyed solution to advance across the bedding plane unevenly, giving the interface between the dyed and colourless solutions an irregular appearance.

D.2 Conduit Formation

The formation of solution conduits began with the introduction of unsaturated solvent into the bedding plane. The dissolution of $CaSO_4$ occurred as the saturated solution initailly filling the bedding plane was displaced by unsaturated solvent.

Initially, solvent flowed through the intergranular void spaces in the plaster surface. Because the diameter of such openings is small, the penetration distance of the unsaturated solvent is also small (approximately 1 cm). Consequently, solutional activity was initially limited to the area immediately surrounding the input point. The remainder of the bedding plane exhibited no signs of modification.

The intergranular spaces varied both in size and in density. The resultant small variations in the hydraulic conductivity of the bedding plane were observed to be closely linked to the initiation of conduit formation. Areas of relatively high hydraulic conductivity tended to concentrate fluid flow and therefore solutional activity. The more rapid enlargement of the original void spaces in such areas further increased the hydraulic conductivity, increasing solvent flow and solute removal. This process resulted in the formation of distinct conduits, extending radially outward from the input point. The conduits were oriented roughly parallel to the flow lines of the Darcy flow net.

Ewers (1972) observed that the rate of conduit growth in such situations was dependent upon the hydraulic gradient along individual flow lines. In effect, the shortest flow line in a given flow net should determine the path of the dominant conduit in a Phase 1 network. In the model configuration shown in figure 4.6, the central flow line possesses the greatest hydraulic gradient. Accordingly, conduit systems should develop a dominant conduit along this flow line. The experiments confirmed the general tendency of Phase 1 networks to develop in this manner. However, in many instances variations in the morphology of the bedding plane (particularly with respect to the spatial variation of hydraulic conductivity) caused significant deviation from the predicted pattern.

The formation and development of distinct conduits was observed to proceed in the following sequence. Initial solutional modification of the bedding plane took the form of anastomotic bands of small conduits less than 1 mm in diameter. The bands were less than 1 cm in width. These conduits were essentially enlarged intergranular void spaces, interconnected in an anastomotic pattern. Continued solvent flow caused the central conduits of the band to coalesce into a single large conduit. This central conduit continued to increase in diameter, while no further development was observed in the remaining anastomotic sections of the conduit. This process frequently resulted in the complete absorption of the anastomotic conduits by the central conduit. The development of a typical conduit is illustrated in figure 4.7.

D.3 Technical Problems

The single surface models proved to be much more successful than the models used in the preceeding series of experiments. However, certain problems were experienced which affected the interpretation of the experimental results.

Three distinct problems were encountered; the presence of air in the bedding plane; improper sealing of the model to the plastic surface; and the accumulation of insoluble material in the bedding plane.

Air pockets frequently built up within the bedding plane. Their size and distribution was significant because fluid flow was effectively excluded from them. Consequently, the pattern of fluid flow no longer corresponded exactly to the flow net shown in figure 4.6. In sufficient quantity, air pockets completely controlled fluid movement and the pattern of conduit formation. The net effect of air pockets

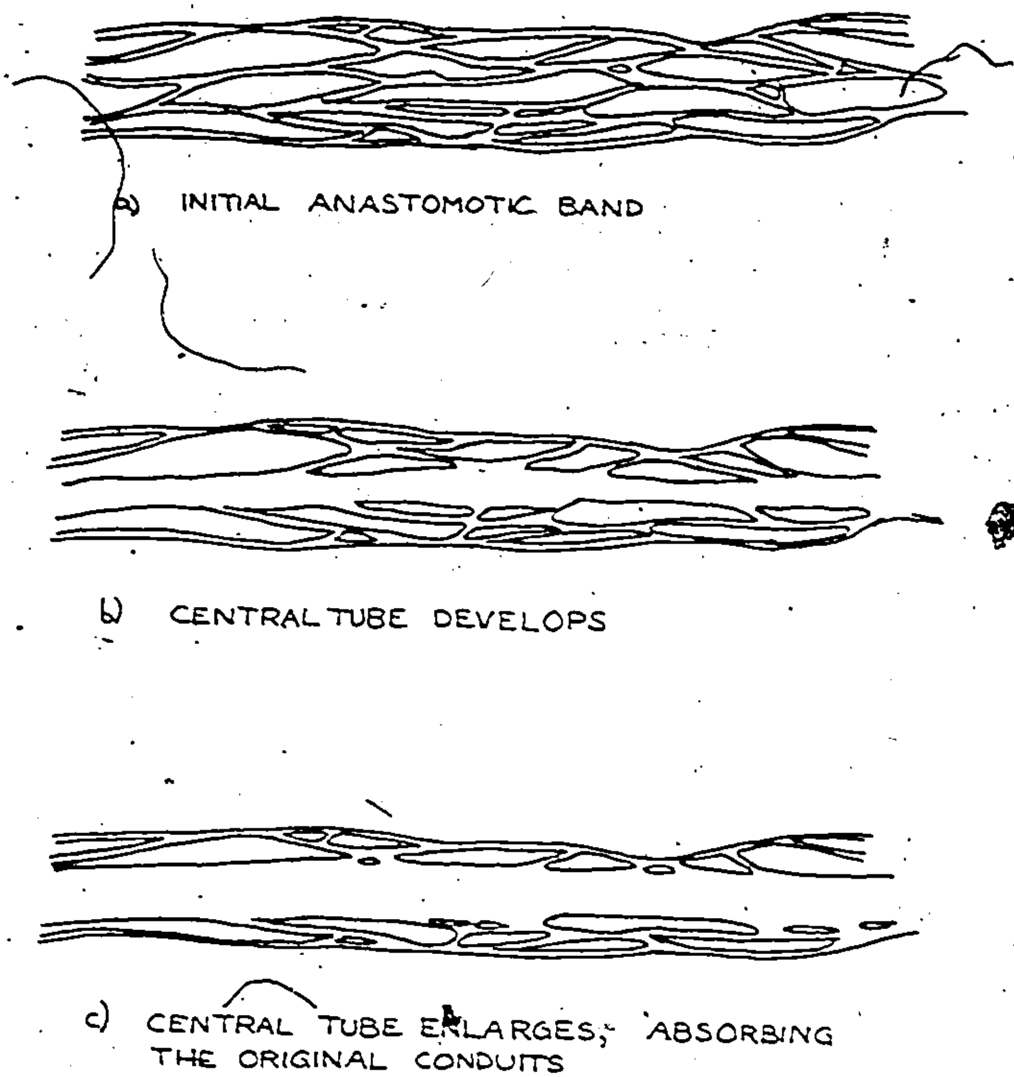

Figure 4.7 Stages in conduit development.

within the bedding plane was to introduce a control on conduit formation which could not be reproduced from one experiment to another.

A second problem was presented by the occasional failure of the seal between the edge of the bedding plane and the plastic surface. Such failures produced effects similar to those observed in the two surface experiments. In brief, the area of sealant failure provided a new output, generally closer to the input than the original output. As a result, fluid flow was diverted from its original path and conduits became oriented toward the new output.

During the latter stages of an experiment, small quantities of material were observed in the fringes of the network. This proved to be the insoluble residue of the dissolved plaster. The accumulation of this material was influenced by the inclination of the bedding plane. At large dip angles, the residue collected in the distributaries of the conduit network, i.e. the lowest points of the conduit system. This effect became less pronounced as the bedding plane approached a horizontal position. In some instances, the presence of such material seemed to cause the distributary network at the tip of an advancing conduit to become more elaborate. The effect of this phenomenon on the overall pattern of network growth is unclear, although the tendency of sediment accumulation to stimulate bifurcation was also noted in the two surface experiments.

These systematic effects were sufficient to cause the failure of approximately 40% of the experiments. Within a period of six months, eleven acceptable experiments were completed, most of which were influenced by these factors to varying degrees. Consequently, each experiment was subject to a unique set of complicating factors, for example the size and distribution of air pockets. The exact replication of bedding plane conditions from one experiment to the next proved impossible. Thus, comparisons between experiments must necessarily be of a general nature.

D.4 Data

Two series of experiments (designated 1 and 2) were conducted under various combinations of bedding plane inclination and hydraulic gradient.

Series 1

The model bedding plane used in this series of experiments was composed of granular elements of approximately equal size, distributed evenly across the surface. Five acceptable experiments were produced with this type of surface, three at an inclination of 15 degrees and two at an inclination of 0 degrees. The resultant conduit networks are shown in Plates 4.1 through 4.5.

The anastomotic nature of conduits in the early stages of formation is clearly evident in the advanced areas of the conduit networks. The more mature conduit sections nearer the input generally appear as deeply

Plate 4.1 Experiment 1, dip 0°, regular bedding plane surface.

Plate 4.2 Experiment 2, dip 0°, regular bedding plane surface.

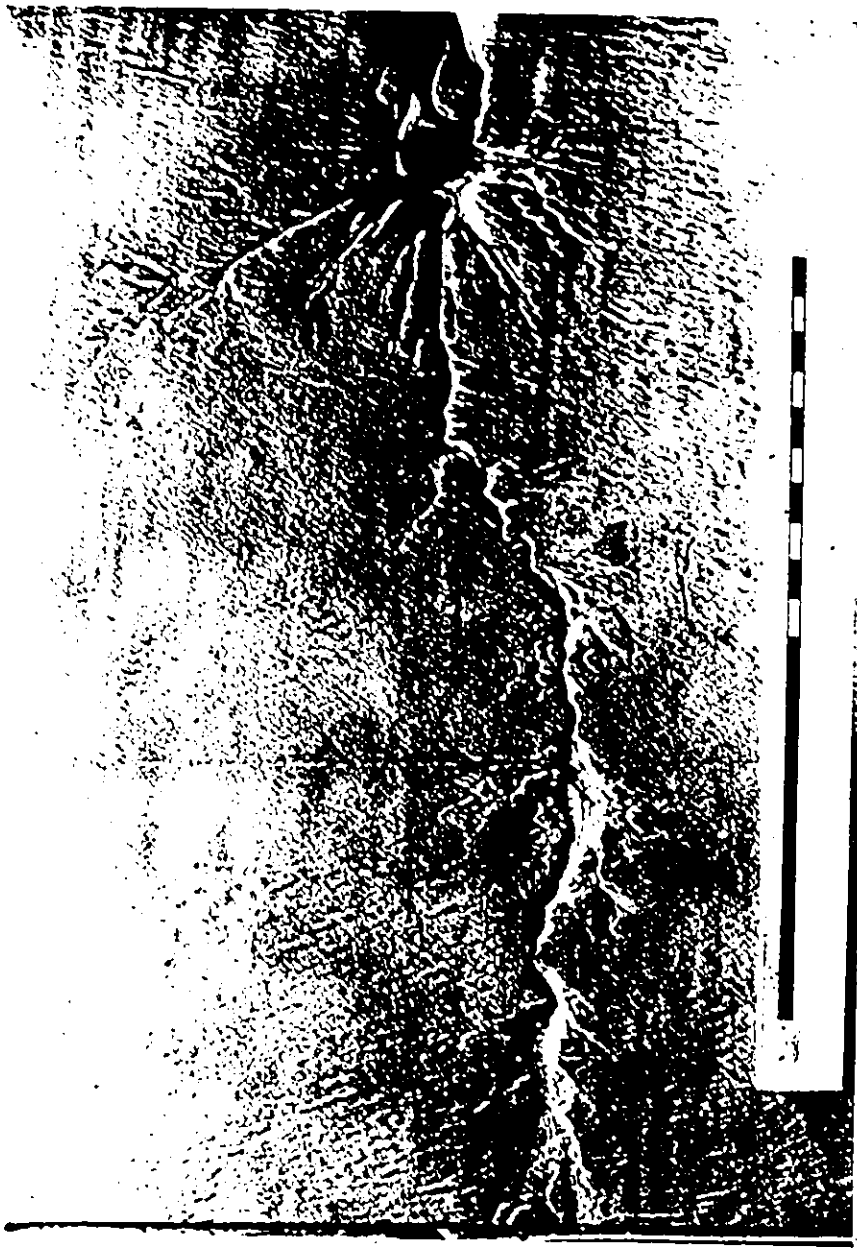

Plate 4.3 Experiment 3, dip 15°, regular bedding plane surface.

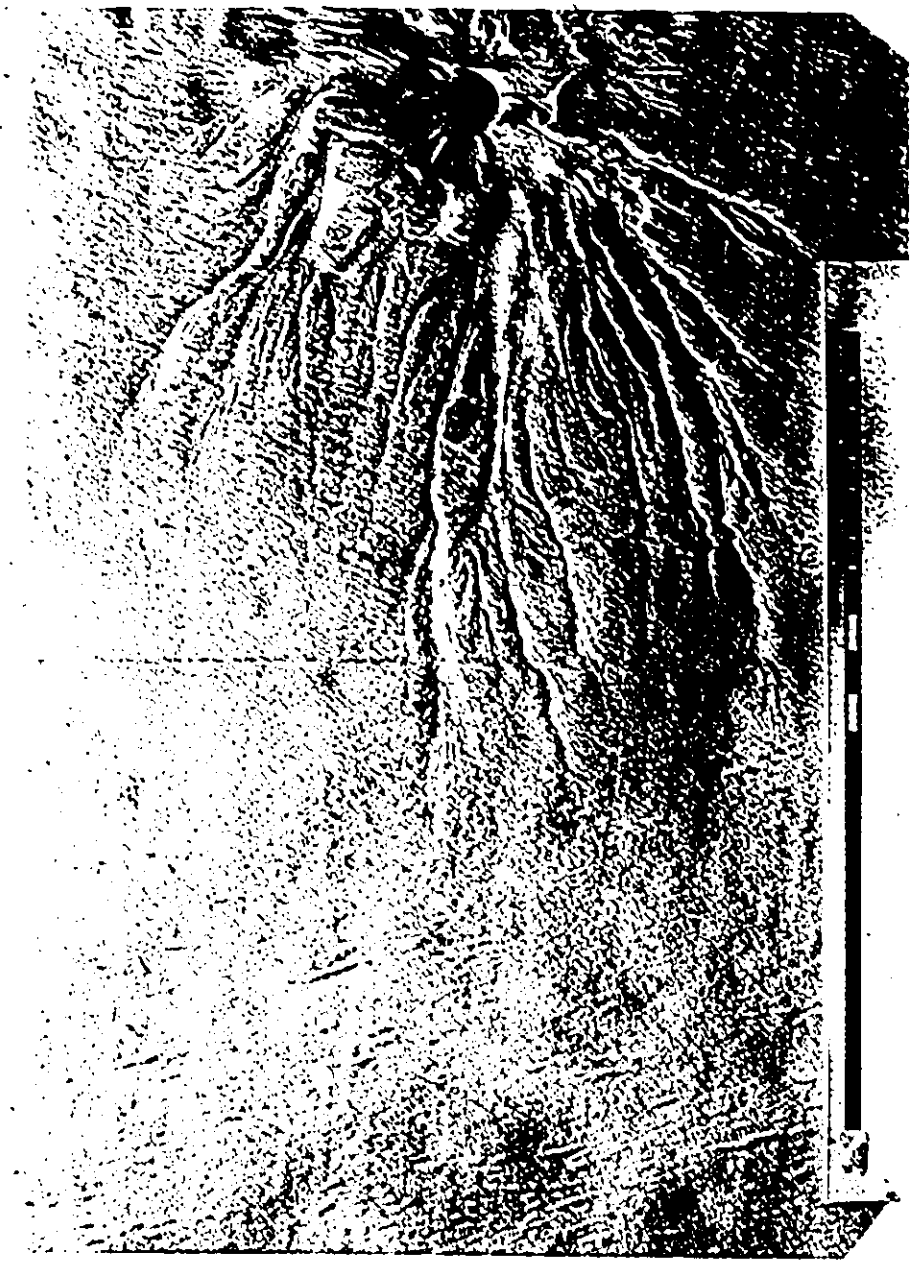

Plate 4.4 Experiment 4, dip 15°, regular bedding plane surface.

Plate 4.5 Experiment 5, dip 15°, regular bedding plane surface.

incised single conduits. This progression of conduit forms was observed in each experiment.

The formation of a large cavity in the input area was observed in several experiments (Plates 4.4 and 4.5). This feature developed at the beginning of solvent flow, increasing in size as the experiment progressed. Its formation may have been due, in part, to the size of the input opening. This phenomenon was not noted in a series of similar experiments conducted by Ewers (1972), in which a much smaller input was used.

The first experiments were conducted at an inclination of 0 degrees, and varying hydraulic gradients. The most successful of these experiments are shown in Plates 4.1 and 4.2. The hydraulic gradient was varied by changing the distance between the input and output points on the bedding plane, while maintaining a constant hydrostatic head. The hydraulic gradients of experiments 1 and 2 were approximately 1:3.5 and 1;2.5, respectively.

Neither experiment was successful in generating a complete conduit network (i.e. a direct connection between input and output). Conduit formation ceased in experiment 1 after failure of the bedding plane seal near the input. Experiment 2 was halted by the accumulation of air in the bedding plane.

The pattern of conduit development in both cases was strongly influenced by the presence of air pockets in the bedding plane. Figure 4.8 shows their distribution in experiment 1. Solvent flow and conduit development were concentrated in the unrestricted area of the bedding plane. The bedding plane in experiment 2 exhibited an even distribution of air pockets across the entire surface. In the latter stages of this experiment, the restrictive effect of these impermeable areas caused the cessation of conduit development.

While conduit network "1" developed freely on an area of the bedding plane which was largely free of air pockets, conduit development in experiment 2 was completely controlled by these obstructions. The widespread distribution of air pockets limited conduit formation to two main routes, presumably areas of comparatively low resistance to fluid movement. By restricting the number of routes available for conduit formation, the obstructions encouraged the development of essentially linear conduits. The relatively unrestricted conduit network of experiment 1, on the other hand, consists of a multiplicity of small, anastomotic conduits.

The importance of variations in hydraulic conductivity is further illustrated by the short lateral conduits visible at points 1 and 2 in Plate 4.1, and point 1 in Plate 4.2. These linear conduits connect the input to small, dome shaped depressions in the plaster surface. These irregularities were inadvertently formed during the casting

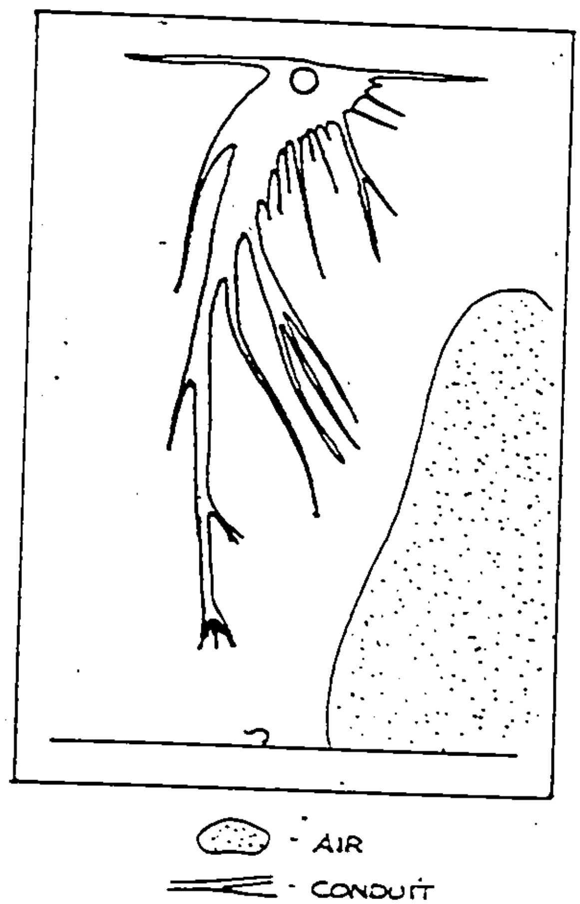

Figure 4.8 Experiment 1: sketch showing distribution of air filled areas and major conduit routes.

process. The plastic surface was unable to conform to the depressions, leaving an opening in the bedding plane. The resistance of such areas is much less than the resistance of the smaller intergranular voids forming the remainder of the bedding plane. Consequently, fluid flow was "attracted" to these areas. Once the opening was connected to the input, conduit development became reoriented toward the output. However, the central conduits of the network had advanced more directly toward the output. raising the hydraulic gradient of the central route. Consequently, solvent flow was gradually diverted from the lateral conduits and they ceased to develop.

In general, the pattern of conduit development in both experiments was strongly controlled by variations in the hydraulic conductivity of the bedding plane. The initial hydraulic gradient of the model system had no discernible effect on the network pattern.

Experiments 3, 4, and 5 were conducted with a constant hydraulic gradient and a dip of 15 degrees. Although the boundary conditions of the experiments are identical, the resulting networks are quite dissimilar. The differences between the networks were apparently the result of variations in bedding plane hydraulic conductivity.

The bedding plane in experiment 3 (Plate 4.3) was largely blocked by a number of small air bubbles. The resulting network essentially consists of a single conduit connecting input and output. The path of this conduit was observed to be controlled by the distribution of impermeable areas (i.e. air pockets) across the bedding plane. The experiment was terminated shortly after the conduit reached the output area, completing Phase 1 conduit development.

In experiment 4 (Plate 4.4), air penetrated the bedding plane in two separate areas. Several large air pockets were inadvertently introduced near the input, as shown in figure 4.9. Smaller air pockets were observed near the left side of the output. The impermeable areas near the input split the solvent flow, causing the formation of a number of small conduits, which developed at similar rates. Further growth of the conduits on the left side of the bedding plane was retarded by reduced hydraulic conductivity near the output. The experiment was stopped at this point after the input system failed.

The bedding plane in experiment 5 (Plate 4.5) was more nearly free of obstructions, although a few small air pockets were observed near the input. The resulting network exhibits relatively poor channelization. In addition, a large cavity developed around the input. Conduits which did develop are comparatively poorly delineated (for example the anastomotic band visible at point 1, Plate 4.5).

The experiments of Series 1 suggested that the pattern of conduit development was strongly influenced by the variability of hydraulic conductivity on the model bedding plane.

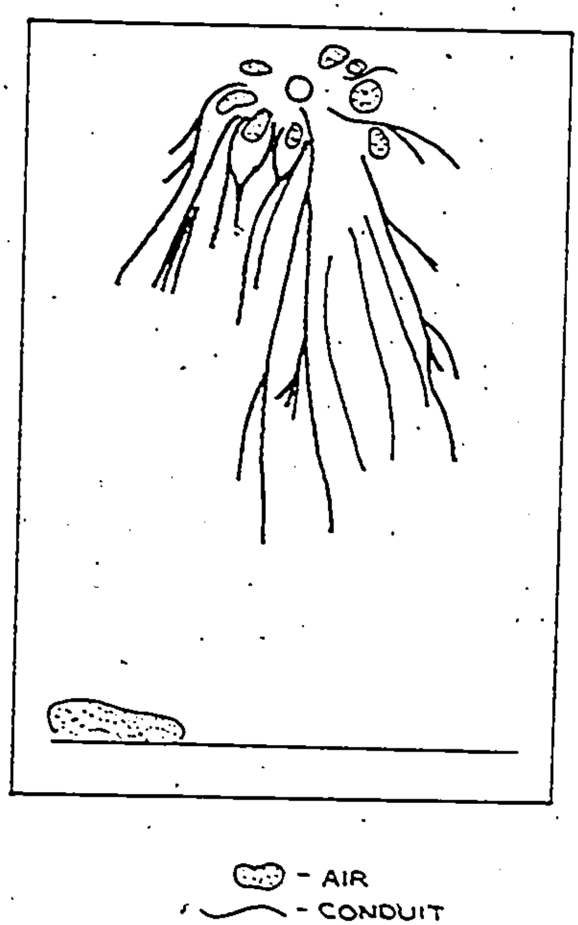

Figure 4.9 Experiment 4: sketch showing distribution of air filled areas and major conduit routes.

The scale and location of impermeable areas on the plane apparently determined the nature and course of the resultant conduit system. The effects of bedding plane inclination and hydraulic gradient, if any, were obscured by this phenomenon.

Series 2

In view of the apparent connection between bedding plane irregularities and the initial channelization of solvent flow, a more irregular plaster surface was employed in this series of experiments. The surface consisted of a number of randomly distributed plaster obstructions within a matrix of smaller granular elements. A cross-section of the bedding plane is shown in figure 4.2. The raised obstructions presented smaller openings for fluid movement when compared with the surrounding intergranular spaces.

The previous experiments had shown that, under "ideal" conditions, conduits tend to develop parallel to flow lines of the Darcy flow net. Because the flow line pattern is independent of hydraulic gradient, it was possible to simplify experimental conditions by holding that gradient constant and varying only the inclination of the bedding plane.

Conduits were successfully generated at dips of 15, 30 and 45 degrees. The results of these experiments are shown in Plates 4.6 through 4.11.

Dye injections showed that the plaster obstructions

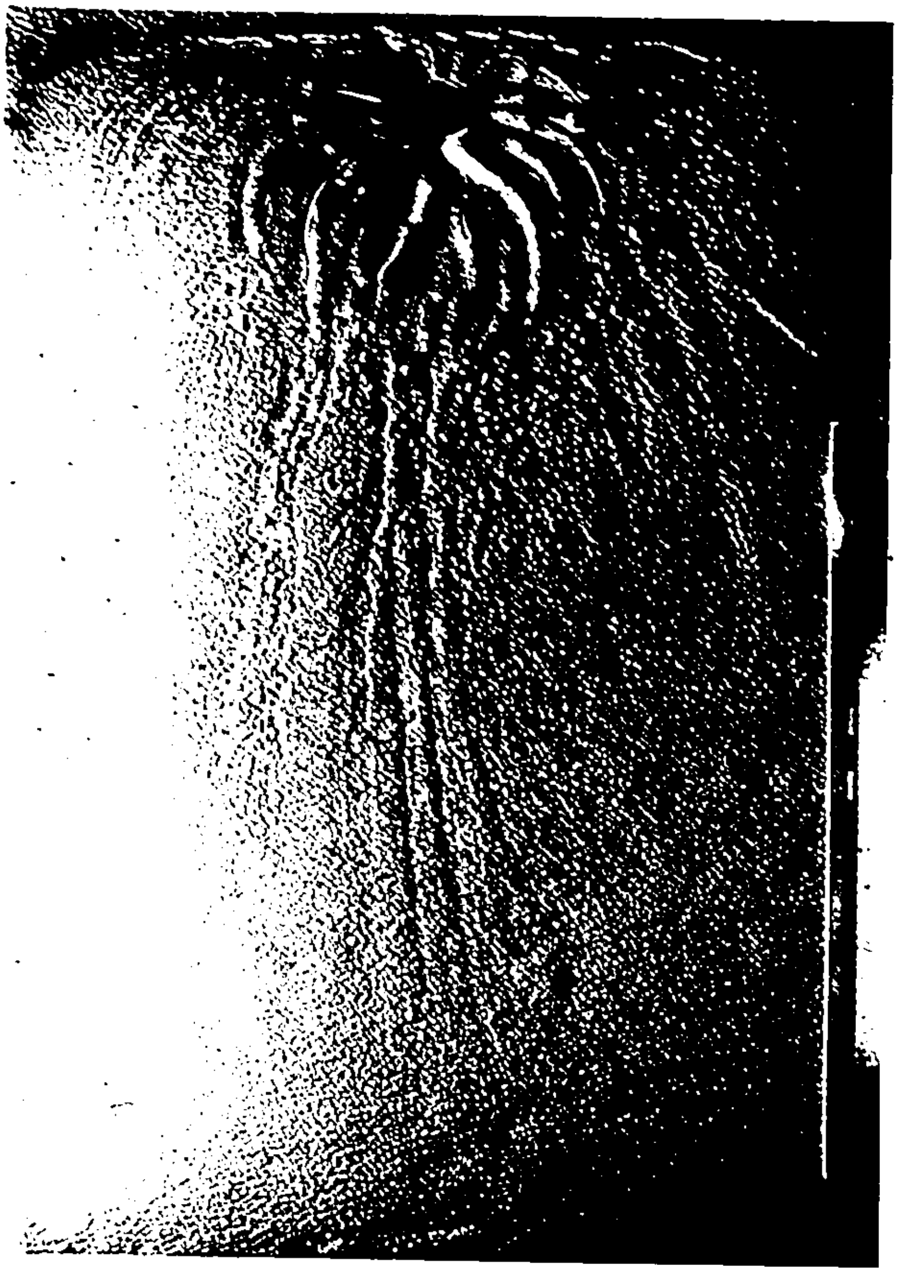

Plate 4.6 Experiment 6, dip 15°, irregular bedding plane surface.

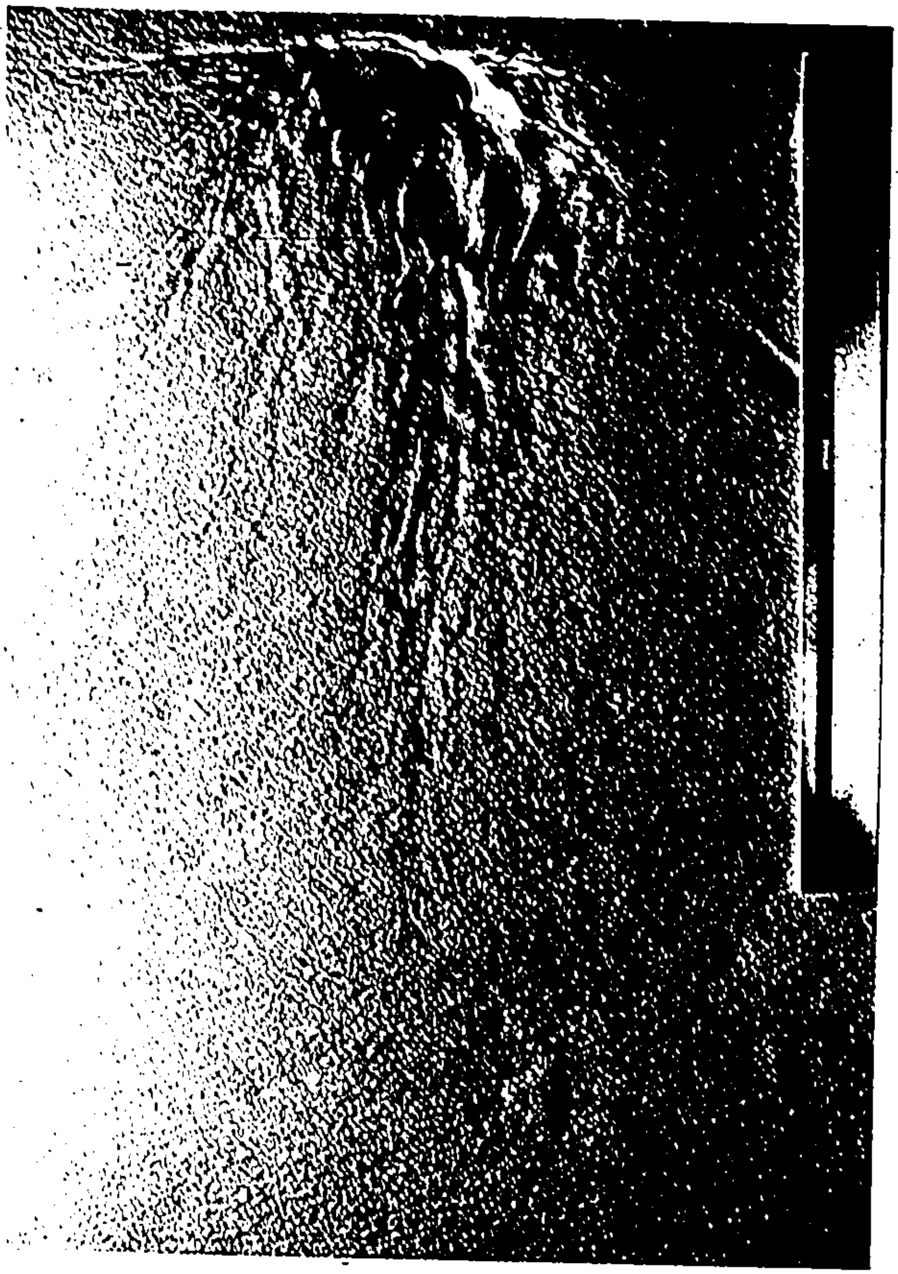

Plate 4.7 Experiment 7, dip 15°, irregular bedding plane surface.

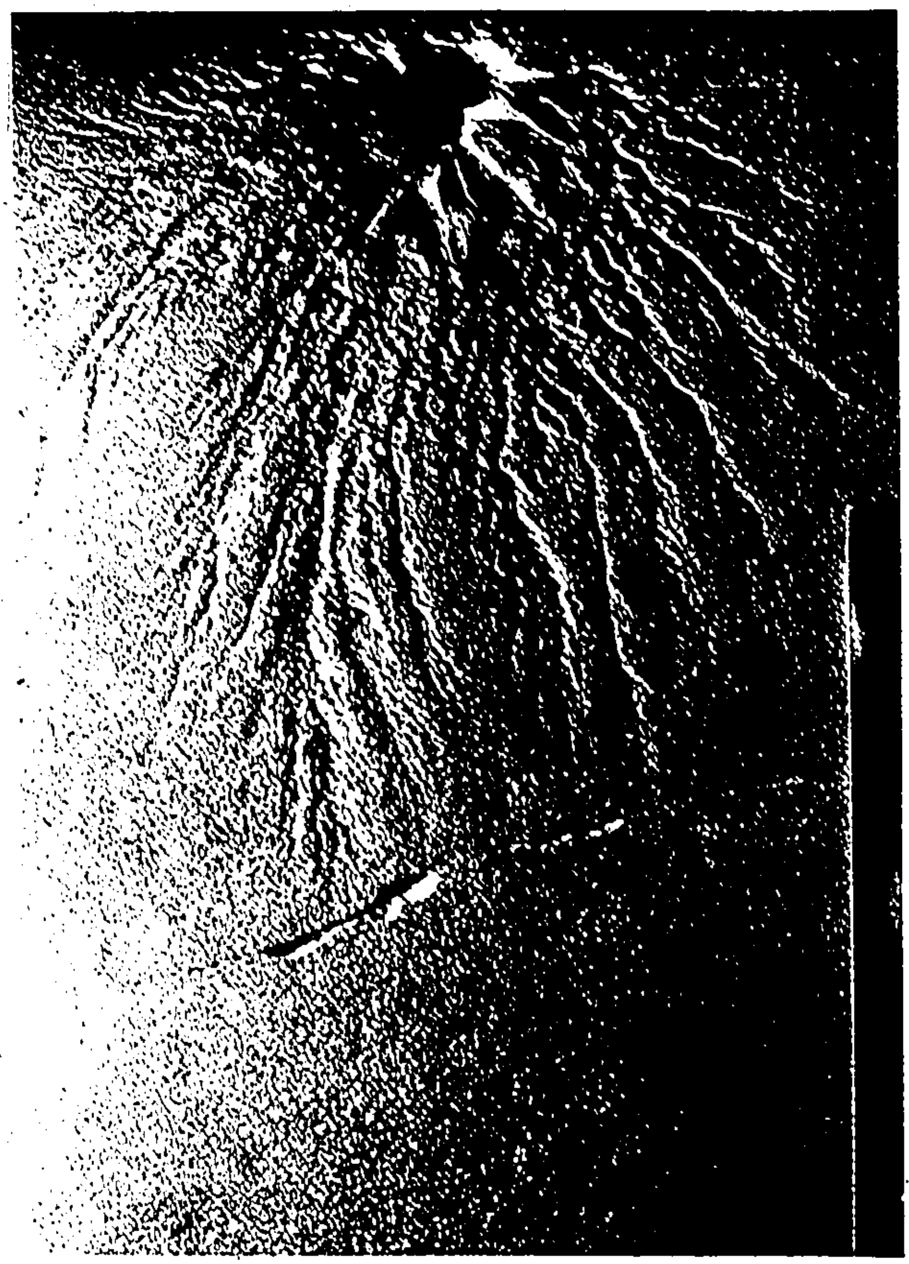

Plate 4.8 Experiment 8, dip 30°, irregular bedding plane surface.

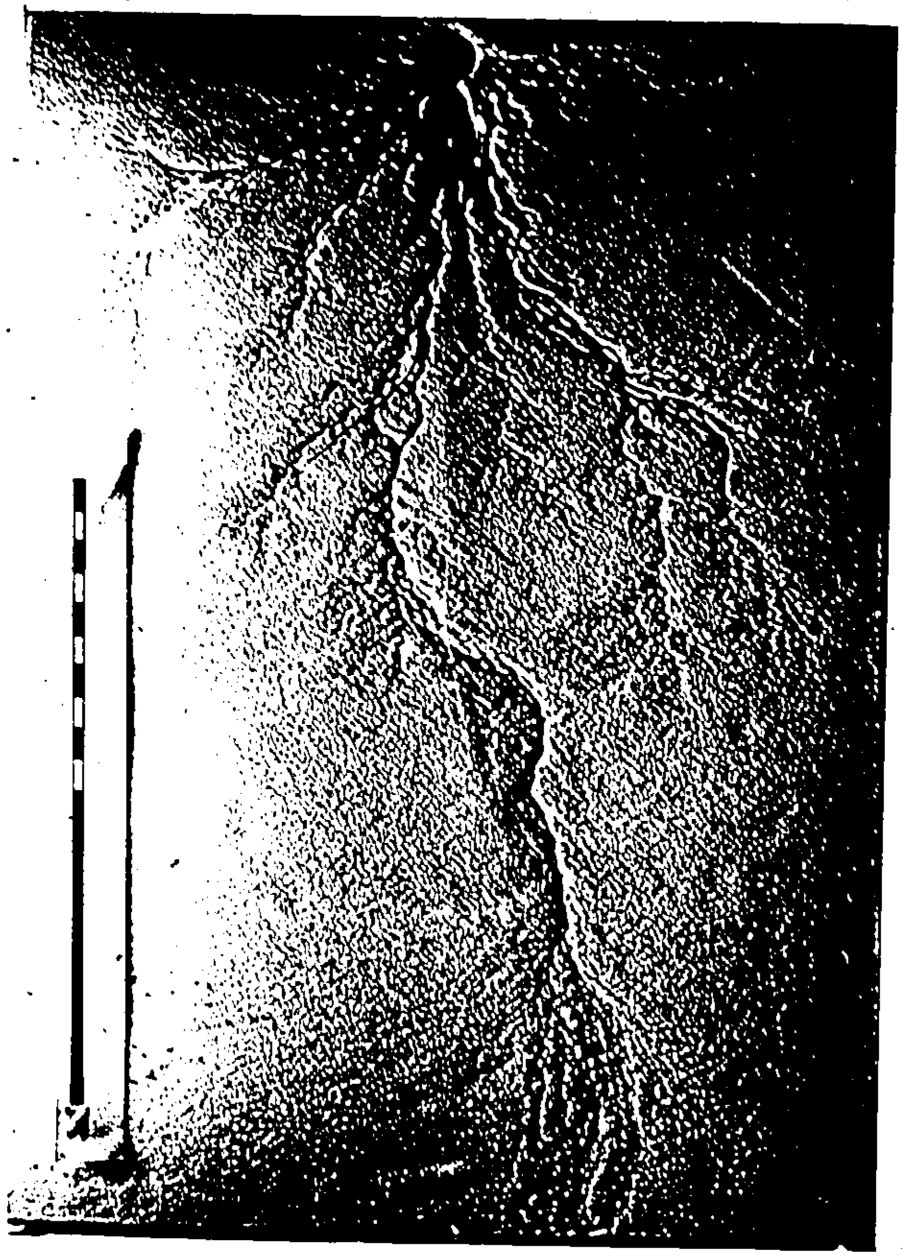

Plate 4.9 Experiment 9, dip 30°, irregular bedding plane surface.

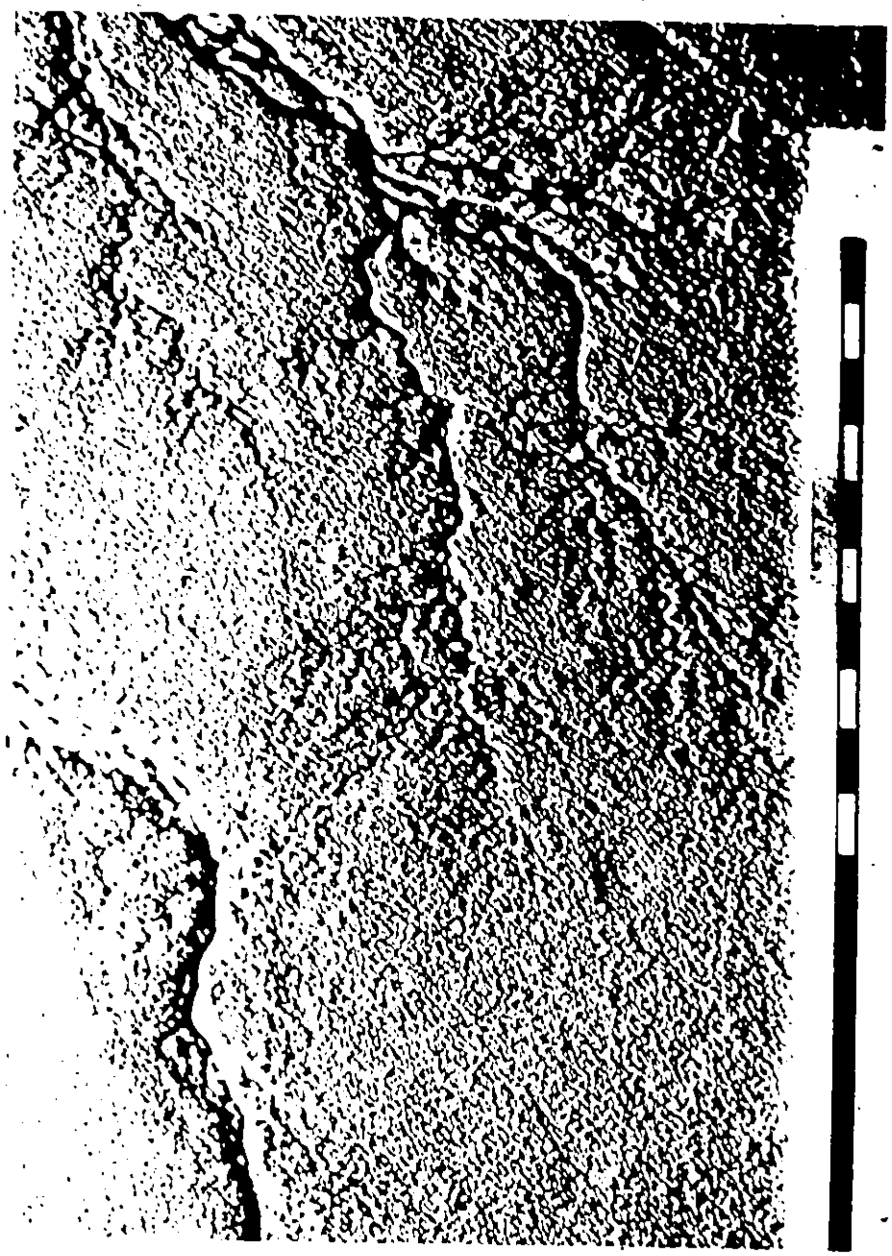

Plate 4.10 Detail of conduit junction, experiment 9.

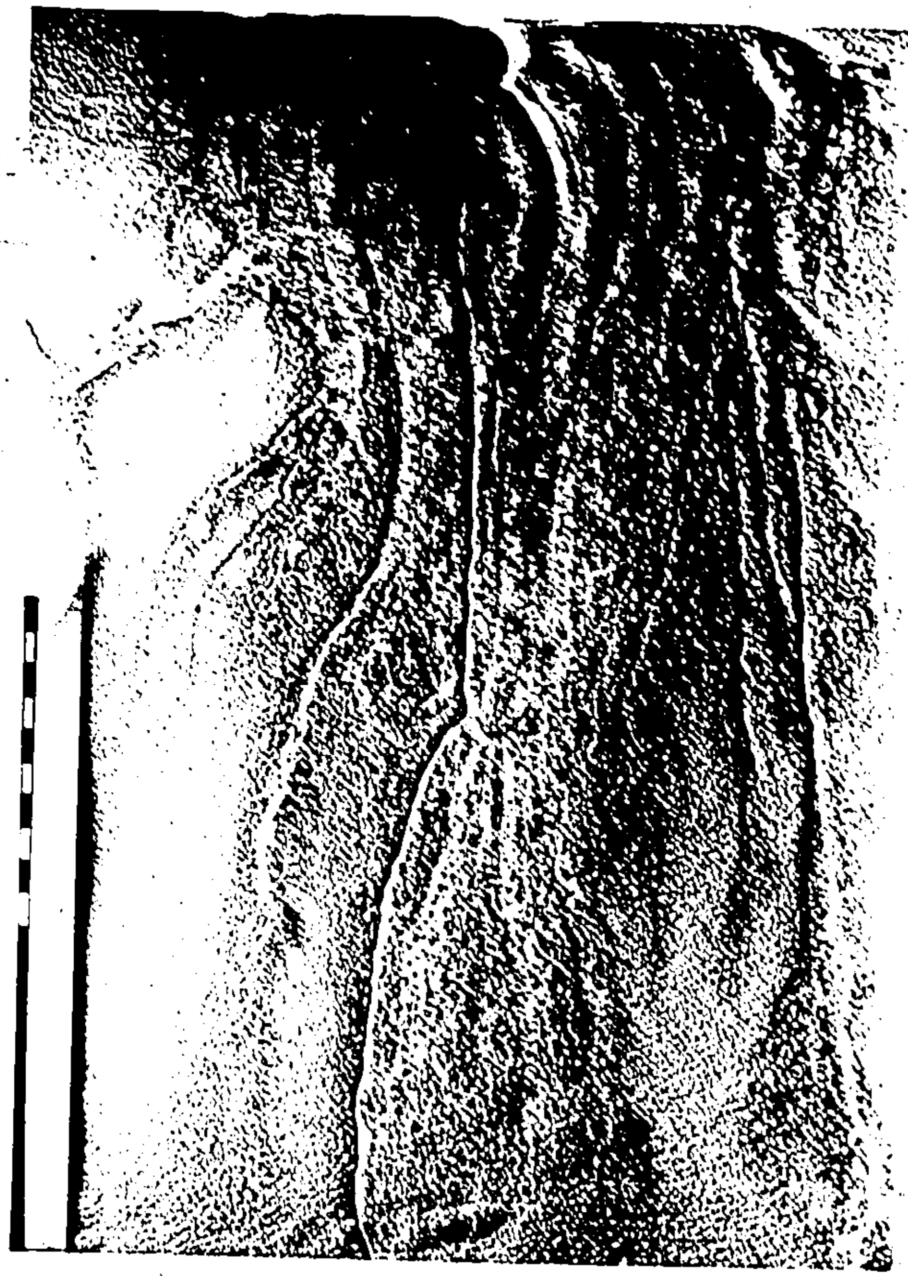

Plate 4.11 Experiment 10, dip 45°, irregular bedding plane surface.

perceptibly affected fluid flow; however their effect on the initial stages of conduit formation appeared slight. Although the obstructions were effective in channelling the earlier solvent flow, lateral solution soon removed the obstructions, allowing the conduits to merge. Consequently, large solution cavities once again formed around the input. In general, the plaster obstructions appeared to be insufficient, both in number and in size, to appreciably affect the process of conduit formation.

The presence of air pockets in the bedding plane was a significant factor in several experiments, exerting definite control on the preferred location of conduits. In general, those experiments in which air pockets significantly affected conduit development were characterized by relatively simple, well defined, linear networks of conduits. Those experiments which were not so affected, on the other hand, are typified by wide, poorly defined bands of conduits.

Experiments 6 and 7 were conducted at an inclination of 15 degrees. Experiment 6 is typical of those experiments in which the bedding plane was free of air pockets.

During the early stages of solvent flow, a multitude of small conduits began to extend outward from the input point. As solvent flow continued, these conduits increased in length, following curving paths approximating flow lines of the Darcy flow net. Continued solution caused the conduits nearest the input to increase in diameter to the point where the conduits merged, forming a large cavity around the input point. As this process continued, the cavity increased in size. Eventually, conduit formation became concentrated along a small number of separate routes, and the cavity ceased to enlarge.

The resulting conduit network is shown in Plate 4.6. Conduit development is concentrated in the centre of the bedding plane and consists of broad bands of anastomotic conduits, of the type common to horizontally bedded limestones (Ford, 1971). The obstructions are preserved in the form of "islands" within the conduit bands, indicating that such features are capable of influencing conduit formation to a certain extent. However, they do not appear to have affected the overall pattern.

A similar network developed in experiment 7 (Plate 4.7). In this instance however, air pockets were observed in several areas of the bedding plane, as shown in figure 4.10. These obstructions distorted the pattern of conduit formation and eventually blocked the output area completely. Once again, conduit development was concentrated in the centre of the bedding plane, in the form of poorly defined bands on anastomotic conduits.

Experiments 8 and 9, conducted at a dip of 30 degrees, produced patterns of conduit development that differed markedly from one another. In both instances, conduit formation was strongly influenced by air pockets in the

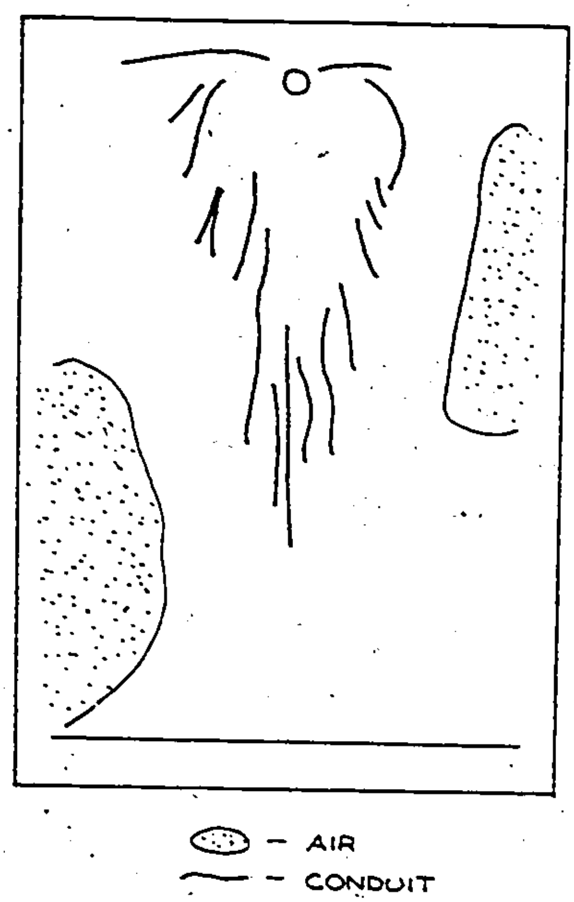

Figure 4.10 Experiment 7: sketch showing distribution of air filled areas and major conduit routes.

bedding plane.

The conduit network which developed in experiment 8, shown in Plate 4.8, was influenced by several small air pockets near the input area. These impermeable areas apparently limited the growth of the solution cavity around the input. The conduits which formed at the margins of the solution cavity are more sharply defined than in the previous experiments. The air pockets divided solvent flow into a number of distinct routes, each of which developed a well defined conduit. These conduits follow curving paths typical of Darcy flow. Once again, conduit development was most extensive in the central zone of the bedding plane. Conduit development ceased at the stage shown in Plate 4.8 following failure of the input system.

The conduit network which developed in experiment 9 was influenced to a much greater degree by air pockets. The distribution of the largest impermeable areas in shown in figure 4.11, although small air pockets were scattered throughout the bedding plane. The resulting conduit network, shown in Plate 4.9, is similar to the network which developed in experiment 3, at a dip of 15 degrees.

Air pockets near the input restricted solvent flow to a small number of routes. Consequently, fluid flow was effectively channelized from the earliest stages, as in experiment 8. During the latter stages of the experiment, conduit development was almost completely controlled by

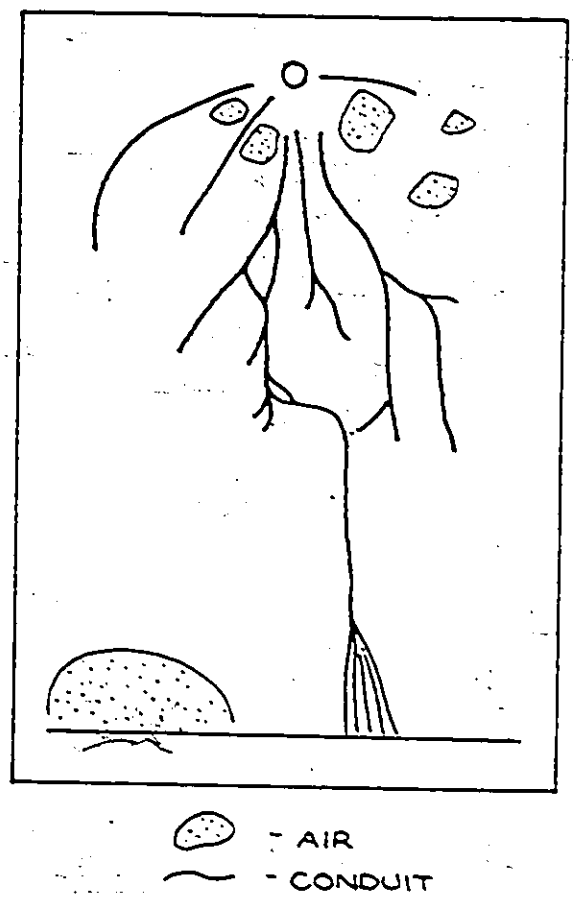

Figure 4.11 Experiment 9: sketch showing distribution of air filled areas and major conduit routes.

impermeable areas in the bedding plane.

The dominant conduit of this network formed in the central area of the bedding plane, along the line of greatest hydraulic gradient. Another large conduit (Plate 4.9, point 1) was cut off by the bend which formed in the more advanced central conduit. Following completion of the central conduit, this conduit experienced renewed growth, joining the central conduit at point 2, Plate 4.9. This junction is shown in detail in Plate 4.10. The anastomotic nature of the primitive conduits may be clearly seen. Further development of the network was inhibited by the limited capacity of the input system.

Conduit network 10, formed at a dip of 45 degrees, is shown in Plate 4.11. This experiment was completely free of the influence of air pockets in the bedding plane. The resulting conduit network exhibits poor channelization. Unrestricted flow during the initial stages of the experiment resulted in the formation of a large number of small conduits extending outward from the input. Lateral solution subsequently caused these conduits to coalesce, forming a single large cavity. Fluid flow eventually became concentrated in a broad anastomotic band of conduits in the centre of the bedding plane. Secondary conduits developed at points 1 and 2 (Plate 4.11).

E. RESULTS

The single surface models were successful in generating Phase 1 conduit networks under a variety of structural and hydraulic boundary conditions. However, the interpretation of the experiment results is hampered by the variability of certain parameters of the model system, notably the hydraulic conductivity of the bedding plane. The variation of such factors from one experiment to the next caused each conduit network to form in a unique environment. Thus, comparison of the experimental results must necessarily be qualitative in nature.

E.1 Network Pattern

The expected relationship between dip and network pattern was not observed in the experimental conduit networks. Indeed, the pattern of the model networks appears to be unaffected by bedding plane inclination. The pattern of conduit formation was apparently determined by: (a) the bedding plane flow field; and (b) the morphology of the bedding plane.

In the absence of other controlling factors, conduits were observed to follow curvilinear patterns approximating the flow lines of the Darcy flow net. The growth rate of individual conduits were proportional to the hydraulic gradient of that particular flow line. Consequently, conduit development was frequently concentrated along the relatively direct flow lines in the centre of the flow field. This pattern was observed by Ewers (1972) in similar experiments.

The pattern of individual conduit networks was frequently influenced by the variability of hydraulic conductivity across the bedding plane. Variations in the size and distribution of relatively impermeable areas within the bedding plane caused marked variations in the pattern of conduit networks developed under otherwise identical boundary conditions.

In general, the more heterogeneous the bedding plane, the more linear was the resultant conduit network. In those experiments in which the bedding plane was relatively homogeneous, conduits developed along a number of hydrodynamically similar routes. Although the central flow route eventually dominated such networks by virtue of its slightly greater hydraulic gradient, the networks characteristically exhibited relatively limited conduit development. Those networks which formed on more heterogeneous bedding planes exhibit marked channelization of solvent flow along a comparatively few flow lines.

The linear networks which developed under conditions of strong bedding plane control are similar to the networks generated by Ewers (1972) on salt surfaces. This suggests that the bedding plane surface employed by Ewers may also have been heterogeneous in nature. Because the fluid flow characteristics of Ewer's models were evidently more stable than those of the present models, this heterogeneity may have appeared in the form of variations in the solubility of the salt surface.

Such variations in the chemical-hydrodynamic characteristics of the bedding plane may conveniently be included in the general term "bedding plane Morphology". The experimental results indicate that changes in network pattern previously attributed to the influence of geologic structure, especially dip, on the pattern of groundwater flow (Ford, 1971) may, in fact, be caused by variations in bedding plane morphology. In those experiments in which the bedding plane remained reasonably homogeneous, bedding plane inclination had no discernible effect on the pattern of the Phase 1 network. The discrepancy between the experimental results and field observations of prototype networks may be caused by several factors.

Because field observations are restricted to abandoned segments of Phase 2 conduit systems, the possibility exists that geologic structure affects only the second phase of speleogenesis. Thus, the relationship between stratal dip and network pattern would not be apparent in studies of Phase 1 networks.

The exploration of many prototype networks may be of insufficient detail to reveal the true nature of the network. The parallel "dip tubes" observed by Ford (1971), for example, could be either separate networks or individual elements of a larger network.

The pattern of sediment accumulation observed in experiments conducted at large dip angles suggests a further explanation, which is discussed in the following section.

E.2 Sedimentation in Conduit Environments

The single surface models used to study the development of Phase 1 conduit systems on inclined bedding planes were not designed to provide data on sediment accumulation. However, the small amount of autochthonous sediment produced in the models indicated that sedimentation may influence the pattern of Phase 2 conduit networks.

The pattern of sediment accumulation was observed to be closely related to the inclination of the bedding plane. If the plane was horizontal, accumulation occurred throughout the network. However, if the model was inclined, sediment accumulation was concentrated in the lowest sections of the developing network. This tendency became more pronounced as dip increased. A larger volume of sediment, whether autochthonous or allochthonous in origin, could severely restrict fluid flow in small conduits, thus diverting solvent flow to the larger, central conduits of the developing network. This process would favour the development of a relatively small number of large conduits, rather than a more complex network of smaller conduits. Similarly, sedimentation occuring after completion of the Phase 1 network would tend to first block the smallest conduits, thereby restricting conduit enlargement to the larger conduits of the network. Thus, the observed tendency of prototype networks to be less complex on steeply dipping surfaces may be the result of localized sediment accumulation during the early stages of speleogenesis. Unfortunately, insufficient data exist to evaluate this hypothesis.

E.3 Conduit Cross-Section

Due to the nature of the single surface models, the experiments were unable to provide data on the shape of conduits in cross-section. However, observations of the early stages of conduit formation suggest that the lateral growth of bedding plane conduits takes in such a way as to favour the eventual development of an elliptical cross-section.

The final form of the majority of model conduits is shown in figure 4.12(a). This form developed under conditions of laminar flow. In the prototype, in which both of the bounding strata are soluble, this pattern may reasonably be assumed to develop as shown in figure 4.12(b). Continued solution will eventually cause the individual conduits to coalesce, giving rise to a single conduit of elliptical cross-section.

F. CONCLUSIONS

The formation of systems of Phase 1 conduits was successfully simulated under a variety of experimental boundary conditions. However, the results were strongly influenced by technical difficulties associated with the model apparatus. The systematic errors thus introduced

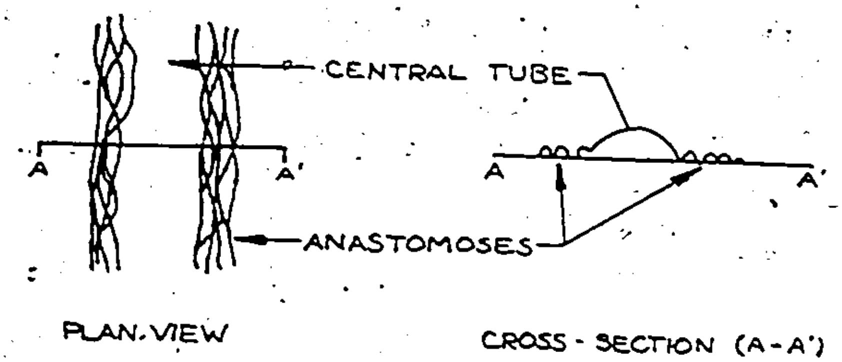

Figure 4.12(a) Model conduit in the later stages of development

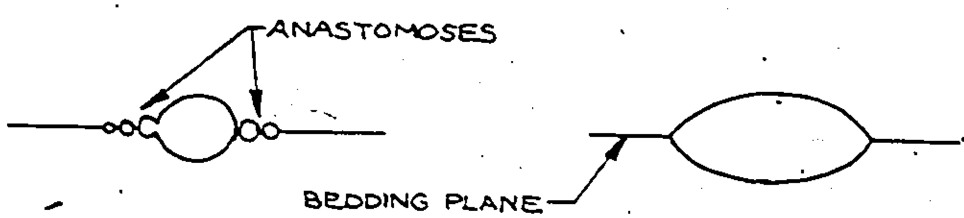

Figure 4.12(b) Hypothetical sequence of prototype conduit forms

restrict the comparisons which may be drawn, both between individual experiments and between model and prototype. Consequently, the experimental results are unsuited to detailed quantitative analysis. However, certain qualitative conclusions may be drawn concerning several aspects of speleogenesis.

1) The pattern of the Phase 1 model networks was apparently unrelated to the hydraulic gradient of the system. Conduits tended to adopt curvilinear courses paralleling the flow lines of the bedding plane flow net. All other factors being constant, the flow line pattern is independent of hydraulic gradient. Because conduit orientation is solely dependent on the direction of solvent flow as governed by the Darcy flow net, network pattern is thus independent of hydraulic gradient.

2) The apparent relationship between network pattern and stratal dip observed in prototype networks was not manifest in the experimental networks. In the absence of complicating factors, the pattern of conduit growth appeared to be controlled by the Darcy flow net peculiar to the boundary conditions of a given experiment. Individual conduits formed in such a way that, at any given point, the conduit paralleled the direction of solvent flow. In this instance, the pattern of solvent flow is a function only of the input/output configuration. The orientation of the model conduits is thus unaffected by the inclination

of the bedding plane. However, this may not be the case for certain input/output configurations in the prototype.

Several hypotheses may be advanced to account for the apparent discrepancy between the experimental results and field observations of prototype networks.

The model system may be an inadequate representation of the prototype. Although the models reproduce the theoretical fluid flow characteristics of an "ideal" bedding plane, several factors of possible significance were not simulated. Such chemical-hydrodynamic factors as mischungs korrosion and variations in rock solubility, for example, were not incorporated into the experiments. In addition, further experimentation is necessary to establish the significance of the systematic errors inherent in the experimental apparatus.

The scale of many prototype networks is a matter of some conjecture. The parallel, coplanar "dip tubes" observed by Ford (1971), for example, may be interpreted as either autonomous or non-autonomous conduits. Detailed field observations of small conduit systems are required to resolve this problem.

Field observations of prototype systems are essentially limited to Phase 2 conduits. The possibility exists that the processes involved in the second phase of speleogenesis are in some way influenced by geologic structure. The present models are inadequate to evaluate this possibility.

3) The pattern of conduit development was strongly influenced by the variability of hydraulic conductivity within the model bedding plane. The size and distribution of relatively impermeable areas in the plane were observed to control the pattern of conduit formation. In the absence of such irregularities, conduits were free to develop along a variety of solvent flow paths. As the density of obstructions increased, conduit formation became confined to fewer routes. Under highly restricted flow conditions, the model networks took on a simplified, linear pattern resembling that of the "dip tubes" observed by Ford (1971) in steeply dipping strata. Unrestricted solvent flow produced more complex networks resembling those commonly observed in horizontally bedded limestones.

It seems reasonable to assume that prototype bedding planes also vary widely in their ability to transmit water. Such factors as the presence of stylolites, the accumulation of argillaceous material, variations in the grain size of the solute surfaces, and the effect of tectonic activity influence the hydraulic conductivity of limestone bedding planes. These phenomena are undoubtedly significant at the level of individual bedding plane units. However, their effect on the overall pattern of network development is as yet undetermined.

4) The distribution of autochthonous sediments within the model networks was observed to be dependent upon the

inclination of the model bedding plane. Although the quantities of sediment present in the models were apparently insufficient to influence the pattern of conduit formation, this may not be the case in the prototype. The relatively impure prototype solute will yield greater quantities of autochthonous sediment. In addition, varying amounts of allochthonous sediment may be supplied by surface streams entering the subsurface drainage system.

Should insoluble sediment be available in sufficient quantity, the smaller elements of a developing network may become wholly or partially blocked, thereby concentrating solutional activity in a small number of larger conduits.

The experiment results are insufficient to evaluate the effect of sedimentation on the pattern of network development. However, it seems probable that this phenomenon may present a link between stratigraphic dip and the pattern of network growth in the prototype. The experimental results suggest that steeply dipping strata present the optimum conditions for selective sediment blocking, and hence the formation of relatively simple networks. Thus, this phenomenon may explain the relationship between network pattern and stratal dip obseved by Ford (1971).

5) The sequence of conduit forms observed in the models appears to offer an explanation for the elliptical cross-section of many prototype conduits. Initially, individual conduits appeared as an anastomatic band of very

small conduits. As the conduit developed, a larger tube formed in the centre of this band. The resultant conduit consisted of a central primary tube flanked by anastomotic bands of smaller conduits. Continued enlargement of this type of conduit in the prototype environment could result in the formation of a single conduit of elliptical cross-section.

CHAPTER V

CONCLUSIONS

Limited success was achieved with the similarity of process models employed in this study. Interpretation of the experimental results was severely restricted by two factors: the random systematic errors inherent in the rather unrefined model apparatus; and the limited number of successful experiments. Consequently, the experimental results are considered to be unsuitable for the detailed quantitative analysis required to establish the effects of individual variables within the model system. However, certain conclusions of a qualitative nature may be drawn on the basis of observations of conduit formation in a model environment.

1) The models were successful in generating conduit networks exhibiting many features common to prototype bedding plane networks. This suggests that the two dimensional porous medium analogue, which forms the basis of the models, adequately simulates the chemical-hydrodynamic environment of prototype bedding planes.

2) The pattern of the model conduit networks appeared to be unrelated to both the hydraulic gradient of the system, and the inclination of the bedding plane. In the absence of severe systematic effects, the pattern of

conduit development was a function of the bedding plane flow field. Individual conduits paralleled the paths of solvent movement described by the Darcy flow net. The pattern of Darcy flow lines in a two dimensional porous medium is solely a function of the geometry of the input/output system. Therefore, the pattern of conduit development was independent of both hydraulic gradient and bedding plane inclination.

The networks which developed in the single surface models were typically complex, composed of anastomotic zones of small diameter conduits. These networks developed a dominant conduit zone in the central area of the bedding plane, along the path of most rapid solvent flow (i.e. the path of maximum hydraulic gradient).

Deviations from this pattern occurred when systematic effects caused hydraulic conductivity to vary across the bedding plane surface. The degree of control exerted by such heterogeneity caused marked differences in the pattern of conduit networks developed under otherwise identical conditions. Differences between individual networks were directly attributable to the affect of variations in bedding plane hydraulic conductivity on the pattern of solvent flow.

It seems reasonable to assume that the same process is operable in small scale prototype networks. However, insufficient data exist to determine the importance of this phenomenon in the development of larger scale cavern systems.

3) Although the experiments were not designed to study sedimentation in a cavernous environment, they indicate that the pattern of conduit growth within a developing network may be significantly affected by the accumulation of insoluble material. The observed relationship between bedding plane inclination and the distribution of sediment within the model networks may offer an explanation for the apparent relationship between stratal dip and the pattern of prototype networks observed by Ford (1971). Further experimentation is required to evaluate this hypothesis.

4) Prototype conduits frequently exhibit an elliptical cross-section, with the bedding plane forming the long axis of the ellipse. White and Longyear (1962) have suggested that this shape is the result of a transition from laminar to turbulent flow in the centre of the conduit, and the subsequent acceleration of solution in the turbulent zone.

The experiments afforded the opportunity to study conduit development under both laminar and turbulent conditions. However, the form of the model conduits appeared to be unrelated to the fluid flow regime. The conduits which developed in the two surface models, for example, maintained a circular cross-section in both laminar and turbulent conditions.

Although the single surface models were unable to supply direct data on conduit shape, the sequence of conduit planforms typical of the experimental conduits could conceivably result in the formation of an elliptical conduit in the prototype environment. In general, the experimental results suggest that an elliptical conduit will develop in those instances where conduit development initially takes the form of anastomotic conduits.

The results of this investigation are generally inconclusive. The experiments show the feasibility of a process similarity approach to the modelling of speleogenesis. However, the experimental apparatus requires considerable refinement to permit detailed investigation of various aspects of speleogenesis. The results of the present experiments suggest possible avenues for future investigation.

Experimentation with various types of bedding plane surfaces should provide a better indication of the relationship between network pattern and the variability af bedding plane hydraulic conductivity.

The experimental results indicate that a similar, less complex model system may be suited to the study of conduits in cross-section. In particular, the relationship between bedding plane permeability and conduit shape appears worthy of further study.

The relationship between bedding plane inclination and the distribution of sediment within a conduit network could easily be studied with models of the single surface type. The possible link between sediment accumulation and the pattern of conduit development could then be investigated for various structural and hydraulic boundary conditions.

In general, the similarity of process model is particularly suited to the study of the initial stages of speleogenesis, given the difficulty of obtaining suitable field data.

BIBLIOGRAPHY

Albertson, M.L., Barton, J.R., and Simons, D.B., 1960: <u>Fluid Mechanics For Engineers</u>. Englewood Cliffs, N.J.: Prentice Hall Inc.

Allen, J.R.L., 1968: <u>Current Ripples: Their Relation to Patterns of Water and Sediment Motion</u>. Amsterdam: North Holland Publishing Co.

Bear, J., Zaslavsky, D., and Irmay, S., 1968: <u>Physical Principles of Water Percolation and Seepage</u>. Paris: UNESCO.

Bedinger, M.S., 1966: Electrical Analog Study of Cave Formation. <u>Nat. Spel. Soc. Bull</u>., 28(3): 117-131.

Bretz, J.H., 1942: Vadose and Phreatic Features of Limestone Caverns. <u>J. Geol</u>., 59: 675-811.

Curl, R.L., 1960: Stochastic Models of Cavern Development. <u>Nat. Spel. Soc. Bull</u>., 22(1): 66-76.

1965: Solution Kinetics of Calcite. paper presented at <u>4th International Congress of Speleology</u>. Ljubljana, Yugoslavia.

1974: Notes on Cave Conduit Competition - Non-autonomous Systems. paper presented at <u>4th Conference on Karst Geology and Hydrology</u>. Morgantown, W. Va.

Davies, W.E., 1960: Origin of Caves in Folded Limestone. <u>Nat. Spel. Soc. Bull</u>., 22(1): 5-18.

Davis, W.M., 1930: Origin of Limestone Caverns. <u>Geol. Soc. Am. Bull</u>., 41(3): 475-648.

De Wiest, R.J., 1965: <u>Geohydrology</u>. New York: Wiley.

Egemeier, S.J., 1969: Origin of Caves in Eastern New York as Related to Unconfined Groundwater Flow. <u>Nat. Spel. Soc. Bull</u>., 31(4): 97-111.

Ewers, R.O., 1966: Bedding Plane Anastomoses and Their Relation to Cavern Passages. <u>Nat. Spel. Soc. Bull</u>., 28(3): 133-140.

Ewers, R.O., 1972: Model for the Development of Subsurface Drainage Routes Along Bedding Planes. M. S. Thesis, University of Cincinatti, Cincinatti, Ohio.

Ford, D.C., 1968: Features of Cavern Development in Central Mendip. Trans. Cave Res. Group of Great Britain, 10(1): 11-25.

1971: Geologic Structure and a New Explanation of Limestone Cavern Genesis. Trans. Cave Res. Group of Great Britain, 13(2): 81-94.

Frank-Kamenetskii, D.A., 1955: Diffusion and Heat Exchange in Chemical Kinetics. Princeton: Princeton Univ. Press.

Gardner, J.H., 1935: Origin and Development of Limestone Caverns. Geol. Soc. Am. Bull., 46(8): 1255-1274.

Goodchild, M., and Ford, D.C., 1971: An Analysis of Scallop Patterns. J. Geol., 79(1): 52-62.

Halliday, W.R., 1960: Changing Concepts in Speleogenesis. Nat. Soc. Spel. Bull., 22(1): 23-29.

Hooke, R.LeB., 1968: Model Geology: Prototype and Laboratory Streams: Discussion. Geol. Soc. Am. Bull., 79: 391-393.

Howard, A.D., and Howard, B.Y., 1967: Solution of Limestone Under Laminar Flow Between Parallel Boundaries. Caves and Karst, 9(4): 25-38.

Hubbert, M.K., 1969: The Theory of Groundwater Motion and Related Papers. New York: Hafner.

Jennings, J.N., 1971: Karst. An Introduction to Systematic Geomorphology, v.7. Massachusetts: M.I.T. Press.

Kaye, C.A., 1957: The Effect of Solvent Motion on Limestone Solution. J. Geol., 65: 35-46.

Lange, A.L., 1963: Planes of Repose in Caves. Cave Notes, 5: 41-48.

Langhaar, H.L., 1951: Dimensional Analysis and Theory of Models. New York: John Wiley and Sons.

Lewis, W.V., and Miller, M.M., 1955: Kaolin Model Glaciers. J. Glac., 2: 535-538.

Malott, C., 1937: Invasion Theory of Cavern Development. Geol. Soc. Am. Proc. for 1937, p.323.

Moore, G.W., 1960: Introduction to the Origin of Limestone Caves. Nat. Spel. Soc. Bull., 22(1): 3-4

Morgan, M.A., 1967: Hardware Models in Geography. in Models in Geography. Chorley, R.J., and Haggett, P. (eds.) London: Methuen and Co.

Reams, M.W., 1963: A Comparison Between Laboratory Models and Naturally Occurring Domepits. Nat. Spel. Soc. Bull., 26: 69-70

Rhoades, R., and Sinacori, M.N., 1941: Pattern of Ground-water Flow and Solution. J. Geol., 49: 785-794

Swinnerton, A.C., 1932: Origin of Limestone Caverns. Geol. Soc. Am. Bull., 43: 663-694

Thrailkill, J.V., 1968: Chemical and Hydrologic Factors in the Excavation of Limestone Caves. Geol. Soc. Am. Bull., 79: 19-46

Waltham, A.C., 1971: Controlling Factors in the Development of Caves. in Symposium on the Origin and Development of Caves. Ford, T.D. (ed.). Trans Cave Res. Group of Great Britain, 13 (2)

Watson, R.A., 1965: Similitude in Direct and Thought Experiments in Cave Geology. Nat Spel. Soc. Bull., 27 (3): 65-76

Weyl, P.K., 1958: The Solution Kinetics of Calcite. J. Geol. 66: 163-176

White, W.B., 1960: Termination of Passages in Applachian Caves as Evidence for a Shallow Phreatic Origin. Nat. Spel. Soc. Bull., 22 (1): 43-53

, and Longyear, J., 1962: Some Limitations on Speleogenetic Speculation Imposed by the Hydraulics of Groundwater Flow in Limestone. The Nittany Grotto Newsletter, 10 (9): 155-167

Yalin, M., 1971: Theory of Hydraulic Models. London: MacMillan.