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# THE DEVELOPMENT OF KARREN KARST FORMS ON THE NEWALA LIMESTONE IN DRY VALLEY, SHELBY COUNTY, ALABAMA

by

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A THESIS

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ABSTRACT

The main objective of this study is to identify karren forms and to evaluate factors affecting their development in an area representative of folded limestones of the Valley and Ridge physiographic province in the southern Appalachians. In Dry Valley, Shelby County, Alabama, karren are abundant and highly diversified on outcrops of the Newala Limestone of Ordovician age. They occur on bedrock surfaces below a thin soil cover and on pinnacles protruding above the soil. Karren range from simple, isolated forms, to complex groups. One form may grade into another as cover conditions vary, or they may be superimposed because of a complete change in environment. Karren have been identified and classified using Alfred Bögli's genetic classification. Bögli's three principal categories of free karren, semi-free karren, and covered karren are represented in the area. Covered karren, characterized by rundkarren, are the most abundant; semi-free karren are the next most abundant; and free karren are the least abundant yet the most diversified of karren forms. Free karren development has been restricted to a few isolated pinnacles and outcrops by a nearly continuous soil cover over the valley floor. Factors controlling karren development in

Dry Valley include: geologic structure, lithology of the limestone, stratigraphy, the presence or absence of a soil cover, climate, and local hydrologic conditions. These factors determine the nature of the chemical reaction involving the limestone, carbon dioxide, and water; the solution rates; and the nature of the water flow over the limestone surfaces. These physical and chemical parameters are directly responsible for fashioning the various karren forms. Geologic structure has had a pronounced effect on the distribution and orientation of karren forms and local hydrologic conditions throughout Dry Valley. Faulting has had little direct effect on karren development with the exception of low angle thrust faulting that has produced a wide and highly permeable fracture zone. One such thrust fault located in the Vulcan Materials quarry has created a bedrock low and a thicker soil zone that limits karren to covered forms. Folding, faulting and subsequent weathering of limestone beds have resulted in limestone surface slopes that range from $90^{\circ}$ to nearly horizontal within the valley; consequently, a full range of karren forms are possible. The Newala Limestone has many of the most favorable lithologic characteristics necessary to produce karren including: fine-grained size, high density, strength, massive bedding and chemical purity. Local hydrology has played an important role in karren development in the valley. Conditions may vary from poorly drained, swampy, permanently wet areas with a very shallow water table to well

drained areas with a deep water table. Karren in the permanently wet areas are characterized by highly developed rundkarren and wide shallow kluftkarren. Karren in the well drained areas are generally more diversified and kluftkarren may achieve maximum development.

# INTRODUCTION

## General Statement

Karren are solution sculptured forms carved into the surface of carbonate rocks by the action of carbon dioxide-charged water. The term karren is synonymous with many local names used in scientific literature such as lapiés, laissines, rascles, schratten, etc. They are the small clefts, furrows, pits, holes, and scallops often observed on outcrops of carbonate rocks.

Throughout much of the world karren have been the subject of detailed studies, not only as a curiosity but as a means of determining the effects of weathering on limestones and the development of landforms. Although much work has been done elsewhere, the study of karren has not aroused much interest in the United States. Geologists and hydrologists familiar with limestone terranes in the United States are aware of the existence of karren, but little effort has been expended in documenting karren occurrence or the factors responsible for their development.

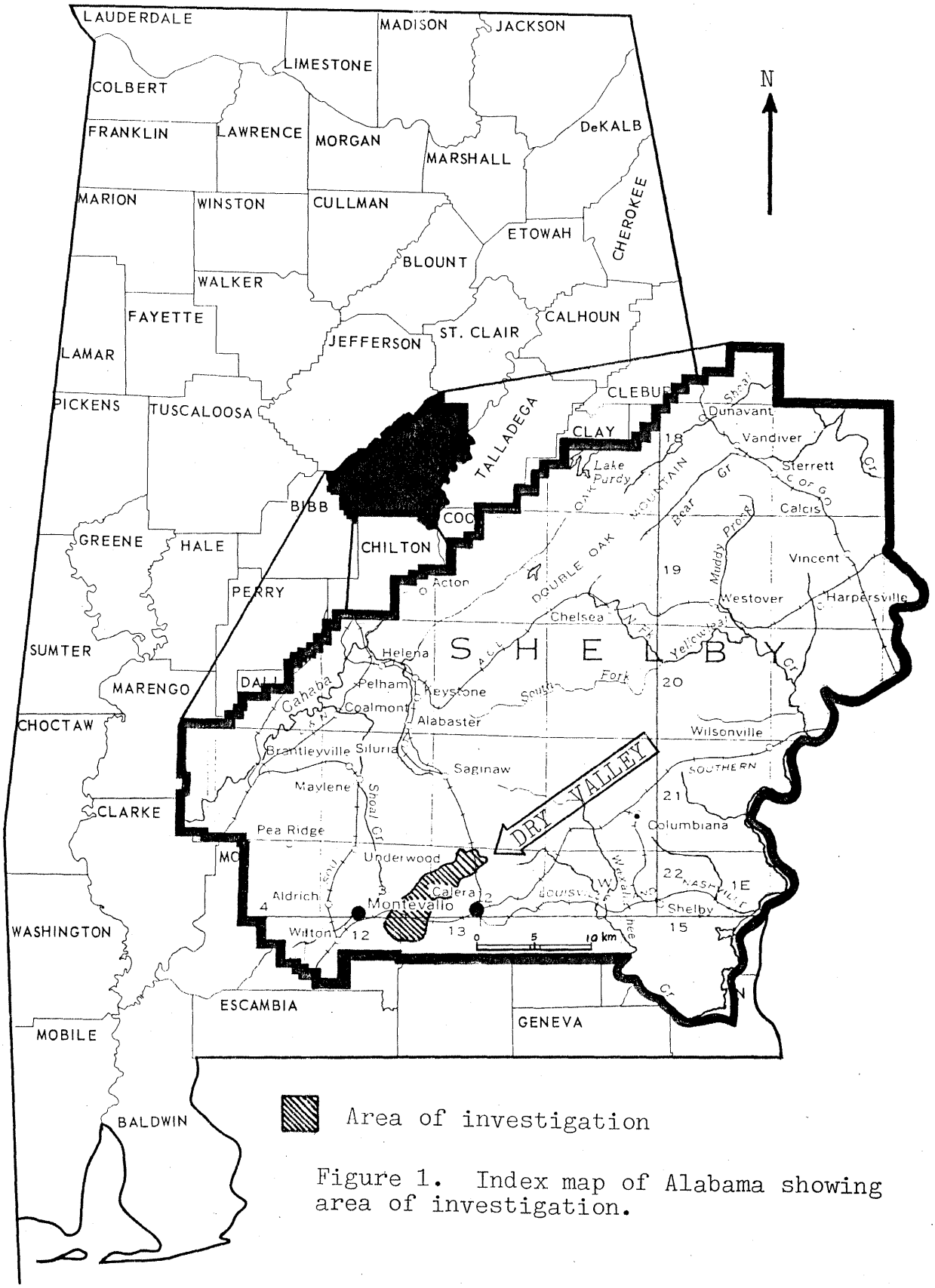
Karren are common features on many limestones in Alabama. They achieve the highest degree of development on massively bedded, pure, dense, fine-grained limestones such as the Ordovician Newala Limestone found in the Valley and Ridge physiographic province of central Alabama.

## Purpose and Scope

The objective of this investigation is to identify and document the occurrence of karren karst forms and to evaluate the factors affecting their development in an area representative of folded limestones of the Valley and Ridge physiographic province in the southern Appalachians. This study is limited to the outcrop areas of the Newala Limestone within the Dry Valley drainage basin (approximately 26 square kilometers) in Shelby County, Alabama. The Dry Valley drainage basin lies in the Cahaba River Valley between Calera and Montevallo, Alabama (Fig.1). This location was chosen for the study area because of the abundance and diversity of karren, and also because of the excellent examples exposed through surface mining activity. Open pit quarries and underground mines have uncovered large areas of the limestone and exposed the rock down to depths greater than 122 m; thus, factors affecting karren development can be studied at significant depths below the land surface.

## Physiographic and Geologic Setting

The Dry Valley drainage basin is in the Cahaba Valley physiographic subdivision of the Valley and Ridge physiographic province. This area is characterized by parallel ridges and valleys underlain by highly folded and faulted sedimentary rocks of Cambrian to Mississippian age. The rocks of the Cahaba Valley, as throughout the Valley and Ridge province, have been intensely folded and faulted, so




Area of investigation

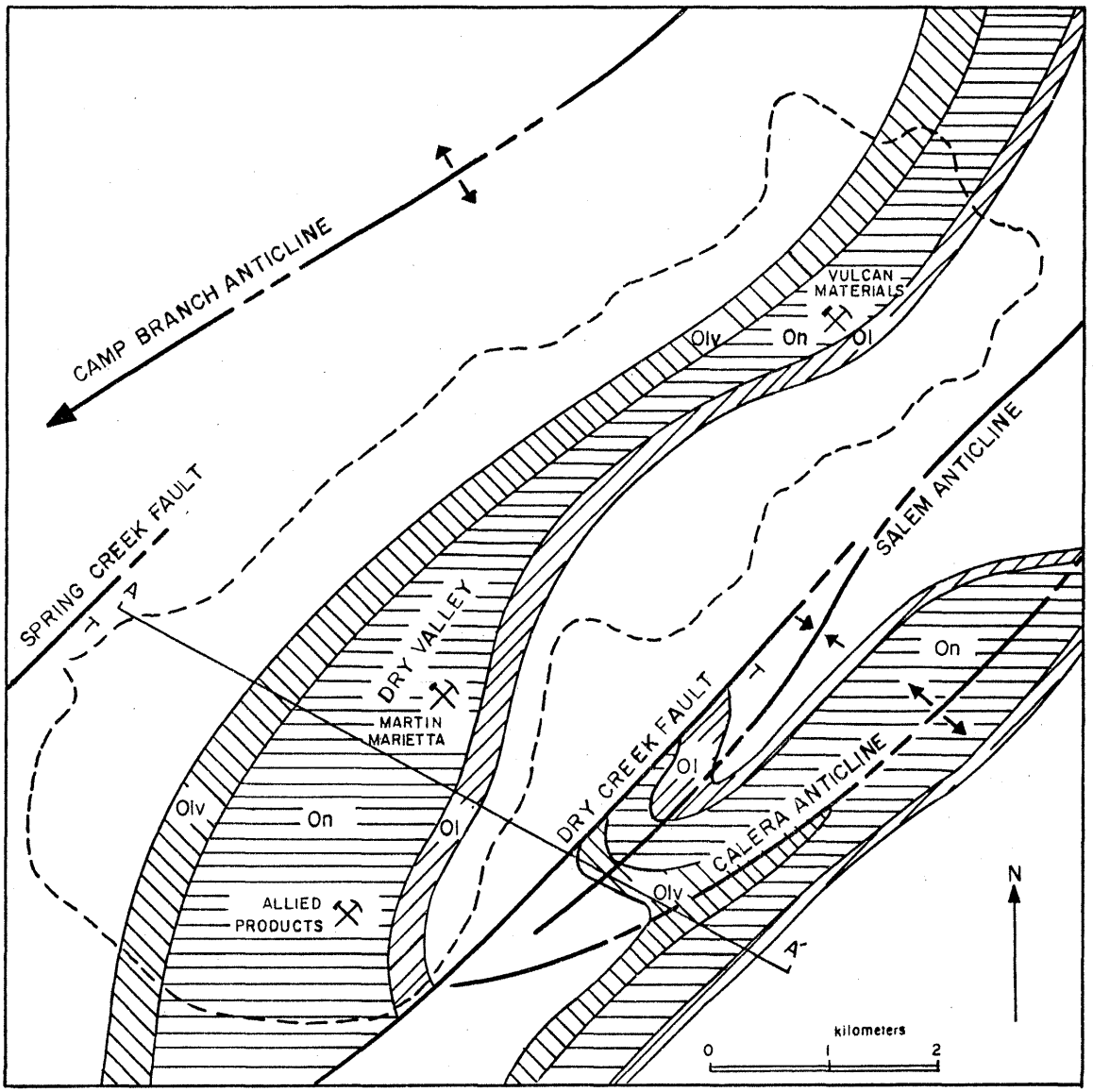
Figure 1. Index map of Alabama showing area of investigation.

that they now lie in great anticlinal arches and synclinal troughs (Butts, 1940). These anticlines and synclines have a general northeast-southwest trend throughout the region. Several large thrust faults, including the Helena and Wilsonville and numerous smaller high angle thrust faults, all trending northeast-southwest, transect the province in and near Dry Valley. Along these faults strata have been greatly disturbed and displaced.

Dry Valley lies on the southeast flank of the Camp Branch anticline, a large doubly plunging northeast-southwest trending structure. In the study area, beds of Paleozoic strata generally dip to the southeast at angles of $15^{\circ}$ to $25^{\circ}$ in relatively undisturbed areas to almost $90^{\circ}$ near faults. The valley with a vertical relief of less than 37 m has formed between two parallel ridges that are oriented in the direction of the regional trend (Fig. 2). The valley floor is underlain by Ordovician limestones: the Longview, Newala and the Lenoir. The ridges are underlain by more resistant rock including Upper Cambrian and Lower Ordovician cherty dolomites of the Knox Group in the northwest, and Upper Devonian and Lower Mississippian sandstones, chert and shale in the southeast (Fig. 3). The south end of the valley is terminated by a northeast-southwest ridge associated with the Dry Creek thrust fault.

## Stratigraphy

The Newala Limestone is the principal unit in Dry Valley on which karren have formed. This unit is about 300 m thick




EXPLANATION

Ordovician

| | |
|---|---|
| Olv | Longview Ls. |
| On | Newala Ls. |
| Ol | Lenoir Ls. |

Quarry

Thrust fault

Anticline

Syncline

Drainage divide

Figure 2. Generalized geologic map of the study area showing distribution of Lower Ordovician limestones and major structural features (modified from Butts, 1940).

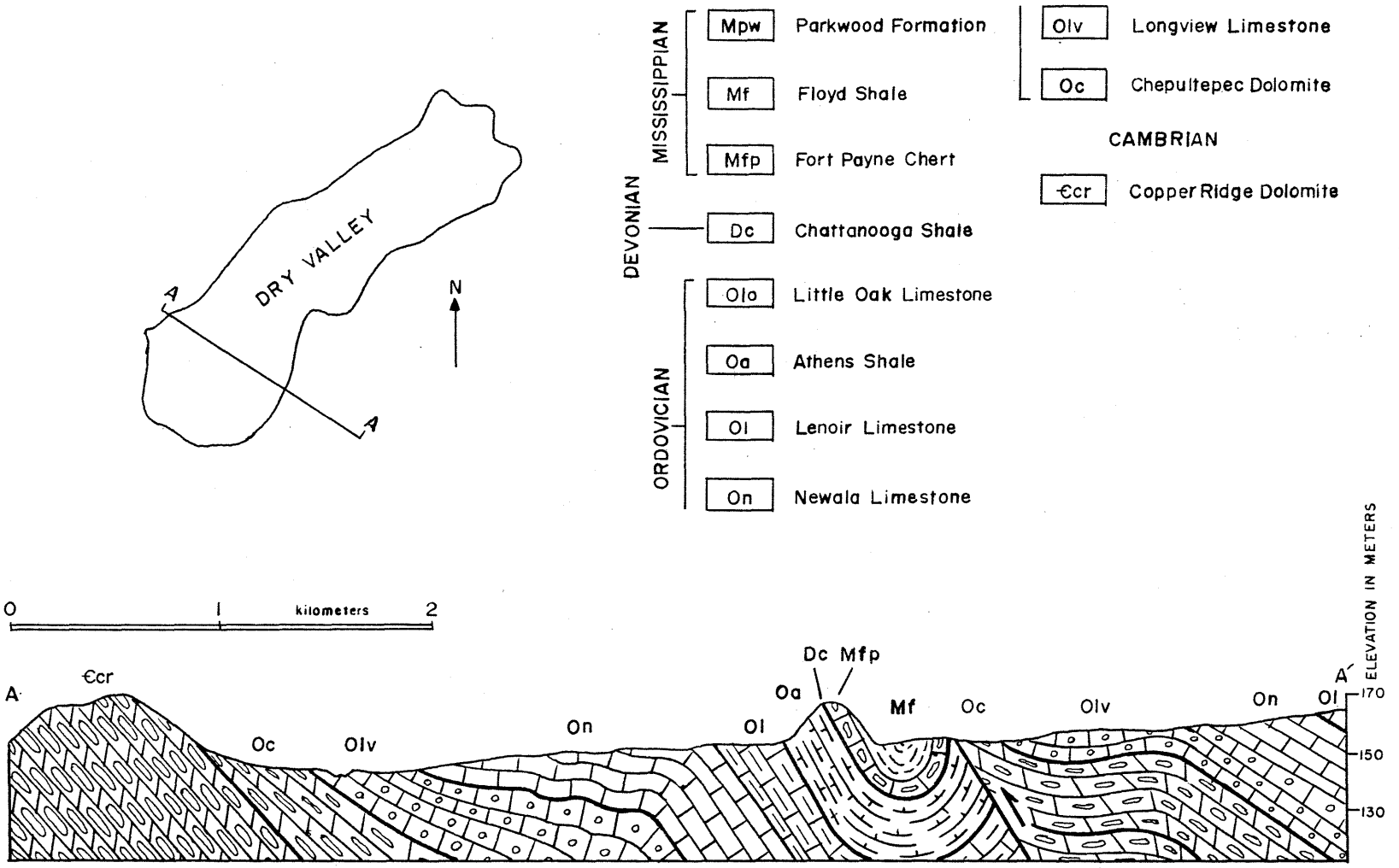



Figure 3. Geologic cross section through Dry Valley, Shelby County, Alabama (modified from Butts, 1940).

in the valley and consists of a fine-grained, dense, massively-bedded, very pure limestone with discontinuous layers of coarse-grained, light colored dolomite. Color of the limestone ranges from dark gray, and dove colored to light gray. The limestone is brittle and breaks with a conchoidal or splintery fracture. Calcium carbonate content of limestone is generally greater than 95 percent, while in dolomites the content may range from 59 to 72 percent. Minor minerals include: barite, flourite, and galena, and represent only a small percent of the total composition of the limestones and dolomites.

Yeager (1971) using Folk's classification of carbonate rocks, described the Newala as being essentially micrites with intrasparite and sparite filling the fractures. A core examined by Yeager representing 43.6 m of stratigraphic section contained approximately nine percent dolomite by thickness. Taylor (1971), using Dunham's classification of limestones, classified the limestones as a lime mudstone and interclast or pelletal packstone.

In some areas the Newala contains a breccia cemented with sparry calcite. The limestone's intense small-scale fracturing and abundant large-scale jointing are the result of the brittle nature of the limestone under near surface conditions and strong tectonic activity in the area. Fractures responsible for producing this breccia have been filled with sparry calcite creating a network of interlocking veins. At some locations, the calcite vein material of the breccia

may be altered or replaced by barite, flourite, dolomite, or other minerals (Hughes and Lynch, 1973).

According to Taylor (1971), the lithology of the Newala is transitional with that of the underlying Longview Limestone. Chert found in the Longview forms a basis for differentiating Longview from Newala. The upper contact of the Newala is a disconformity with the overlying Lenoir Limestone. This contact is marked by conglomeratic basal layers of the Lenoir that contain pebbles of chert and limestone. Throughout Dry Valley, the Newala is buried beneath a soil cover containing clay, stream alluvium, and chert derived from weathering of the nearby ridges and formations.

## Structure

The Newala Limestone outcrops in the floor of Dry Valley as a continuous sinuous band that is much wider in the south end of the valley than in the north end. Butts (1940) attributes the increased width to a series of minor folds with their axes paralleling the valley trend. Near the middle of the valley the outcrop narrows rapidly as the folds disappear and the beds assume a regular southeast dip. Minor faulting occurs at several locations in Dry Valley. A high and a low angle thrust fault and several left-lateral strike-slip faults have been identified by the author.

## Climate

Dry Valley is in a temperature subtropical region characterized by high humidity and moderate temperatures.

Precipitation is almost entirely in the form of rain and averages about 142 cm annually. The greatest amount of precipitation generally occurs in December-March and the least in September-October. The winters are mild with an average temperature of 14° C, and summers are long and hot with an average temperature of 28° C. The average temperature is 21° and the growing season averages 229 days.

## Hydrology

The study area lies in the Cahaba River drainage basin where all streams flow south with the exception of the north-flowing Buck Creek. Streams and tributaries to Dry Creek, which drain Dry Valley, are intermittent and only flow during the wet season or during storm runoff. Where streams and tributaries cross outcrops of the Newala, they lose flow to well developed solution cavities in the rock, and swallow holes are common in stream beds crossing the limestone.

Ground water occurs in openings in the limestone along faults, joints, and bedding plane cavities. Water enters the rock through swallow holes in streams, sinkholes, and the downward percolation of water through a soil cover into well developed bedding plane cavities, lapiés wells, and solutionally enlarged joints. Ground water movement in the limestone appears to be through a well integrated system of deep solutionally enlarged joints and cavities developed along joints, faults, and bedding planes.

## Methods of Investigation

A detailed search was made for outcrops of the Newala Limestone in Dry Valley to locate areas of potential karren development. Aerial photography was utilized in the initial search to accurately locate outcrops for field examination. Karren forms identified in the field were photographed and described in detail. Measurements were made on pertinent features of the karren such as length, width, and depth of runnels or troughs, their special orientation, and slope of the rock surface on which the feature formed. The area around outcrops exhibiting karren development was examined to ascertain what factors were present that might affect the origin of karren, including geologic structure, presence or absence of cover, type of cover, and evidence of local hydrologic conditions.

The limestone on which karren forms were identified was examined to determine lithologic characteristics of the rock and the relationship between lithology and karren development. A hand lens and hydrochloric acid were used to differentiate limestone from dolomite and carbonates from other minerals. Fifteen rock samples were collected for laboratory examination to verify field identification of minerals and to classify the limestone.

The geologic structure of the study area was determined through the use of existing geologic maps, aerial photographs, and standard field methods. The hydrology of Dry Valley was evaluated by means of examining solution features

on limestone outcrops, in open pit quarries, and in underground mines. Additional hydrologic data was collected by the author and associates during previous investigations in Dry Valley, including a complete inventory of water levels in domestic wells, and a stream flow reach study of Dry Creek and its tributaries.

Laboratory methods were limited to identifying minerals and classifying the limestone in samples collected in the field. Rock samples were cut and one surface polished smooth. The polished surface was etched with dilute hydrochloric acid, stained with alizarine red, an organic dye used to differentiate calcium carbonate from dolomite, and examined under a binocular microscope. The limestone was classified according to composition and depositional texture.

## Previous Investigations

The general geology of Dry Valley was discussed by Charles Butts (1926) in "Geology of Alabama" and portrayed on the accompanying "Geologic Map of Alabama" published by the Geological Survey of Alabama. A more detailed description of the geology, structure, and stratigraphy are presented by Charles Butts in the U. S. Geological Survey Portfolio "Description of the Montevallo and Columbiana Quadrangles" (1940). Detailed subsurface mapping of the Newala Limestone has been accomplished in a few limited areas by companies operating limestone quarries in Dry Valley including Vulcan Materials Company, Martin Marietta

Cement, and Allied Products. Information produced by these industries has not been published extensively.

Petrographic descriptions of the Newala Limestone have been presented by Yeager (1971) and Taylor (1971). Sinkhole and subsidence problems were investigated in Dry Valley by the Geological Survey of Alabama and several reports have been published: LaMoreaux and Warren (1973), and Warren and Wielchowsky (1973). Karren karst features in the Cahaba Valley were examined and discussed by Moravec (1974).

## CLASSIFICATION OF KARREN

### Definition and Use of the Term Karren

The term karren is German in origin and was originally used to describe runnels cut into limestone. "The first modern reference to karren was in a short paper by Heim in 1878, 'Uber die Karrenfelder'" (Sweeting, 1972, p. 74). In recent karst literature the usage of the term has changed so that karren is now a general term employed to describe the total complex of superficial solution forms, as found on the compact pure limestones of the Alps (Williams, 1967). Bögli (1960) states that karren also form on dolomite as well as pure limestones.

The study of karren karst features is known to have begun before Heim published his first work in 1878, but it was not until 1893 when Cvijič presented a short paper which included a section on karren that any interest was aroused. As a result, a number of descriptive works on karren in different parts of Europe were produced. The most important, according to Sweeting (1972) was "Gottesackerplateau, ein Karrenfeld in Allgau" by Max Eckert in 1902. Sweeting says that this paper is the most thorough ever written on karren. In the first quarter of the twentieth century many works about karren were produced by European authors such as Duparc, Royer, Rollier, Martel, Simonovič, and Cvijič. Few

of these works have been translated into English. Cvijič's "Evolution of Lapiés" written in 1924 is one exception and the paper has become a classic.

The most important advances in classifying karren and determining their mode of origin have been made since 1960 by the work of Bauer in Austria, Miotke in the Pyrenees, and Bögli in Switzerland. One of the most important papers on karren development and classification is that by Bögli (1960) and this paper has been translated into English by Dr. Eberhard Werner of the University of West Virginia. Bögli's (1960) paper forms much of the basis for this study.

## Major Factors Affecting Karren Development

Karren have been identified in a wide variety of climates: extreme cold of the Alps, Bögli (1960); cold low wetlands, Sweeting (1966) and Williams (1967); coastal regions, Cvijič (1924); humid tropical, Wilford and Wall (1965) and Panoš and Štelcl (1968); and arid hot, Smith and Albritton (1941) and Jennings (1971). In all climates and geographical locations, the development of karren can be related to similar factors. Sweeting (1972, p. 75) has grouped these factors as follows:

"(a) The nature of the chemical reaction involving the limestone, carbon dioxide and water.

(b) The amount and distribution of and nature of the precipitation, whether in the form of rain or snow.

(c) The nature and texture of the limestone.

(d) The slope or dip of the limestone and their structures.

(e) The nature (or absence) of the vegetation cover, soil, peat, etc.

(f) Past climatic phases, since many of the present small-scale features on karst limestones are related to former climatic phases."

These are general catagories and must be broken down into sub-catagories in any detailed investigation of karren forms, as has been in the following section of this paper "Factors Controlling Karren Development".

## Classification and Origin of Karren

Bögli (1960) devised a genetic classification of karren forms based on the chemical phases of the limestone solution process under natural conditions and the flow of corroding water over the limestone surface (Table 1). Bögli's classification is divided into six catagories based on origin: free karren, semi-free karren (partial cover), covered karren, cave karren, surf karren, and sea karren. This study will only be concerned with the first three catagories.

Table 1.--Classification of karren (Bögli, 1960) and equivalent terms

Dimensions: D, depth; W, width; H, height; L, length; Dia., diameter.

| Karren form | Average size | Category | Slope | Description |
|---|---|---|---|---|
| Rillenkarren (groove or furrow karren) | D = 1-2 cm, W = 2-3 cm, L = up to 50 cm | Free | $40^{\circ}$ to $80^{\circ}$ | Small side by side grooves with sharp crest and rounded troughs. |
| Trittenkarren (step or funnel karren) | H = 3-50 cm, W = 20-100 cm | Free | $10^{\circ}$ to steep | Resemble a step cut in sloping surface with flat bottom and rounded back. |
| Regenrinnenkarren (rain trough karren) | Approximately 3X larger than rillenkarren | Free | Steep to vertical | Resemble rillenkarren but deeper and less regularly arranged. |
| Rinnenkarren (trough karren) | D = up to 40 cm, W = 40-50 cm, L = up to 20 m | Free | Moderate ($30^{\circ}$ to $50^{\circ}$) to steep | Long, slightly curving to straight runnels in a sub-parallel to parallel series. |
| Mäanderkarren (meander karren) | D = up to 40 cm, W = 50 cm, L = up to 20 m | Free | Gentle slopes | Meandering runnels similar to rinnenkarren. |
| Wandkarren (wall karren) | - | Free | Near vertical | Very straight parallel runnels cut by water flowing down a near vertical surface. |
| Kluftkarren (crevice karren) | D = few cm to 4 m W = up to 4 m L = wide range | Free and covered | $0^{\circ}$ to $90^{\circ}$ | Clefts and furrows formed along joints. |
| Kamentiza (solution basins) | Dia. = up to 3 m D = up to 50 cm | Semi-free | Nearly horizontal | Round or oval flat bottomed depressions or basins. |
| Korrosionskehlen (corrosion furrows solution notches) | H = up to 1 m, D = up to 1 m | Semi-free | Steep to vertical | Horizontal furrows or notches cut in near vertical walls at or near the soil-free air interface. |
| Hohlkarren (undercut runnels) | D = 60-100 cm, W = 50 cm, L = 15 m | Semi-free | Moderate to gentle | Solution runnels with undercut wall, bag-like cross section |
| Rundkarren (round karren) | D = 12-50 cm, W = 12-50 cm, L = up to 15 m | Covered | $0^{\circ}$ to $90^{\circ}$ | Rounded crest and troughs, either single troughs or integrated drainage networks. |

## KARREN FORMS IN DRY VALLEY

### Introduction

Karren are common features on the outcropping Newala Limestone in Dry Valley, and many of the forms have been identified by the author using Bögli's classification. Both primary and secondary forms occur in the valley and they have been grouped by origin into Bögli's three principal catagories of free karen (no cover), semi-free karren (partial cover), and covered karren.

In Dry Valley, as in most of the Cahaba Valley physiographic subdivision, the Newala is a very pure carbonate rock that weathers rapidly under the prevailing subtropical climatic conditions. As a result, the Newala is found in valley bottoms almost entirely covered by a veneer of residual clay soil with only a limited number of pinnacles protruding above the soil cover. Pinnacles are more numerous on areas of higher topographic relief, however slight, and in stream beds. The best limestone exposures in the valley are in large open pit quarries where the Newala has been uncovered by stripping away the soil cover. The Newala is also exposed in underground mines to a depth of over 122 meters.

In Dry Valley, Bögli's three catagories of karren are partially represented. Free karren forms are limited to

isolated pinnacles and the older stripped areas near open pit quarries. Semi-free karren forms occur where exposures of limestone are found or where the soil is very thin. Covered karren are the principal forms in the valley because of a soil mantle that covers the valley floor.

Karren forms range from the simple to complex groups. One simple form may grade into another form as cover conditions vary, or one form may be superimposed over another as a result of a complete change in environment.

## Free Karren

The most abundant simple free karren forms identified in the study area are rillenkarren (furrow or groove karren). They are the small parallel or radiating runnels with sharp crests and rounded troughs (Pl. 1, Fig. 1). Where rillenkarren are well developed they may exceed 25 cm in length, 3 cm in width, and 1.5 cm in depth. They develop on steep slopes between 40° and 80° along the crest of exposed pinnacles and blocks. They die out where the slope exceeds 80° or becomes less than 40°. Rillenkarren are best formed on old, naturally exposed pinnacles, but they are also abundant on limestones exposed by mining activity less than 12 years ago as in an area 1,000 meters northeast of the Martin Marietta open pit quarry.

Regenrinnenkarren (rain trough karren), rinnenkarren (trough karren), and mäanderkarren (meanderkarren) are less common free karren forms occurring in the area. The occurrence and distribution of these types are very limited in

Figure 1. Rillenkarren formed along the crest and sides of a recently uncovered limestone pinnacle.

Figure 2. Rinnenkarren formed on a gently sloping limestone surface and modifying rundkarren.

Plate 1.

Dry Valley because of the small area in which conditions are favorable for their development. These karren forms are larger in scale than rillenkarren. As a result, they require a large bare limestone rock surface that has been exposed to direct precipitation for many years. Naturally occurring limestone blocks or pinnacles with the preceeding parameters are practically nonexistent in Dry Valley although they may occur elsewhere in the Cahaba Valley. The only examples of these forms are found in areas where the soil cover has been stripped off of the limestone in recent years. Therefore, they are poorly developed and are probably modifications of other karren forms.

Rinnenkarren have been found only on a few sloping limestone blocks scattered around in an area northeast of the Martin Marietta open pit quarry. The blocks have only been uncovered within the past decade and the rinnenkarren appear to be a modification of rundkarren (Pl. 1, Fig. 2). On this block rinnenkarren vary from 8 to 10 cm in width, up to 8 cm in depth, and from 1 to 2 m in length. In other parts of the world, they may be as wide as 50 cm, as deep as 40 cm, and as long as 15 to 20 m (Sweeting, 1972).

Regenrinnenkarren look very similar to rinnenkarren in some forms and they may grade into each other. Jennings (1971) differentiates one from the other by means of cross sections; regenrinnenkarren retain the same cross section throughout their length. There are fewer examples of regenrinnenkarren than rinnenkarren in Dry Valley. On the sloping

limestone block in Plate 2, Figure 1, regenrinnenkarren have developed on the upper part of the sloping surface, and they grade downward into rinnenkarren. The degree of development in this example is typical for the study area.

Meanderkarren are somewhat similar to rinnenkarren in general appearance, but they develop on less steep slopes so that the flowing water forms a wandering channel over the rock surface giving rise to meandering solution channels. Meanderkarren are small forms cutting into the limestone surface with relatively constant, slightly decreasing, downward cross section which serves to differentiate them from rinnenkarren (Bögli, 1960). In some climates, such as the alpine regions of Switzerland, meanderkarren may vanish down stream because, according to Bögli (1960, p. 18), "of a decrease in aggressiveness of the water as it flows and a decrease of volume because of evaporation".

Some excellent examples of meanderkarren are found in Dry Valley on very gently sloping limestone blocks (Pl. 2, Fig. 2). They may be as wide as 15 to 20 cm, as deep as 10 to 15 cm, and extend up to 3 m in length. In most cases a main channel has developed with smaller branches flowing into it to form a dendritic pattern very similar to a stream pattern. In some cases a channel may be cut into the rock at an angle almost parallel to the strike of the rock, then the channel, exhibiting partial fracture control, may turn to flow almost down slope. Some meanderkarren (Pl. 2, Fig. 2) in Dry Valley have been noted to vanish downstream

Figure 1. Regenrinnenkarren developing on the upper half of a moderately steep dipping limestone surface.

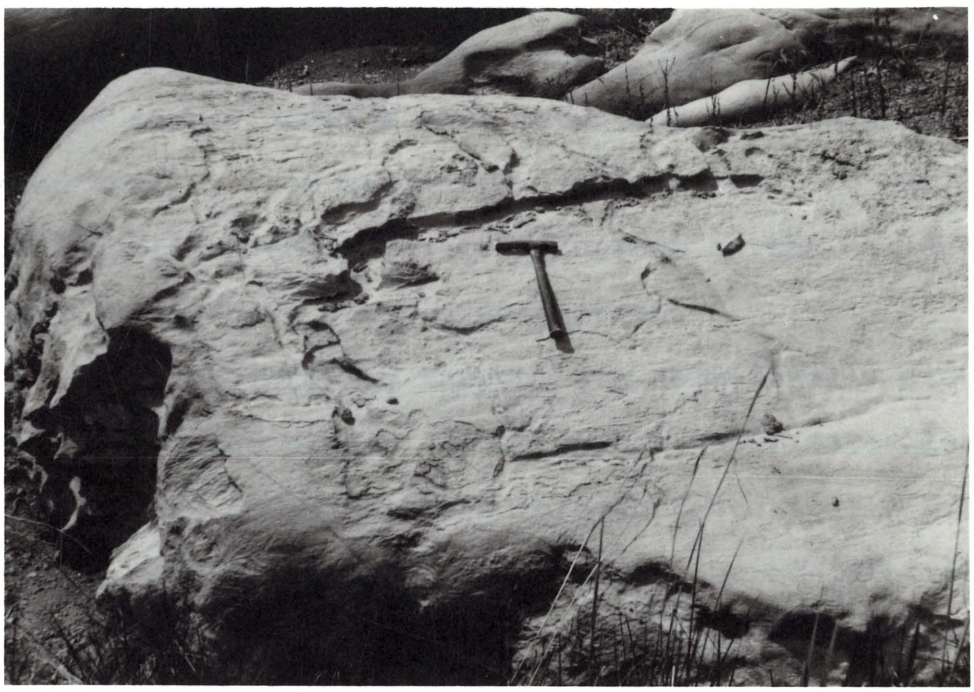


Figure 2. Meanderkarren cut into a gently sloping surface and exhibiting partial joint control.

Plate 2.

in a manner similar to that described by Bögli in Switzerland, but in the study area meanderkarren development is restricted by a change of cover conditions from bare limestone to a soil cover.

Wandkarren (wall karren) form on vertical walls which, because of their shape, receive very little direct rainfall. As a result, runoff or water flowing down from above must account for their origin. In Dry Valley examples of wandkarren are extremely rare, only developing on vertical walls in old quarry pits (Pl. 3, Fig. 1). In this example, the vertical furrows are 15 to 20 cm in width, up to 15 cm in depth, and about 1 m in length. The troughs have rounded bottoms and the crests between troughs are relatively sharp.

Other vertical furrows or grooves are common along the walls of enlarged joints in the study area; however, these karren are formed under a soil cover and have an entirely different origin from wandkarren (Pl. 3, Fig. 2). Williams (1967) identified these vertical furrows on the walls of enlarged joints as a form of rundkarren.

Kluftkarren (crevice karren) are solutionally widened joints or cleavage planes. They appear where water leaves the surface and moves downward through tectonically formed fractures. The solution of limestone by carbon dioxide-charged water may widen the joints and cleavage planes into gaping cracks. Bögli (1960, p. 18) groups kluftkarren as a free karren form but states that, "Because of their origin, they are not strictly connected with free limestone

Figure 1. Wandkarren developed on a vertical wall of an open pit quarry.

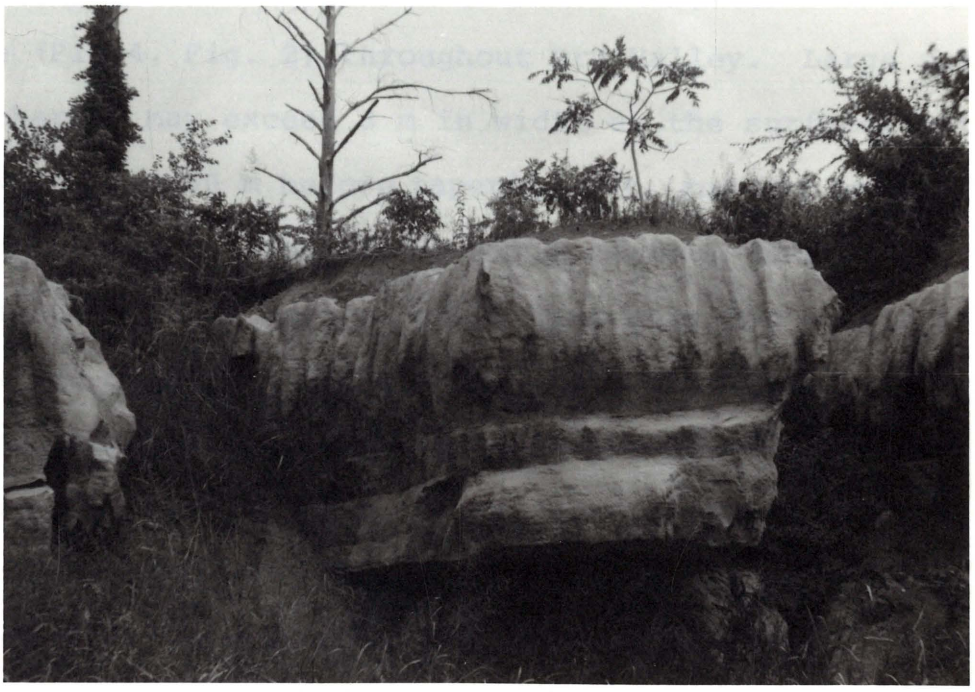


Figure 2. An example of rundkarren forming vertical furrows similar to wandkarren.

Plate 3.

surfaces, but are grouped here because they do not show the typical peculiarities of the other groups." Williams (1967), on the other hand, indicates that the large grike (kluftkarren) of northern England are formed under a soil cover and thus disagrees with Bögli. Within Dry Valley, kluftkarren with the exception of some small scale kluftkarren developed on recently exposed limestone, appear to have been formed under a soil cover. They are filled with soil to their maximum depths, lie beneath a soil cover, exhibit rounded surfaces typical of karren formed under a soil cover, and they are associated with karren forms developed below a soil cover, e.g. rundkarren.

Kluftkarren are one of the most common karren forms occurring in both large scale (Pl. 4, Fig. 1) and small scale (Pl. 4, Fig. 2) throughout Dry Valley. Large scale kluftkarren may exceed 3 m in width at the surface, extend downward over 30 m before tapering out, and may be over 100 m in length. They reach their maximum development in the south central part of the valley near the Martin Marietta limestone quarry. In the south and central part of Dry Valley, large scale kluftkarren are preferentially oriented along east-west striking joints (see section on Factors Controlling Karren Development, Structure, this paper). In the north end of the valley, distribution of kluftkarren is apparently more evenly divided among joint sets. Most kluftkarren form an integrated network of intersecting troughs along joint and fracture patterns.

Figure 1. Large kluftkarren exposed along the rim and far wall of an open pit limestone quarry.

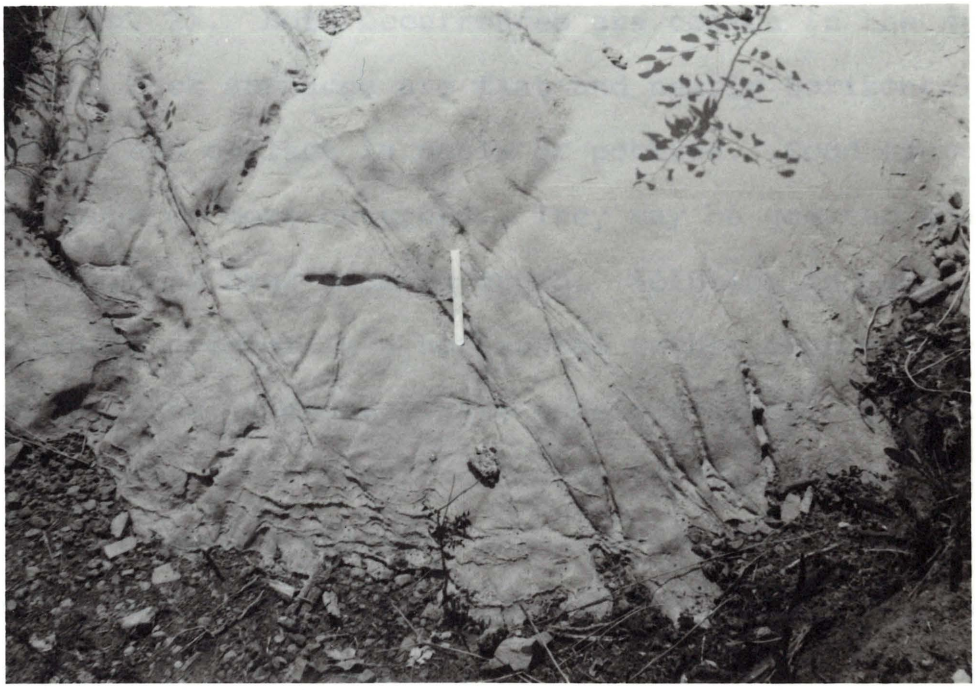


Figure 2. Small kluftkarren developed along minor jointing.

Plate 4.

Small scale kluftkarren may be only 2 to 3 cm in depth and 1 m in length as in the example Plate 4, Figure 2. They can be found on sloping or vertical surfaces of limestone blocks as straight or segmented clefts. These clefts often divert surface water flow in directions away from the dip of the blocks thus the normal gravity flow across the rock surface may be deflected. As a result, the development of other small scale karren may be affected by the presence of kluftkarren.

## Semi-free Karren

Kamenitza (solution basins) are basin-like, flat-bottomed depressions that may occur as singular forms (Pl. 5, Fig. 1) or aligned in groups along joints like beads on a string (Pl. 5, Fig. 2). Both occurrences are common in the study area where rock surfaces are flat and nearly horizontal so that water can collect in pools or pockets. Good examples may be found on most outcrops. They may be greater than 25 cm in width and over 6 cm in depth. Solution in kamenitza is generally greater in a horizontal rather than vertical direction; thus, kamenitza have undercut sides. One explanation for their development according to Bögli, 1960, is that carbon dioxide diffuses into the standing water from the atmosphere where it is utilized by growing algae in the stagnate water. As a result, carbon dioxide is concentrated near the water surface and solution proceeds sideways.

Although kamenitza may form in a free atmosphere environment (Pl. 5, Fig. 1), some kamenitza form under a thin

Figure 1. A simple isolated kamenitza, partially filled with water and small gravel, formed on a nearly horizontal limestone surface.

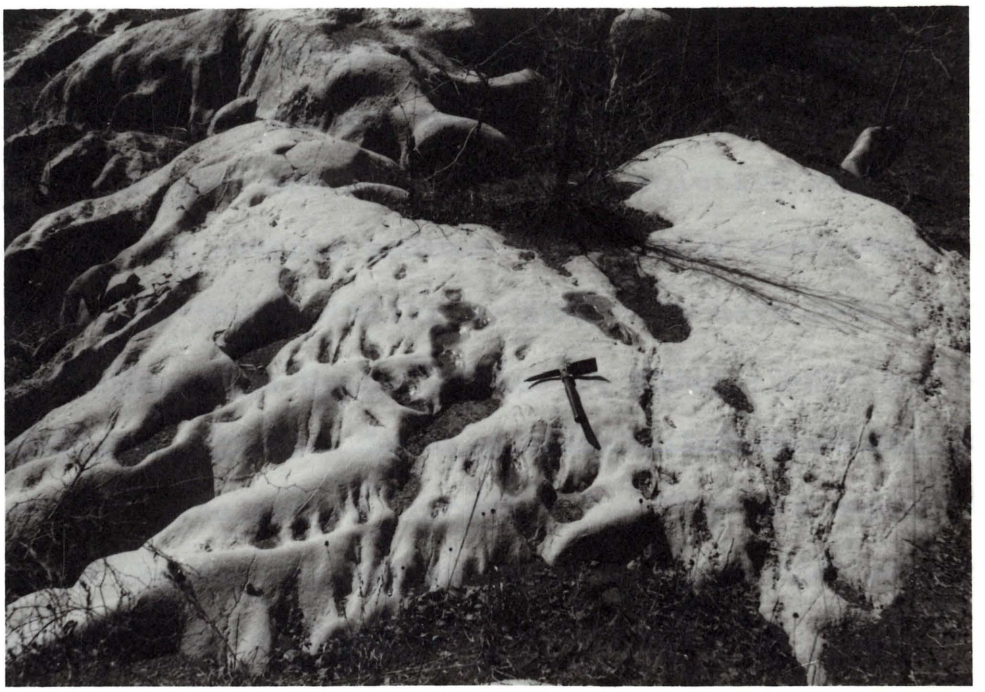


Figure 2. Kamenitza developed in a series along a set of parallel joints.

Plate 5.

soil cover in a manner similar to the formation of rundkarren. In the formation of kamenitza, water that percolates downward through a thin humus soil becomes enriched with biogenic carbon dioxide and attacks the underlying bedrock surface. When the downward percolating water encounters a relatively flat limestone surface with some irregularity that retards the horizontal and vertical movement of water, such as a root scar or cemented joint, a depression will begin to form because of the prolonged contact of the limestone and carbon dioxide-charged water. Once a depression has formed, fresh carbon dioxide-charged water will collect and enlarge the depression with each new rain. Under a thin soil cover roots from plants will use up water caught in bedrock depressions; therefore, fresh water from ensuing rains is necessary for the process to continue. In Dry Valley, heavy rains are common throughout the year, so that the development of solution depressions (kamenitza) on covered bedrock is a nearly continuous process.

Solution forms similar to kamenitza have been identified in the southwestern United States by Udden (1925) and Smith and Albritton (1941). Locally these solution etched basins are called "tinajas" or "tinajitas". They are apparently formed in the same manner as kamenitza in a free atmosphere and are probably equivalent karren forms.

Korrosionskehlen (corrosion furrows) are horizontal furrows cut into limestone pinnacles or blocks where a periodically or permanently wet humus soil is in contact with a

steeply sloping limestone surface (Bögli, 1960). Korrosionskehlen are best developed in the upper part of the soil zone where the amount of carbon dioxide is highest. The upper limit of the soil zone can be identified by the nature of the karren. Above the soil zone, karren are free forms such as rillenkarren while below the contact, karren are covered forms such as rundkarren.

Throughout Dry Valley, korrosionskehlen are evident on outcrops where the soil has been recently removed (Pl. 6, Fig. 1 and Fig. 2). Pinnacles and blocks are undercut at or just below the soil rock contact in many cases leaving a pronounced overhang. Furrows are generally horizontal and may be from 2 cm to over 15 cm in depth.

Solution holes, pipes, "geologischen orgeln" (Jennings, 1971), are cylindrical or conical holes in limestone. They frequently form along joints and fractures and have a round or oval cross section. Holes and pipes result from the movement of ground water through a partially open joint or fracture, so that solution is concentrated into a specific channel which enlarges with time.

Solution holes or pipes are relatively common and occur throughout the study area (Pl. 7, Fig. 1). They range from a few centimeters to 24 cm in diameter and from a few centimeters to over 2 m in length. Pipes and holes which occur most frequently in highly corroded blocks beneath a soil cover, may vary from vertical to nearly horizontal in orientation.

Figure 1. Deep korrosionskehlen cut into the near vertical wall of an exposed pinnacle. The depth of development demonstrates the effectiveness of the soil water solution.

Figure 2. Horizontal furrows cut by solution from ground water below the soil zone-free atmosphere contact.

Plate 6.

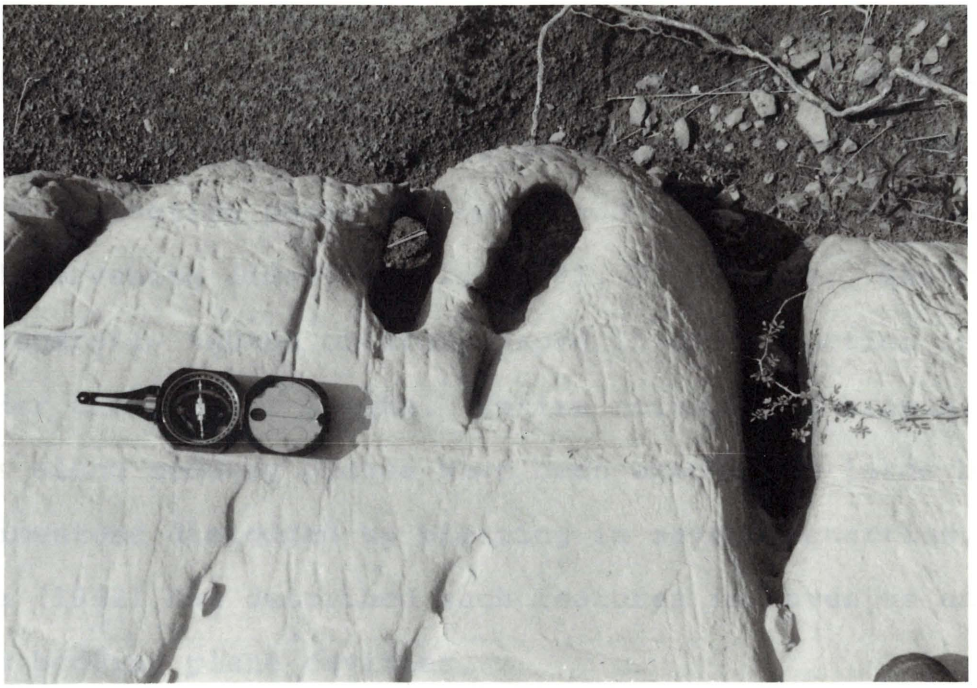


Figure 1. Vertical holes developed along joints in a highly corroded limestone block below a soil cover.

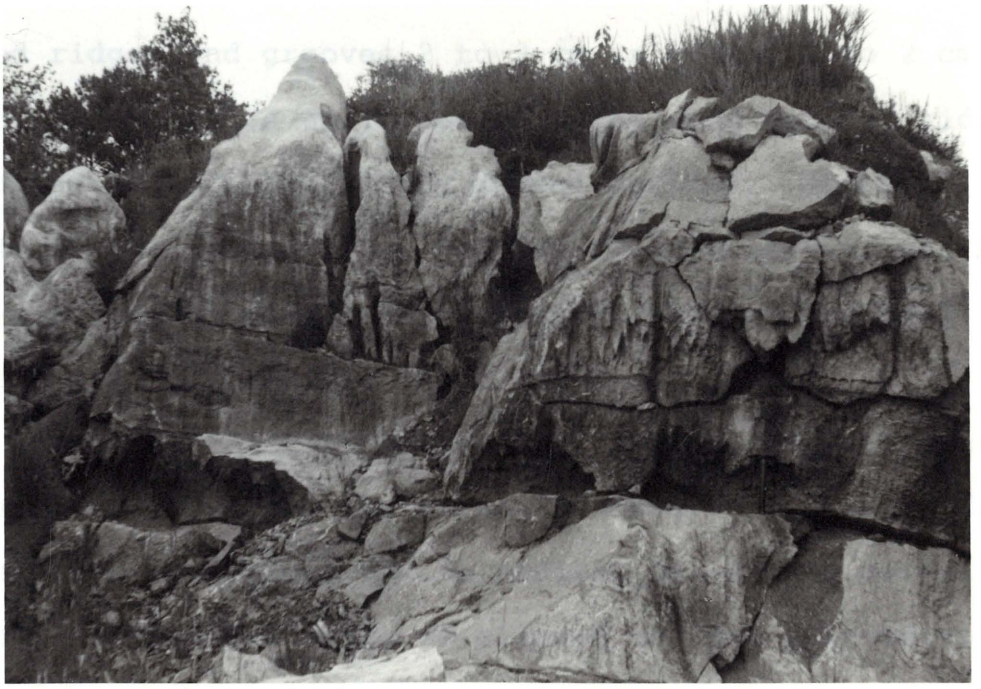


Figure 2. Tubes of an anastomosed bedding plane solution cavity exposed on the near vertical walls of large kluftkarren.

Plate 7.

Networks of branching tubes have also developed along dipping bedding planes in the Newala limestone. They are frequently exposed in walls of large scale-kluftkarren and form a connecting passage between two kluftkarren through the intervening limestone block (Pl. 7, Fig. 2). The tubes are generally square or arch-shaped in cross section and meander along their length. Entire networks of branching tubes along bedding planes have been exposed on large blocks of limestone dislodged by blasting in several quarries. Bretz (1942) has described such features in caves as anastomosed bedding plane cavities.

Ripple marks or scallops have been noted on many concave and near vertical limestone surfaces throughout the study area (Pl. 8, Fig. 1). They are parallel, regularly spaced ridges and grooves 2 to 3 cm in width, 1 to 2 cm in depth, and up to 24 cm in length. The long axis of ridges are oriented parallel to the ground surface. Similar ripple marks, formed under varying climate conditions, have been reported by other investigators, Wilford and Wall (1965) in Sarawak, and Jennings (1971) in Australia.

Ripples on nearly vertical and concave limestone surfaces are believed by the author to have formed under free atmospheric conditions and in shallow air-filled cavities in the soil zone where water is allowed to flow uninterrupted down rock surfaces in thin sheets. A free atmospheric origin for ripple formation is indicated by such evidence as thin knife-like edges on ridges separating ripples, uniformity

Figure 1. Ripple marks or scallops formed on a concave surface in the side of a recently exposed pinnacle.

Plate 8.

of ripple sets, and orientation--ripples occur parallel to the ground surface and perpendicular to the downward flow of water. Wilford and Wall (1965) have indicated that the origin of ripples on vertical surfaces under free atmospheric conditions are related to water flowing down the surface in thin sheets during heavy rains. Ripples found in concave limestone surfaces in the shallow soil zone appear to be similar in size and appearance to those found on surfaces exposed to a free atmosphere. Ripples developed in the shallow soil zone are probably formed in a similar manner as those formed in a free atmosphere by thin sheets of water flowing down a limestone surface. This concept is supported by evidence that concave rock surfaces on the Newala Limestone shelter air filled cavities in the shallow soil zone. Free atmospheric conditions capable of producing ripples may occur in such air-filled cavities above the water table.

## Covered Karren

Covered karren are forms created under soil cover. As a result of a more uniform contact of the limestone surface with the soil, these forms are generally more rounded in nature than the other karren types. Solution is very rapid in a subtropical climate such as Dry Valley where ground water is highly charged with biogenic carbon dioxide. Consequently, solution of the limestone is very deep and karren forms are highly developed below the soil zone. Of all the karren forms in the valley, rundkarren are the most numerous and reach the highest degree of development.

Rundkarren (round karren) are grooves and channels cut into the limestone below a soil cover. They are similar in size to rinnenkarren, about 12 to 50 cm in width, 12 to 50 cm in depth, and range in length from a few centimeters to more than 10 meters. The troughs, crests, and sides are rounded and are generally smooth as a result of solution by carbon dioxide-charged water held in nearly continuous contact with the limestone surface. Rundkarren are basically drainage features, their longitudinal profile generally steeper downstream, and their development is normally related to the slope and dip of the rock surface (Williams, 1966). They occur in single forms or integrated networks.

The abundance of rundkarren in Dry Valley can be directly attributed to the fact that most of the limestone in the valley is covered by a soil mantle. Mining activities have uncovered numerous varieties including single forms (Pl. 9, Fig. 1) and integrated networks (Pl. 9, Fig. 2). They occur on nearly horizontal to vertical surfaces. Where troughs cross horizontal surfaces, they often form branching networks resembling the dendritic patterns of surface streams, so that ground water may drain over the surface of the rock and into large scale kluftkarren which normally border the larger limestone blocks.

Frequently parallel sets of runnels form on the vertical sides of large scale kluftkarren where ground water flows off the limestone blocks. These runnels may be relatively short, approximately 1.5 m, as in Plate 3, Figure 2,

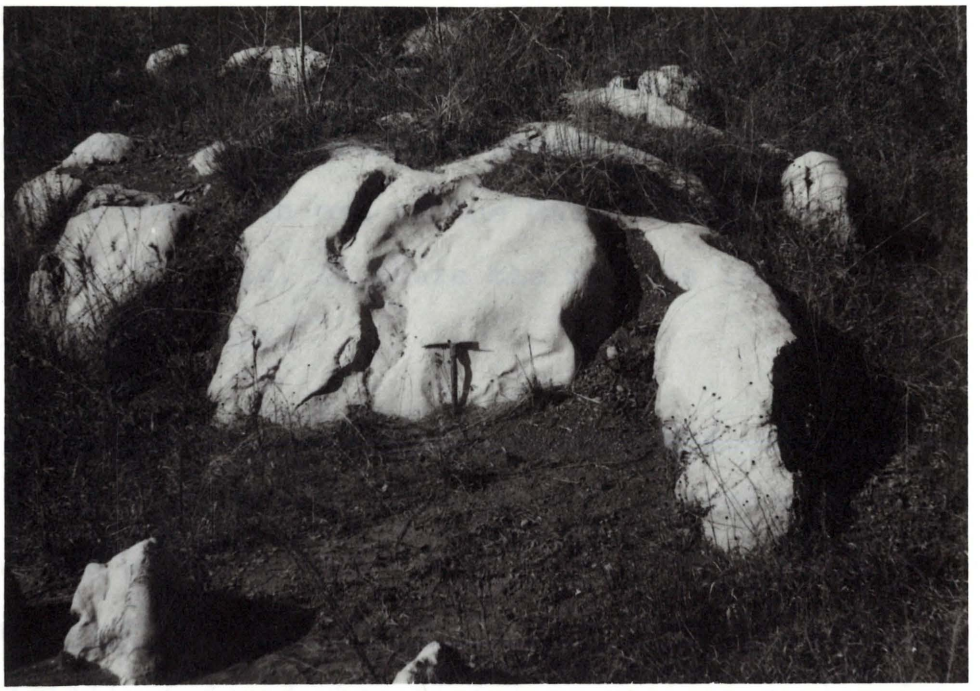


Figure 1. Simple rundkarren developed on a gently sloping limestone block.

Figure 2. Rundkarren forming an integrated network of runnels across a sloping limestone block. The runnels drain into large kluftkarren.

Plate 9.

or they may in rare cases exceed 10 m in length along the walls of deep subsoil kluftkarren. One example of extremely long vertical runnels occurs along a joint face exposed in the north end of the Martin Marietta open pit quarry (Pl. 10, Fig. 1) where the runnels reach a maximum length of 10 meters.

## Complex Karren Forms

Single karren forms may be superimposed one upon another as a result of climatic change or a change in environment. In the study area a change in environment was artificially induced when mining operations stripped away the soil cover and allowed karren formed under a partial or complete soil cover to be directly exposed to a free karren environment. Consequently, free karren forms have begun to develop over semi-free and covered karren forms.

One example of this type of superimposed karren is shown in Plate 10, Figure 2 where rillenkarren have developed over rundkarren. In this example, rundkarren are the shallow almost dish-shaped depressions in the rock surface and rillenkarren are the small grooves radiating toward the center of the depressions. Another example is rillenkarren and regenrinnenkarren superimposed over kluftkarren (Pl. 11, Fig. 1).

In other cases, one karren form may grade into another where cover conditions have been disturbed as shown in Plate 11, Figure 2. In this example, free atmospheric conditions on a sloping limestone block are rapidly converting rundkarren formed under a soil cover into rinnenkarren.

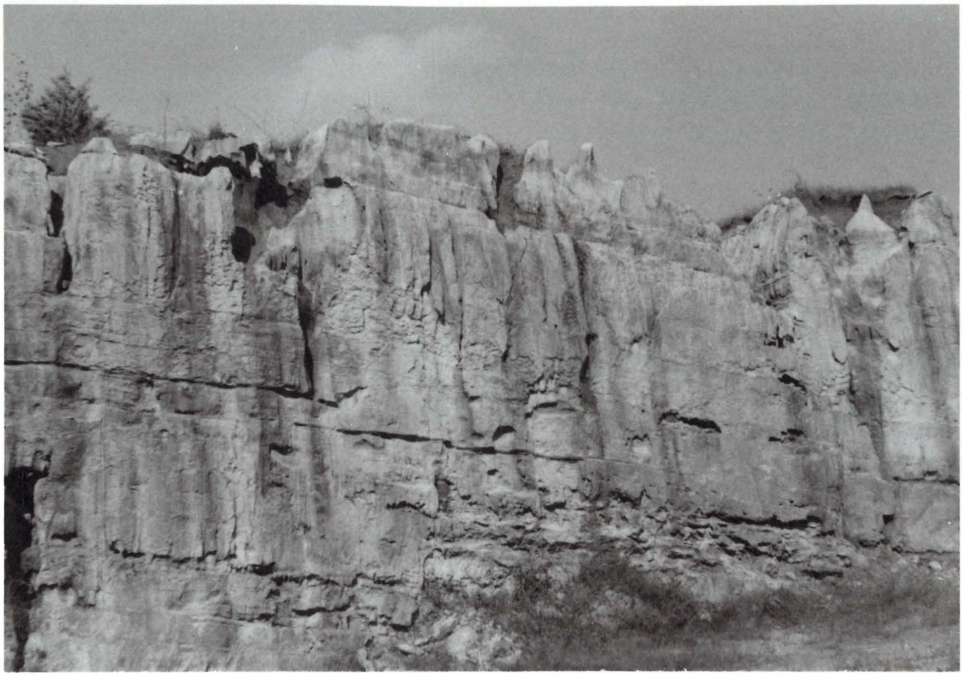


Figure 1. Rundkarren approximately 10 m in length exposed along a joint face in the wall of an open pit quarry.

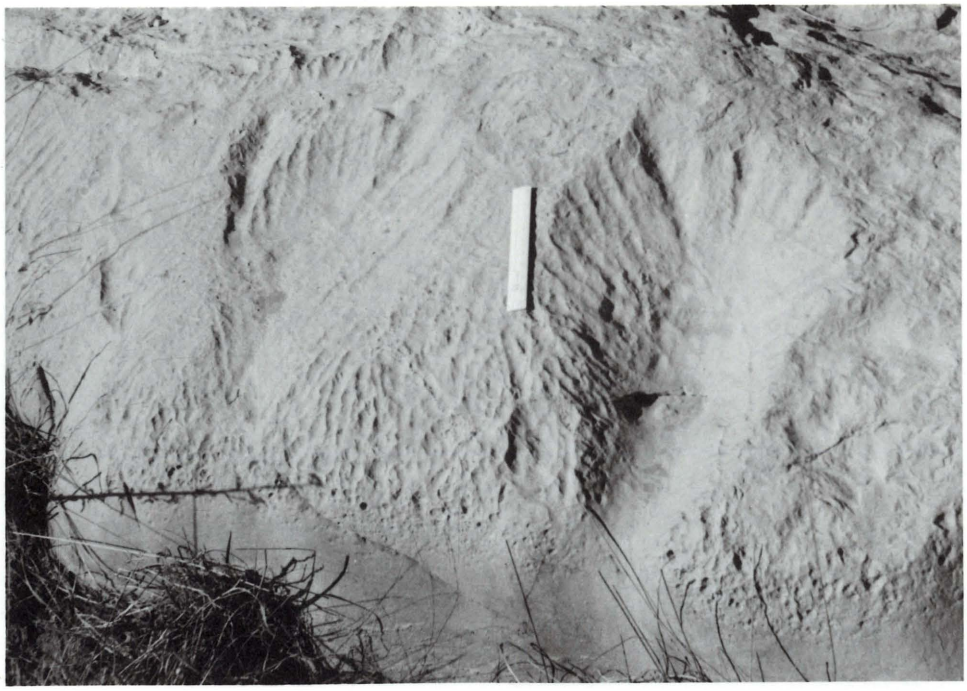


Figure 2. An example of rillenkarren superimposed over rundkarren resulting from a change in soil cover to free air environment.

Plate 10.

Figure 1. An example of rillenkarren and regen-rinnenkarren superimposed over kluftkarren.

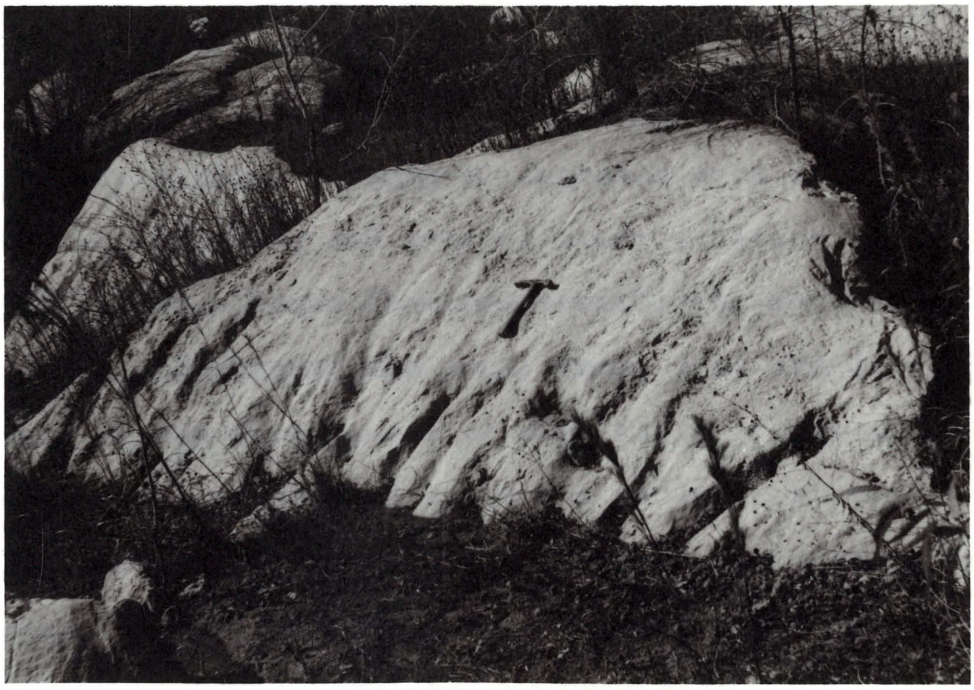


Figure 2. An example of rundkarren being modified into rinnenkarren due to loss of soil cover.

Plate 11.

# FACTORS CONTROLLING KARREN DEVELOPMENT

## Introduction

Factors controlling karren development in Dry Valley are the result of a complex interplay of geologic structure, lithology, stratigraphy, presence or absence of soil cover, climate, local hydrologic conditions, and historical events. These factors determine the nature of the chemical reaction involving the limestone, carbon dioxide, and water; the solution rates; and the nature of the water flow over the limestone surfaces. These chemical and physical parameters are directly responsible for fashioning the various karren forms.

## Geologic Structure

In Dry Valley, structural features such as jointing, fracturing, faulting and folding greatly affect the development of karren. These features control the movement of water over and through the rock; thus, they are directly involved in the development of most karren forms above and below the soil cover. Although the geologic structure is complex throughout the region, certain relationships between structure and karren development are apparent.

### Joints and Fractures

The Newala limestone is a dense, massively bedded limestone that has been highly fractured and jointed. Both

large and small scale systematic and small scale non-systematic joints abound in the area. The large scale systematic joints may be as long as several hundred meters, as indicated by aerial photography, and they may penetrate the limestone to depths greater than 122 m, as evidenced by clay filled joints in the lower reaches of an underground mine owned by Martin Marietta. Small scale jointing and fracturing are so intense within individual beds at some locations that the limestone may be best described as a cemented breccia.

The most significant parameters of jointing and fracturing affecting karren development are direction, frequency and magnitude. These parameters combine to determine the surface area and shape of limestone blocks and pinnacles. The surface area is a limiting factor on the size and type of karren. Blocks or pinnacles with a small surface of only a few square meters may exclude completely the development of medium to large scale karren forms, while a large surface of several hundred square meters may host complex groups of karren forms including large scale features. Also, the shape of pinnacles and blocks control the flow of water over the limestone surface; thus, shape is an essential element in determining the karren form produced on a given surface (Bögli, 1960).

Joints and fractures are planes of weakness in the dense and impermeable Newala Limestone. Open joints and fractures provide avenues for water to enter the limestone and, in

doing so, the joints and fractures become enlarged by solution (Pl. 4, Fig. 1). Under free karren conditions, filled or cemented joints and fractures tend to weather faster than the dense fine-grained limestone and often form grooves and furrows (Pl. 4, Fig. 2). The filled or cemented joints and fractures apparently cause an irregularity on the limestone surface that tends to channel the flow of runoff water along the joint. More limestone is dissolved because of the increased volume of carbon dioxide-charged water and channel flow along the joint; thus, furrows and grooves may be cut into the rock.

The development of large and small kluftkarren is directly influenced by the direction, frequency, and magnitude of jointing. The large systematic joints in Dry Valley produce wedge-shaped kluftkarren that may exceed 2 to 3 m in width at the top and slowly taper downward to depths as great as 30 meters. Kluftkarren of this magnitude appear to be directly related to location within the Dry Creek drainage basin. The largest and deepest occur in the lower reaches of the drainage basin near the Martin Marietta quarry. Along the drainage divides of the basin in the vicinity of the Vulcan Materials quarry and the Allied Products quarry, large kluftkarren are shallower and less developed.

Ground water volume and transit time are two major factors that determine the amount of limestone which can be

removed in a given area. Therefore, the magnitude of kluft-karren development can be explained in part by the volume of ground water flowing through the limestone and ground water transit time at these locations.

In the south central part of Dry Valley the volume of ground water moving through the Newala is much greater than at the other two locations, the Vulcan Materials quarry and the Allied Products quarry, both of which are located near drainage divides. A stream flow study conducted by the Geological Survey of Alabama on Dry Creek and its tributaries in Dry Valley (Warren, Hays, and Moravec, 1973, open file report) gives an indication of the volume of ground water at various locations in the valley through the contribution of ground water discharge into surface streams by quarry operations. The study was conducted in October during the period of low stream flow for the year so that the only contribution to stream flow was from natural base flow or discharge from quarry dewatering operations (ground water). The stream reach study revealed that the only water flowing in Dry Creek, approximately 30 cubic feet per second, was immediately below the discharge ditch from the Martin Marietta quarry. No discharge was evident from the other two quarries, Vulcan Materials and Allied Products.

The large discharge of ground water from the Martin Marietta quarry in south central part of the valley can be directly attributed to location with Dry Valley. At this

location the quarry intercepts most of the ground water flow from about 80 percent of the drainage basin. The other two quarries are located near the drainage basin divides. At these locations they intercept only a fraction of the total volume of ground water moving through the valley.

Ground water transit times prior to quarry development should have been longer in the south central part of the valley where gradients are low and ground water movement slow. Along the drainage divides gradients are much higher; consequently, much rain drains from the area as runoff, and ground water movement is much faster.

Because of the greater volume of ground water moving through the south central part of the valley and longer ground water transit time, a greater volume of limestone has been removed by solution; as a result, development of large kluftkarren and other covered karren forms have been enhanced at this location.

The direction of large kluftkarren development appears to be a function of both structure and local hydrologic conditions. Bearings of all visible bedrock fractures taken during a foundation study by Dames and Moore in 1973 at the northeast end of the Martin Marietta quarry indicated that the predominant joint direction is N. 75$^{\circ}$ E. and N. 05$^{\circ}$ E. as is shown in Figure 4 (Bagnall and Luster, 1974). However, bearings taken on 140 solutionally enlarged joints from around the entire perimeter of the quarry by the author indicate that the main trend is clustered around N. 85$^{\circ}$ E.

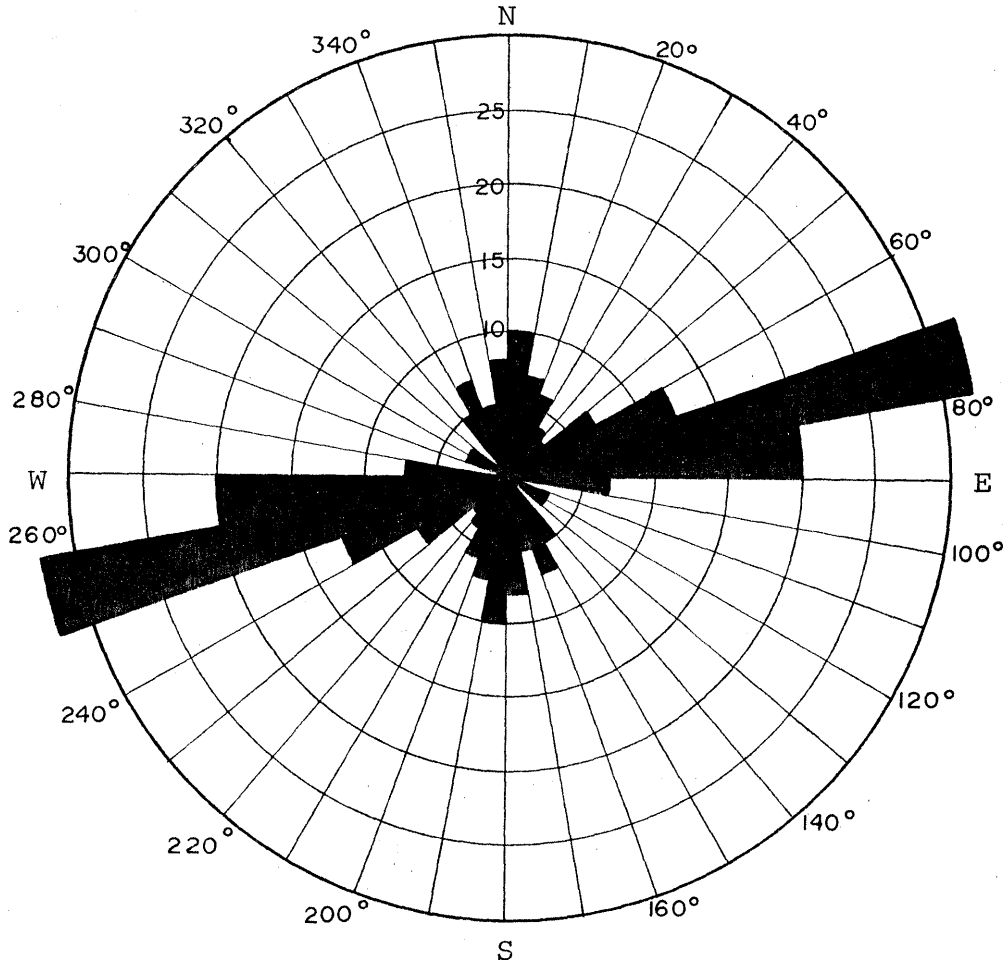



Figure 4. Orientation of all visible bedrock fractures, north end of quarry, Martin Marietta Cement Roberta Plant (adapted from Bagnall and Luster, 1974).

with minor trends bearing N. 15° W. and N. 65° W. (Fig. 5). Therefore, the direction for most solutionally enlarged joints (kluftkarren) is approximately east-west at this location.

A similar direction of solutionally enlarged joints exists in the Allied Products quarry approximately one mile south of the Martin Marietta quarry. At this location, bearings taken on 42 solutionally enlarged joints indicate a strong east-west trend with minor trends bearing N. 20° W., N. 25° E., and N. 45° E. (Fig. 5). The pronounced similarity of the bearings of solutionally enlarged joints at the two quarry locations indicates a local trend.

Additional evidence to support the conclusion that the preferential solution enlargement of east-west joints is a local trend limited to the south end and central part of Dry Valley can be found by examining solution enlargement of joints in the Vulcan Materials quarry at the north end of the valley. At this location, bearing measurements taken on solutionally enlarged joints show a noticeable change in the trend. A strong nearly east-west trend bearing N. 85° W. is still present, but the greatest development is on a bearing N. 05° W. Examination of the rose diagram for the Vulcan Materials quarry (Fig. 5) shows that solution enlargement is more evenly divided between the joint directions of the major joint set.

Local hydrologic conditions may be responsible for the preferential direction of large kluftkarren development near

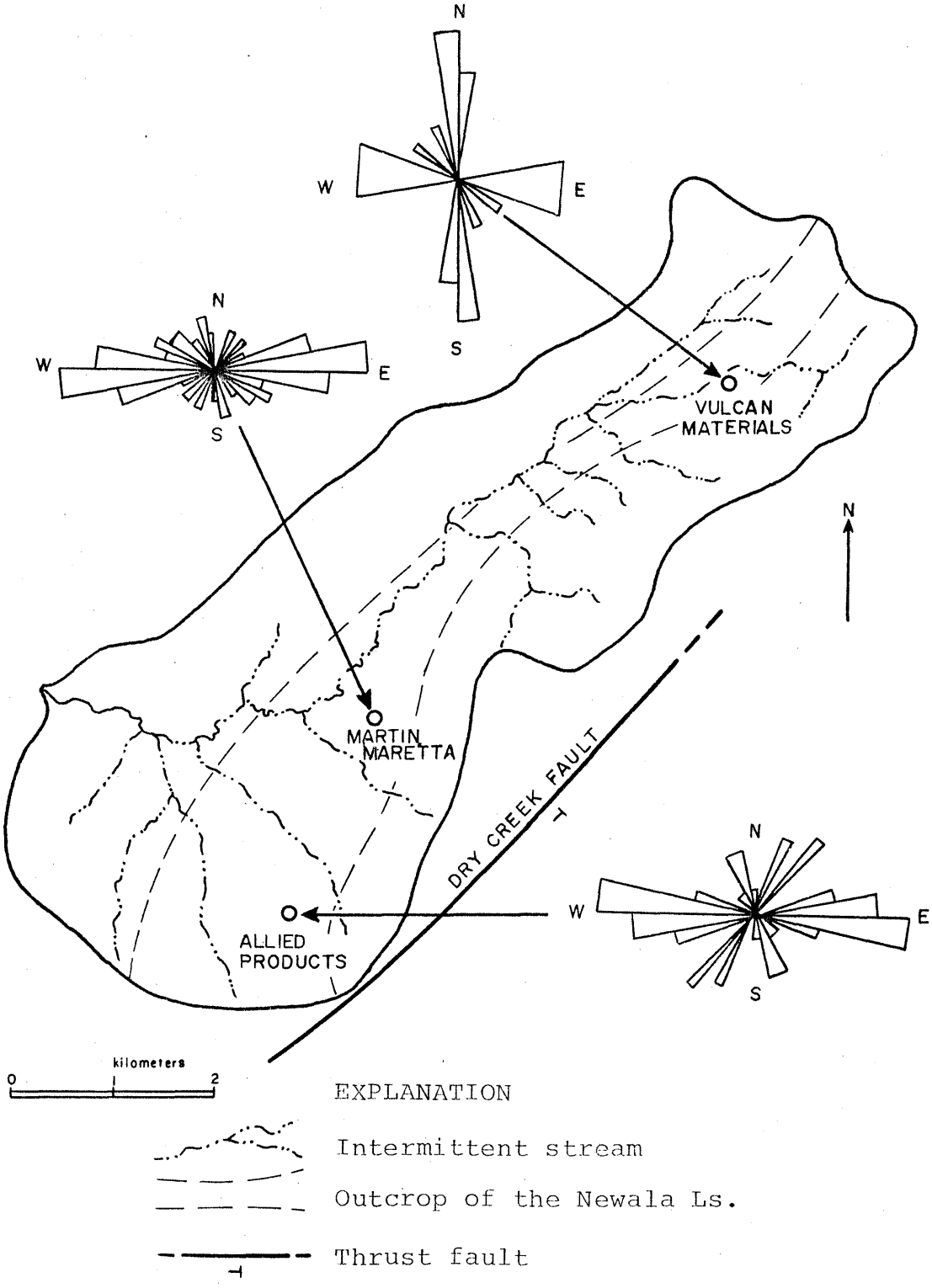



Figure 5. Hydrologic map showing relationships among Dry Creek fault, stream direction and large kluftkarren orientation.

the southwest end of Dry Valley. In this area the direction of surface water drainage is to the west along Dry Creek and exits the valley through a water gap (Fig. 5). The sudden shift in the direction of surface water flow from down the axis of the valley to the west is due to a ridge created by Dry Creek fault across the south end of the valley. Dry Creek fault is a high angle reverse fault striking northeast-southwest. The fault cuts and offsets part of the outcropping Newala and may act as a barrier to ground water flow as well as surface flow. If ground water flow is deflected to the west as is surface flow, then the east-west joint trend would receive the greatest amount of ground water flow; consequently, this joint direction would be preferentially enlarged. The general lack of deep solution development in the Allied Products quarry near the fault indicates that ground water flow has been deflected.

Hamilton (1958) in describing solutional features of limestones in Kentucky found that a process of directional development of solutionally enlarged joints does exist. "In areas where the two sets of joints trend perpendicular, respectively, to a valley, the perpendicular set was greatly developed by solution. This is due to the movement of water from topographic high toward topographic low" (Hamilton, 1958, p. 46). He also found that where two sets of joints intersect a valley in a diagonal pattern, the joints will be solutionally developed in a herringbone pattern pointing

down stream. In effect, Hamilton has demonstrated that local hydrologic conditions play a major role in determining the direction of solutionally enlarged joints. Local hydrologic conditions appear to be a major factor in determining the direction of solutionally enlarged joints in Dry Valley particularly in the vicinity of the Martin Marietta quarry where large volumes of ground water pass through the valley, and the direction of ground water flow may be predicted to a limited extent through geologic structure and surface gradients.

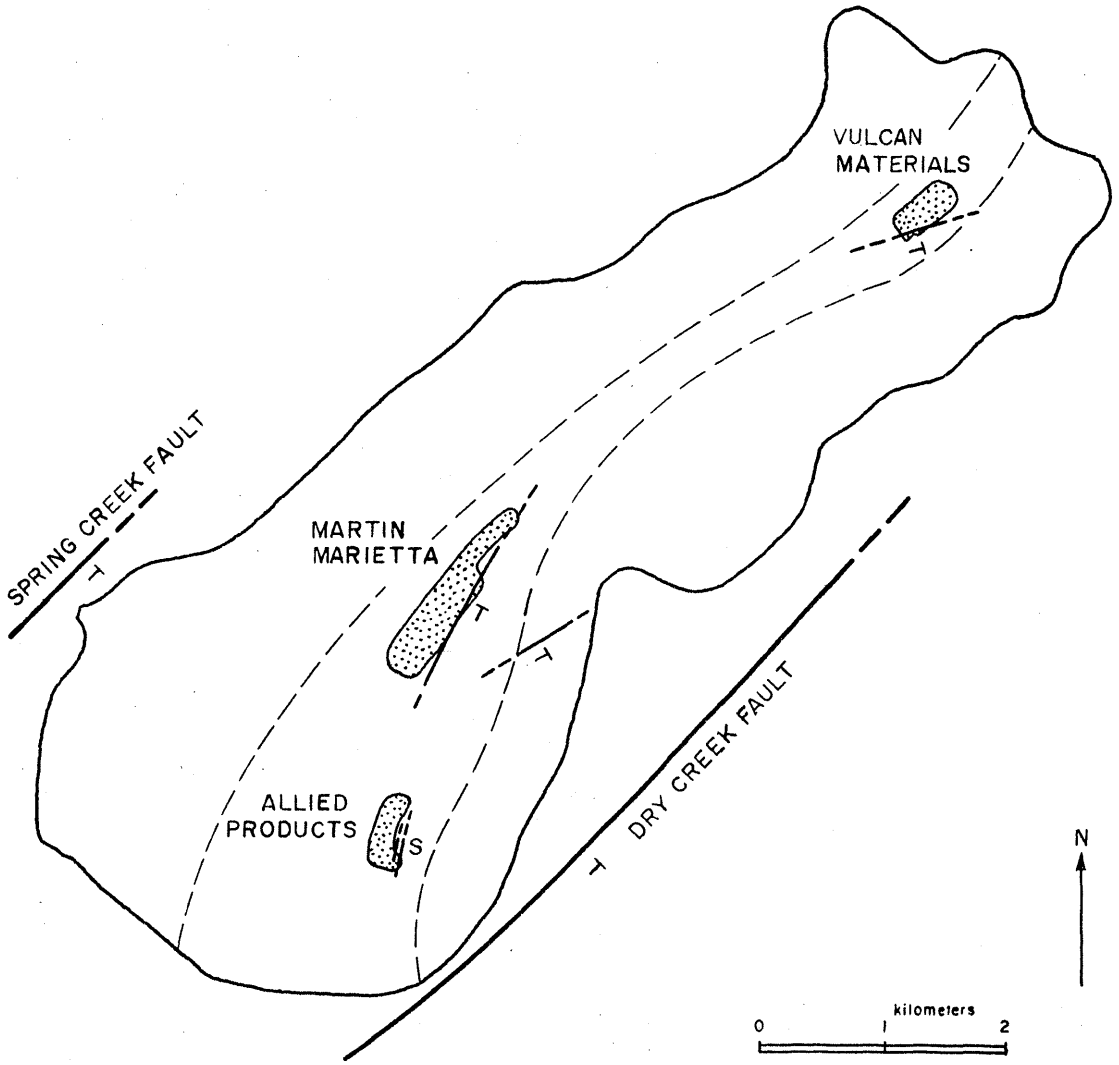
Small systematic and non-systematic joints occur in profusion throughout the Newala Limestone. In some areas joints are separated by only centimeters as shown in Plate 4, Figure 2, and Plate 6, Figure 2. Within the study area, small joints and fractures have been filled by sparry calcite and to a lesser extent barite, flourite and other minerals to form an intricate system of veins throughout the rock. These veins may weather in positive or negative relief depending on the slope of the rock surface and whether or not the rock is covered by soil. Below the soil zone veins are commonly in positive relief, and may form box work structures on the limestone breccias. On bare rock where veins are exposed to direct precipitation or channel flow, they produce negative relief (Pl. 4, Fig. 2, and Pl. 6, Fig. 2). Where veins have weathered into negative relief, small kluftkarren are formed.

## Faults

Faults may affect the local development of karren forms by controlling ground water movement through the nature and degree of rock fracture. In Dry Valley a number of previously unmapped faults (Fig. 6) were evaluated for their effects on karren development. A high and a low angle thrust fault and several strike-slip faults were included in the evaluation. These faults were exposed in open pit quarries at various locations in the valley.

The high angle thrust fault located along the southeast wall of the Martin Marietta open pit quarry and several minor strike-slip faults located on the southeast wall of the Allied Products open pit quarry have had little effect on karren development. Fracturing has been limited to a very narrow zone less than a few meters wide on either side of the fault planes. The fault planes are very tight and little obvious solution has taken place along them. On the other hand, a low angle thrust fault cutting through the southeast corner of the Vulcan Materials quarry has had a pronounced local effect on karren development. At the point where the fault plane intersects the land surface a deep zone of weathering occurs which produces a bedrock depression and a thicker soil cover. Karren are limited to those forms developed under a soil cover, namely, rundkarren and kluftkarren.

The fault trends N. 70$^{\circ}$ E. and dips to the southeast at an angle of about 22$^{\circ}$ sub-parallel to the limestone beds.




EXPLANATION

Open pit quarry

Outcrop of the Newala Ls.

Thrust fault

Strike-slip fault

Figure 6. Map of Dry Valley giving location of previously unmapped faults

There is little surface expression of the fault because the limestone bedrock surface has been reduced below the valley floor and lies beneath a uniform soil cover. However, in the subsurface this fault has produced a complex structure of folds, and deep solution cavities along joint, fault, and bedding planes (Fig. 7).

A wide fracture zone exists on either side of the fault plane approximately 100 m in width. Fracturing and jointing appear to be most intense in the over thrust block. Ground water circulation in the intensely fractured and jointed limestone has produced a deeply weathered zone that has reduced the bedrock surface to form a bedrock depression. At depth within the zone, free circulating ground water has created numerous large solution cavities along joints, fault planes and bedding planes. The largest cavity is estimated to be 3 m by 5 m in cross section and has developed within 10 m of the bedrock surface.

The primary effect that the low angle thrust fault has had on karren development is to produce a bedrock depression along the fault zone where the fault plane intersects the bedrock surface. The resulting depression lies below the valley floor and is filled with a thick soil accumulation. Consequently, only covered karren forms have developed on the limestone bedrock surface in the depression.

## Slope

The slope of the limestone surface affects the nature of the karren which will form by influencing the nature of

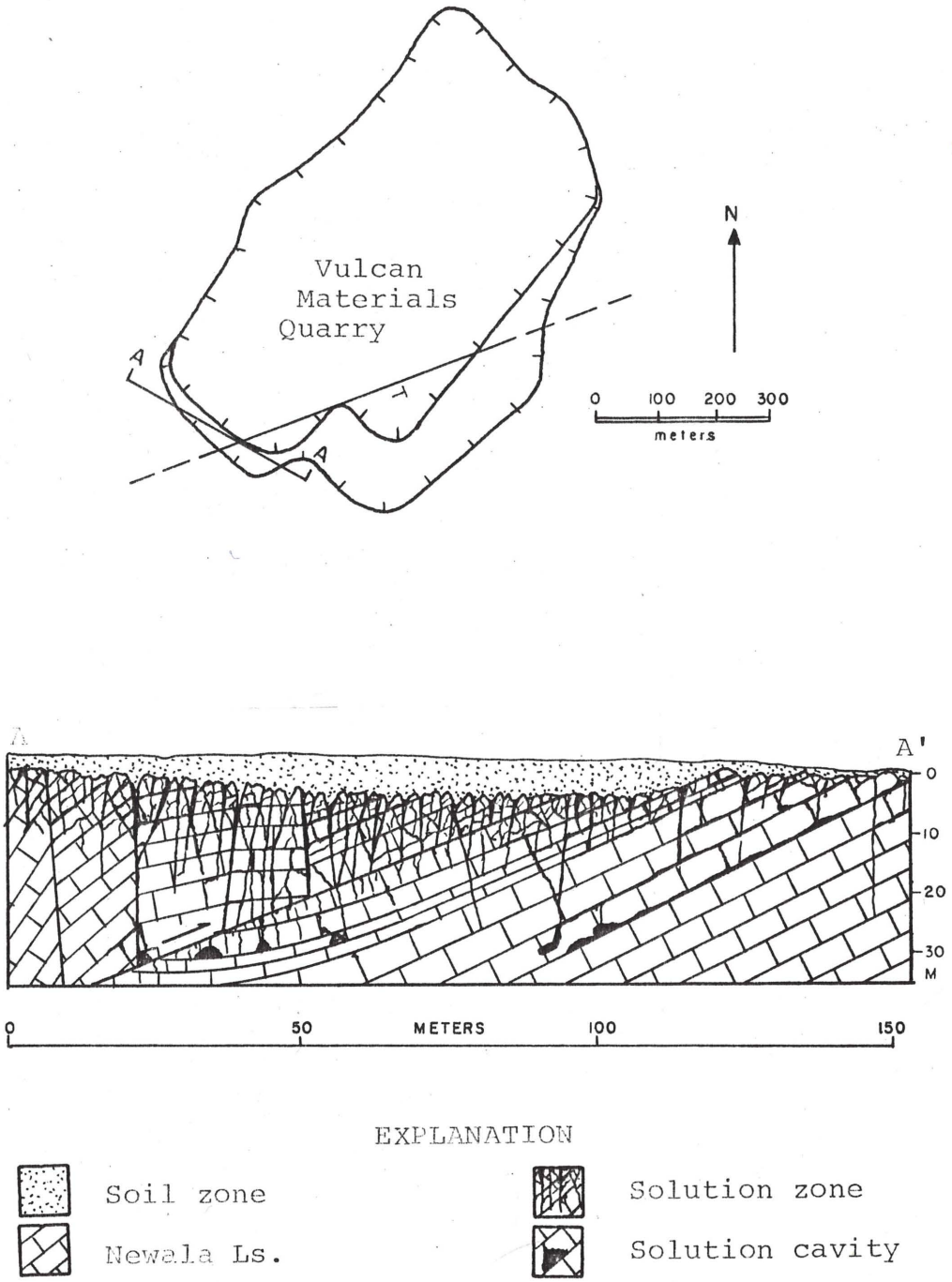



Figure 7. Cross section of a low angle thrust fault in the Vulcan Materials Company limestone quarry indicating effects of faulting upon karren development.

water flow over the rock surfaces. Many investigators have reported the effects of slope on karren development (Smith and Albritton, 1941; Bögli, 1960; Williams, 1966; Sweeting, 1972; and Jennings, 1971). In Dry Valley the following relationships between slope and karren development have been observed by the author. Where rock surfaces are very steep to vertical, water becomes channeled producing straight, parallel furrows such as wandkarren. As the slope decreases, other karren forms are enhanced. At angles between $40^{\circ}$ to $80^{\circ}$, rillenkarren are best developed while on more moderate slopes rinnenkarren are more characteristic. On moderately gentle slopes channels of water begin to wander over the rock's surface and meanderkarren develop. Where slopes are nearly horizontal, pools of water may collect and remain for long periods of time and kamenitza are produced.

Under a soil cover, the slope of the rock surface has less effect because soil may hold water in contact with the rock even on very steep slopes. However, in very porous soils the effects of slope on gravity drainage are very pronounced as in the sloping troughs of rundkarren (Pl. 9, Fig. 2). On the limestone block shown in the preceding figure, troughs maintain a gentle slope across the block surface until intersecting an open joint then the gradient of the trough increases rapidly.

In Dry Valley, beds of the Newala Limestone dip at angles from $15^{\circ}$ to $25^{\circ}$ to the southeast. However, the slope

of surfaces on outcropping limestone blocks and pinnacles may vary from near horizontal on crests to vertical along solutionally enlarged joints. Concave surfaces occur on limestone blocks and pinnacles where they have been undercut by bedding plane cavities, kluftkarren and korrosionskehlen. Therefore, a full range of slope angles can be found in the study area above or below the soil zone, and any karren form may develop provided the other necessary conditions are present.

## Lithology and Stratigraphy

Karren occur on limestone of all ages, but the degree of development and type of karren may be affected by the nature of the limestone. Very little is known about the effects of lithology on the development of karren. Some generalizations have been made based on field observations and limited field experiments (Sweeting, 1972), but few controlled experiments have been attempted.

The development of karren is affected by certain lithologic characteristics. Cvijič (1924) has stressed the importance of limestone purity and thickness of bedding. Other investigators also have reputed certain effects of lithology on karren development (Sweeting, 1972; Jennings, 1971; Williams, 1967; Bögli, 1960; and Pluhar and Ford, 1970). Table 2 is a summary of some of the most important lithologic characteristics and their effect on karren development.

Table 2.--Summary of important lithologic characteristics for the development of karren.

| Lithologic characteristic | Description | Karren development | Remarks |
|---|---|---|---|
| Crystal or grain size | Coarse | Good | Produces granular surfaces, rounded crest and troughs. |
| | Fine | Excellent | Produces smooth surfaces, sharp fine crest and rounded troughs. |
| Composition | Limestone: Pure | Excellent | May develop most karren forms. |
| | Limestone: Impure | Poor | Increasing percentages of impurities affect the nature and development of karren forms, produce more rounded edges or ribs and less distinct forms. |
| | Limestone: Dolomitic | Poor | May produce irregular rough surfaces. |
| | Dolomitic | Poor | May produce many karren forms, but limit karren development when interbedded with limestones. |
| Porosity (density) | High | Poor | Highly porous limestones adsorb precipitation and reduce surface water flow essential for karren development. |
| | Low | Excellent | Produces maximum runoff on surface water flow. |
| Strength | High | Excellent | Produces fine edges and sharp karren features. Crumbles easily producing indistinct or rounded karren. |
| Bedding thickness | Massive | Excellent | May produce large scale karren. |
| | Thick | Good | May produce medium to large scale karren. |
| | Thin | Fair | Generally produce small karren forms or if very thin, the limestone may crumble easily. |

The Newala Limestone possesses many of the best lithological characteristics necessary to produce karren. The limestone is fine-grained, dense, strong, massively bedded, and chemically pure. Fine-grained limestones weather to produce characteristically smooth surfaces and sharp intricate karren such as rillenkarren. Density, strength, and thickness of bedding are physical properties of the rock necessary for karren to form and to resist destruction once formed. Pure limestones (high percentage of calcium carbonate) produce better karren than impure limestones, because impurities such as high percentage of clay render the rock weak and friable thus incapable of producing karren.

The favorable lithological properties of the Newala enhance karren development so that karren are abundant and diverse. However, where beds of dolomite occur over beds of limestone, the development of karren is restricted. Dolomite is more resistant to corrosion by carbon dioxide-charged water (Holt, 1948; Murray, 1960), and, as a result, dolomite often forms a resistant cap rock essentially devoid of karren features (Pl. 12, Fig. 1). Beds of dolomite tend to shelter the limestone beds from precipitation and thus retard the formation of karren. In Dry Valley dolomites exhibit few karren. However, Pluhar and Ford (1970) have described many karren forms on the dolomite pavements exposed along the crest of the Niagara Escarpment, Ontario, Canada. A striking feature of the dolomite karren is that they are nearly all rock controlled forms developing in

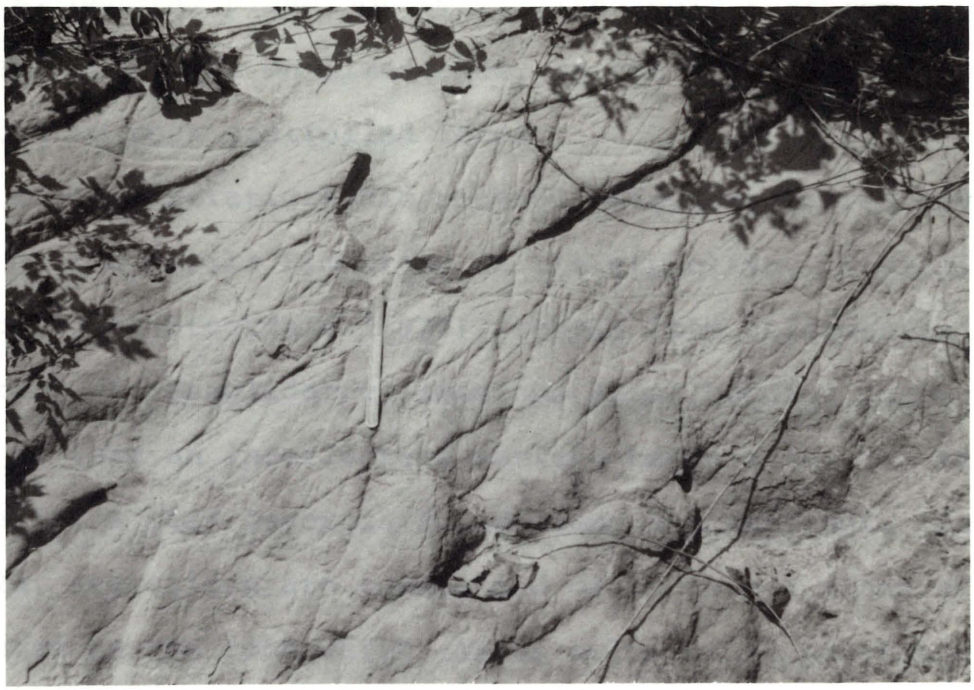


Figure 1. Dolomite rock surface demonstrating typical degree of karren development on dolomite in Dry Valley.

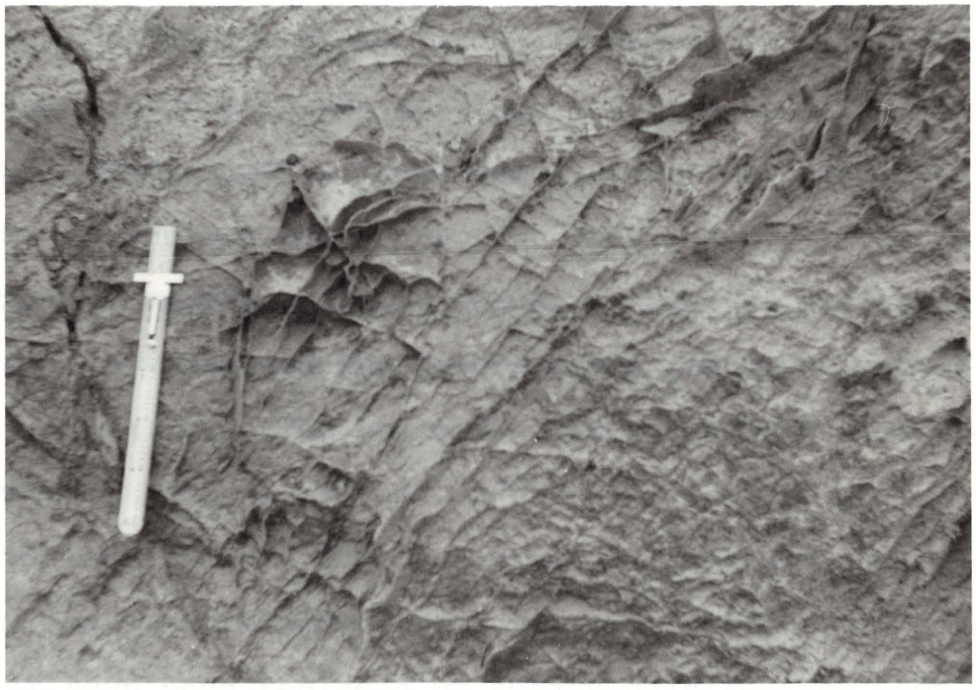


Figure 2. Typical box work structures formed by differential solution of sparry calcite veins and micritic limestone under soil cover.

Plate 12.

joints, bedding planes or small lithologic features. Development of karren on limestones, on the other hand, is not limited to rock controlled forms.

Another stratigraphic control affecting karren development on the Newala Limestone is the stylolite. Stylolites, according to Stockdale (1926), result from differential solution of consolidated limestone along bedding plane partings to form an interlocking surface between the two sides. Normally, a clay layer is found along the partings. In the Newala, stylolites are common and often form a plane of weakness in the rock which allows solution to penetrate the limestone. Consequently, stylolites may be responsible for the development of horizontal grooves and depressions along the walls of kluftkarren and the sides of pinnacles.

In addition to those karren forms previously mentioned, the Newala produces some solution features which are almost entirely controlled by lithologic variations. One such feature is the box work structure produced by differential solution of sparry calcite, dolomite, barite, and other minerals in veins and the fine-grained limestone matrix (Pl. 12, Fig. 2). The box work structures form where beds of cemented breccia weather under a soil cover. In a covered environment, the fine-grained limestone dissolves faster leaving the sparry calcite vein in relief. Where fossils have been replaced by sparry calcite they, too, are left in relief. Above the soil zone, veins of sparry

calcite exposed to free atmospheric conditions weather faster than the fined-grained limestone producing negative relief. Veins are exposed to mechanical weathering in the form of freeze-thaw and cavitation during heavy rain. In addition, veins cause an irregularity on the rock surface which tend to channel runoff flow and increase solution; thus, veins exposed to the free atmosphere generally weather in negative relief.

Another solution feature results from the differential solution of small rounded irregular masses of dolomite, possibly filled worm tubes, and the fine-grained limestone of the mottled limestone facies of the Newala Limestone. This feature can be found above and below the soil zone where the dolomite is generally removed faster than the fine-grained limestone giving the rock surface a pitted or worm-eaten appearance. Microscopic examination by the author of two cores taken of the mottled limestone has shown that the dolomite patches contain significant porosity whereas the fine-grained limestone contains very little. Because of the greater porosity, the dolomite is more likely to weather faster than the limestone when exposed to free circulating water.

## Soil Cover and Biological Processes

The importance of soil in the weathering of limestone has long been recognized (Holt, 1948; Wilford and Wall, 1965; Bögli, 1960; and Douglas, 1968). In the soil, carbon

dioxide is constantly being given off through the respiration of all living organisms and through the decay of humus. Rainwater percolating from the surface through the soil is greatly enriched by the carbon dioxide in the soil atmosphere and becomes more acidic than surface water.

Humidity and temperature of soil are important factors for formation and retention of carbon dioxide. If the soil is wet, microbiological activity is increased and the waterlogging of the soil enhances the retention of carbon dioxide. Douglas (1968) has suggested that the availability of water and the warm temperatures of wet tropical areas increase biological activity and, consequently, the production of carbon dioxide. Bögli (1960, p. 8), makes a similar statement, "Humus of higher acidity and aggressiveness occur in humid tropical and subtropical areas rather than in cold climatic regions because of a higher production rate and decay of organic matter in the former."

According to Bögli (1960, p. 8), the soil air contains from 10 to 100 times as much carbon dioxide as the free atmosphere due to respiration from plant roots and to decaying humus. Ground water enriched by biogenic carbon dioxide completely dissolves all available calcium carbonate in the soil and attacks the bedrock beginning at the soil-free atmosphere contact. This contact is often marked by korrosionskehlen, horizontal grooves or undercuts on the sides of pinnacles and blocks. Korrosionskehlen result from the

differences in solution rates between the free atmosphere and soil atmosphere, and the continual presence of water in the soil zone. Below the soil zone karren forms are very rounded in nature due to the continuous soil moisture contact with the rock, and rundkarren are the characteristic karren forms.

In Dry Valley, the Newala Limestone is covered by a soil-humus mantle with the exception of a few isolated pinnacles. The soil is dark brown to reddish brown in color and consists primarily of clay and humus material. The clay is probably in part a residual weathering product of the limestone and can be found filling most near surface solution cavities. The soil has a very low permeability; therefore, a high soil moisture level is maintained which promotes an almost continuously high rate of biogenic carbon dioxide production.

Because of the continuous soil cover, the low permeability, and the supposedly high carbon dioxide level in the soil environment, the Newala weathers rapidly below the soil zone to produce predominantly rounded karren forms, mainly rundkarren and kluftkarren. Korrosionskehlen are common solution features on pinnacles that penetrate the soil cover. Because of the common occurrence and high degree of development of korrosionskehlen, the solution of limestone in the soil zone appears to be much greater than in the free atmosphere.

## Local Hydrologic Conditions

Local hydrologic conditions in the valley and in the limestone have played an important role in karren development on the Newala. They are largely responsible for soil moisture conditions, the time that ground water is in contact with the limestone, and the movement of ground water over and through the limestone. The hydrology of the valley is very complex and may vary considerably within a short distance; therefore, the effects of hydrologic conditions on karren development can only be evaluated for a small area.

In Dry Valley streams are intermittent, and drainage of the basin is through a system of subterranean cavities in a manner somewhat resembling a free flow aquifer described by W. B. White (1960). Evidence, such as deep kluftkarren, karrenröhen (lapiés wells), extensive bedding plane solution, and solution cavities along joints, examined in quarry walls indicate that a highly integrated subsurface drainage system exists (Pl. 13, Fig. 1).

Water enters the system through large kluftkarren, karrenröhen, and along outcropping anastomosed bedding plane cavities. The general direction of ground water movement appears to be along the strike of the limestone beds in master conduits. The master conduits are large solution cavities which may be as much as 5 m across their greatest dimension. Ground water movement is restricted in some

parts of the study area by residual clay which fills many of the cavities and solutionally enlarged joints. Wet or swampy areas on the ground surface may be indicative of such conditions.

There is ample evidence, such as solution features exposed in quarry walls, that shallow water table conditions have existed, at least locally, in the Newala Limestone. For example, at one location in the Martin Marietta quarry, vertical and horizontal solution features along an exposed joint indicate that a water table probably existed at a level of 10 to 15 m below land surface. Along the joint face (Pl. 13, Fig. 1), kluftkarren and karrenröhen drop vertically 12 to 13 m before intersecting nearly horizontal bedding plane and joint controlled cavities. A water table probably occurred at a level where the first significant horizontal solution cavities developed, because, according to LeGrand and Stringfield (1971, p. 1284), "The circulation of water and solution activity tend to be greatest in the upper part of the zone of saturation and tend to lessen with depth." In other words, the greatest amount of solution development occurs at or near the water table. In addition, Holt (1948, p. 17) has stated, "If joints are continuous to the water table, little more than widening of the crack can be expected." Therefore, solution development should be primarily vertical in nature above the water table and have a greater horizontal development at or below the water table.

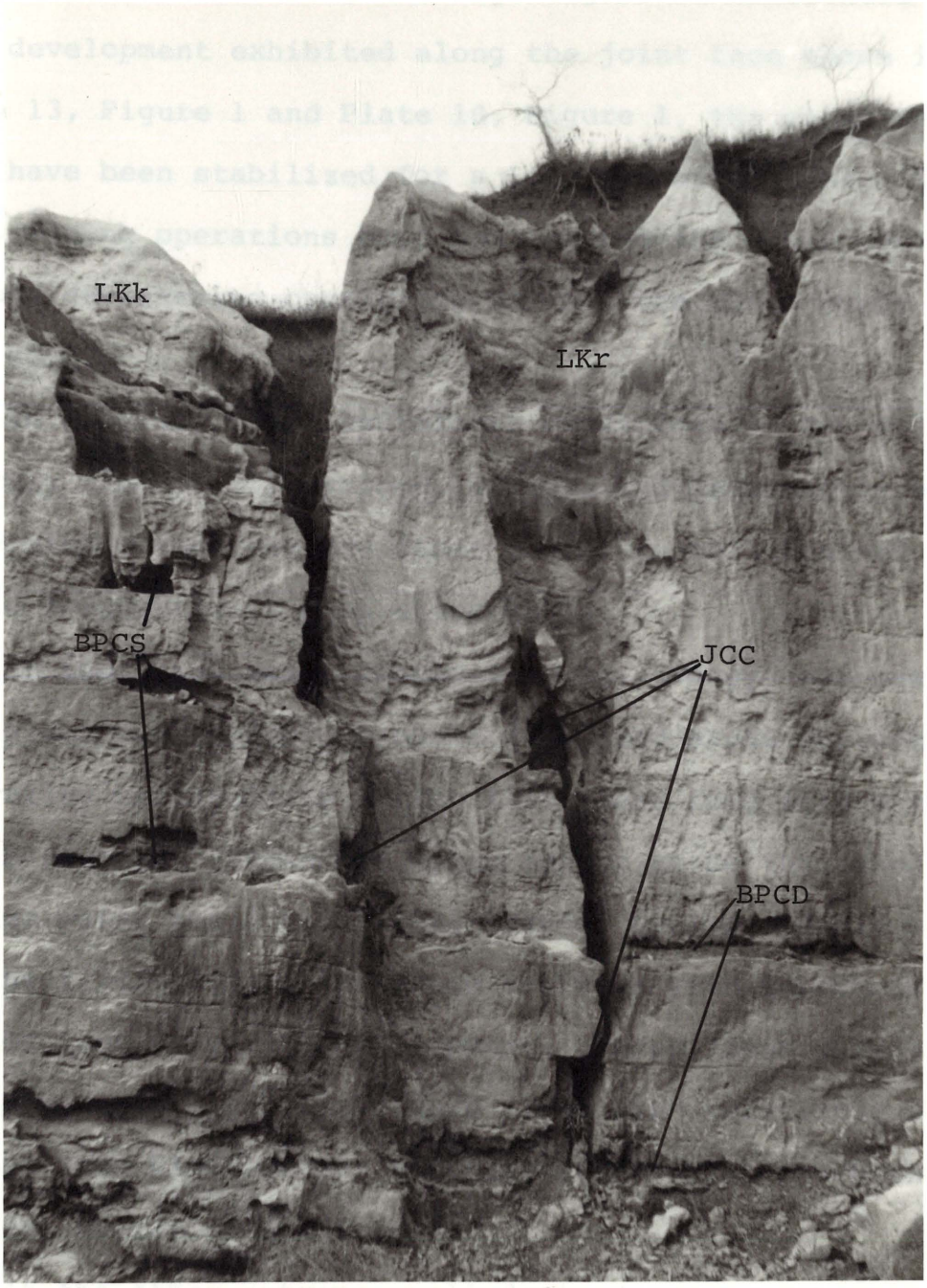



Figure 1. Solution development along joint face showing a highly integrated system of subsurface drainage.

Code: BPCS, Bedding Plane Cavity Strike; BPCD, Bedding Plane Czvity Dip; JCC, Joint Controlled Cavity; LKk, Large Kluftkarren; LKr, Large Karrenröhen.

Plate 13.

In order to achieve the high degree of horizontal solution development exhibited along the joint face shown in Plate 13, Figure 1 and Plate 10, Figure 1, the water table must have been stabilized for a long period of time. However, mining operations have now lowered the water table through de-watering operations so that the water table is very deep.

In general, local hydrologic conditions in Dry Valley may vary from poorly drained, swampy, and permanently wet areas with a very shallow water table, to well drained areas with a comparatively deep water table.

In the first case, poorly drained, swampy, and permanently wet areas occur in small localized areas throughout the valley particularly in low flat areas long intermittent stream courses. These wet areas appear to be the result of perched water table conditions created by impermeable soils and the filling of subterranean cavities with impermeable clay or lack of cavity development. Under these conditions, rundkarren are highly developed along with relatively shallow but wide kluftkarren, and korrosionskehlen reach their greatest degree of development.

At the other extreme, well drained areas with fairly deep water tables cover a large percentage of the valley. Although these conditions produce extensive rundkarren, kluftkarren achieve their maximum development in these areas. As previously mentioned, large kluftkarren are particularly

well developed in the lower end of the valley where the volume of ground water moving through the valley is very large. The degree and direction of large kluftkarren appear to have a direct relationship to the volume and direction of ground water movement in the valley. Hamilton (1948) has described similar joint enlargement with preferred orientations in limestone valleys near Lexington, Kentucky. Large kluftkarren in Dry Valley appear to have developed in much the same manner as joint enlargement in Kentucky.

Vertical runnels similar to wandkarren develop on the walls of large kluftkarren where the water table is deep. Wilford and Wall (1965) have described similar features in Sarawak and attribute their origin to ground water flow down the interface between the limestone and soil fill. Most kluftkarren examined in quarries throughout Dry Valley are filled with a clay that has little permeability; therefore, a similar origin of the vertical grooves is indicated.

## Climate

Climate is important to karren development because of the effects of precipitation, and temperature on the limestone solution processes. Variations in precipitation and temperature result in variations of the rate of limestone solution and the volume of limestone removed. Climate effects on biogenic processes, cover and the flow of water over bare limestone surfaces may enhance or retard the development of various karren forms. Although climatic factors

may affect the solution of limestone, the basic chemical and physical processes do not change from climate to climate, so that corresponding karren forms may be found in different climatic regions with the exception of a few karren forms caused by unique climate related features such as glaciers.

Temperature not only affects the reaction rate of limestone solution, but the solubility of limestone. While the reaction rate of limestone and carbon dioxide-charged water may double with an increase of about $10^{\circ}$ C, the solubility of limestone in water decreases with increased temperature. The effects of the two processes tend to cancel each other depending upon the time that the water is in contact with the limestone. Temperature may indirectly affect limestone solution in tropical climates by promoting the rapid production of biogenic carbon dioxide within the soil cover.

Precipitation is essential for the development of karren, not only because karren are created by the solution of limestone through carbon dioxide-charged water, but because precipitation also affects the nature of the water flow over limestone surfaces. In desert regions karren development is severely restricted because channeling caused by water flow and normally associated with karren may be absent. However, in arid climates with as little as 24 cm of annual precipitation, karren have been identified (Smith and Albritton, 1941).

The nature of the precipitation is of fundamental importance in determining the speed and type of chemical reaction. Snow, for instance, produces little immediate solution of limestone, but melted water from carbon dioxide-charged snow is an effective solvent producing long rinnenkarren. On the other hand, heavy rainfall on bare limestones produces extensive runneling such as rillenkarren, particularly in warm climates where the rate of limestone solution is enhanced by temperature. The solution of limestone is greater in the tropics than in cold climatic regions because of the increased biogenic carbon dioxide, the higher gaseous diffusion rates in the soil cover, the type and extent of cover, and the greater amount of precipitation.

Climatic conditions in Dry Valley are very favorable for the development of most karren forms. The climate is subtropical, but climatic conditions responsible for karren development more closely resemble those of the tropics than any of the other climates described. Ample rainfall and warm temperatures result in a high degree of development of karren forms above and below the soil zone. The climate provides for a long growing season, so that the production of biogenic carbon dioxide is relatively high and nearly continuous. As a result, solution of the limestone below the soil cover is rapid and produces extensive, well developed covered karren forms.

Solution of limestone in the free atmosphere also appears to be rapid in the valley. Free karren have

developed on limestone surfaces exposed to free atmospheric weathering for a period of only 12 years or less. Microforms such as rillenkarren have reached a higher degree of development than the larger karren forms. However, comparison of free karren and covered karren indicate that the greatest amount of solution has taken place under a soil cover where ground water movement is slow and the production of biogenic carbon dioxide is very high.

## SUMMARY

In conclusion, karren forms are common features on the outcropping Newala Limestone in Dry Valley. The forms are diversified and the three main catagories (Bögli) of free karren, semi-free karren, and covered karren are represented in varying degrees. The most abundant forms are those which develop beneath a soil cover, primarily rundkarren and kluftkarren. The next most abundant forms are those created under a partial cover (semi-free karren), mainly korrosionskehlen and kamenitza. Free karren forms are relatively rare and only occur on isolated blocks and pinnacles protruding above the soil zone. Rillenkarren are the most common and best developed free karren form. Rinnenkarren, regenrinnenkarren, and meanderkarren are rare forms that have only been observed on a few limestone blocks near open pit limestone quarry operations. They are poorly developed except for meanderkarren.

The factors affecting karren development in Dry Valley appear to be a complex interplay of geologic structure, lithology, stratigraphy, the presence or absence of soil cover, climate, and local hydrologic conditions. These factors determine the nature of the chemical reaction involving the limestone, carbon dioxide, and water; the solution

rates; and the nature of the water flow over the limestone surfaces. These chemical and physical parameters are directly responsible for fashioning the various karren forms.

Joints, fractures, faults and folds are structural features that, along with bedding plane cavities, control the movement of water over and through the rock; thus, they are directly involved in the development of karren forms above and below the soil cover in Dry Valley.

Joint and fracture direction, density, and magnitude combine to determine the size and shape of limestone blocks which ultimately limit the size of karren that may develop on a single block. Joints and fractures are responsible for the occurrence of some karren forms, primarily kluftkarren and box work features. They also affect other karren forms by exerting a strong influence on the movement of water over and through the limestone. Where joints or fractures occur on a limestone block, they may interrupt the normal surface water runoff and interfere with free karren development.

Faults affect karren in much the same manner as joints and fractures but generally on a larger scale. One high angle thrust fault and several small strike-slip faults examined had little effect on karren development because of a narrow fracture zone and tight fault planes. However, a low angle thrust fault in the Vulcan Materials quarry with a wide and highly permeable fracture zone produced a bed rock depression and thicker soil zone which limited local karren development to covered karren forms, primarily rundkarren.

The slope of limestone surfaces affect the development of free karren more than any of the other forms by affecting the flow of water over the rock surface. Steep slopes produce straight runnelled karren forms mainly rillenkarren and wandkarren while moderate slopes produce rinnenkarren and regenrinnenkarren. Gentle slopes produce meanderkarren and kamenitza. Under a soil cover, the slope of the rock surface has less effect because soil may hold water in contact with the rock even on very steep slopes. However, in very permeable soils, the effect of slope on gravity drainage is very pronounced as shown by variations in the gradient of some rundkarren troughs.

Lithologic and stratigraphic characteristics of the limestone basically determine if a limestone is capable of producing karren. The Newala has many of the most favorable lithologic characteristics necessary to produce karren including fine-grain size, density, strength, massive bedding and chemical purity. However, some stratigraphic characteristics such as discontinuous beds of dolomite and beds of cemented breccia tend to retard development of some karren forms.

A soil cover mantles most of the outcrops of the Newala Limestone in Dry Valley; as a result, covered karren are the most abundant forms. These covered karren forms are directly related to the increased solution development below the soil zone due to the rapid production of biogenic carbon dioxide,

and low soil permeability. Solution features on pinnacles in Dry Valley indicate that the solution of limestone is much higher in the soil zone than in the free atmosphere.

Local hydrology has played an important role in karren development in the valley. Hydrologic factors such as low soil permeability, gradients, type and size of solution cavities, and orientation of cavities, are responsible for soil moisture conditions, the time that ground water is in contact with the limestone, and the movement of water over and through the limestone. Local hydrologic conditions in Dry Valley may vary from poorly drained, swampy, permanently wet areas with a very shallow water table, to well drained areas with a deep water table. Karren that are formed in the wet areas of the valley are highly developed rundkarren and wide shallow kluftkarren. Karren in the well drained areas are more diversified and kluftkarren achieve their maximum development.

The climate in Dry Valley is very favorable for the development of most karren forms. Adequate rainfall and warm temperatures produce highly developed and diversified karren.

## REFERENCES


Bagnall, F. C., and Luster, G. R., 1974, Sinkhole investigation Roberta, Alabama, Plant: Martin Marietta Cement, Baltimore, Md., unpublished report, 20 p.

Bögli, Alfred, 1960, Kalklosung und karrenbildung (Solution of calcium carbonate and the formation of karren): Zeitschr. Geomorphologie, Supp. 2, Internationale Beitrage zur Karstmorphologie, p. 4-21.

Bretz, J. H., 1942, Vadose and phreatic features of limestone caverns: Jour. Geology, v. 50, no. 6, pt. 2, p. 675-811.

Butts, Charles, 1940, Montevallo-Columbiana folio, Alabama: U. S. Geol. Survey, Geol. Atlas, Folio 226, 20 p.

Cvijič, Jovan, 1924, The evaluation of lapiés, A study in karst physiography: Geog. Review, v. 14, p. 26-49.

Douglas, Ivan, 1968, Some hydrologic factors in the denudation of limestone terrains: Zeitschr. Geomorphologie, N. F., v. 12, p. 241-255.

Goodchild, M. F., and Ford, D. C., 1971, Analysis of scallop patterns by simulation under controlled conditions: Jour. Geology, v. 79, p. 52-62.

Hamilton, D. K., 1948, Some solution features of the limestone near Lexington, Kentucky: Econ. Geology, v. 43, no. 1, p. 39-52.

Holt, R. B., 1948, The nature and origin of limestone porosity: Quart. Colo. Sch. Mines, v. 43, no. 4, p. 5-51.

Hughes, T. H., and Lynch, R. E., Jr., 1973, Barite in Alabama: Alabama Geol. Survey Circ. 85, 43 p.

Jennings, J. N., 1971, Karst: Cambridge, The M.I.T. Press, v. 7, p. 252.

LaMoreaux, P. E., and Warren, W. M., 1973, Sinkhole: Geotimes, v. 18, no. 3, p. 15.

LeGrand, H. E., and Stringfield, V. T., 1971, Development and distribution of permeability in carbonate aquifers: Water Resources Research, v. 7, no. 5, p. 1284-1294.

Moravec, G. F., 1974, Development of karren karst forms on the Newala Limestone in the Cahaba Valley, Alabama (abs.): Proceedings, 4th Conference on Karst Geol. and Hydrol., Univ. W. Va.

Murray, R. C., 1960, Origin of porosity in carbonate rocks: Jour. Sedimentary Petrology, v. 30, no. 1, p. 59-84.

Panoš, V., and Štelcl, O., 1968, Physiographic and geologic controls in development of Cuban mugotes: Zeitschr. Geomorphologie, N. F., v. 12, no. 2, p. 117-165.

Pluhar, A., and Ford, D. C., 1970, Dolomite karren of the Niagara Escarpment, Ontario, Canada: Zeitschr. Geomorphologie, N. F., v. 14, p. 392-410.

Smith, J. F., Jr., and Albritton, C. C., Jr., 1941, Solution effects on limestone as a function of slope: Geol. Soc. America Bull., v. 55, p. 61-78.

Stockdale, P. B., 1926, The stratigraphic significance of solution in rocks: Jour. Geology, v. 34, no. 5, p. 399-414.

Sweeting, M. M., 1966, The weathering of limestones with particular reference to the Carboniferous limestones of Northern England: London, Essays in Geomorphology, ed. G. H. Dury, p. 177-208.

_____,1972, Karst landforms: London, McMillan, 362 p.

Taylor, R. S., 1971, Petrology and depositional history of Ordovician rocks of Cahaba Valley, Shelby County: in Drahovzal, J. A., and Neathery, T. L. (ed.), The Middle and Upper Ordovician of the Alabama Appalachians: Ala. Geol. Soc. Guidebook, 9th Ann. Field Trip. p. 115-123.

Udden, J. A., 1925, Etched potholes: Texas Univ. Bull. 2509, 9 p.

Warren, M. W., and Wielchowsky, C. C., 1973, Aerial remote sensing of carbonate terranes in Shelby County, Alabama: Ground Water, v. 11, no. 6, 12 p.

White, W. B., 1969, Conceptual models for carbonate aquifers: Ground Water, v. 7, no. 3, p. 15-21.

Wilford, G. E., and Wall, J. R. D., 1965, Karst topography

in Sarawak: Jour. Tropical Geography, v. 21, p. 44-70.

Williams, P. W., 1967, Limestone pavements with special reference to western Ireland: Inst. Brit. Geol. Trans. 40, p. 155-172.

Yeager, D. W., 1971, Petrology of the Newala Limestone in northern Shelby County, Alabama: Jour. Ala. Acad. Science, v. 42, no. 1, p. 3-9.