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KARSTIFICATION ON THE NORTHERN VACA PLATEAU, BELIZE

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Quantification of limestone petrology and structure in a 25 km^2 section of the northern Vaca Plateau, Belize, facilitated development of a model of speleogenesis and evolution of area caves and the karst landscape. The limestones in the study area are mostly depositional breccias developed between the mid-Cretaceous and mid-Tertiary adjacent to the emergent Maya Mountain Fault Block. Micritic and some fossiliferous-pelletic lithoclasts of the Cretaceous Campur Formation are cemented by sparite which formed in a shallow-sea high energy environment adjacent to the emergent area. Planes of structural weakness developed in the Campur Limestone have similar orientations to contemporary karst landform features including solution valleys, the long-axis of depressions, and cave passages. This correspondence suggests an important structural control on the formation and evolution of area caves and the karst landscape. Base level modification by way of valley incision and the development of secondary permeability enhanced interfluve development, causing caves to be truncated along valley sides and abandoned as active flow routes. The dry valleys and stair-step cave profiles indicate that the lowering of base level through time was interspersed with stable periods when horizontal cave passages were excavated.

Geologic, geomorphic, and speleological research has been conducted for six field seasons (1990-1995) within a 25 km^2 area of the northern Vaca Plateau centered 6 km east of the border between Guatemala and Belize, and 15 km south-southeast of the Augustine Forestry Station (see location map on page 68). The research design for this project includes (1) reconnaissance of surface and subsurface geology and geomorphology, (2) exploration and mapping of caves, (3) collection of rock, soil, and sediment samples, (4) collection of data regarding area joint, fault, dry valley and cave orientations, and (5) the petrographic analysis of carbonate rocks. Our research is the first attempt to quantify physical landscape components in the northern Vaca Plateau (i.e. limestone petrology, structure, geomorphology and hydrology) and to relate these parameters to landscape and cave formation and evolution.

The suite of karst landforms within the study area includes an integrated system of dry karst valleys separated by residual limestone hills and interfluves, single inlet and compound sinkholes, isolated cockpits, cutters, solution corridors, solution fissures, open joints, and caves. To date, over 100 cave entrances have been located and 60 caves have been explored. The majority of the caves are located along or close to the surface drainage divide between the Macal River (8 km east of the study area) drainage basin, and the Chiquibul River (15 km west) drainage basin. All the caves in the study area are formed in the heavily brecciated Campur Limestone (Figure 1). A breccia is a coarse-grained rock composed of angular broken rock fragments held together by a mineral cement or in a fine-grained matrix (Bates & Jackson, 1987).

Specific research regarding the physical landscape in this portion of Belize has not been conducted previously. The only sources for such information are very general country-wide or regional assessments, citations in publications regarding the Mountain Pine Ridge and Maya Mountain section of Belize, or detailed studies in other areas with similar geologic characteristics.

PREVIOUS WORK

Ower (1928) produced a manuscript on the geology of British Honduras (now Belize). Therein, the Cretaceous limestones in west-central Belize were mentioned, but few details were presented. Dickenson and Weisbord (1931) described the Cretaceous limestones in Belize generally, but provided few specific details. Flores (1952) reviewed the nature of the Cretaceous limestones in northern Belize, and in 1957 Dixon produced an 85 page monograph on the geology of southern Belize wherein the Cretaceous limestones were discussed. Wright and others (1959) discussed the geology of the Vaca Plateau as part of a land use survey of British Honduras. Because of its unique geology, the Vaca Plateau was considered a major subregion in their land use classification, but they

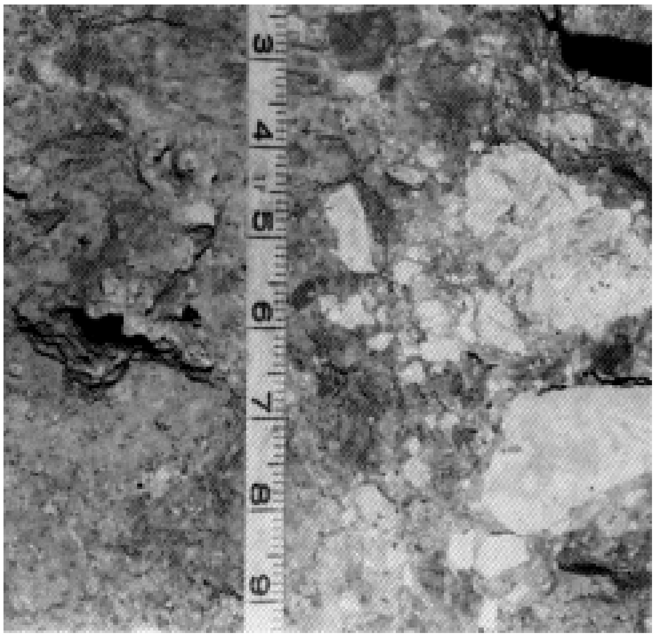

Figure 1. Limestone breccia composed of micritic lithoclasts. Scale is in tenths of feet (0.1 ft = 3 cm).

misinterpreted the geology in that they indicated it is "horizontally bedded limestone" with no mention made of brecciation.

Detailed information regarding the Cretaceous limestones found in the Coban-Purulha area of central Guatemala was presented by Walper (1960). Walper was probably the first geologist to propose that the breccias of the Ixcoy Formation (the upper Ixcoy is analogous with the Campur Formation in Belize) originated as depositional breccias, "pseudobreccias" or both (Blount & Moore, 1969). Lattimore (1962) noted shale and limestone pebble conglomerates overlain by angular carbonate boulders in a clay matrix in the Ixcoy Formation and determined that the boulders are composed of carbonate clasts in a matrix of fine-crystalline, occluded dolomite. He suggested that the breccia formed by carbonate dissolution, collapse and recementation. Vinson (1962) published a detailed description of the Upper Cretaceous stratigraphy of Guatemala, with references to Belize. He described the Campur Formation, relates it to other Upper Cretaceous formations in Guatemala and Belize, and summarized the paleoenvironmental conditions under which these formations were deposited. Blount and Moore (1969) discussed the formation of carbonate breccias in the Ixcoy Formation in a 250 km^2 area in east-central Guatemala. They classified and posed formative mechanisms for five different types of breccias, including depositional breccias, non-depositional breccias (evaporite-solution collapse, tectonic, caliche breccias), and pseudobreccias.

The oldest rocks exposed in Belize are the 350 million year old granitic rocks of the Mountain Pine Ridge portion of the Maya Mountains which border the eastern edge of the northern Vaca Plateau. Bateson and Hall (1971 & 1977), Hall and Bateson (1972), Bateson (1972), and Kesler and others (1974), discussed various aspects of the Mountain Pine Ridge Granite, and the metasedimentary rocks of the upper Paleozoic aged Santa Rosa Group which comprise a major portion of the Maya Mountains. They also discussed the relationship between the Campur Limestone and the Santa Rosa Group, which in places it unconformably overlies (Figure 2).

In 1984, Hartshorn et al. published an environmental profile of Belize which generally described the soils, geology, and hydrology. Day (1986) described slope form and process in the Campur Limestone in the Hummingbird Karst region of central Belize. Miller (1986, 1987, 1989, 1990) provided details about the Campur Formation on the southern Vaca Plateau which was studied in conjunction with the exploration of the Chiquibul Cave System (55 km of mapped cave passage). The Chiquibul River, which receives allogenic recharge from the Maya Mountains, has played an important role in the creation of this extensive cave system. Most of the caves are developed in brecciated limestone and are influenced by joint sets and topographic dip (Miller, 1986). It is estimated that the development of the karst in the southern Vaca Plateau began around 700,000 years BP (Miller, 1990).

Geologic Setting

The most complete description of the Campur Formation is provided by Vinson (1962). The type section for the Campur Limestone is located in central Guatemala near the town of Languin, where a nearly complete but faulted 808-m-thick sequence is exposed. A complete 850-m-thick reference section exists near the type section, on the flanks of Chinaja Mountain. Vinson (1962) describes the Campur Formation as composed of principally gray, gray-brown, and tan limestones which were deposited in reef-associated environments. The formation contains minor amounts of dolomite, and locally is interbedded with thin beds of shale, siltstone, and limestone breccia or conglomerate. Along the flanks of the Maya Mountains is an unconformity which represents transgressive onlap of the Campur Formation onto the older Coban Formation (Figure 2). The Maya Mountains are an extension of the Libertad Arch, which is an east/west striking anticlinal structure that extends almost the entire width of north-central Guatemala (Weyl, 1980). The Maya Mountains are an uplifted fault block consisting of a synclinorium trending east-northeast, and sloping to the northwest at about ten degrees following the dip of the geologic structures (Weyl, 1980). The Maya Mountains are bordered on the north and south by major faults (Bateson & Hall, 1977). The structure of the western boundary of the Maya Mountain fault block is completely obscured by the Cretaceous limestones which lie unconformably on the metasediments of the Santa Rosa Group. The Campur Limestone is a common outcrop in both Guatemala and Belize,

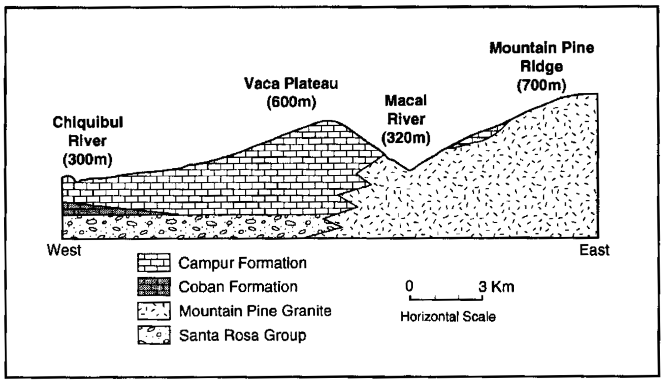

Figure 2. Generalized lithologic section across the western flank of the Mountain Pine Ridge and the Northern Vaca Plateau (structural features are not shown).

and it forms karst topography in both countries (Vinson, 1962). The main orogeny which deformed the Maya Mountain Block occurred in the Permian and early Triassic. Between the middle Cretaceous and mid-Tertiary, the block was subjected to periodic uplift (Bateson & Hall, 1977).

Blount and Moore (1969) completed a detailed study of the Cretaceous breccias in the Chiantla Mountain area. They recognized five types of carbonate breccia, and determined that depositional breccias as thick as 500 m are widespread within the Cretaceous Ixcoy Formation. They determined that the lithoclasts within the breccia were eroded from adjacent emergent areas, which probably resulted from faulting (Blount & Moore, 1969). They also found a 250-m-thick sequence of evaporite solution breccias in the lower part of the Ixcoy Formation, which correlates with the Lower to Upper Cretaceous Coban Formation which underlies the Campur Limestone in Belize. Tectonic breccias were noted to form by fracturing during periods of deformation associated with faulting. Caliche breccias formed by caliche cementation of carbonate rubble at the base of slopes (Blount & Moore, 1969), and localized pseudobreccias formed by selective grain growth.

Research Methods

Data regarding the petrology of the Campur Formation in the study area were obtained by analyzing thin sections prepared from 25 rock samples. Rock specimens were collected at five general landscape positions and were grouped as follows: (1) residual hilltops (7 samples), (2) residual hillside slopes (9 samples), (3) dry valley bottoms (2 samples), (4) cave entrances (4 samples), and (5) cave walls (3 samples). Three of the cave entrance samples were collected in dry valley bottoms, and one was from a residual hillside slope. The cave passages from which samples were collected have entrances located on a residual hilltop (1 sample) and on a residual hillside slope (2 samples).

Thin section analysis was used to identify rock constituents. Initial investigation indicated a large degree of heterogeneity, making the point count method of analysis (Folk, 1962) inadequate. On brecciated rocks the point count method may be misleading because of variations in lithology of the clasts, and the type and amount of cement. The relative abundance of sparite, micrite, fossils or other characteristics becomes meaningless in these rocks, and it is more appropriate to classify the rock by using field relationships, stratigraphy and petrographic analysis. The samples were therefore classified first using systems described by Pettijohn (1975), and then as described by Blount and Moore (1969).

Data were also compiled on the orientation of 133 dry valleys within and adjacent to the study area using topographic map sheet 28 from map series E755 (scale 1:50,000, 40-m contour interval). The long axis orientations of 40 sinkholes were also obtained from this map. The orientations of 29 cave passages in nine different caves in the study area were derived from cave maps (Reeder, 1993). Dry valley, depression long axis, and cave passage trends were plotted on rose diagrams using 100 class intervals. Preferred orientations were estimated visually from the rose diagrams.

Petrology of the Campur Limestone on the Northern Vaca Plateau

Twenty-one samples from the study area are classified as breccias and four are classified as non-breccias. Using Pettijohn's (1975) system, the breccias were classified into four types: (1) micrite clasts dominate, sparite cement (12 samples) (Figure 3a); (2) sparite clasts dominate, sparite cement (3 samples) (Figure 3b); (3) fossiliferous micrite clasts dominate, sparite cement (3 samples) (Figure 3c); and (4) pelletic micrite clasts dominate, sparite cement (3 samples) (Figure 3d). The non-breccias were classified as follows: (1) micrite dominates with some pellets (2 samples) (Figure 3e); and (2) sparite (2 samples) (Figure 3f).

The four breccia types were further classified using Blount and Moore's (1969) system, which is based upon the origin of the breccias as determined from field relationships, stratigraphy, and petrographic analysis. All 21 breccia samples are lithoclastic (reworked fragments of an older lithified limestone). They consist primarily of pre-existing limestone fragments with some samples containing rudistid (a bivalve mollusk) fossil fragments and/or pellets (probably mollusk feces). The clasts are considered lithoclasts, rather than intraclasts (penecontemporaneous, usually weakly consolidated carbonate sediment that eroded from adjoining parts of the sea floor (Folk, 1962), because the lithoclastic interval is over 200 m, based upon the elevation difference between breccias found deep in vertical caves and on the highest hilltops.

In 12 samples, micrite clasts dominate and the matrix is sparite (Figure 3a). The lithology of the lithoclasts is similar to non-lithoclastic limestones from the same formation, indi-

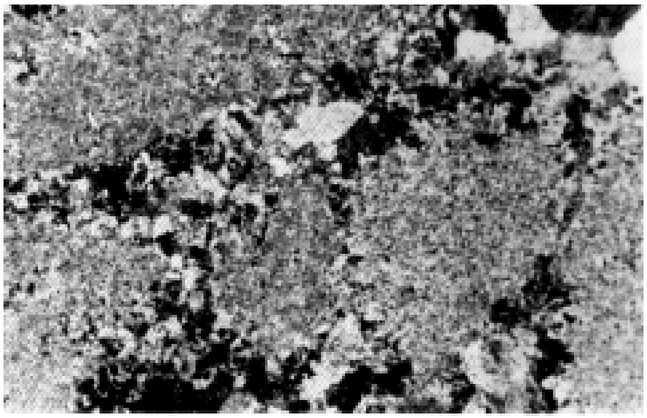

Figure 3a.

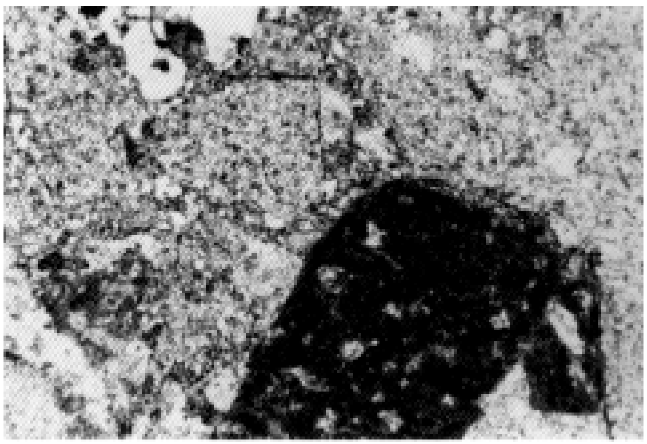

Figure 3b.

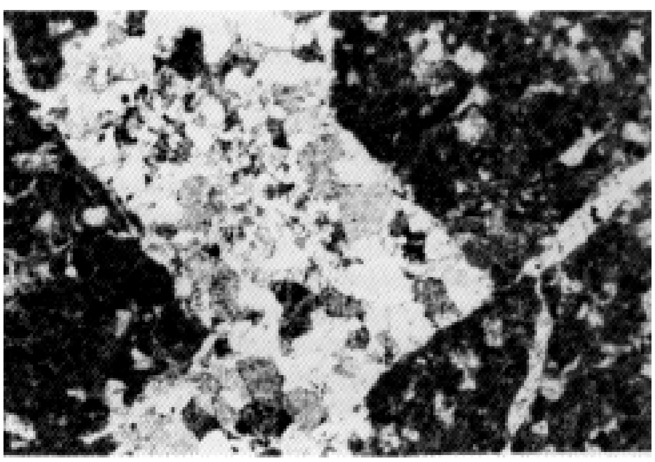

Figure 3c.

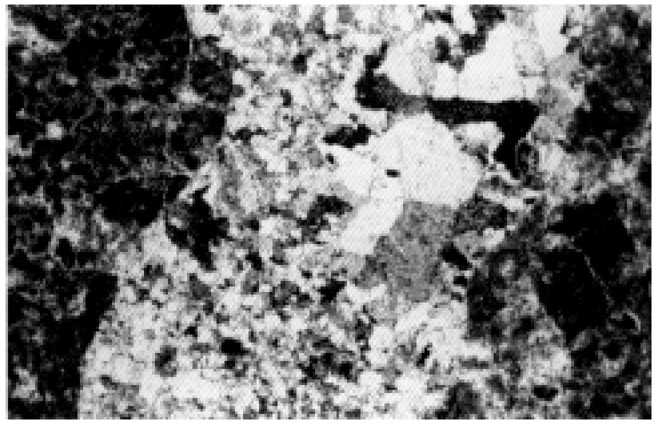

Figure 3d.

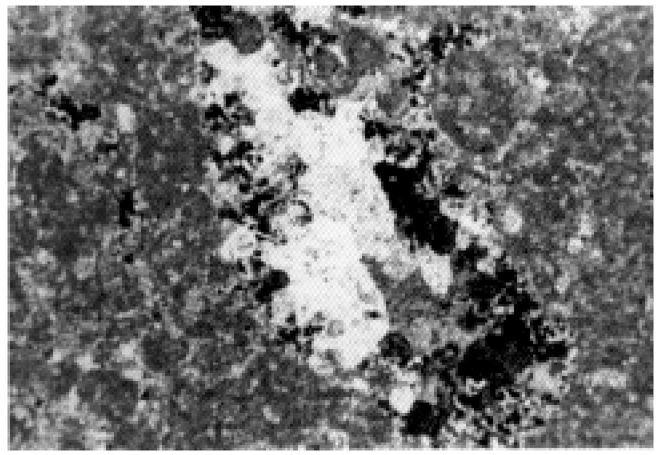

Figure 3e.

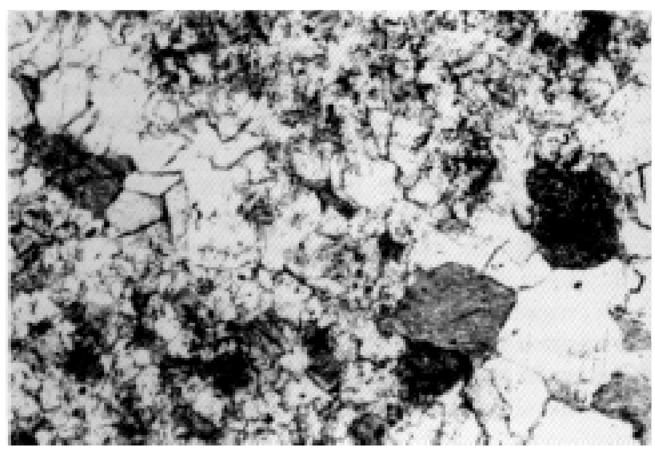

Figure 3f.

Figure 3. Thin sections of breccias and individual clasts. They are classified as follows: 3a: depositional breccia, micrite clasts dominate, sparite cement; 3b: tectonic breccia, sparite clasts dominate, sparite cement; 3c: depositional breccia, fossiliferous micrite clasts dominate, sparite cement; 3d: depositional breccia, pelletic micrite dominates, sparite cement; 3e: non-breccia, micrite clast with pellets; and 3f: non-breccia, sparite clast. (magnification 4X)

cating they are intraformational (from the same geologic formation). Based upon these characteristics, and criteria outlined by Blount and Moore (1969), these samples are designated depositional breccias. They probably formed when uplift along major faults caused certain areas to become emergent. Erosion then transported weathered micritic clasts from emergent areas to nearby areas (based upon the angularity of the lithoclasts), where they were deposited with lime muds. The sparite cement formed in the high energy environment adjacent to the emergent areas. Stylolitic contacts are rare in these specimens which suggests limited pressure solution in a deeper water environment.

In three other breccia samples, sparite clasts are embedded in a secondary matrix of sparry calcite cement (Figure 3b). The clasts also contain a small amount of micrite. These breccias have very angular clasts, and contain numerous matching clast boundaries. Clast size is highly variable, and the sparry calcite, which is simple vein fill, is continuous with smaller veins of calcite present within the clasts. These specimens are classified as tectonic breccias (Blount & Moore, 1969). Tectonic breccias with a matrix of secondary sparry calcite result from the precipitation of calcite in voids caused by fracturing, but without dislocation of breccia clasts. These tectonic breccias probably formed near faults tributary to the larger faults north and south of the study area. Two of these samples were collected near the bottom of dry karst valleys, which may be fault controlled, and the third sample was collected from the top of an outcrop in an area of narrow, deep, cave entrances. The transformation of the micrite in the clasts to sparite may be a direct result of tectonic activity.

In three samples, fossiliferous micrite clasts dominate within a sparite cement (Figure 3c). The fossils appear to be broken rudistid fragments and, as discussed above, the lithoclasts are intraformational. These specimens are classified as depositional breccias. The presence of rudistid fragments within the lithoclasts can be attributed to regional faulting. The rudistid fragments within the micrite lithoclasts represent the lithology of the pre-existing limestone prior to uplift and erosion. Small rudistid banks may have also formed near the edges of uplifted fault blocks, and were later eroded and deposited along with the lithoclasts (Blount & Moore, 1969). All three samples were collected at different topographic positions (hilltop, side slope and valley bottom), perhaps indicating the discontinuous nature of deposition, which seems plausible if the deposition scenario outlined above is correct.

In three samples, pelletic micrite fragments are cemented by sparite (Figure 3d). The pellets within the lithoclasts are probably rudistid feces that mixed with lime muds prior to lithification, uplift and erosion. These specimens are classified as depositional breccias. Two of these samples were collected from hilltops, while the third was collected from the entrance to a vertical cave located on a residual hillside slope.

Two samples classified as non-breccias are probably homogeneous fragments of the breccia. Following Pettijohn's (1975) classification system, they were dominated by micrite mixed with some pellets and exhibited no veining (Figure 3e). These samples are petrologically similar to the pelletic micrite lithoclasts discussed above, suggesting that they formed in the same paleoenvironment. The thin sections prepared from these samples were probably cut from a single, larger lithoclast, hence the sparite cement was excluded from the sample. Based upon this conclusion, even though the pelletic micrite lithoclasts are not embedded in sparite cement, we believe them to be a part of the breccia. One of these samples was collected from a hilltop, and the other was collected on a residual hillside slope just below a hilltop.

Two other samples were composed entirely of sparite (Figure 3f). Based upon their homogeneous carbonate mineral composition, they were classified as non-breccias, but they are probably directly related to area breccia formation. The intensity of veining in tectonic breccias is noted to increase with proximity to large surface fractures or faults (Blount & Moore, 1969). These two samples probably represent void fill between clasts, rather than a combination of clast and cement. When the thin section was cut, only void fill was included on the slide. These samples were both collected in a dry valley bottom near a fracture controlled cave entrance.

Structural Control of Karst Features

Numerous dry karst valleys, residual limestone hills, single inlet and compound sinkholes, isolated cockpits, cutters, solution corridors, solution fissures, open joints, and caves exist within the study area. The dry valley bottoms are covered by a thick mat of vegetation in various stages of decay which obscures some of these features. The residual hill slope angles range from moderate (30°) to vertical. The moderate to steep (30°-60°) slopes are covered with a thin mat of decaying vegetation, and with increasing slope angle more bedrock is exposed. Prominent escarpments exist at the top and along many of the residual hillside slopes. The relative relief between valley bottoms and hilltops is approximately 100 m.

The existence of the lithoclastic limestones in the study area is associated with uplift caused by faulting and subsequent erosion from the emergent areas of a previously deposited, well lithified carbonate sequence (Blount and Moore, 1969). Very little research has been conducted on faulting within the Cretaceous limestones in Belize, but unnamed east-northeast striking faults exist 8 km south and 12 km north of the study area (Weyl, 1980). It is also likely that smaller faults and fractures are associated with these faults (Alt, 1995). Faults usually occur in groups of the same type, hence larger faults may be accompanied by a set of smaller parallel faults (Park, 1983). A horst, like the east-northeast striking Maya Mountain Block, is often bounded by sets of faults of the same type but opposite movement (Park, 1983). The Maya Mountain Block may therefore be bounded to the west by downthrown fault blocks that generally trend east-northeast.

Fractures and smaller faults associated with larger faults are generally assignable to the same stress that caused the larger faults (Stearns & Friedman, 1977). Experimental results and theory can also be used to predict the relationship between the orientation of the principal stress axis and the development of the two main shear fracture planes. The two resulting fractures have been noted in the literature to form angles of 30° (Billings, 1954) to 45° (Park, 1983). The greatest principal angle of stress in the study area is 67.5° which translates into theoretical fracture orientations between approximately 330° and 345°. But because of the anisotropy of the rock fabric in the Campur Limestone, and hence directional variation in shear strength, prediction of fracture orientations is difficult (Mandl, 1988).

Based upon the down valley axis of orientation for 133 dry valleys in and adjacent to the study area, rose diagrams were prepared. Dry valley orientations were measured in the Chiquibul (n=69) and Macal (n=64) drainage basins and plotted on separate rose diagrams (Figures 4 & 5). The valleys in the Macal River drainage basin have a pronounced northeast orientation, with 24 valleys (38%) oriented between 10° and 60° (Figure 4). Within this 50° range, the modal orientation is 30° (n=8). A less prominent trend is to the northwest, with 14 valleys (21%) oriented between 300° and 335°. Within this 35° range, the modal orientation is 310° (n=6). Fifty- nine percent of the measured valley orientations generally coincide with the fractures theorized by Billings (1954) and Park (1983), the orientation of the Maya Mountain Block, possible minor faults, and/or the documented faults located north and south of the study area.

The dry valleys in the Chiquibul drainage basin have a pronounced northwest orientation with 25 valleys (34%) oriented between 300° and 350° (Figure 5). Within this 50° range, the modal orientation is 320° (n=7). Another prominent trend is west to southwest (280° to 220°) where 30 valleys (43%) are oriented. These ranges of valley orientations (77% of the total valleys measured) generally coincide with the theorized fracture orientations (34%), and the orientation of the Maya Mountain Block and existing and postulated fault orientations (43%).

Based upon the long axis orientations of 40 sinkholes in and adjacent to the study area, a rose diagram was prepared which includes data from both the Macal and the Chiquibul River drainage basins (Figure 6). The long axis orientations have a pronounced northeast through east trend, with 20 sinkholes (50%) oriented between 20° and 90°. Within this 70° range, the modal orientations are 40° and 80° (n=5). Another prominent trend is northwest through west, with 15 sinkholes (37%) oriented between 130° and 100°. Within this 30° range, the modal orientation is 130° (n=6).

Based upon the sinkhole long axis data, it appears that lines of structural weakness within the bedrock influence sinkhole orientation. Sinkholes often form along high permeability pathways through the vadose zone. These areas are often sites of fracture concentrations and fracture intersections (White, 1988). Sinkholes form by some combination of dissolution and collapse. Collapse can originate at some depth in the bedrock if it is assisted by fracture zones. The land surface is lowered by a combination of dissolution and mechanical erosion because the underlying bedrock is weakened by vertical dissolution along joints and fractures (White, 1988).

Sinkholes may become elongated along lines of major weakness. Fifty percent of the measured sinkholes trend northeast through east which corresponds with the orientations

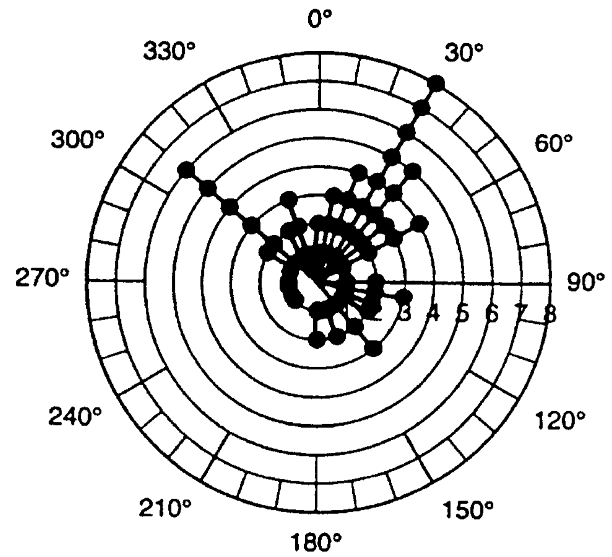

Figure 4. Down valley orientations in the Macal River drainage basin (n = 64).

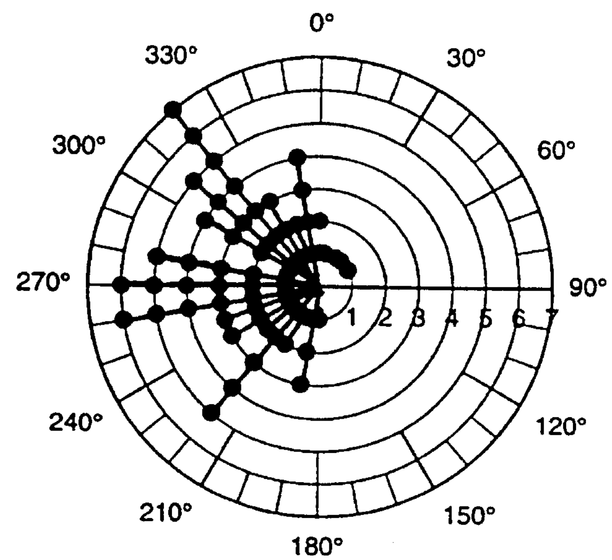

Figure 5. Down valley orientations in the Chiquibul River drainage basin (n = 69).

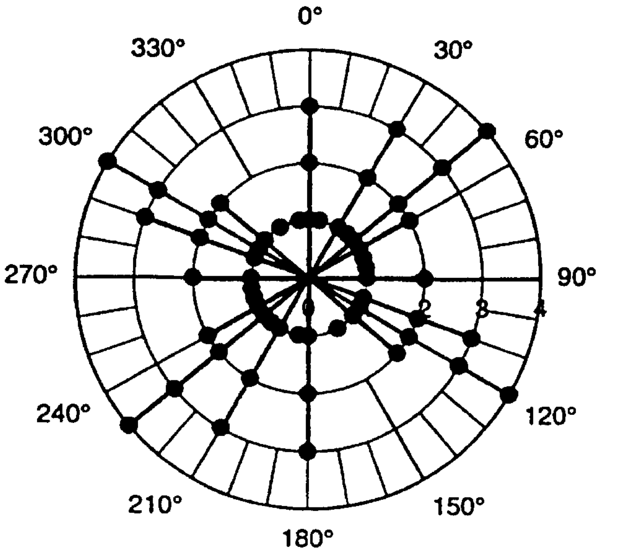

Figure 6. Depression long axis orientations in the Macal and Chiquibul drainage basins (n = 69).

of the Maya Mountain Block, the faults located north and south of the study area, and the postulated orientation of unknown faults. Thirty-seven percent of the sinkholes trend northwest through west which generally corresponds with the theorized orientation of fractures.

Based upon the orientation of 29 segments of cave passage in nine surveyed caves, a rose diagram was prepared (Figure 7). The cave passages have a pronounced northeast-southwest trend, with 10 cave passages (34%) oriented between 30° and 60°. Within this 30° range the modal trend is 50° (n=4). Another prominent trend is northwest-southeast, with nine cave passages (31%) oriented between 110° and 130°. Within this 20° range the modal trend is 120° (n=4). A minor north-south trend also exists, with three cave passages (10%) oriented at 0°.

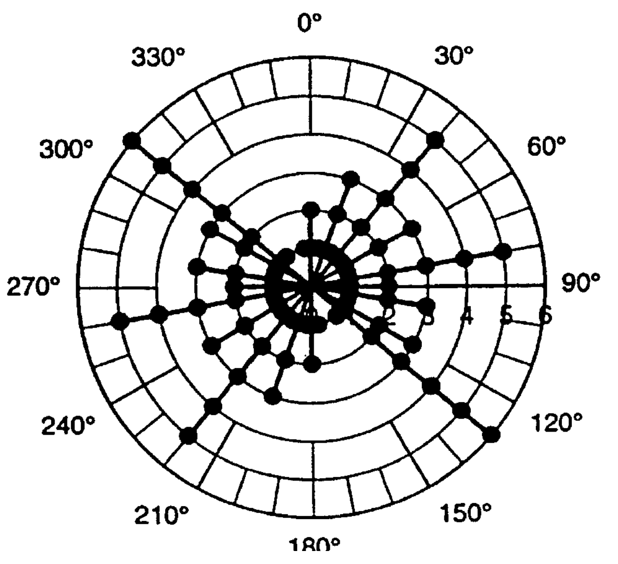

Figure 7. Orientation of 29 segments of cave passage in nine caves in the Macal and Chiquibul drainage basins.

The orientations of the cave passages also indicate structural control. Based upon field observations, the Campur Limestone contains very few bedding planes, and cave formation is focused along planes of weakness such as joints, fractures and faults. Cave passages oriented northeast-southwest (34%) correspond with the orientation of the Maya Mountain Block, the faults located north and south of the study area, and faults which are theorized to exist based upon known fault orientations. Cave passages oriented northwest-southeast (31%) correspond with the theorized orientation of fractures in the study area. Exploration and survey of the caves indicate that joints structurally control the cave pattern, and no direct evidence of faulting has been found.

Karst Landscape Formation and Evolution

As indicated by Miller (1990), the karst in the southern Vaca Plateau (Chiquibul region) began to develop around 700,000 years BP. The limestones in the northern Vaca Plateau are of similar age and composition, but because the study area is located at a drainage divide and is dominated by autogenic recharge, the Chiquibul area is probably geomorphically younger. In the Chiquibul region, recharge water flows westward from the Maya Mountains drainage divide across the Carboniferous-Permian metamorphosed fine-grained argillaceous rocks of the Santa Rosa Group (Weyl, 1980). This allogenic recharge is highly undersaturated with calcium carbonate ($CaCO_3$) because the waters have not contacted the Campur Limestone. These allogenic waters represent an import of energy capable of both chemical and mechanical work (Ford & Williams, 1989).

Recharge on the northern Vaca Plateau is entirely autogenic with water derived entirely from meteoric precipitation falling on the Campur Limestone. Allogenic recharge water flowing west from the Mountain Pine Ridge section of the Maya Mountains is intercepted by the south-north flowing Macal River before contacting the Campur Limestone. Karst areas with large inputs of allogenic water experience more chemical erosion than areas entirely recharged by autogenic water, with the size of the catchment area contributing allogenic recharge greatly influencing the rate of solution. For these reasons, development of the karst on the northern Vaca Plateau differs from that in the Chiquibul area.

Currently, autogenic recharge in the study area enters the subsurface drainage network by diffuse means and at discrete locations. Infiltration through area soils is more common than discrete input (which usually occurs where structural features extend to and are open at the surface). The deepest cave discovered thus far in the study area (105 m) extends 95 m below dry valley elevations, but active flow has never been observed in caves or dry valleys even after heavy, prolonged precipitation events. However, fieldwork has been conducted during the dry season, and it is possible that limited surface and vadose flow does occur during the wet season.

Valleys in the study area are mostly interconnected and are bounded by interfluvial residual hills. Drainage through the dry valley systems is deranged. Remnant stream channels are rare and only short (< 5 m), isolated segments of channel are found, which terminate at discrete recharge points into the subsurface drainage network.

Periodic uplift forming or accentuating lines of structural weakness occurred adjacent to, or within these limestone breccias into mid-Tertiary time. Faulting in northern Central America continued into the Quaternary (Weyl, 1980) with numerous fault systems like the Chixoy-Polochic and Motagua in Guatemala still active. It is probable that valleys trend along lines of structural weakness such as faults, fractures and joints. The previously discussed results regarding dry valley and sinkhole long axis orientations indicate that area geologic structures influence valley and sinkhole orientations.

Surface streams formerly flowed across the karst landscape along lines of structural weakness. As the subsurface drainage network developed, secondary permeability increased and a portion of the surface flow moved into the subsurface. Eventually, all surface flow was pirated to the subsurface, surface stream channels were abandoned, and slope processes along the valley sides buried the valley bottoms and the former stream channels. The residual hills in the study area are the remains of the interfluves between the integrated valley systems. On many of the hills, dissolutionally sculpted features such as solution corridors, fissures, and natural bridges indicate integrated surface and phreatic flow in the geologic past. Many of these features are located 150 m above the contemporary dry valley bottoms.

Sinkholes (and several cockpits) in and adjacent to the study area range in size from a few meters across to over 1 km and occur in variable topographic positions. Miller (1987) determined that sinkholes in Searranx, Guatemala marked the location of dissected river valleys that have become unrecognizable because of karstic collapse. Some of the larger sinkholes (cockpits) in the study area may have formed in this way, while smaller sinkholes formed as the buoyant support was lost as base level was lowered, and the land surface subsequently collapsed.

Contemporary base level in the study area is now controlled by the Chiquibul River to the west and the Macal River to the east. The maximum relief between the highest point in the study area (approximately 600 m above mean sea level) and the Macal (320 m) and Chiquibul rivers (300 m) is 280 m. Taking into account the hydraulic gradient between the elevated portions of the Vaca Plateau and base level, the depth to the water table is probably greater than 250 m.

Cave Formation and Evolution

Caves in the study area contain both horizontal and vertical passages. The caves fall into the following genetic patterns: (1) blind vertical shafts, (2) vertical shafts connected to horizontal passages, (3) multiple drop vertical caves, (4) shelter caves, and (5) horizontal caves. Within some of these patterns, variations result from differences in site-specific geologic conditions, topographic position and evolution.

The majority of cave entrances are vertical and formed by dissolution along planes of structural weakness that extend to the surface. Some of the entrance shafts comprise the full extent of the cave, while others lead to horizontal segments of passage. These horizontal passages sometimes intersect other shafts, which in turn often intersect additional horizontal passage. Hence, some caves exhibit a stair-step profile in which the vertical extent of the cave is achieved by a series of drops offset by sections of more gently inclined passage (White, 1988).

Some caves are entirely horizontal in profile. Shelter type caves are dissolution pockets in the limestone bedrock that were exposed by erosion, or they formed by stoping within a surface exposure along planes of structural weakness. Other horizontal caves are remnants of meandering phreatic tubes which, in some cases, have been modified by vadose flow as regional base level was lowered. Some caves appear to have formed entirely within the vadose zone.

Certain cave patterns correspond with particular landscape positions, while others occur throughout the study area. Caves with vertical entrances generally occur on residual hill slopes, in the bottom of sinkholes, or on hilltops. They are rarely found in valley bottoms. The profiles of all types of cave in the study area indicate strong vertical control. This is attributed to the numerous fractures and possible faults within the bedrock. Because bedding planes are few, most caves have developed along vertical planes of structural weakness. Vertical caves are generally not exposed within dry valley bottoms because they have been filled with organic material, soil, and sediment from slope wash. The few vertical entrances not blocked by debris in valley bottoms are discrete recharge points that are kept open by shaft flow during the wet season. Shafts on hilltops are usually blind, and are blocked by breakdown.

In many caves, entrance shafts lead to segments of horizontal passage. The entrances to these caves are generally located on residual hillside slopes or sinkhole bottoms on side slopes. Many of the entrances are located at topographic positions not affected by slope wash, hence, they are not clogged with debris. The entrances in sinkhole bottoms are kept open by concentrated recharge during the wet season. The horizontal sections of passage generally follow the same trends as the lines of structural weakness; these passages probably formed by lateral chemical erosion during periods when the water table was stable. In many caves the horizontal passages connect to another shaft. These shafts formed as base level was lowered and recharge was focused vertically along lines of weakness, and the horizontal passages formed under a stable water table. Some caves have as many as four horizontal levels connected by shafts. The deepest cave has three horizontal levels which are connected by drops of 60 (the entrance shaft), 20, and 10 m.

Shelter caves occur in all topographic positions in the study area, but are least common on hilltops and most common on or at the base of residual hill slopes. Entirely horizontal caves generally occur on side slopes. A few horizontal caves in the study area appear to have formed entirely in the vadose zone. These caves are generally narrow, tortuous fissures formed by vadose flow moving along planes of structural weakness. Several horizontal caves contain segments of phreatic tubes indicating that they formed below the water table (Figure 8). These caves are, in some cases, located 50 meters above dry valley elevation and 200 meters above the contemporary water table. They formed at a time when base level was higher, contemporary valleys were not as incised or did not exist, and the net thickness of area bedrock was greater because the denudation process was not fully advanced. These caves also provide clues about the evolution of the karst landscape on the northern Vaca Plateau.

Uplift, faulting, and fracturing increased the secondary permeability in the rocks, and autogenic water began to dissolve the nearly pure (98% $CaCO_3$) limestone along these planes of structural weakness. During this period, the water table was fairly stable and close to the surface, and dissolution tubes began to form in the shallow phreatic system. As the valleys deepened, base level was lowered, the elevation of the water table decreased, interfluves developed between valleys, and caves in the shallow phreatic zone drained. Phreatic development continued deeper within the landscape, and drained phreatic tubes were modified by vadose flow. These passages developed the classic "keyhole" shape as canyons were cut into the bottom of phreatic tubes (Figure 8).

Valleys continued to widen and deepen, base level and the water table continued to lower, upper level cave passages were abandoned and phreatic development kept pace with the water table. Eventually, almost all surface flow ceased, and flow through the subsurface drainage network was enlarging only areas of preferential flow. Caves higher in the landscape shifted from an erosional stage to depositional and were filled with sediment and formations. Valley widening and incision slowed and the most significant areas of dissolution were below the water table which was probably >300 m below the surface interfluves.

The contemporary landscape contains numerous karst features that seem out of phase with their topographic position. Large shafts are located on residual hillside slopes with small catchments. Passages containing well developed phreatic tubes are located at the top of narrow interfluves tens of meters above valley level, and hundreds of meters above the water table. Large sinkholes with sizable catchments are located on steep residual hill slopes. These features are relicts of the former landscape in that they formed under conditions different from those at present. All of these features show clear evidence that they once transported substantial volumes of water. The contemporary residual hilltops were once in the phreatic zone below valley level. The now hydrologically abandoned shafts on valley side slopes in the contemporary landscape were probably once the focus of recharge waters moving from the surface to the subsurface within an active fluvial system. The sinkholes now located at mid-hill slope were also probably once part of the active fluvial system that existed in valley bottoms.

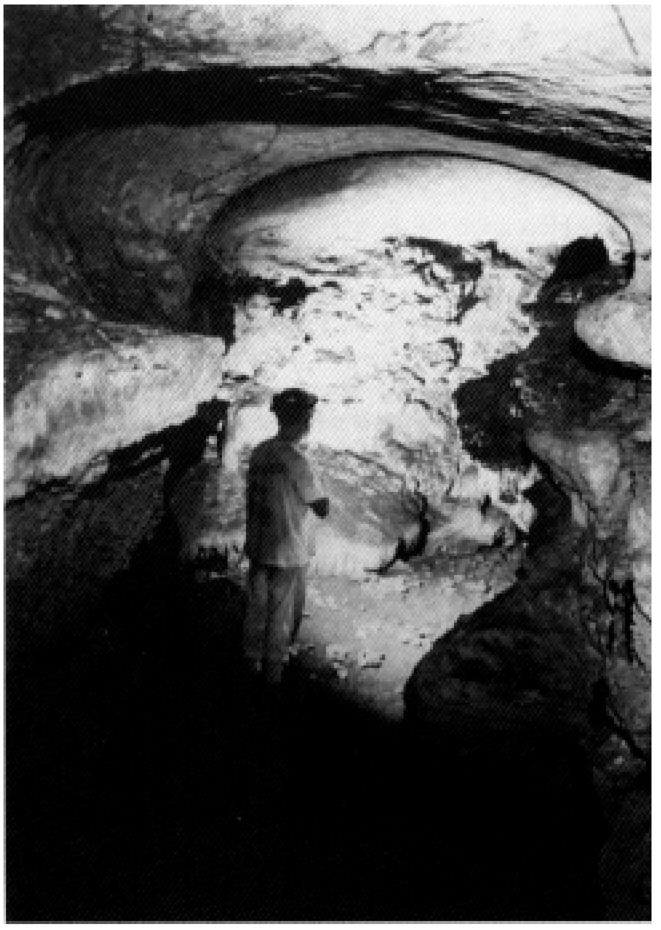

Figure 8. "Keyhole" passage in Bushman Cave. This type of passage formed first under phreatic conditions, and then as regional base level lowered a vadose canyon formed at the base of the tube.

Conclusions

Analysis of lithologic and geomorphic features within the 25 km^2 study area in west-central Belize revealed that the karst landscape is greatly influenced by the lithology and structure of the bedrock. The majority of limestone in the study area formed adjacent to a structurally emergent area, as a depositional breccia consisting mostly of lithoclasts of micrite with a sparry calcite cement. Variations in composition of the lithoclasts reflect local variations in the depositional environment. Geologic structures including faults, joints, and fractures formed during periods of uplift in and adjacent to the study area. These periods of uplift account for the existence of some tectonic breccias in the study area.

The geologic structures in and adjacent to the study area have similar orientations to karst landforms including solution valleys, depression long axes, and cave passages. This correspondence demonstrates the influence that structure has had on landscape and cave formation and evolution. The evolution of the surface karst landscape and the caves has also been greatly affected by base level modifications. The lowering of base level incised valleys, enhanced interfluve development, and caused caves within the interfluves to be truncated along valley sides and abandoned as active flow routes. The stair-step pattern of caves in the study area demonstrates that there have been periodic shifts in base level followed by periods of stability.

Through time, numerous landscape features were abandoned as active zones of solution as regional base level was lowered. They are now fossils representing the former landscape. By studying these features, and related petrology and structure, it was possible to gain a limited understanding of the formation and evolution of the northern Vaca Plateau's caves and karst landscape. Future research in this little studied area of Central American karst will provide additional information about karst processes in the tropics.

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