AN ABSTRACT OF THE THESIS OF Pam Eastlick for the Master o
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Title: Production and deposition rates of stromatolites o
the Asmafines River in southern Guam.

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Stromatolitic deposition has been noted in the stream beds of some of the rivers of southern Guam, one of the Mariana Islands in the western Pacific. To determine accumulation rates of this material, Plexiglas plates were attached to the stream bed with concrete nails at five sites along the upper Asmafines River. Plate sets (consisting of one plat at each site) were left in place for varying periods of time from 7 to 442 days. Some plate sets were designed to assess possible differences in accumulation rates in the rainy and dry seasons. Accumulated material was analyzed for weight, thickness, percent organic content and density as well as insoluble residue percentages. The pH and calcium content of the water were also measured. It was ascertained that stromatolitic deposition occurred at all sites but at very different rates. The amount of deposition appeared to be correlated with the presence or absence of limestone inclusions immediately upstream of th sampled site. Deposition occurred faster in the dry

season. Data indicate that the water of the Asmafines River is supersaturated with calcium bicarbonate much of the time and literature references indicate this is also true for most of the sites world-wide, where stromatolites form in freshwater.

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INTRODUCTION

The Mariana Island chain is composed of fifteen islands (Fig. 1, map drawn by H. Manner) and is located in the western Pacific, roughly 2200 km east of the Philippines, 2800 km south-southeast of Japan and 1900 km north of Papua New Guinea. These islands are the high points of a submarine volcanic ridge that developed during several episodes of volcanism as a result of the subduction of the Pacific plate at the Mariana Trench. The islands of Guam, Rota, Aguijan, Tinian, Saipan and Medinilla and several submerged banks are the remnants of a forearc that is no longer active while the remaining islands (and several submerged volcanos) are part of a new, active arc. All of these newer islands have volcanos that have been active in the Recent past (Tracey *et al*, 1964; Reagan and Meijer, 1984).

Guam is the southernmost island of the Mariana chain and its capital, Agana is located at 13°28′30"N and 144° 45′00"E. The northern half of the island is a raised limestone plateau composed of such permeable limestone that no rivers arise in it. The southern half is a intensely weathered volcanic upland (though the eastern coast is limestone and the higher peaks are capped with limestone) drained by several permanent streams (Fig. 2).

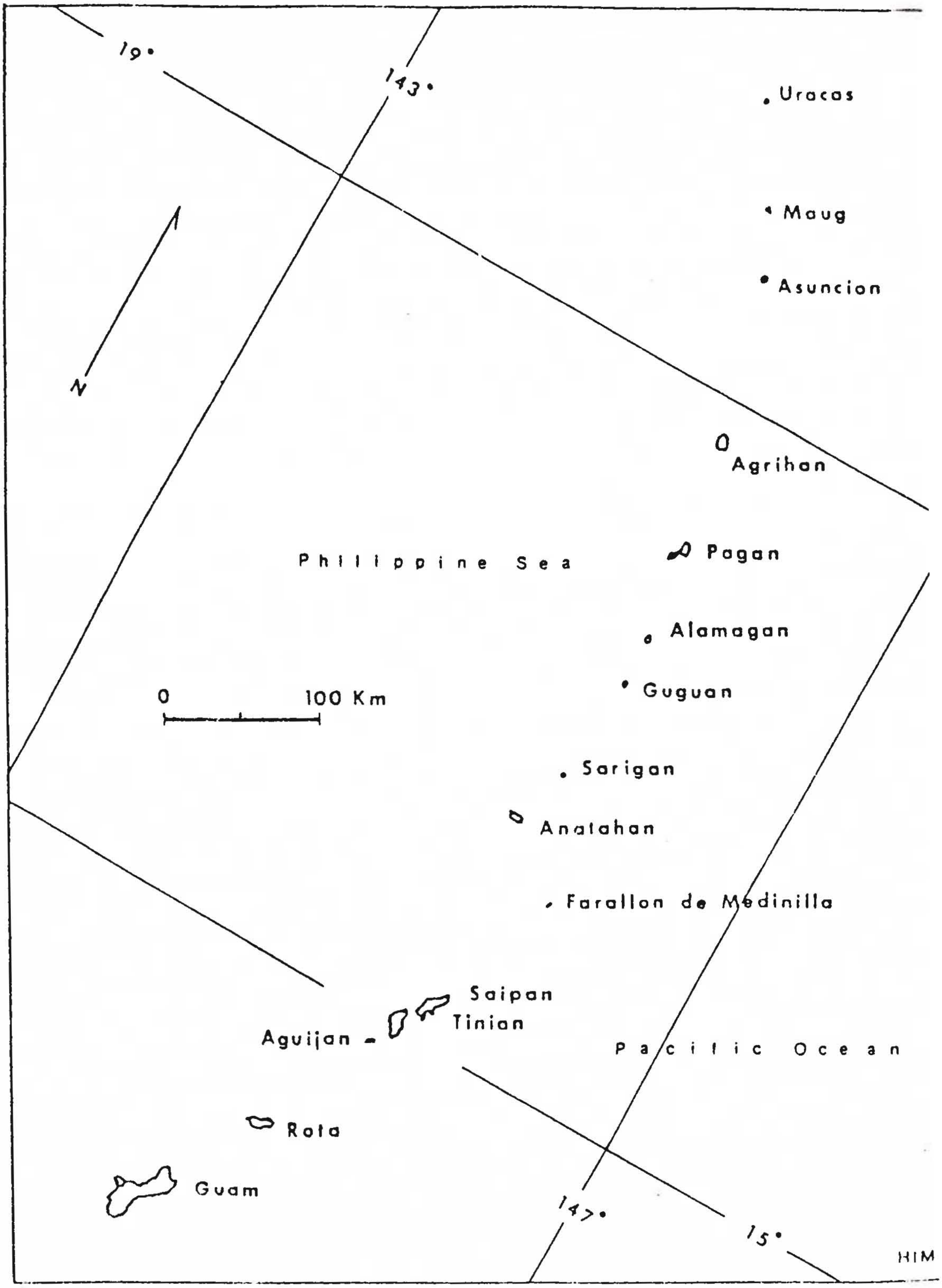


Figure 1. The Mariana Islands.

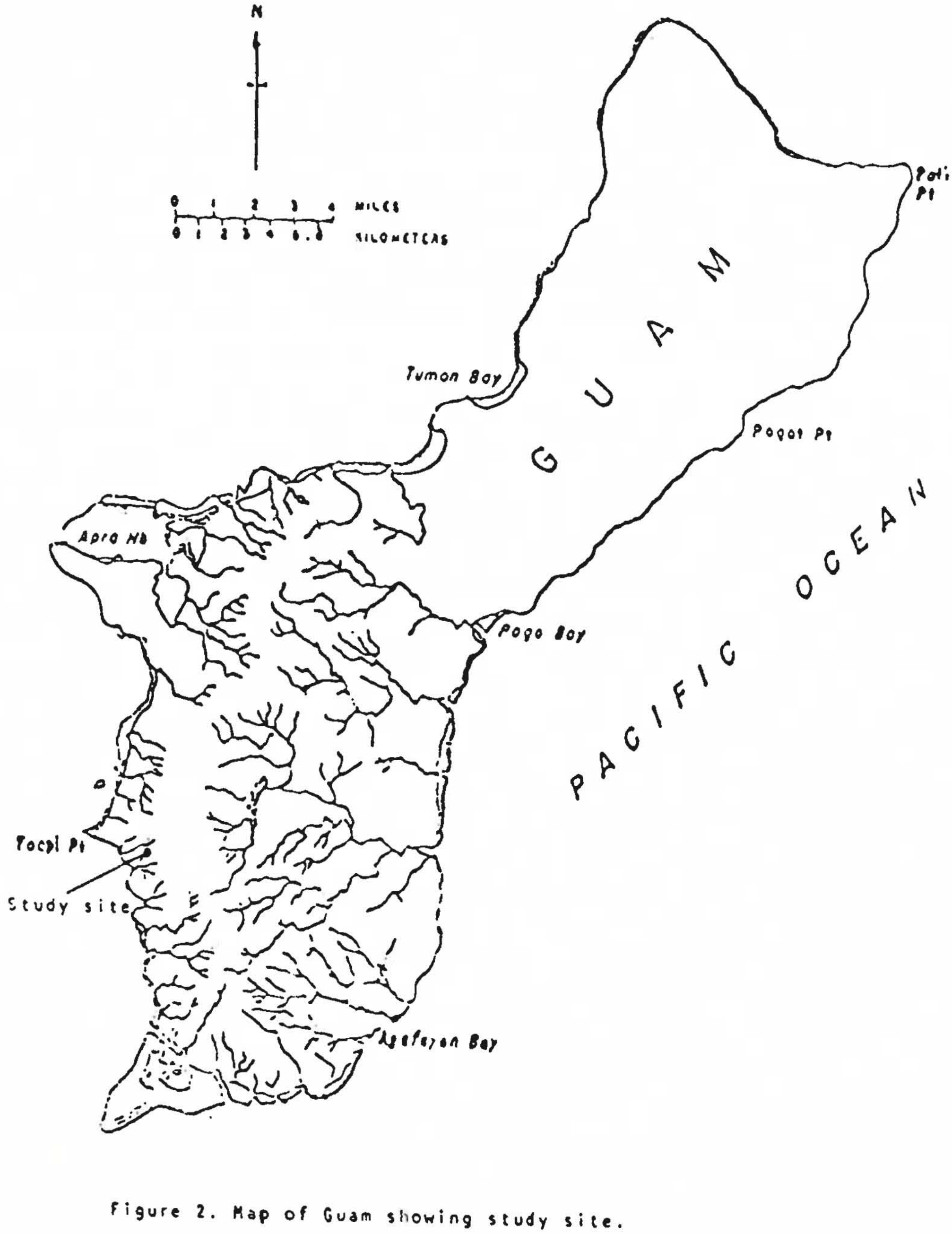


Figure 2. Map of Guam showing study site.

Although no published accounts exist, several people (R. Randall and A. Rinehart among others) have noticed the occurrence of stromatolite growths on the bedrock of many of the rivers which arise in the volcanic uplands of southern Guam. Their presence is discontinuous; not all streams have them and they occur sporadically along those streams which do have them. Superficially similar structures are known to occur on the Mariana islands of Rota (riverine) and Pagan (lacustrine).

The stromatolitic structures that occur in the beds of Gu streams are thick, well-bedded deposits that are typicall dome-shaped and occur most frequently at cascades. Analysis shows they are limestone and typically much lighter in color than the dark volcanic bedrocks of the stream. They can occur in such quantity that the bed of the stream may develop a pronounced convex profile. When these deposits are fractured, layers usually 1-3 mm thick are exposed. The layers are fenestrated, and depending or the age of the deposit are crumbly to well-indurated. Often organic matter such as plant leaves can be seen trapped between the layers.

The present study was designed to measure rate accumulatio of stromatolites presently forming along the upper Asmafines River and its tributaries (13°20′10"N and 144° 39′50"E) (Fig. 3) which have several areas of stromatoliti

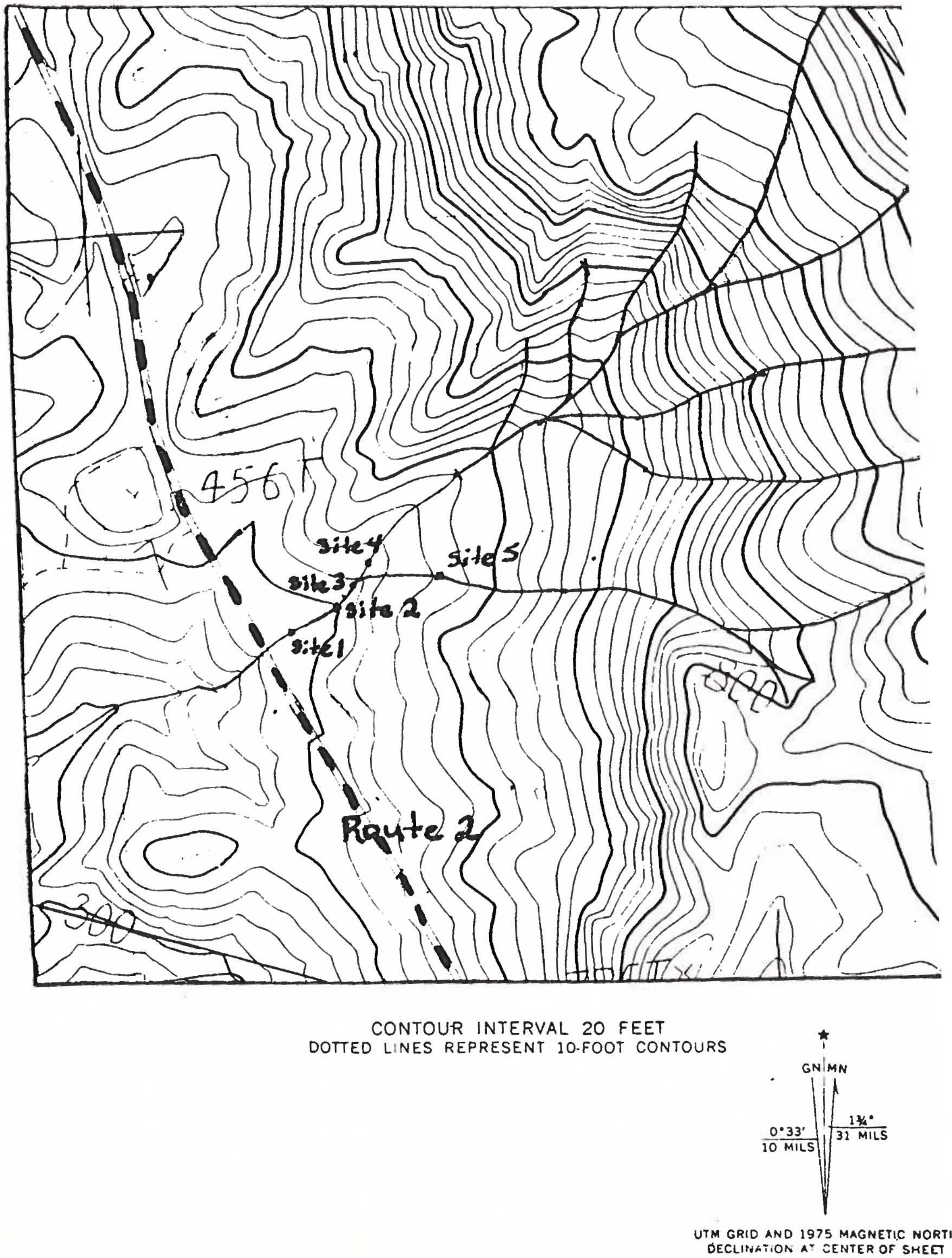


Figure 3. Map showing locations of Sites 1-5
(Enlargement of Agat Quadrangle, USGS map)

growth. The river is located on the west side of the island between the villages of Agat and Umatac and drains the western slopes of Mt. Lamlam, Guam's highest peak (405 m).

Maps and observations indicate that some of the flow of t Asmafines originates in an small lens of Maemong Limeston that is ca. 3.2 km east of Facpi Point and is visible fro the Agat-Umatac Road. This lens is the first Maemong deposit described in Tracey *et al*, (1964). They state "About 30 feet (9 meters) of Maemong limestone member is exposed between pillow lavas of the Facpi member. The Maemong is made up of alternating beds 3 to 12 inches thick, of fine-grained gray globigerinid-rich limestone a dense medium-grained white limestone containing foraminiferal and algal detritus in a fine-grained well-crystallized calcite matrix." There are several limestor lenses in the volcanic hills of southern Guam. These are believed to be remnants of deep forereef slope deposits that formed around the ancient volcanos and were buried by subsequent volcanic deposits.

Since of Guam's southern streams have short, steep gradients (the Asmafines River drops ca. 250 m in ca. 1 km stromatolitic deposition of any magnitude is unusual. Literature reports of freshwater stromatolites are infrequent. This study examined the accumulation rates of stromatolitic material at five different study sites alo: the Asmafines River from May 1988 to September 1989.

Organic content and density of the accumulated material were calculated and several factors that seemed to affect rate changes such as pH of the water, total rainfall, calcium and the bicarbonate ion in the water column and time of year were also examined.

As do the structures it has been used to describe, the te "stromatolite" has a long history. The word was first us by E. Kalkowsky in 1908 to describe the layered aspect of the rocks he was studying (Awramik, 1984; and Walter, 1976c). Since this first use, many definitions have been proposed. Awramik & Vanyo (1986) said stromatolites are organo-sedimentary constructions produced by photosynthet: microorganisms that trap, bind or precipitate sediment. Gerdes & Krumbein (1984) used the words "laminated rocks, the origin of which can clearly be related to the activity of microbial communities". Golubic & Focke (1978) characterized stromatolites as "laminated sedimentary rock with predominantly upward convex laminations. They are usually interpreted as organo-sedimentary structures, that originate at the sediment-water interface as a result of interaction between microbial populations and sediment".

Hartman (1984) said that stromatolites are "organosedimentary structures produced by microbial mats" He further defined microbial mats as three-layered structures with an upper layer of cyanobacteria, a middle layer of purple or green sulfur bacteria and a bottom lay of sulfate reducers. Semikhatov *et al* (1979) called stromatolites "laminated, lithified sedimentary growth structures that accrete away from a point or limited surface of attachment. They are commonly, but not necessarily, of microbial origin and calcareous composition". Pratt (1982) defined stromatolites as "organosedimentary structures produced by the activities c micro-organisms (mainly blue-green algae) that occur in sedimentary rocks ranging in age from Archean to Holocene"

Burne and Moore (1987) used the term "microbialite" to describe "organosedimentary deposits formed from interaction between benthic microbial communities (BMC's) and detrital or chemical sediments. Consideration of the term 'stromatolite' shows that it is currently used in at least three distinct ways: to refer to products of microbial sedimentation in general; to describe laminated structures of probable microbial origin; or to describe discrete laminated lithified bodies". Monty (1976) stated that many algal structures have now been discovered which cannot be called "stromatolites" and suggested Aitken's term "cryptalgal" be used to refer to this wide range of structures.

The definition provided by M.R. Walter (1976c) is the one used by many authors. He stated "Stromatolites are organosedimentary structures produced by sediment trappin binding and/or precipitation as a result of the growth an metabolic activity of micro-organisms, principally cyanophytes". Since this definition seems to fit the structures examined in this study, it is the one adopted for this report.

A review of the history of stromatolitic structures is an examination of the origin of life on Earth. Stromatolites provide the oldest known fossil evidence for life and for at least half the history of the solidified Earth, they ar the primary evidence for the existence of life.

The oldest known stromatolites are from the Warrawoona Group of western Australia (Groves *et al*, 1981; Lowe, 1980 and Walter *et al*, 1980), they occur in rocks that have bee dated at 3.5 gya (1 gya = 1 billion [10^9] years). As the oldest known sedimentary rocks date from 3.8 gya, life probably occurred very early in Earth's history.

Additional evidence for the early evolution of life are the banded iron formations which are vast fields of iron oxides apparently resulting from the production of free oxygen (Cloud, 1976; Mendelsohn, 1976; and Trudinger & Mendelsoh 1976). According to current theory, there could have bee little to no free oxygen present during the early history of Earth (Chapman & Schopf, 1983). The banded iron formations imply that enough free oxygen became available to combine with existing iron to form iron oxide. Such free oxygen was presumably a product of living organisms that engaged in aerobic photosynthesis - since anaerobic photosynthesis does not produce free oxygen (Cloud, 1976; Hartman, 1984; LaBerge, 1967; Veizer, 1983; and Walker *et al*, 1983). The largest banded iron formations were deposited ca. 2.5 to 1.9 gya but the earliest occurred >3.76 gya (Cloud, 1976; Gebelein, 1976b; Schopf *et al*, 1983). The banded iron formations and the earliest known stromatolites (which contain microfossils) imply that life evolved before the 3.8 gya age of the oldest known rocks.

Archean stromatolites are comparatively rare; Walter (1983) mentions only eleven examples: the Warrawoona Group (mentioned above) and three other sites in Australia, the Onverwacht of South Africa (Engel *et al*, 1968), the Bulwayan of Zimbabwe (Schopf *et al*, 1971), the Ventersdorp Supergroup and the Insuzi Group in South Africa and three sites in Canada. Stromatolites became common after the Archean/Proterozoic boundary (ca. 2.5 gya) and many authors report stromatolites from the Proterozoic (Awramik, 1984;

Awramik & Semikhatov, 1979; Barghoorn & Tyler, 1965; Barghoorn *et al*, 1965; Byerly *et al*, 1986; Cloud, 1976; Cloud & Morrison, 1980; Donaldson, 1976; Engel *et al*, 196 Eriksson *et al*, 1976; Fenton & Fenton, 1937; Glaessner *et al*; 1969; Groves *et al*, 1981; Hartman, 1984; Hoffman, 1976a; Hofmann, 1975; Horodyski, 1976; Meinschein *et al*, 1964; Schopf, 1968 & 1975; Schopf & Barghoorn, 1967 & 196 Schopf & Blacic, 1971; Schopf & Sovietov, 1976; Schopf *et al*, 1971; Semikhatov *et al*, 1979; Serebryakov, 1976; Truswell & Eriksson, 1973; and Tyler & Barghoorn, 1954).

The laminated stromatolites themselves are not the only evidence for life. Cyanobacterial microfossils are found at many sites. Although rare in the Archean, microfossils have been found in the Warrawoona and Fortescue Groups in Australia (Schopf & Walter, 1983). Like the stromatolitic structures, microfossils are much more common in the Proterozoic. One of the most diverse assemblages is the microbiota of the Gunflint Iron Formation in Canada. Thes deposits date from approximately 2 gya (Awramik & Semikhatov, 1979; Barghoorn & Tyler, 1965; Cloud, 1965; an Tyler & Barghoorn, 1954). Barghoorn and Schopf (1966) described Proterozoic microfossils from South Africa. LaBerge (1967) reviewed microfossils from banded iron formations; Hofmann & Schopf (1983) listed at least forty occurrences of microfossils in rocks from 2.5 to 1.6 gya and Schopf & Walter (1982) stated that over 100 stromatolitic microbial biocoenoses have been reported fr the Pre-Cambrian.

In contrast to the vast age of the prokaryotes, the earliest known eukaryotic fossils date from deposits of 1 gya (Schopf & Blacic, 1971 and Schopf & Oehler, 1976) and fossils of metazoans do not enter the record until roughl 0.7 gya (Schopf & Walter, 1982). For 80% of Earth's history the banded iron formations and stromatolites and their microfossils provide the only evidence of life.

As metazoans increased, stromatolites declined abruptly ar have never regained their former dominance. As can be see from Fig. 4, however, stromatolite abundance appears to increase at major divisions of the time scale (*ie* between the Paleozoic and the Mesozoic). These divisions are draw at major extinction events which supports the hypothesis c Garret (1970) and others (Gebelein, 1976b; Awramik, 1971a) that stromatolite decline was caused by the evolution of burrowing metazoans that tore the algal mats to pieces before deposition could occur. Pratt (1982) argued that this concept is too simplistic and that Phanerozoic stromatolites are much more widespread throughout the fossil record than is commonly thought. He suggested that the decline had more to do with competition for space and a decrease in precipitable material in the water column caused by increased removal by metazoan animals and plants.

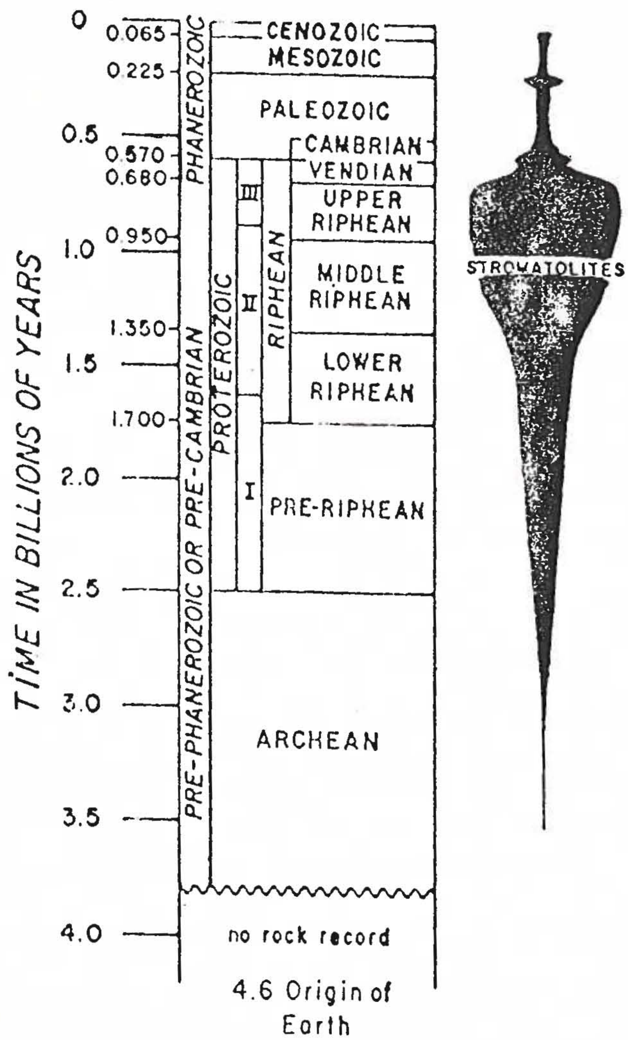


Fig. 4. Geologic time scale. The subdivision of the Riphean (1,700 to 570 Ma) into four periods is based on biostratigraphically distinctive stromatolites. The spindle diagram to the right depicts relative abundance of stromatolites plotted against geologic time. (Awramik, 1984)

Though comparatively scarce, stromatolites are found throughout the Phanerozoic (Abell *et al*, 1982; Ahr, 1971; Bertrand-Sarfati & Trompette, 1976; Clemmensen, 1978; Fairchild *et al*, 1973; Gebelein & Hoffman, 1973; Goldring 1937; Haslett, 1976; Horodyski, 1976; Johnson, 1937, 1940 1946; Krylov, 1982; La Porte, 1971; Link *et al*, 1978; Malan, 1964; Monty, 1981; Newell, 1955; Oder & Bumgarner, 1961; Otte & Parks, 1962; Playford & Cockbain, 1969; Playford *et al*, 1976; Pratt, 1982; Surdam & Wray, 1976; Twenhofel, 1919; and Wolfenden, 1958). Because there has been less geologic alteration of the rocks from Phanerozo: times, it has been possible to speculate about the habitat of many of the more recent stromatolites. Although many were thought to have formed in the sea, Phanerozoic stromatolites also occurred in other environments. Lacustrine stromatolites are reported from the Devonian ir Texas (Fairchild *et al*, 1973), the Triassic in Greenland (Clemmensen, 1978), the Eocene in Wyoming (Surdam & Wray, 1976), and the Pliocene in Kenya (Abell *et al*, 1982), California (Link *et al*, 1978) and the Altai Mountains on the Sino-Soviet border (Krylov, 1982).

Additionally, two sets of Archean stromatolites possibly formed in fresh water: the Ventersdorp (riverine pools) and the Fortescue (lakes) (Walter, 1983). One report of mid Pre-Cambrian stromatolites (Hoffman, 1976a) implies formation in fresh water since the described stromatolites apparently formed at the distal ends of alluvial fans.

Most references list cyanobacteria as the principal "constructors" of stromatolites. Cyanobacteria are prokaryotic organisms as they lack membrane-bound organelles. Photosynthesis occurs in thylakoids that are free in the cytoplasmic matrix. Cyanobacteria are generally more complex than the other prokaryotes and produce specialized exospores, endospores and akinetes (al reproductive structures) and heterocysts which are thought to be the site of nitrogen fixation (Dawes, 1981).

Evidence exists that not all stromatolites are cyanobacterial products. Some believe that Archean stromatolites were constructed by anaerobic bacteria (Cloud, 1976; Gebelein, 1976b; and Walter *et al*, 1972). However, some Archean stromatolites do show evidence (filament orientation) that phototatic organisms formed them (Walter, 1983). Filament orientation does not prove photosynthesis, however; Doemel & Brock (1974) showed that a similar stromatolitic filament orientation was produced by aerotaxis.

Anaerobic photosynthesis apparently developed earlier than 3.5 gya but cyanobacteria use a form of photosynthesis (Photosystem II) which produces free oxygen. Since the major production of free oxygen did not occur until the Archean-Proterozoic boundary (ca. 2.5 gya), it is possib: that at least some of the Archean stromatolites were bui: by organisms which employed only anaerobic photosynthesis (Chapman & Schopf, 1983; Gest & Schopf, 1983; and Schopf Walter, 1983). Hartman (1984) speculated that the bandec iron formations were produced by anaerobic photosynthesizers, not cyanobacteria.

Modern stromatolites have been described from thermal springs in areas too hot to support cyanobacteria. These structures are built primarily by the motile photosynthet bacterium *Chloroflexus aurantiacus* Pierson and Castenholz (Doemel & Brock, 1974 & 1977; Walter, 1976a; and Walter *e al*, 1972).

Eukaryotes can also form stromatolitic structures. Winsborough and Golubic (1987) described two sets of stromatolitic assemblages, one on a quarry ledge (Germany) and one in a shallow stream (Mexico) that were apparently formed by diatoms. Layers of cyanobacteria were interspersed with the diatom layers in the Mexican stream. Monty & Hardie (Andros Island; 1976) and Eggleston & Dean (Green Lake, New York; 1976) described diatoms as a part o the stromatolitic mats they studied. Weed (1889, in Walte: 1976b) reported that marshes surrounding the geysers in

Yellowstone National Park supported an abundant diatom flora which produced a layered sediment that was almost pure diatomite. Weed also said the diatom beds covered many square kilometers and were 2 m thick in some places. Diatom stromatolites probably date only from the Phanerozoic as no diatoms have ever been found in rocks from the Pre-Cambrian (Walter, 1976a).

Keating (1978) reported that over a five year period, diatom blooms in Linsley Pond, Connecticut, varied inversely with the levels of cyanobacteria, and that cell-free filtrates of cyanobacteria cultures inhibited the growth of diatoms in the laboratory. Apparently this was not the case in the double-layered stromatolites studied b Winsborough and Golubic (1987).

Klappa (1979) reported that some fossil stromatolites may not have formed in water at all but could have been formed on land by lichens. He listed several different circumstances which could induce lichens to form the characteristic layers of the typical fossil stromatolite. Lichen symbioses often includes a cyanobacterium as the "producer" partner of the symbiosis.

Despite evidence that other organisms (including multicellular eukaryotic algae) may build stromatolites, the majority of both ancient and modern forms are thought to have been produced by cyanobacteria. Many Proterozoi(microfossils are demonstrably cyanobacteria (Awramik, 19' & 1984; Awramik *et al*, 1976; Doolittle, 1982; Hofmann & Schopf, 1983; Schopf & Walter, 1982). A sheath-enclosed filamentous prokaryote described as "*Lyngbya*-like" has be found in the 2.8 gya Fortescue Group of western Australia (Schopf & Walter, 1982 & 1983). Schopf & Blacic (1971) describe the microfossils found in the Bitter Springs Formation of central Australia (ca. 1 gya) as being "...morphologically similar to and in some cases indistinguishable from modern-day forms." Empty sheaths, unicells (some dividing), elaborate filaments, and cells clusters have been described from many assemblages.

Clearly cyanobacteria were successful life forms in the past and evolved under very different conditions than thos found in most places on the Earth today. They can be four in many habitats but are most abundant in habitats that could be described as marginal, where abiotic factors are inclement to living things; in many of these marginal habitats they may be the only life-forms.

To survive in these marginal habitats cyanobacteria displa a wide range of tolerance to most abiotic factors. Cyanobacteria can survive brief periods at 100°C and thermophilic cyanobacteria found in thermal hot springs photosynthesize and grow at temperatures up to 70-73°C

(Brock, 1967 & 1976; Doemel & Brock, 1977; and Ward *et al* 1985). Freezing seems to be the lower limit although communities of *Calothrix scopulorum* found in Norway fix nitrogen at temperatures between -5° and 11° C (Whitton & Potts, 1982). Cameron reported in 1963 (Schopf & Blacic, 1971) that cyanobacterial components of lichens could survive to -80° C and photosynthesize at -30° C. Cyanobacteria also grow in abundance in permanently froze lakes in Antarctica (Wharton *et al*, 1983).

Cyanobacteria are euryhaline, tolerating salinity ranges from freshwater (0 ‰) to hypersaline in areas such as the Great Salt Lake (ca. 320 ‰ (Carozzi, 1961; and Halley, 1976)), the Dead Sea (ca. 315 ‰ (Schopf & Blacic, 1971)), and hypersaline arms of the ocean includi those in the Persian Gulf at Solar Lake (Sinai) (Krumbein *et al*, 1977) and the Gavish Sabkha (Sinai) with salinities of 50-360 ‰ (Gerdes & Krumbein, 1984), the Trucial coast with salinities of 42-70 ‰ and above (Kinsman & Park, 1976); in Mexico at Laguna Guerro Negro (Javor & Castenholz, 1981 & 1984) and Laguna Mormona (Baja California) with salinities to 70 ‰ (Horodyski, 1977; Horodyski & Von der Haar, 1975; and Horodyski *et al*, 1977) and the hypersaline areas of Shark Bay, Australia with salinities of 55-70 ‰ (Golubic, 1985; Hoffman, 1976b; Logan, 1960; and Playford & Cockbain, 1976). Whitton & Potts (1982) reported that endolithic cyanobacteria flourish in small pools along the Adriatic where salinity ranges from 240 ‰ to near freshwater after rain.

The reactions of cyanobacteria to light are complex. Cyanobacteria generally prefer lower light levels than those tolerated by the eukaryotes (Van Liere & Walsby, 1982). In stromatolites, light attenuation occurs rapidly and light levels at 3 mm depths within mats may be 3-4% of surface levels (Brock, 1976). Pentecost measured the attenuation of laser light in a stromatolitic deposit and found the light penetrated only 1% per millimeter (Van Liere & Walsby, 1982). Less than 1% of incident light penetrates the thick ice cover of permanently frozen lakes in Antarctica (Wharton *et al*, 1983) and during the long Antarctic winter, there is no light at all.

Cyanobacteria are also tolerant of high light levels and survived UV radiation that killed non-photosynthesizing bacteria. Cyanobacterial mats and stromatolites often occur in areas with no shade other than that provided by the mat/stromatolite. Certain species have survived exposure to 2.5×10^6 R of gamma radiation (the absolute limit for eukaryotes is less than 2×10^5 R) and X-ray radiation of 2×10^5 rads; they are the most X-ray tolerant organisms known. Cyanobacteria appear to carry multiple copies of their genome (Herdman, 1982); these aid in the repair of damage caused by mutagens. If one copy of the genome is damaged or destroyed, there are other identical copies to provide the proper template. There wa no ozone layer when cyanobacteria developed and these multiple copies plus their abilities of self-shading with both calcium sheaths and pigments probably enabled them tc tolerate solar radiation far in excess of anything known today (Schopf & Blacic, 1971).

Although they tolerate alkaline pH ranges (to 10.5-11) cyanobacteria are unable to grow at a pH of less than 4 an appear to be limited by acidic conditions (Brock, 1973 & 1976). Acid rain not only destroyed the calcareous nodule described by Golubic & Fischer (1975) but the organisms that formed them as well. Their tolerance for the upper p levels may, however, give then an advantage over eukaryoti algae in alkaline environments (Gibson & Smith, 1982).

Cyanobacteria have been found 400 m deep in the ocean and growing as endoliths on mountains more than 5100 m above sea level. They are extremely resistant to desiccation an grow in the Atacama desert in Chile where it rains approximately every 50 years. A specimen of *Nostoc* was revived and grew after 88 years as a dried herbarium specimen. It was redried and revived again 19 years later (Schopf & Blacic, 1971). Oehler (1976) artificially fossilized *Lyngbya majuscula* and produced microfossils that resembled those actually found in Proterozoic rocks.

Just as cyanobacteria are found in many modern habitats, stromatolites are not limited to being "relicts of the past". Black (1933) made the first widely-recognized report of modern stromatolites, describing several different types from freshwater to haline environments. Prior to Black's study, it was believed ancient stromatolites formed in fresh or brackish water because cyanobacteria could precipitate calcium carbonate in non-marine environments. Black's report of present-day marine forms, combined with the discovery that many of the ancien stromatolites were formed in the sea, switched the focus o stromatolite study to marine forms (Awramik, 1984). Actually, modern stromatolites are found in many habitats.

The most widely publicized stromatolites in recent years are those of Shark Bay in western Australia (Awramik & Vanyo, 1986; Golubic, 1985; Hoffman, 1976b; Logan, 1960; Playford, 1980; and Playford & Cockbain, 1976). These stromatolites occur in the hypersaline shallow arms of a bay where tidal action and flushing are minimal. This is an extremely restricted environment and there is limited animal life. This led to the misconception that stromatolites could form only in environments with restricted animal life which supported the idea that grazing animals caused the stromatolitic "crash" at the onset of the Phanerozoic (Fig. 4).

Living stromatolites occur in less restrictive environments. Modern marine stromatolites range from subtidal forms off the coast of West Africa (Schwartz *et al*, 1975) and in the Caribbean (Bathhurst, 1967; Dean & Eggleston, 1975; Dill *et al*, 1986; Gebelein, 1969 & 1976a; Golubic & Focke, 1978; Sharp, 1969; and Simmons *et al*, 1985) to intertidal forms in the Middle East (Krumbein, 1979) and the Caribbean (Gebelein, 1976a). Stromatolites from hypersaline environments similar to that of Shark Bay were described from the Persian Gulf (Gerdes & Krumbein, 1984; Kinsman & Park, 1976; and Krumbein *et al*, 1977) and off the coast of Mexico (Horodyski *et al*, 1977; Horodyski Von der Haar, 1975; and Javor & Castenholz, 1981 & 1984). Stromatolites also occur in the Great Salt Lake in Utah (Carozzi, 1961 and Halley, 1976). Microbial mats formed by non-photosynthesizing bacteria are found near deep-sea thermal vents (Jannasch & Wirsen, 1981).

Freshwater cyanobacterial stromatolites (and those formed by non-photosynthesizing bacteria) are found in hot springs, a reflection of the temperature tolerance of the cyanobacteria that form them (Walter, 1976b; Walter *et al*, 1972; Walter *et al*, 1976; and Ward *et al*, 1985); they are also found in marshes (Monty & Hardie, 1976), and there are several examples of modern lacustrine stromatolites. Brunskill (1969) and Eggleston & Dean (1976) studied the stromatolites that occur as lobate overhanging ledges around the periphery of Green Lake, New York. Pentecost (1985) described stromatolites from another of New York's Finger Lakes and Osborne *et al* (1982) described stromatolites from brackish, carbonate-saturated Walker Lake in Nevada. Stromatolites also occur in similar lake in Australia (Von der Borch, 1976; Von der Borch *et al*, 1977; and Walter *et al*, 1973).

Of all the marginal habitats described for modern stromatolites, probably the harshest conditions exist in the frozen lakes of the Antarctic. These lakes are cover with permanent ice 3-6 m thick and cyanobacterial mats gr on the lake bottoms to a depth of at least 30 m where lig levels are less than 1% of those at the surface. There a no macrometazoans present. Several types of mats and stromatolites are described ranging from mat pieces frozen in the ice to columnar benthic stromatolites that are calcified to varying degrees depending on the amount of alkalinity in the lake. Pinnacle mats similar to those described for hot springs (Walter *et al*, 1976) and some ancient forms are found in some of the lakes and aerobic and anaerobic prostrate, non-calcifying mats are also described (Canfield & Green, 1985; Simmons *et al*, 1985; an Wharton *et al*, 1983).

Stromatolites are occasionally reported from freshwater streams. Roddy described "calcareous nodules" in Little

Conestoga Creek, Pennsylvania, in 1915; in 1966, Golubic Fischer (1975) began an examination of these encrustation: By 1969, acid rain had lowered the pH of this stream to tl point that nodule formation ceased completely and the remaining nodules were being destroyed by solution. Fritsch & Pantin (1946) found unattached calcareous nodul‹ in a drought-dried creek in Britain; they decalcified som‹ of them and produced a soft gelatinous mass the same size as the original nodule. Both cyanobacteria and green alg‹ were found in this mat.

Pentecost (1985) described five freshwater sites; two were seepage areas in the tower karst of southeast China, two were streams in Great Britain and one was a "calcareous" Finger Lake in New York. Cyanobacteria only occurred in the mats at the Chinese sites but eukaryotic green algae were found at the stream and lake sites. Laminations parallel to the stromatolitic surface were found at all sites except one of the karst sites in China.

Stromatolites have also been found in freshwater streams o the island of Guam and this study was made in an attempt t learn more about their growth rates and factors which may affect that growth.

MATERIALS AND METHODS

Five sites were chosen along the course of the upper Asmafines River (Fig. 3). Site 1 was located 23.1 m from the east side of a culvert which allowed the river to pass under the Agat-Umatac road (Route 2) and contained a cascade which fell roughly 75 cm to the surface of the pool. Site 2 was located 31.5 m upstream from Site 1 (54. m from the culvert) and contained a large cascade which fell ca. 4 m to the surface of the pool and was ca. 3 meters wide. Site 3 was located 20.5 m upstream from Site 2 (75.1 m from the culvert) at the beginning of a small open area and contained a small drop of ca. 40 cm. A unnamed tributary (Stream 1) joins the Asmafines ca. 6 m above Site 3. Site 4 was located 21.3 m upstream from Sit 3 (96.4 m from the culvert) on another small unnamed tributary (Stream 2) and contained a cascade ca. 1.4 m hig which emptied directly into the Asmafines. Site 5 was located on Stream 1, 113.8 m upstream from Site 3 (188.9 m from the culvert) and had a cascade ca. 2 m high. (Measurements from the culvert cannot be reproduced. The entire culvert area was altered and expanded during reconstruction of the Agat-Umatac road in 1990 and the cascade at Site 1 was destroyed.)

To determine accumulation rates of the deposition of stromatolite material along the beds of the Asmafines Rive1 and its tributaries, Plexiglas plates of known dimensions (most of the plates were ca. 5 cm wide, 15 cm long and 6 m1 thick) and weight were attached to streambed rocks with concrete nails. Most of these plates were scored along opposite diagonals and the top edges of the plates were beveled so that water would flow over the surface and not arc over the top. A plate was placed at each site and those five plates constituted a set. Thus the plate designated "11-3" is the plate from the eleventh set placec at Site 3. Each plate set was left attached to the bottom for periods of time ranging from seven to 442 days.

When each plate was removed, it was air-dried in an Imperial II laboratory incubator at 37^{o}C and then weighed using a Mettler H10 analytical balance. The thickness of the deposited material was measured with calipers at ten standardized points (Fig. 5) and the average thickness determined. These data and the areal measurements were used to calculate the density (D = M/V) of the material.

Organic content was calculated by burning a known weight o1 material in a Cyberon Thermaline muffle furnace at 450^{o}C for five hours. The material was then reweighed and the difference reported as a percentage of the unburned material.

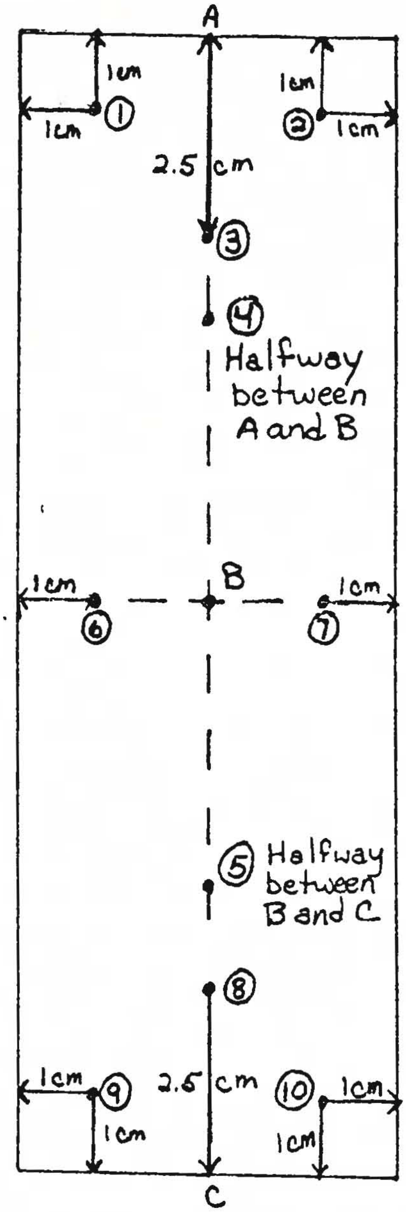


Figure 5. Standardized measurement points for material thickness. (Plate sizes varied)

pH readings were taken at the top & bottom of each cascade (except Site 5) and at the culvert using a Cole-Parmer digital pH wand (listed accuracy: $\pm$0.01 pH units, $\pm$1 digit). Range readings were confirmed using a Markson Selectro Mark 4503 pH meter located at the Water and Energy Research Institute of the Western Pacific (WERI).

Water chemistry analyses were conducted at WERI according to APHA standards (APHA, 1985). Calcium and magnesium data were obtained with a Perkin-Elmer Atomic Absorption Spectrophotometer 560 using flame atomization according to standard operating procedures.

Insoluable fraction data were determined by dissolving a known weight (ca. 0.5 g) of powdered deposited material in 50 ml of 0.1 N HCl. After ca. 2 hours, 1.5 ml of 6 N HCl were added to each sample to complete the dissolution process. Three replicates were vacuum filtered using AP 4 Millepore glass filters (pore size unspecified) of known weight and three replicates were filtered using HA membrane filters of known weight with a 0.45 micrometer pore size. Samples were then dried at 104^{o}C for 3 hours and reweighed. Residue weights were reported as a percent of the original powdered deposit.

Stream flow meter readings were taken using a Teledyne Gurley flow meter and rates were calculated according to instructions which accompanied the instrument. Rainfall data were obtained from the National Weather Service on Naval Air Station; data from the Agat station were used.

RESULTS & DISCUSSION

There was deposition of stromatolitic material on most of the Plexiglas plates placed for the study that accrued in similar fashion on those plates where it occurred.

Figure 6 is a picture of Plate 15-5, a 7-day plate placed in the rainy season. There was no measurable growth. The plate is still translucent and the information written on the back (plate weight & dimensions) is clearly visible.

Generally, within one to two weeks, a tan or reddish frosting appeared on the plate and the material became opaque, obscuring the writing on the back of the plate (Figs. 7 & 8). After three to four weeks, the buildup was noticeably thicker and had the texture of fine sandpaper (Figs. 9 & 10). On many of the plates, small sand-sized areas appeared which may have been trapped grains of sand or perhaps sites of increased deposition (Figs. 11 & 12). Small structures that were shaped like bracket fungi also appeared (and were subsequently overgrown) on the beveled surfaces of some plates.

Differences in deposition rates between the smooth surface of the plate and the incised grooves were usually apparent after one month. On some plates (most notably Plate 4-4, Fig. 13) the smooth surface remained relatively free of

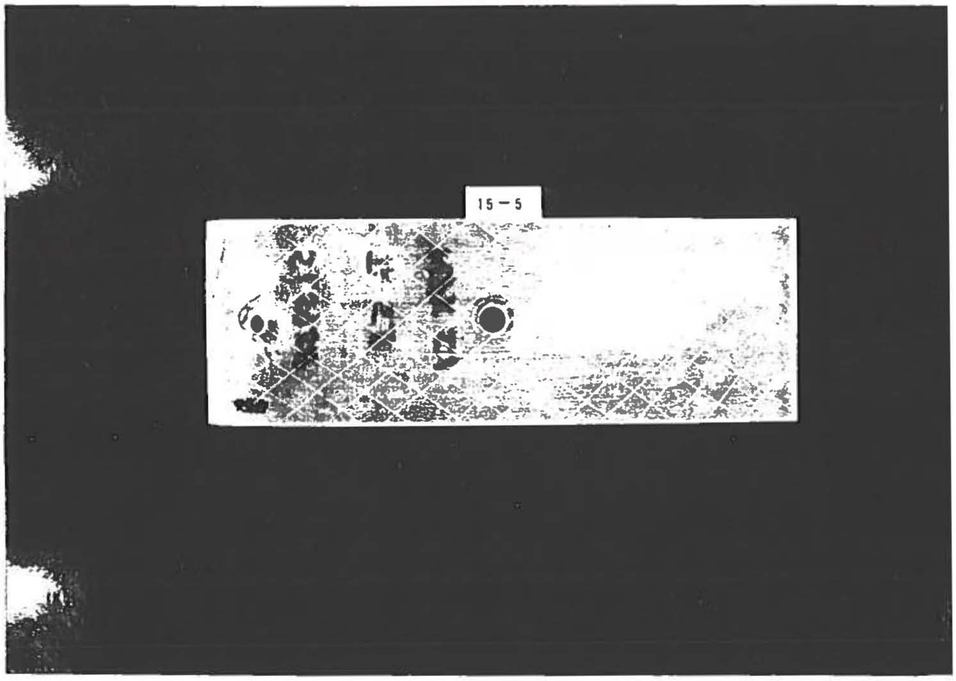


Figure 6. Plate 15-5. A 7-day plate.

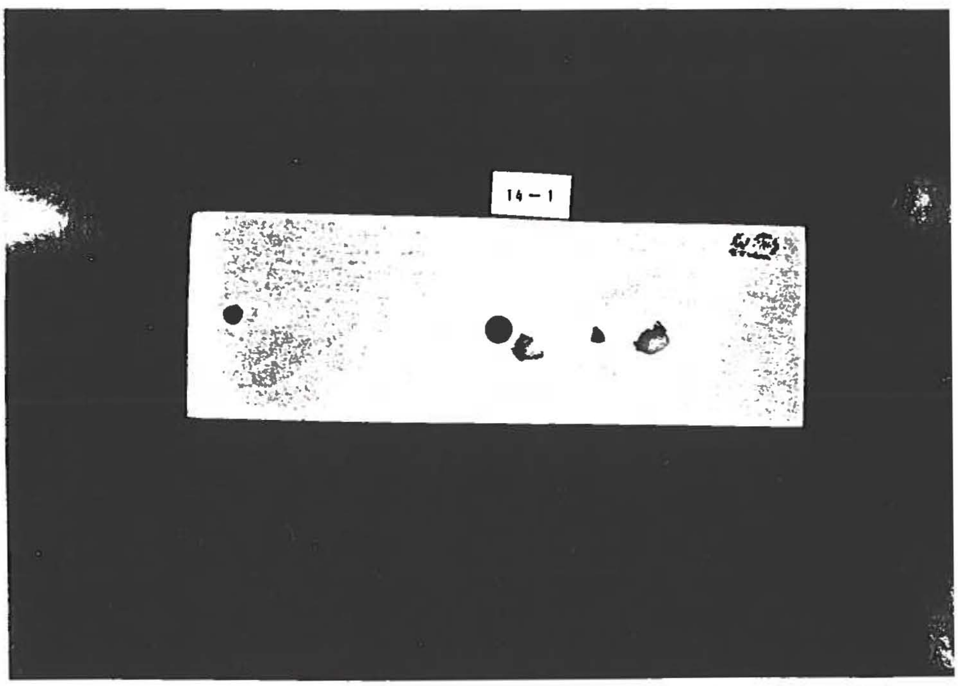


Figure 7. Plate 14-1. A 14-day plate.

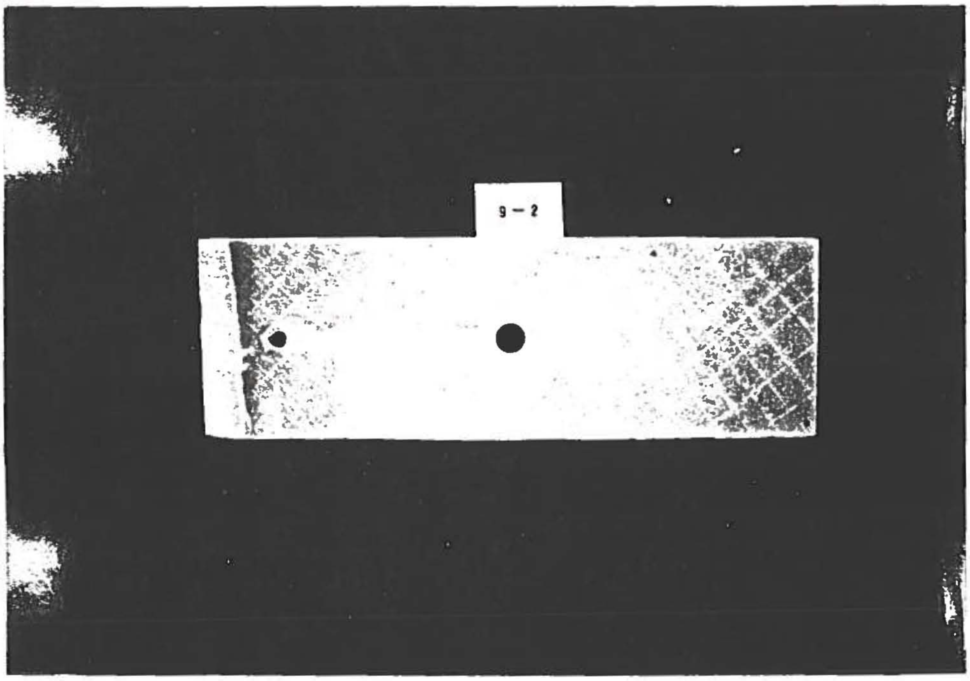


Figure 8. Plate 9-2. A 15-day plate.

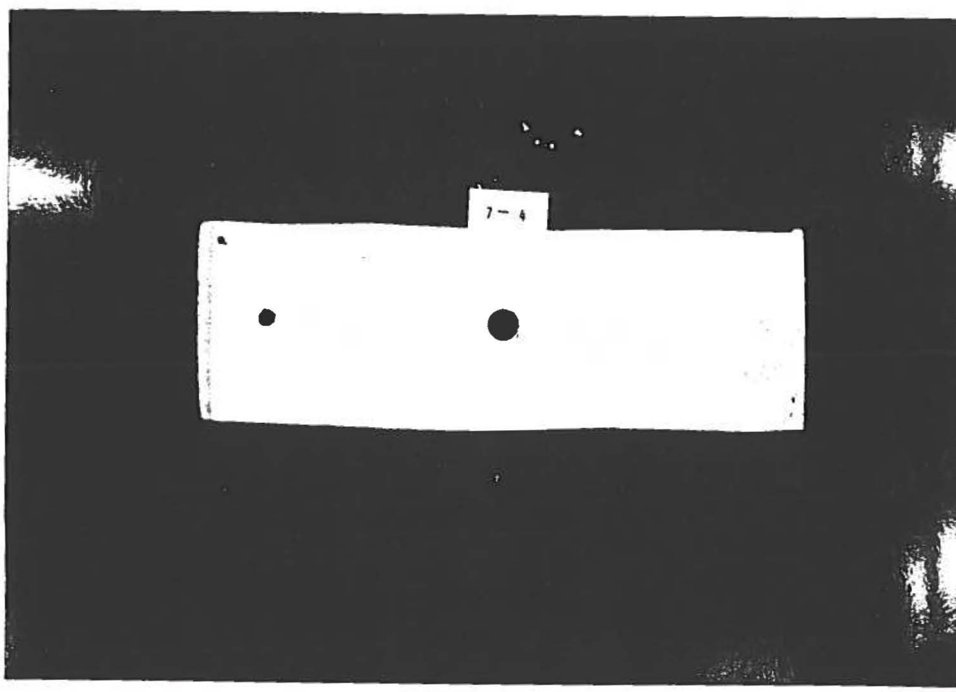


Figure 9. Plate 7-4. A 21-day plate.

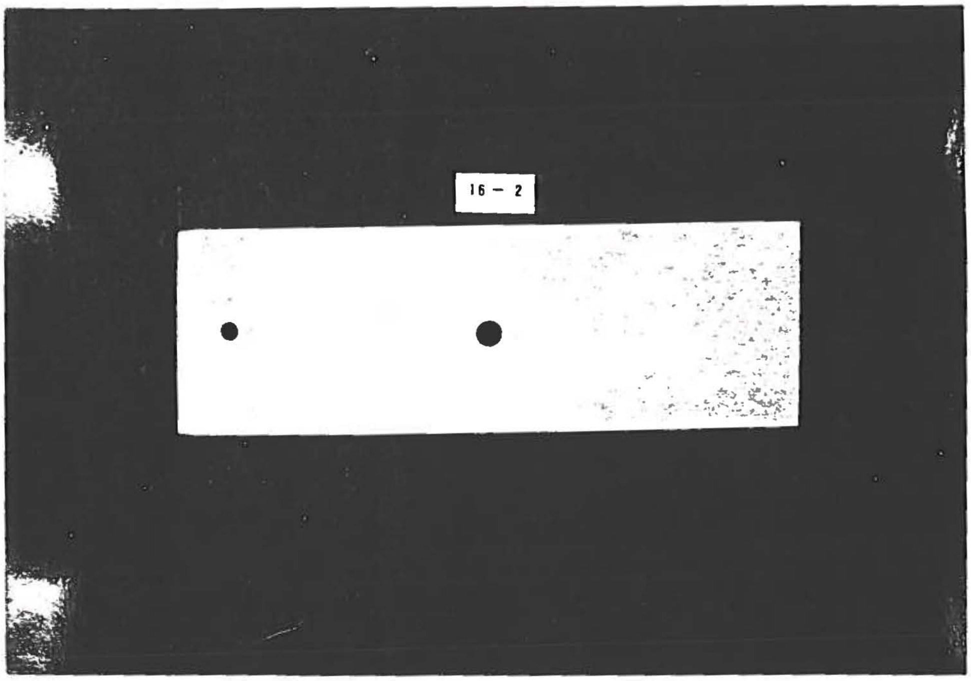


Figure 10. Plate 16-2. A 28-day plate.

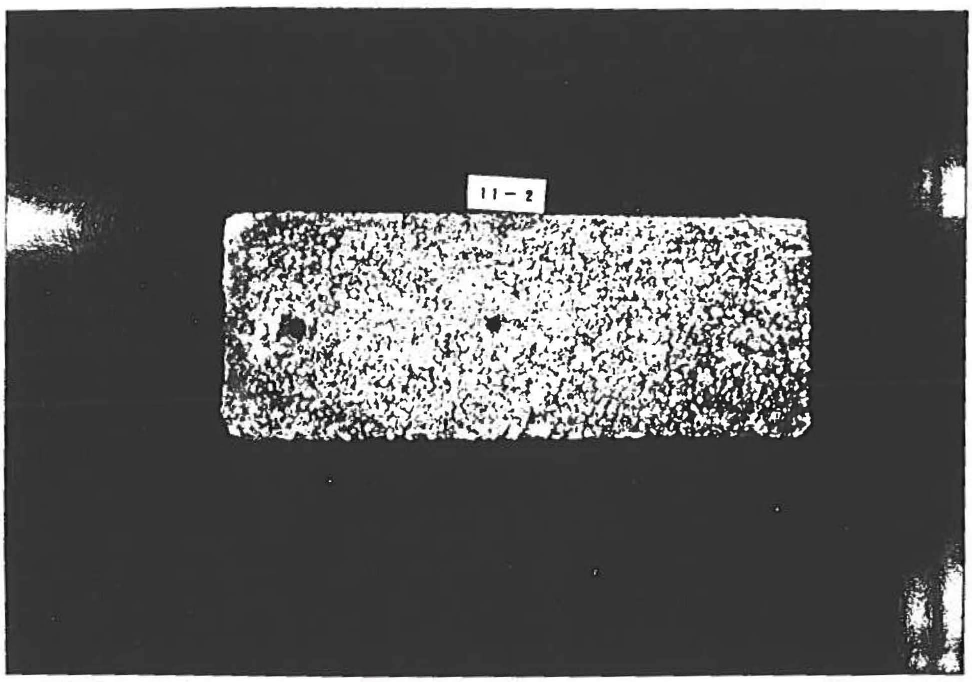


Figure 11. Plate 11-2. A 119-day plate.

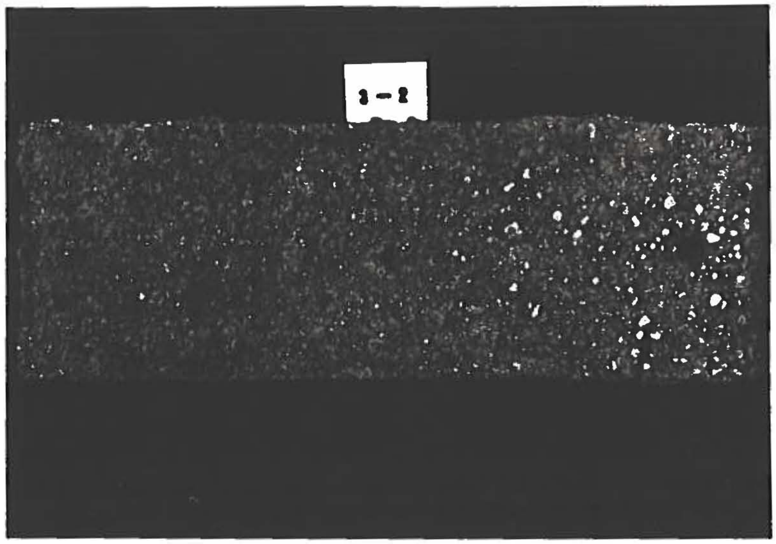


Figure 12. Plate 3-2. A 162-day plate.

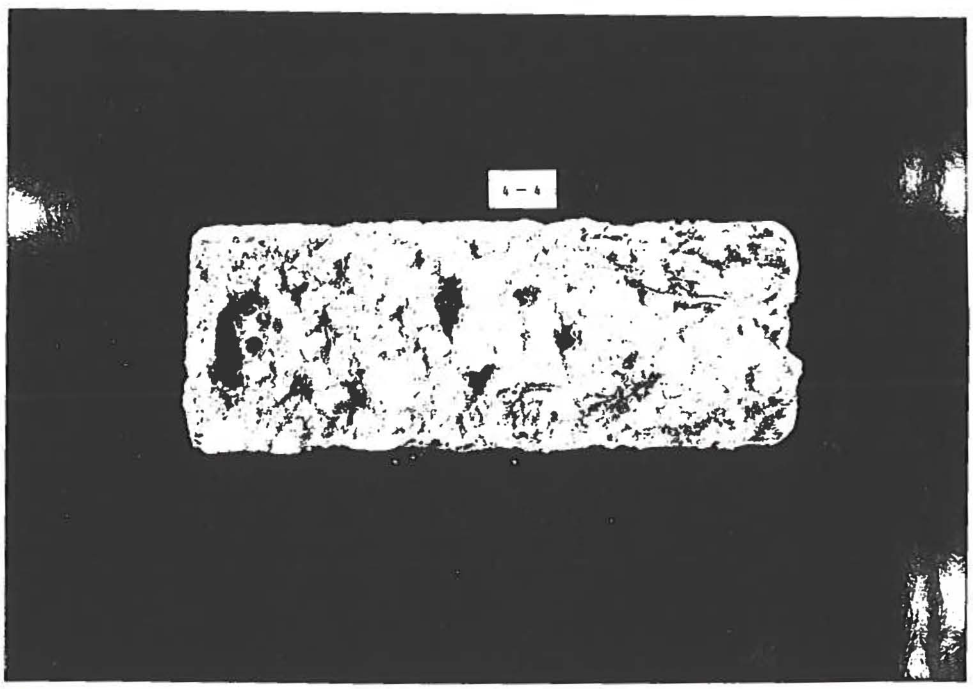


Figure 13. Plate 4-4. A 182-day plate.

deposition while large quantities of material were deposited along the grooves. This gave Plate 4-4 a trellised appearance since the plates were scored on opposite diagonals creating a diamond pattern.

By the end of two to three months, plates were generally uniform in appearance and were usually lighter in color than the underlying substrate (Fig. 14). At this point th edges of many plates were being overlapped by deposition o the surrounding substrate and the plate surfaces felt like rough sandpaper.

After three to six months, many plates had edges completel overlapped (Figs. 15 & 16). Plate 3-4 (Fig. 17) was totally covered by stromatolitic growth. The surfaces of all six-month and year plates on which substantial deposition occurred (Figs. 18, 19, 20 & 21) were for the most part indistinguishable in appearance and to the touch from the adjacent bedrock deposits (Plate 4-4 [Fig. 13] wa a notable exception). All of these plates had their edges overgrown and the case of Plate 1-4 (Fig. 22), no trace of the plate's location was visible on the surface of the cascade.

Abrasion of previously deposited material was evident on many plates and its severity ranged from shallow scratches to deep gouges (Figs. 23 & 24). Material was knocked from

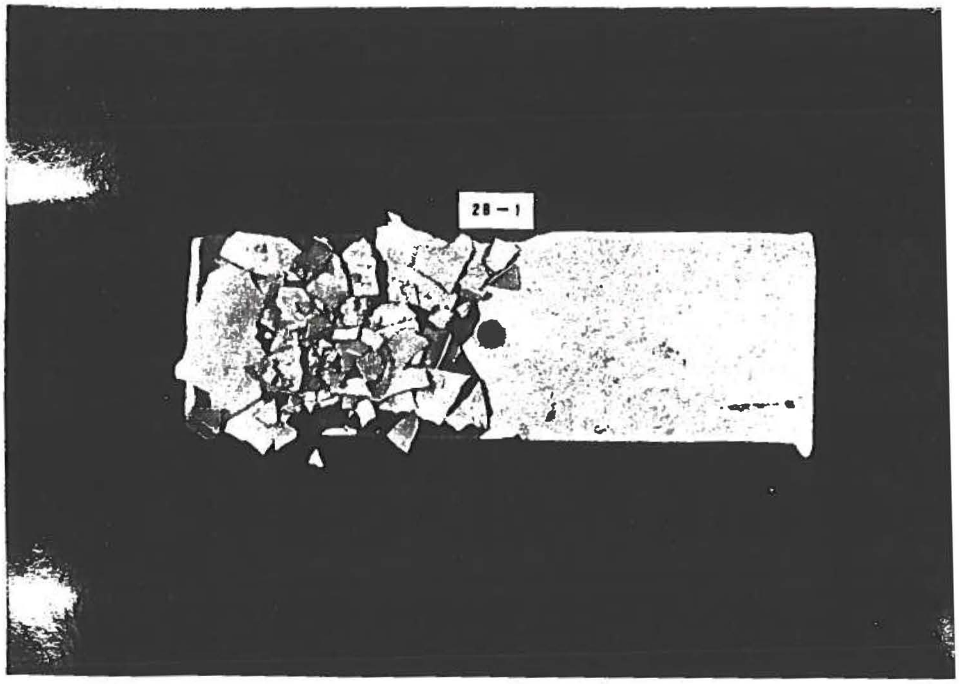


Figure 14. Plate 2B-1. An 80-day plate.

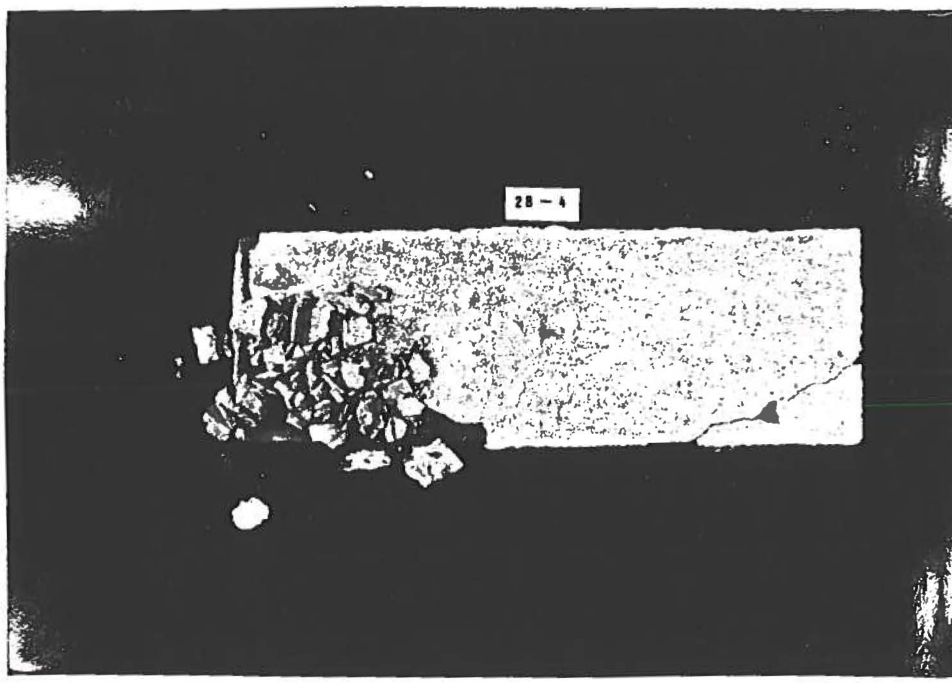


Figure 15. Plate 2B-4. An 88-day plate.

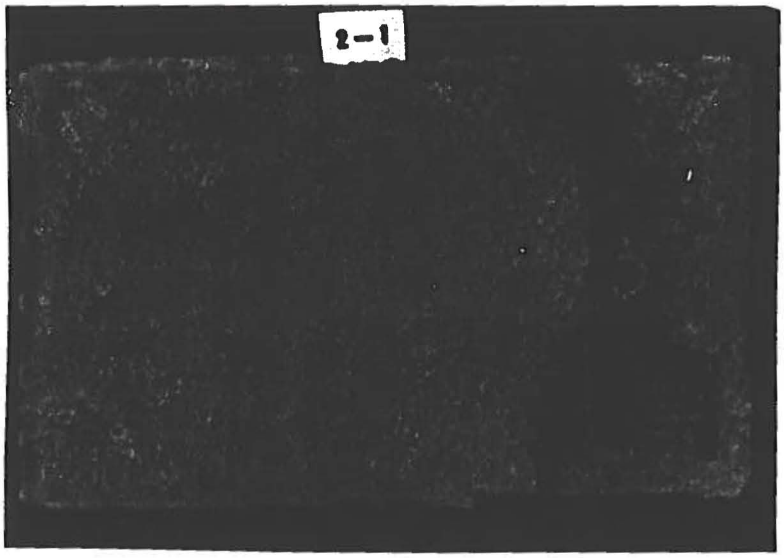


Figure 16. Plate 2-1. A 164-day plate.

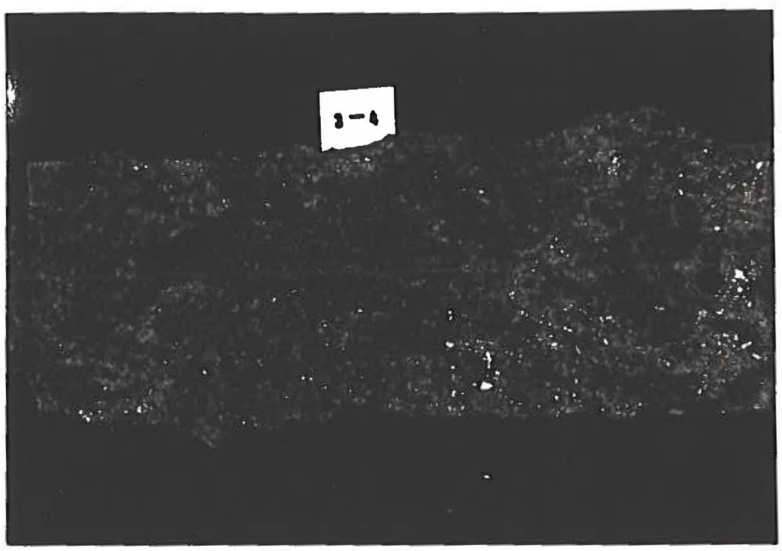


Figure 17. Plate 3-4. A 162-day plate.

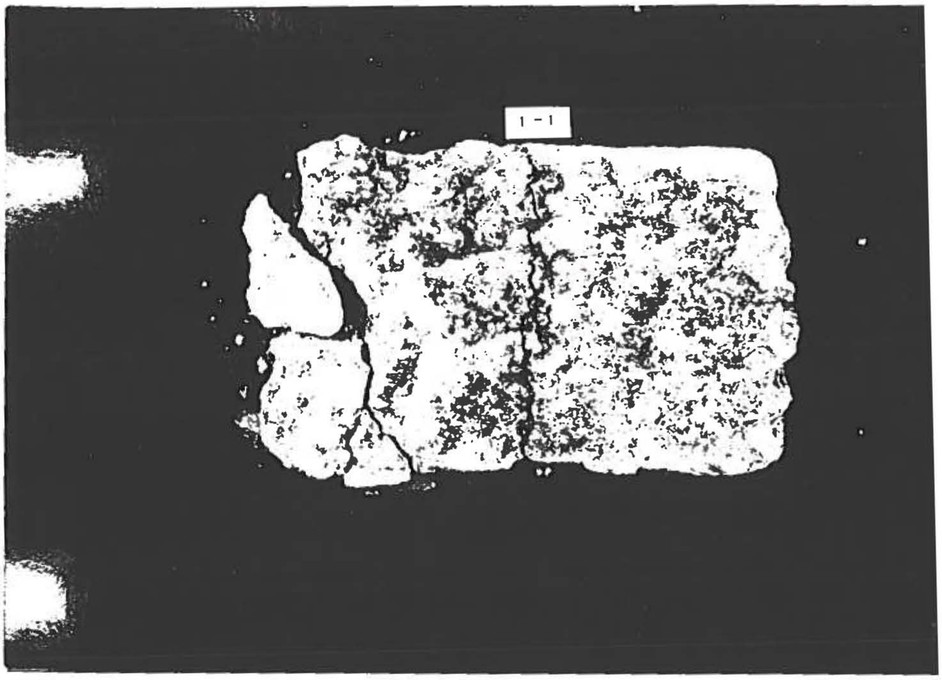


Figure 18. Plate 1-1. A 442-day plate.

Figure 19. Plate 1-4. A 442-day plate.

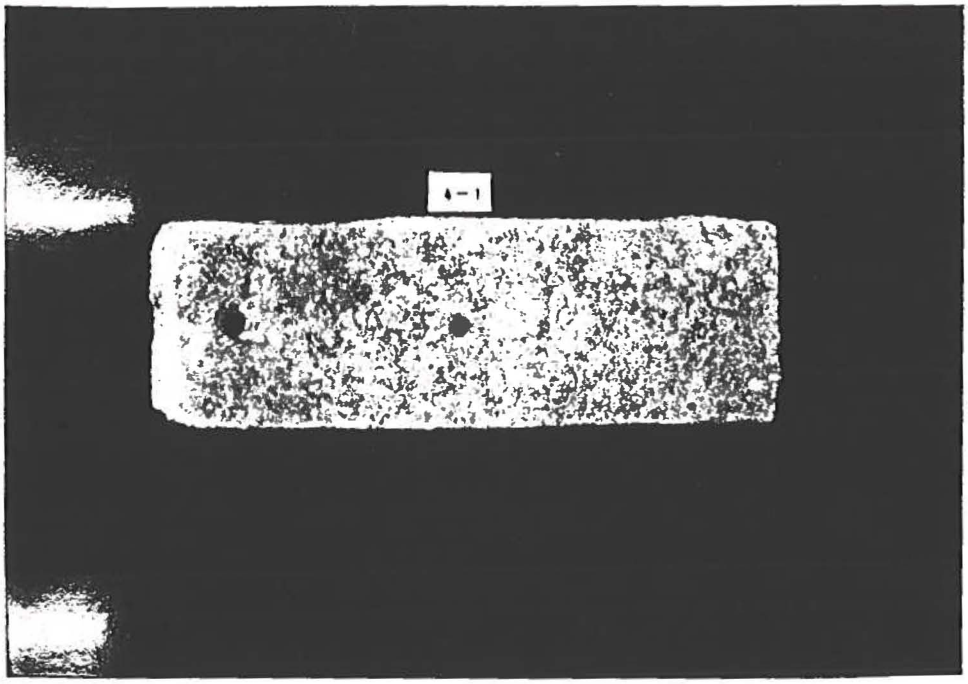


Figure 20. Plate 4-1. A 182-day plate.

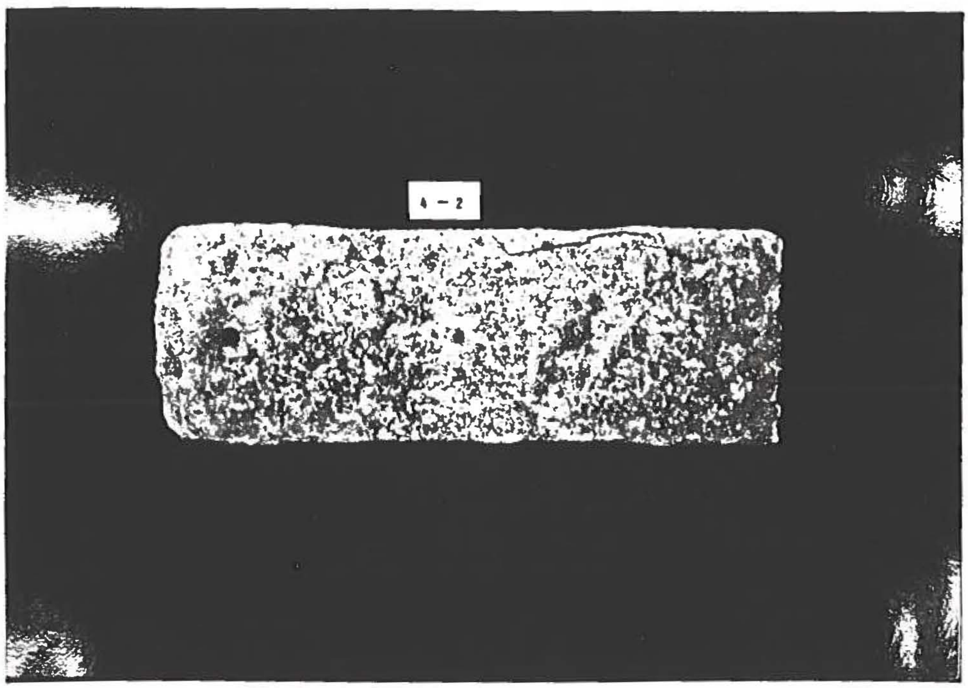


Figure 21. Plate 4-2. A 182-day plate.

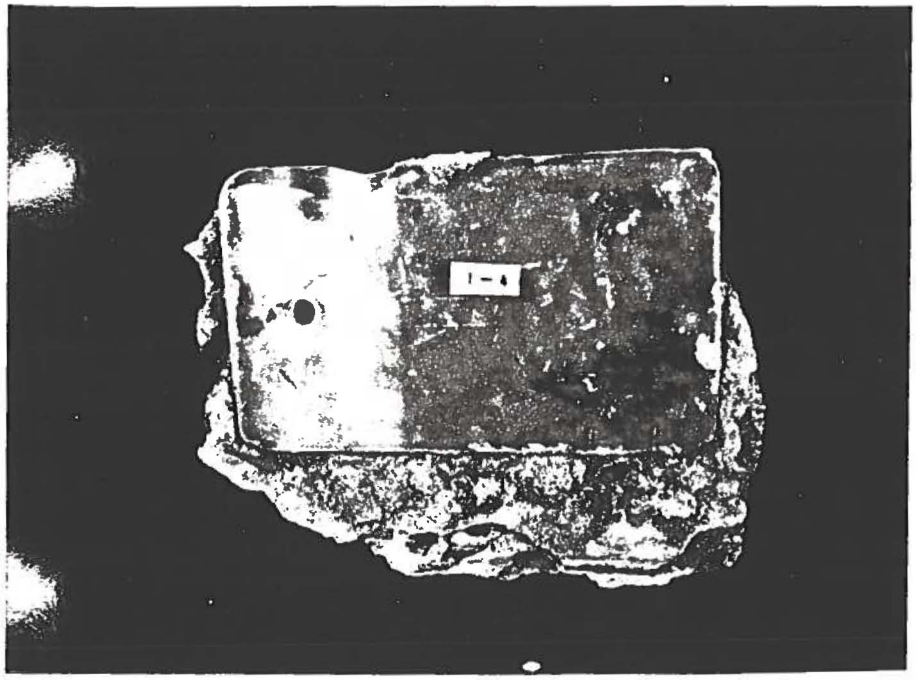


Figure 22. Plate 1-4. A 442-day plate. Shows underside of plate.

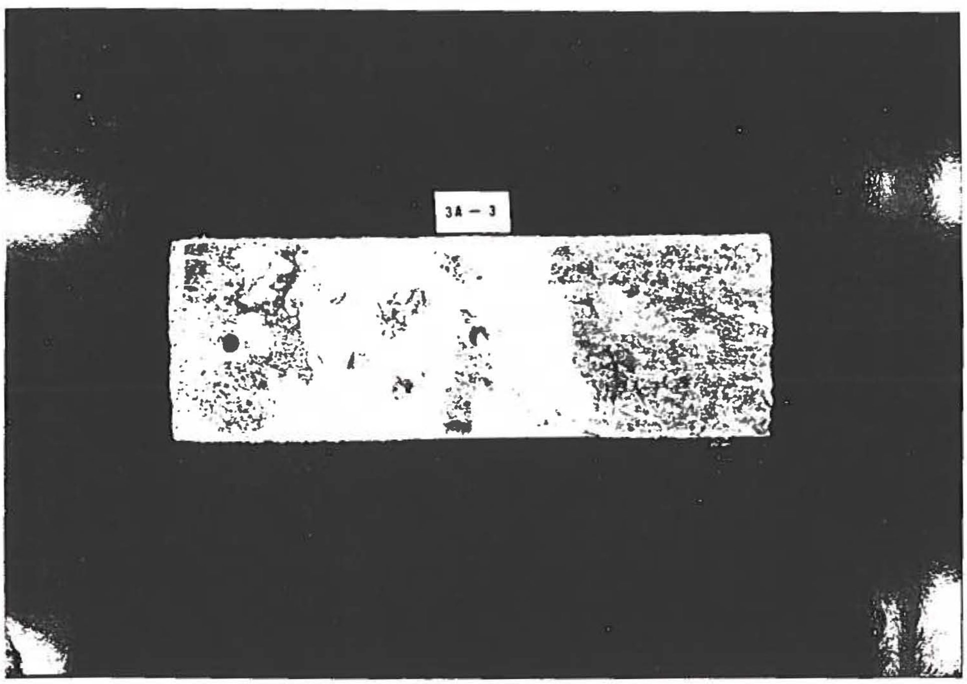


Figure 23. Plate 3A-3. A 99-day plate. Shows surface abrasion.

the surfaces of many plates creating pits of various sizes that sometimes exposed the bare plastic (Fig. 25). The upper half of the material deposited on Plate 2A-2 (Fig. 26) was completely removed. Deposition recurred on the stripped portion but it never attained the height of the lower half. Abrasion scars occurred more frequently in th rainy season.

Deposition on the long-term plates (three months and longer) showed a layered appearance when split (Fig. 27). Some of the layers were fenestrated and open; some appeare more dense - color variations occurred. Many of the thicker buildups contained leaves and other organic and inorganic debris trapped between the layers.

Plate recovery rates varied among the sites. At Site 1, 78% (14 out of 18 placed) of the plates were recovered. Site 1 was nearest the road and some of the plates may hav been removed by people hiking the stream. However, at least two of the plates at Site 1 were apparently removed by stream debris. At Site 2 the plates were placed on the face of a steep cascade and 95% (18 out of 19 placed) of them were recovered. The plate lost at this site was apparently removed by stream flow debris. Site 3 was located on a low cascade. It had the lowest recovery rate (75%, 12 out of 16 placed). The underlying rock was very soft and spongy and secure attachment of the plates was

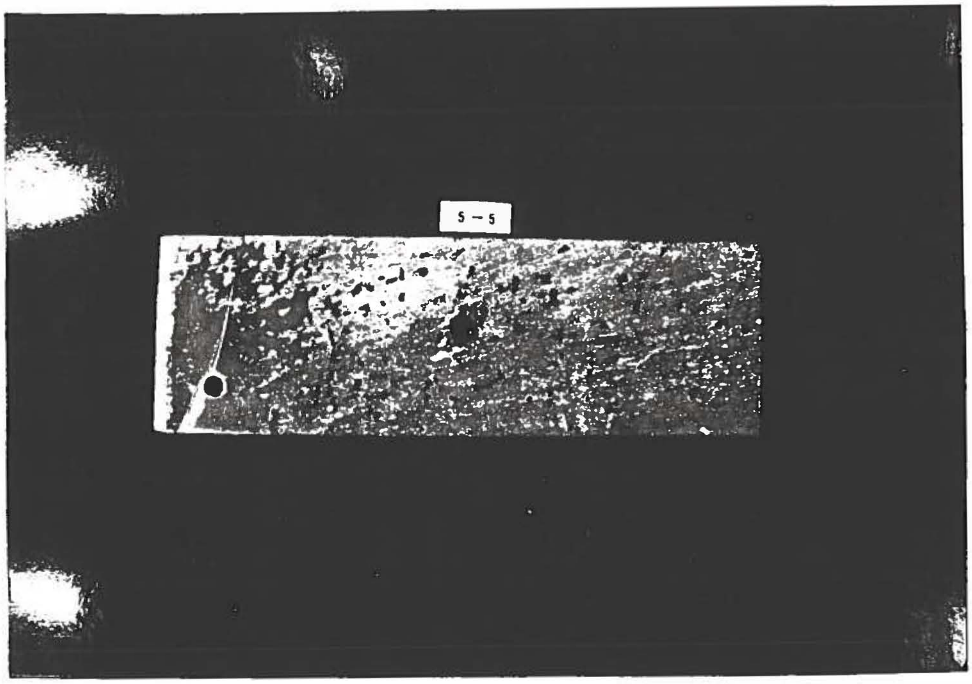


Figure 24. Plate 5-5. A 118-day plate.
Shows surface abrasion.

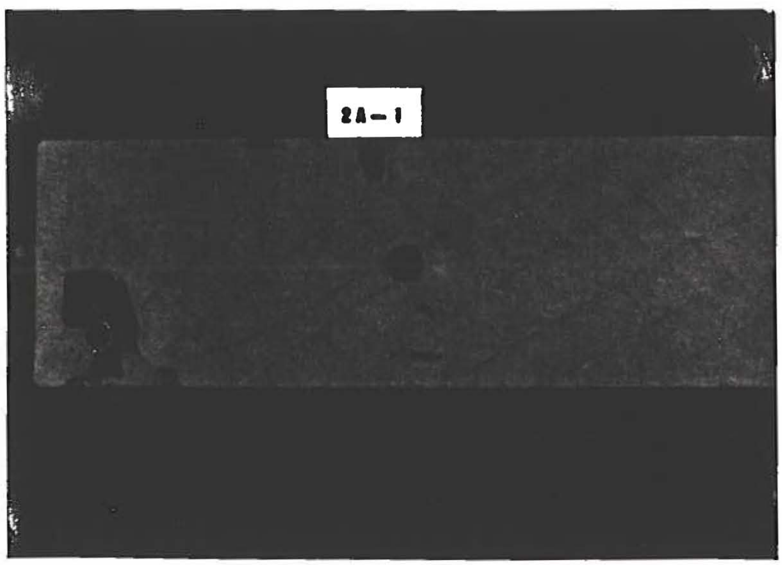


Figure 25. Plate 2A-1. A 30-day plate.
Shows surface abrasion.

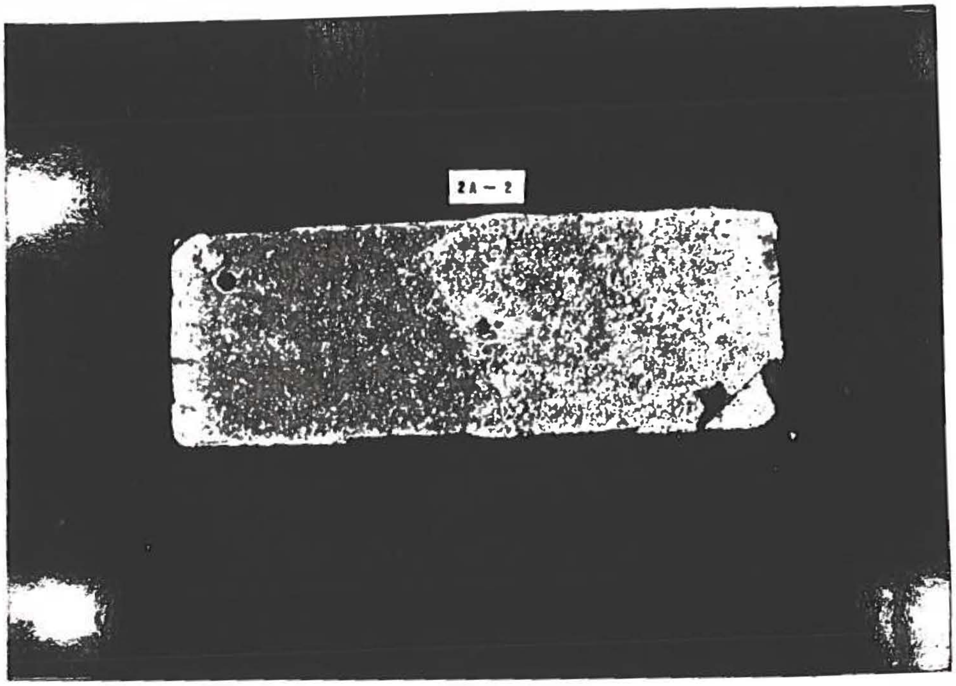


Figure 26. Plate 2A-2. A 110-day plate. Upper half (left side) of deposition was totally removed.

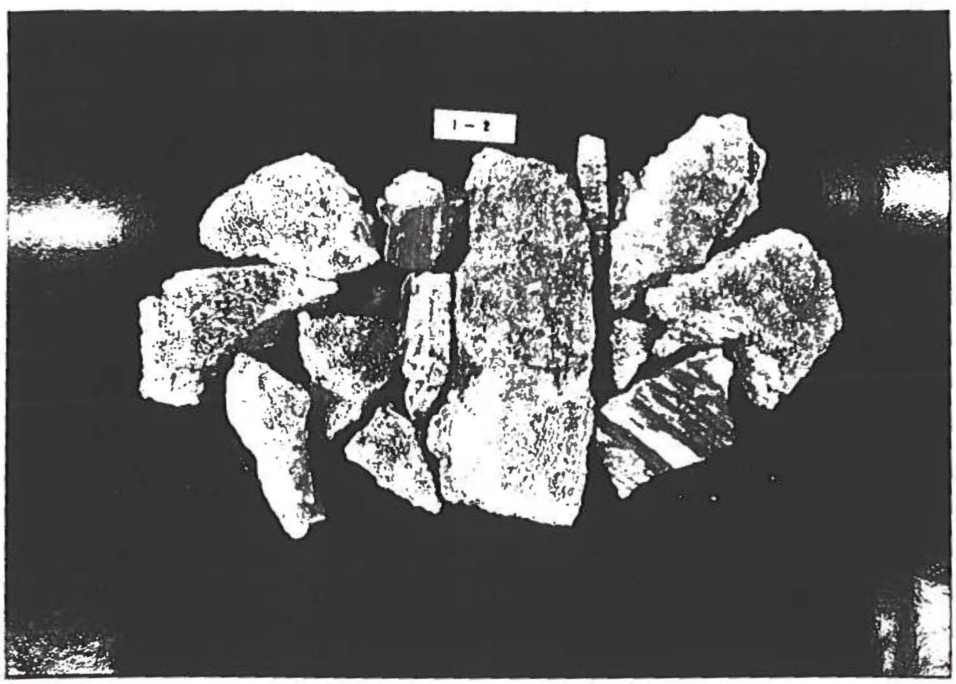


Figure 27. Plate 1-2. A 442-day plate. Some pieces turned on edge to show layering.

difficult. On one occasion, the attached plates were removed and left neatly stacked on a rock next to the sit Sites 4 and 5 had 100% recovery rates; the combined recovery rate for all sites was 90%.

The stromatolitic deposits were weighed and density and organic content were calculated (Table 1). Some factors that may have affected deposition were accumulation time, rainfall, site location and the pH of the water.

Time and deposition weight showed a strong positive correlation (Figs. 28-32). The r^2 for Site 2 is 0.9859 a above 0.9 for all other sites (see Figs. 28-32 for exact values). Analyses of variance performed on these data (Table 2) indicate a large and significant portion of the variance in the plate weights is explained by the length c time the plates remained in the stream.

Organic content is reported as a percentage of total deposition weight. Time and organic content do not show the strong positive correlation of the previously mentione weight data. Graphs of these data (Figs. 33 & 34) have curves that are generally asymptotic (Site 5 is graphed separately because the plates from this site have much higher organic contents than those from the other four sites). Short-period plates show a higher proportional organic content than long-period plates with more inorgani

TABLE 1
PLATE DEPOSITION DATA

PLATE	SITE	DAYS	RAINFALL*	WEIGHT+	HEIGHT@	%ORG CONT#	DENSITY~	PLACED	REMOVED
1	1	442	349.35	139.5125	9.27	1.69	0.16	14 May 88	20 Jul
1	2	442	349.35	116.8179	12.00	1.77	0.10	14 May 88	20 Jul
1	3				MISSING PLATE			14 May 88	
1	4	442	349.35	261.6280	21.70	1.51	0.13	14 May 88	20 Jul
1	5	442	349.35	3.6017	NMG	4.26	NMG	14 May 88	20 Jul
2	1	164	208.56	18.2257	1.34	1.65	0.15	28 May 88	8 Nov
2	2	164	208.56	38.9221	2.93	1.25	0.15	28 May 88	8 Nov
2	3				MISSING PLATE			28 May 88	
2	4	164	208.56	50.9052	3.63	1.19	0.16	28 May 88	8 Nov
2	5	164	208.56	0.6424	NMG	9.13	NMG	28 May 88	8 Nov
2A	1	30	15.90	3.5739	0.32	0.85	0.15	8 Nov 88	8 Dec 8
2A	2	110	53.85	30.5682	1.74	0.99	0.22	8 Nov 88	26 Feb 8
2A	3				NOT PLACED				
2A	4	118	53.85	24.2826	2.63	0.76	0.12	8 Nov 88	6 Mar 8
2A	5	30	15.90	0.0036	NMG	47.22	NMG	8 Nov 88	8 Dec 8
2B	1	80	38.28	13.3408	0.82	1.42	0.21	8 Dec 88	26 Feb 8
2B	2	88	38.28	19.9795	2.16	0.83	0.21	8 Dec 88	6 Mar 8
2B	3				MISSING PLATE				
2B	4	88	38.28	25.1173	1.43	1.24	0.22	8 Dec 88	6 Mar 8
2B	5	88	38.28	0.3757	NMG	13.53	NMG	8 Dec 88	6 Mar 8
3	1				MISSING PLATE			18 Jun 88	
3	2	162	179.48	29.1957	2.20	1.07	0.17	18 Jun 88	27 Nov 8
3	3				MISSING PLATE			18 Jun 88	
3	4	162	179.48	52.3373	4.72	1.98	0.15	18 Jun 88	27 Nov 8
3	5	162	179.48	0.5951	0.02	8.40	0.39	18 Jun 88	27 Nov 8
3A	1				MISSING PLATE			27 Nov 88	
3A	2	11	3.81	2.3265	0.25	0.87	0.13	27 Nov 88	8 Dec 8
3A	3	99	41.76	4.7294	0.44	1.85	0.15	27 Nov 88	6 Mar 8
3A	4	11	3.81	0.1768	NMG	0.68	NMG	27 Nov 88	8 Dec 8
3A	5	91	41.76	0.1777	NMG	6.02	NMG	27 Nov 88	26 Feb 8
4	1	182	104.70	32.2048	3.13	1.38	0.14	21 Aug 88	19 Feb 89
4	2	182	104.70	45.4646	3.01	1.04	0.20	21 Aug 88	19 Feb 89
4	3				NOT PLACED				
4	4	182	104.70	42.8488	3.44	2.21	0.17	21 Aug 88	19 Feb 89
4	5	182	104.70	0.8578	0.06	5.18	0.16	21 Aug 88	19 Feb 89
5	1	118	76.28	16.4153	2.14	0.87	0.10	25 Sep 88	21 Jan 89
5	2				MISSING PLATE			25 Sep 88	
5	3				NOT PLACED				
5	4	118	76.28	46.9705	1.42	3.28	0.44	25 Sep 88	21 Jan 89
5	5	118	76.28	0.9291	NMG	5.26	NMG	25 Sep 88	21 Jan 89
6	1	65	28.35	8.9080	0.61	0.76	0.19	31 Dec 88	6 Mar 89
6	2	65	28.35	19.1232	1.23	0.73	0.20	31 Dec 88	6 Mar 89
6	3	65	28.35	3.1000	0.24	3.85	0.17	31 Dec 88	6 Mar 89
6	4	65	28.35	21.9750	1.18	0.48	0.25	31 Dec 88	6 Mar 89
6	5	65	28.35	0.0983	0.05	14.29	0.03	31 Dec 88	6 Mar 89
7	1	21	2.64	2.4734	0.15	3.29	0.22	14 Jan 89	4 Feb 89
7	2	21	2.64	5.2612	0.43	3.41	0.17	14 Jan 89	4 Feb 89
7	3	21	2.64	0.3351	0.08	2.17	0.06	14 Jan 89	4 Feb 89
7	4	21	2.64	4.7073	0.39	0.86	0.16	14 Jan 89	4 Feb 89
7	5	21	2.64	0.0045	NMG	NMG	NMG	14 Jan 89	4 Feb 89
8	1	7	1.02	0.3393	NMG	9.13	NMG	14 Jan 89	21 Jan 89
8	2	7	1.02	0.5574	NMG	5.33	NMG	14 Jan 89	21 Jan 89
8	3	7	1.02	NMG	NMG	NMG	NMG	14 Jan 89	21 Jan 89
8	4	7	1.02	0.1762	NMG	13.07	NMG	14 Jan 89	21 Jan 89
8	5	7	1.02	NMG	NMG	NMG	NMG	14 Jan 89	21 Jan 89
9	1	15	22.61	1.8361	0.01	4.82	0.24	11 Feb 89	26 Feb 89
9	2	15	22.61	3.4170	0.07	3.60	0.66	11 Feb 89	26 Feb 89
9	3	15	22.61	0.5699	0.05	6.52	0.16	11 Feb 89	26 Feb 89
9	4	15	22.61	4.6229	0.12	2.96	0.53	11 Feb 89	26 Feb 89
9	5	15	22.61	NMG	NMG	NMG	NMG	11 Feb 89	26 Feb 89

TABLE 1 CONT.
PLATE DEPOSITION DATA

PLATE	SITE	DAYS	RAINFALL*	WEIGHT+	HEIGHT@	%ORG CONT#	DENSITY~	PLACED	REMO
10	1	23	22.61	2.4648	0.29	2.29	0.12	11 Feb 89	6 Ma
10	2	15	11.56	5.0522	0.35	10.28	0.18	19 Feb 89	6 Ma
10	3	23	22.61	1.2465	0.13	9.97	0.13	11 Feb 89	6 Ma
10	4	23	22.61	7.4782	0.67	1.43	0.15	11 Feb 89	6 Ma
10	5	23	22.61	0.1140	NMG	NMG	NMG	11 Feb 89	6 Ma
11	1				MISSING PLATE			2 Apr 89	
11	2	119	75.72	29.9532	2.57	1.54	0.15	2 Apr 89	30 Jul
11	3	119	75.72	10.9187	0.66	8.05	0.22	2 Apr 89	30 Jul
11	4	119	75.72	33.5326	2.69	1.43	0.16	2 Apr 89	30 Jul
11	5	119	75.72	0.6701	NMG	NMG	NMG	2 Apr 89	30 Jul
12	1	98	49.12	17.6702	1.67	3.17	0.14	23 Apr 89	30 Jul
12	2	98	49.12	24.3452	1.87	1.86	0.18	23 Apr 89	30 Jul
12	3	98	49.12	7.1690	0.61	5.03	0.17	23 Apr 89	30 Jul
12	4	98	49.12	33.3308	2.59	1.53	0.17	23 Apr 89	30 Jul
12	5	98	49.12	0.0080	NMG	32.50	NMG	23 Apr 89	30 Jul
13	1	7	8.69	0.0174	NMG	15.00	NMG	19 Aug 89	26 Aug
13	2	7	8.69	0.0160	NMG	3.95	NMG	19 Aug 89	26 Aug
13	3	7	8.69	NMG	NMG	NMG	NMG	19 Aug 89	26 Aug
13	4	7	8.69	NMG	NMG	NMG	NMG	19 Aug 89	26 Aug
13	5	7	8.69	NMG	NMG	NMG	NMG	19 Aug 89	26 Aug
14	1	14	9.47	1.7946	0.06	0.93	0.39	19 Aug 89	2 Sep
14	2	14	9.47	3.2158	0.16	0.83	0.27	19 Aug 89	2 Sep
14	3	14	9.47	0.2019	0.03	3.17	0.09	19 Aug 89	2 Sep
14	4	14	9.47	1.5885	0.15	0.91	0.14	19 Aug 89	2 Sep
14	5	14	9.47	0.0359	NMG	NMG	NMG	19 Aug 89	2 Sep
15	1				MISSING PLATE			19 Aug 89	
15	2	21	27.03	4.1114	0.28	0.92	0.20	19 Aug 89	10 Sep
15	3	21	27.03	0.4512	0.07	2.95	0.08	19 Aug 89	10 Sep
15	4	21	27.03	2.3333	0.17		0.18	19 Aug 89	10 Sep
15	5	21	27.03	NMG	NMG	NMG	NMG	19 Aug 89	10 Sep
16	1				MISSING PLATE			19 Aug 89	
16	2	28	28.50	6.6513	0.27	0.80	0.32	19 Aug 89	16 Sep
16	3	28	28.50	1.1461	0.09	2.76	0.17	19 Aug 89	16 Sep
16	4	28	28.50	2.6876	0.19	0.89	0.19	19 Aug 89	16 Sep
16	5	28	28.50	0.1050	NMG	NMG	NMG	19 Aug 89	16 Sep

* Total rainfall in centimeters for plate attachment time.
\+ Total deposition weight in grams.
@ Thickness measured in millimeters according to Fig. 5.
\# Calculation method stated in Materials & Methods.
~ Unit is g/cm^3. Calculation method stated in Materials & Methods.

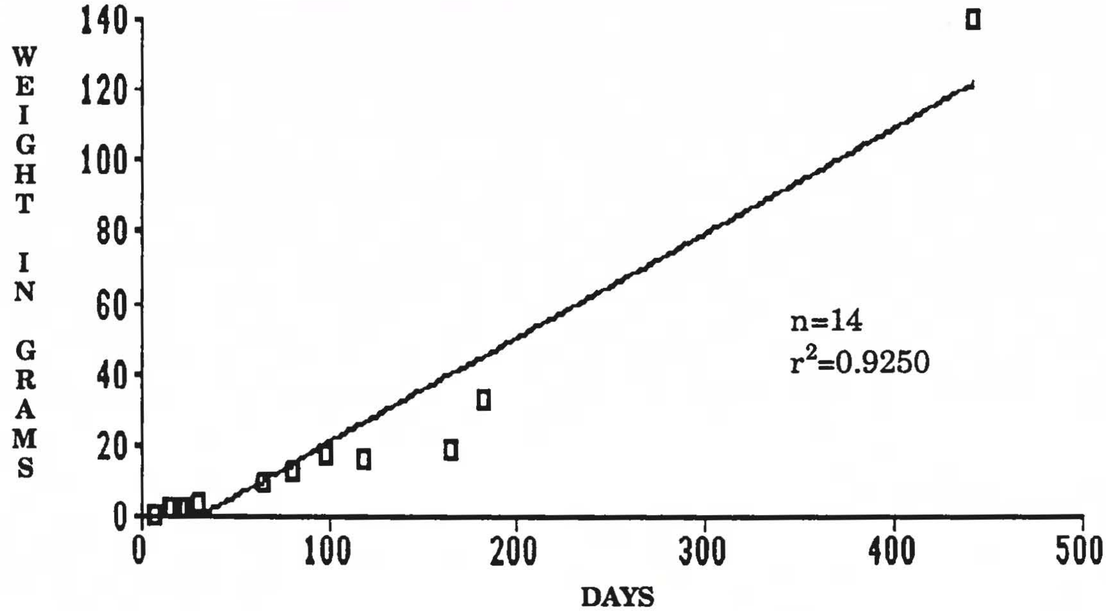


Figure 28 Time versus Material Weight Showing the Regression Line Site 1

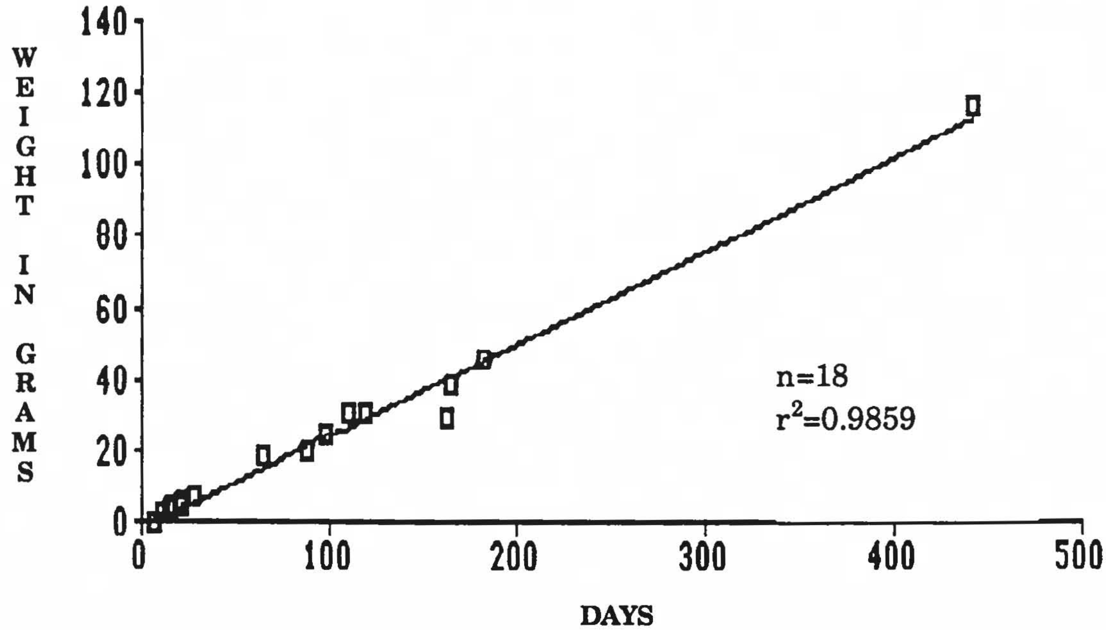


Figure 29 Time versus Material Weight Showing the Regression Line Site 2

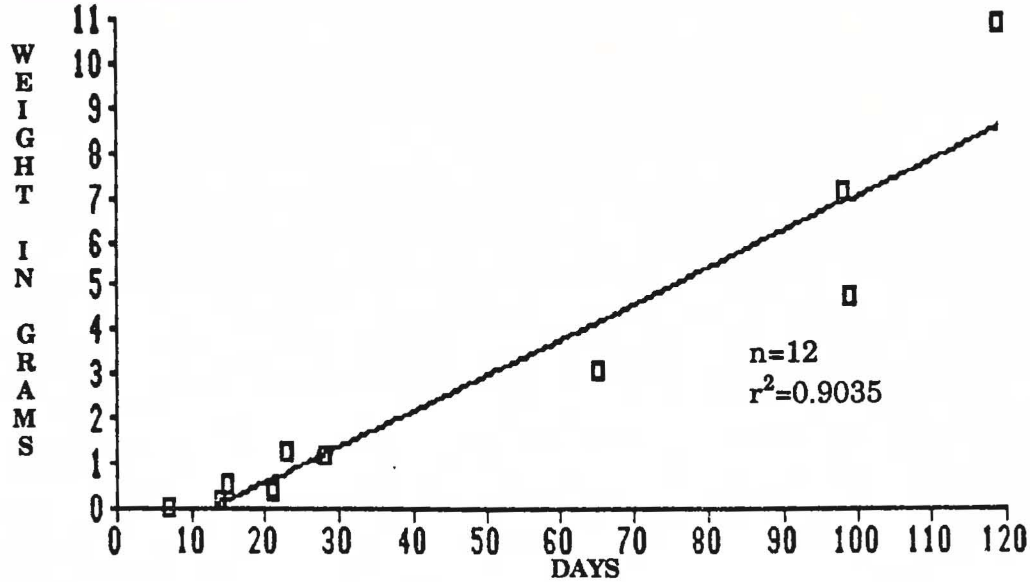


Figure 30 Time versus Material Weight Showing the Regression Line Site 3

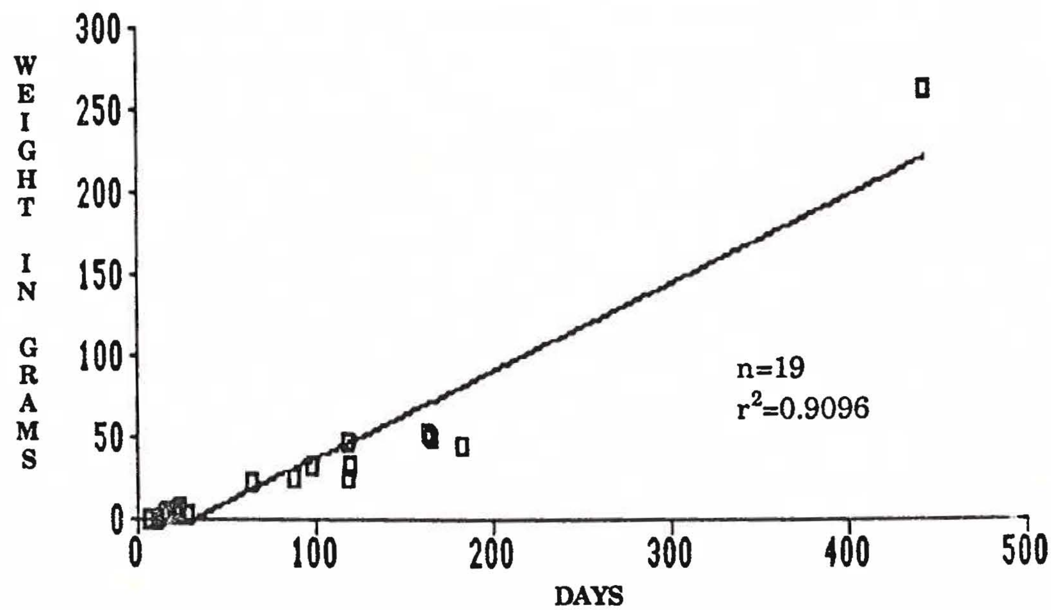


Figure 31 Time versus Material Weight Showing the Regression Line Site 4

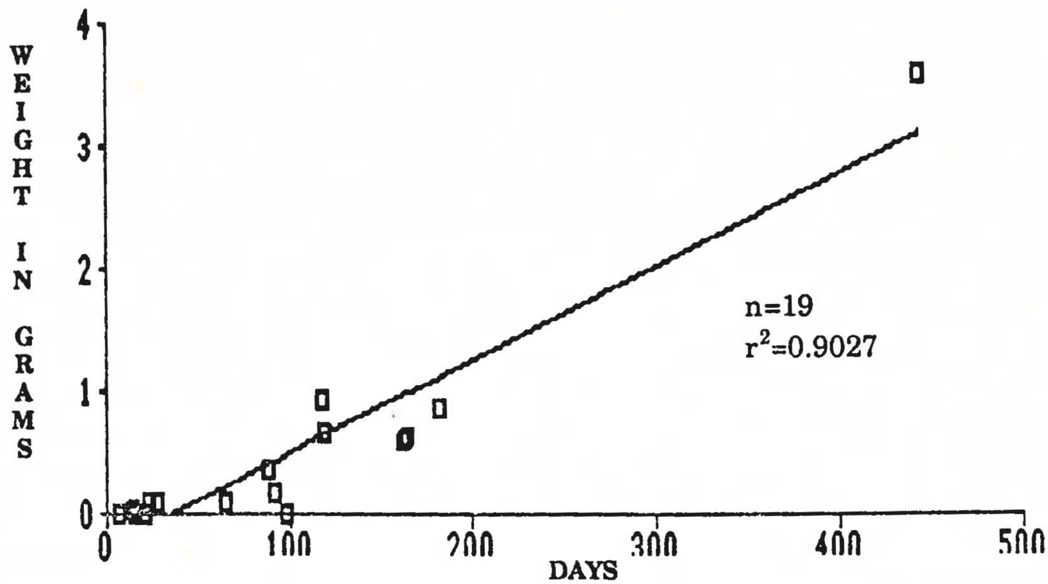


Figure 32 Time versus Material Weight Showing the Regression Line Site 5

TABLE 2. ANOVA TABLE OF REGRESSIONS PERFORMED ON WEIGHT VS. TIME DATA

SITE 1

Source of variation	*df*	*SS*	*MS*	F_s
Explained-caused by linear regression	1	15039.4773	15039.4773	102.56*
Unexplained-error around regression line	13	1906.1865	146.6297	
Total	14	16945.6638		

$F_{.05[1,13]} = 4.67$ $F_{.01[1,13]} = 9.07$ $F_{.001[1,13]} = 17$

SITE 2

Source of variation	*df*	*SS*	*MS*	F_s
Explained-caused by linear regression	1	12991.8112	12991.8112	1115.02*
Unexplained-error around regression line	16	186.4251	11.6516	
Total	14	13178.2363		

$F_{.05[1,16]} = 4.49$ $F_{.01[1,16]} = 10.6$ $F_{.001[1,16]} = 16.$

SITE 3

Source of variation	*df*	*SS*	*MS*	F_s
Explained-caused by linear regression	1	119.0850	119.0850	93.67**
Unexplained-error around regression line	10	12.7131	1.2713	
Total	11	131.7981		

$F_{.05[1,10]} = 4.96$ $F_{.01[1,10]} = 10.0$ $F_{.001[1,10]} = 21.$

TABLE 2 CONT. ANOVA TABLE OF REGRESSIONS PERFORMED ON WEIGHT VS. TIME DATA

SITE 4

Source of variation	*df*	*SS*	*MS*	F_s
Explained-caused by linear regression	1	56378.4581	56378.4581	170.99*
Unexplained-error around regression line	17	5605.1922	329.7172	
Total	18	61983.6503		

$F_{.05[1,17]} = 4.45$ $F_{.01[1,17]} = 8.4$ $F_{.001[1,17]} = 15.$

SITE 5

Source of variation	*df*	*SS*	*MS*	F_s
Explained-caused by linear regression	1	11.2383	11.2383	157.72*
Unexplained-error around regression line	17	1.2113	0.0713	
Total	18	12.4496		

$F_{.05[1,17]} = 4.45$ $F_{.01[1,17]} = 8.4$ $F_{.001[1,17]} = 15.7$

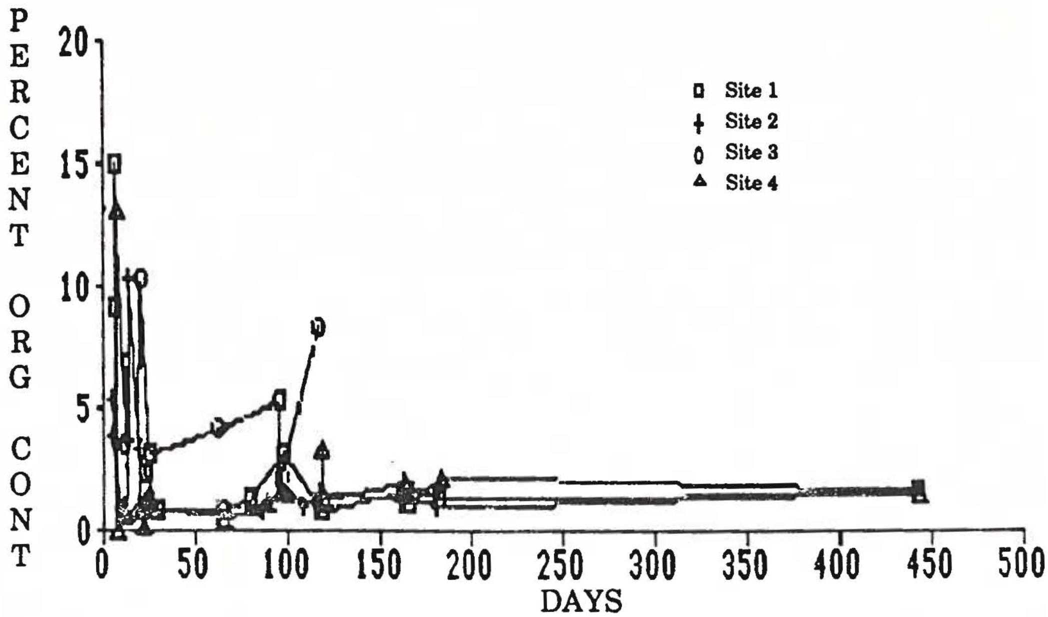


Figure 33 Percent Organic Content versus Time
Sites 1 - 4

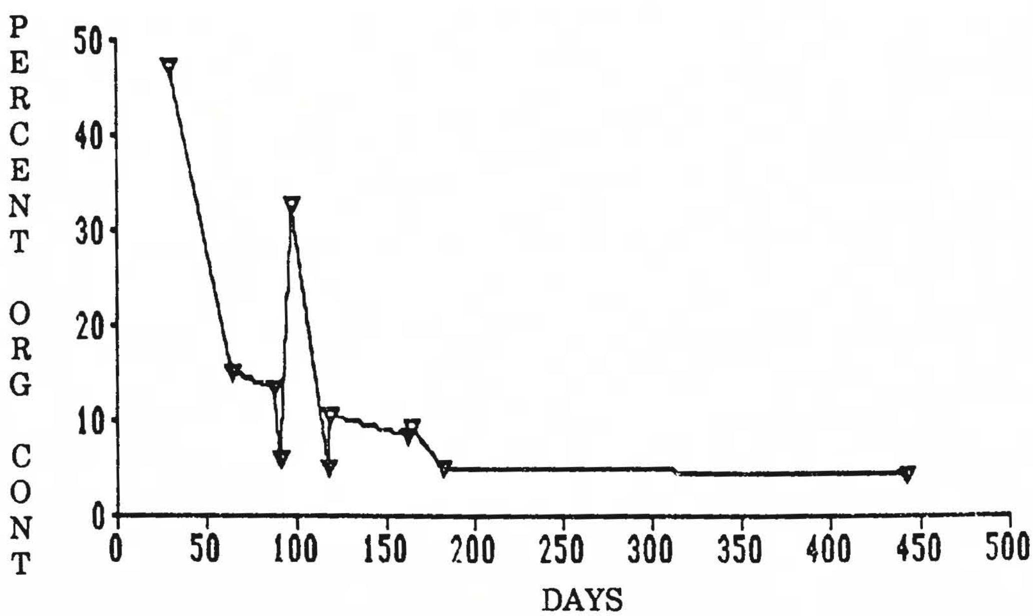


Figure 34 Percent Organic Content versus Time
Site 5

deposition. This would be expected since the layer of plant matter can grow efficiently only at the surface of the deposition or at the most a few millimeters down. As more inorganic material builds beneath the layer of plant cells, the percentage of organic material drops. Organic content percentages were also higher in general at Sites and 5 where less inorganic deposition took place [mean organic content at Site 5 (low total weight) was 14.15%; Site 2 (high total weight) it was 1.8%].

Inorganic content (insoluble fraction) data were taken fr rocks from Site 4. Three replicates were filtered througl AP40 glass filters. These samples yielded an average insoluble residue of 4.84%. Three replicates were filter through HA membrane filters. These samples yielded an average insoluble residue of 5.12%. These figures are within the ranges reported by Hathaway and Carroll (1964) who found insoluble residue percents in samples from the Maemong Limestone Member to range from 0.1% to 24%.

Time and density, graphed (Fig. 35), show the same general asymptotic trend as the graphs of the organic content data This may indicate the filling in of fenestra voids or possible material accumulation within the matrix. The deposited materials were not very dense and had, for the

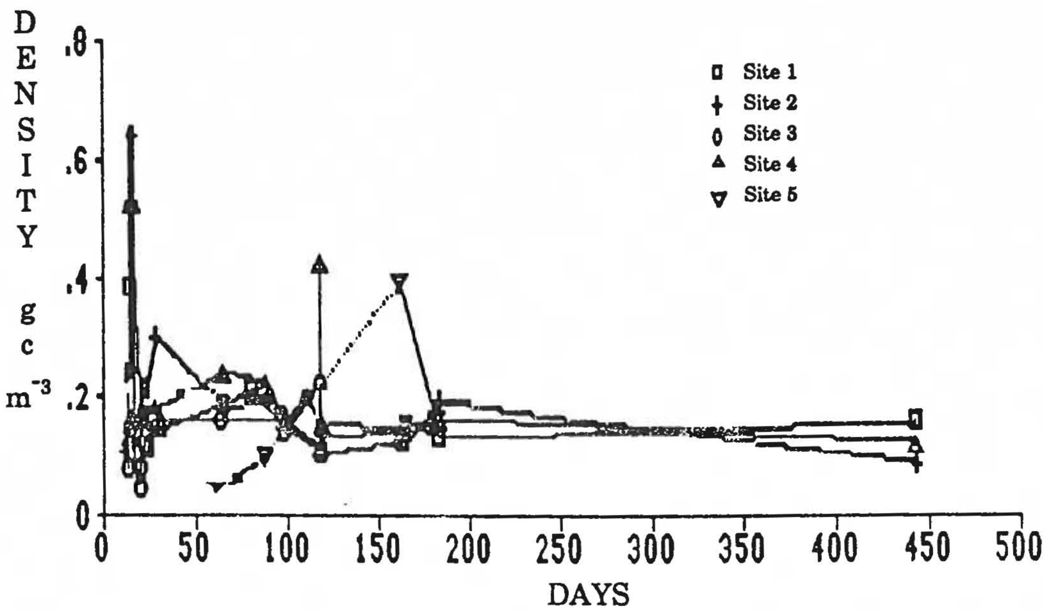


Figure 35 Density versus Time Sites 1 - 5

most part, specific gravities comparable to that of balsa (Weast, 1973). This low density is probably caused by th fenestrated nature of the deposition.

Rainfall and weight (Figs. 36-40) were positively correlated although not as strongly as time and weight. Analyses of variance performed on these data (Table 3) indicated a large and significant portion of the variance in the plate weights was explained by rainfall. Since accumulated rainfall increases the longer the plate is in place, this positive correlation would be expected.

Regression analyses showed that rainfall and organic content and rainfall and density were not strongly correlated. These data, graphed, (Figs. 41-43) show asymptotic curves similar to those of the time vs. organic weight data. These data sets probably also reflect the increase of total rainfall over time. Some of the short term plates were designed to be matched sets; one set placed in the rainy season and the other in the dry season The effects of rainy vs. dry seasons will be discussed later in this paper.

By far, the largest differences among the plate sets were caused by their location along the stream (Table 4). Deposition among the sites was not uniform and varied by orders of magnitude. Plate set pictures that show this

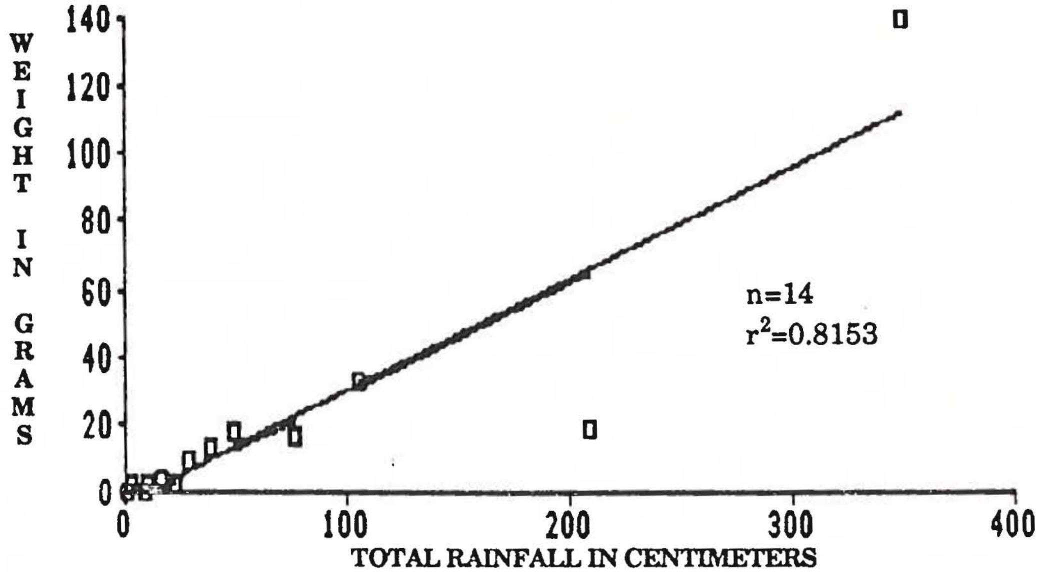


Figure 36 Total Rainfall versus Material Weight Showing the Regression Line Site 1

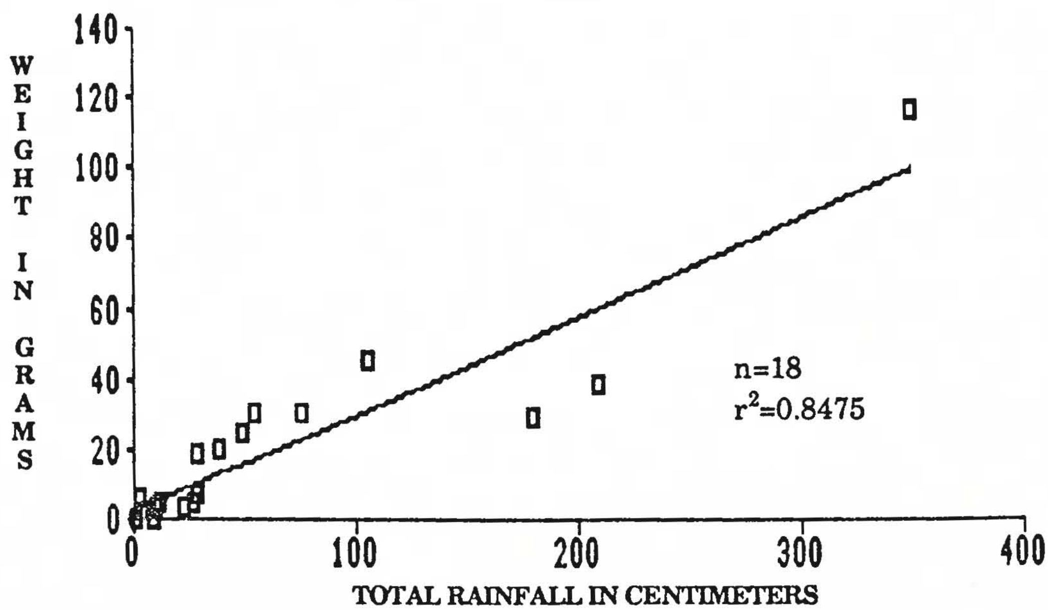


Figure 37 Total Rainfall versus Material Weight Showing the Regression Line Site 2

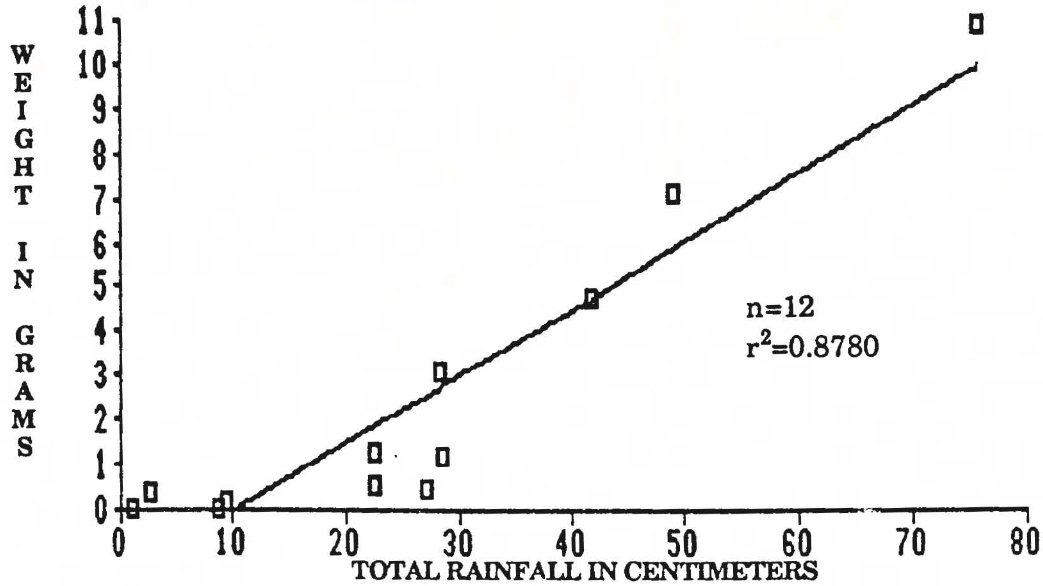


Figure 38 Total Rainfall versus Material Weight Showing the Regression Line Site 3

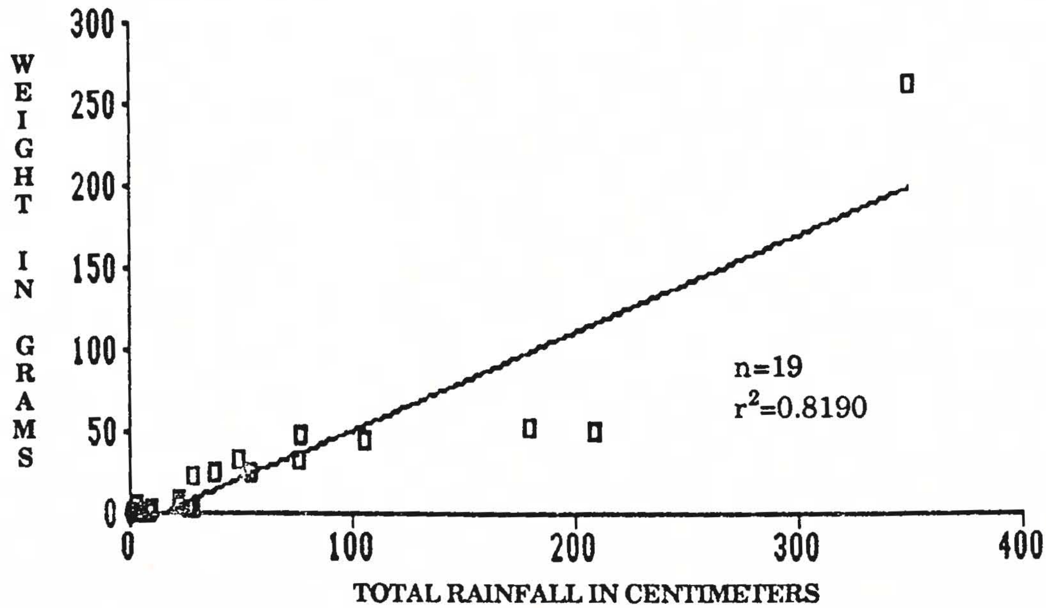


Figure 39 Total Rainfall versus Material Weight Showing the Regression Line Site 4

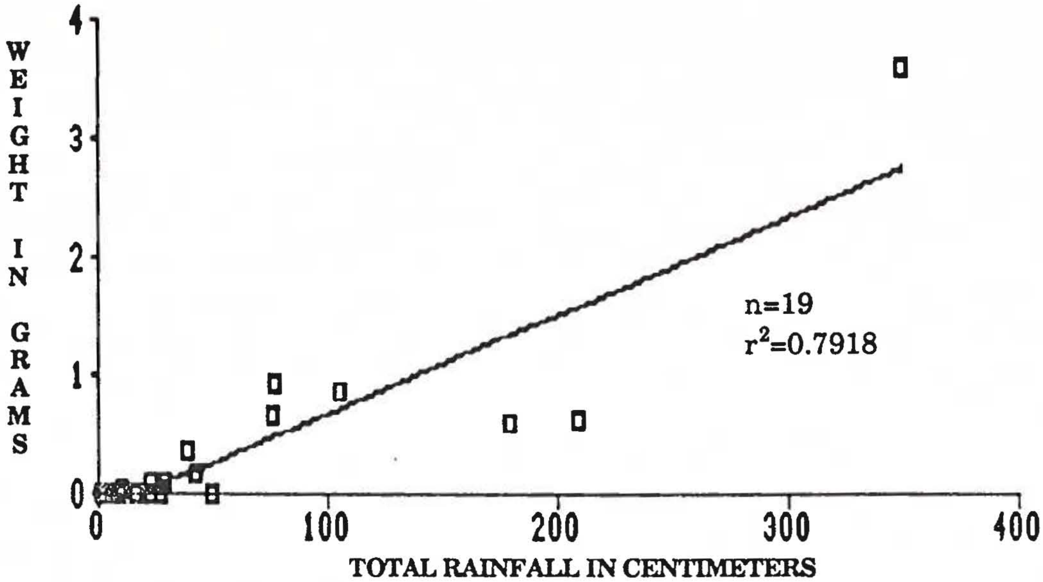


Figure 40 Total Rainfall versus Material Weight Showing the Regression Line Site 5

TABLE 3. ANOVA TABLE OF REGRESSIONS PERFORMED ON WEIGHT VS. RAINFALL DATA

SITE 1

Source of variation	*df*	*SS*	*MS*	F_s
Explained-caused by linear regression	1	12277.5465	12277.5465	34.19*
Unexplained-error around regression line	13	4668.1173	359.0859	
Total	14	16945.6638		

$F_{.05[1,13]} = 4.67$ $F_{.01[1,13]} = 9.07$ $F_{.001[1,13]} = 17.$

SITE 2

Source of variation	*df*	*SS*	*MS*	F_s
Explained-caused by linear regression	1	11167.9980	11167.9980	88.89**
Unexplained-error around regression line	16	2010.1484	125.6343	
Total	17	13178.1464		

$F_{.05[1,16]} = 4.49$ $F_{.01[1,16]} = 10.6$ $F_{.001[1,16]} = 16.$

SITE 3

Source of variation	*df*	*SS*	*MS*	F_s
Explained-caused by linear regression	1	115.7147	115.7147	71.95**
Unexplained-error around regression line	10	16.0833	1.6083	
Total	11	131.7980		

$F_{.05[1,10]} = 4.96$ $F_{.01[1,10]} = 10.0$ $F_{.001[1,10]} = 21.$

TABLE 3 CONT. ANOVA TABLE OF REGRESSIONS PERFORMED ON WEIGHT VS. RAINFALL DATA

SITE 4

Source of variation	*df*	*SS*	*MS*	F_s
Explained-caused by linear regression	1	50764.8277	50764.8277	76.92*
Unexplained-error around regression line	17	11218.8226	659.9307	
Total	18	61983.6503		

$F_{.05[1,17]} = 4.45$ $F_{.01[1,17]} = 8.4$ $F_{.001[1,17]} = 15.$

SITE 5

Source of variation	*df*	*SS*	*MS*	F_s
Explained-caused by linear regression	1	9.8575	9.8575	64.64*
Unexplained-error around regression line	17	2.5925	0.1525	
Total	18	12.4500		

$F_{.05[1,17]} = 4.45$ $F_{.01[1,17]} = 8.4$ $F_{.001[1,17]} = 15.$

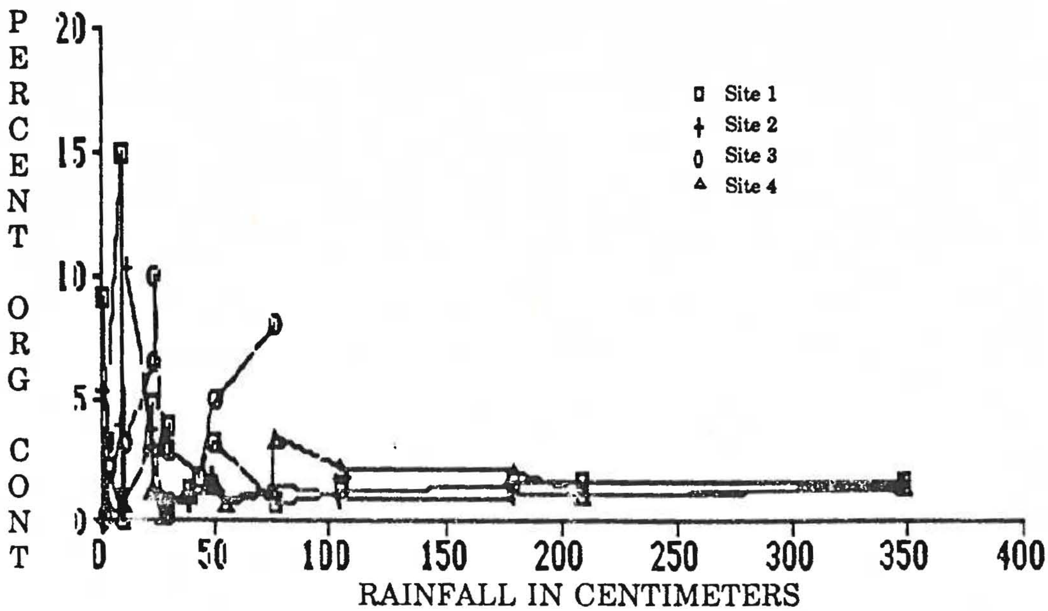


Figure 41   Percent Organic Content versus Rainfall
Sites 1 - 4

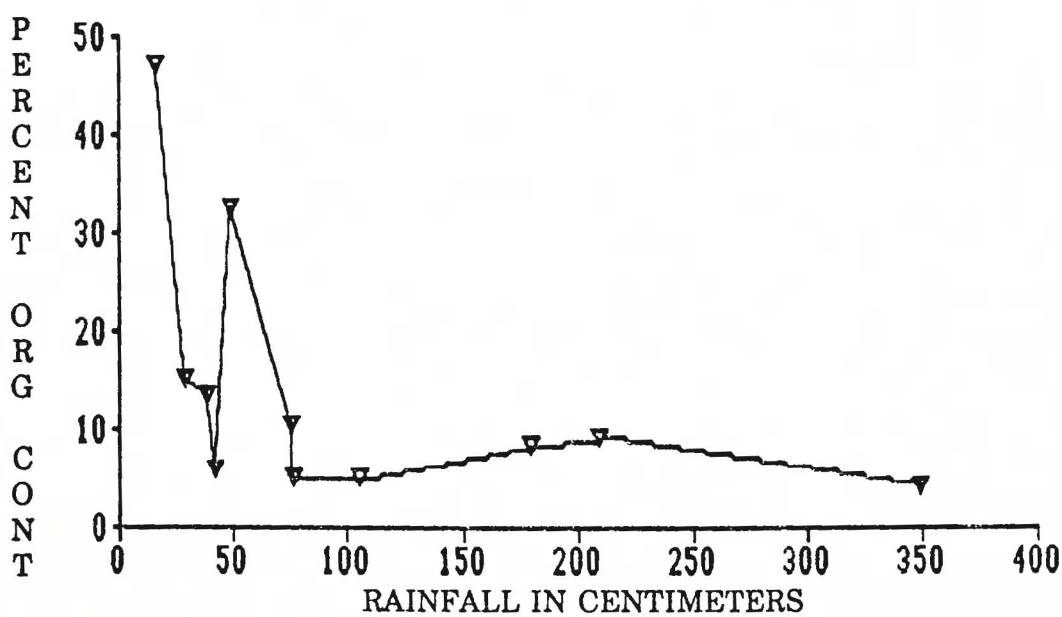


Figure 42   Percent Organic Content versus Rainfall
Site 5

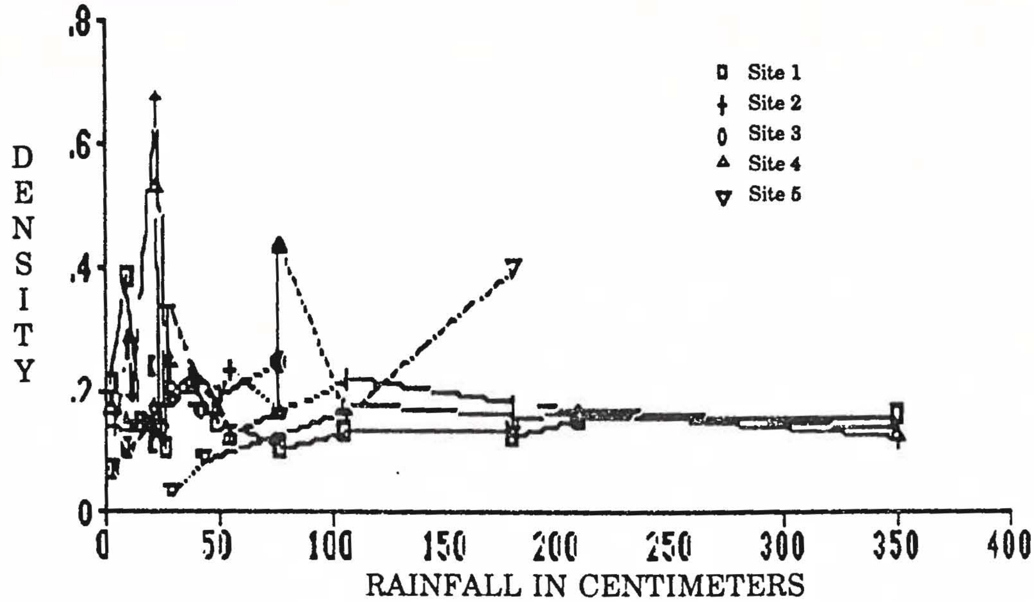


Figure 43   Density versus Rainfall   Sites 1 - 5

TABLE 4. TOTAL WEIGHT (g), MEAN PERCENT ORGANIC CONTENT AND MEAN DENSITY FOR EACH SITE

SITE	TOTAL WEIGHT	MEAN % ORGANIC	MEAN DENSITY
1	258.79 (n=14)	3.32 (n=14)	0.18 (n=13)
2	384.98 (n=16)	1.80 (n=18)	0.22 (n=16)
3	29.87 (n=10)	4.64 (n=10)	0.14 (n=10)
4	617.90 (n=17)	2.14 (n=17)	0.21 (n=16)
5	8.21 (n=13)	14.15 (n=11)	0.16 (n= 5)

difference appear in Figs. 44 & 45 (Plate sets 6 & 12). Pictures of the 442-day plates from Sites 1 & 5 appear in Fig. 46.

Mean organic content data were inversely related to weight As was mentioned before, organic content was highest at those sites that showed the least amount of inorganic accumulation. This is to be expected since short-term plates would tend to have more algae in relation to the amount of deposited calcium carbonate while long-term plates would have more deposition in relation to the thin layer of algal material at the surface of the stromatolite However, Site 4, which had the greatest amount of inorgani accumulation did not have the least organic matter. This higher than expected organic content was probably caused b the inclusion of hepatics in the matrix.

The sites with lower material weights had lower densities except that the deposition at Site 2 was more dense than that of Site 4 possibly because the deposition from Site 4 usually contained more fenestra than that from Site 2. The mean density was also higher for Site 3 than Site 5, but the sample size for Site 5 was so small that valid conclusions probably cannot be drawn from it.

pH data are shown in Table 5 and distribution ranges of these data are shown in Fig. 47. Some high values were

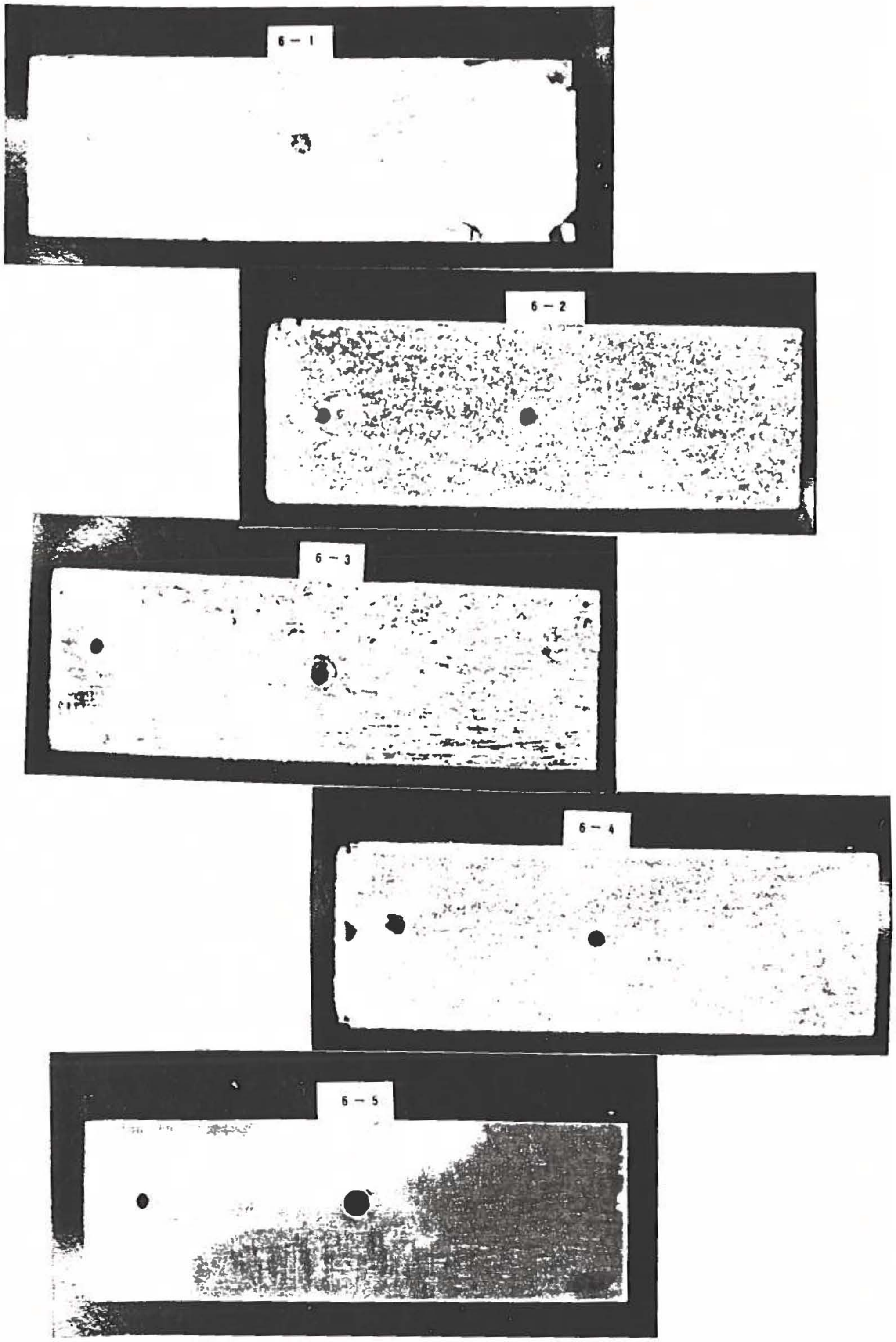


Figure 44. Plate set 6. These are 65-day plates.

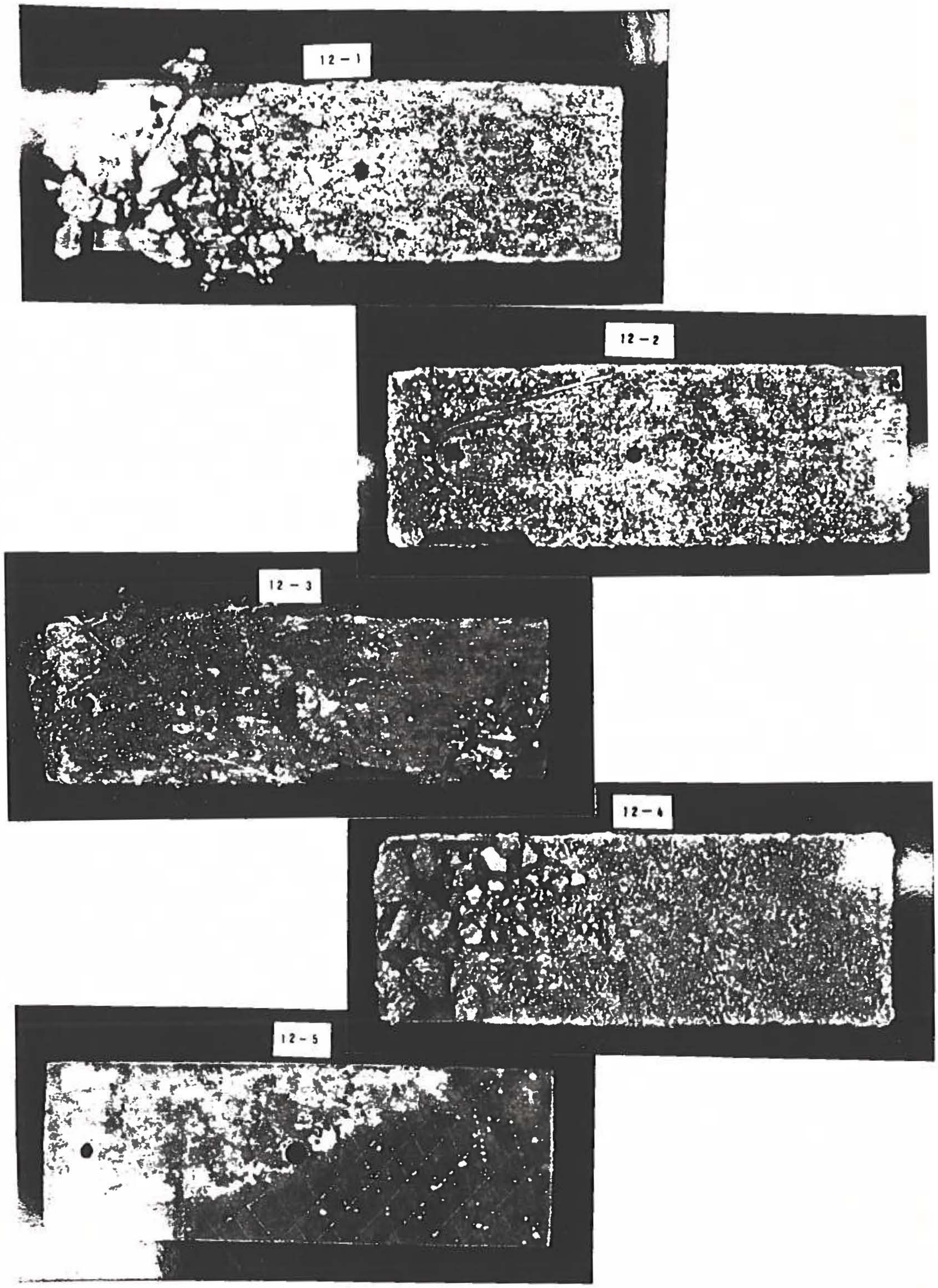
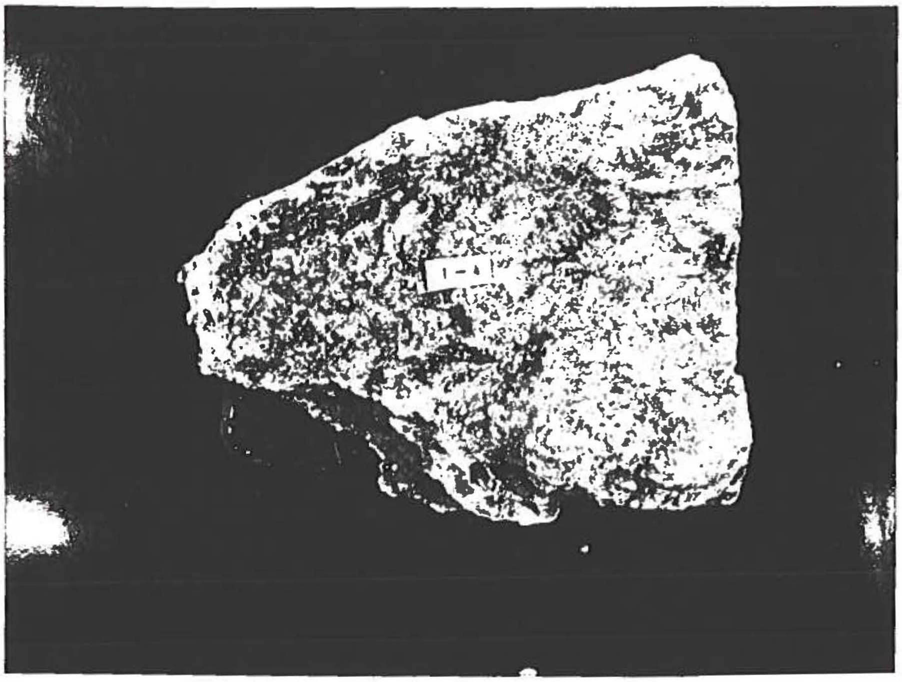


Figure 45. Plate set 12. These are 98-day plates.



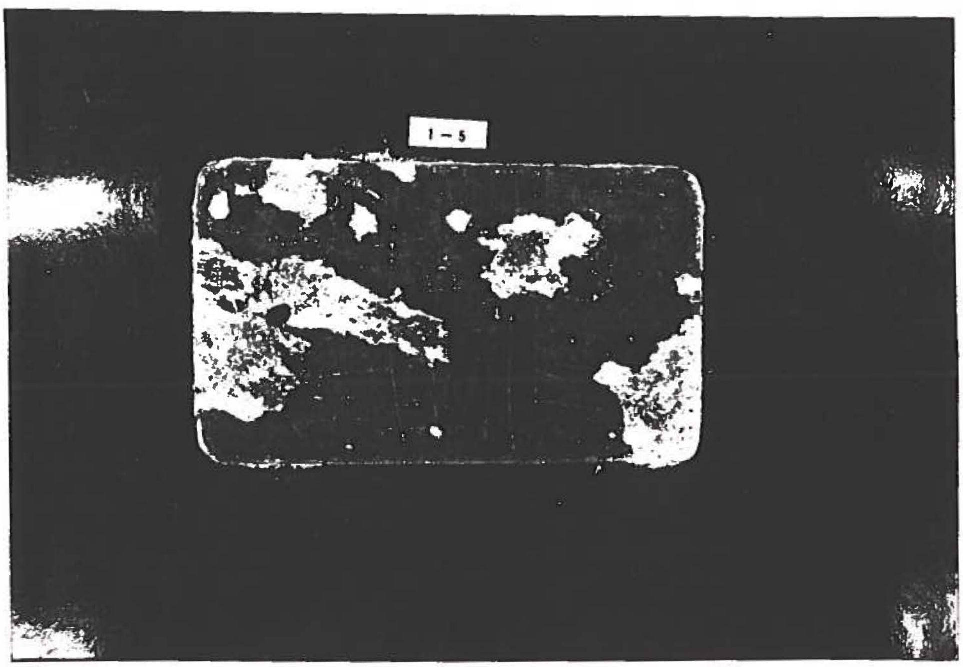


Figure 46. Plate 1-4 & 1-5. These are 442-day plates.

TABLE 5
pH DATA

DATE	CULVERT	1 LOWER	1 UPPER	2 LOWER	2 UPPER	3 LOWER	3 UPPER	4 LOWER	4 UPPER	SITE 5
28-May-88	7.58	7.53		7.53		7.77	7.87	7.14		7.91
11-Jun-88	7.70	7.72		7.67	7.75	7.82	7.88			
18-Jun-88	7.57	7.62		7.87		7.75		7.55		7.82
26-Jun-88	7.48	7.55		7.47		7.66		7.58		7.95
30-Jul-88	7.07	7.33		7.41		7.15		7.15	7.23	
13-Aug-88	7.54	7.55		7.56	7.98	7.88	7.93	7.92	8.05	8.16
21-Aug-88	7.80	7.92		7.92		7.82		7.86	8.14	8.66
28-Aug-88	7.66	7.83		7.85	8.07	7.85		7.87	7.93	8.04
11-Sep-88	7.95	8.21	8.32	8.11	8.22	8.18	8.14	8.04	8.00	
25-Sep-88	7.92	8.05	8.16	8.41	8.31	8.24	8.29	7.95	8.05	8.42
1-Oct-88	7.43	7.66	7.85	7.91	7.98	8.00	8.11	7.84	7.86	8.30
9-Oct-88	7.57	7.68	7.57	7.47	7.42	7.30	7.38	7.21	7.31	7.90
16-Oct-88	7.76	7.98	8.00	8.01	7.98	7.92	8.02	7.89	8.06	
3-Nov-88	8.50	8.70	8.00	9.00	8.90	8.60	8.55			
27-Nov-88	8.32	8.36	8.31	8.20	8.23	8.52	8.58	9.11	9.07	
1-Dec-88		7.94	8.02	8.12	8.10			8.00	8.02	
8-Dec-88	8.21	8.21	8.26	8.03	8.23	8.83	8.93			
31-Dec-88	7.93	7.96	8.02	7.90	7.91	7.85	7.87	7.75	7.71	8.07
15-Jan-89	8.04	8.03	8.04	7.99	7.98	7.90	7.90	7.88	8.06	
21-Jan-89	7.69	7.76	7.78	7.80	7.83	7.78	7.87	7.79	7.77	8.00
4-Feb-89	7.85	7.93	7.93	7.85	7.91	7.83	7.91	7.82	7.78	8.04
11-Feb-89	8.03	8.04	8.03	7.98	8.05	7.99	7.99	7.91	7.81	8.05
19-Feb-89	8.12	8.09	8.14	8.15	8.29	8.25	8.27	8.56	8.54	9.92
6-Mar-89	7.93	8.03	8.10	7.97	8.01	7.94	8.03	7.91	7.94	8.13
2-Apr-89	8.09	8.16	8.13	8.10	8.13	8.05	8.07	7.98	7.91	8.22
30-Apr-89	7.98	8.05	8.06	8.06	8.04	8.02	8.05	7.90	7.86	8.12
14-May-89	7.95	8.03	8.01	8.01	8.02	7.99	7.97	7.91	7.83	8.08
30-Jul-89	7.96	8.03	8.06	8.02	7.95	7.90	8.00	7.83	8.04	8.16
19-Aug-89	7.77	7.88	8.01	7.87	7.91	7.86	7.98	7.79	7.80	7.96
2-Sep-89	7.91	8.08	8.07	8.10	8.12	8.03	8.07	8.02	7.95	8.02
10-Sep-89	7.70	7.77	7.76	7.86	7.87	7.79	7.87			

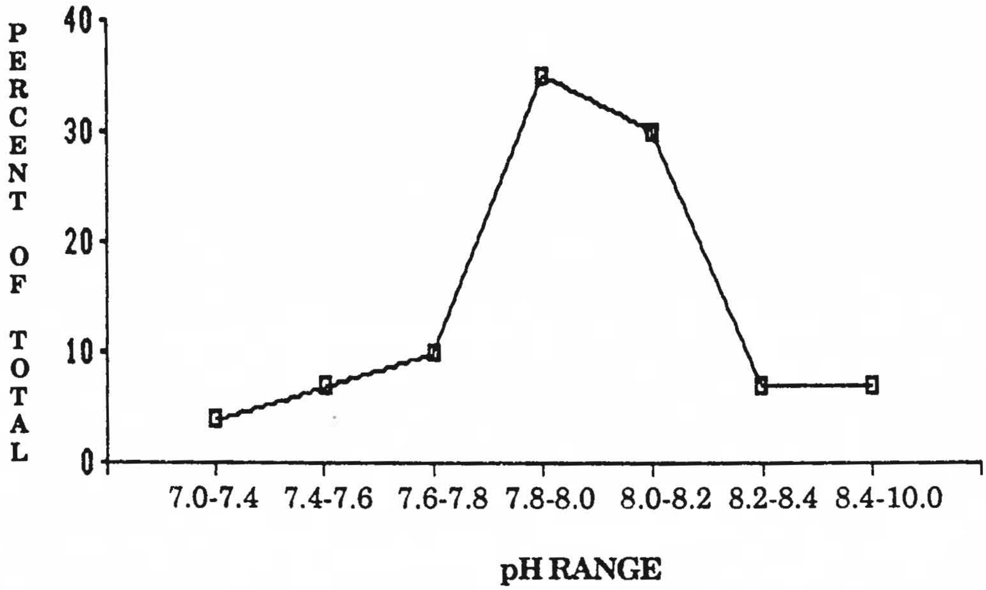


Figure 47 pH Values by Ranges Reported as percent Total obtained, particularly at Site 5, where a pH of 9.92 was recorded on 19 February 1989. Neubauer (1981) reported mean pH values of two small streams in south central Guam as 7.5 (range 6.5-8.1) and 7.7 (range 6.4-8.4). Zolan an Ellis-Neill (1986) reported mean pH values of four statio along the Pigua River as 7.32 (range 6.91-7.60); 7.4 (ran 7.12-7.70); 8.01 (range 7.08-8.55) and 7.82 (range 7.0-8.38). They reported mean pH from the La Sa Fua River to be 7.90 (range 7.45-8.39); from the Umatac River to be 7. (range 7.15-8.09) and from the Geus River to be 7.89 (ran (7.00-8.60). Mean pH data from the Asmafines sites are shown in Table 6.

Because of the relationship between pH and the amount of calcium bicarbonate ions in the water column, pH readings were taken above and below each cascade (except Site 5) to determine possible significant differences between the readings. Although mean pH is higher for the cascade top in all instances (Table 6), paired comparison analyses sho no significant difference in the upper and lower pH except at Site 3 which had the shortest cascade (Table 7). Paire comparison analysis of the pH readings from the culvert an Site 5 (which essentially treats the entire study area as one long cascade) were significantly different and are reported in Table 8.

TABLE 6. MEAN pH DATA

SITE	MEAN pH	RANGE	STD	N
Site 1 lower	7.93	7.33-8.70	0.271	31
Site 1 upper	8.03	7.57-8.32	0.169	23
Site 2 lower	7.94	7.41-9.00	0.299	31
Site 2 upper	8.05	7.42-8.90	0.249	25
Site 3 lower	7.95	7.15-8.83	0.323	30
Site 3 upper	8.06	7.38-8.93	0.290	25
Site 4 lower	7.86	7.14-9.11	0.376	27
Site 4 upper	7.95	7.23-9.07	0.343	24
Site 5	8.19	7.82-9.92	0.429	21

TABLE 7. ANOVA TABLE OF PAIRED COMPARISON ANALYSIS OF UPPER AND LOWER pH VALUES

SITE 1

Source of variation	*df*	*SS*	*MS*	F_s
Upper vs lower pH	1	0.0004	0.0004	0.03 n
Time of year taken	25	2.7134	0.1085	8.41**
Remainder	25	0.3232	0.0129	
Total	51	3.0370		

$F_{.05[1,25]} = 4.24$ $F_{.001[24,25]} = 3.66$ $F_{.001[30,25]} = 3.5$

SITE 2

Source of variation	*df*	*SS*	*MS*	F_s
Upper vs lower pH	1	0.0272	0.0272	4.57
Time of year taken	25	3.4716	0.1389	23.33**
Remainder	25	0.1488	0.0060	
Total	51	3.6476		

$F_{.05[1,25]} = 4.24$ $F_{.01[1,25]} = 7.77$ $F_{.001[24,25]} = 3.6$

SITE 3

Source of variation	*df*	*SS*	*MS*	F_s
Upper vs lower pH	1	0.0332	0.0332	28.59**
Time of year taken	24	4.3321	0.1805	155.23**
Remainder	24	0.0279	0.0012	
Total	49	4.3932		

$F_{.001[1,24]} = 14.0$ $F_{.001[24,24]} = 3.74$

SITE 4

Source variation	*df*	*SS*	*MS*	F_s
Upper vs lower pH	1	0.0144	0.0144	3.43 n
Time of year taken	23	5.7759	0.2511	59.78**
Remainder	23	0.0968	0.0042	
Total	47	5.8871		

$F_{.05[1,23]} = 4.28$ $F_{.001[24,23]} = 3.82$

TABLE 8. ANOVA TABLE OF PAIRED COMPARISON ANALYSIS OF pH VALUES FROM THE CULVERT (LOWER) AND SITE 5 (UPPE

Source of variation	*df*	*SS*	*MS*	F_s
Upper vs lower pH	1	1.5893	1.5893	25.25**
Time of year taken	20	3.1462	0.1573	1.98 *n*
Remainder	20	1.5859	0.0793	
Total	41	6.3241		

$F_{.001[1,20]} = 14.8$ $F_{.05[20,20]} = 2.12$ $F_{.01[20,20]} = 2.94$

Flow meter data are summarized in Table 9. Current velocity ranged from 0 (not enough flow to activate the meter) to 12 cms^{-1} (centimeters per second). These readings were taken just downstream from Site 3. This was one of the few areas along the entire study site where flowing water (as opposed to pool water) was deep enough t activate the flow meter.

Calcium and magnesium ion data were taken in the rainy anc dry seasons (June and December). Alkalinity and pH were obtained at the same time. Calcium, alkalinity and pH wer used to calculate the Langelier indices (Kemmer, 1979) (Tables 10 & 11). These are measures of the amount of $CaCO_3$ saturation in the water; they were obtained using th graph in Fig. 48. All samples had positive Langelier indices which show the water was supersaturated with calcium, but those from the dry season had much higher readings (the higher the number, the greater the instability).

Four sets of plates were set out in the dry and the rainy seasons to determine if there were any difference between rates of deposition. These plate sets were left down for seven, fourteen, twenty-one and twenty-eight days. The results are listed in Table 12. Comparison pictures of th 28-day rainy and dry season plates placed at Site 4 appear in Fig. 49.

TABLE 9. FLOW METER DATA
(reported in centimeters per second)

	30 cm from W bank	Middle	30 cm from E ba:
28 MAY 88	NOT ENOUGH FLOW TO ACTIVATE METER		
11 JUN 88	8.5 cms^{-1}	5.0 cms^{-1}	7.5 cms^{-1}
13 AUG 88	3.5 cms^{-1}	5.5 cms^{-1}	12.0 cms^{-1}
09 OCT 88	6.5 cms^{-1}	3.5 cms^{-1}	1.5 cms^{-1}

TABLE 10
LANGELIER INDEX DATA JUNE 1989

Sample number	Ca [mg\l]	CaCO3	Alkalinity	pH	pHs	Langelier Index
1 Culvert	21.5	53.75	194	8	7.9	0.1
2 Site 1 upper	21.7	54.25	196	8.1	7.9	0.2
3 Site 1 lower	22.0	55.00	202	8.1	7.9	0.2
4 Site 2 drip	24.8	62.00	207	8.2	7.7	0.5
5 Site 3	28.5	61.25	217	8.1	7.7	0.4
6 Site 4	23.6	59.00	190	8.1	7.8	0.3

TABLE 11
LANGELIER INDEX DATA DECEMBER 1989

Sample number	Ca [mg\l]	CaCO3	Alkalinity	pH	pHs	Langelier Inde:
1 Site 1 drip	38.2	95.5	200	7.9	7.6	0
2 Site 1 upper	39.2	98.0	200	8.0	7.6	0
3 Site 2 drip	42.0	105.0	207	8.1	7.6	0
4 Site 2 upper	42.3	106.0	205	8.1	7.6	0.
5 Site 4 lower	62.7	157.0	252	8.0	7.3	0.
6 Site 4 upper	64.8	162.0	262	8.0	7.2	0.

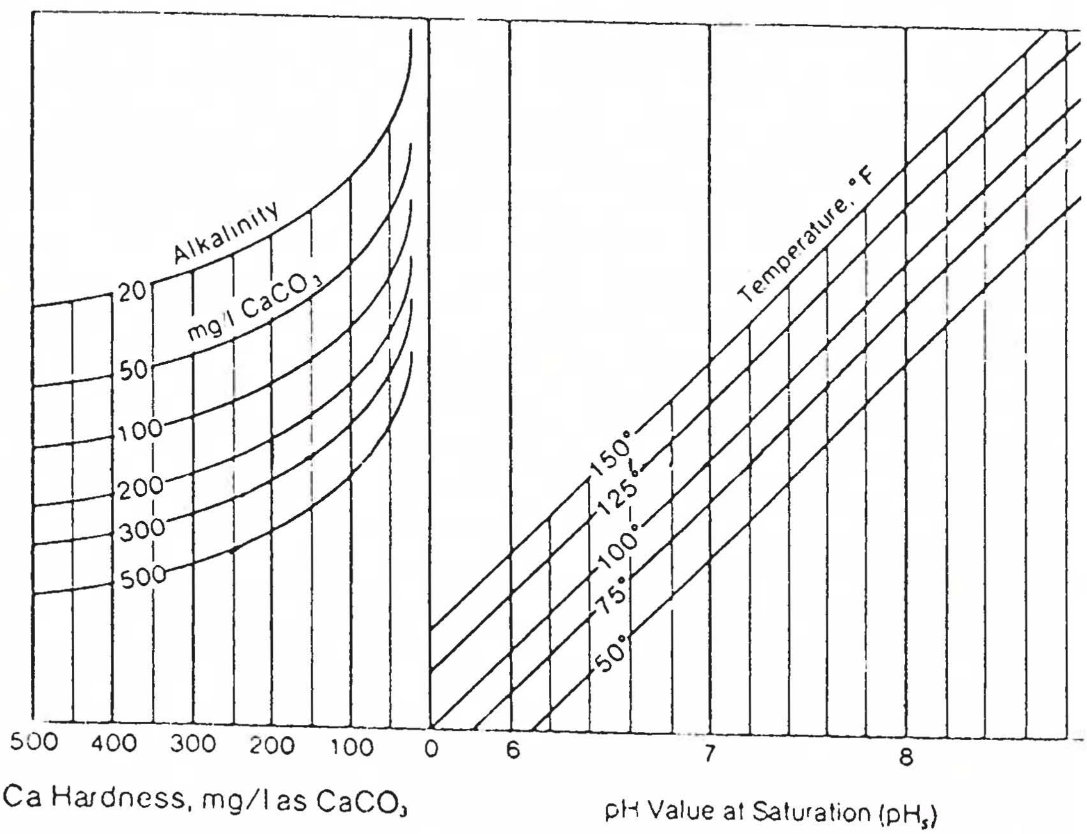


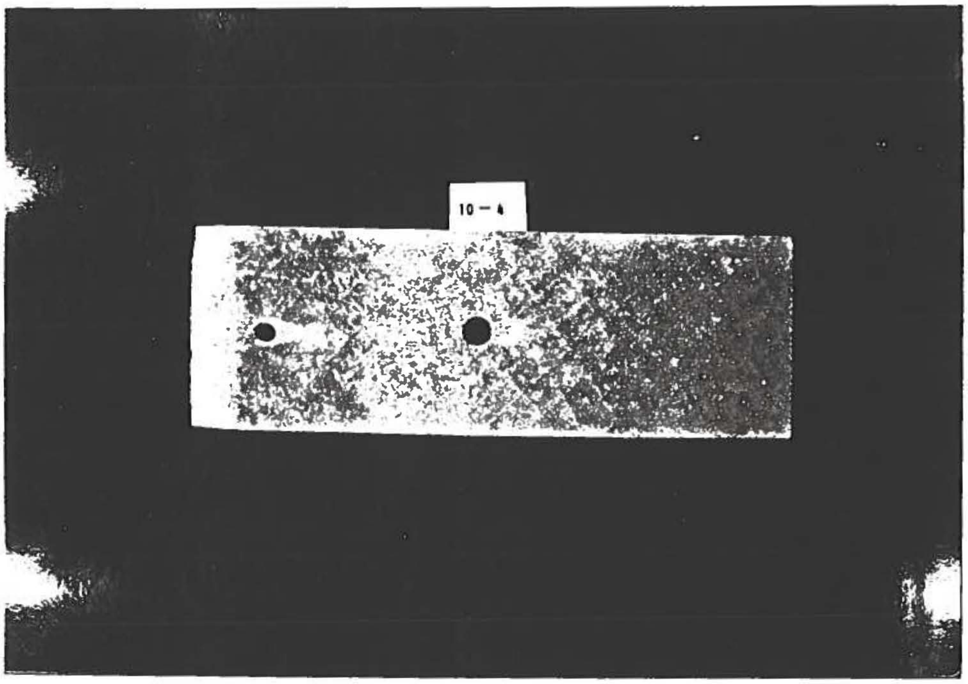
Figure 48. Nomagraph for Langelier data. (Kemmer, 1979)

TABLE 12. DRY SEASON PLATES VS. WET SEASON PLATES
(Growth weight in grams)

	DRY (NOV-FEB)		WET (AUG-SEP)
7 DAYS			
Site 1	0.3393	<--	0.0174
Site 2	0.5574	<--	0.0160
Site 3	NMG	--	NMG
Site 4	0.1762	<--	NMG
Site 5	NMG	--	NMG
14 DAYS			
Site 1	1.8361	<--	1.7946
Site 2	3.4170	<--	3.2158
Site 3	0.5699	<--	0.2019
Site 4	4.6229	<--	1.5885
Site 5	NMG	-->	0.3590
21 DAYS			
Site 1	2.4834	--	MISSING
Site 2	5.2612	<--	4.1114
Site 3	0.3351	-->	0.4512
Site 4	4.7073	<--	2.3333
Site 5	0.0045	<--	NMG
28 DAYS			
Site 1	3.5739	--	MISSING
Site 2	MISSING	--	6.6513
Site 3	1.2465	<--	1.1461
Site 4	7.4782	<--	2.6876
Site 5	0.1140	<--	0.1050

Arrow points to higher reading

NMG means "No measurable growth"



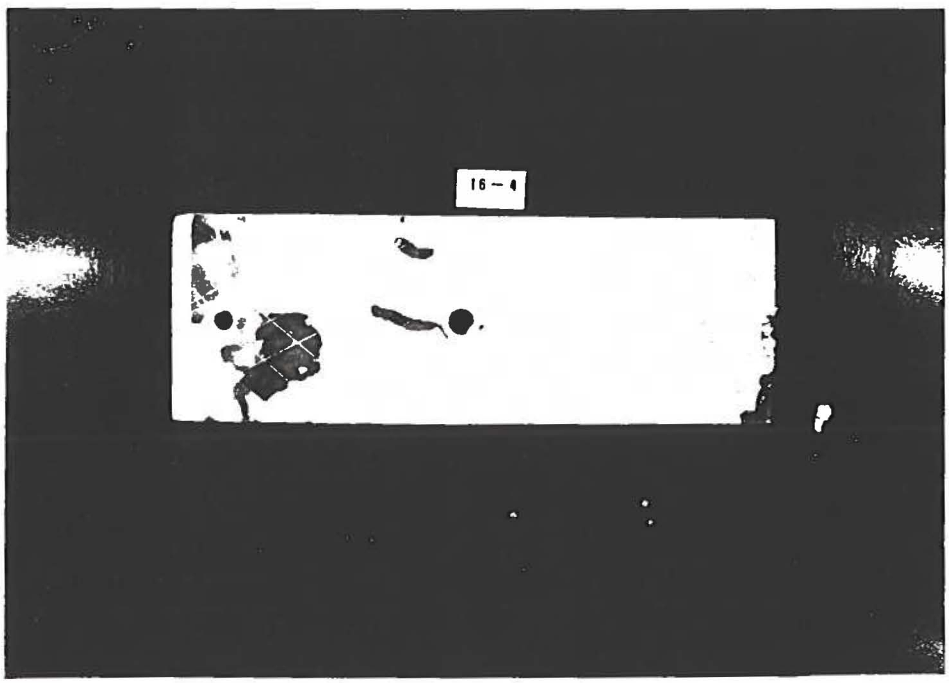


Figure 49. Plates 10-4 & 16-4. These are 28-day plates. Dry (10-4) and rainy (16-4) season plates.

More deposition occurred on the plates placed during the dry season. Paired comparison analysis of these data (Table 13) showed a significant difference between the deposition weight of the rainy and dry plates at the 95% confidence level and a significant difference among the sites at the 99.9% confidence level.

Deposition of stromatolitic material occurred at all study sites along the Asmafines River at vastly different rates. Since this material completely dissolved in 0.01 N HCl and had the appearance of carbonate material it is assumed to be calcium carbonate ($CaCO_3$) (It was also identified as calcium carbonate by Dr. Frank Kilmer).

Deposition (and dissolution) of $CaCO_3$ is controlled by pH, and the relative amounts of carbon dioxide (CO_2), bicarbonate ion (HCO_3^-), and carbonate ion ($CO_3^=$) in the water column.

Their relationships are expressed in the following equations:

(1) $CaCO_3 + CO_2 + H_2O \leftrightarrow Ca(HCO_3)_2 \leftrightarrow Ca^{+2} + 2(HCO_3^-)$

(2) $CO_2 + H_2O \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ CO_3^=$

TABLE 13. ANOVA TABLE OF PAIRED COMPARISON ANALYSIS OF DEPOSITION WEIGHT ON PLATES PLACED IN THE RAINY AND DRY SEASONS

Source of variation	*df*	*SS*	*MS*	F_s
Season placed	1	5.5995	5.5995	5.49*
Site	14	94.0063	6.7147	6.59**
Remainder	14	14.2733	1.0195	
Total	29	113.8791		

$F_{.05[1,14]} = 4.60$ $F_{.01[1,14]} = 8.86$ $F_{.001[1,14]} = 17.1$
$F_{.05[14,14]} = 3.66$ $F_{.01[14,14]} = 4.25$ $F_{.001[14,14]} = 5.8$

The relative amounts of carbon dioxide (CO_2), bicarbonate ion (HCO_3^-), and carbonate ion ($CO_3^=$) in the water column are controlled by pH. Their relationships are shown in Fig. 50. At pH 7.6, only 5% of the total carbon is presen as free CO_2. This steadily decreases until at a pH of 8.2 there is no free CO_2.

Calcium bicarbonate remains in solution only if excess carbon dioxide is present in the water. If carbon dioxide is removed (by any process) a corresponding amount of calcium bicarbonate is broken down to yield carbon dioxide water and calcium carbonate which is insoluble and immediately precipitates (Equation 1 is driven to the left). Processes that can remove CO_2 from the water colum include its release to the atmosphere from supersaturated groundwater in spring outlets (outgassing) and its removal by plants in the process of photosynthesis (Schwoerbel, 1987 and Smith, 1985).

As shown in Fig. 47, 89% of the pH values from this study were above 7.6. Fourteen percent were above 8.2. At these pH values very little free carbon dioxide occurs in the water (0%-5%) and little to no calcium bicarbonate in solution. The Langelier indices (Tables 10 & 11) indicate the water of the Asmafines River is supersaturated with $CaCO_3$ and these indices are higher in general for the dry season data.

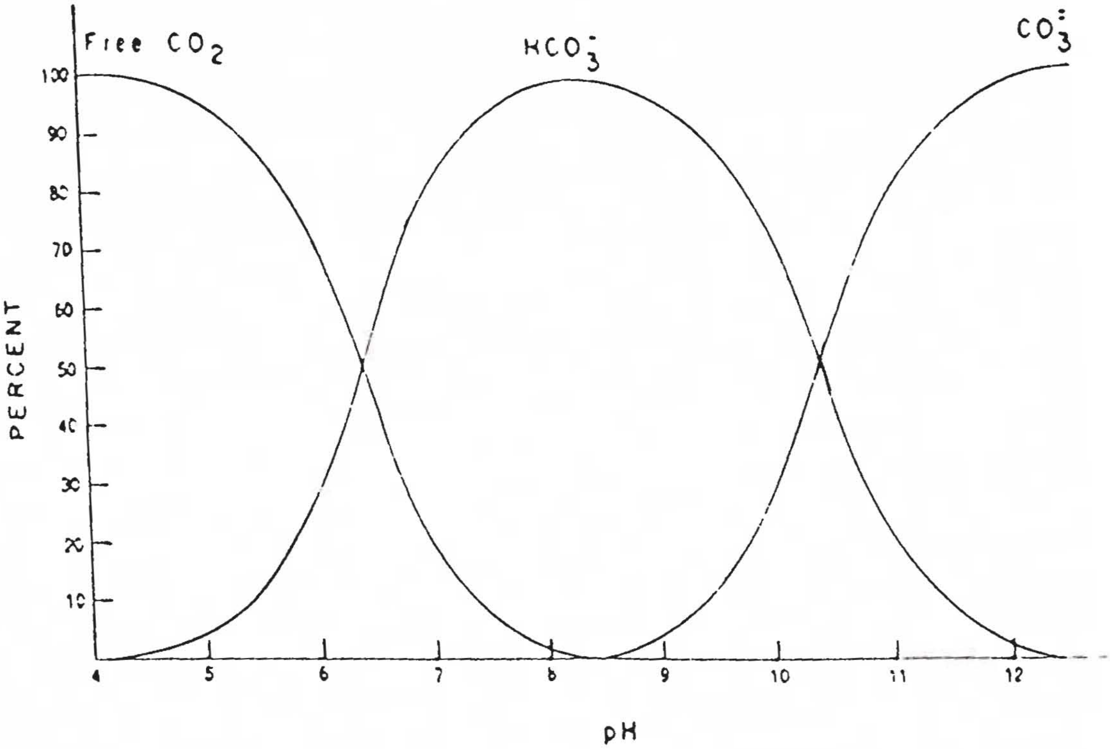


Figure 50, The relative amounts of CO_2, HCO_3-, and $CO_3=$ are dependent on pH. (Brower & Zar, 1985)

Stromatolite formation (precipitation of calcium carbonat along the Asmafines River is controlled essentially by th presence or absence of free CO_2 in the water column. Wit excess CO_2, calcium bicarbonate remains in solution; if C is removed, calcium carbonate is precipitated until there is excess CO_2, and the pH is lowered. Ordering of the me pH data in Table 6 from highest to lowest yields the site ranking shown in Table 14.

Site 5 had the highest mean pH of all the sites; these readings were taken at the cascade base and they imply ver little or no calcium bicarbonate could have been carried b the water. There was little to no deposition of calcium carbonate at Site 5.

Site 4, on the other hand had the lowest mean pH readings of all the sites, both above and below the cascade. This implies free carbon dioxide was present in significant quantities [up to 15% at some of the lower readings (Table 5 & Fig. 50). One of the features of the deposition at Sites 3 and 4 was the abundance of hepatics that grew on the cascades (Figs. 17, 51 & 52). Site 4 had more hepatic growth than Site 3 and living hepatics were presen at Site 4 during most of the time of this study. The hepatic growth at Site 3 was restricted for the most part to the rainy season. These plants were not present in any

TABLE 14. MEAN pH READINGS FOR EACH SITE LISTED IN DESCENDING ORDER

MEAN pH	SITE
8.19	Site 5
8.06	Site 3 upper
8.05	Site 2 upper
8.03	Site 1 upper
7.95	Site 4 upper
7.95	Site 3 lower
7.94	Site 2 lower
7.93	Site 1 lower
7.86	Site 4 lower

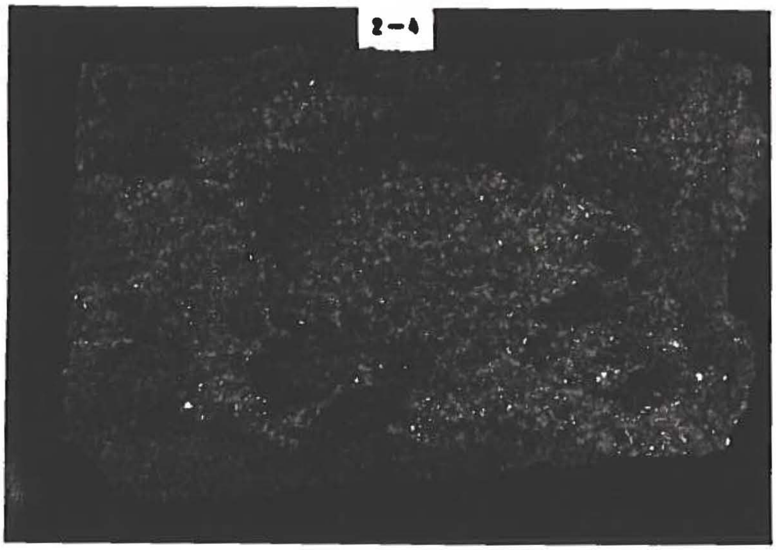


Figure 51. Plate 2-4. A 164-day plate.

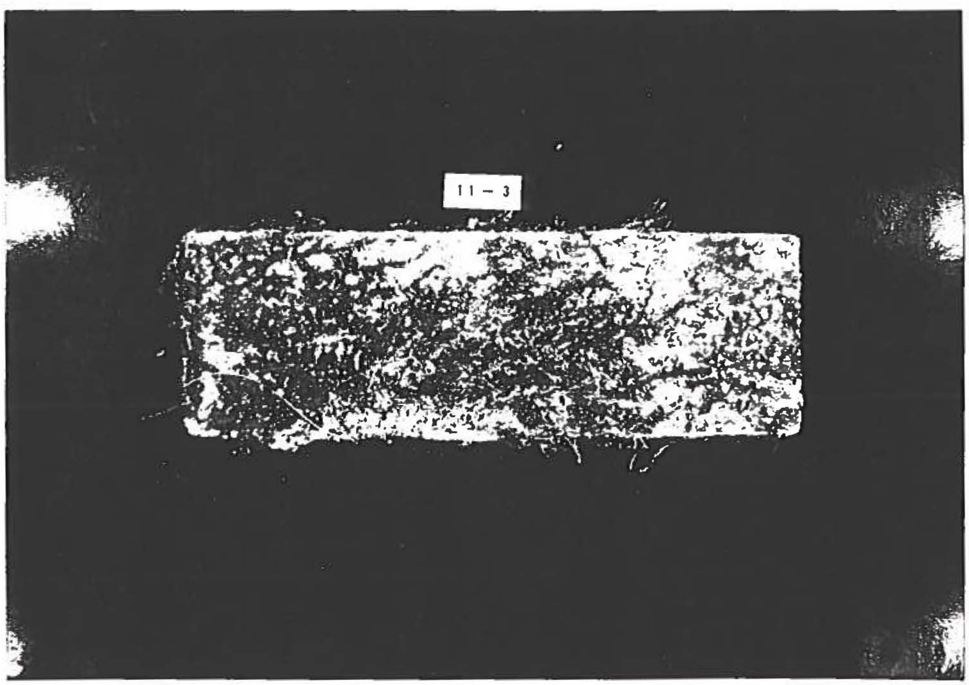


Figure 52. Plate 11-3. A 119-day plate.

quantity at any other site. If these hepatics (and other photosynthesizers present) removed significant quantities of CO_2 from the water, then dissolved calcium bicarbonate would be precipitated. This would replace free CO_2 in th water and restore equilibrium between CO_2 and HCO_3^-.

If all (or almost all) the dissolved calcium bicarbonate were precipitated, pH would be lowered because equilibriu would be restored at a lower point. If, on the other hanc there was an abundance of dissolved calcium bicarbonate, CO_2 removal would not necessarily cause all of it to precipitate (as calcium carbonate) and no net change in pH would occur.

Mean pH at Site 4 was higher above the cascade, but there were times when the pH at the bottom of the cascade was higher than the pH at the top. This was generally true of dry season readings (Table 5) which suggests either no calcium carbonate was removed, or not enough was removed t lower the pH. As removal did take place, and large quantities were deposited, an abundance of calcium bicarbonate must have been carried in the water column at those times. The area at the base of the cascade at Site was flat and terraced with several rimmed shallow pools (> 5 cm deep) where large amounts of deposition also occurred. Visible deposition of calcium carbonate occurred along the stream bed for ca. three meters downstream from Site 4.

Site 3 had much less total deposition than Sites 1, 2 and 4, although it had more buildup of material than Site 5. The rock of the cascade at Site 3 looked similar to the stromatolitic material of the other sites, but it was very soft and spongy; it was difficult to attach plates because the nails kept working loose and several plates were lost before longer nails were used. The mean pH at upper Site was 8.06 (Table 14) the highest mean pH after that of Site 5. At this pH, little to no calcium bicarbonate could be carried. If most of the calcium bicarbonate available in the water column had been removed by precipitation of calcium carbonate upstream at Site 4, then removal of more CO_2 from the water column by plant activity or outgassing would cause the pH to drop significantly and in fact, Site 3 was the only site for which paired comparison tests between the upper and lower pH values showed a highly significant drop.

Downstream from Site 3 was a pool ca. 4 m in diameter and m deep that is surrounded and underlain by large limestone boulders. There may also be a spring beneath it since outflow from it seems to be somewhat greater than inflow. If there is a spring, its waters would probably contain a high amount of CO_2 (Schwoerbel, 1987). The influx of CO_2 would drive Equation 1 to the right and cause dissolution of the limestone rocks until equilibrium was restored. In addition, decaying vegetable matter in stream pools can produce acid waste which would also drive Equation 1 to t right.

Stromatolitic coating of the stream bed began again in th channel just above Site 2 and continued to produce the massive stromatolitic formation of the cascade at Site 2. Stromatolites were intermittent along the stream bed between Sites 2 and 1. Site 1 had a lower total depositi weight than Site 2, possibly because much of the calcium bicarbonate dissolved in the pool above Site 2 had alread been removed.

Since deposition can also be controlled by the amount of calcium bicarbonate available to the water column, Dr. Frank Kilmer aided in the identification of significant sources of calcium carbonate in the area of the study site

There were no sources of calcium carbonate immediately upstream from Site 5. The entire streambed was volcanic for at least 100 m upstream from Site 5. Immediately abov Site 3 on the stream that formed the cascade of Site 5 (Stream 1), there was a long (ca. 15 m) straight run that was relatively steep. This entire area was covered with a thin stromatolitic crust overlying a volcanic bed. This stromatolitic deposition abruptly ceased close to the top of the hill. On the small stream that formed the cascade of Site 4 (Stream 2), stromatolitic deposition abruptly ceased ca. 30 m upstream from Site 4. On the Asmafines River proper, there was no stromatolitic deposition for c 60 m upstream from Site 4. At that point, stromatolitic deposition began and continued for ca. 40 m upstream and then abruptly ceased.

All three of these stromatolitic deposits (the crust on Stream 1, the area above the cascade and the cascade at Site 4 [Stream 2], and the deposit on the Asmafines upstream from Site 4) appeared immediately downstream fron a light-colored band or seam in the ground that crossed each stream bed. This seam was readily visible in the darker bedrock of the streams. Because of the roughness c the terrain and density of plant growth, I was unable to trace its exact path, but I believe the same seam crossed all three streams. The material of this seam dissolved in 0.1 N HCl and was probably calcium carbonate. This seam may be a lens of limestone and as such could provide a source of calcium bicarbonate and dissolved carbon dioxide to the water column.

Apparently stromatolitic deposition at the study site occurred only if there was a source of calcium carbonate immediately above the area of deposition; deposition ceasec after most of the dissolved calcium bicarbonate had been redeposited because of CO_2 removal.

As was mentioned earlier, deposition appears to proceed faster in the dry season than in the rainy season. Sever factors may be important. Abrasion (some of it severe) o the material on the plates occurred almost exclusively during the rainy season. The monthly rainy season rainfa total for July 1988 was 72.3 cm; for August 1989 it was 64.8 cm. In contrast, the dry season rainfall total for January 1989 was 3.5 cm. Rainy season rainfall levels cause great amounts of water to run off the mountains of southern Guam. Loose gravel can be picked up from the bottom of the stream and scour its way downstream. Erosi(in the watershed during a particularly heavy rain that occurred in the dry season produced a deposit below the Site 5 cascade that raised the stream bed ca. 25 cm. This large amount of erosion occurred from an uncut, unburned, undisturbed watershed. Runoff of this magnitude is also capable of moving leaves, sticks, and small and large rocks. Plates 6-1, 6-2, 12-2 & 15-2 (Figs. 44, 45 & 53) show evidence of plant strands that have caught under the attachment nail of the plate. On Plate 12-2 (Fig. 45), the strands have become coated by deposition and cemented to the plate.

A "table" of limestone rock lies in the middle of the stream bed upstream from Site 4 on the main body of the Asmafines. This "table" is very flat on top and ca. 2.4 m long, 1.2 m wide and 0.6 m high. The bottom is roughly

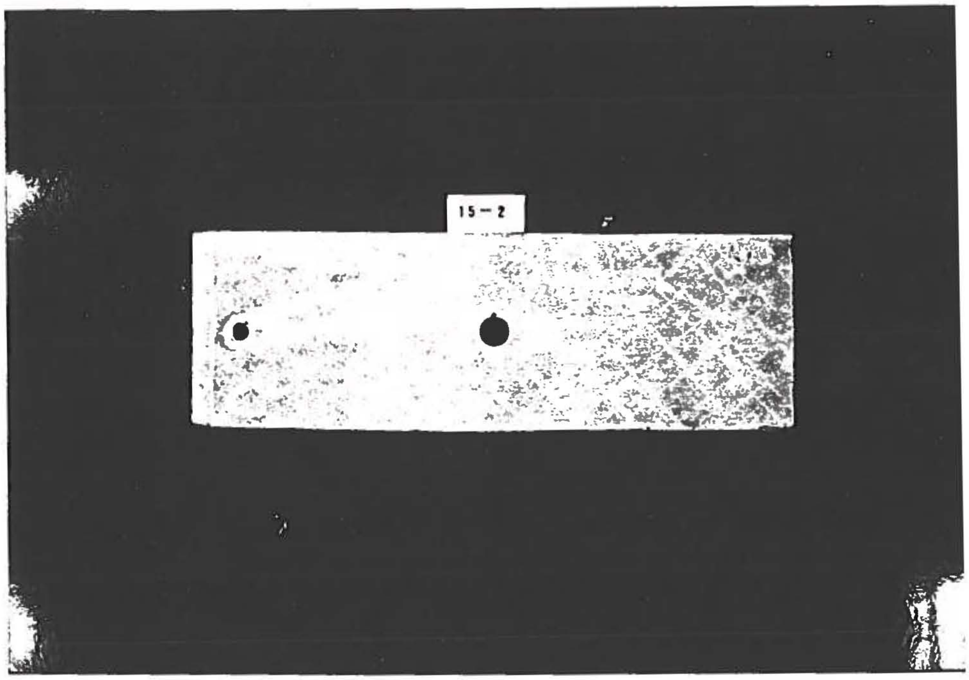


Figure 53. Plate 15-2. A 21-day plate.

keel-shaped, and it apparently slid down the stream bed at some point in the distant past. During the course of this study, plates were knocked loose and broken by the impact and abrasion of water-borne debris; deposited material was knockws loose and scoured from plate surfaces. Mechanical removal of deposition during the rainy season affects tota accumulation.

Chemical restriction or removal of deposition probably als occurred; stream water was more acidic during the rainy season. Rainwater is usually acidic because atmospheric CO_2 dissolves into it, producing carbonic acid. The pH of rain falling near the U.O.G. Science building was measured on 18 August 1989 and found to be 6.63; there was no measurable salt contamination. Runoff water during heavy rain would probably be more acidic; pH measures in the study were usually lower after periods of heavy rain (though none was below pH 7.0). This lowered pH would allow more $CaCO_3$ to be dissolved. If the rainfall were acidic enough, the deposits could have been dissolved.

Plant material was also removed during the rainy season. The cascade at Site 3 lost its entire plant coating (and several centimeters of rock as well) between 11 and 25 September 1988. Site 4 lost most of its hepatic growth during November of that year. Loss of these plants and their CO_2 removal capabilities meant that deposition probably occurred at a lower rate in their absence.

In the dry season, runoff is severely curtailed because t limited rainfall is absorbed by plants to replace evapotransportation. Much of the dry season flow in southern streams (the Asmafines flows year-round) is from springs and limited runoff. Water flow does decrease substantially along the Asmafines; on 28 May 1988 there wa not enough flow to activate the flow meter (Table 9) and there was no water flowing over the cascade at Site 4.

The volcanic soil and rocks of southern Guam have overall low permeability (Ward *et al*, 1965) and are close to water saturation. Perched limestone lenses hold more water than the surrounding volcanics, but during periods of little to no rainfall, discharge rates are low. Therefore, water is retained in the water table for longer periods of time during the dry season. Stark (1965) reported the CO_2 content for the soil near the study site to be 0.05%, whic is fairly low for soils [bog soils can have CO_2 contents o up to 3.77% (Schwoerbel, 1987)] but higher than that of th atmosphere (0.03%). Water retained in the soil would have more CO_2 than the atmosphere and water in perched limeston would also dissolve $CaCO_3$. Any rain would force the discharge of these supersaturated waters, and CO_2 removal by outgassing or by plants would precipitate $CaCO_3$.

During the rainy season, soil water would be flushed constantly and not retained long enough to absorb excessi amounts of CO_2 and $CaCO_3$. Although the rainy season Langelier Indices (Tables 10 & 11) still show supersaturation, the levels are generally lower than thos of the dry season.

The stromatolites on the Asmafines seem to be limited to sites that are downstream from areas that provide high levels of carbon dioxide and calcium bicarbonate to the water column. The literature indicates that many modern freshwater stromatolites may occur in similar circumstances. Present-day freshwater stromatolites were reported in both lakes and small streams but not in large rivers.

Lacustrine freshwater stromatolites have been reported fro five sites. Walter *et al* (1973), and Von der Borch (1976) described stromatolites in two ephemeral lakes near Cooron Lagoon in southwest Australia and Von der Borch *et al* (1977) described stromatolites in nearby Marion Lake. All of these lakes lie on carbonate substrates; the two near Coorong Lagoon dry up completely in the summer. The pH of these lakes is 8.2-9.9 and the salinity ranges from 0.8-15 ‰. Walter *et al* (1973) stated that calcium precipitatio in these lakes occurs naturally and there is no indication that the cyanobacteria present in the stromatolites are necessary to cause precipitation.

Lacustrine stromatolites also occur in Green Lake, New Yo (Brunskill, 1969 and Eggleston & Dean, 1976) and Squaw Island Lake, New York (Pentecost, 1985). Green Lake is c. 1 km long and 0.3 km wide with a small drainage area (4.3 km^2). Most of its water is supplied by groundwater. Eggleston & Dean (1976) stated "The entire lake is saturated or supersaturated with calcite throughout the year as a result of surface and groundwater influx of CaCC from limestone in the drainage area". Pentecost (1985) noted that in most of the environments he studied, calcite precipitation would result even in the absence of cyanobacteria.

Stromatolites also occur at Walker Lake in Nevada (Osborne *et al*, 1982). Walker Lake is a mountain lake with no outlet and the authors stated "Walker Lake is clearly saturated with calcium carbonate and precipitation is likely". They reported pH ranges of 9-9.3 and speculated that the cyanobacteria found in the area may use the carbonate ion as their carbon source since no free CO_2 exists at the pH ranges reported.

The permanently frozen lakes of Antarctica lie in depressions and have no river outlets. This lack of drainage causes ion concentration. Stromatolitic forms i these lakes range from gelatinous mats to hardened column Lake Fryxell has the highest alkalinity and also the highest proportion of hardened (calcified) stromatolites (Canfield & Green, 1985; and Wharton *et al*, 1983).

Monty & Hardie (1976) reported stromatolites from freshwater marshes on Andros Island, Bahamas and in the Everglades in southern Florida. They stated that both sites are over a karst in Pleistocene bedrock overlain wi calcite mud. Data on water chemistry were not provided.

Stromatolites have been reported from running water at si sites. Several authors studied stromatolites that form ir the outflow from hot springs in Yellowstone National Park. Walter *et al*, 1976, stated that cyanobacterial stromatolites formed in pH ranges of 7-9 and temperature ranges of 32-59°C. Of the ten sites studied, silica precipitated at nine and $CaCO_3$ precipitated at the remaining site.

Fritsch & Pantin (1946) reported finding calcareous nodule in the bottom of Bourne Brook (Great Britain) after part o its run had completely dried up following a severe drought They stated "Cambridgeshire waters are generally rich in calcium carbonate and nodules similar to those of Bourne Brook have been found in other local streams". They compared their findings with those of Roddy (1915, in Fritsch and Pantin, 1946) who found similar nodules on Little Conestoga Creek (Pennsylvania), and quoted Roddy as saying that he found nodules in neighboring streams, but only those with a high content of dissolved salts "presumably calcium carbonate". Golubic & Fischer (1975) studied the nodules of Little Conestoga Creek starting in 1966, but by 1969 acid rain had lowered the pH; no further deposition took place and the remaining nodules were being destroyed.

Pentecost (1985) also studied stromatolites in British streams and said that the streams arose from Carboniferous limestone formations. He believed the calcium carbonate precipitation was caused by outgassing of CO_2 when the supersaturated ground water was released. In the same paper, he also reported stromatolites forming in temporary seeps from tower karst in China.

Winsborough and Golubic (1987) found stromatolites being formed by diatoms in carbonate-saturated seeps in the Schicker-Ecke quarry in Germany. The pH was 8.1. They also found diatom stromatolites in a spring-fed stream in Mexico that arises in limestone. At both sites "water is close to saturation with respect to calcite and precipitation of $CaCO_3$ is frequent".

Gelatinous bacterial mats were found around hydrothermal vents in Crater Lake, Oregon (Dymond *et al*, 1989). The authors believed that these previously unreported volcanic seeps may be responsible for anomalously high concentrations of ions in Crater Lake. These mats show no calcification. One ion that is not concentrated in the waters of Crater Lake is calcium. The average calcium concentration in the normal deep lake water of Crater Lake was only 6.73 mg/l. In the immediate area of the bacterial mats/seeps the calcium level was only 12.6 mg/l (compare with the calcium levels in Tables 10 & 11).

In **all** of the above-mentioned studies, it is implied or stated that the waters from which lithified stromatolites formed were saturated or supersaturated with calcium, usually in the form of calcium bicarbonate (although at the pH levels reported for the Australia and Walker Lake sites it is more likely that calcium hydroxide [$Ca(OH)_2$] was produced from the hydrolysis of calcium carbonate). In the one study where no lithification occurred (Crater Lake), the water was deficient in calcium. Although sites may exist where lithified stromatolites are forming in freshwater with "normal" calcium bicarbonate levels, I did not find reports of any.

Calcium may not be the only limiting factor. Rothschild and Mancinelli (1990) collected data about carbon fixation rates of microbial mat systems (non-lithified) in evaporation ponds of the salt company Exportadora de Sal, SA, Mexico (west coast of Baja California). They constructed a model from their data and suggested that th massive decline of stromatolites just prior to the Cambri may have resulted from a decrease in carbon fixation following a decreased availability of atmospheric inorgan carbon.

Carbon dioxide is released into the atmosphere by volcanos and other hydrothermal processes at a rate high enough to double the total amount of atmospheric carbon in only 400,000 years (Walker *et al*, 1983). Since this doubling does not occur, atmospheric CO_2 must be removed; this occurs through the process of weathering of silicate minerals and the deposition of carbonate minerals. Silicate weathering is strongly influenced by ambient temperature, which can be a function of the amount of CO_2 in the atmosphere (the "greenhouse" effect). Thus carbon dioxide and global temperature are closely linked in a feedback system.

It is generally assumed that solar luminosity was lower during the formation and early development of the Earth. In order to understand how liquid water could have existed on the early Earth (as it undeniably did) a mechanism must be found that would have raised the temperature of the early Earth to the point where liquid water could have be sustained. If there were, in fact, a significantly highe level of atmospheric CO_2 than is present today, this woul have provided the requisite rise in temperature.

Although extremely high atmospheric CO_2 levels are detrimental (algal respiration is limited when CO_2 partia pressure is raised to 1000 times its present level) atmospheric CO_2 levels much higher than present day level were definitely possible in Earth's early atmosphere (Walker *et al*, 1983). A steady increase in the luminosit of the sun would have gradually warmed the Earth and increased the rate of weathering thus removing CO_2 from tl atmosphere. This would have decreased the ready availability of free CO_2 and gradually decreased the rate of carbon fixation. The evolution and subsequent increase of photoautotrophs would have permitted the removal of fre CO_2 at a steady rate.

Rothschild and Mancinelli (1990) stated that carbon fixation rates were at a maximum shortly after 3.5 gya (th time generally accepted for the genesis of stromatolites). Rates then began to decrease and they plummeted during the final few million years of the Pre-Cambrian. Eukaryotes are thought to have arisen around 1.5 gya and the metazoa by 680 mya. These dates correspond, in Rothschild and Mancinelli's data, to the initial decrease and the sudden sharp final decrease in carbon fixation rates. They speculated that the decreased amount of readily available and easily fixed CO_2 was the prime factor that led to the drastic decline in the abundance of the organisms that formed stromatolites, and not metazoan grazing as was proposed by other authors.

Walker, *et al* (1983) also noted that most plants respond increases in carbon dioxide with increased rates of photosynthesis provided their other needs are met. This implies that the mechanism for photosynthesis evolved to maximally efficient at higher levels of atmospheric CO_2 than exist today. They also speculated on the relationships between CO_2 and the solubility of calcium carbonate. Increased amounts of CO_2 would increase the amount of calcium bicarbonate carried in water and make it precipitation difficult except through the removal of CO_2 (as by autotrophs). This could have inhibited the ability of heterotrophs to form carbonate tests or shells. Thus, the rapid rise of shelled forms in the Cambrian could have been a direct consequence of the newly available $CaCO_3$ in the water caused by the decline in atmospheric CO_2.

Today, freshwater stromatolites may form in areas that most resemble their habitats of old - places where carbon dioxide is, by present day standards, abnormally high and the water column contains a high concentration of calcium bicarbonate. Perhaps we will even see an increase in life's most ancient forms as man and his mechanization contribute to the increase of carbon dioxide in the atmosphere, at least in non-industrialized areas where there is no acid rain.

CONCLUSIONS

1. Stomatolitic deposition occurred on the Asmafines River at all sampled sites.

2. The amount of stromatolitic deposition was strongly positively correlated with the length of time the pla remained attached to the stream bed.

3. Stromatolitic deposition occurred at different rates a the various sampling sites along the rivers. The amount of deposition seemed to be correlated to the presence or absence of limestone inclusions in the immediate vicinity (upstream) of the sampled site.

4. Stromatolitic deposition occurred at a faster rate in the dry season.

5. Data indicate that the water of the Asmafines River is supersaturated with calcium carbonate much of the time literature references indicate that this is also true for most other freshwater sites.

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