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GEOLOGY OF THE PERLITE DEPOSITS
OF THE NO AGUA PEAKS
TAOS COUNTY, NEW MEXICO

by

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Abstract

Most of the perlite produced in the United States is obtained from an accumulation of rhyolitic rock which underlies the No Agua Peaks, Taos County, New Mexico. Two quarrying operations yielded about 8 million tons of crude perlite in 1950-79. The perlite, most of it devoid of onionskin texture, forms discrete bodies, associated with bodies of glassy rhyolite and lithic rhyolite. All of the units are mappable, showing well defined, although commonly gradational, contacts. The units are distinguishable megascopically by marked differences in vesicularity, crystallinity and color.

The rhyolitic accumulation is confined to an area of about five square miles where it forms four hills. The perlite and glassy rhyolite units of each hill show a crudely annular pattern in plan. On each hill, the contacts between the two rock types, as well as the flow banding within individual bodies, tend to dip inward, apparently toward a central vent. We thus interpret each hill as the site of an individual extrusion dome. The bodies of lithic rhyolite, of various shapes and sizes, cut across the annular pattern and are interpretable as dome bursts.

Exposed at the crest of each hill is a body of relatively compact perlite. The lower slopes of each are underlain successively by a body of glassy rhyolite and a body composed mostly of relatively vesicular perlite. Locally and successively exposed beneath the latter are units of glassy rhyolite, perlite, and perlite tuff-breccia. Analyses of samples of 27 perlite show an average H_2O content of 2.76 wt. percent; 7 samples of glassy rhyolite averaged 2.33 wt. percent H_2O.

The H_2O may have been derived mostly by hydration of obsidian by long-continued circulation of meteorite water after the formation of the

~~formations of th~~e domes, or it may have been magmatic water exsolved from rhyolite melts during vesiculation and later reabsorbed during the cooling of the magma. We favor the later interpretation for most of the hydration as (1) the water apparently is uniformly distributed in the vesicular units, both perlite and glassy rhyolite, (2) the degree of hydration ~~being~~ is unrelated to proximity to the surface or to zones of fracturing and brecciation, and (3) the perlite characteristically lacks the onionskin texture associate with late hydration. We also interpret each body of perlite and glassy rhyolite as emplaced as a separate flow, because features indicative of flow surfaces were observed at the top of the upper glassy rhyolite unit.

Introduction and Acknowledgments

The principal source of perlite in the western hemisphere, and perhaps the world, comprises a group of deposits in the No Agua Peaks of northern New Mexico. The deposits form part of an accumulation of rhyolitic volcanic rocks which form the peaks. They were first worked in 1950. Through 1979, they probably had yielded a total of about 8 million tons of commercial perlite, nearly all obtained from two properties. One is now owned and operated by the Johns-Manville Products ~~Company~~ Corporation, and the other by the General Refractories Company (Grefco).

This report is concerned primarily with the economic geology of the No Agua perlite deposits, but it also includes a brief description of the Brushy Mountain perlite deposit, about 15 miles east of the No Agua Peaks. The report consists mainly of material contained in the doctoral thesis of the senior author (Naert, 1974) and is based on field and laboratory investigations pursued during the period 1971-1974.

The field work involved the preparation of the geologic map of Plate 1 and the sampling reported herein. It was confined largely to the summers of 1971 and 1972 when the project was supported by two successive grants from the New Mexico Bureau of Mines and Mineral Resources. Another phase of the investigation of the No Agua perlite deposits concerned variations in the thermal expansion characteristics of the perlite and their possible relation to variations in certain physical and chemical characteristics of perlite, specifically chemical composition, bulk density, and percentage by volume of glass, crystallites, and vesicles. A brief summary of the measurement of these variations and of a statistical analysis of the results is included herein.

Most of the field work and all of the petrography was done by Naert. Chemical analyses were made, also by Naert, in the Mineral Constitution Laboratories, Pennsylvania State University. Wright conceived of the project, arranged for the grants from the New Mexico Bureau of Mines and Mineral Resources, contributed about seven days to the initial and end stages of the field work, field-checked the map and served as thesis advisor. Thornton served on Naert's thesis committee, also field-checked the map, and contributed to theoretical parts of the report. At Naert's invitation, Wright assembled the report in its present form. He also prepared Figures 7, 12, 28, and 29.

Personnel of the Johns-Manville Products Corporation Grefco and the Silbrico Company authorized the examination of their respective properties and assisted in many other ways. The Johns-Manville Products Corporation, in particular, generously supplied funds for the analytical part of the study and made available a topographic map (scale 1 in.: 400 ft.) of its property.

F. L. Kady and Irving Friedman, in critical reviews of the manuscript, contributed numerous helpful suggestions and observations, as well as their preferred interpretation of the internal structure of the rhyolitic accumulation of the No Agua Peaks and the origin of the perlite. C. W. Burnham also helpfully reviewed the manuscript and provided, for quotation, observations on the theoretical role of water in the formation of the No Agua deposits. Naert, Wright and Thornton, however, are solely responsible for the field and analytical data and for the interpretations placed upon them.

Definitions of Perlite, Origins of the Perlite Industry and Treatment and Uses of Perlite

The term "perlstein" was first used by Fichtel (1791) who defined it as glassy volcanic rock with a pearly luster. This definition was also employed by Esmark (1798). Beudant in 1822 introduced the term "perlite" as a synonym for perlstein. The observation that volcanic glass will expand if heated to suitable temperatures apparently was first made by J.W. Judd (1886). Concerning the heating of obsidian nodules, he stated, "If the temperature be now raised to whiteness the whole mass swells up to cauliflower-like excrescences, till it has attained eight or ten times its original bulk".

From the early definition of perlite and from the observation of the thermal expansion of obsidian have evolved the two presently used definitions of perlite, one petrologic and the other commercial. In a petrologic sense, the term is commonly applied to glassy volcanic rock of rhyolitic to dacitic composition, containing two to five percent combined water, and displaying an onionskin texture and a pearly luster. The perlite of commerce is ordinarily defined as any glassy volcanic rock which, upon heating, expands to at least ten times its original volume without the production of excessive fines or excessive unexpansible material. Although commercial perlite is defined very broadly, it has proved to be chemically similar to the material that fits the petrological definition. As commercial perlite commonly lacks the pearly luster or onionskin texture, in this report the term "onionskin perlite" will designate rock that falls within the petrologic definition of perlite. Rock to which the commercial definition applied will be termed simply "perlite".

The perlite deposits of commrce occur mainly in three geologic settings: (1) borders of rhyolitic flows, (2) full thicknesses of rhyolitic flows, and (3) variously shaped bodies that form parts or all of rhyolitic domes. The largest and most uniform perlite deposits have proved to be associated with the rhyolitic domes, the No Agua deposits being a noteworthy example.

Expanded perlite apparently was first used commercially in Germany where, in 1924, it was employed as an ingredient in abrasive bricks (Jaster, 1956). Perlite is reported to have been first used in the United States in 1940. In that year, expanded perlite was employed as an aggregate in plaster at a plant near Las Vegas, Nevada; it was also used experimentally as an ingredient in enamel ~~in~~ at Superior Arizona (Anonymous, Chem. and Met. Eng., 1945; Taylor, 1950). Domestic production of perlite was first recorded in 1946, and was obtained mostly from deposits in Arizona. In the late 1940's and early 1950's interest in perlite as an industrial material grew rapidly, and much effort was devoted to prospecting, testing, and the development of uses. At scores of localities in the western United States deposits of volcanic glass were explored and tested as possible sources of perlite (Fig. 1). Hundreds of claims were staked, and attempts were made to place many of the deposits in operation. But no more than 25 were reported active in a given year. The crude material was shipped to various points, mostly in the western United States, where it was expanded and sold to local markets, mainly as a lightweight aggregate.

The value of a given deposit proved to depend mainly on four factors: (1) the expansion characteristics of the perlite, (2) size of the deposit, (3) physical accessibility and ease of operation of the deposit, and (4) location of the deposit with reference to actual or potential markets. Many of the early attempts to quarry perlite profitably ended in failure, as operators experienced difficulty in producing perlite with uniform expansion characteristics. This problem was caused, in part, by variations in the composition and texture of the rock quarried and, in part, by nonselective mining practices. Difficulties also were experienced in perfecting the technique of expanding perlite. Consequently, in the mid-1950's the mining of perlite in the U.S. became dominated by a few large companies which controlled large deposits and were capable of producing marketable perlite of uniform quality. In 1977, a total of 871,000 tons of crude perlite was quarried in the United States. Eighty-nine percent of this production was obtained from New Mexico and principally the No Agua deposits.

At present, perlite is expanded in two types of furnaces, one horizontal and the other vertical. Each is operated at temperatures in the general range of 1400° to 1800°F (600°C-1000°C). Crude perlite, ground to specified sizes, is retained only a short time in the furnace. Upon expansion, it is carried away with the hot gases to an air classifier where it is separated into several sizes and the excessively fine material is removed. In the milling and expanding process, care is taken to produce a minimum of fines.

The usefulness of expanded perlite stems mainly from a combination of physical and chemical properties, most notably (1) low bulk density, (2) low thermal conductivity, (3) high heat resistance, (4) low sound transmission, (5) large surface area of individual particles and (6) chemical inertness. The four first-listed properties have led to the principal use of expanded perlite, namely as an aggregate in insulation boards, plaster, and portland cement concrete. Between 50 and 60 percent of the expanded perlite produced in the United States is used for these purposes. It is also used as a filter, low-temperature insulating material, filler, abrasive, foundry castable and bonding agent and for numerous other purposes.

History of Discovery and Development of the No Agua and Brushy Mountain Perlite Deposits

The historical summary that follows was based on informal conversations with M.B. Mickelson, J. Graham, and D. Griffiths who, in 1971 and 1972, were managers of Johns-Manville, General Refractories and Silbrico perlite operations of northern New Mexico. These accounts attribute the recognition of potentially economic deposits of perlite in the No Agua Peaks area to M.B. Mickelson of Antonito, Colorado. In 1948 Mickelson obtained a sample of commercial perlite from the deposit near Superior, Arizona. In August of that year, while picnicking in the No Agua Peaks, he noted a similarity between the sample and a rock unit extensively exposed in the area of the peaks. He had previously prospected the No Agua Peaks area for volcanic cinders unaware that he was walking across one of the world's largest deposits of perlite. A few days after the picnic he staked claims covering much of the north (Fig. 3) and east part of the area.

At nearly the same time claims covering the west and southwest parts of the mountains (Fig. 3) were staked for the Great Lakes Carbon Comapny, now a Division of the General Refractories Company (Grefco). The claims now owned by the Silbrico Company, on the south slope of east hill, were staked for United Mines of Taos. Also at nearly the same time Mercedes Ortiz, a government trapper, discovered and claimed a perlite deposit (Figs. 31 and 32) here referred to as the Brushy Mountain deposit, just north of Cerro Montoso 15 miles east of the No Agua Peaks.

The perlite claims of the No Agua area thus compose three properties (Fig. 3), each separately owned since the claims were staked. The present owners, consisting of the Johns-Manville Corporation, the Grefco and the Silbrico Company, acquired these properties through the sales and mergers shown in Figure 4 . Since 1965 all of the perlite produced from the No Agua deposits has been obtained from the Johns-Manville and Grefco quarries.

The Silbrico quarry was operated only in 1965 when about 500 tons of perlite was removed by a former owner, the U.S. Perlite Company.

Perlite from the property of the Johns-Manville Corporation is quarried by blasting and is stockpiled near a mill on the property. The crude perlite is crushed, dried, screened and distributed to storage bins. The prepared perlite is transported 25 miles in covered hopper trucks to storage and blending facilities at a railhead in Antonito, Colorado. At the Grefco property, perlite is scraped from the quarry without blasting and is milled similarly to the perlite quarried by the Johns-Manville Corporation.

In both operations the milling produces a minus 120-mesh fraction that composes as much as ten percent of the crushed perlite. This fraction is of no present value and is placed in waste piles on the property. A still finer fraction, produced during the sizing and drying, is collected in bag houses and is also piled on the property.

All of the perlite produced in the Johns-Manville operation and most of the perlite produced by Grefco is shipped in bulk or in bags to expansion plants throughout the United States and Canada. Grefco expands some of its product in a plant at the Antonito railhead.

General Topographic and Geologic Features of the No Agua Peaks and Vicinity

The No Agua Peaks occupy an area of about five square miles which lies athwart the common boundary of the La Seguita Peaks and Tres Piedras 7½ minute quadrangles of New Mexico. U.S. Highway 285 passes close to the western margin of the peaks, connecting the perlite operations with Antonito, Colorado, 25 miles to the north and with Tres Piedras, New Mexico, 7 miles to the south.

The No Agua Peaks rise above the surface of the Taos Plateau (Fig. 5) which, at that locality, is about 8000 feet above sea level. The peaks are actually four relatively large hills (West, North, East and South Hills) spaced as to form the corners of a square about 4000 feet on a side. The hills crest at elevations 900 to 1200 feet higher than the surrounding plateau. The western part of this topographic high is lower and commonly referred to as the "Low Hill area" (Fig. 6). The No Agua Peaks are dwarfed by San Antonio Peak, a dome-strato volcano whose crest is about seven miles northeast of them and is 10,833 feet above sea level.

The general geological features of the vicinity of the No Agua Peaks (Fig.7) were described by Butler (1971) in a paper which covers a much larger area extending mainly to the west and south of the peaks. As noted by him, the dome-forming rhyolitic bodies of the No Agua Peaks are part of a succession of late Cenozoic volcanic and sedimentary rocks which, in north-western Taos County and northeastern Rio Arriba County, rest depositionally upon Precambrian metamorphic and igneous rocks. This succession is broadly divisable into an older part and a younger part.

The older part was originally termed the "Los Pinos gravel" (Atwood and Mather, 1932). It was renamed the Los Pinos Formation by Butler (1971) who, in the area of Figure 7 , recognized three members. In upward order these are (1) the coarsely porphyritic quartz latite member composed of tuffaceous sandstone, tuff, and conglomerate containing clasts of porphyritic quartz latite, (2) the La Jarita Basalt Member, and (3) the rhyolite member composed of sandstone, conglomerate, tuff, and flows, the volcanic units being mostly rhyolitic. The younger part of the late Cenozoic succession, comprising the Hinsdale Formation and the overlying Servilleta Formation, consists mainly of basalt flows interlayered with subordinate sand and gravel.

Volcanic domes which form San Antonio Peak and Cerro Aire are composed of hypersthene-bearing quartz-latite, a unit which predates the Servilleta formation and may be younger than the lower part of the Hinsdale Formation (Butler, 1971).

The rhyolitic units of the No Agua Mountains are older than the Hinsdale Formation and younger than much of the Los Pinos Formation, although the uppermost strata in exposures of the Los Pinos Formation, along Highway 285 about one mile northwest of the northwest border of the No Agua Peaks, contain clasts of glassy, rhyolitic rock which were derived from the No Agua domes (Figs. 8 and 9). Logs ~~of drill~~ from a 1147-foot rotary drill hole (R.D.H. 2), collared near the Johns-Manville plant (Fig. 10), indicate that successively beneath the rhyolitic units of the No Agua Peak are a 170-foot thickness of basalt (probably the La Jarita Basalt Member of the Los Pinos Formation) and a 450-foot thickness of sandstone, shale and conglomerate.

The rhyolite bodies of the No Agua Peaks have yielded a 3.5 m.y. radiometric date (analysis of potassium and argon isotopes from feldspar phenocrysts by W.A. Bassett) and 4.8 m.y. fission track date (Lipman and others, 1970). Another fission track analysis, this one of a sample of the upper glassy rhyolite, indicated an age within 11 to 13 million year interval (analysis by M.G. Seitz, Geophysical Laboratory, Carnegie Institue, Washington, D.C., 1972). The volcanic rocks of the Hinsdale Formation in the vicinity of the No Agua Peaks have yet to be dated radiometrically, but they probably were deposited near the end of Hinsdale volcanism (Butler, 1971).

The geological setting of the No Agua Peaks is typical of many volcanic terranes where bodies of rhyolitic and basaltic rock are closely associated. Such a relationship between lavas of bimodal compositions has been explained in various ways. One explanation would derive the acidic lavas through the partial melting of earlier felsic rocks and involves a heat source related to the basaltic rocks. The acidic lavas of the No Agua Peaks may have been derived in such a fashion from the Precambrian basement rocks, presumed to consist largely of granitic gneiss, that lie at shallow depths beneath the accumulation of rhyolitic rocks.

Investigations of Other Perlite Deposits and of the Origin of Perlite

Although the origin of perlite has been treated in a number of papers, published mainly in the period 1958-1966, relatively little has been written concerning the petrologic and structural features of large deposits of perlite. The available descriptions indicate that most or all of the perlite bodies of present or potential commercial interest occur as parts of rhyolitic domes. Individual domes range in diameter from a few tens of meters to as much as one kilometer. Some of the domes consist simply of a centrally located body of perlite surrounded, in plan, by rhyolite or glassy rhyolite and featured by inward dipping flow banding. Examples include the Cedar Top perlite deposit, San Bernandino County, California (Wright and others, 1954), and the Fish Springs perlite deposit, Inyo County, California (Chesterman, 1957a). Other domes, such as the Ardov dome, U.S.S.R. (Nasedkin, 1963), consist of alternating layers of perlite, glassy rhyolite, and lithic rhyolitic, but also arranged concentrically in plan. Brief descriptions of still other perlite deposits also imply a concentric structure. These include the Puketara Tholoid and Opal Deposits, Tairua district, New Zealand (Thompson and Reed, 1954), deposits near Socorro, New Mexico (Weber, 1963), and the Numinbah Valley deposit, New South Wales, Australia (Hamilton, 1966). The conical internal structure, implied by the in-dipping flow banding and concentric plan common in perlite-bearing rhyolitic domes also has been shown in idealized representations of rhyolitic domes in general (Fig. 11 ; von Leyden, 1936).

The perlite bodies of the rhyolitic domes ordinarily show gradational contacts with the glassy rhyolite. Analyses of the associated glassy rhyolite, as well as analyses of the perlite, commonly show a water content in excess of two percent. Characteristically included in the bodies of perlite and glassy rhyolite, are occurrences of massive obsidian which clearly predate the bordering water-rich glassy rock and which analyze only a small fraction of a percent of water. Much of the obsidian is in the form of black nodules, from less than 1 cm to 12 cm in diameter, surrounded by perlitic material with an onionskin texture. ~~and~~ informally termed "marekanites" or "Apache tears",

That perlite, as defined petrologically, forms by hydration of obsidian was first proposed by Chesterman (1954). He based this conclusion on the contrast in water content, gradational contacts between the massive obsidian and onionskin perlite, and the observation that the perlite is concentrated along fractures that extend into the obsidian. "Perlitization" according to Chesterman (1957b) occurs when "volcanic glass, originally containing only a few hundreths percent water, becomes fractured and brecciated, and hydrated to perlite". He observed that the necessary water could have been derived in part from ground water and in part from extrusive bodies emplaced nearby.

Ross and Smith (1955) also concluded that the onionskin perlite that encloses cores of water-poor obsidian has formed by secondary hydration of the obsidian. They attributed the onionskin texture to volume change produced by hydration of the surface layer of obsidian. Nasedkin and Petrov (1962) observed that volcanic glass, when partially hydrated experimentally, acquired the concentric cracks characteristic of onionskin texture. They concluded that the cracks were the result of stresses between layers of differing degrees of hydration. Friedman and Smith (1958) measured the relative deuterium concentrations in eleven samples of coexisting obsidian and onionskin perlite and compared them with deuterium concentrations in meteoric waters. They concluded that the meteoric waters were unrelated to the water in the obsidian, but were related to the water in the perlite, and that the hydration thus occurred in the presence of meteoric waters.

Geological Features and Rock Units of the No Agua Mountains

Previous Investigations

The perlite deposits of the No Agua Peaks have been described only in a very general way by previous workers. Two chemical analyses of the glassy rocks were reported by Shepherd (1938). Butler (1946), in reference to the peaks, described them as an erosional remnant of an extinct volcano. He noted a range in lithology from "black spherulite-bearing obsidian to purple-gray, finely flow-layered, spherulite-bearing pitchstone" and estimated an age of late Middle Tertiary.

In a brief report on the economic geology of the No Agua perlite deposits, Schilling (1960) described them as a volcanic dome extruded from several vents during the late stages of the Pliocene-Pleistocene volcanism. He estimated the reserve~~d~~s of commercial perlite at several millions of tons. The possibility of the presence of several domes, rather than a single dome, was suggested by Weber (196~~3~~5). May (1965) suggested that the rhyolitic bodies are parts of a single, extensive flow, almost 1000 feet thick, which has been eroded into several hill-forming remnants. In 1971, the No Agua Peaks were referred to by Butler as an erosional remnant of a local mass of rhyolite which was extruded after all or nearly all of the uppermost member of the Los Pinos Formation had been deposited and before the Lower Basalt Member of the Hinsdale Formation was emplaced.

General Features

Most of the rhyolitic material of the No Agua Peaks is separable into; (1) perlite, (2) glassy rhyolite, and (3) lithic (stony) rhyolite. These compose mappable units distinguishable by differences in the ratio of glass to crystalline and cryptocrystalline material, and by differences in the degree of vesicularity. Contacts between perlite and glassy rhyolite are ordinarily gradational, but the gradation generally occurs within a few feet, permitting well exposed contacts to be shown as solid lines on the geologic map. The mapping also was aided by persistent differences in color. Locally exposed within the rhyolitic terrane is a fourth mappable unit which qualifies as a "tuff-perlite breccia".

The perlite is persistently the most vesicular of the three. Its vesicularity, however, ranges widely from body to body and, to a lesser degree, from place to place within a given body. The perlite specimens examined in thin section proved to be within the range of 5 to 20 percent vesicles. Specimens of glassy rhyolite showed a vesicularity of 2 to 5 percent. Specimens of lithic rhyolite were non-vesicular. The contacts between bodies of perlite and bodies of glassy rhyolite, although gradational, consistently mark an abrupt change in vesicularity, The water content (H_2O expelled in the range of 110°C to 950°C) of the major rock types, as indicated by analysis of 60 samples (Table 1), decreases from an average 2.76 percent in the perlite to an average of 2.33 percent in the glassy rhyolite, and thence to an unmeasured, but obviously much lower percent in the lithic rhyolite. We can detect no other significant differences in chemical composition from rock type to rock type (Table 1) within a given dome. As indicated below, however, systematic differences have been detected in a comparison of the composition of the western part of the volcanic pile with the composition of the rest of the pile.

Much or all of the cryptocrystalline material in the glass-bearing units apparently has formed by the devitrification of glass. The coarser crystalline material consists predominantly of plagioclase which, where identifiable in thin section, proved to be in the albite-oligoclase range. Phenocrysts of quartz and biotite are minor constituents of all of the rhyolitic units. Black obsidian, in the form of semi-angular nodules (marekanites) generally 1 to 3 cm in diameter, are present, but uncommon, in all of the bodies of glassy rhyolite. They are persistently surrounded by perlite. Nearly all of the observed marekanites are in the upper glassy rhyolite unit.

The perlite, glassy rhyolite, and lithic rhyolite are characteristically flow banded. The individual bands of all three rock types are generally thin, most of them within the .5 mm to 2 mm range and rarely exceeding 1 cm in thickness. The banding is expressed by differences in the proportions of glass to cryptocrystalline and microcrystalline material, and, in the perlite units, by differences in the abundance of vesicles. It

Number and rock unit	SiO_2	Al_2O_3	TiO_2	FeOX	MnO	MgO	CaO	Na_2O	K_2O	Rb-PPM	H_2O-Min	H_2O-450	H_2O-950	H_2O-450 plus H_2O-950	H_2O-TOTAL
N-35 B	51.50	16.15	1.240	11.00	0.160	6.500	8.42	3.30	1.80	20.0					
N-69 UGR	75.60	13.15	0.130	0.76	0.080	0.190	1.10	4.32	4.25	115.0					
N-88 LR	75.99	13.02	0.015	0.65	0.165	0.050	0.60	4.23	4.25	270.0					
SPECIMENS RECOVERED FROM RDH-2 (Diamond Drill Hole shown on Plate 1)															
60' MP	74.50	13.35	0.075	0.78	0.060	0.080	0.79	4.17	4.65	115.0					
80' MP	73.30	13.15	0.075	0.75	0.060	0.110	0.83	3.80	4.50	115.0					
100' MP	73.37	12.82	0.070	0.85	0.080	0.100	0.91	3.58	4.37	128.0					
160' MP	73.37	13.05	0.215	0.73	0.070	0.080	0.77	4.00	4.67	124.0					
230' MP	72.00	13.00	0.130	0.80	0.070	0.120	0.77	4.02	4.60	110.0					
320' MP	70.45	12.92	0.052	0.80	0.085	0.420	1.10	2.95	4.09	123.0					
410' MP	83.00	9.00	0.215	0.77	0.040	0.310	0.89	1.90	2.60	37.0					

Table 1. Chemical analyses of volcanic units of the No Agua Peaks. Number-letter designations refer to sample locations on Plate 1. TPB = tuff perlite breccia unit; LP = lower perlite unit; LGR = lower glassy rhylite unit; MP = middle perlite unit; UGR = upper glassy rhyolite unit; UP = upper perlite unit; LR = lithic rhyolite unit. FeOX = combined FeO and Fe_2O_3; H_2O-Min = H_2O released below 110°C; H_2O-450 = H_2O released between 110°C and 450°C; H_2O-950 = H_2O released between 450°C and 950°C. Percentages of SiO_2, Al_2O_3, TiO_2, Fe_2O_3, MnO, MgO and ppm of Rb were obtained by means of Perkin Elmer 303 and 403 atomic absorption spectroscopes. Percentages of Na_2O and K_2O were determined with a flame photometer 1L143. Analytical precision, established by replicate analysis, is within ± 1.5 percent for all components except TiO_2 and Rb. Accuracy of TiO_2 is within ± 10 percent and for Rb is within ± 5 percent.

Number and rock unit	SiO_2	Al_2O_3	TiO_2	FeOX	MnO	MgO	CaO	Na_2O	K_2O	Rb-PPM	H_2O-Min	H_2O-450	H_2O-950	H_2O-450 plus H_2O-950	H_2O-TOTAL
4-4 UP	73.60	13.27	0.070	0.70	0.071	0.127	0.87	3.78	4.48	137.0	0.0900	2.5342	0.3440	2.8783	2.9682
4-5 UP	75.10	13.34	0.070	0.75	0.066	0.043	0.79	3.35	4.36	135.0	0.1873	2.4895	0.4876	2.9772	3.1644
4-6 UP	73.60	13.24	0.065	0.67	0.069	0.032	0.84	3.79	4.48	132.0	0.0958	2.5581	0.3730	2.9311	3.0269
4-7 UP	73.00	13.35	0.085	0.76	0.079	0.040	0.85	3.81	4.50	134.0	0.0673	2.6873	0.3238	3.0111	3.0784
4-8 UP	72.35	13.12	0.085	0.78	0.065	0.075	0.85	3.80	4.53	128.0	0.2798	2.6099	0.3145	2.9244	3.2042
4-9 VGR	73.45	13.20	0.070	0.68	0.065	0.040	0.85	3.89	4.57	138.0	0.1137	2.5755	0.2631	2.8386	2.9523
4-10 UGR	74.25	13.35	0.080	0.74	0.073	0.050	0.89	3.86	4.50	132.0					
4-11 LR	73.60	12.95	0.075	0.70	0.073	0.060	0.85	3.91	4.54	141.0					
4-12 UGR	73.10	12.47	0.090	0.77	0.074	0.115	1.30	3.82	4.22	130.0	0.2119	2.7777	0.6509	3.4286	3.6405
4-13 MP	74.00	13.22	0.070	0.67	0.071	0.030	0.87	3.82	4.54	128.0	0.0999	2.8932	0.3126	3.2058	3.3057
4-14 VGR	73.40	13.35	0.080	0.67	0.071	0.020	0.84	3.82	4.53	130.0	0.0918	2.5946	0.2597	2.8544	2.9461
4-15 MP	75.00	13.42	0.080	0.65	0.071	0.045	0.91	3.87	4.49	132.0	0.1438	2.1475	0.2720	2.4196	2.5633
4-16 MP	74.10	13.30	0.070	0.67	0.071	0.057	0.88	3.58	4.77	137.0					
4-17 TPB	74.10	13.34	0.070	0.65	0.073	0.025	0.91	3.85	4.54	137.0	0.0915	2.4037	0.3161	2.7198	2.8113
5-1 UP	76.90	13.68	0.095	0.73	0.072	0.040	0.93	3.95	4.70	157.0	0.1459	1.9888	0.2137	2.2024	2.3484
5-2 UP	74.00	12.68	0.062	0.70	0.070	0.130	0.82	3.95	4.84	142.0	0.1692	2.0427	0.1974	2.2392	2.4083
5-3 UGR	73.00	12.88	0.080	0.67	0.075	0.030	0.84	3.85	4.90	137.0	0.1766	1.9566	0.2090	2.1656	2.3422
5-4 MP	73.60	13.00	0.065	0.67	0.073	0.040	0.92	3.93	4.69	130.0	0.3946	1.8381	0.2416	2.0797	2.4743
5-5 MP	73.90	12.90	0.075	0.68	0.070	0.035	0.84	3.96	4.67	137.0	0.0603	2.3841	0.3882	2.7723	2.8326
5-6 MP	73.75	13.15	0.070	0.85	0.076	0.035	0.87	4.06	4.97	136.0	0.1986	1.6356	0.1865	1.8221	2.0207
5-7 MP	71.00	12.82	0.095	0.70	0.067	0.040	0.86	3.88	4.52	117.0	0.0596	2.3101	0.3236	2.6336	2.6933
G-1 TPB	72.10	12.70	0.060	0.60	0.142	0.015	0.52	4.33	4.54	267.0	0.3500	2.3075	0.2969	2.6045	2.9544
G-2 MP	74.00	12.95	0.060	0.61	0.145	0.010	0.52	4.25	4.67	262.0	0.4435	1.3050	0.2605	1.5655	2.0090
G-3 MP	74.00	12.90	0.215	0.62	0.140	0.060	0.52	4.50	4.32	255.0	0.4560	2.4830	0.3444	2.8274	3.2834
G-4 MP	74.60	12.98	0.100	0.59	0.150	0.017	0.55	4.14	4.45	256.0	0.2944	2.5867	0.3044	2.8911	3.1855
G-5 MP	73.70	12.70	0.145	0.59	0.140	0.030	0.45	4.60	4.60	250.0	0.5646	2.2880	0.2943	2.5823	3.1469
G-6 MP	73.55	12.74	0.080	0.58	0.145	0.025	0.53	4.24	4.70	255.0	0.3942	2.3342	0.2855	2.6198	3.0139
G-7 MP	72.60	12.60	0.052	0.61	0.140	0.020	0.54	4.10	4.27	267.0	0.3449	2.5683	0.2758	2.8442	3.1890
G-8 MP	74.70	13.00	0.052	0.61	0.145	0.020	0.54	4.07	4.27	267.0	0.3680	2.5898	0.3001	2.8899	3.2579
G-9 MP	73.60	12.62	0.060	0.58	0.144	0.030	0.74	4.23	4.41	252.0	0.3968	2.4546	0.3303	2.7850	3.1817
G-10 MP	74.10	12.77	0.015	0.60	0.145	0.020	0.60	4.03	4.15	263.0	0.2695	2.8012	0.8252	3.6264	3.8959
G-11 MP	73.75	12.70	0.060	0.57	0.147	0.015	0.52	4.32	4.52	265.0	0.3287	2.5705	0.3156	2.8862	3.2148
G-12 MP	75.50	12.90	0.070	1.60	0.140	0.030	0.47	4.45	4.42	250.0	0.2957	2.2968	0.3089	2.6057	2.9014
G-13 MP	73.75	12.77	0.065	0.59	0.145	0.005	0.51	4.27	4.35	247.0	0.3500	2.5154	0.2599	2.7753	3.1253
G-14 LGR	74.00	12.98	0.065	0.59	0.150	0.015	0.53	4.44	4.53	240.0	0.4518	1.2166	0.2088	1.4254	1.8772
G-15 LP	72.00	12.62	0.70	0.56	0.147	0.020	0.78	4.27	4.46	251.0	0.4226	2.5484	0.3018	2.8501	3.2728
G-16 LP	75.20	12.77	0.015	0.62	0.150	0.020	0.53	4.12	4.27	264.0					
G-17 MP	74.25	12.85	0.100	0.61	1.470	0.050	0.51	4.25	4.47	272.0	0.2747	2.6903	0.2859	2.9763	3.2509

is accentuated by an elongation of the vesicles. Where present, the marekanites tend to occur in rows parallel with the flow banding and clearly represent remnants of unusually thick (as much as 10 cm) flow bands of original, water-poor obsidian now partly altered to perlite.

In basic geologic features the four hills are similar in that the crest of each is underlain by a body of relatively compact perlite, the higher slopes largely by glassy rhyolite, and the lower slopes largely by vesicular perlite. Additional support for the separate dome interpretation exists in the observation, elaborated upon in a following section of this report, that all of the perlite and glassy rhyolite units of the Low Hills - West Hill area contain lower percentages of Al_2O_3, TiO_2, Fe_2O_3, MgO, CaO, and K_2O and higher percentages of MnO, Na_2O and Rb, than do the rhyolite units of the rest of the No Agua Peaks.

Upon observing the consistent distribution of the same rock types, from dome to dome, Naert based his designation of mappable units upon two factors, lithology and position in the domes. Thus the names "upper perlite", "middle perlite", and "lower perlite" are applied, in that order, to the bodies of compact perlite exposed on the crest of each hill, to the vesicular perlite of the lower slopes, and to the vesicular perlite beneath the glassy rhyolite of the Low Hill area. The two units of glassy rhyolite are designated as "upper glassy rhyolite" and "lower glassy rhyolite", whereas the two other rhyolitic units are simply termed "tuff-perlite breccia" and "lithic rhyolite". Because the "lower perlite" is exposed only in the Low Hill area and the lower parts of the four domes are hidden beneath talus and alluvium, the designation of a "middle perlite body" on each of the four domes does not necessarily imply that each is featured by a still lower body of perlite now hidden from view. Indeed, ~~a~~ the rotary drill hole, near the Johns Manville mill, passed through ~~a 150 m~~ the 400-ft (125m) thickness of the middle perlite directly into Tertiary basalt and sedimentary units, indicating the absence there of the lower units of the North Hill area (Fig. 10).

General Features and Petrology of the Rhyolitic Units

Tuff-vitrophyre

Tuff-perlite breccia, as shown on the geologic map (Pl. 1), is of very limited exposure. Where noted at the locality in the Low Hill area, it apparently underlies a westward extension of the lower glassy rhyolite unit of the West Hill. The tuff-perlite breccia, exposed on the south side of the west-trending ridge west of the Johns Manville plant, appears to underlie the middle perlite unit of the North Hill. On the southwest side of the East Hill, tuff-perlite breccia also underlies perlite of the middle perlite unit, but its position with respect to the structure of the East Hill dome is unclear.

The tuff-perlite breccia is typically gray to reddish brown and consists of fragments of onionskin perlite. Most of the fragments are within the range of 5 mm to 15 cm in diameter. They are contained in a matrix composed of powdery, red tuffaceous material (Fig. 13). The unit ranges from poorly to well bedded.

Because of its limited exposure and obscure pattern of distribution, the position of the tuff-perlite breccia in the internal structure of the domes ~~are~~ is also obscure. Much of this unit may have formed in front of advancing flows of perlite and have involved in part, the mixing of fragmented perlite with ash from an underlying layer. Underlying ash was observed at the locality northeast of the Grefco plant and may record the initial event of the rhyolitic volcanism.

Lower perlite unit

The lower perlite unit, which was recognized only in the Low Hill area of the western part of the mountains, is nonresistant and commonly covered by talus. Where the unit is exposed, its lower part is consistently hidden beneath Quaternary alluvium. It is exposed well enough laterally, however, to indicate that it probably continuously underlies the western part of the Low Hill area and thus forms a body that is about 2000 m in north-south dimension. It is generally overlain by the lower glassy rhyolite unit and, in a place west and northwest of the Grefco quarry, by the lithic rhyolite unit. Quarrying of the lower rhyolite unit would require the removal of much overburden of glassy rhyolite and lithic rhyolite and thus would be uneconomic at present.

The lower perlite unit is gray to pale brown and very vesicular, the vesicles composing about 20 percent of the rock. The ratio of glass to crystalline and cryptocrystalline components appears to be slightly greater than 1:1. Flow banding is common.

Lower glassy rhyolite unit

The lower glassy rhyolite unit which is exposed only in the Low Hill area, is resistant, ledge-forming, gray in color and weathers a dark gray. It ranges in estimated thickness from 10 m to 50 m. It is much more extensively exposed than the underlying lower perlite and tuff-perlite breccia units. It forms most of the foot wall of the middle perlite unit in the Low Hill-West Hill area. It is essentially coextensive with the overlying middle perlite unit, the two units extending, coulee-like, well to the west of the central part of the West Hill dome. The lower glassy rhyolite is unexposed east of the Low Hill area. If present in the area of the four domes it is hidden beneath alluvium and overlying volcanic units. Where exposed, the lower and upper contacts of the lower glassy rhyolite unit tend to parallel the topographic contours, indicating a generally horizontal attitude.

The lower glassy rhyolite unit, is strongly flow banded. Along the lower contact the banding, in general, is parallel with the contact and dips gently inward. In the higher parts of body the banding shows a wide range in orientation, apparently resulting from flowage in a viscous lava. The lower glassy rhyolite is much less vesicular than the overlying middle perlite unit, the vesicles forming no more than two percent of the volume of the specimens examined. Approximately two thirds of the solid material consists of cryptocrystalline and microcrystalline material, considerably more than contained in the overlying perlite. The glassy fraction, which forms the remaining third shows a pearly luster in hand specimen and an onionskin texture in thin section. The relatively high proportion of non-glassy, unexpansible material makes the glassy rhyolite unusuable as perlite.

Middle perlite unit

The middle perlite unit, immediately underlies most of the area of the Low Hills to form there the aforementioned ore body on the Grefco property. It also underlies most of the lower slopes of each of the four hills where, unlike its occurrence in the Low Hills area, it is commonly hidden beneath talus derived from the overlying upper glassy rhyolite member. Where the unit is exposed, it displays flow banding that, in the vicinity of the domes, commonly dips inward toward the centers of the hills, although less obviously than does the flow banding in the upper glassy rhyolite and upper perlite. Thus, we tentatively interpret the middle perlite unit as issuing from vents at each of the four domes, the contacts between the four bodies being obscured by popr exposures and relatively uniform lithology.

The middle perlite unit is gray to pale brown and weathers mostly to pale brown. Like the lower perlite unit, it averages about 20 percent vesicles, but displays a considerable range in vesicularily. The solid fraction, as is typical of the No Agua perlites, displays 1:1 to 6:5 ratios in the proportion of glass to cryptocrystalline and crystalline material. The vesicles are, in general, larger than in the lower perlite layer, commonly about 5 mm in maximum dimension, and they are abundant enough to permit the perlite to be quarried without blasting.

In some places, including the south side of the East Hill, the middle perlite contains zones of less vesicular and more crystalline rock that resemble the middle glassy rhyolite. An interlayering of glassy rhyolite and perlite of the middle perlite unit is shown in a generalized way (P. 1) on the south side of the North Hill.

Recent excavation on the south side of the West Hill have shown that the middle perlite unit there is strongly and irregularly brecciated through much of its thickness. As it resembles brecciation that commonly features the fronts of rhyolite flows, we interpret it in this way.

Upper glassy rhyolite unit

The upper glassy rhyolite unit, which underlies the middle to high slopes of each of the four hills and forms bodies that tend to be annular in plan, is generally resistant and well exposed (Fig. 15). The bodies range in estimated thickness from about 50 to 150 m. The rock is gray on fresh surfaces and weathers to reddish gray. It is locally vesicular, but, like the lower glassy rhyolite, much less so than the bordering bodies of perlite. Some is distinctly flow banded (Fig. 16), some only faintly so.

The configuration of the flow banding of the upper glassy rhyolite unit provides the principal evidence that each of the hills is the site of an extrusion dome (Pl. 1, Fig. 12). Although variously oriented in detail, the flow banding, in general, dips inward toward the centers of the hills and parallel with contacts between the upper glassy rhyolite and the overlying and underlying units.

The flow banded facies closely resembles the lower glassy rhyolite, being characterized by alternating laminae of glass-rich and glass-poor material (Fig. 17). The onionskin texture, so common in the lower unit is generally undetectable in handspecimens of the upper glassy rhyolite, but is commonly observable in thin sections of the upper unit. About two thirds of both the well banded and poorly banded rock, like the lower glassy rhyolite unit, consists of cryptocrystalline and crystalline material (Figs. 18, 19, 20).

Where especially well exposed on the North and East Hills, the upper part of the upper glassy rhyolite unit is shown to consist of a zone characterized by an onionskin texture of the glass (Fig. 21), a pink color, a clay-size alteration mineral, and scattered cores of obsidian (marekanites) an inch or less in diameter. Locally the zone also contains scattered masses of pumice as much as 20 cm. long. Downward from the overlying unit of perlite the onionskin texture disappears.

Upper perlite unit

As the upper perlite unit underlies much of the crest of each of the four hills and is underlain by the inward-dipping upper glassy rhyolite unit, we interpret it as occupying the central and highest part of each of the domes. The domes of the North and East Hills contain the two bodies of greatest areal extent, each being irregularly ovoid in plan, 700 m and 900 m long and 400 m and 500 m in maximum width respectively. The upper perlite body of the West Hill is of comparable dimensions, but is transected and made very irregular by two intrusive bodies of the lithic rhyolite. The upper perlite body of the South Hill is poorly exposed, but is apparently by far the smallest of the four, as mapped being only about 350 m long.

The upper perlite unit displays a relatively uniform lithology from hill to hill. It is colored grayish brown and weathers pale brown. It is vesicular but the vesicles compose only 5 to 15 percent of the volume of rock, compared with the 20 percent average vesicularity of middle and lower perlite bodies. The perlite of the upper body is thus much more compact than the perlite of the other two. The vesicles are elongate and generally 1 to 3 mm long. As with the other perlite units, fifty to sixty percent of the solid fraction of the rock consists of glass; the remainder is cryptocrystalline and crystalline material (Fig. 23).

The flow banding of the upper perlite unit is generally well defined, but in some places is indistinct. It ranges widely in attitude within an individual body. A large proportion of the measured attitudes, however, strike approximately parallel with the trace of the contact with the underlying glassy rhyolite (Pl. 1, Fig. 7). Most of these also dip inward toward the centers of the domes. Tension fractures, ordinarily 2 to 20 cm long and arranged in echelon, are common, and apparently formed during the end stages of consolidation. The physical characteristics of the upper perlite unit, like those of the middle perlite unit, differ from place to place within a given dome and from dome to dome, and introduce problems of quality control. The differences appear to be mainly in the abundance of vesicles and the degree to which onionskin texture is developed. Although most of the upper perlite lacks the onionskin texture, Johns-Manville personnel report its presence in perlite quarried south of the fault on the North Hill. A body of onionskin perlite also was encountered in the main quarry on the North Hill. It is crudely circular in plan, a few tens of meters in diameter and contains pink clay-like material. The operators observe that perlite of onionskin texture produces a relatively high percentage of fines during processing. They also report that perlite recovered from shallow drill holes shows a decrease in vesicularity with depth. Nevertheless, the upper perlite unit appears to consist almost entirely of rock of proved or potential value as expansible perlite.

Lithic rhyolite unit

The intrusive bodies of lithic rhyolite are irregular in outline and cut all of the other major lithologic units. These are widely distributed, occurring in each of the four domes and in the Low Hill area. We interpret them as dome bursts marking the final event in the volcanic history of the No Agua domes. They range in exposed length from about 100 m to 1800 m. The lithic rhyolite is colored a characteristic bluish gray. As flow banding is developed to various degrees, the rock ranges from well laminated to massive. Both the laminated and massive facies consist mostly of cryptocrystalline and crystalline material. They contain various proportions of glass (Fig. 25), but also an overall higher proportion of the nonglassy constituents than the glassy rhyolite. Where glass is locally abundant, the unit is difficult or impossible to distinguish in outcrop from the upper glassy rhyolite. The flow banding displayed in the laminated rock is variously oriented, but is generally concordant with the outlines of the bodies.

Breccias

In addition to the tuff-perlite breccia, and the flow breccias, two other types of breccia were noted in the No Agua rhyolite terrane. One is a fault breccia and the other apparently formed at the sites of extrusion spines (Fig~~ure~~ 26). The fault breccia characterizes all of the faults shown on Plate 1. It is especially well exposed and about 10 meters wide along the west-striking fault that cuts the center of North Hills. There it consists of angular fragments of the bordering units in a finely crushed matrix of the same unit. A similarly large zone of breccia characterizes a west-striking fault which cuts the southern part of the Low Hill area.

Geochemical Evidence for Magmatic Differentiation in the No Agua Rock Units

The chemical analyses of the 72 rock samples, representing all of the units exposed in each dome (Table 1), show apparently significant differences between samples collected in the West Hill-Low Hill area and samples gathered in the other three hills.

Frequency distributions demonstrate the presence of two populations. The most obvious difference is in the rubidium content, one population containing 120 to 140 ppm Rb, the other 240 to 280 ppm. All of the low Rb samples were obtained from the North, East and South Hills; all of the high Rb samples were obtained from the West Hill and the Low Hill area.

A cluster analysis, devised by Friedman and Rubin (1967), was performed on the chemical analyses of the 72 samples (Table 1). This analysis also identifies two distinct groups (Fig. 27), one comprising all the samples from the North, East and South Hills and the other comprising all of the samples from the West Hill and the Low Hill area. The means for Al_2O_3, TiO_2, Fe_2O_3, MgO, CaO, and K_2O are consistently higher and the means for MnO, Na_2O, and Rb are consistently lower in the analyses of samples from the North, East, and South Hills as compared with analyses of samples from the West Hill and Low Hill area. An identical separation is indicated in a plot of the values for the Crystallization Index versus the Alkali Index on a variation diagram. In a closed system, Fe, Mg and Ca are generally removed from the magma at an early stage of crystallization, while Mn, Na and Rb become relatively enriched in the remaining magma. Thus the compositional differences strongly suggest that, if rhyolite of the No Agua domes was extruded from a single magma chamber, the differences in the composition of the rocks are a result of magmatic differentiation, and indicate that the various bodies of rhyolitic rock in the area of the North, East, and South Hills were emplaced before the bodies of the West Hill and Low Hill area.

Extrus~~t~~ion History of the No Agua Domes

Models

In attempting to reconstruct the extrusion history of the No Agua rhyolitic terrane, we have considered the four models of Figure 28. They are based upon observations in the No Agua rhyolitic terrane, and on descriptions and interpretations of typical rhyolitic domes elsewhere (Williams, 1932; von Leyden, 1936; Putnam, 1938; Chelikosky, 1940; Smith, 1973). The models pertain especially to the lower glassy rhyolite, middle perlite, upper glassy rhyolite, and upper perlite units of the No Agua Peaks. Model A features a single, laterally extensive flow, bounded top and bottom be perlitic outer zones and a more crystalline inner part. It rests at least in part, upon an earlier flow of glassy rhyolite. The ~~zones~~ flow is deeply eroded, and the hills are erosional remnants.

Model B involves smaller domes coincident with the hills. Each dome is formed by a single flow which has grown upward and outward from beneath the center of the dome. Each consists of an outer perlitic zone and an inner core of the more crystalline glassy rhyolite. Flow banding in the lower part of the domes dip inward toward the conduit and, in the upper parts, is concordant with the outlines of the domes. It is much less eroded than dome of Model A.

Model C also involves hill-forming domes of about the dimensions of the domes of model B, but constructed of two flows extruded from the same vent. Each flow comprises two cooling units; a vesicular, very glassy upper part (the upper perlite unit) and a less vesicular and less glassy lower part (the glassy rhyolite unit). Flow banding in the inner part of each flow dips inward.

Model D resembles model C, but instead of involving two flows, it would make each of the four units a separate flow contrasting with the underlying and overlying units in degree vesicularity and proportion of crystals. Some of the flows form bodies of perlite, others form bodies of glassy rhyolite. As in model C, the flow banding of the inner part of each flow dips inward.

The term "endogenous extrusion dome" has been commonly applied to features like those portrayed in model B. It is defined by Williams (1932) as a "volcanic dome that has grown primarily by expansion from within and is characterized by a concentric arrangement of flow layers". The type of dome illustrated in model C has been termed an "exogenous extrusion dome" and defined by Williams (1932) as "a volcanic dome that is built by surface effusions of viscous lava from a central vent or crater." Model D is best described as partly endogenous and partly exogenous, the highest and latest flow being essentially endogenous and the others exogenous (Fig. 29)

Origin of the perlite

Pertinent to an evaluation of the four models, is the question of the origin of the perlite. Was it formed by the process, well documented in some perlite occurrences, involving the perlitization of obsidian through hydration by meteoric waters and over a lengthy period well after solidification of the glass; or did the No Agua perlite form in the course of the volcanic event?

The abundance of obsidian nodules (marekanites), ~~as residual~~ in the onionskin perlite-bearing zone at the top of the upper glassy rhyolite of the North and East Hills, demonstrate that at least some of the dome-forming rhyolitic rock originally solidified as nonvesicular obsidian which was later partly perlitized. The primary vesicules, so persistent in the rest of the glassy rhyolite and in the perlite of the No Agua domes point against the possibility that these rocks also were once composed of nonvesicular obsidian. Also lacking is evidence that the water in the vesicular rock was introduced by surface or ground waters. The variations in water content of the perlite and glassy rhyolite samples are relatively small (Table 2) and apparently unrelated in space to the pre-quarry ground surface or to zones of severe fracturing or brecciation.

An alternate interpretation, which we view as more consistent with the available field, petrographic, and analytical observations, holds that most of the water in the glassy rocks is magmatic in origin, was present as a volatile in the vesicles, and was reabsorbed by the glass upon cooling. We discussed this possibility with C.W. Burnham who helpfully provided the following observations."

"Perlitization through reabsorption of water that previously exsolved from the rhyolite melts during vesiculation is compatible with the known H_2O solubility relations (Burnham, 1979, Fig. 3.1). If all of the water now present in the perlites, which averages 2.7 percent in the 27 analyzed samples, is restored to the original melts, these melts would be saturated with H_2O at a depth of approximately 2 km. Upon extrusion of these melts at temperatures in excess of approximately 700°C, more than 90 percent of the H_2O would exsolve in vesiculation. The end product, in this case, however, would be pumice containing more than 90 percent vesicles, which is not in accordance with an observed maximum vesicularity of 20 percent. The vesicles would undergo some compression during cooling under a load of overburden, of course, but the discrepancy is much too large to be accounted for by this mechanism.

"An alternative explanation involving magmatic "water" is to assume that, as the magmas ascended from depths of approximately 2 km or greater, and underwent partial vesiculation, temperatures declined below approximately 700°C prior to extrusion, thereby metastably "freezing" into the glass most of the original H_2O content. Accordingly, a vesicularity of 20 percent would be produced by exsolution of only 0.5 wt. percent H_2O at a depth between 800 and 900 m. Lower vesicularities would be produced by correspondingly less exsolved H_2O at greater depths."

Evaluation of the models.

If we have correctly interpreted the markenite-bearing zone at the top of the upper glassy rhyolite unit as also the top of an individual flow and thus the upper perlite unit as a later flow, model C must be preferred, as the other three are nonpermissive of the two units as separate flows.

We reject model A, partly for this reason, but also because it is inconsistent with the generally inward dipping configurations of flow banding and of the geological contacts which characterize each of the hills, an observation made in a preceding section of this report. The single flow interpretation also is incompatible with the compositional differences, cited earlier, between the specimens from the Low Hill-West Hill area and those from the other hills. In addition, the topographic low, between the four hills also is difficult to explain by erosion of a single flow. Post-flow collapse is a possibility, but the mapping shows no evidence for this.

Model B, although more compatible with the observed geological data than model A, lacks evidence for a connection between the upper and middle perlite units. It also is apparently inconsistent with the configuration of the flow banding of the upper perlite unit, and also with the presence of obsidian and pumice in the zone at the top of the upper glassy rhyolite unit.

Model C more clearly accommodates the flow banding pattern of Plate 1 than do models A and B. But it also does not explain the distribution of ~~water-poor,~~ nonvesicular bodies of obsidian and ~~fragments~~ lenses of pumice in ~~a~~ the well-defined layer ~~in the central part of a given fl~~ow. at the top of the glassy rhyolite unit. Also unexplained, is the observation that, in the subsurface (RDH-2; Fig. 10) of the Johns Manville mill area, the middle glassy rhyolite unit, in addition to the lower units, is missing, and the middle perlite unit rests directly upon Tertiary basalt.

Model D, we feel, faces none of the objections cited for the other three models. But in our conversations with other geologists concerning the credibility of model D, some have suggested that individual flows should not show gradational contacts with the underlying and overlying volcanic units and should display flow breccias and other evidences of cooling along their upper surfaces. Some geologists also have suggested that the differences in texture and water content, from unit to unit, are difficult to explain theoretically in a model based on individual flows, particularly if variations in the water content of the magma are implied. A gradational contact, however, can be explained if an individual flow was emplaced before the underlying flow was completely solidified. Also, the marekanite-bearing zone, and its contained ~~blocks~~ lenses of pumice qualify as flow margin phenomena. Moreover, the percentage of water contained in a given unit seems best interpreted as controlled, in large part, by the availability of water vapor in the vesicles and the availability of glass to absorb it. ~~We thus prefer model D and interpret the variation in water content as controlled primarily by the vapor and crystal content of individual flows.~~

ANALYSIS OF THE CHARACTERISTICS OF PERLITE

An attempt was made by Naert (1974) to devise a method of predicting the expansion characteristics of perlite by relating them to variations in the physico-chemical characteristics of the crude material. Numerous earlier attempts have been aimed at the same objectives. These include research and observations by Judd (1896), Kozu (1929), Wilson and Roseveare (1945), King and others (1948), Murdock and Stein (1950), Taylor (1950), Wilfey and Taylor (1950), Keller and Pickett (1954), Weber (1955), Albert (1958), Leineweber (1961), Yavits (1962), Nasedkin (1963), Kadey (1963), Salat and Oncacova (1964), and May (1965). Each suggested that expansion characteristics can be predicted by observing variations in one or more of the following: (1) luster, (2) abundance of obsidian nodules, (3) specific gravity, (4) percentage of combined water, (5) percentages of microscopic inclusions and phenocrysts, (6) chemical composition, (7) texture of the rock, (8) color, (9) degree of devitrification, (10) temperature of expansion, and (11) retention time in the furnace.

A statistical analysis of 106 chemical analyses of perlite samples gathered throughout the world showed that, with regard to chemical composition, the No Agua perlites are a random sample of this world population (Naert, 1974). The following characteristics were measured on 153 samples of the No Agua perlites:

1. Chemical composition (SiO_2, Al_2O_3, TiO_2, Fe_2O_3 (total iron) CaO, MgO, MnO, Na_2O, K_2O, Rb in ppm, and H_2O released at 110°C, 450°C and 950°C);
2. Proportions of glass, crystallites and vesicles as determined by point count under the microscope;
3. Bulk density of the rock as measured with a mercury balance; and

4. Ranking on the basis of presence of banding, relative size of crystallites, presence and degree of development of onionskin texture, and degree of devitrification.

Attempts were made to measure the crystallinity of the glass by X-Ray diffraction, to determine H_2O bonding characteristics of the water by infrared absorption, and to measure differences in the refraction indices of glass, but these pro~~b~~ved unsuccessful.

At the Lompoc, California, laboratories of the Celite Division of the Johns-Manville Corporation, 22 expansion characteristics were measured on 47 of the 72 samples of perlite from the No Agua domes. Samples from the Low Hill area, as well as samples of lithic rhyolite, were excluded from the tests. The tests included data on feed rate, temperature, expanded density, loss on ignition, sieve analyses of the expanded material (percent retained by weight and volume), expanded density of the various size fractions, percent weight of the various size fractions of the expanded material, percent by weight of yield (percent of the crude that expanded) and sinks (unexpansible material), the density of the sinks and the necessary temperature to obtain a 7-8 pcf. expanded density. Data on at least 18 of these 22 variables were obtained for each sample.

Statistical control of the observations was established by employing several designs on replicate analysis. The data were processes and examined with the aid of the following statistical computer programs:

NORMSTAT,	The Pennsylvania State University Dept. of Geosciences
ANOVR,	Games and Gray, 1972, The Pennsylvania State University

STATPAC,	Statistical Package Program, Verity, 1970, The Pennsylvania State University, Computation Center
CLUS,	A Cluster Analysis, and Taxonomy System for Grouping and Classifying Data, Rubin and Friedman, 1968 IBM Corp.
FSCORE	Kohr, 1969, The Pennsylvania State University, Computation Center.

When all of the measured variables were related to the expanded density values, the expansion characteristics were found to be unrelated to differences in the chemical compositions of the perlite samples. On the other hand, more than 85 percent of the variation in expanded density was found to be attributable to the combined effects of 1) the percentage of volatiles released between 110°C and 450°C, 2) the bulk density of the rock, 3) the crystallite and vesicle content (log base e). The combined effects of these varibles upon the expansion characteristis of perlites differ from perlite to perlite. The discriminant functions, obtained from the classification of a set of perlite samples of known expansion behavior, permit one to assign a given sample of unknown expansion behavior to one or three groups based on expandability (good, medium, and poor).

Classification of a sample of unknown expansion characteristics first requires the transformation of the four variables into a standardized form using the following formula:

ote zi and
xi are lc.

$$z_i = (x_i - \overline{X})/\hat{\sigma}$$

z_i is the standardized value; x_i is the value of the individual variable for the unknown sample: $\overline{X}$ is the mean value of the individual vairable from a set of samples of known expansion behavior; $\hat{\sigma}$ is the standard deviation of the individual variable from a set of samples of known expansion behavior.

Variable	Mean ($\bar{X}$)	Standard Deviation ($\hat{\sigma}$)
Percentage of volatiles released at 450°C (H450)	2.335	3.3478
Bulk density	2.022	1.6167
Percentage of crystallites	44.9698	83.279
Vesicle content (log base e)	1.777	6.453

Each standardized value is multiplied by the discriminant value for the corresponding variable obtained from the cluster analysis on the set of samples of known expansion behavior. For the three groups as recognized by the cluster analysis and corresponding to the commercial classification of perlites, there are two discriminant functions. The Z values (discriminant coefficients) for each of the variables for both functions are listed below.

Variable	Z_1	Z_2
H 450	1.3038	-1.3100
Bulk density	-1.8682	-1.1416
Vesicle content	-0.8232	-0.3758
Crystallite content	-0.6768	-0.4757
Eigenvalue	5.9874	0.7238
% of total variation explained by the discriminant	89.215	10.785

The sum of the products of the standardized value of each of the characteristics and the corresponding discriminant coefficient will give the Z-value for the corresponding axis of the known sample groupings.

Example: Z_1

H450: (-0.2618)(1.3039) = -0.2826
Bulk density: (0.1045)(-1.8682) = -0.1952
Crystallite content: (-0.0856)(-06768) = 0.0579
Vesicle content: (0.0469)(-0.8232) = 0.0386
Sum = -0.4585

Because Z_2 ~~only~~ accounts for only 10% of the discrimination, it is not necessary to calculate the Z_2 value, as a sample will be clearly defined by Z_1 alone.

Plot of the Unknown Sample

The value of Z_1 is plotted on the Z_1 axis of Figure ~~34~~ 30 and places this particular sample into group C, the hard or poorly expanding perlite group.

Region of Uncertainty in the Classification (at the .05 level of significance - 2σ)

Range of Z_1	Between Groups
-0.2765 to -0.1208	B and C
0.1569 to 0.2207	A and B

On the basis of the boundaries between groups, a percentage misclassification in the present groupings may be calculated.

Boundary Between Groups

A and B $(\bar{Z}_A + \bar{Z}_B)/2 = 0.2032$

B and C $(\bar{Z}_B + \bar{Z}_C)/2 = -0.2297$

($\bar{Z}$ = mean discriminant value for the various groups)

On the basis of these values only two samples or 6.2 percent of the samples were misclassified between groups B and C while none between groups B and A were misclassified. As shown in Figure 30, the classification of the perlite samples as "good", "medium" and "poor" actually involves an arbitrary subdivision of a continuum.

F. L. Kadey (personal communication, 1975) observed that the results of the Lompoc, California, pilot plant tests on perlite expansion differed from the results obtained in testing the same samples in the Johns Manville research laboratories. In each procedure, however, the samples tested could be assigned to the "good", "medium," and "poor" categories In general, a given sample fell within the same category regardless of the location and method of testing. Thus, in a relative sense, the tests at Lompoc were, indeed, useful.

Brushy Mountains Deposit

The Brushy Mountain perlite deposit was investigated by Naert, but in much less detail than the No Agua perlite domes. The deposit lies about 15 miles east of the No Agua deposits and 16 miles west of the Canyon of the Rio Grande. It is connected with U.S. Highway 285 by a well-graded dirt road. The deposit was opened circa 1965 and has been operated by Silbrico since then.

Brushy Mountain actually consists of two low hills, confined to about one square mile, which rise above the Taos Plateau (Figs. 30 and 31). The hills and the higher Cerro Montoso to the south are underlain mainly by flows of the Rio Grande Basalt, which is, in fact, a mixture of basalt and andesite. In the vicinity of Brushy Mountain the basalt-andesite (?) is covered by Quaternary alluvium. Perlite is exposed in three places; at each it is overlain by the basalt flows. The most extensive of the three exposures is about 4000 feet long and forms the lower southwest slope of the more southerly of the two hills. A much smaller exposure is low on the south slope of the northern hill. The third has been uncovered by trenching through the alluvium adjacent to the north margin of Cerro Montoso.

At each locality, the contact of the perlite with the overlying basalt is intrusive and dips moderately toward the hill. At each also, the basalt is deformed whereas in the surrounding area it displays a gentle, apparently initial dip. Thus, the basalt appears to have been pushed upward by the intruding acidic rock.

The basalt rests upon an irregular layer of baked clay, possibly a soil that formed before the basalt flows were emplaced. Between the clay layer and the perlite body, and well exposed in the main quarry, is a transition zone composed of perlite fragments in a matrix of baked clay, the matrix grading in color from dark to light red toward the perlite. 1, the perlite is everywhere highly brecciated and contains relatively large proportions of quartz and feldspar phenocrysts; in these respects, particularly, the Brushy Mountain deposits differ from the No Agua deposits.

The quarrying operations were originally confined to the western half of the single large exposure (Fig. 31). But in 1976, quarrying was begun on an exposure near the north edge of Cerro Montoso. In 1975, the main quarry was about 3000 feet long, 500 feet wide and was bordered on the east by a wall that ranged in height from about 10 feet to about 100 feet.

Low in the quarry, near its southern edge, is a subcircular exposure, about 150 feet in diameter, of porphyritic rhyolite. The rhyolite, which is reddish brown and unbrecciated, has essentially the same chemical composition as the perlite (Table 3), and appears to be a feeder pipe for the perlite mass.

The outcrop of perlite at the north edge of Cerro Mountain could represent the eroded remnant of a part of the perlite body exposed on the south hill or it could represent a separate body. ~~The present~~ Continued quarrying of the southern deposit should tell which. The more northerly exposure of perlite appears to mark a separate dome. Quartz porphyry, which underlies two small hills northeast of Brushy Mountain, also has essentially the same chemical composition as the perlite, and the two are probably genetically related.

	B1	B2	B3	B4	B5
SiO_2	61.12	77.3	74.13	75.57	75.0
Al_2O_3	15.10	10.90	11.91	12.15	12.30
TiO_2	.905	.19	.125	.16	.13
Fe_2O_3	5.80	1.50	.79	.81	.80
MnO	.085	.097	.071	.061	.070
MgO	.179	.058	.152	.10	.122
CaO	4.96	.31	.49	.44	.38
Na_2O	4.31	3.83	3.35	3.68	3.70
K_2O	2.92	4.48	5.03	5.01	5.07
Rb_{ppm}	48	114	155	164	142
Sr	*	*	10ppm	<5ppm	*
H_2O(+110°C)	*	*	2.40	*	*
H_2O(−110°C)	*	*	.49	*	*

*Not determined

(Figs. 31 and 32)

Table 2. Chemical analyses of samples of rock units of the Brushy Mountain perlite-bearing area. B1 is andesite from exposure on northwest slope of Brushy Mountain; B2 is from body of porphyritic rhyolite east of Brushy Mountain ; B3 is perlite from main quarry. B4 and B5 are rhyolite from an apparent feeder dike.

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CAPTIONS FOR ILLUSTRATIONS
NO AGUA PEAKS

~~Plate 1.~~ Geologic map and fence diagram of perlite deposits of the No Agua Mountains, Taos County, New Mexico.

Figure ~~2~~1. Perlite-bearing localities in the United States, modified from Jaster (1957), showing location of quarries active in 1974 as ~~a~~reported in U.S. Bur. Mines Minerals Yearbook, 1975.

Figure 2. Graph showing data on production of perlite in the United States, 1946-1975, from U.S. Bur. Mines Minerals Yearbook. date ?

Figure 3. Map of No Agua Peaks showing principal topographic features and property boundaries.

Figure 4. Diagram showing history of ownership of the three perlite properties of the No Agua Peaks.

Figure 5. View, looking southeastward, of No Agua Peaks, showing facilities of the Johns-Manville Products Company (right-center), North and East Hills (left), and West Hill (far right).

Figure 6. View of Low Hill area, looking southwestward from West Hill, showing main quarry of General Refractories Company (Grefco).

Figure 7. Generalized geologic map of the region of the No Agua. Modified from Butler (1977).

Figure 8. Exposure along U.S. Highway 285, and about 2 miles northwest of No Agua Peaks, showing contact between basalt of Hinsdale Formation and an underlying conglomerate probably of the rhyolite member of the Los Pinos Formation (Butler, 1971). The conglomerate contains clasts of perlite apparently eroded from domes of the No Agua Mountains.

Figure 9. Detail of conglomerate in exposure from Figure 9.

Figure 10. Logs of diamond drill hole R.D.H.-2, about 400 feet north-northeast of mill of Johns-Manville Company (Plate 1).

Figure 11A. Sketch of a radially fissured dome (after Leyden, 1936) C = crust, P = primary dome rock, Rf = filling of radial fissures, Rs = unfilled radial fissure, Cs = central summit depression between the hills.

Figure 11B. Sketch of an extrusion dome (after Leyden, 1936). Cc = collapse crater, Sp = structural pattern, C = crust, T = talus.

Figure 12. Map showing distribution of rock bodies and general structural features of the rhyolitic domes of the No Agua Peaks.

Figure 13. Photomicrograph of tuff-perlite breccia, showing fragments of perlite (light) in a microcrystalline matrix. Length of field is 2 mm.

Figure 14. Photomicrograph of vesicular perlite from middle perlite unit vesicles. Length of field is 1.3 mm.

Figure 15. Cliff-forming upper glassy rhyolite unit overlying the middle perlite unit near the U.S. perlite (Silbrico) quarry of Plate 1.

Figure 16. Exposure of upper glassy rhyolite showing irregularities in flow banding.

Figure 17. Photomicrograph of glassy rhyolite of upper glassy rhyolite unit showing bands of microcrystalline and cryptocrystalline material (light) in glass (dark); biotite phenocryst lower left. Length of field is 0.7 mm.

Figure 18. Photomicrograph of glassy rhyolite of upper glassy rhyolite unit showing phenocrysts of plagioclase (light) in a ground mass of glass (dark) and microcrystalline and cryptocrystalline material; (light); crossed nicols. Length of field is 2 mm.

Figure 19. Photomicrograph of glassy rhyolite of upper glassy rhyolite unit showing phenocrysts of plagioclase in a ground mass of glass and microcrystalline material; partly crossed nicols. Length of field is 2 mm.

Figure 20. Photomicrography of glassy rhyolite of upper glassy rhyolite unit showing glass-rich layers (light) alternating with layers rich

in microcrystalline and cryptocrystalline matieral. Glass displays onionskin texture. Length of field is 2 mm.

Figure 21. Photomicrograph of glass (light) in upper part of upper glassy rhyolite unit with typical onionskin texture. Length of field is 0.4 mm.

Figure 22. Exposure of upper part of upper glassy rhyolite unit of North Hill containing nodular remnants black obsidian (marenkanites). The larger light, lenticular masses consist of pumiceous material.

Figure 23. Photomicrograph of perlite from upper perlite unit showing irregular distributed cryptocrystalline material (light) in the glassy ground mass. Length of field is 2 mm.

Figure 24. Exposure of upper perlite unit on top of the West Hill; Perlite displays horizontal flow banding.

Figure 25. Photomicrograph of glassy facies of lithic rhyolite unit which is composed mostly of layers of cryptocrystalline material (dark) which alternate with glass-rich layers (light). Length of field is 2 mm.

Figure 26. Exposure of rhyolitic rock interpretable as eroded remnant of extrusion spine.

Figure 27. Graph showing partitioning of samples of rhyolitic material from deposits of No Agua Peaks. Partitioning is determined by a cluster analysis based on chemical analysis of a representative suite (62 samples) of rocks from the No Agua Peaks. The C_1 and C_2 represent the first two factors in the statistical analysis.

Figure 28. Hypothetical cross sections showing four interpretations of the rhyolitic flows of the No Agua Peaks and involving the four major units exposed there. LGR = lower glassy rhyolite unit; MP = middle perlite unit; UGR = upper glassy rhyolite unit; UP = upper perlite unit. Solid lines are flow boundaries; dash lines are cooling unit boundaries. All sections imply the same areal distribution of perlite and glassy rhyolite, but cross section A was drawn without reference to attitudes of flow banding. Other cross sections show generalized pattern of flow banding represented by attitudes of Plate 1. Cross sections are evaluated in text.

Figure 29. Idealized sketch of typical rhyolite dome of the No Agua Peaks, based on model D of Figure 11 and showing the five principal units and their geologic setting: (a) crystalline rocks of the Precambrian basement; (b) cover of Tertiary sedimentary rocks including basalt flow (c) initial flow of perlite; (d) flow of glassy rhyolite; (e) later flow of perlite; (f) body of lithic rhyolite, intrusive and probably also extrusive. Dotted line shows approximate location of present topographic surface. Diameter of dome is 2000 to 3000 feet.

Figure 30. Plot of the No Agua Peak ? samples partitioned in three groups designated by circles, squares and triangles. The partitioning is based on a cluster analysis of a matrix based on values for bulk density, amount of volatiles released at 450°C, the crystalline and vesicle content. P represents the plot for an unknown sample as calculated in the accompanying text. The axes z_1 and z_2 represent the first two factors from the statistical analysis.

Figure 31. Geologic sketch-map of Brushy Mountain area showing deposits of the Silbrico Company.

Figure 32. View looking northward of Brushy Mountain and perlite quarry of Silbrico Company, showing crushing plant (extreme left). Basalt-andesite flow caps perlite on upper slopes of mountain. Impure perlite underlies lower slopes to right of quarry.

Figure 33. Photomicrograph of perlite from Brushy Mountain deposit showing phenocrysts of plagioclase in a ground mass composed of layers of glass and microcrystalline material. Length of field is 1.6 mm.

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whether this was redrafted
for our initial manuscript
If so, I don't have a
copy. It should be
in drafted form, however.
Fig. 1 Geo

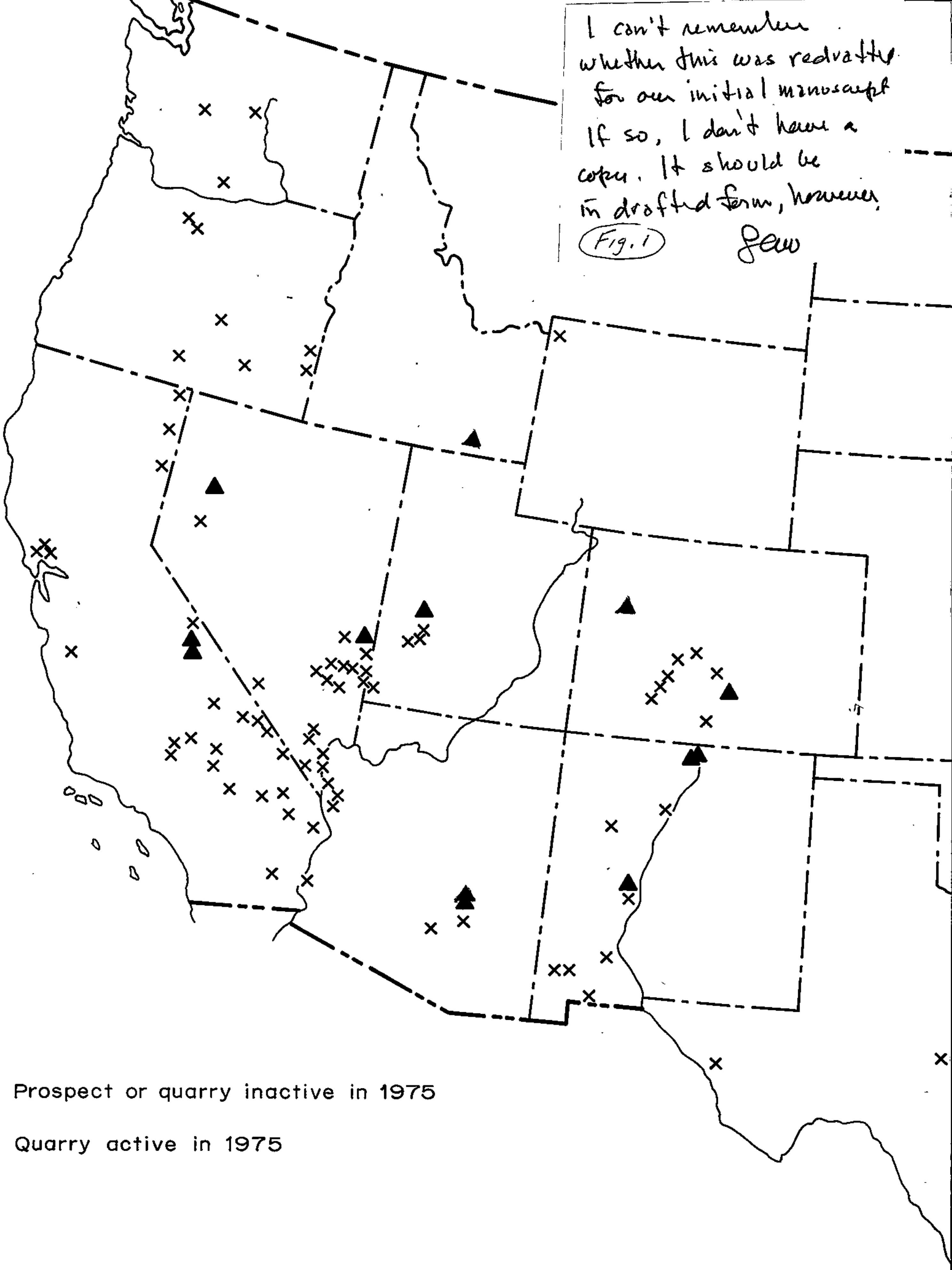


Fig. 2.

This illustration could be updated by reference to Minerals Yearbook, but would also have to be re~~da~~drafted

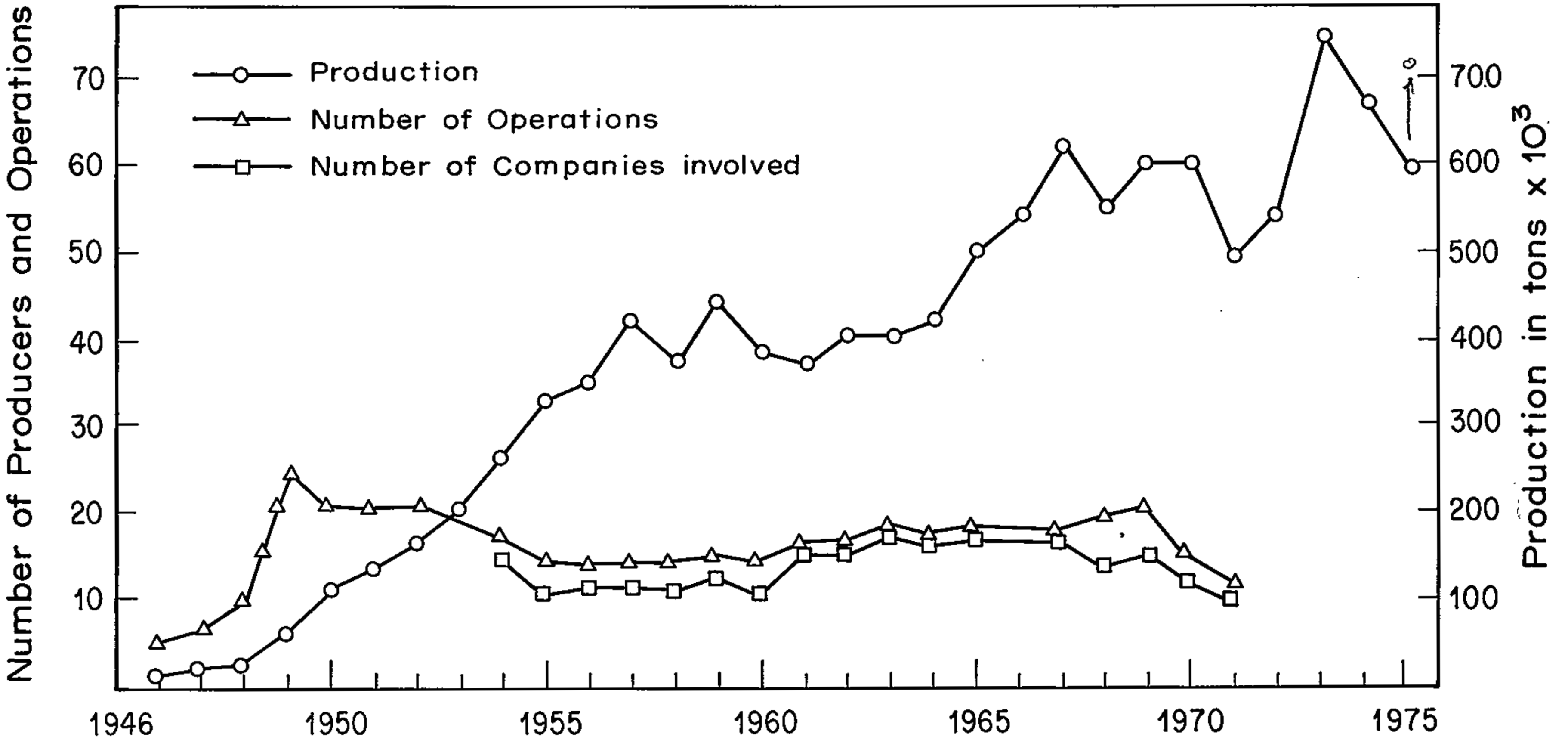
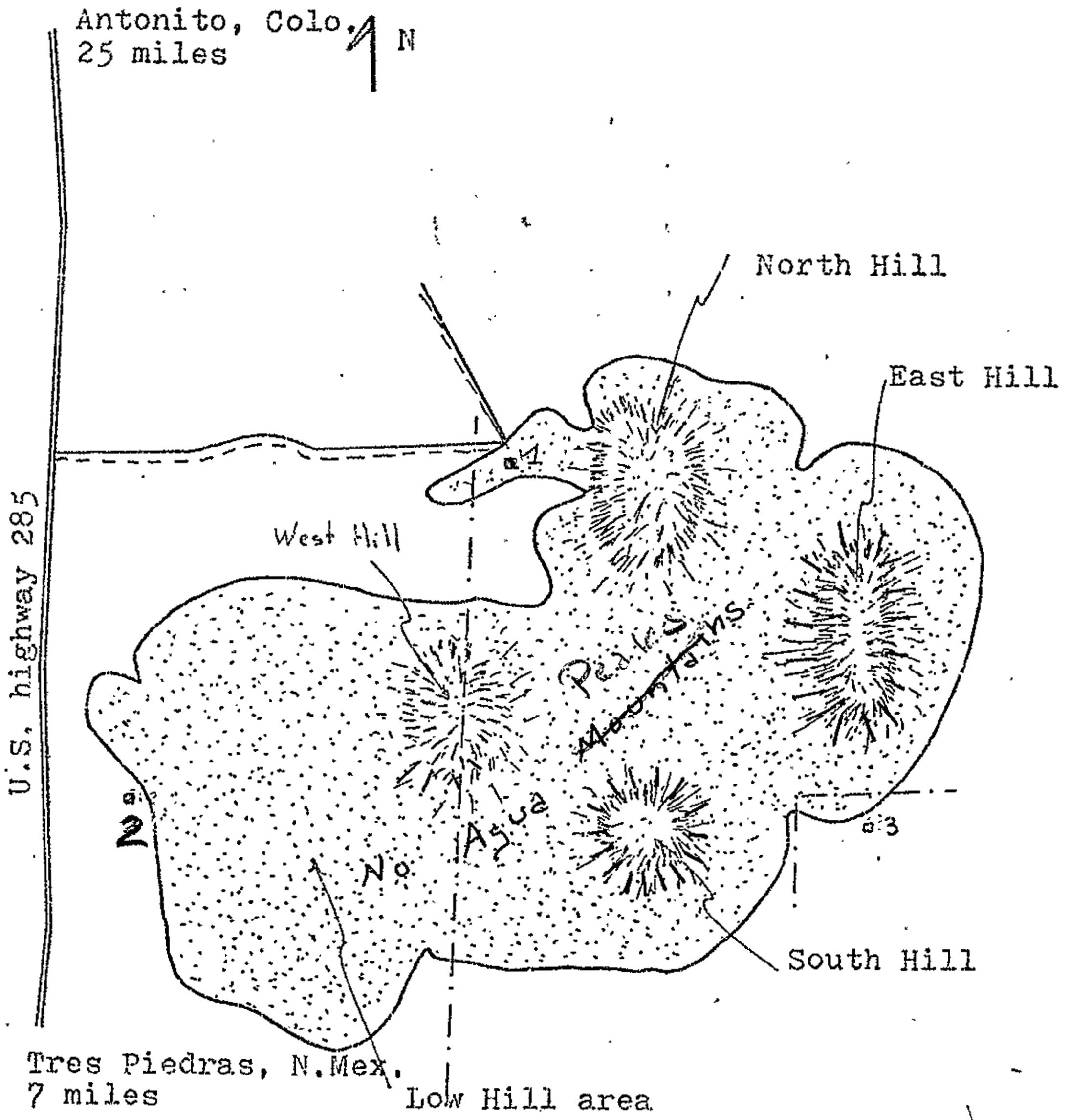


Fig. 2.



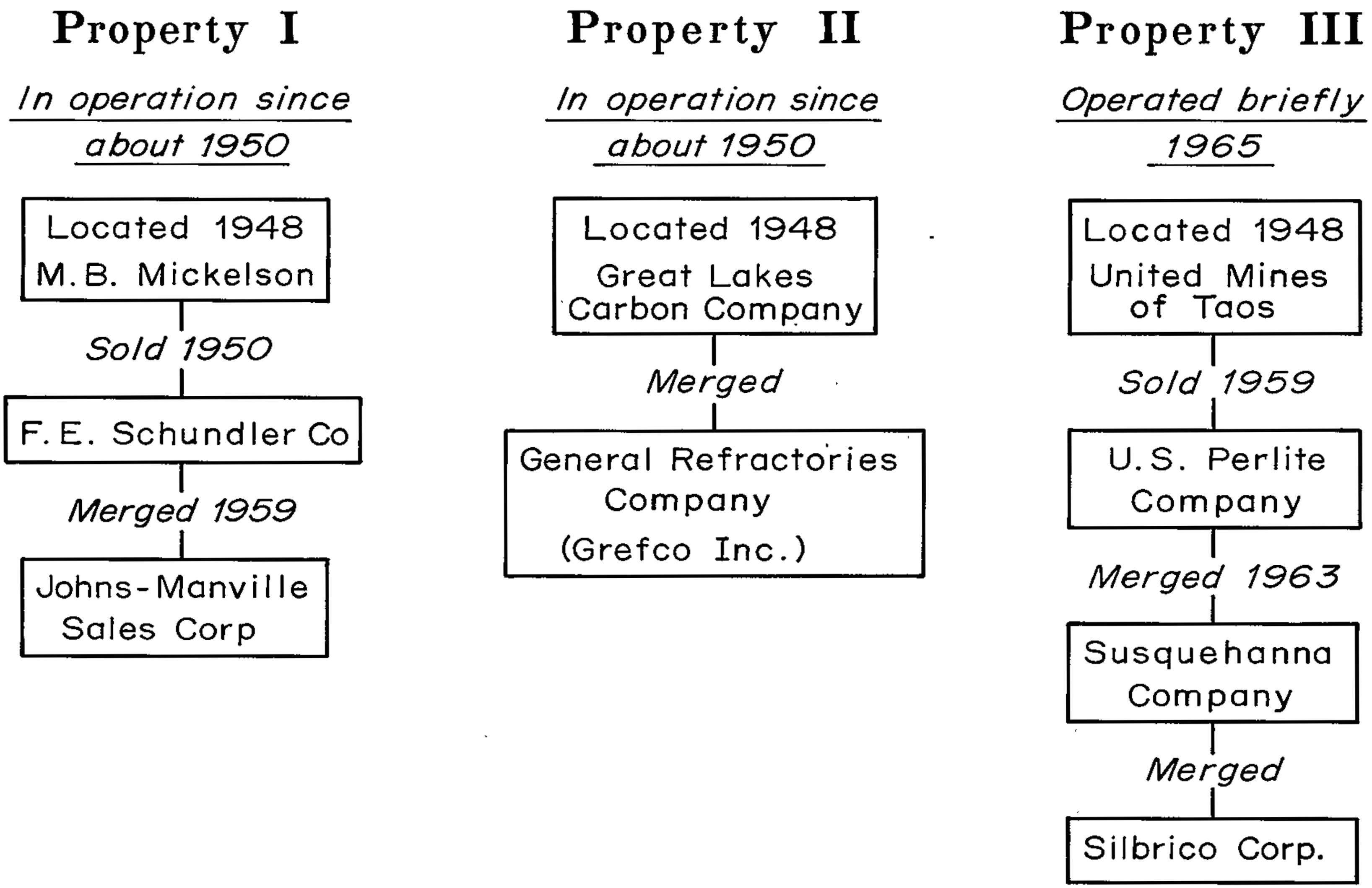
Plant sites
■ Active, ~~1973~~ 1980?
□ Inactive, ~~1973~~ 198?

1 Johns-Manville Corporation
2 Grefco Company
3 Silbrico Company

2000 ft

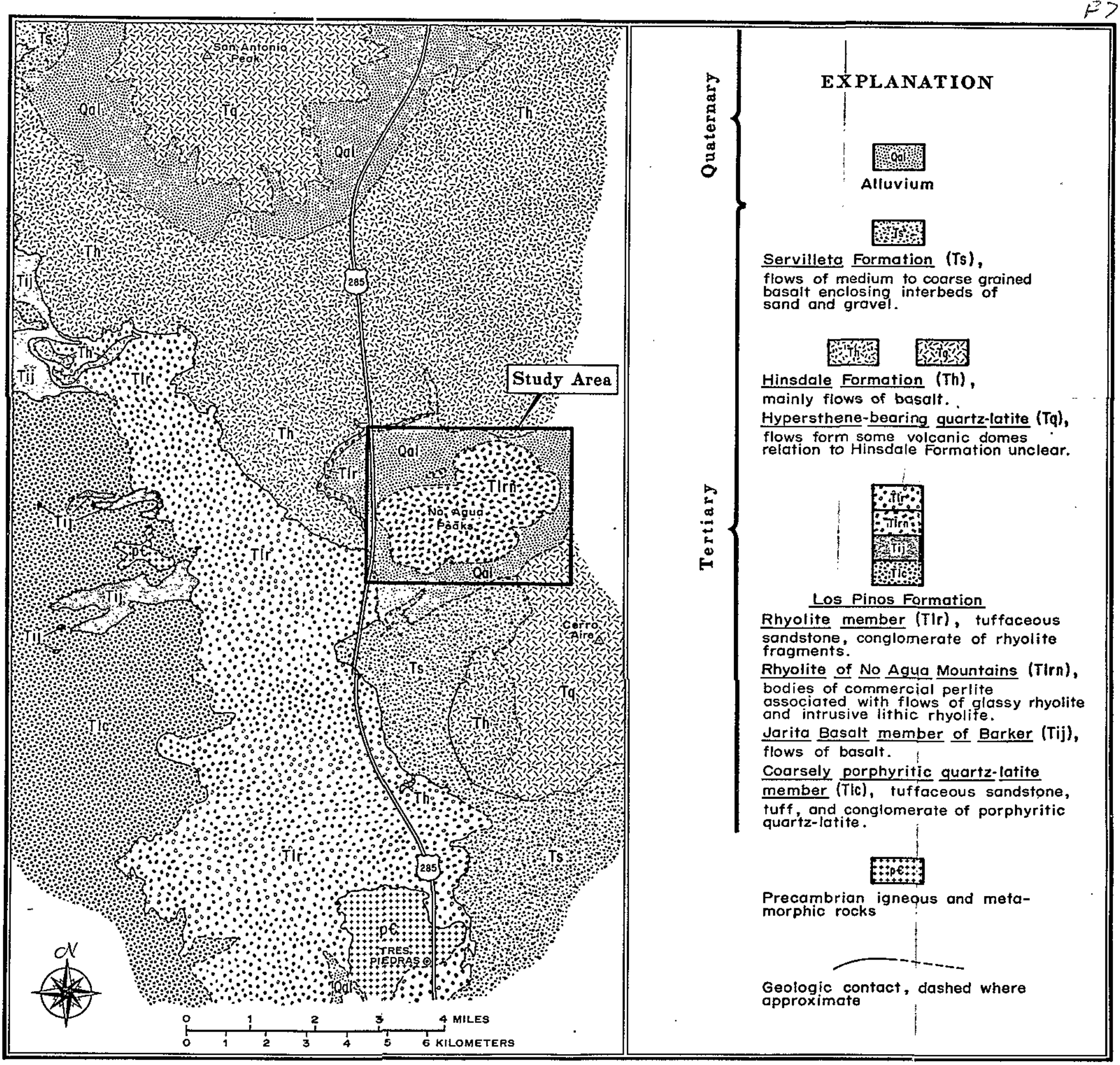
-·-·- Approximate property lines
▨ Surface exposure of the rhyolitic rocks

Does not show the three properties mentioned on page 8.


Property I
In operation since about 1950
Located 1948 M.B. Mickelson
Sold 1950
F.E. Schundler Co
Merged 1959
Johns-Manville Sales Corp
Property II
In operation since about 1950
Located 1948 Great Lakes Carbon Company
Merged
General Refractories Company (Grefco Inc.)
Property III
Operated briefly 1965
Located 1948 United Mines of Taos
Sold 1959
U.S. Perlite Company
Merged 1963
Susquehanna Company
Merged
Silbrico Corp.

This is a fuzzy photo.
If a better one is available,
we'd readily approve of a
substitution

P7



EXPLANATION

Alluvium

Servilleta Formation (Ts), flows of medium to coarse grained basalt enclosing interbeds of sand and gravel.

Hinsdale Formation (Th), mainly flows of basalt.

Hypersthene-bearing quartz-latite (Tq), flows form some volcanic domes relation to Hinsdale Formation unclear.

Los Pinos Formation

Rhyolite member (Tlr), tuffaceous sandstone, conglomerate of rhyolite fragments.

Rhyolite of No Agua Mountains (Tlrn), bodies of commercial perlite associated with flows of glassy rhyolite and intrusive lithic rhyolite.

Jarita Basalt member of Barker (Tij), flows of basalt.

Coarsely porphyritic quartz-latite member (Tlc), tuffaceous sandstone, tuff, and conglomerate of porphyritic quartz-latite.

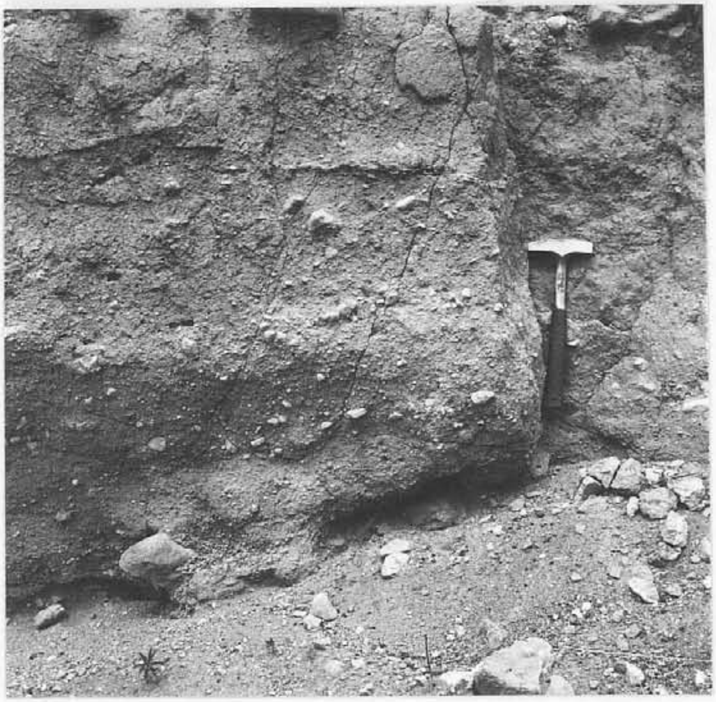
Precambrian igneous and metamorphic rocks

Geologic contact, dashed where approximate

Karl did have ~~a~~ the original copy of this. He said he was mailing it to you. I assume you have it by now.

Law

caption states "modified from Butler, 1977".



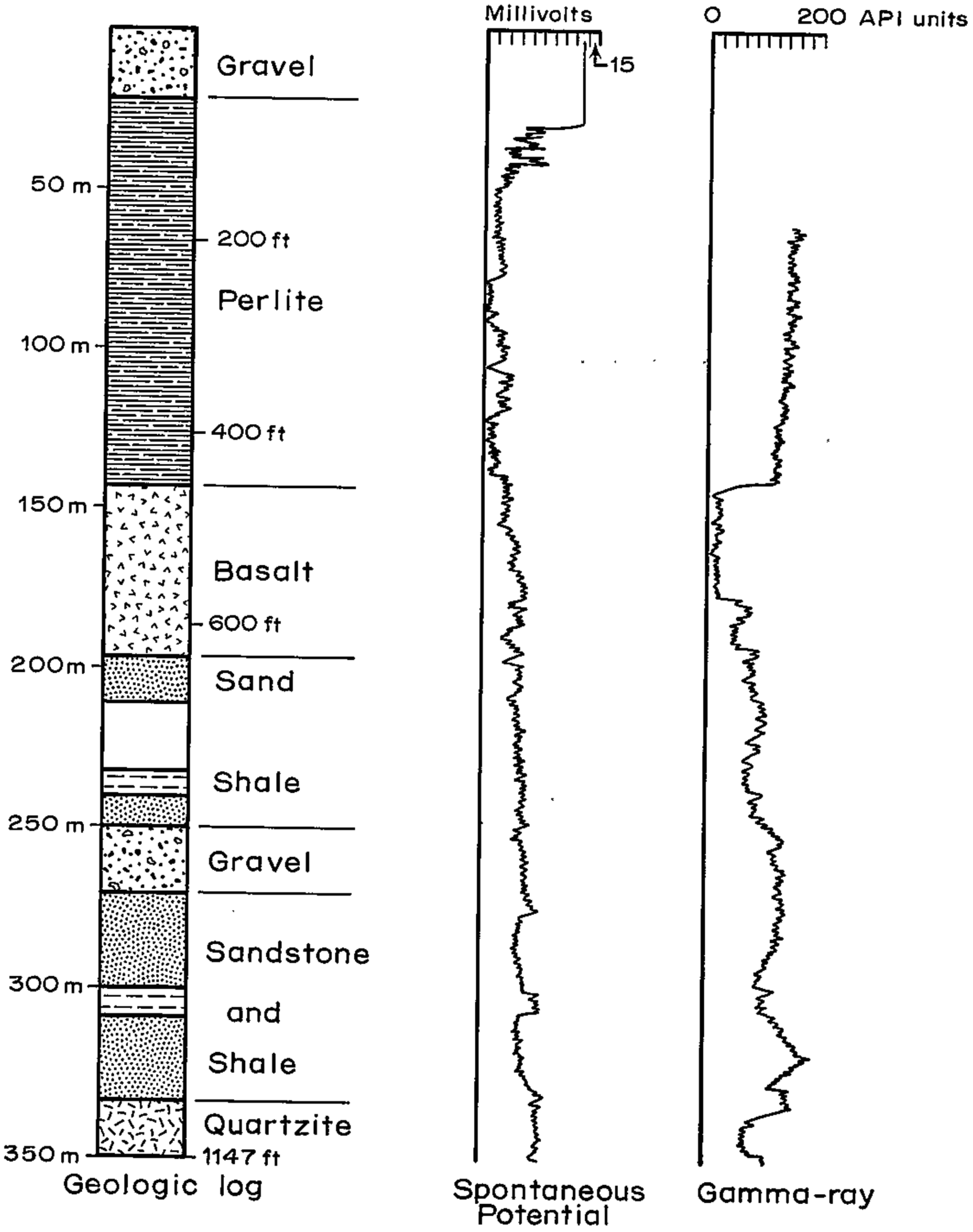
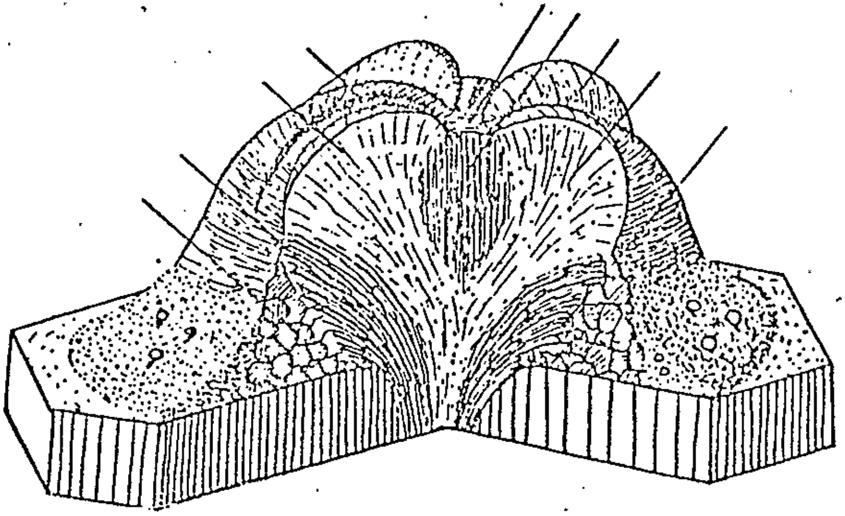
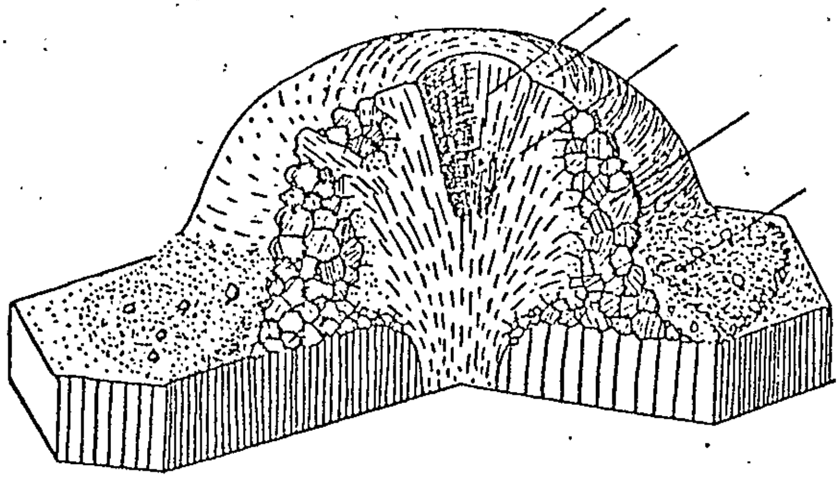

Gravel
Perlite
Basalt
Sand
Shale
Gravel
Sandstone
and
Shale
Quartzite
50 m
100 m
150 m
200 m
250 m
300 m
350 m
200 ft
400 ft
600 ft
1147 ft
Geologic log
Millivolts
15
Spontaneous Potential
0
200 API units
Gamma-ray

Fig. 10

F.11

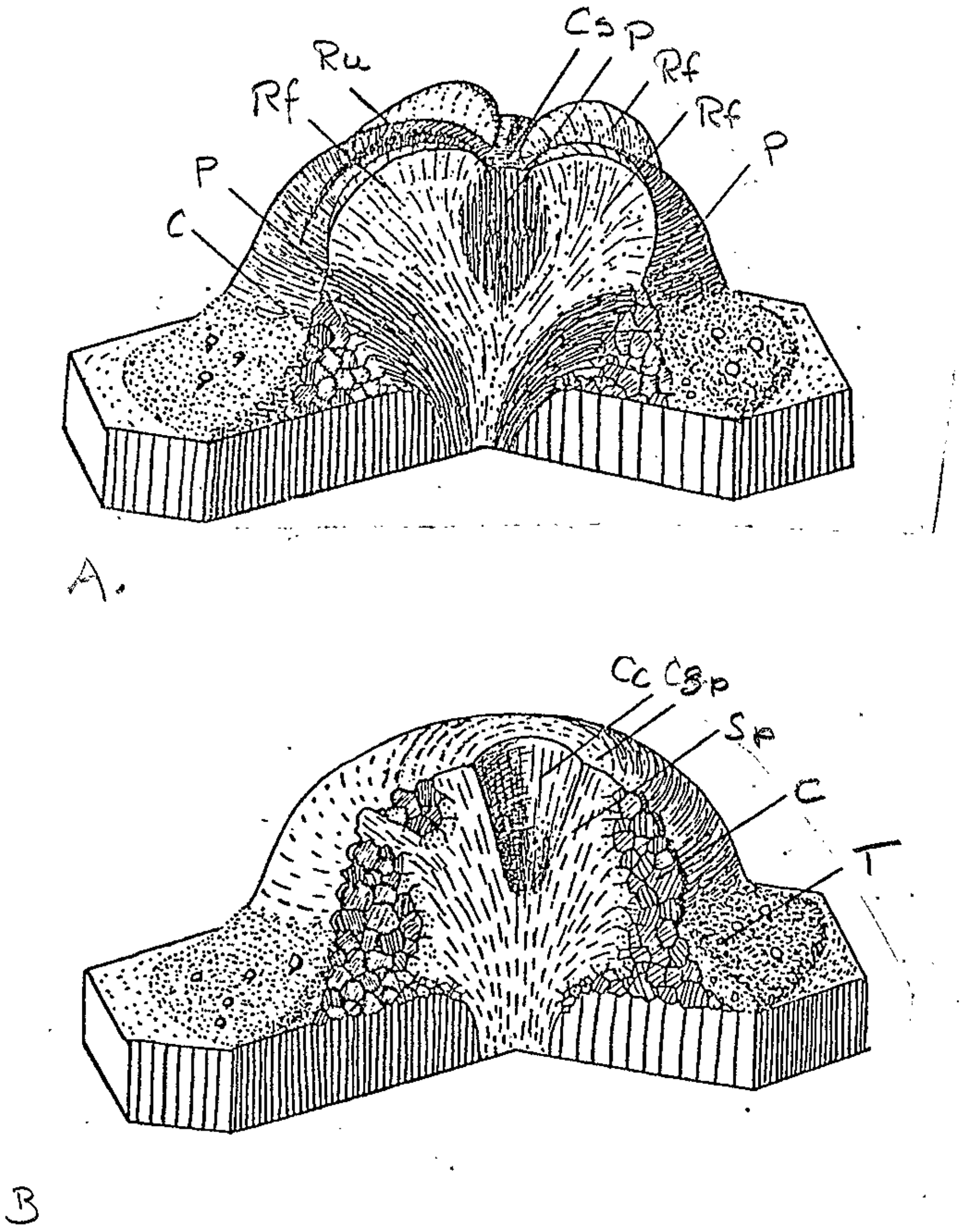




These are xerox copies of Leyden's illustrations. I hope the are suitable for reproduction.

They should be relettered according to the attached version.

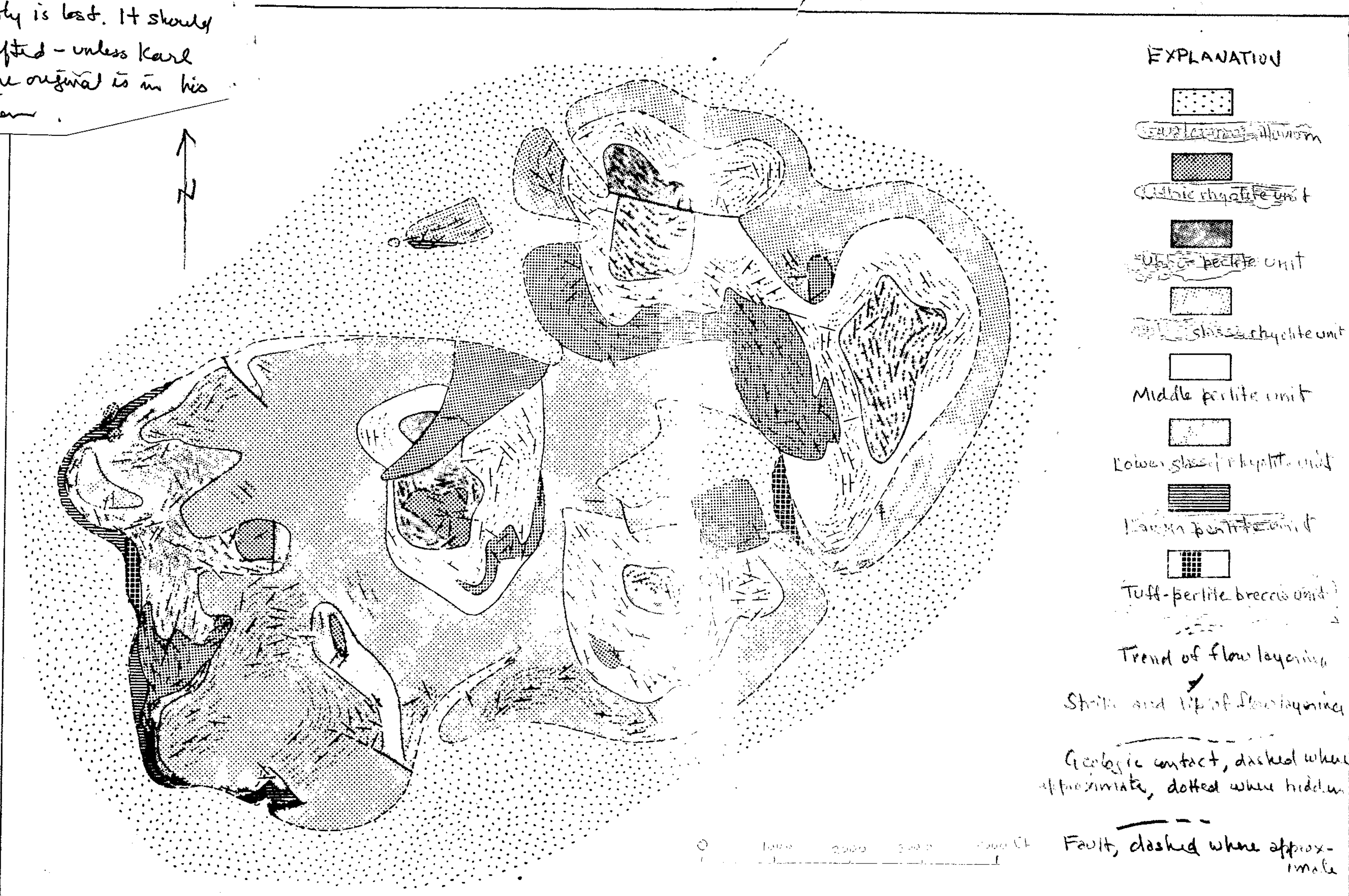
Fig. 11



This is a poor copy of an illustration whose original apparently is lost. It should be redrafted - unless Karl finds the original is in his possession.

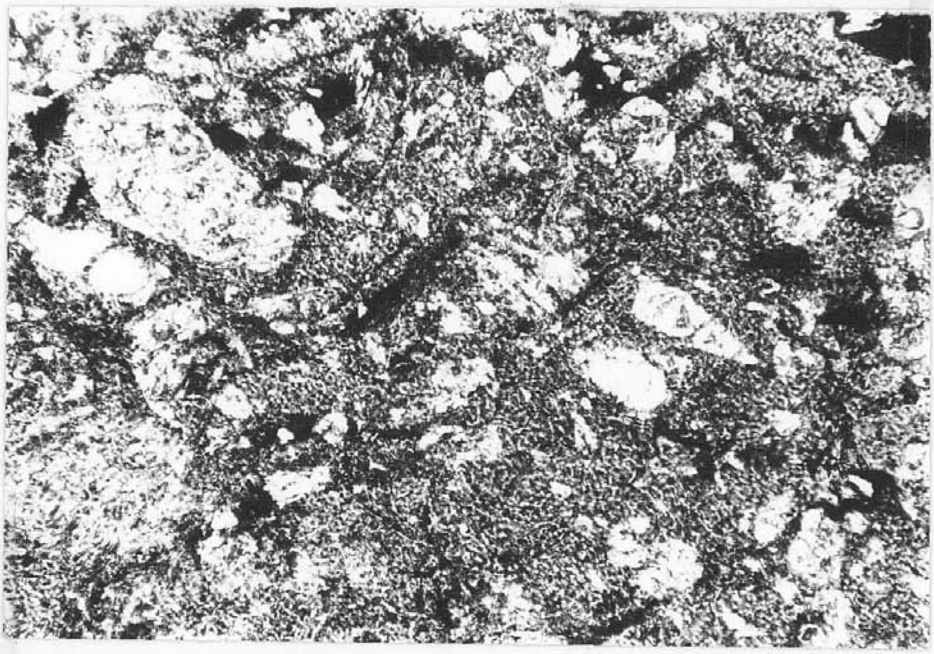
This map needs some sort of grid or reference to locate

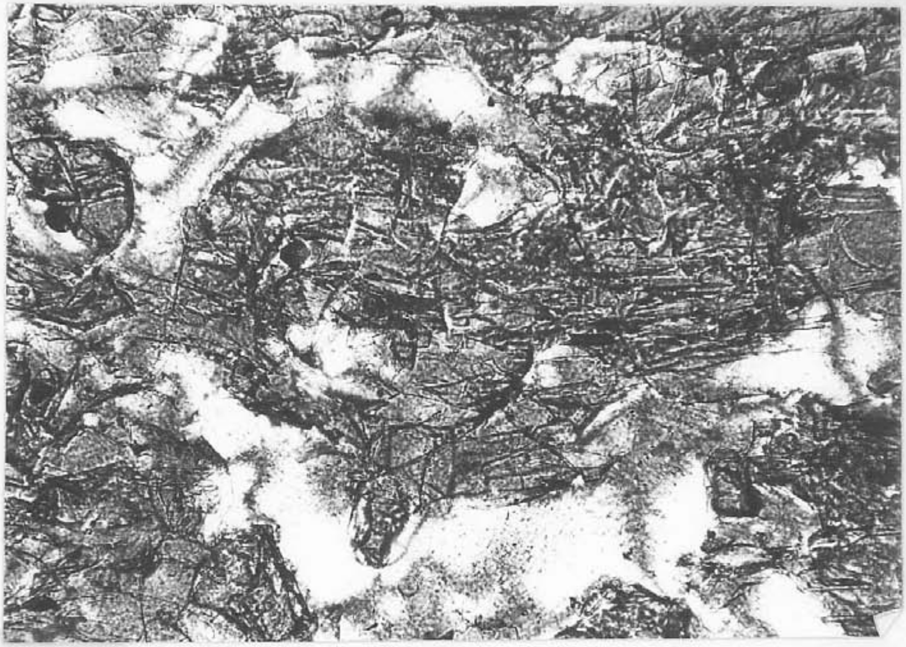
F. 12

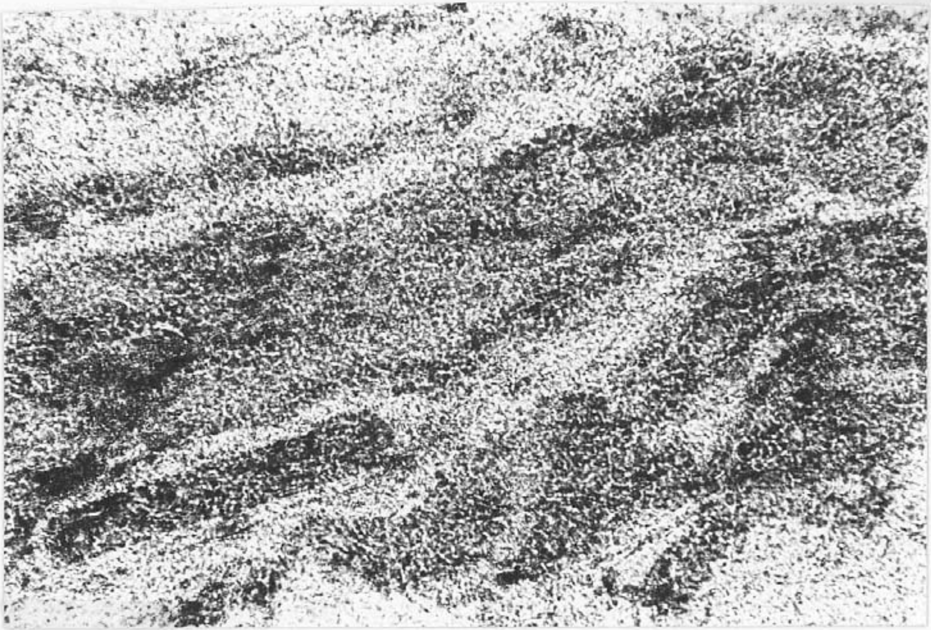


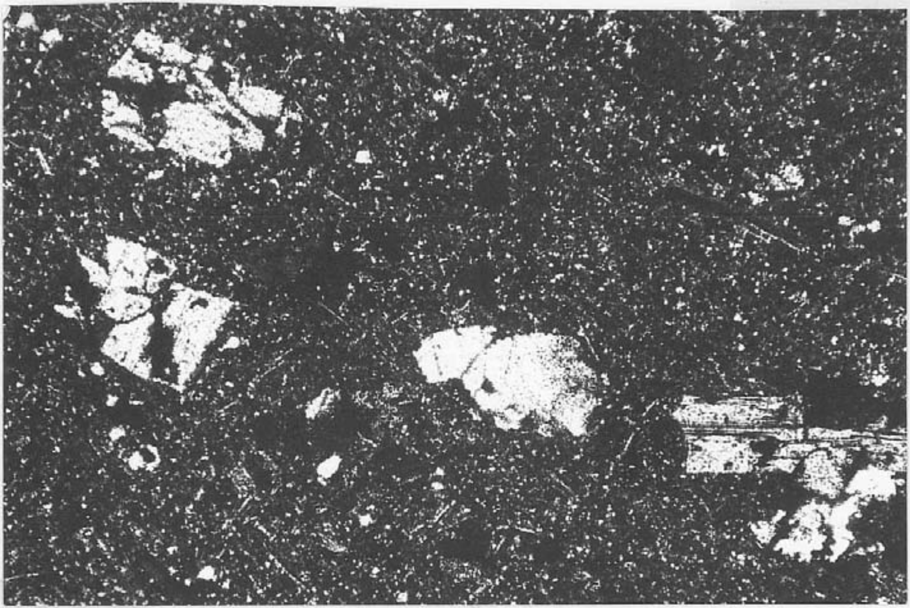
q?

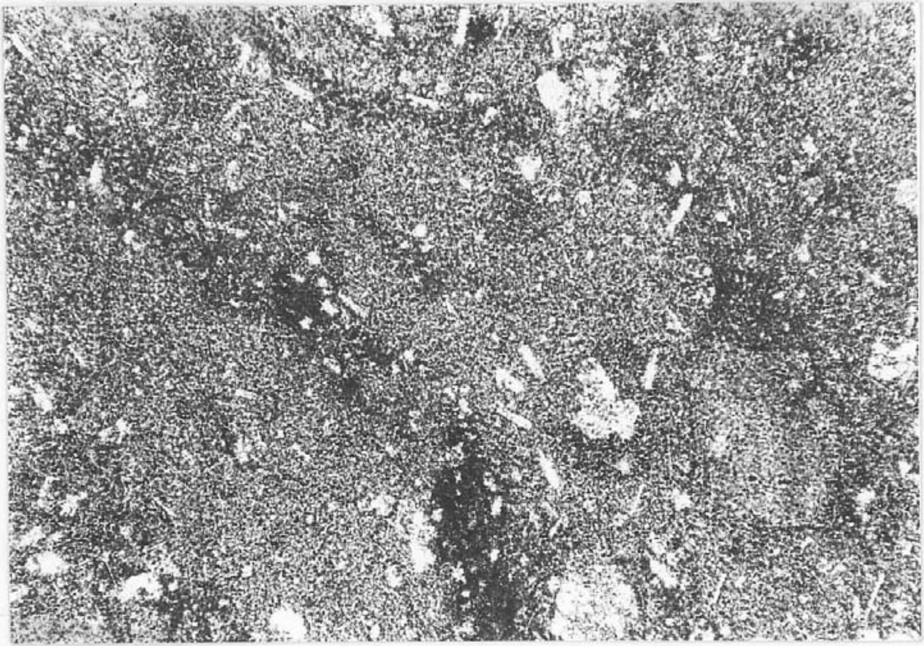
Fig. 11

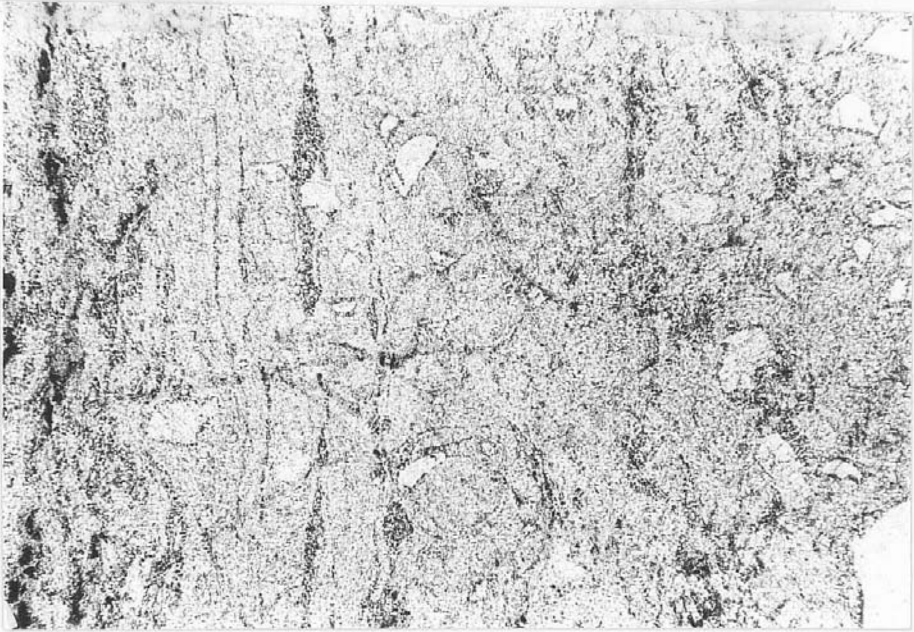


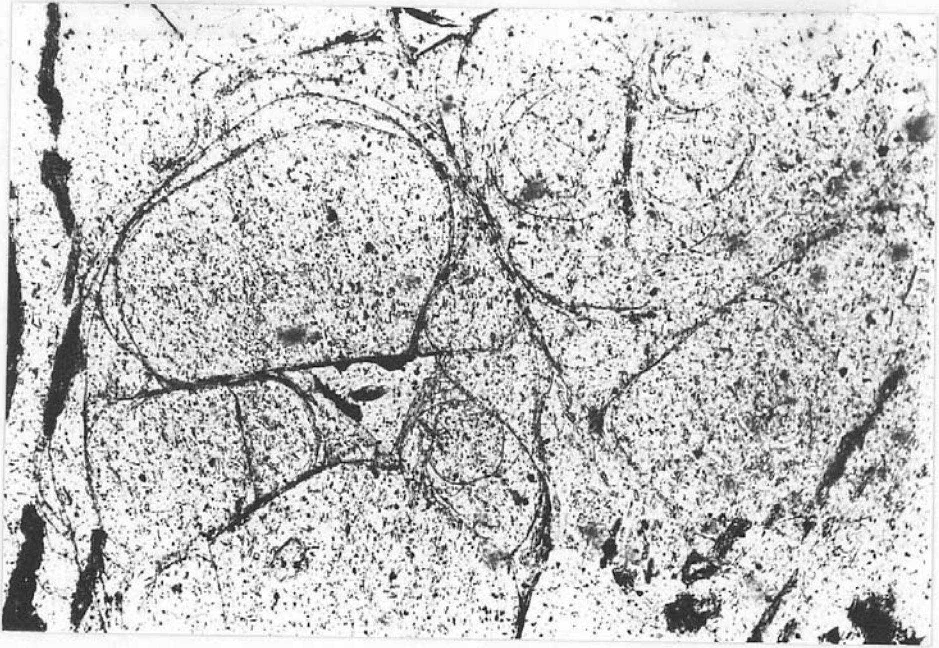


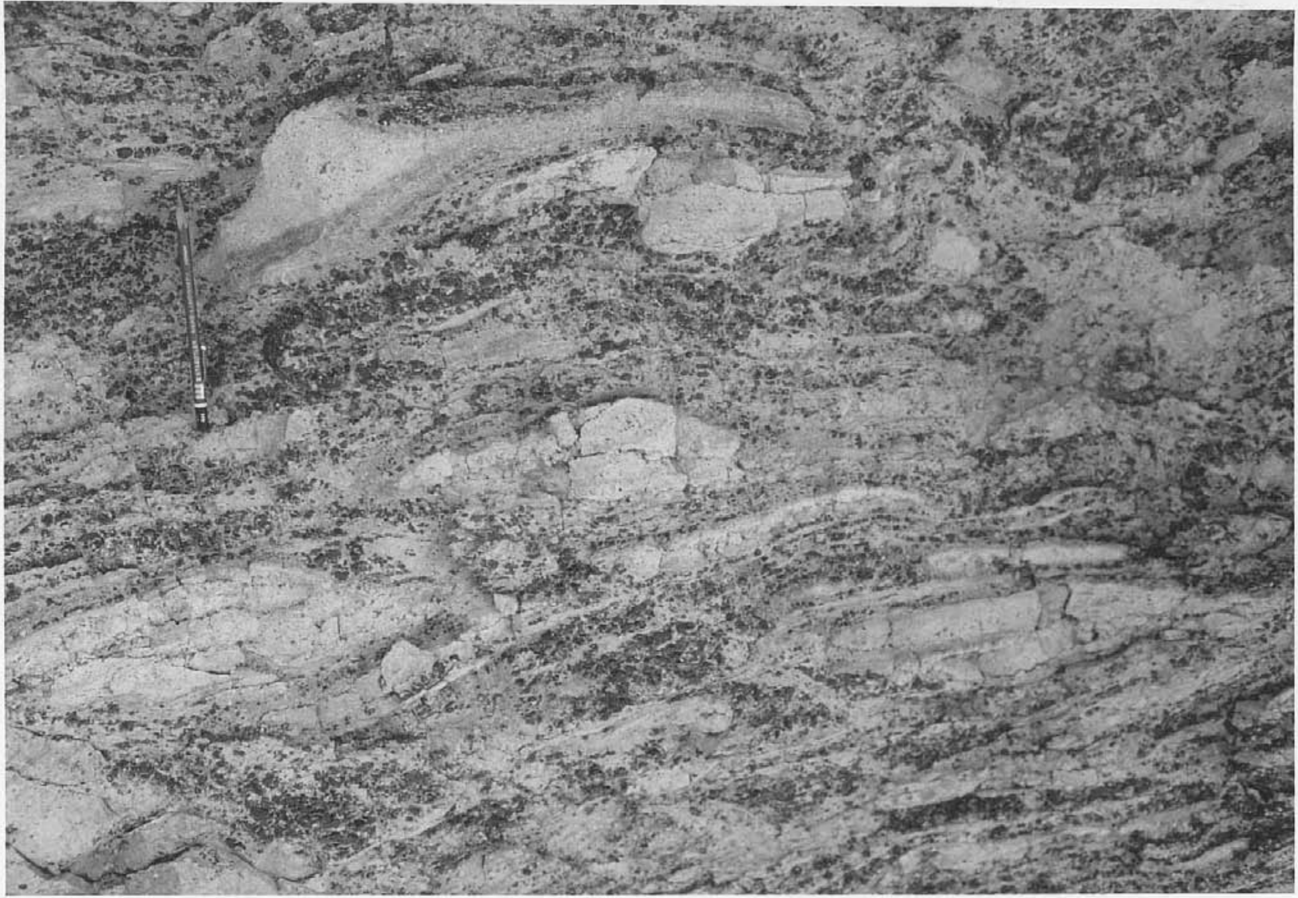


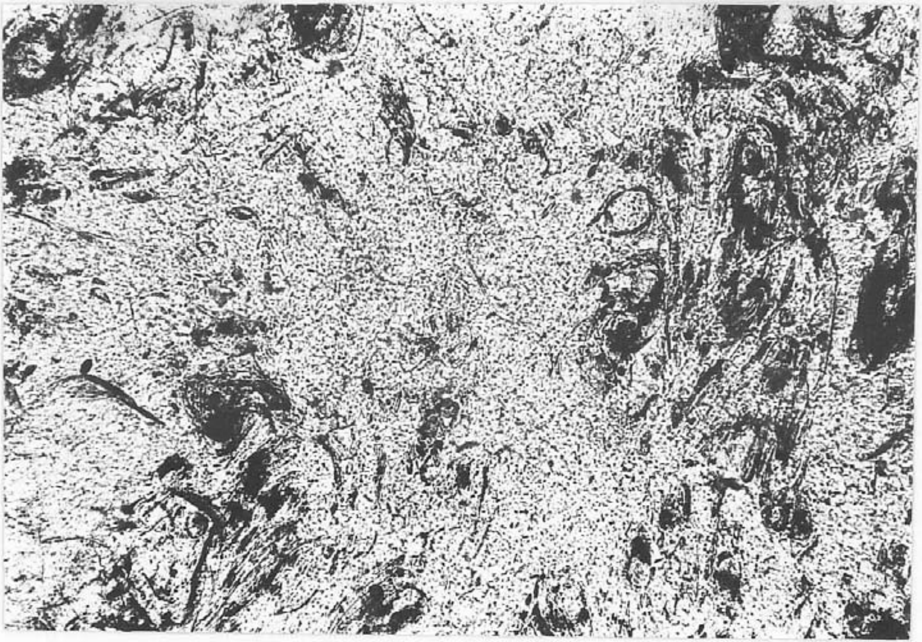


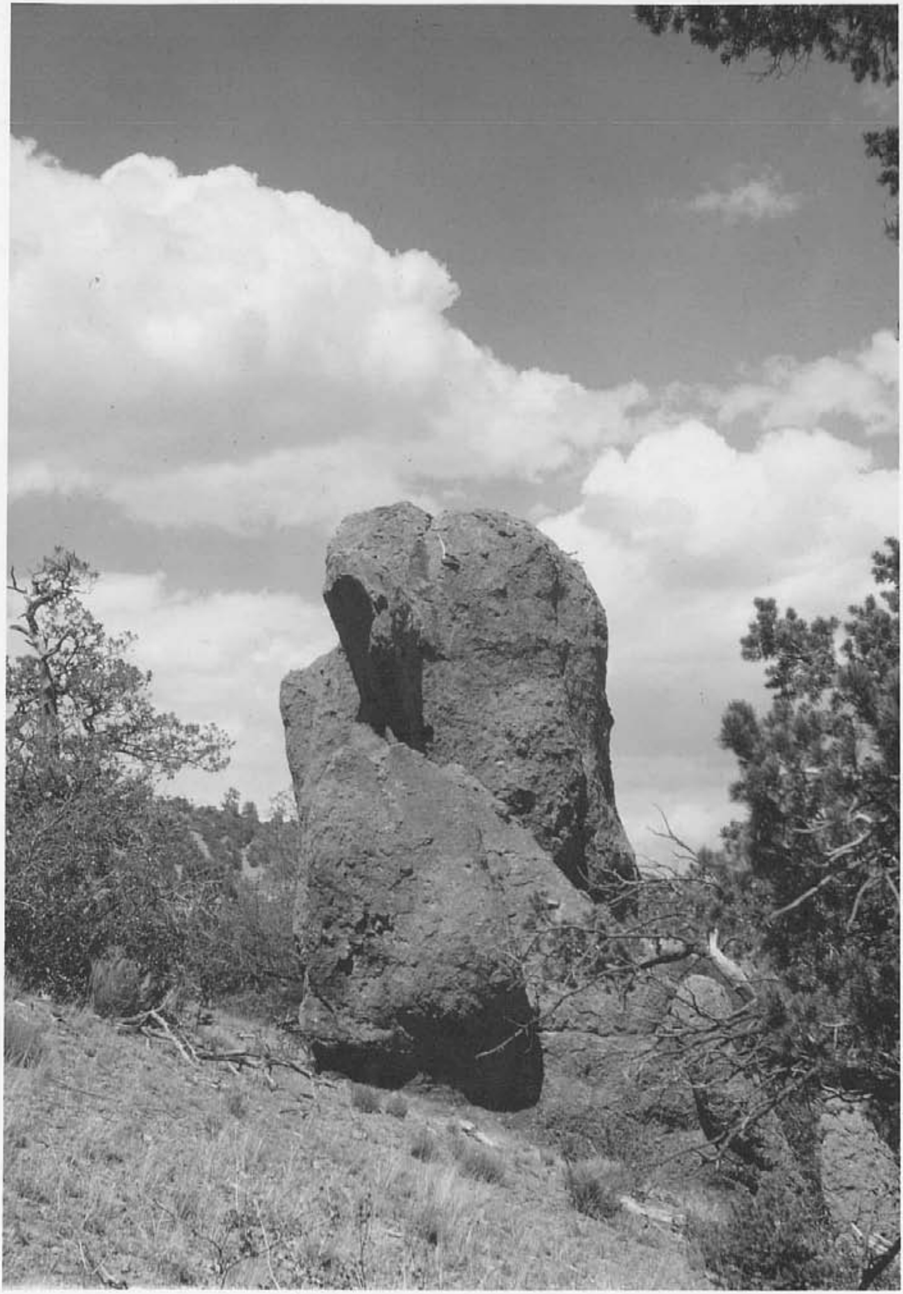




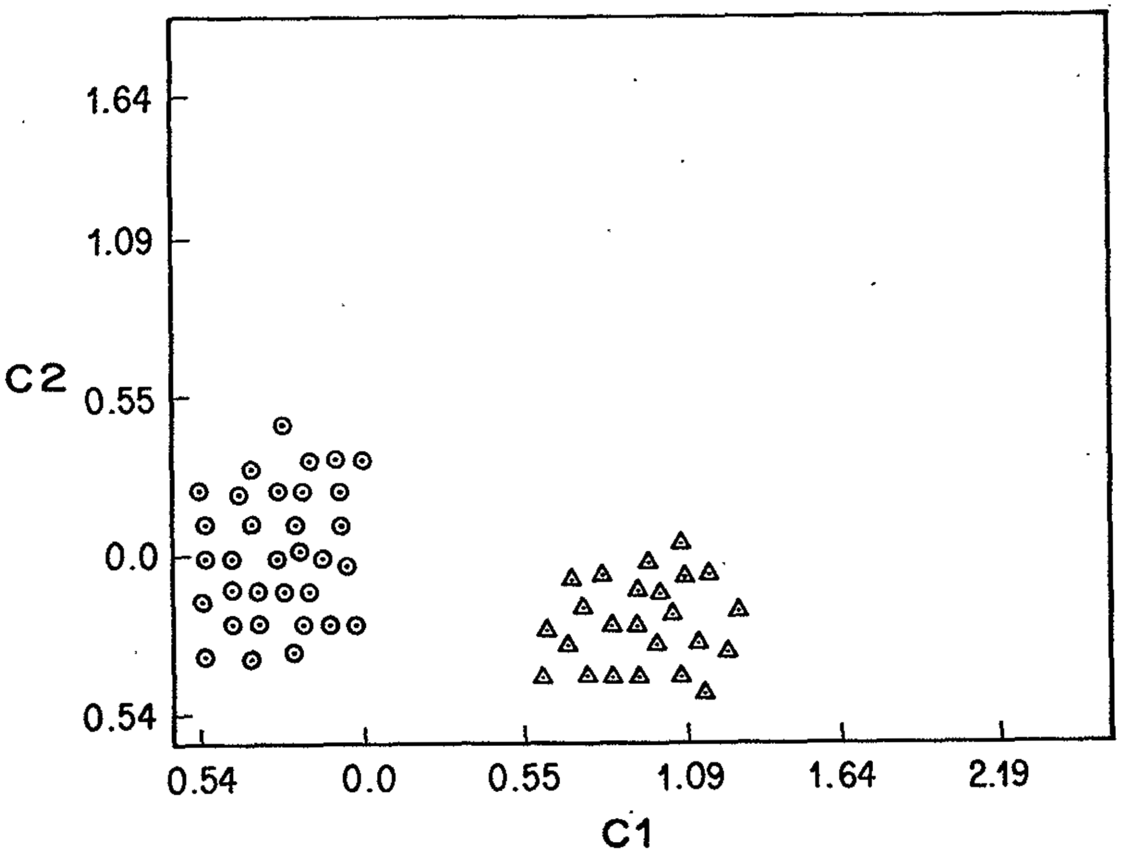








F27



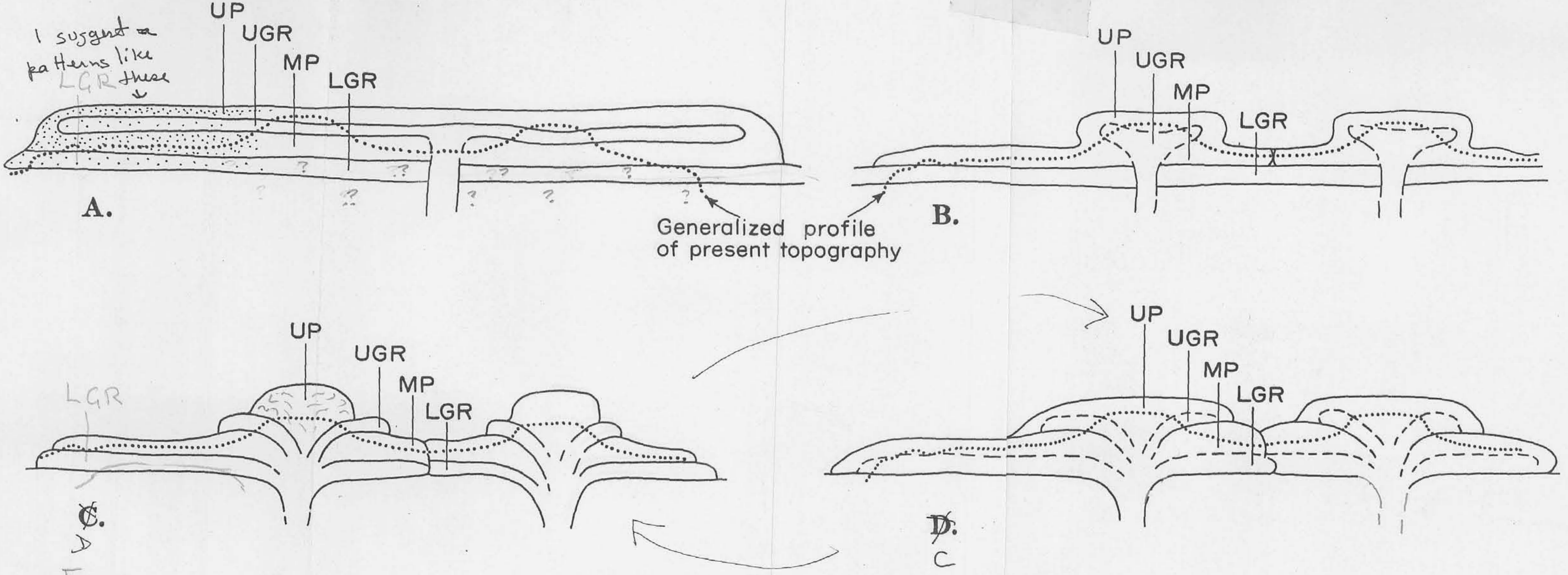
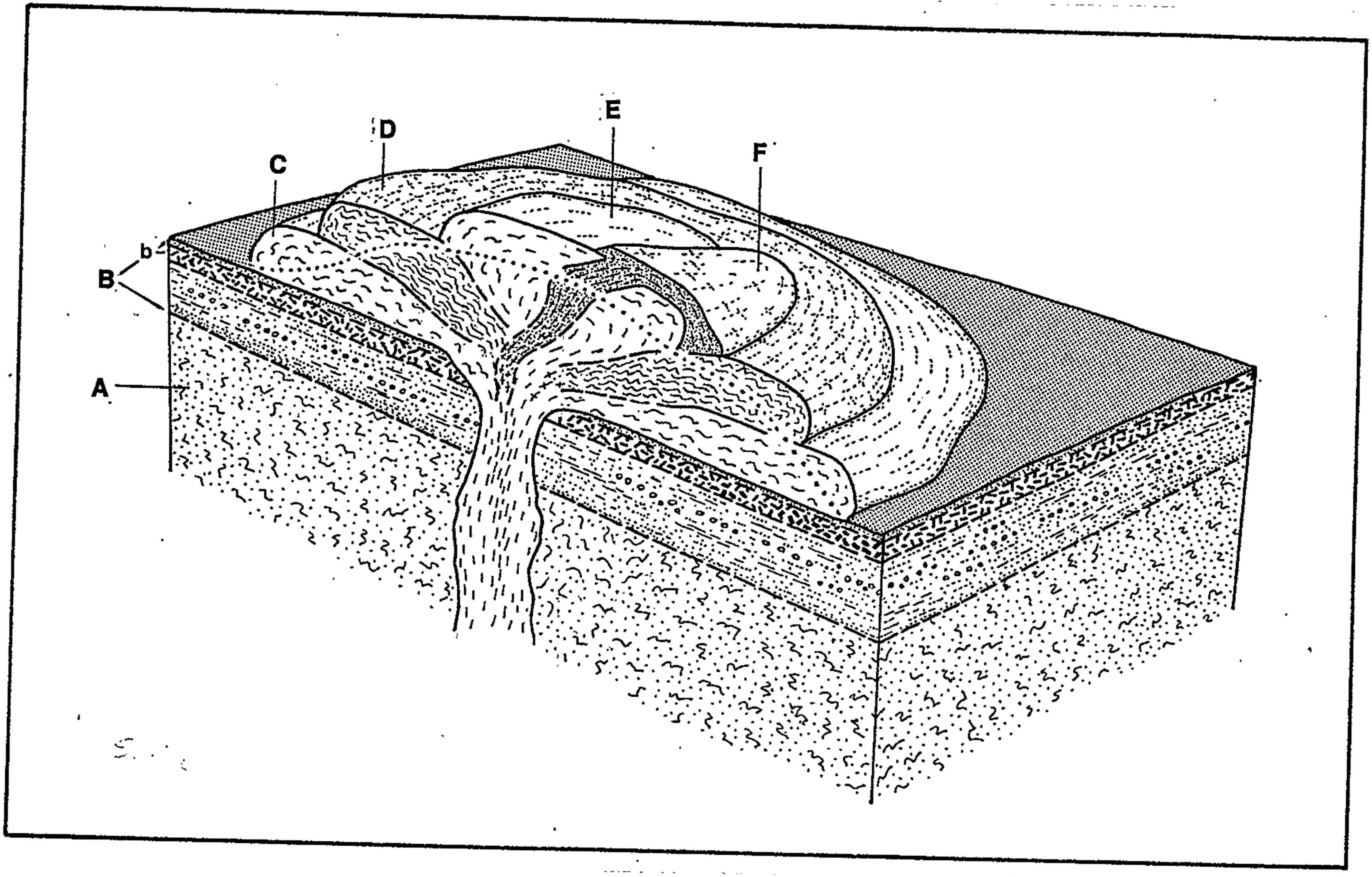
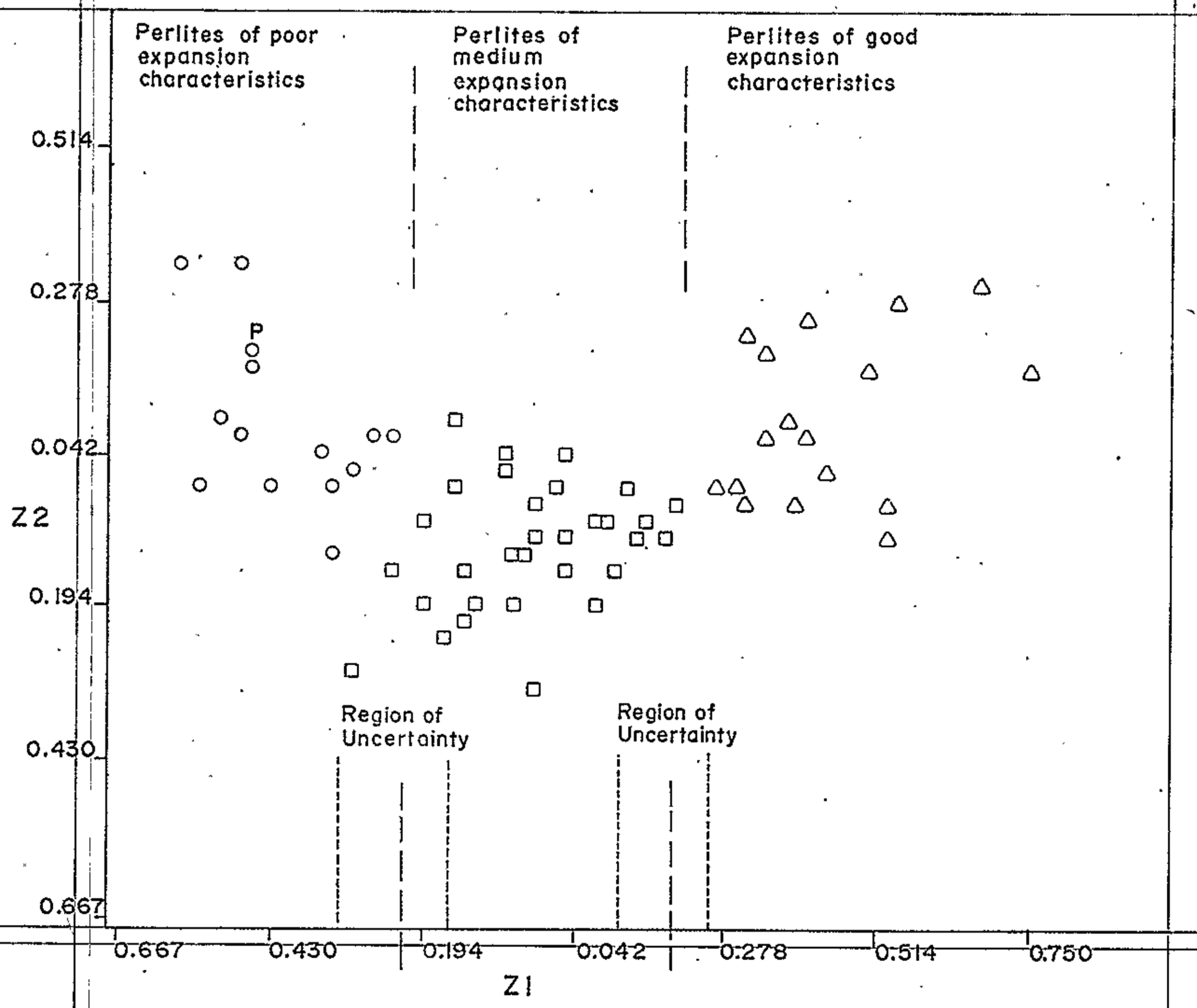

I suggest ~~a~~ patterns like these
LGR
UP
UGR
MP
LGR
A.
Generalized profile of present topography
UP
UGR
MP
LGR
B.
LGR
UP
UGR
MP
LGR
~~C.~~
D
UP
UGR
MP
LGR
~~D.~~
C

Figure 26.

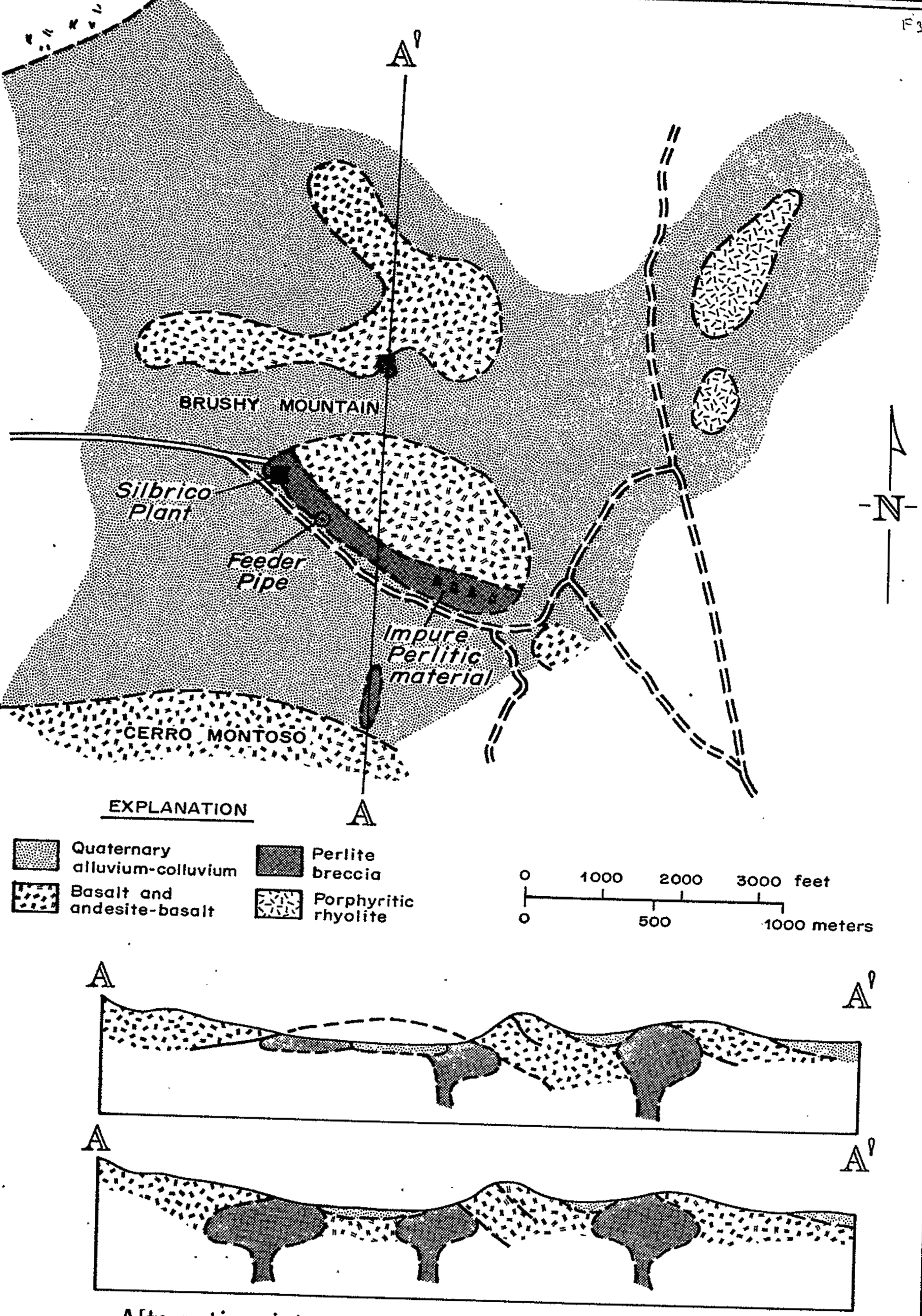


E
D
F
C
b
B
A


Perlites of poor expansion characteristics
Perlites of medium expansion characteristics
Perlites of good expansion characteristics
P
Region of Uncertainty
Region of Uncertainty
Z2
0.514
0.278
0.042
0.194
0.430
0.667
Z1
0.667
0.430
0.194
0.042
0.278
0.514
0.750

F. 3

F31



Alternative interpretations for cross-sections through the Brushy Mountain Perlite deposits