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THE STRUCTURE AND STRATIGRAPHY OF THE GARDNER MOUNTAIN AREA, NEW HAMPSHIRE.

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Geology

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THE STRUCTURE AND STRATIGRAPHY
OF THE GARDNER MOUNTAIN AREA,
NEW HAMPSHIRE

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BY

Gerald D. Prager

B.S. University of Kansas, 1962

UNIVERSITY OF CINCINNATI

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I hereby recommend that the thesis prepared under my supervision by Gerald D. Prager

entitled The Structure and Stratigraphy of the Gardner Mountain Area, New Hampshire

be accepted as fulfilling this part of the requirements for the degree of Doctor of Philosophy

Approved by:

William F. Jenks

Frank L. Koucky

Edward L. Lasser

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ABSTRACT

A detailed geologic investigation was carried out in the Gardner Mountain area, New Hampshire, in the summers of 1968, 1969, 1970. The primary objective of the field work was originally to decipher the internal stratigraphy of Amonoosuc formation (middle Ordovician meta-volcanics). The results of this study led, in turn, to a reevaluation of the stratigraphy which had been developed by Billings (1937) for the area as a whole. According to the proposed interpretation, the Albee formation, a thick sequence of mixed metasediments originally mapped as the oldest unit exposed in the area, is actually several younger units. These are the Partridge black slates (middle Ordovician) and Clough quartzite (Silurian), with a metasedimentary unit between them for which the name "Albee formation" has been retained.

The revised stratigraphy developed in this study has necessitated a rather sweeping revision in structural interpretation as well. In view of constraints imposed by the stratigraphy, and of the results of a program of detailed structural analysis carried out in the summer of 1970, it is considered that the Gardner Mountain area is underlain by the normal limb of a major westward facing recumbent fold. In addition, stratigraphic and structural evidence lead to the conclusion that the lower, eastern part of the Gardner Mountain fold is a tectonic slide which has evidently excised part of the section in the eastern half of the area. Two periods of folding followed formation of the recumbent fold and slide. The first was an intensive phase of the Acadian orogeny and the second a much later broad folding with a northwesterly axial trend. Locally four distinct S-surfaces are visible .

The interpretations presented in this study appear to be consistent with the more recent work elsewhere in the region, especially in southwestern New Hampshire and eastern Vermont. Thompson et.al. (1968) have shown the existence of a series of nappes less than thirty miles along strike to the south of Gardner Mountain, and Goodwin (1962, 1963) and Ern (1963) have proposed a major recumbent fold adjacent to this study area to the west.

ILLUSTRATIONS

INTRODUCTION

Location and Geologic Setting

The Gardner Mountain area is located in and just east of the Connecticut River valley in northwestern New Hampshire, and includes portions of the Littleton, Moosilauke, Woodsville, and St. Johnsbury quadrangles. The area of this study is delimited by the Ammonoosuc fault on the south and east and by the Connecticut River and the "Monroe Line" on the west and north (Fig. 1).

Gardner Mountain itself constitutes one of the largest and most westerly foothills of the White Mountains, with a maximum elevation of 2330 feet and surprisingly high relief locally. During the last century the area was extensively farmed, about eighty percent having been cleared for this purpose, but gradual abandonment of these farms, particularly in the last thirty or forty years, has resulted in the present pattern of widespread second-growth woodlands interspersed with small pastures and an occasional cluster of farm buildings. This rankness of natural growth combines with an abundance of bogs, thick local accumulations of glacial materials, and the lack of a really good base map to make working conditions difficult for bedrock field geology; however, adequate aerial photos of the area are available, and access to even the more remote locations through dirt roads, jeep tracks, paths, and a number of power transmission lines is relatively easy.

Geologically, the Gardner Mountain area occupies a strategic position in a major northwestward-pointing salient in the northern

GENERAL INDEX MAP

Quadrangles:

1. Island Pond
2. Dixville
3. Errol
4. Burke
5. Guildhall
6. St. Johnsbury
7. Littleton
8. Whitefield
9. Woodsville
10. Moosilauke
11. Randolph
12. Mt. Cube
13. Hanover
14. Mascoma
15. Claremont

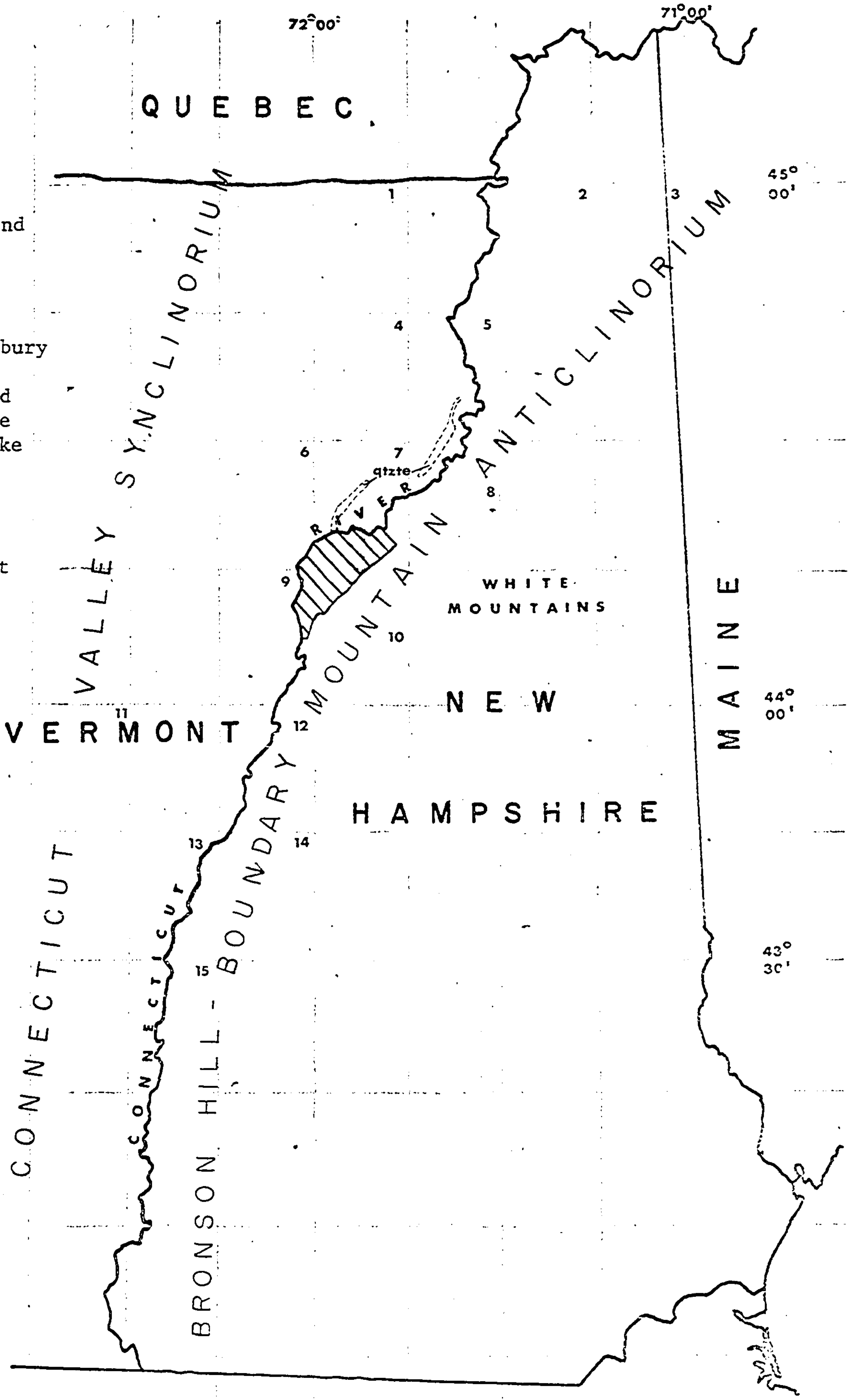

Figure 1.

Appalachian lower and middle Paleozoic eugeosynclinal sequence. In terms of the regional tectonic features, its location and lithology place it on the northwest flank of the Bronson Hill-Boundary Mountain anticlinorium, with the transitional (eugeosynclinal-miogeosynclinal) Connecticut Valley-Gaspe synclinorium just to the west (Fig. 1). Further west is the intensively-studied Green Mountain-Sutton Mountain anticlinorium, and well to the southeast is the much less well known Merrimac synclinorium. It has been noted by Cady (1969) that two distinct major fold styles are seen in the Bronson Hill-Boundary Mountain anticlinorium: doubly plunging axial anticlines with subsidiary minor folds, on the Green Mountain anticlinorium pattern, and broadly arched "Oliverian" domal anticlines, associated with intrusive bodies. Gardner Mountain has, since its first modern mapping by Billings (1937), been considered typical of the first of these fold types. However, more recent work in the region, particularly that of Thompson et al. (1968) on strike to the south, has given some indication that the geology of this area may be more complex than heretofore envisaged--a conclusion with which this paper tends to agree.

Structure and stratigraphy in the area are both complex. There is clear evidence in many locations of multiple deformation, and the presence of three or four metamorphic S-surfaces in a single outcrop is not unusual. Also, it is fairly common for one or more formations to be missing at any given location, either through structural excision, unconformity, or facies change, and considerable variation of stratigraphy within the formations from place to place is the rule rather than the exception. Adding to these complications is the regional metamorphism, which, although lowest in grade in this part of New England, is uneven within the area and increases rapidly in all directions outside of it, making detailed correlations more difficult, particularly over larger distances.

History of Investigations

The first mention of the Gardner Mountain area in the geological literature was in a general survey of New Hampshire geology by C.T. Jackson (1844). Shortly thereafter, the finding of small quantities of copper, lead, zinc, silver, and gold stimulated geologic interest in the area, as well as a short-lived mining fever which made the tiny hamlet of Lyman a minor boom town in the 1870's. The Hitchcocks, father and son, formed a dynasty of New Hampshire State Geologists and led the early investigations of the "Ammonoosuc mining district." Edward Hitchcock, like most geologists of his time, believed the great extent of presumed unfossiliferous metamorphic rocks of New Englend to be Precambrian in age, and even tried to correlate the Gardner Mountain area with the northern Michigan copper districts. These notions were finally dispelled by his son, who on September 28, 1870, found Silurian fossils just north of the town of Littleton (C.H. Hitchcock, 1874a), and thereby inaugurated the era of modern geology in northern New England.

C.H. Hitchcock followed up his initial find with an updated survey of New Hampshire geology (1874b, 1877) and further work in the "Ammonoosuc District" (1904, 1905). This work was followed by the discovery of Devonian fossils just west of Littleton by F.H. Lahee

(1912, 1913, 1916) and C.P. Ross (1923).

These early investigations certainly contributed something significant to the understanding of the area's geology. Lahee, for example, first suggested the structural nature of the Walker Mountain syncline and noted the volcanic nature of part of C.H. Hitchcock's old "Lyman series," and Ross first mapped the Ammonoosuc fault. However, no one at this time had established a real stratigraphic basis for mapping in this region, a fact which was recognized and acted upon by Marland P. Billings. Billings' maps of the Littleton and Moosilauke quadrangles (1937) furnished the necessary stratigraphy for later workers in the region. Mapping of the Gardner Mountain area itself was rounded out by completion of the Woodsville (White and Billings, 1951) and St. Johnsbury (Hall, 1959) quadrangles, and later mapping was done on strike to the south (Hadley, 1942; Lyons, 1955) and north (Eric and Dennis, 1958; Johansson, 1963; Green and Guidotti, 1968), all utilizing Billings' stratigraphic sequence. All during this period, beginning with C.H. Richardson (1902, 1906, 1919), similar work was proceeding across the Connecticut River in Vermont, although with considerably less agreement among geologists as to stratigraphic sequence and structure (Murthy, 1958; White, 1959; Goodwin, 1962). Correlation between the two States was inhibited almost from the beginning by the finding of the problematical "Monroe Line" (Eric, White, and Hadley, 1941), which led to a regional stratigraphic division into a "New Hampshire sequence" and a "Vermont sequence." Although many more recent papers, of which those of Cady (1960) and Thompson et. al. (1968) are among the most significant, have been published that have an important bearing on the study of the Gardner Mountain area, the work of Billings and his students remains the only systematic mapping to be published on this area to date.

Methods and Objectives

It has been noted that geological interest in the Gardner Mountain area has historically been engendered by two major factors: the presence of metallic sulfides (even though in uneconomic concentrations) and the presence of fossils, which gave a firm foundation for stratigraphy. This study resulted largely from the first of these factors; interest was initially generated by the availability of good geologic maps and by the history of small scale mining experienced by the area. In actuality, most of the "mines" scattered around Gardner Mountain are little more than prospect pits, and represent, for the most part, only stock promotion schemes. Mineralization, however, although minor wherever seen at the surface, is nevertheless widespread, and its close spatial relationship to the mapped volcanic units raised hopes that genetic relationships of general interest might be discovered here. Field work was thus begun here in the summer of 1968 with a primary orientation toward Economic Geology.

It became apparent quite early in the study that an understanding of the origin of the scattered sulfides around Gardner Mountain is contingent on a thorough understanding of the detailed stratigraphy and structure of the units with which they are associated, particularly the Ammonoosuc volcanics. The problem thus resolved itself into a detailed study of this formation. By using Billings' map and working into the unit from upper and lower mapped contacts, wherever exposures permitted, an internal stratigraphy of the Ammonoosuc formation was developed. This stratigraphic pattern led, in turn, to a reevaluation of the general stratigraphy of the area. Finally, in order to fit the various lithologic data into a coherent, integrated whole, detailed structural analysis was carried out in selected locations. The conclusions derived from these methods present a geologic picture rather different, and more complex, than that which has hitherto been accepted.

ACKNOWLEDGEMENTS

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Finally, the help of Miss Rita Kinne, who prepared the prints, and of Miss Brenda Stamm, who assisted in typing the manuscript, is gratefully acknowledged.

STRATIGRAPHY

Established Stratigraphic Sequence

The currently accepted stratigraphy in the Gardner Mountain area is that developed by M.P. Billings, first published in its entirety in 1934. Because the Littleton and Moosilauke quadrangles were the first in the entire region to undergo modern mapping, it is also the type area of many of the units of the Bronson Hill-Boundary Mountain anticlinorium, and its stratigraphy is the foundation of most of the mapping and structural interpretation of that major belt of rocks.

The formations, as defined by Billings, are the Albee (upper Ordovician, dominantly quartzites, with more or less abundant metapelites and even a few calcareous rocks), Ammonoosuc (upper Ordovician, dominantly metavolcanics), Partridge (upper Ordovician, black slate), Clough (Silurian, quartz conglomerate), Fitch (Silurian, largely calcareous metasediments, with some gray slate), and Littleton (Devonian, mixed metasediments, black slates and metavolcanics). In addition to these stratified units, two intrusive units are mapped in the Gardner Mountain area: the Highlandcroft granodiorite of the late Ordovician Highlandcroft Magma Series and the Moulton diorite of the Devonian (age dated) New Hampshire Magma Series. These intrusives are discussed more thoroughly by Billings and Keevil (1946).

The ages of the formations were based on the fossils which had been discovered in the Littleton and Fitch formations. Cleaves restudied the available fossil suites and agreed with Schuchert

(Hitchcock, 1904) that the Fitch was middle Silurian and with J.M. Clarke (Lahee, 1913) that the Littleton was lower Devonian (Billings and Cleaves, 1933); later (Billings and Cleaves, 1934), he concurred with Pumpelly (1888) that the Fitch was Niagaran, and considered the Littleton to be of Oriskany age. More recently, Boucot and Arndt (1960) restudied Cleaves' fossils along with new material and concluded that the Littleton is of Camden rather than Oriskany age, correlating with the lower Devonian Camden chert of Tennessee. Naylor and Boucot (1965) consider the Fitch in western New Hampshire to be of early Ludlow age, and to the south to be "as old as Wenlock or Late Llandovery age" (p. 161).

It should be noted that fossils, and therefore strict age control, were available to Billings only for the Fitch and Littleton; ages of all the older formations were inferred from geologic relationships. Later mapping, however, showed that the Clough formation contains fossils elsewhere. These Clough fossils were first reported by Edward Hitchcock (1835) at Bernardston, Massachusetts, and have been found at numerous localities since (Boucot and Thompson, 1958; Boucot et al., 1958; Boucot and Thompson, 1963). Studies of these fossils have confirmed Billings' original opinion of the Clough as Silurian, placing it as Llandovery C3-C5 (Boucot and Thompson, 1963).

In lieu of fossils, various other means have been employed in the attempt to more accurately fix the ages of the pre-Clough formations of the area. Rubidium-strontium age dating has been a popular technique, used by Brookins (1968) on rocks of the Ammonoosuc formation in Massachusetts to give an age of 460 ± 15 m.y., with reservations because of incipient weathering and possible metasomatism. Long-range correlation has been used where neither fossils nor age dates are available. Berry (1968) correlates the Partridge with the Beauceville formation of Quebec and an unnamed unit in west-central Maine, both of which contain zone 12 graptolites. These data, then, indicate an age for the Ammonoosuc and Partridge formations somewhere between Porterfield and Trenton, again confirming the original conclusions of Billings.

The least well-documented unit here in terms of age is the Albee. Tentative correlations of the Albee with better-known units in Quebec, Maine, and, particularly, Vermont, have been made on the basis of sequence and lithology by Cady (1960, 1969) and several others. However, as Cady rightly observes, "lateral variations, particularly across the strike, are the rule rather than the exception in geosynclinal deposits..." (1960, p. 553), and such correlations must, without other direct evidence, be considered tenuous at best. The importance of the lack of good documentation of the age of the Albee will be seen later in this chapter.

Descriptions of Units

Brief descriptions of the formations defined by Billings will be given in this section, with the exception of the Ammonoosuc, which is covered separately and in more detail. Descriptions are based on those of Billings and later workers, and on personal observations, and are intended only to provide a general acquaintance with the various lithologies as a background to understanding problems of stratigraphic interpretation which are treated later. Much more detailed descriptions of the units are given by Billings (1937) and others (Hadley, 1942; Chapman, 1939), and some chemical analyses, whole-rock and constituent, are given by Billings and Wilson (1964).

Albee Formation

The Albee formation consists of a highly variable sequence of white quartzites, "dirty" quartzites, and black and green slates and phyllites, with occasional lenses of carbonate rocks. The black slates generally occur at its contacts with the Ammonoosuc volcanics. Further toward the center of the Albee outcrop area are found interbedded chlorite-rich quartzites; within the biotite zone of regional metamorphism these often appear with "pinstripe bedding," a metamorphic feature often considered especially typical of the Albee. Near the center of the outcrop area is a distinct and mappable belt of massive white quartzite, which holds up the main ridge of Gardner Mountain. The bottom of the formation is not exposed, it being mapped as the oldest unit present; however, Billings estimated that a thickness of approximately 4,000' is exposed in the area. Of all the units defined by Billings, the Albee is probably the most variegated lithologically.

Partridge Formation

The Partridge black slates are much more uniform in lithology than the Albee, although variations are seen from place to place. Throughout most of the area, the formation consists of very fine-grained slate, splintery because of two cleavages intersecting at a low angle, and often with numerous small grains of pyrite which appear on cleavage surfaces as tiny lumps. When exposed to weathering for any length of time, these pyrite-rich slates acquire a distinctive rusty appearance. Locally, particularly in the southern part of the area, the Partridge contains a large amount of quartz; in these localities the normally incompetent formation stands up fairly well to erosion (Fig. 2). Sericite is the dominant mineral everywhere, with considerable amounts of quartz, variable chlorite, and minor pyrite and graphite.

Clough Formation

The defined nature of the Clough formation has changed significantly since it was first mapped. First described by Billings as a quartz conglomerate of very limited and highly variable thickness, it was later noted, after extended mapping away from the Gardner Mountain area, to be a much thicker orthoquartzite unit with a basal conglomerate and quartz mica schist (Chapman, 1939; Hadley, 1942), and, most recently, to contain locally polymict conglomerates, micaceous quartzites, mica schists, and calc-silicate rocks (Thompson et al., 1968). The variability in thickness of the Clough is still agreed upon, although maximum thickness is now thought to be at least 800 feet. This variation is evidently both a tectonic and primary sedimentary feature (Billings, 1937). It is particularly notable that while the Clough formation has been extensively mapped along strike to the south of the Gardner Mountain area--C.H. Hitchcock (1912) considered this striking ridge-former to be the key marker bed--it has been conspicuously absent from maps of areas to the northeast.

Fitch Formation

The Fitch and Littleton formations are, as noted above, the best dated in the area. The Fitch is a relatively thin unit, with a maximum thickness of only about 400 feet. Brown-weathering, silty calcareous metasediments make up the bulk of the formation, with fairly numerous

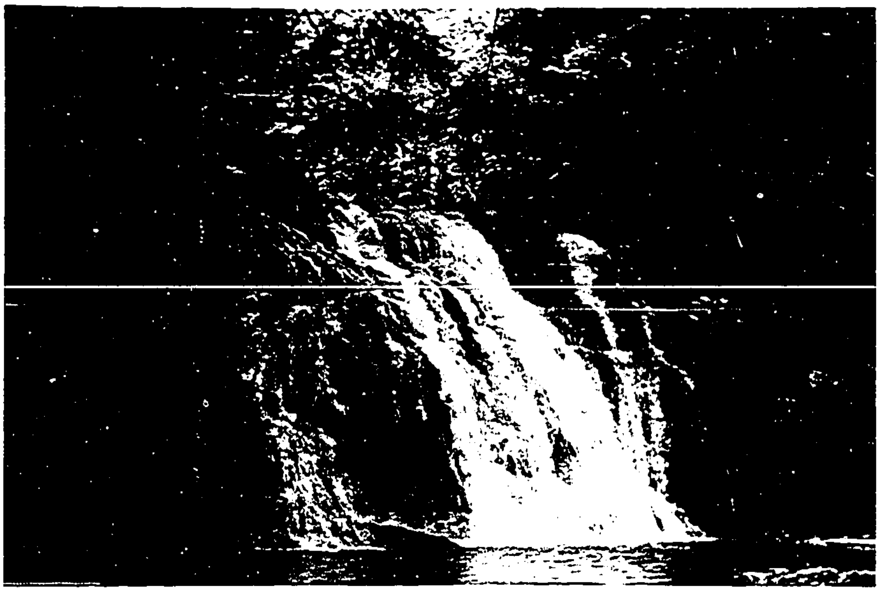

Figure 2. Partridge formation: black slates holding up ledge at Pettyboro Falls, 2 miles north of Bath. Entrance to small graphite mine at left. Note subhorizontal cleavage, from late rotation near Amonoosuc fault.

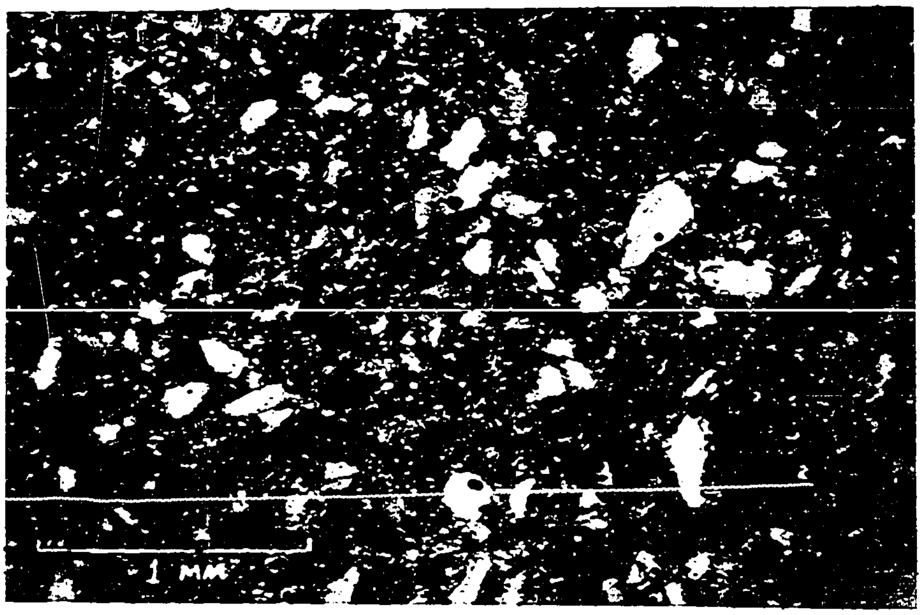

Figure 3. Mullikin Brook member, Ammonoosuc formation. Sample # 159a. Nicols crossed. **Mostly quartz, with sericite and minor plagioclase.**

veins of bluish-gray marble, up to several feet thick. Near the bottom of the formation, gray slates are common. Although thin, the Fitch is rather uniform and quite persistent over a large area, except where removed structurally or by unconformities. Its high carbonate content and the peculiar weathering appearance which results are usually sufficient to identify it in the field.

Littleton Formation

The Littleton formation is typically a dark gray or black slate with a scattering of arenaceous interbeds, although other types of metasediments may appear in places. Thin belts of metavolcanics, mostly quite mafic, occur near the bottom of the unit. The top is not exposed in the Gardner Mountain area, but a considerable thickness is evident even in that portion of the formation which can be seen. Confusion of the volcanic portions of the Littleton with the Ammonoosuc formation can be a problem; in this study area the problem is minimized by the much higher percentage of felsites within the Ammonoosuc, but some difficulties of this nature may have been experienced to the south (Griscom and Bromery, 1968, p. 428).

The Ammonoosuc Volcanics

The metavolcanic rocks of the Ammonoosuc formation in the salient of the Bronson Hill-Boundary Mountain anticlinorium occur in four major parallel belts. Of these, the two east of the Ammonoosuc fault are wider in outcrop and extend far to the south, where they are involved in the major recumbent folds described by Thompson et al. (1968) and the mantled domes studied by Naylor (1968, 1969). The two belts west of the

Ammonoosuc fault are geographically restricted almost to within the limits of this study area. The westernmost belt has a rather small, elliptical outcrop area in the Connecticut River valley, nearly all on the New Hampshire side; the other is longer, of highly variable outcrop width, disappearing to the south at the town of Woodsville and nearly cut off to the north by intrusive bodies and the Ammonoosuc fault (Billings, 1956).

The most distinctive of the rock types within the Ammonoosuc volcanics is a massive felsite, largely composed of that group called "soda-rhyolite tuff" by Billings (1937). This generally stands out as a good marker bed and has been used during this study as the basis for mapping the internal stratigraphy of the formation wherever it occurs. The composition of these felsites is variable from place to place, as Table 1 shows, but their mineralogy is always dominated by quartz and muscovite (or, more commonly, sericite), and, except for some difficulty in distinguishing feldspar-poor examples from orthoquartzite (with which they may be megascopically apparently identical), they are easy to recognize in the field. The plagioclase in these felsites, as noted by Billings (1937), is close in composition to the albite end member. Texturally, they may be considered as fine-grained granular rocks (Fig. 3); the quartz is usually fairly equigranular, with well-rounded equidimensional grains which are seldom over 1 mm. across. Sericite is often interstitial, with occasional larger concentrations, and plagioclase is typically in large twinned, euhedral, and much-altered grains up to several mm. across. Cleavage, where visible at all, is seldom well-developed, a fact which contributes to the very massive appearance of these rocks in the field. Because this group of rocks, like the other rock types within the Ammonoosuc formation, is easily recognized in the field and is mappable as a unit, it has been assigned a name as the Mullikin Brook member, from an outcrop on Mullikin Brook at a small power transmission line just over 0.1 mile south of Route 18.

A second distinguishable rock type within the Ammonoosuc is a fairly dark to very light blue-gray schist, well foliated and usually calcareous, with somewhat irregular cleavage surfaces which give it a lumpy appearance (Fig. 4). These bluish schists are easily weathered, often leaving small brown pits where carbonate has been removed; as a result, there is often a paucity of outcrops in areas underlain by them. As indicated in Table 2, compositional variation is probably greater in this group than any other within the Ammonoosuc. The plagioclase of this member is less sodic than that of the Mullikin Brook; it is estimated to average about An_{35}. Grain size averages as fine as that of the Mullikin Brook rocks, and the cleavage shows up strongly on the microscopic scale in the muscovite and chlorite. The unit has been assigned the name of West Bath member, from exposures around and to the south of the old West Bath school site.

A third major rock type which is mappable within the Ammonoosuc is a massive blue-gray rock, which is almost invariably calcareous (Fig. 5). This can usually be distinguished without much difficulty from the West Bath member in the field by a darker color and much less well developed cleavage. The distinction between the two types is also reflected in the modes (Table 3); although there is some slight overlap, the modal averages of the West Bath member and the massive blue rocks show a clear

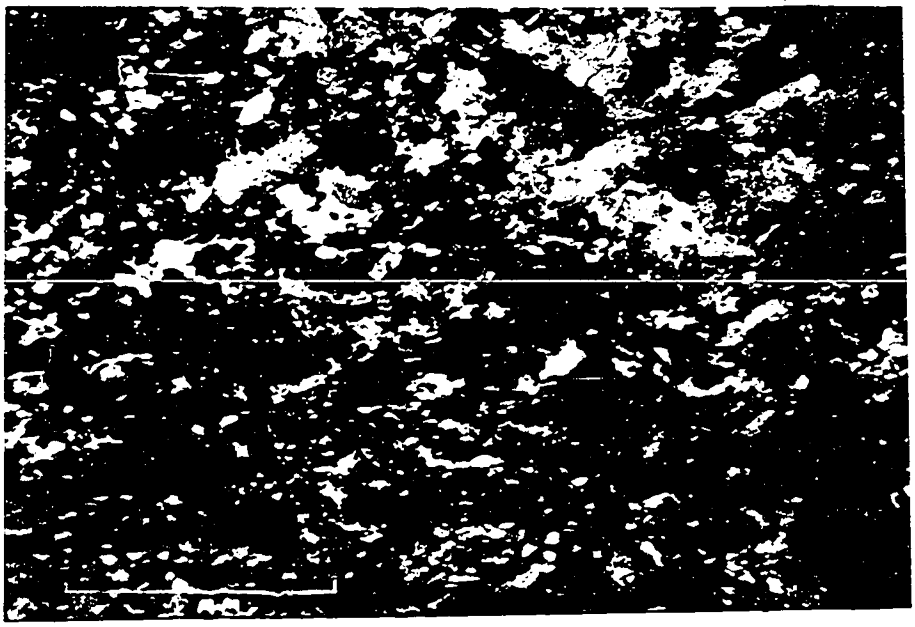

Figure 4. West Bath member, Ammonoosuc formation. Sample # 112. Nicols crossed. Quartz, chlorite, sericite, and plagioclase; masses of carbonate in the upper right.

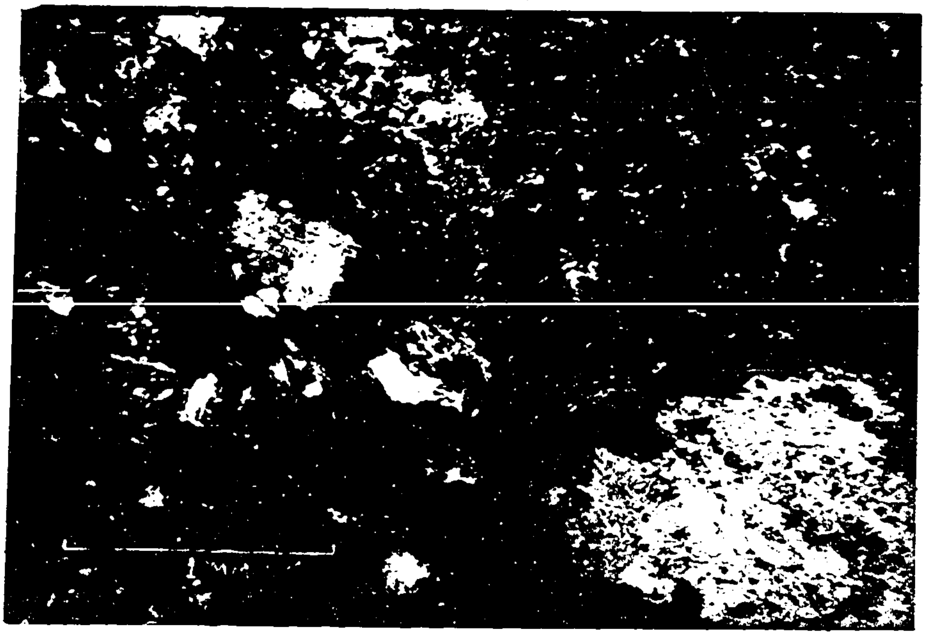

Figure 5. Smutty Hollow member, Ammonoosuc formation. Sample # 92. Nicols crossed. Mostly plagioclase in a chlorite groundmass, with some quartz.

TABLE 1

MODES OF MULLIKIN BROOK MEMBER, AMMONOOSUC FORMATION

MASSIVE FELSITE

SAMPLE NO. / COMPONENT	63	64	198	10a	20a	22a	26a	159a	163a	Ave.
QUARTZ	45	53	75	74	60	62	80	70	86	67
CHLORITE	15	--	--	--	5	5	--	--	--	3
MUSCOVITE	38	45	9	14	7	15	10	17	2	18
PLAGIOCLASE	--	--	16	12	18	--	9	4	7	8
BIOTITE	--	--	--	--	--	--	--	--	--	--
CARBONATE	--	--	--	--	10	18	--	9	--	4
EPIDOTE	--	--	--	--	--	--	--	--	--	--
AMPHIBOLE	--	--	--	--	--	--	--	--	--	--
OTHER	2	2	--	--	--	--	--	--	5	1

SAMPLE LOCATIONS:

63: Falls of Smith Brook in Smutty Hollow Gorge.
64: Same as above.
198: On Route 18 at southern tip of Moore Dam Lake.
10a: Southwest slope of Wheeler Hill, northwest of Littleton.
20a: Falls in creek 0.25 miles northwest of Ogontz Lake.
22a: Same as above, 0.1 miles downstream.
26a: Top of hill 0.65 miles southwest of old Slate Ledge school site.
159a: Top of hill 0.6 miles west-northwest of Lake Gardner.
163a: Ridge 0.8 miles northwest of Lake Gardner.

TABLE 2

MODES OF WEST BATH MEMBER, AMMONOOSUC FORMATION

BLUE-GRAY SCHIST

SAMPLE NO. / COMPONENT	46	55	59	74	78	112	197	13a	29a	Ave.
QUARTZ	29	42	40	42	35	25	21	23	29	32
CHLORITE	26	36	4	16	26	25	8	7	8	18
MUSCOVITE	27	--	4	30	6	17	12	22	8	14
PLAGIOCLASE	4	--	22	9	--	3	38	35	18	14
BIOTITE	--	--	--	--	2	--	--	1	12	2
CARBONATE	--	20	30	--	14	30	20	12	12	6
EPIDOTE	3	--	--	--	17	--	1	--	--	2
AMPHIBOLE	11	2	--	--	--	--	--	--	--	1
OTHER	--	--	--	3	--	--	--	--	13	1

SAMPLE LOCATIONS:

46: 1.1 miles north of Ogontz Lake.
55: 0.7 miles northeast of Ogontz Lake.
59: Just west of the southern tip of Moore Dam Lake.
74: Intersection 1.7 miles south-southeast of North Monroe Church.
112: On Coppermine Hill road, 1.5 miles northeast of Monroe.
197: 0.7 miles northeast of Partridge Lake.
13a: 0.5 miles southeast of North Littleton school.
29a: One mile north-northeast of Partridge Lake.

separation. Despite its relative massiveness, this rock type seldom stands up very well to weathering (one cliff-like outcrop north of Partridge Lake is an exception), probably because of its high carbonate content. Calcite is commonly found in veinlets and as white sheets on fracture surfaces in fresh outcrops of this unit; weathered outcrops are often brownish and have a "rotten" appearance. The plagioclase is also fairly calcic, much of it being optically positive; it is estimated to range in composition from about An_{45} to An_{55}. Grain size tends to be distinctly larger than in any other member; the plagioclase is coarsely twinned in most samples and is frequently in altered, euhedral grains over one or two mm. across. The quartz, as is usual throughout the Ammonoosuc formation, is almost invariably highly strained. These massive bluish rocks have been designated the Smutty Hollow member, from outcrops near the outlet of Smith Brook in Smutty Hollow gorge.

The final rock type which has been distinguished within the Ammonoosuc formation is a mafic chlorite schist (Fig. 6). The color is an intense, usually very dark, green, and cleavage is nearly always well developed, although the rock type appears as a rather massive greenstone in a few places. The irregularity of the cleavage surface which imparts a lumpy appearance to the West Bath member is also found in some of the greenschists, but a slaty structure is probably slightly more common, especially very near the Partridge contact. In Burton Brook, to the south of the area, this member is a very dark blue-gray slate with a distinctive surface sheen. The composition of the unit is greatly dominated by chlorite in the lower grade areas (Table 4). Most of the plagioclase is optically positive, and lies almost entirely within the

TABLE 3

MODES OF SMUTTY HOLLOW MEMBER, AMMONOOSUC FORMATION

MASSIVE INTERMEDIATE SCHIST

COMPONENT	38	92	95	132	15a	32a	132a	154a	214a	Ave.
QUARTZ	35	5	3	17	25	14	26	12	20	17
CHLORITE	35	22	30	33	--	3	32	24	30	23
MUSCOVITE	--	9	--	--	4	21	4	13	--	6
PLAGIOCLASE	13	26	42	11	22	40	7	12	14	21
BIOTITE	--	--	6	--	--	--	--	--	--	tr.
CARBONATE	13	21	15	23	32	22	28	12	18	20
EPIDOTE	--	17	--	13	16	--	--	3	8	6
AMPHIBOLE	4	--	--	--	--	--	--	8	4	3
OTHER	--	--	3	3	--	--	3	6	6	4

SAMPLE LOCATIONS:

38: 0.4 miles southwest of North Monroe Church.
92: Hilltop 0.4 miles west-southwest of Ogontz Lake cemetery.
95: 1.0 mile south-southwest of Ogontz Lake.
132: 0.3 miles northwest of East Ryegate.
15a: 0.8 miles east-southeast of Moulton Hill cemetery.
32a: 0.5 miles east of Partridge Lake.
132a: 0.5 miles west of Lake Gardner.
154a: 0.3 miles east of south tip of Moore Dam Lake.
214a: Smith Brook falls, Smutty Hollow gorge.

TABLE 4

MODES OF LYMAN MEMBER, AMMONOOSUC FORMATION

MAFIC GREENSCHIST

SAMPLE NO. / COMPONENT	33	72	73	75	76	16a	149a	153a	182a	Ave.
QUARTZ	13	15	12	13	10	11	14	8	22	13
CHLORITE	30	67	17	45	35	30	52	47	43	41
MUSCOVITE	6	--	--	--	6	8	12	8	--	4
PLAGIOCLASE	12	--	17	15	5	19	14	4	10	11
BIOTITE	18	--	--	--	--	--	3	--	--	2
CARBONATE	8	--	--	25	34	17	2	6	9	11
EPIDOTE	--	--	3	2	7	13	--	16	11	6
AMPHIBOLE	10	13	44	--	--	--	--	11	--	9
OTHER	3	5	7	--	3	2	3	--	5	3

SAMPLE LOCATIONS:

33: 0.9 miles north of Carbee school.
72: 1.1 miles east of Barnet bridge.
73: 1.3 miles east of Barnet bridge.
75: Coppermine Hill road, 2.5 miles northeast of Monroe.
76: 0.4 miles east of #75.
16a: In Moulton Hill Brook, 0.22 miles from junction with Teter Meadow Brook.
149a: 2.0 miles northwest of village of Lyman.
153a: 0.5 miles east of south tip of Moore Dam Lake.
182a: 0.45 miles southwest of North Monroe Church.

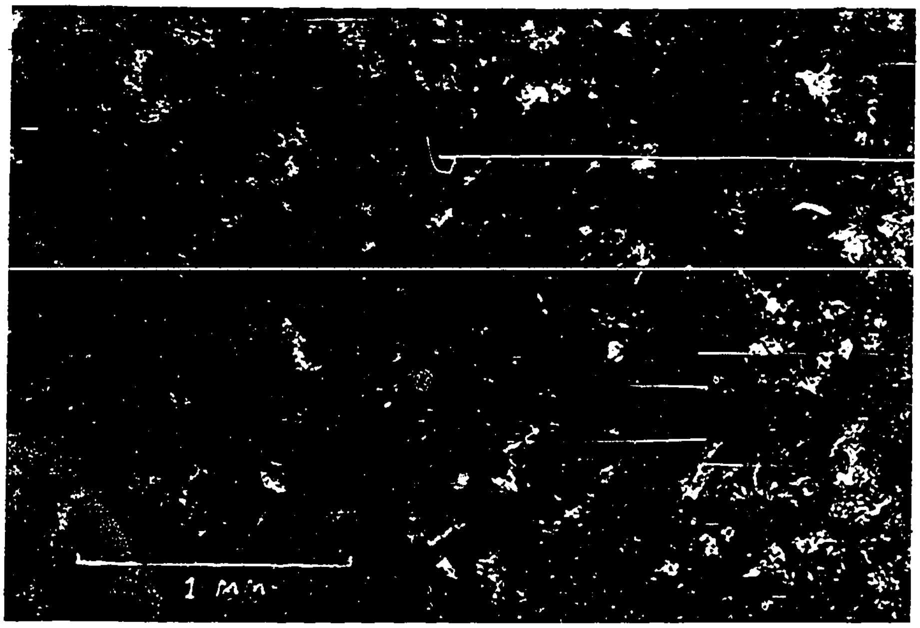

Figure 6. Lyman member, Ammonoosuc formation. Sample # 75. Nicols crossed. **Dominantly chlorite, with some quartz, plagioclase, and carbonate.**

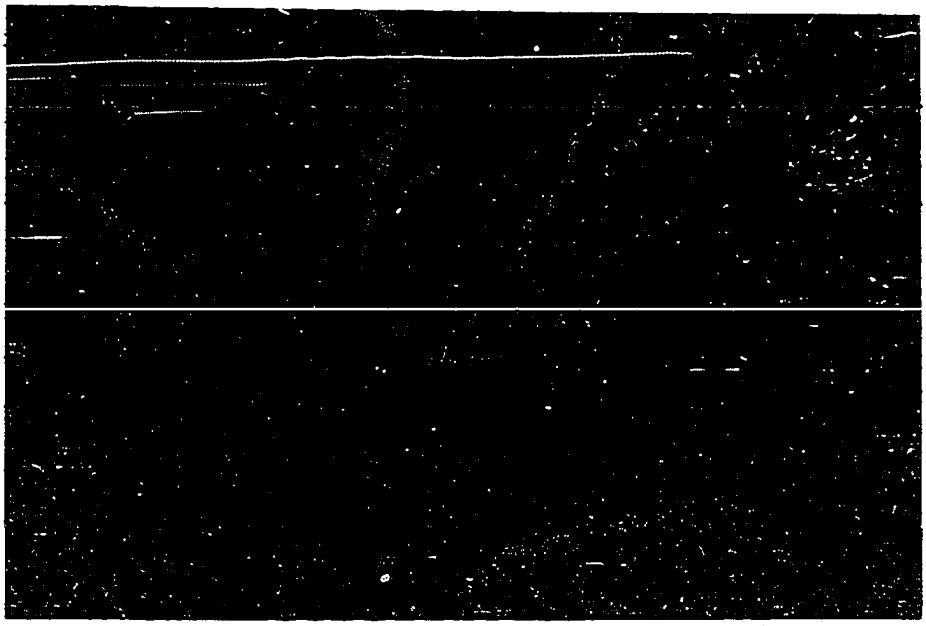

Figure 7. Albee formation, near North Monroe Church: isolated staurolite crystal in greenschist facies quartzite.

labradorite range of composition. Grain size is quite fine, with a good deal of shearing evident on the microscopic scale, and the cleavage is shown up very well by linear distribution of the chlorite. This rock type has been given the name of Lyman member, from numerous exposures in the town of Lyman, especially in Moulton Hill Brook near its junction with Teter Meadow Brook.

The thicknesses of these members, as for the formation as a whole, are difficult to estimate with any accuracy because of structural replications and the scattered nature of the exposures. Rough estimates have been attempted on the basis of outcrop widths in better-exposed areas, however, and give maximum thicknesses of 400 feet for the Lyman member, 500 feet for the Smutty Hollow, and 370 feet for the West Bath in the Gardner Mountain area; the bottom of the Mullikin Brook is not exposed, but an estimated 450 feet can be seen. Thicknesses of the individual members vary considerably over the area, with the result that the areal distribution of the members, as shown on the geologic map (Plate 1) is far from uniform. The Mullikin Brook dominates to the northeast, the Lyman in the middle area, and the West Bath to the south of the larger belt, while the Smutty Hollow dominates the smaller belt. Nevertheless, none of the members is restricted to just one area, and in several places, such as around Partridge Lake and near the south scarp of Gardner Mountain, all four are represented. Thus, although outcrop coverage is not nearly complete enough to permit mapping of contacts between members with anything approaching absolute confidence, and alternate interpretations are uncomfortably abundant, the data are consistent enough over the area as a whole to permit construction of a stratigraphic column within the Ammonoosuc formation with a good degree of confidence, and to base larger stratigraphic interpretations on this internal stratigraphy.

Construction of the internal stratigraphy and development of the larger interpretations have proceeded together, resulting in the following column of members within the Ammonoosuc volcanics, oldest first: Mullikin Brook; West Bath; Smutty Hollow; Lyman. This shows a steady progression upward from felsic through intermediate to mafic, just the opposite of that detected by Thompson et al. (1968, p. 206) to the south. A possible explanation for the apparent inversion is given later in this chapter.

The source and original nature of the Ammonoosuc volcanics has been a matter for speculation since Lahee (1916) first found them to be volcanic. Billings (1937) considered them to be tuffs, deposited here after being carried by wind and water from volcanic centers to the east. Speculation that the Highlandcroft Magma Series might provide a closer source, and that the massive felsites might be resulting flow materials, is apparently negated by a lead-alpha age date of 385 ± 27 m.y. for the Highlandcroft (Lyons et al., 1957), much younger than Brookins' (1968) results for the Ammonoosucs. However, later age date data (Naylor, 1968) indicates that the earlier age date for the Highlandcroft may be in error (Thompson et al., 1968, p. 208), and concentration of the felsites in areas surrounding bodies of Highlandcroft still makes the idea of a Highlandcroft source attractive. Perhaps a more telling argument against it may be the relative orderliness of Ammonoosuc internal stratigraphy, which indicates that at least the three upper members were probably carried in and deposited, thereby supporting Billings' idea. The location of the central postion of the main volcanic island belt of the early Paleozoic eugeosyncline to the east (Berry, 1968) further confirms Billings' thinking about the source area. However, although it will be difficult to prove without detailed mapping of the two easterly belts of Ammonoosuc, there is a good possibility that the source may have been much closer than previously thought, and that the felsites, at least, may have been originally ignimbrites. Some of these ideas will be examined in greater detail in the final chapter.

Metamorphism

The entire Gardner Mountain area is mapped within the chlorite and biotite zones of regional metamorphism, the greater part of it within the former. Metamorphic grade, as was mentioned earlier, increases with a rather steep gradient in all directions away from the area, which is one reason Billings chose it for establishing the stratigraphy. There are, however, complexities in the metamorphic pattern, mostly involving fairly widespread retrogression. In all of the formations except possibly the Partridge, some higher grade minerals, such as staurolite, can be found (Fig. 7), generally having partly retrogressed to lower grade forms, but it is notable that the vast majority of examples come from the Ammonoosuc formation.

Typical examples of retrogression in the Ammonoosuc formation are biotite to chlorite (Figs. 8 and 9), garnet to chlorite (Fig. 10), and hornblende to chlorite (Figs. 11 and 12). Not uncommonly a stepwise retrogression can be observed; for example, hornblende may have retro-

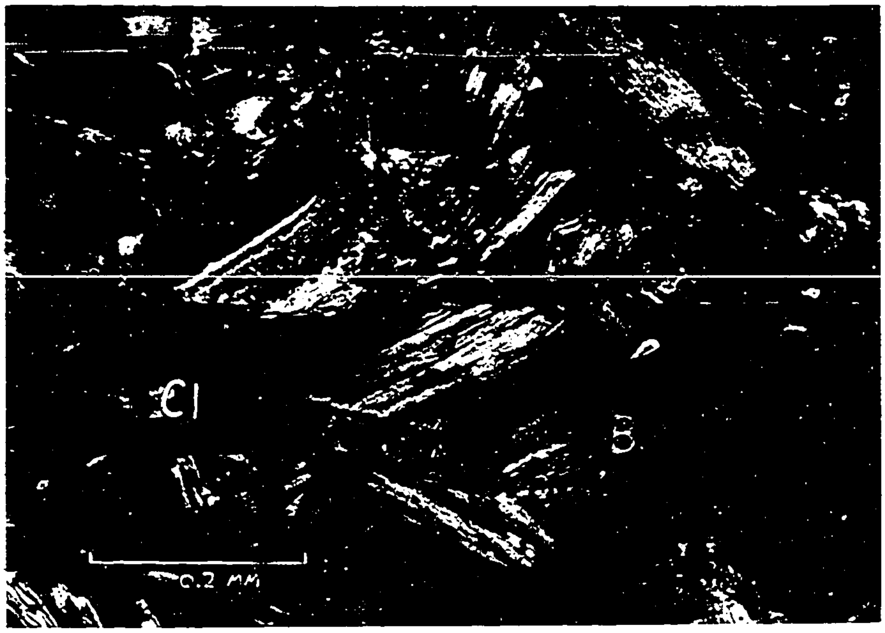

Figure 8. West Bath member, one mile west of North Monroe Church: retrogression of biotite (B) to chlorite (Cl). Nicols crossed.

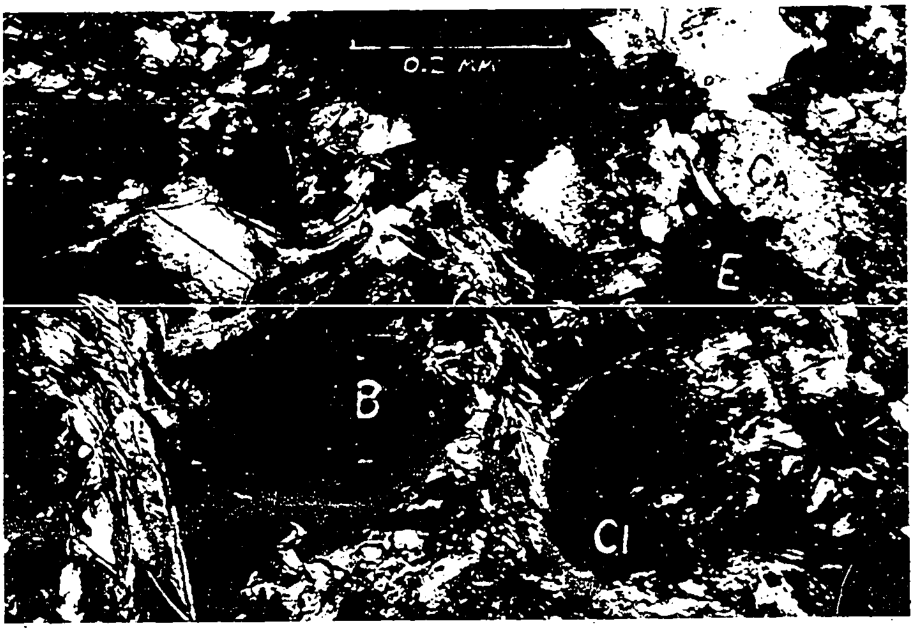

Figure 9. Smutty Hollow member, southwest of Ogontz Lake: retrogression of biotite (B) to chlorite (Cl); also, carbonate (Ca) breaking down to form epidote (E). Carbonate is probably ankerite. Nicols crossed.

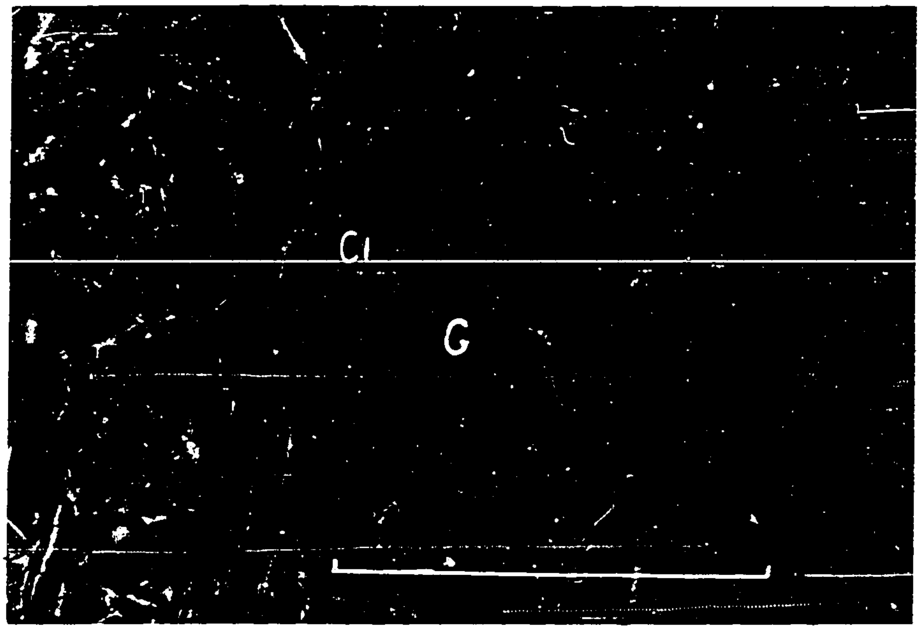

Figure 10. Mullikin Brook member, Smith Brook falls: garnet (G) retrograding to chlorite (Cl).

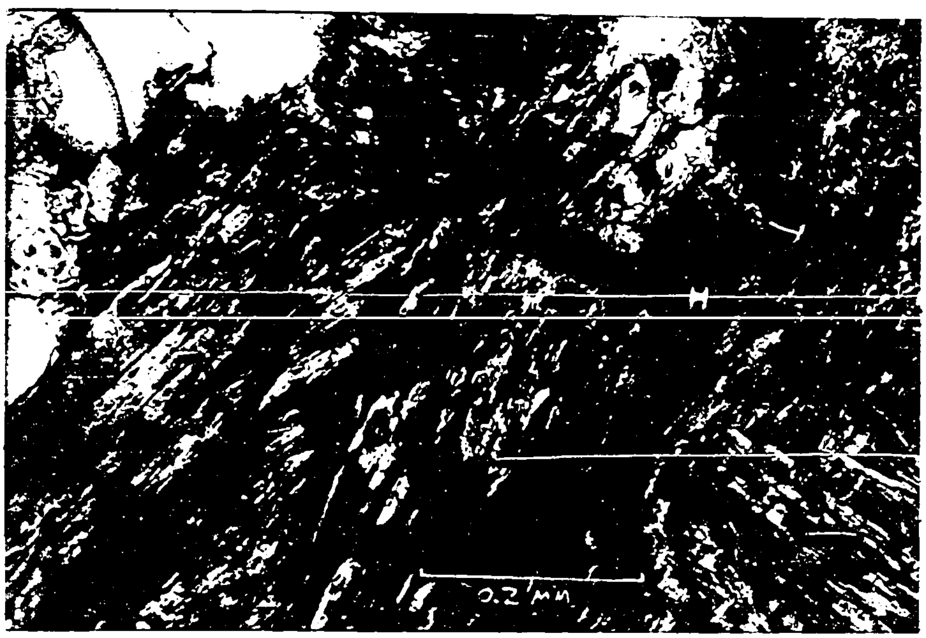

Figure 11. West Bath member, one mile north of Ogontz Lake: hornblende (H) retrograding to chlorite (Cl). Nicols crossed.

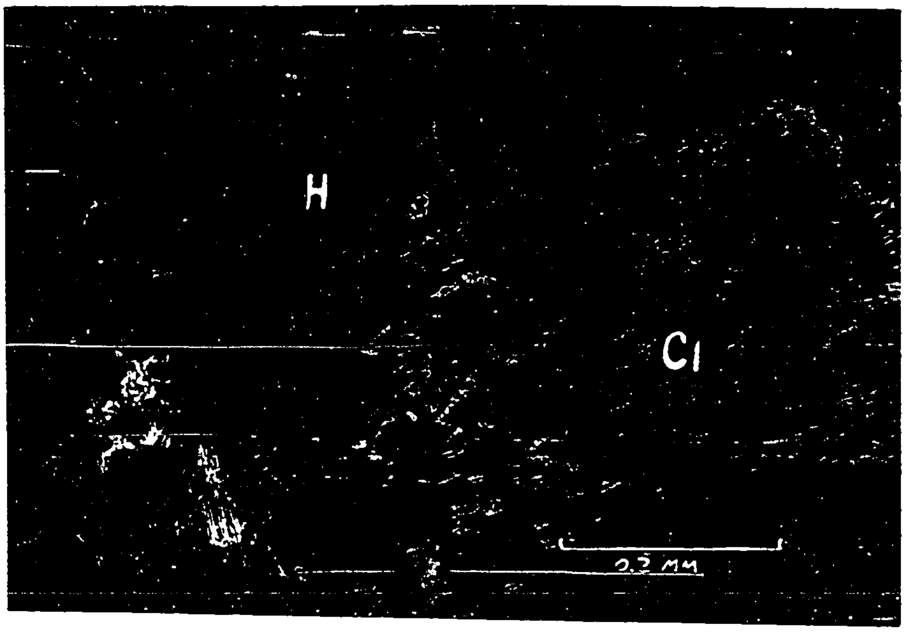

Figure 12. Smutty Hollow member, just east of south end of Moore Dam Lake: hornblende (H) retrograding to chlorite (Cl) in a distinctive patchwork pattern. Nicols crossed.

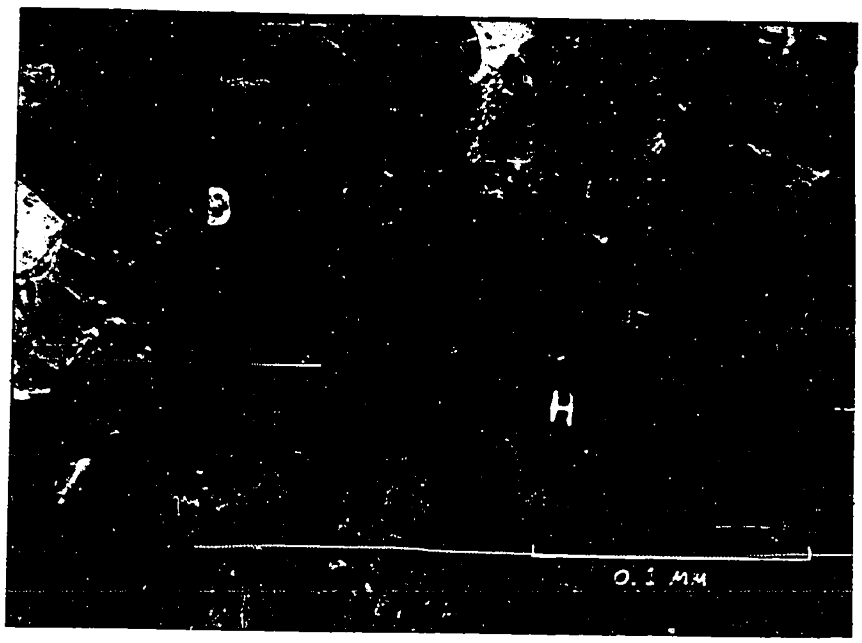

Figure 13. Mullikin Brook member, just east of Ammonoosuc fault near Lisbon: retrogression of hornblende (H) to biotite (B). Nicols crossed.

graded to biotite, and biotite in turn retrograded to chlorite, in the same hand specimen (Figs. 13 and 14). Another alteration, which is less diagnostic in terms of metamorphic grade but nevertheless interesting, is plagioclase, probably andesine, to carbonate at several locations in the Smutty Hollow member (Fig. 15). Such widespread retrogression indicates that much of the rock material now within the chlorite isograd must at one time have been significantly higher in metamorphic grade, some of it as high as the amphibolite facies. Another possibly significant fact is that the retrograde effects are concentrated within the Ammonoosuc formation. Although this clue must be considered unreliable by itself, it may indicate that the Ammonoosuc was at one time higher in grade than the other formations in the area, which could, in turn, indicate possible deeper burial. In view of the fact that the Albee has been represented as older than the Ammonoosuc, this may seem unusual; the next section provides a possible solution.

Of course, it is hardly likely that the area as a whole has been retrogressed en masse; it is difficult to envision the black slates, for example, as ever having been significantly higher in metamorphic grade than they are now. At the same time, the numerous examples of retrogression seen over most of the area cannot be entirely ignored. Thin sections reveal a pervasive shearing throughout the area which would permit retrogression to occur (Fig. 16), and, in places, cleavages clearly indicate four stages of deformation in a single outcrop. It should not be too surprising, then, that some complexities appear in the overall metamorphic pattern.

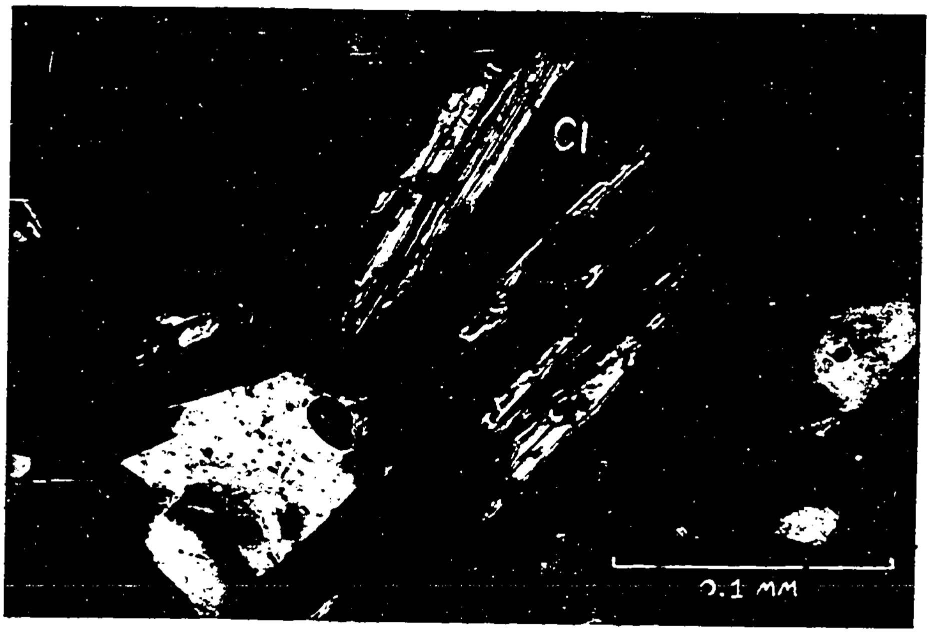

Figure 14. Same specimen as in Fig. 13. Biotite retrograding to chlorite (Cl), parallel or subparallel to cleavage. Nicols crossed.

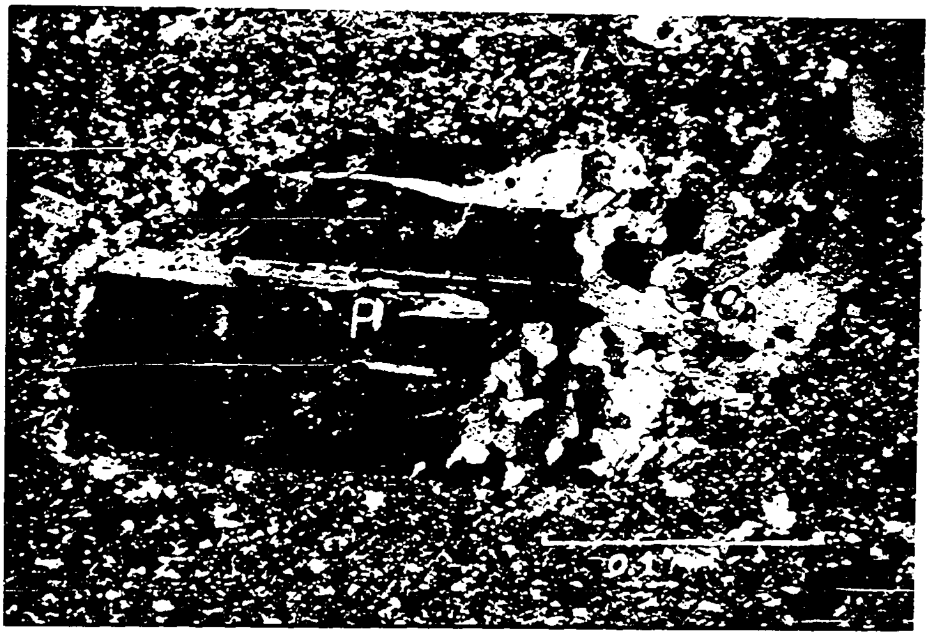

Figure 15. Smutty Hollow member, falls above Ogontz Lake: alteration of large plagioclase (probably andesine) grain (P) to carbonate (Ca). Nicols crossed.

Figure 16. West Bath member, one mile west of North Monroe Church: large plagioclase crystal offset along a microfault. Nicols crossed.

Proposed Stratigraphic Revision

Difficulties cropped up from the beginning in trying to decipher the internal stratigraphy of the Ammonoosuc formation. As rock types were mapped out, in location after location a mirror-image pattern emerged in the vertical sequence: mafic greenschists at the bottom, near the Albee contact; then intermediate, calcareous massive and schistose rocks; then felsites in the middle, usually quite massive; then more intermediate bluish schists; and finally, near the Partridge contact, more mafic greenschists that in places seemed gradational into the dark green and black slates of that formation (this being, of course, a composite section, all units not being present everywhere). In addition, it was noticed that the rocks at the upper and lower contacts of the Ammonoosuc formation were similar in most places: black slates, often with siliceous materials and admixtures of coarser metasediments.

The contacts themselves can be seen only at a few key localities. one of these is on a small knob 2.1 miles south-southwest of the West Bath school site, just south of the type area of the West Bath member, where the Ammonoosuc-Partridge contact is exposed (Fig. 17, location A). The Partridge here is a distinctive black slate with small (about 1 mm. or less across) grains of pyrite, and the Ammonoosuc is a lumpy blue schist of the typical West Bath sort. This contact may be traced discontinuously across some low hills to the north, to an abandoned road which crossed Gardner Mountain to Carbee school. According to the map of Billings (1937), the entire Ammonoosuc section should be crossed in little more than a half mile traverse along the eastern section of this road. Starting from its eastern entrance and working west, the rock

Figure 17. Base maps: Littleton (1931), Moosilauke (1932), Woodsville (1941), and St. Johnsbury (1945) quadrangles, USGS.

Figure 18. Base maps: Littleton (1931) and Moosilauke (1932) quadrangles, USGS.

types are: black slate, West Bath schist, Mullikin Brook felsite, West Bath schist again, and finally, on the road and even better in the woods south of the road, a black slate with small pyrite grains, identical to the one on the small knob at the Ammonoosuc-Partridge contact to the south. This second black slate, however, is mapped Albee (Billings, 1937). A somewhat similar sequence is seen in Moulton Hill Brook, less than one half mile from its junction with Teter Meadow Brook (Fig. 17 , location B). Here, the order of rock types across strike is black slate (Partridge), Lyman greenschist, Mullikin Brook, Lyman greenschist, and black slate (also Partridge); some of the massive Smutty Hollow member mantles the Mullikin Brook outcrop on the north.

Another key contact location is to the north, at the Albee-Ammonoosuc contact along the road about one mile west-northwest of Partridge Lake (Fig. 18 , location C). Just south of the road to the east of the contact, near a small lake in the middle of the Ammonoosuc outcrop area, is a typically massive Mullikin Brook felsite. Approaching the contact, one encounters, in order, West Bath schist, Smutty Hollow, and, just to the south at the contact, Lyman schist. The rock type on the Albee side of the contact is black slate. This slate becomes progressively interbedded with quartzites further to the west, and disappears within about 0.6 miles of the contact. A similar sequence can be seen along the abandoned road just south of this location (Fig. 18, location D). Other important localities are north and south of Partridge Lake. To the north and east, the Smutty Hollow member is abundant; to the south, it is largely absent, and West Bath blue schists are in direct contact with the Lyman member, which in turn is in contact with the black slates of the Partridge. It is here (Fig. 18, location E) that the contact between Lyman member and Partridge formation appears particularly gradational.

It would appear from a study of these key areas (as well as many other, less well documented ones) that either the upper half of the Ammonoosuc formation is a mirror image of the lower, a symmetry that extends at least partly into the formations above and below, or that the internal stratigraphy given earlier in this chapter is correct, and that the black slates at all these contacts belong to the Partridge formation. An indication of which of these alternatives is the more likely might be found in some very important work to the south. J.B. Hadley (1942), mapping the Mt. Cube area for the first time, found in the towns of Piermont and Orford what appeared to him to be the bottom of the Albee formation and the top of the next older formation, which he named the Orfordville. Lyons (1955) and Chapman (1942, 1952) followed this stratigraphy (Lyons with some revisions) in their work south of the Mt. Cube quadrangle. It is significant that the lowest part of the Albee, which Hadley named the Piermont member, consists mostly of dark schists, and that the Orfordville has a complex internal stratigraphy which includes black slates, quartzites, and volcanics. It should not be surprising, then, that when Thompson remapped much of the Claremont and Hanover quadrangles (in Thompson et al., 1968), he should have discarded the Orfordville as a separate, older, formation, and split it up instead into the familiar, and younger, formations which Billings had established to the north. The type area of the Orfordville in the Mt. Cube quadrangle has not yet been remapped, but it seems likely that it will eventually share the fate of its southward extension. Interestingly, this whole revision was foreshadowed over a decade ago by Cady (1960, p. 552).

Not only does a unit older than the Albee evidently fail to appear south of the Mt. Cube quadrangle, but the Albee itself is missing. In the most recent mapping, the Ammonoosuc is the oldest stratified unit, underlain only by the gneisses of dome cores. A look at Billings' (1956) map of New Hampshire will show that the Albee has never, in fact, been mapped very far to the south of the Gardner Mountain area. In an area of the structural complexity of southwestern New Hampshire, there are only two convincing reasons why the Albee formation should not have been mapped: a.) it is not present; and b.) it has not been recognized because it is stratigraphically in the "wrong" place. The question of the missing Albee formation has never been attacked directly, but the first answer seems at first glance to be the more conservative. Still, the disappearance of a formation of mixed metasediments (including many pelites) of such thickness over such a relatively short distance along strike would not appear to be a very attractive answer if a suitable alternative were presented. This is more especially so since the mechanism formerly given for its disappearance--cutting out by the Northey Hill thrust fault (Lyons, 1955)--has been largely discredited by the recent mapping (Cady, 1969, p. 94). The alternative reason will therefore be examined.

Both Eric and Dennis (1958) and Johansson (1963) map belts of quartzite within the Albee formation to the north and northeast of the Gardner Mountain area (Fig. 1). That of Eric and Dennis is directly on line with the band of striking white quartzite which holds up the main ridge of Gardner Mountain, and is evidently a continuation of this same quartzite to the north of the Connecticut River. Like the Gardner Mountain quartzite, it is a prominent ridge-former. Johansson's belt is to the east, still parallel to the regional strike; it has the same long, narrow sort of outcrop pattern and is also marked by a prominent ridge line. In short, this quartzite, originally mapped as part of the Albee formation, has a great resemblance to the Clough formation as that formation appears to the south.

Certain other minor data from previous work can also be collated to bear upon the problem. Johansson (1963), for example, finds that the volcanics in his Partridge rocks are soda-rhyolite tuff, the same as the rocks at his Albee-Ammonoosuc contact area, and states that "the strong similarity of the pebbles and cobbles in the Clough to the Albee quartzite strongly suggests that they were derived from the Albee"(p. 31), an observation made by others as well. Eric and Dennis (1958) note that "green slate is confined to the extreme upper part of the Albee in the chlorite zone" (p. 16), and their description of this slate, despite the outward color difference, is very similar to that of some of the Partridge slates in the Gardner Mountain area. Another point which might easily be overlooked is that the zone of concentration of mafic dikes and sills shown on the maps of Billings (1937), Eric and Dennis (1958), and Hall (1959) is cut off very cleanly by the outcrop pattern of the massive quartzite, a fact which might indicate a younger age for the quartzite (although the conclusions of Billings and White, 1950, would appear to deny this). A similar occurrence can be observed on the power transmission line between Hunt's Mountain and Black Mountain, near the South Paddock mine (Fig. 17, location F), where a small outcrop area of black slate is cut by a mafic dike, but the surrounding rocks are not.

There is also the previously mentioned point about the apparent inversion of mafic and felsic rocks within the Ammonoosuc. An alternative would be to consider the Ammonoosuc to be the oldest formation exposed in the area. Then, only the upper part of the formation, dominated by the Mullikin Brook felsites, would be observed; the more mafic volcanics presumably exist beneath them, and the overlying greenschists are a relatively thin and possibly local sequence compared to the formation as a whole. The picture which results from this view is summarized in Table 5, a comparative graphic representation of Billings' stratigraphy and the proposed revision of this study. Column A shows the vertical sequence of rock types which corresponds to the stratigraphic interpretation of Billings (1937); column B is that which corresponds to the interpretation of this study. It can be seen that the black slates at the top of Billings' Albee formation are considered to be Partridge in this study, and the central white quartzite is thought to be Clough. This leads to a consideration of the following sequence as the stratigraphic column in the vicinity of the Gardner Mountain area:

Littleton formation (Devonian)
Fitch formation (Silurian)
Clough formation (Silurian)
Albee formation (Upper Ordovician?)
Partridge formation (Middle Ordovician)
Ammonoosuc formation (Middle Ordovician)
  Lyman member
  Smutty Hollow member
  West Bath member
  Mullikin Brook member

TABLE 5

COMPARISON OF STRATIGRAPHIC INTERPRETATIONS

BILLINGS, 1937	COLUMN A	COLUMN B	THIS PAPER
Fitch and Littleton Formations			Fitch and Littleton Formations
Clough Formation	Quartz conglomerate with mica schist	Orthoquartzite	Clough Formation
Partridge Formation	Black slate		
		Mixed metasediments	Albee Formation
	Mafic volcanics		
	Intermediate volcanics	Black slate	Partridge Formation
Ammonoosuc Formation	------Felsites------	Mafic volcanics	Ammonoosuc Formation: Lyman Member
	Intermediate volcanics	Intermediate volcanics	Ammonoosuc Formation: Smutty Hollow and West Bath members
	Mafic volcanics		
	Black slate		
Albee Formation (bottom not exposed)	Mixed metasediments	Felsites	Ammonoosuc Formation: Mullikin Brook Member
	Orthoquartzite		(bottom not exposed)

Implications of the Proposed Revision

The effects which may be expected from this sort of revision on the geological thinking about a region may be divided into two sets: those on the immediate area and those on the region outside the area. In this case, the proposed revision must necessarily have a great effect only on a relatively small area, because this area is somewhat geologically isolated. The Ammonoosuc fault, the Monroe Line, and some large intrusive bodies to the north between them tend to greatly limit opportunities for direct tracing of units continuously from the enclosed area to outside areas. It should be emphasized, then, that the placing of the Albee formation above the Partridge in the Gardner Mountain area does not necessarily imply that what has been mapped Albee elsewhere, as the unit below the Ammonoosuc stratigraphically, belongs in the higher position, with all the attendant structural revisions such a move would involve.

At the same time, certain adjustments and reevaluations will be necessary if this revision of stratigraphy is accepted. First, Albee Hill, in the north of the Gardner Mountain ridge, is the type locality for the Albee formation, so some change in nomenclature for rocks which are in fact older than the Ammonoosucs will be desirable. In addition, there are problems in New England geology for which the present revision may prove useful. One of the most important of these is the Monroe Line problem, which has hindered regional correlation and resisted attempts at solution for decades. Cady (1960) discusses the question of whether the Monroe Line is more likely a fault or an unconformity. If an unconformity, he reasons, it would have to be an unusually deeply penetrating one according to the old stratigraphy, and "such a profound unconformity would be unnecessary if it could be shown that the Orfordville and its associated volcanic rocks are facies of the Albee and Ammonoosuc" (p. 552). He then seems to lean toward the fault interpretation, but notes that "in view of...regional relationships, and because the only reported exposure of the contact is that north of Monroe, the evidence for a fault in other than the type locality is primarily stratigraphic. Therefore, demonstration of the thrust depends upon the vicissitudes of stratigraphic interpretation" (p. 552). The stratigraphic interpretation upon which the Monroe Line was based has already been altered to the south, and the purpose of this chapter is of course to alter it in the Gardner Mountain area. The question of the nature of the Monroe Line is thus open to new interpretation. This question will be pursued in the next chapter, and some other problems of regional geology upon which the stratigraphic revision here proposed may have an effect will be mentioned in the final chapter.

Of more immediate concern are the effects of this revision upon the geology of the study area and its vicinity. Most of these effects are structural in nature, and will be covered in the next chapter, but one question of a stratigraphic nature remains. Johansson (1963) states that in the Lunenburg-Brunswick-Guildhall area, Vermont, the Meetinghouse slate lithology is variable, and not at all distinct from the Partridge lithology. This is true in the Gardner Mountain area as well, and it can be seen that the Meetinghouse is included in with the Partridge in Plate 1. The correlation is tentative, but its confirmation would provide a good key for regional correlations. It might be argued that the zone of mafic dike concentration cited above in support of the revised stratigraphy separates the Partridge from the Meetinghouse, but in fact mafic dikes can be seen in the Meetinghouse just north of the town of McIndoe Falls, Vermont, and Hall (1959) shows the dike zone overlapping the Meetinghouse further to the north.

Implications of the revised stratigraphy on structural interpretation will naturally be profound. For one thing, the idea of a relatively simple anticlinorium under Gardner Mountain (Billings, 1937) is evidently no longer tenable; if anything, with a Silurian core, Gardner Mountain would be a synformal mountain under the proposed stratigraphy. The next chapter will deal in detail with the geologic structure of the area as seen in the light of the new stratigraphic interpretation.

CROSS-SECTIONS:

First Alternative

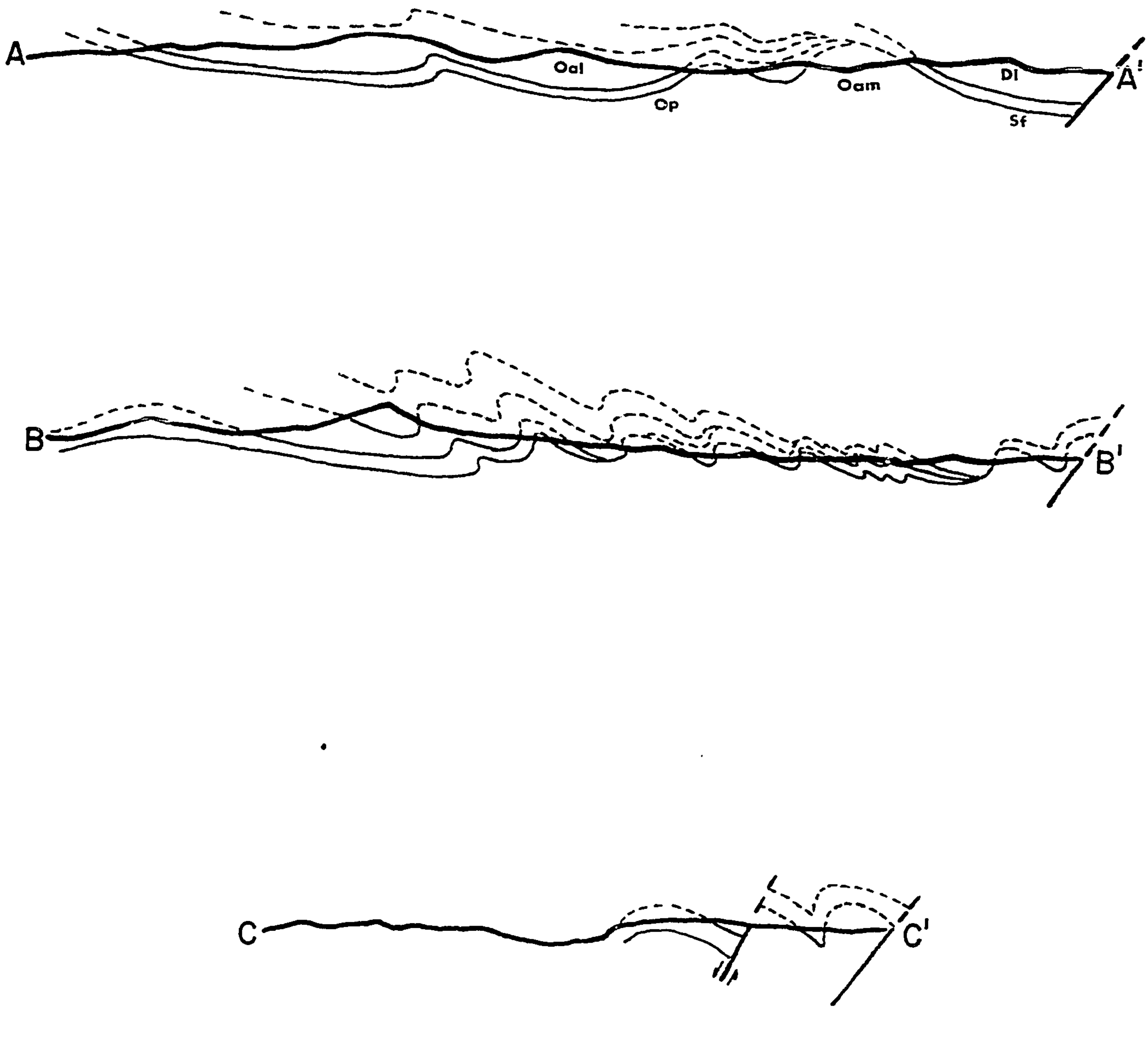

Figure 19.

CROSS-SECTIONS:

Second Alternative

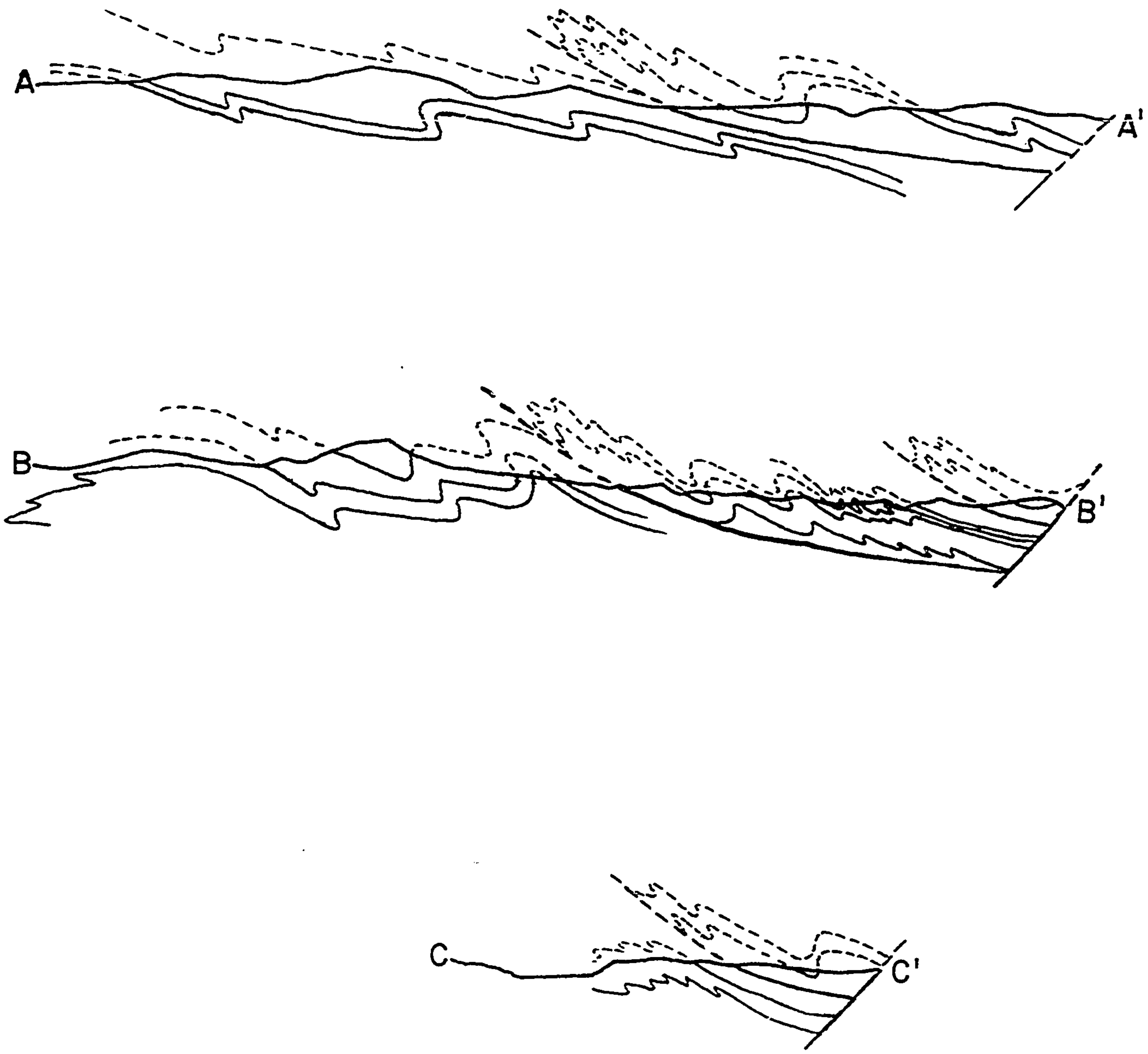

Figure 20.

STRUCTURE

Observations throughout the Gardner Mountain area indicate that the large majority of minor folds are asymmetric, overturned, or even recumbent toward the west. It would therefore appear that possible alternatives for a structural interpretation are immediately restricted to westward-facing major folds of some sort, and naturally the stratigraphy imposes further restrictions. Keeping in mind the work of Thompson et al. (1968) not so far to the south, two major sets of structural interpretations can be considered: one set involves regular major folds asymmetric toward the west, and the other involves some kind of nappe structure, with or without associated thrusts or slides. Generalized representatives of the two sets of possibilities are shown in Figures 19 and 20; these are merely hypothetical cross sections to illustrate the kinds of alternatives which are available. The decision of what structural interpretation is best for this area must be based on more quantitative structural techniques.

Structural Analysis

In an area of multiple deformation and isoclinal refolding of older cleavage surfaces, it soon becomes evident that the sort of data which is useful for the interpretation of structurally simpler areas--individual strike-and-dip readings on scattered outcrops--is of extremely limited value. It has been a common practice in the past to record average, typical, or overall strikes and dips for one or more sets of foliations or lineations at a particular locality or outcrop area, in order to simplify the often bewildering variations which occur more often than not even in single outcrops. This simplification is intended to bring some order to the diverse data in the field, where it is best seen, for later ease of structural interpretation; however, in an area such as this, it is often the variations themselves which give the most valuable clues to the structure. In order to make use of these clues, a program of detailed, statistical structural analysis is imperative. This involves the plotting of a large number of observations, preceded by a careful and accurate sorting out of all structural elements in the field. It was decided to utilize these methods in analysing selected outcrops and outcrop areas as an aid in deciphering the geology of Gardner Mountain. The locations selected were: a large road outcrop just north of Woodsville (Fig. 17, location G); a cow field one half mile north of this (Fig. 17, location H); in the Connecticut River below the dam at Monroe (Fig. 17, location I); and a five mile long traverse along the power transmission line across Gardner Mountain east of Monroe. The latter has been divided into a northern and a southern section at the Lyman-Monroe road, and, for the data on minor fold axes only, the northern section has been further divided into two subsections (Fig. 17, locations J, K, and L). The data of the structural analysis--locations and plots for the various structural elements--is summarized in Plate 2.

There are two major cleavages in the Gardner Mountain area, the relationship between them the same as that described by White (1949) and White and Billings (1951). The older cleavage (S_1) is a schistosity that is at least roughly parallel to the bedding (S_o), and presumably was developed during an early period of isoclinal folding (F_1); it has been folded isoclinally and is now obscured in most places by an axial plane slip cleavage (S_3). There are in addition to these major cleavages two others (S_2 and S_4); these are, however, distinctly subordinate to the S_1 and S_3, and since they can only be observed in a very few places, they have not been utilised in this structural analysis.

The S_1 cleavage is best observed in the outcrop near Woodsville and below the dam at Monroe, where it is wrapped around minor fold noses in a striking fashion (Fig. 21). At both of these locations, and indeed wherever the two major cleavages can be seen together, the later cleavage is clearly seen not to be entirely parallel with the axial planes of the folds, but to be rotated somewhat toward the F_3 fold nose (Fig. 22). It may be noted in this connection that the maximum in each of the stereonet plots--for both S_1 and S_3--in Plate 2 is binary. This is interpreted essentially the same way for both cleavages: for S_1, the two maxima represent measurements on either limb of minor (F_3) fold sets; for S_3, since the cleavage planes on either limb tend to "toe in" toward the nose of the F_3 folds, the effect is much the same. It should also be noted that for many of the plots, one of the maxima in a pair is distinctly higher than the other. This is interpreted as a sampling bias which reflects asymmetry in the minor folds. Statistically, in other words, one of the limbs in a set of minor folds was measured more often than the other because it is longer than the other, and thus more often exposed. Of course, such a bias can also be introduced by topography and other factors, but statistically these will tend to be

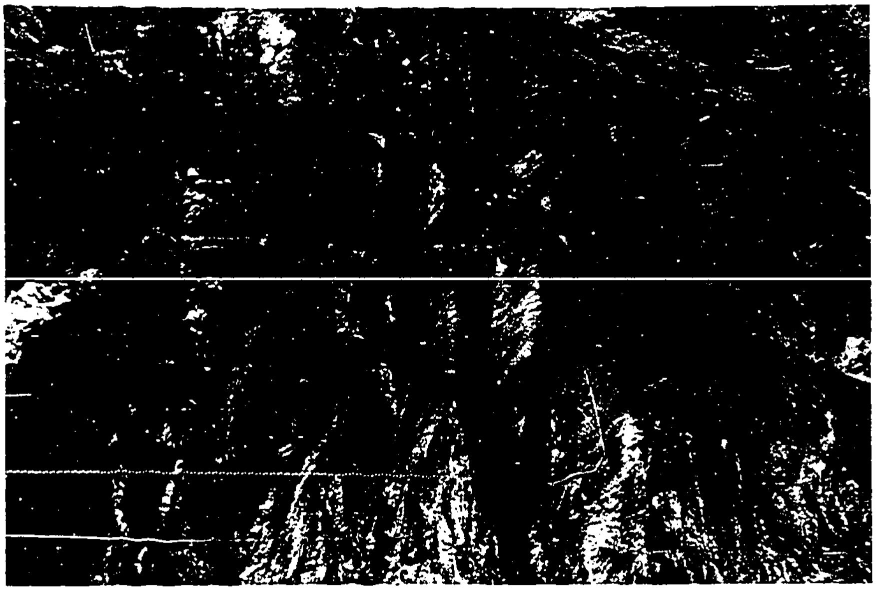

Figure 21. Cleavage folds under the dam at Monroe. S_1 is wrapped around fold noses; S_3 is approximately parallel to axial planes. S_2 visible as lineation over fold noses.

TOP

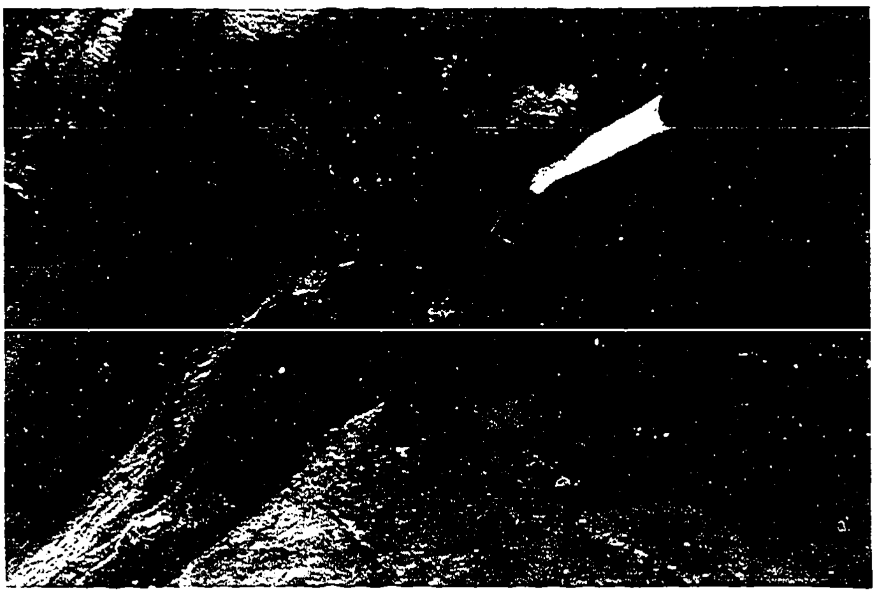

Figure 22. Minor fold near Woodsville. Note relationships between axial plane, left limb orientation, and S_3 cleavage. Right limb is partly sheared off. Surface of exposure of fold (vertical) is plane of S_4.

cancelled out, and care was taken to ensure as random a sampling as possible

Although enough direct measurements of minor cleavage fold axes and axial planes could be made in some places to justify a stereonet plot, it was felt that a more accurate picture of these structural elements could be obtained by calculation on a Wulff net, using the intersections of the limbs represented by cleavage maxima. In addition, it was thought that data calculated in this manner might give a definitive clue as to which cleavage was being observed in a location where both could not be seen. These data--cleavage maxima, observed axial plane and axis maxima, and calculated axial plane and axis maxima--are given in Table 6. An equality sign is shown where there is no significant difference in the intensity of the maxima of a cleavage in a locality. It was considered that the orientation of the calculated cleavage fold axes, in particular, would give a good indication of the identity of the cleavage. However, on Table 6, comparing the axis orientations of the S_1 and S_3 at Woodsville, where they are easily identified, to those along the power transmission line, where only one cleavage is visible, gives no real indication as to which set the power line cleavage belongs. A possible solution is suggested by the orderly change in axis orientations observable on Plate 2; axes tend to plunge gently northward in the northernmost section of the power line, are nearly horizontal in the center section, and plunge distinctly southward in the southern section. This trend continues southward to Woodsville, where the southerly plunge is so steep as to be almost vertical. This is evidently a manifestation of a later broad cross-folding with northwest-trending axes, which has

TABLE 6

PRESENT ORIENTATION

LOCATION	CLEAVAGE		OBSERVED		CALCULATED	
	DOMINANT	SUBORDINATE	AXIAL PLANE	AXIS	AXIAL PLANE	AXIS
POWER LINE (N)	020, 52E ≠	011, 59E	008, 69E	011, 16N	016, 55E	167, 35SE
POWER LINE (C)	020, 52E	011, 59E	008, 69E	013, 8N	016, 55E	167, 35SE
POWER LINE (S)	055, 58S	029, 57E	004, 80E	198, 48SW	042, 57E	136, 56SE
COWFIELD	046, 82S	089, vert.			069, 86S	089, 78E
WOODSVILLE (S_1)	056, 89S	083, 79S	068, vert.	240, 75SW	069, 84S	235, 68SW
WOODSVILLE (S_3)	030, 73E ≉	076, 80N			053, 87S	058, 58NE
MONROE DAM (S_1)	050, 65N	015, 70W	074, 83S	252, 17W	033, 67W	326, 65NW
MONROE DAM (S_3)	323, 80E ≠	311, 81N			317, 80E	052, 80NE

TABLE 7

ROTATION TO HORIZONTAL ABOUT A N55°W HORIZONTAL AXIS

LOCATION	CLEAVAGE			OBSERVED		CALCULATED	
	DOMINANT		SUBORDINATE	AXIAL PLANE	AXIS	AXIAL PLANE	AXIS
POWER LINE (N) (18)	033, 50E	≠	021, 54E	014, 62E	012, horiz.	027, 52E	148, 47SE
POWER LINE (C) (8)	026, 50E		016, 56E	011, 66E	013, horiz.	021, 53E	161, 40S
POWER LINE (S) (49)	020, 55E		006, 73E	006, 74W	207, horiz.	013, 64E	175, 31S
COWFIELD (76)	030, 77E		053, 38S			041, 58E	205, 20S
WOODSVILLE (S_1) (76)	039, 69E		035, 41E	044, 58E	221, horiz.	037, 55E	041, 6NE
WOODSVILLE (S_3) (76)	018, 89W	≉	058, 54S			038, 72E	198, 41S
MONROE DAM (S_1) (21)	058, 72N		024, 64W	070, 70S	250, horiz.	041, 68W	278, 63W
MONROE DAM (S_3) (21)	322, 80W	≠	308, 87N			315, 83NW	311, 48NW

also been noted in Vermont. The axis of the broad arch in this area has been estimated to trend about N55°W; as will be seen, a variation of up to about 20° either way from this figure will make no essential difference to the results. It is also assumed that the cross-folding is at least approximately horizontal. A more informative body of data might thus be obtained by reconstruction of the folds to their orientations before the later cross-folding. This can be accomplished by rotating all the data at each location in the sense and by the angle necessary to bring the calculated minor fold axes maximum at that location to horizontality, when rotated about an axis oriented N55°W. This assumes, of course, original approximate horizontality of the minor fold axes, a reasonable enough supposition. The results of these rotations are given in Table 7, with the angle of rotation for each location listed under the location name. It can be seen immediately from Table 7 that the calculated minor fold axis orientations on the power line correspond much more closely to the S_3 than the S_1 orientations at Woodsville, a result which might have been expected from relationships in the field. Moreover, a continuous clockwise swing in strike from north to south is evident, from 148° in the northernmost section of the power line to 198° near Woodsville.

Using the ideas on the relationship of unequal maxima to minor fold asymmetry outlined previously and the data of Table 7, drawings of fold senses at the various locations have been made. Figure 23 shows the fold senses as they would appear in horizontal projection (i.e., in the plane of the earth's surface). Figure 24 shows the same folds as seen in the down-structure view for each fold; these drawings are accompanied

FOLD SENSES CALCULAT

FROM S_3 CLEAVAGE

As seen in plane of
erosion surface

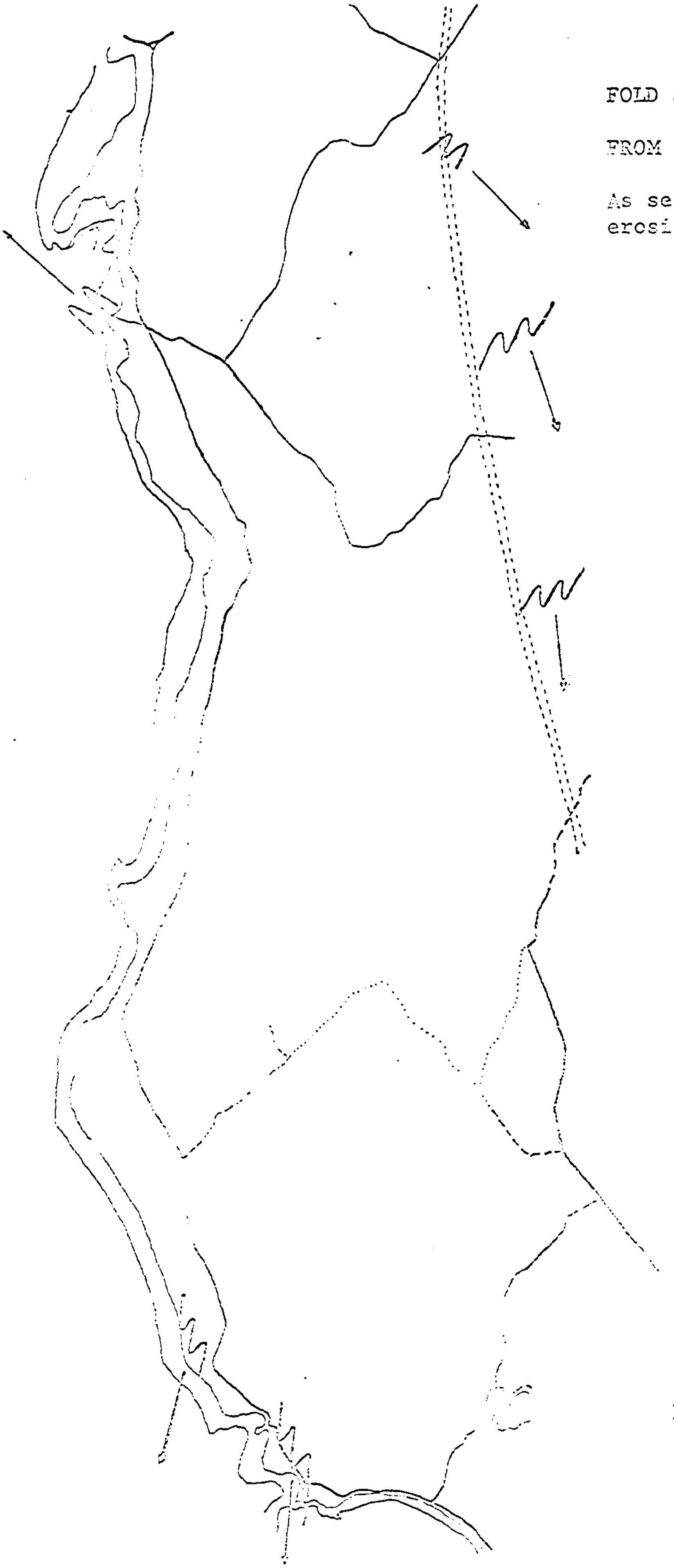

Figure 23

FOLD SENSES CALCULATED

FROM S_3 CLEAVAGE

As seen looking
down-structure

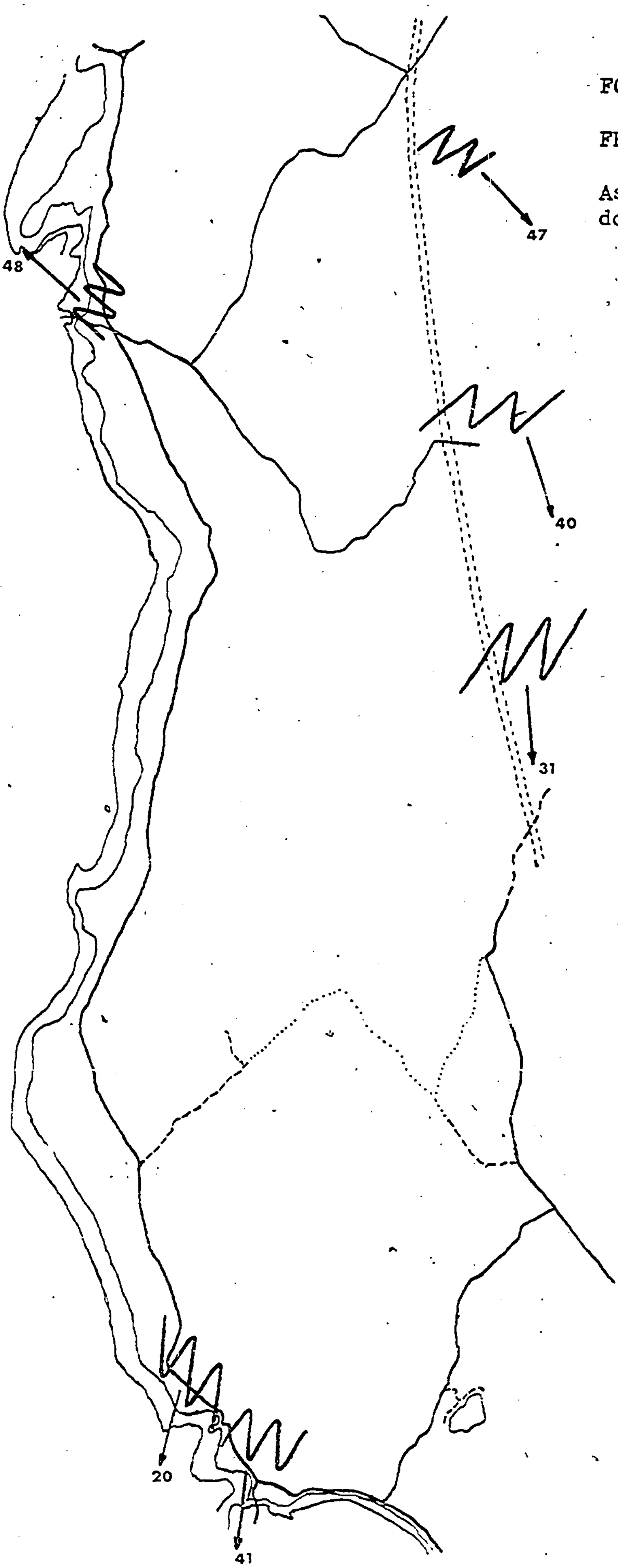

Figure 24

by an arrow representing the orientation of the calculated axis maximum at that location, the drawing being the form one would see looking at the calculated fold directly down the arrow. In this manner, it is hoped that the same result has been achieved as would be gained by direct observation of minor fold senses in a structurally simpler terrane.

Interpretation of the Structural Analysis

The important point to observe in interpreting the structural data is that, in accordance with the techniques of the previous section, the relationship between the cleavages and the bedding is a direct one. That is, since the S_1 cleavage is approximately parallel to bedding, it can be expected that where that cleavage can be seen folded, the bedding, could it be seen, would be folded in much the same manner (except, of course, at the F_1 fold noses, which are almost never seen). At the same time, the fold senses calculated from the S_3 cleavage maxima, as explained above, will also be the same as the fold senses of the bedding and the S_1 cleavage, even though the actual orientation of the S_3 cleavage planes will be somewhat different from that of the bedding and S_1 cleavage planes at practically any given point. This observation provides the leverage for the following interpretations.

The presence of a number of major recumbent folds only thirty miles to the south of Gardner Mountain (Thompson et al., 1968), and the possibility of another just to the west (Goodwin, 1963; Ern 1963), in Vermont, necessitates a consideration of the sort of structure represented by Figure 20 in determining which structural pattern best fits the available data. In this case, the positive identification of a nappe is made more difficult by the fact that an inverted stratigraphic sequence has not been observed within the study area; therefore, if a nappe is present here, only the normal limb is exposed. However, a rather distinctive minor fold pattern should be expected, from development of digitals along this normal limb. Specifically, for a nappe with the westward translation which would be expected from the work to the south and from paleogeographic considerations which will be mentioned later, the minor folds associated with the nappe's normal limb should be almost all distinctly asymmetric or overturned toward the west. That this is in fact the case along most of the power line can be seen from Figures 23 and 24, and also from the field drawings of minor folds on Plate 2. Also, most of the dips of both cleavage and bedding on Gardner Mountain itself, particularly along its crest and on its eastern slope, are easterly, and at a much lower angle than dips in the area as a whole tend to be; this can be clearly seen on the older maps (Billings, 1937; White and Billings, 1951). In view of the foregoing discussion, this data would suggest minor folds asymmetric toward the west.

It must also be significant that the fold patterns in the northernmost section of the power line and near Woodsville are nearly symmetrical, as derived from the data of Table 7. This may be compared to the older maps, on which the strike-and-dip symbols west of the crest of Gardner Mountain show a much less uniform pattern than to the east, with the cleavage mostly vertical, or nearly so, and the bedding at diverse orientations, evidently reflecting a major fold closure. These data are difficult to reconcile with a structural interpretation similar to the one illustrated in Figure 19, regardless of which stratigraphic sequence--

established or proposed--is used. It is apparent that the asymmetric minor folds occur on the limb between the bands of Albee and Ammonoosuc; this is precisely the opposite of what would normally be expected. On the other hand, the same data may be made to fit into the pattern of a deformed nappe very nicely. According to this interpretation, minor folds which, being associated with the normal limb of a major recumbent fold, are asymmetric toward the west, will be rotated in a clockwise manner (looking north) on the east limb of an uplift formed when the nappe is shortened during deformation. In this case, the anticline which has deformed the original nappe structure is shown by the outcrops of Ammonoosuc northeast of Monroe and north of Woodsville; it can also be seen on the map of White and Billings (1951) that cleavages dipping at relatively low angles to the east occur in the structural low between the two Ammonoosuc outcrop areas.

The argument as so far presented is thus self-reinforcing. If the Ammonoosuc is the oldest formation present, its appearance near Woodsville and Monroe represents material nearer the core of the nappe than surrounding units, and provides the anticline to account for rotation of minor folds, thereby fitting the nappe interpretation. Similarly, the presence of such a fold pattern as would result from the rotation of minor folds on the normal limb of a nappe with the subsequent formation of an anticline where the Ammonoosuc now outcrops supports the idea that the Ammonoosuc is the oldest unit in the study area. Self-consistency is a necessary condition for a valid argument, but unfortunately not a sufficient one; the existence of a nappe here cannot, therefore, be considered a proven fact. There is, however, another important way in which the nappe interpretation is helpful in deciphering the geology of this area.

One important detail of the structural analysis has not yet been mentioned: the minor fold pattern below the dam at Monroe is apparently spectacularly out of step with the rest of the geology of the area. It is, in fact, difficult even to imagine the sort of rotation which would be necessary to reconcile the Monroe data with the rest. The solution to this dilemma may be the same as that which could explain another, apparently unrelated, problem--the absence of the Albee formation in the southeastern half of the study area. It was mentioned in the previous chapter that the disappearance of a major unit of mixed metasediments within less than twenty miles along strike is a definite problem; disappearance of the same formation within three miles across strike in its type area is hardly less puzzling. The nappe interpretation provides an interesting idea to account for both problems: a tectonic slide.

Since the work of Bailey (1910) in the Scottish Highlands, this kind of fault has been well-known and frequently mapped in terranes similar to that of the northern Appalachians. More recently, Fleuty (1964) defined a slide as "a fault formed in close connection with folding, which is broadly conformable with a major geometric feature (either fold limb or axial surface) of the structure, and which is accompanied by thinning and/or excision of members of the rock-succession affected by the folding." Besides the criteria included in the definition, Fleuty considers it particularly characteristic of slides that the plane of movement is rarely marked by extensive crushing or brecciation, although these may occur locally or from later movement on the earlier structure. Also, in areas with a multiphase tectonic history, "sliding frequently but not invariably occurs during an early tectonic phase (p. 453). Subsequent metamorphism and further deformation can then make recognition of the slide more difficult.

There is nothing in this study area inconsistent with Fleuty's criteria, and much which follows them closely. Attenuation and deletion of the Albee and Partridge formations, and possibly even the Clough, can be explained by this mechanism as easily as by an unconformity, and the necessity for a very deep unconformity less than three miles from a locale in which no unconformity at all is observed is obviated. Brecciation was seen at only two places along the main fault trace through the center of the area: about one and a half miles northeast of the Woodsville covered bridge, and one half mile west of the old West Bath school site. Otherwise, the plane of the slide is not directly visible, although some mineralization appears along the trace. Generally, the best record of the slide consists of the stratigraphic discontinuities across the regional strike, as interpreted in Plate 3. It is probably significant that the slide plane is located largely within the structurally incompetent Partridge formation, which contains much graphite in places.

Naturally, the later events which deformed the nappe structure also warped the slide plane, the result being a very irregular surface which nearly coincides, in places, with the present erosional surface. Because the sense of any minor folding engendered by the sliding would be the same as that on the normal limb of the nappe itself, and because the subsequent structural history would be the same, one could not expect to identify material involved in the slide by structural analysis. An exception to this might be found near the toe of the slide, where considerable crumpling could be expected. This accounts very nicely for the otherwise practically unexplainable anomalous fold pattern below the Monroe dam. The tectonic slide interpretation thus has the virtue of explaining several diverse phenomena at once.

Implications of the Structural Interpretations

It is perhaps no coincidence that the Monroe dam outcrop, with its anomalous minor fold pattern, is located less than one fourth mile from the Monroe Line. As Cady (1960) points out, the only evidence for a structural discontinuity along the whole trace of this feature occurs nearby, just north of the village of Monroe (Eric and Dennis, 1958, p. 55). Cady (1969, p. 94) further points out that the Monroe Line probably exists only at this type locality, the stratigraphic problems which it was extended elsewhere to solve having largely disappeared. Putting the evidence presented in this study together with the results of recent mapping and regional syntheses, it would now appear that the Monroe Line may be the western margin of a tectonic slide which stripped off the Albee and parts of other formations several miles to the east. Again, this result cannot be considered proven conclusively until confirmed by further detailed mapping in that part of the region outside the study area, but the range of problems which it helps explain make it an attractive idea.

There appears to be little conflict between the structural interpretations of this study and the regional geologic picture as it is emerging in the most recent work. To the south, as has been noted, Thompson et al. (1968) have mapped three major recumbent folds, stacked one atop the other, which have been deformed by subsequent folding and gneiss dome formation. The oldest of these, the Cornish nappe, increases in size toward the north, whereas the middle one, the Skitchewaug nappe, reaches its greatest width in southernmost New Hampshire. This fact has led Rodgers (1970) to suggest a relationship between the Cornish nappe and a large recumbent fold which has been postulated in east-central and northeastern Vermont (Goodwin, 1963; Ern, 1963). Such a relationship might also apply to the Gardner Mountain nappe, a possibility which will be discussed in more detail in the final chapter.

Of the work to the south, that of Rosenfeld (1960, 1968) is of interest in connection with the behavior of carbonate rocks in the Gardner Mountain area. Plate 1 shows small outcrops of Fitch formation in several unexpected places, most strikingly in the large road outcrop just north of Woodsville. The emplacement of small carbonate bodies outside the larger contiguous masses of the formation to which they belong evidently involves considerable flowage during deformation. This is described on a larger scale by Rosenfeld, who documents intrastratal extrusion of an entire carbonate sequence; on a smaller scale, it could account for the lenses and veins of Fitch in odd places around Gardner Mountain. Similar flowage, though probably over much shorter distances, can be seen in interbedded phyllites of the Albee formation in the cow field one mile north of Woodsville. There is a possibility, of course, that the small bodies of carbonates referred to were never part of the

Fitch formation, but their appearance in the field is very strongly suggestive of Fitch, and flowage in such structurally incompetent material is not an unreasonable idea.

Implications of the structural interpretations to the east and northeast are less certain than those to the south and west. The roots of the Gardner Mountain nappe might be expected to be found among the large bodies of Bethlehem gneiss to the east, near the core of the Bronson Hill anticlinorium. This study, however, does not cover that area, and it is possible that the Ammonoosuc fault will greatly hinder structural correlation. To the northeast, mapping thus far shows no large recumbent structures, nor any pronounced asymmetry in minor folds to indicate they may exist (Green and Guidotti, 1968), but direct structural correlation is made difficult by intervening intrusive masses. Due north, in the Island Pond quadrangle, Vermont, a large nappe has been proposed by Goodwin (1963), but this is not on strike with the Gardner Mountain area and involves different units. For the present, then, this structural interpretation of the area is best viewed as an extension of recent work to the south, resting primarily on evidence found within the area itself.

Ages of Deformation

The large recumbent fold in this study area, like those to the south, apparently involves rocks of the lower Devonian Littleton formation. It would therefore appear that the events which produced deformation of the nappe and the later cleavage were phases of the Acadian orogeny. In view of this, the importance of the Acadian in this region, emphasized by Billings (1937) and others, is evident. At the same time, the possibility that the Taconic orogeny was also a major event in this area cannot be overlooked. The extreme importance of the Taconic in the Green Mountain anticlinorium, to the west, is well established, and work by Albee (1961) to the northeast indicates that the magnitude of the Taconic in the Boundary Mountain anticlinorium on the New Hampshire-Maine boundary may have "involved major deformation rather than just a tilting of the older rocks."

Stratigraphic evidence of Taconic movements is cited by Billings (1937) in the form of an unconformity which beveled formations older than the Clough in the Gardner Mountain area, although the interpretations of this study indicate the unconformity may not be nearly so pronounced as heretofore thought. This is not so unusual; Skidmore (1967) records a large belt in the Gaspe Peninsula, extending southward through New Brunswick, in which there is apparently no unconformity whatever. It would appear, in fact, from the synthesis of Pavlides et al. (1968) that the effects of the Taconic orogeny in this region are very spotty--some areas are rather intensely affected while others are scarcely affected at all. In the Gardner Mountain area, the Taconic orogeny was relatively unimportant, evidently, although the basal Clough conglomerate is stratigraphic evidence of some movement. The Acadian phases were at any rate the dominant events.

Other periods of deformation, although distinctly subordinate in importance to the Acadian and Taconic, may have affected the Gardner Mountain area. Riorden (1957) cites evidence for an early, pre-Taconic disturbance in southeastern Quebec which may have extended to northern

New England as well. More important, probably, are the Permian disturbances of the Appalachian Revolution, which, while relatively mild in New Hampshire, may have affected K-Ar radiometric ages (Zartman et al., 1970). Woodward (1957) has pointed out that the late Paleozoic folds in southern New York swing around to an east-west orientation across southern New England, cutting across the north-trending Taconic and Acadian structural elements. There may easily have been some effects in the adjacent region of northern New England, however, such as the broad, later, northwesterly cross-folding found in the Gardner Mountain area. The last orogenic period of importance to the area apparently left at least one major sign of its activity--the Ammonoosuc fault. This fault has for some time been considered a normal rather than a thrust fault (note Cady, 1969, Plate 1) because of regional relationships and the fact that younger rocks would be thrust over older along much of its length (although Billings, 1932, demonstrated the possibility of such a relationship). Also, none of the textural criteria for thrusting given by Balk (1952) have been observed near the Ammonoosuc fault. Finally, Rodgers (1970) notes that the south end of the Ammonoosuc fault almost connects with an established normal fault which forms the eastern boundary of the Triassic basin in northern Massachusetts, and makes the very reasonable suggestion that the Ammonoosuc could be a Triassic normal fault, even though its dip is rather low (about 40°) for such a fault. Rodgers makes a further point that the Ammonoosuc is the only well documented fault of appreciable size in that part of New England, concluding that the rocks were too plastic during metamorphism and deformation for failure. This is probably generally true, with the exception of tectonic sliding, which has commonly been found to occur under the plastic conditions of nappe formation.

It would appear, then, that orogenic events have left a mark on northern New England rocks from the Ordovician--possibly before-- to the Triassic. The sequence of deformational events at Gardner Mountain was probably the following: possible broad folding at the end of the Ordovician; development of a westward-moving nappe with associated tectonic sliding in response to regional uplift to the east during the Devonian (possibly contemporaneous with deposition of the upper part of the Littleton formation, which has in places some flysch-like aspects); tight folding and metamorphism, possibly in more than one stage, as a later and more intense phase of the Acadian orogeny; some disturbance in the Permian, possibly as a broad cross-folding with a northwesterly axis; and finally, formation of one large normal fault in the Triassic. In addition, Faul et al. (1963) have found age date evidence for a Jurassic disturbance in parts of northern New England, but no physical evidence of this has been reported in northern New Hampshire. The sequence of events given here is of course somewhat conjectural, but until further work in precise dating is done it can probably be accepted as a broad outline of the major events.

REGIONAL RELATIONSHIPS

Summary of Significant Work

Modern mapping in the quadrangles to the south of the Gardner Mountain area can be divided into two phases. The first was of course inaugurated by Billings'work, which provided the stratigraphic control for most of the region east of the Monroe Line. Mapping proceeded rapidly during the next two decades, with publications by Hadley (1942), Chapman (1939, 1942, 1952), Lyons (1955), and others. The culmination of this phase was included in a major work by Billings himself (1956). The second phase probably began with the discovery of the Skitchewaug nappe by Thompson (1954, 1956), and, buttressed by new structural ideas and methods, was continued by Rosenfeld (1960, 1965, 1968), Robinson (1967a, b), Dixon and Lundgren (1968), and numerous others. Much of the work of this phase to date is brought together in Thompson et al. (1968), but of course some problems remain and work in this second phase is continuing; it has been mentioned that the present study can be viewed as an extension of this phase toward the north.

Elsewhere in the region, progress has not been so rapid. To the northeast, this may be partly due to relative difficulty of access to many areas. Most of the work in this region to date has been of a reconnaissance nature, although more detailed mapping has been done by Hatch (1963), Green (1964, 1968), and some others. Much of the present knowledge of the Boundary Mountain anticlinorium (the northeastward extension of the Bronson Hill anticlinorium) and surrounding areas has been consolidated by Green and Guidotti (1968). In general, the work in the region seems to correspond more closely to the first of the two phases of modern mapping previously mentioned, involving thus far an effort to extend the stratigraphy of better-known areas to provide the control for more detailed mapping. However, recent work by Moench (1970) may signal an advance into the more sophisticated structural work typical of the second phase.

Also indicating a possible transition in geological thinking to the northeast may be the reevaluation of the present stratigraphy (essentially that of Billings, 1937) by a number of workers (Boone et al., 1970). In this connection, it is worthwhile to review some of the more detailed mapping in the region in the light of the proposed stratigraphic revision in the Gardner Mountain area. Green (1964, p. 57) shows four alternative structural interpretations for the Errol quadrangle, on the Maine-New Hampshire boundary. It is notable that the simplest interpretation, and that which fits the minor fold pattern best, is the one which corresponds to an inverted stratigraphic section for the pre-Silurian formations. This would, according to Green's map, give a synform plunging north-northeast in the central part of the quadrangle. Green, however, prefers the interpretation of a southwest-plunging anticline, even though a separate deformational stage to form the minor folds must then be postulated, since he reasonably considers the structural overturning of the section on a regional scale unlikely in the absence of evidence for major recumbent folding. Also, in the northwest corner of the Errol quadrangle, outcrop patterns lead Green to interpret the structure as "a shallow, north-northeast-trending syncline" (p. 47); however, his "top sense" observations chart (p. 48) indicates an anticlinal nose here. Some difficulties of a similar nature can be found in the work of Hatch (1963) and Green (1968), both using the same stratigraphic sequence.

It will be remembered that special care has been taken to emphasize the relative geological isolation of the Gardner Mountain area, and to indicate that the proposed inversion in sequence there does not necessarily mean adjustments are required elsewhere. At the same time, consideration of this proposal could not fail to spur reevaluation of stratigraphy in the geologically less well-known areas to the northeast, particularly where a similar revision would apparently simplify some existing problems.

In Vermont, despite the considerable amount of high quality work which has been done, progress has again not been so rapid as in southwestern New Hampshire. The primary reason for this is probably the lack of a stratigraphic sequence as well documented and established as that of Billings in New Hampshire. This, in turn, seems to derive from the lack of reliable organic data. Fossils have been reported in Vermont rocks by Richardson (1916, 1919), Richardson and Camp (1919), Currier and Jahns (1941), Doll (1943a, b), and Cady (1950), but in each case they have either been subsequently rejected as inorganic structures or have failed to provide the key for establishing a firm stratigraphy. The reported graptolite finds of Richardson in the Northfield and Waits River formations seemed very promising; as late as 1947 an eminent authority, Ruedemann, said of them: "There is no doubt in the writer's mind, since many have the distinct outlines of *Tetragraptus*, *Phyllograptus*, and *Climacograptus*..." that they were in fact graptolites (p. 63). Despite

Ruedemann's statement, dating the formations as lower to middle Ordovician, the supposed fossils have been written off as inorganic by apparently all contemporary workers. The organic nature of Doll's finds has also been questioned (White and Jahns, 1950; White and Billings, 1951). The discovery of presumed cup corals by Cady in the Waits River formation led to the placing of that formation below the Albee and Ammonoosuc (White and Billings, 1951) and some severe complications in regional correlations, but Cady (1960) later rejected the reliability of the find himself. As it turns out, only the Cram Hill formation (middle Ordovician) is fossil-dated with any degree of reliability.

The paucity of reliable fossil data in a complex terrane is largely responsible, in central and eastern Vermont, for what Cady has aptly termed "the vicissitudes of stratigraphic interpretation." There is no need to trace out the details of these vicissitudes in this paper. Suffice to state that the first phase of modern mapping probably began with the development of a stratigraphy in central Vermont by Currier and Jahns (1941), and that subsequent additions and revisions were proposed by Doll (1943a, 1951), Dennis (1956), and Murthy (1958). Paralleling this work were a series of structural interpretations of considerable insight and quality: White (1949), White and Jahns (1950), and White and Billings (1951). The major results of this first phase are succinctly stated by White (1959) in his reply to Murthy's proposed stratigraphic revision, and crystallized in the centennial map of Vermont (Doll et al., 1961).

White's summary makes it perfectly clear that the problems with stratigraphy in Vermont are not yet solved. This tends to explain why the second phase of mapping has proceeded thus far so uncertainly: that solid stratigraphic control provided by workers under Billings in the first phase period in New Hampshire is missing, and without it the mapping of complex and large-scale structures is exceedingly difficult. Nevertheless, a major recumbent fold in central and eastern Vermont has been suggested by Goodwin (1962, 1963), Ern (1963), and Woodland (1965), on the basis of stratigraphic convenience and structural feasibility. The work of Rosenfeld (1960, 1968) to the south on rotated garnets would appear to give substantial support to this interpretation, as noted by Rodgers (1970). As drawn by Goodwin and Ern in cross-section, the Monroe Line marks the intersection of the surface of the normal limb of this nappe with the present erosional surface.

It seems evident that the interpretations of this study must be of some importance to the correct assessment of the newer, and as yet unverified and undeveloped, structural interpretation in adjacent Vermont, and vice versa. There appear to be two main possibilities: that the Monroe Line represents the western limit of the Gardner Mountain nappe and the appearance of another (presumably older) to the west, in an arrangement similar to the "stacked up" nappes to the south; or, that the Gardner Mountain nappe is the same as the one mapped in Vermont, and the Monroe Line is only the western margin of material involved in the previously mentioned tectonic slide. The choice between these two possibilities must finally rest on correlations between the "Vermont sequence" and "New Hampshire sequence" rocks, which will in turn depend on, in large part, the establishment of the Vermont stratigraphic sequence. The Partridge formation has already been tentatively equated with the Meetinghouse of the "Vermont sequence" in this study, on the basis of lithologic similarities, but further regional studies will of course be necessary to confirm this as well as to establish a general correlation of the sequences. In the meantime, some support for the tentative correlation can be found in the fact that the nappes to the south all hinge on the Partridge formation. If the Vermont nappe is closely related to those in New Hampshire, as seems very likely, it is not unreasonable to suppose that the black slate on which it hinges might also be Partridge, or a correlative of the Partridge.

It was mentioned previously that Rodgers (1970, p. 104) considers the Cornish nappe most likely for the core of the Vermont recumbent structure, although the latter appears to be offset considerably to the west in terms of strike. The Gardner Mountain nappe might be a more likely candidate to relate with the Cornish nappe, but the intervention of the Ammonoosuc fault makes the relationship unclear. At any rate, there appears to be a good possibility that the nappe at Gardner Mountain and that in Vermont may be the same. If this is confirmed, and regional relationships indicate it might be, a structural continuity will have been established across the Monroe Line, which might lead directly to a stratigraphic continuity. The Meetinghouse and Northfield formations in Vermont have already been correlated in most modern interpretations, so confirmation of the Partridge correlation would establish a base for firm correlation of the entire section over most of the Connecticut Valley synclinorium. Spatial relationships of the features pertinent to the discussion of this section are illustrated by Figure 25.

SUPPLEMENTARY INDEX MAP

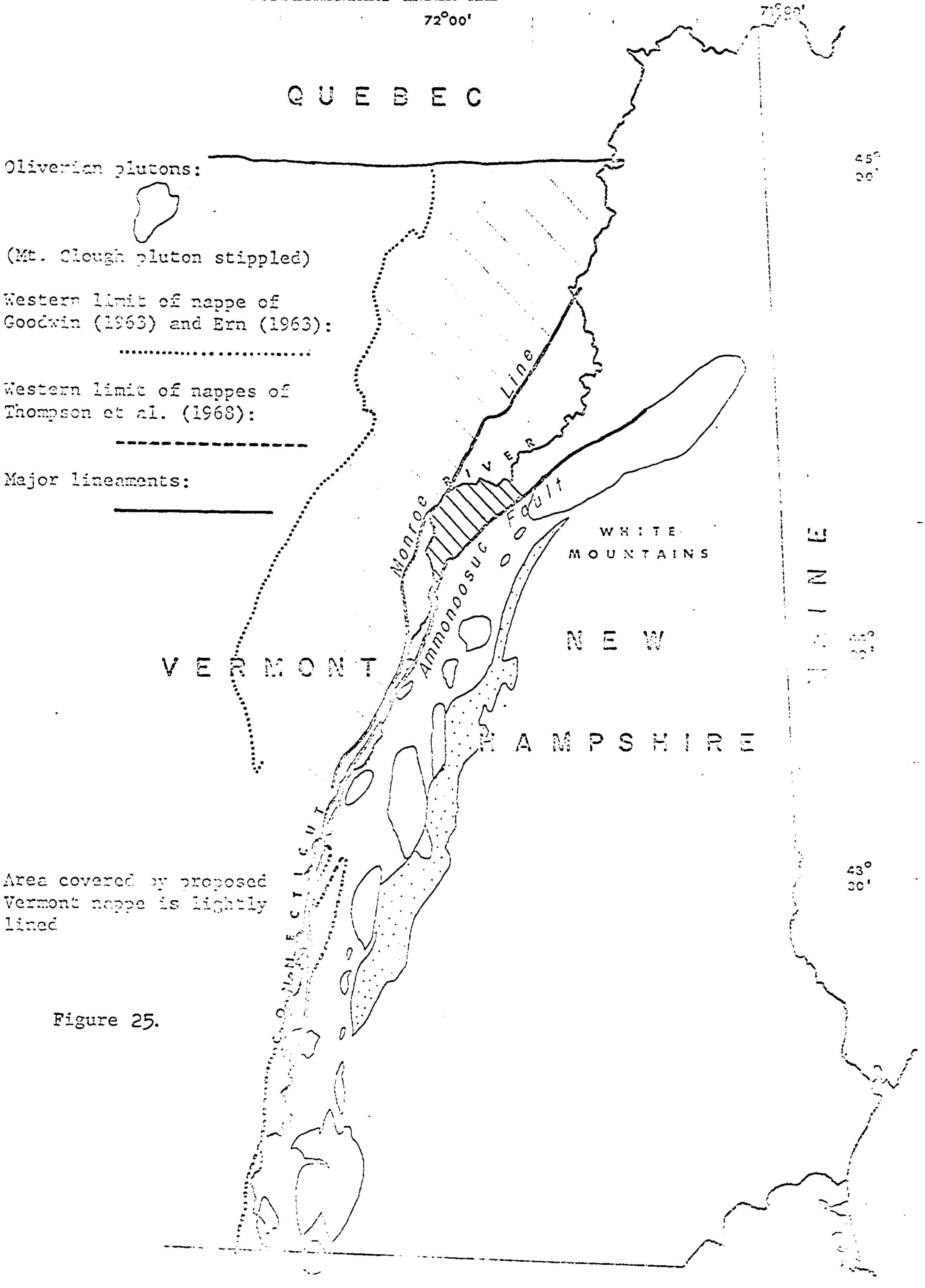

Figure 25.

Nappe Formation

A general appreciation of the tectonic and paleogeographic setting of the northern Appalachians has been possible for at least two decades. Cross-sections by Kay (1951) give a general picture of the geography of northern New England at the end of the Ordovician which, in its broad outline, is still largely held to be correct. In Kay's picture, the Gardner Mountain area occupies part of the northwest slope of a belt of volcanic islands, surrounded on either side by shallow seas. This picture of the geography of the Ordovician is greatly expanded by Berry (1968), largely on the basis of graptolites, but except for a period in the early middle Ordovician, the study area is still represented as lying in shallow seas just northwest of a persistent island arc. The paleogeography of the area during the Silurian and Devonian is described by Boucot (1968). The picture during these periods is considerably more complex, a fact reflected in the variable lithologies of post-Ordovician formations, particularly the Littleton, and in their variable thicknesses as well. One trend is evident, however, and that is the eastward migration of the volcanic belt, which during the upper Llandovery and Ludlow stages is located along the present New England coast. This correlates with Cady's observation (1968, p. 153) that the transition from miogeosynclinal zone to the eugeosynclinal zone moved southeast during the middle Paleozoic.

During the Silurian a land area existed at or just to the west of where Gardner Mountain is now; in the Devonian the situation, as shown by Boucot's maps, was much different. The western land mass disappeared after the Silurian, and a larger land area rose to the southeast of

Gardner Mountain and persisted throughout the Devonian. In the middle and late Devonian, then, during the time when nappe formation evidently occurred, the Gardner Mountain area was again located on the northwest slope of a major positive region. The geological setting was thus correct for formation of large recumbent folds on the western flank of the uplift, possibly as a large-scale version of the flowage folding discussed by Bain (1931). One of these folds, presumably, slid over what is now the Gardner Mountain area, where a section of its normal limb slid a few miles further downhill. If this interpretation is correct, that slide was to greatly increase the complexity of the stratigraphy of what was to be an important type area some 370 million years or so later.

Gneiss Doming and Instrumental Data

The relationship between the Oliverian dome gneisses and the overlying stratified rocks of the Bronson Hill anticlinorium has been a matter of speculation since the nineteenth century; Rodgers (1970), in fact, considers it to be the key tectonic problem in this belt. C.H. Hitchcock (1883) was the first to propose a direct genetic relationship between core rocks of the domes and the mantling metavolcanics, suggesting that the domes mark the positions of former volcanic islands, although he later (1908) changed his mind and considered the core gneisses to be younger intrusives. Billings (1956; Billings and Keevil, 1946) agreed substantially with the latter interpretation, believing the Oliverian rocks to be intrusives emplaced during an early phase of the Acadian orogeny. Recent work by Naylor (1969), however, has resulted in Rb-Sr age dates of 440 ± 25 m.y. for both the core rocks and the Ammonoosuc volcanics which mantle them. Naylor's conclusions, which are substantially the same as those of Thompson et al. (1968), are that the core rocks of the Mascoma dome, which he considers a typical Oliverian dome, "are part of a metavolcanic and intrusive complex which formed at about the same time as the (Middle Ordovician) Ammonoosuc Volcanics" (1969, p. 417). In general, then, he leans toward the view of a volcanic origin for the protolith of the core gneiss, a view fitting in both with Hitchcock's idea and, as Thompson et al. (1968, p. 217) point out, with the Ordovician volcanic archipelago of Kay (1951).

Naylor (1968) also notes the similarity in age and, with modifications which can be partly explained by different metamorphic histories, in composition between the Oliverian and Highlandcroft rocks. It can further be seen that the Highlandcroft is also mantled by Ammonoosuc volcanics in the Gardner Mountain area, specifically by the Mullikin Brook felsite member. To the north it is mostly mantled by the Albee formation, but in view of the stratigraphic interpretations of this paper, these rocks mapped as Albee might be younger than the Ammonoosuc, and mantling of Oliverian domes by units younger than the Ammonoosuc is not uncommon. Furthermore, Naylor notes (1968, p. 238) that the Mascoma and several other Oliverian domes contain small granitic plutons rather similar to the Highlandcroft material. He concludes that the Highlandcroft bodies might be geologically equivalent to the Oliverian domes, but separated from them by a regional stratigraphic facies boundary. Further light may be shed on this subject by recent instrumental surveys.

Surveys and appraisals of gravity anomalies in New Hampshire and

Vermont have been carried out by Bean (1953), Joyner (1963), Innes et al. (1967), and Diment (1968), and an aeromagnetic study has been done by Griscom and Bromery (1968). Negative Bouguer anomalies occur, as expected, primarily in connection with large felsic intrusive bodies. Of particular interest are the large negative anomalies, noted by Bean and confirmed by the other studies, through the Connecticut River valley. In particular he states (1953, p. 533) that "although a large negative anomaly appears to be associated with the Fairlee quartz monzonite, Diment reports that the trend continues to the northeast through the Woodsville quadrangle." One inference which might be drawn from these observations is that gneiss domes, unrevealed as yet by erosion, might exist at depth along much of this part of the Connecticut Valley. Griscom and Bromery (1968) have shown that the Oliverian domes to the south are accompanied by a distinctive high magnetic expression; an aeromagnetic survey in the Gardner Mountain area might thus be used to support this suggestion, made on the basis of gravity alone. At present, the idea of doming at depth in this area is little more than speculation, but it does raise the interesting possibility that a nappe-gneiss dome relationship similar to that described to the south might also exist in this part of the Connecticut Valley.

Summary of Conclusions

The main conclusions of this study are a modification of the stratigraphy of the Gardner Mountain area as proposed by Billings, and the concomitant development of a structural picture in closer accord with the results of modern detailed mapping in the regions adjoining the area. In connection with the first point, the wide belt of dominantly arenaceous rocks, originally mapped as stratigraphically beneath the Ammonoosuc volcanics, which underlies most of Gardner Mountain itself and has been mapped as a separate formation, the Albee, is considered in this study to be several younger formations. These are the Partridge slates and Clough quartzite, previously defined and mapped in this area and elsewhere, and an intervening formation with a mixed protolith of pelites and arenites, for which the name "Albee" is retained, this being the type area of the Albee formation as defined by Billings. The structural picture which is thought to fit this stratigraphic interpretation consists of a large recumbent fold, the normal limb of which is exposed in the present surface of erosion, and a tectonic slide which occurred in conjunction with the recumbent folding, and which may be inferred to be the cause of the Monroe Line.

It is to be hoped that, if the results of this study are confirmed by future work, the Gardner Mountain area might serve as a bridge between the better-known region to the south and those areas to the north, west, and northeast, where the second phase of geological mapping, as discussed above, is only beginning. The history of geologic investigation in the Gardner Mountain area is already long and spectacular, beginning with C.H. Hitchcock's discovery of fossils in 1870 and the discovery that the metamorphic terranes of northern New England are amenable to detailed mapping. It was here that the work of Billings in the early nineteen thirties furnished the stepping-off point for this detailed mapping, and eventually for the second phase of mapping which, to the south, is following through on Billings' work. Perhaps the

Gardner Mountain area may again contribute to the knowledge of New England geology by giving some impetus to this second phase of mapping in the north of New Hampshire and Vermont.

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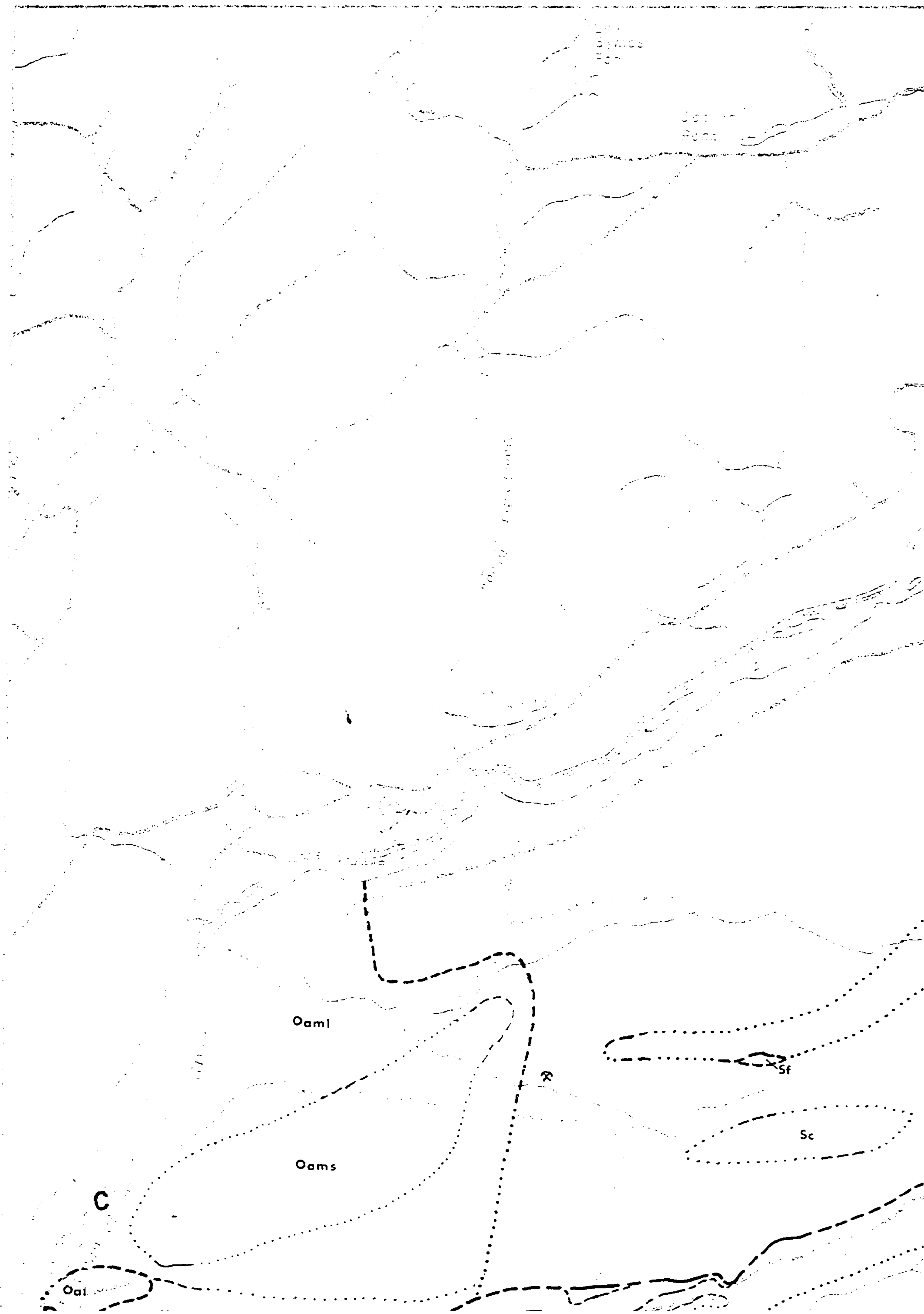
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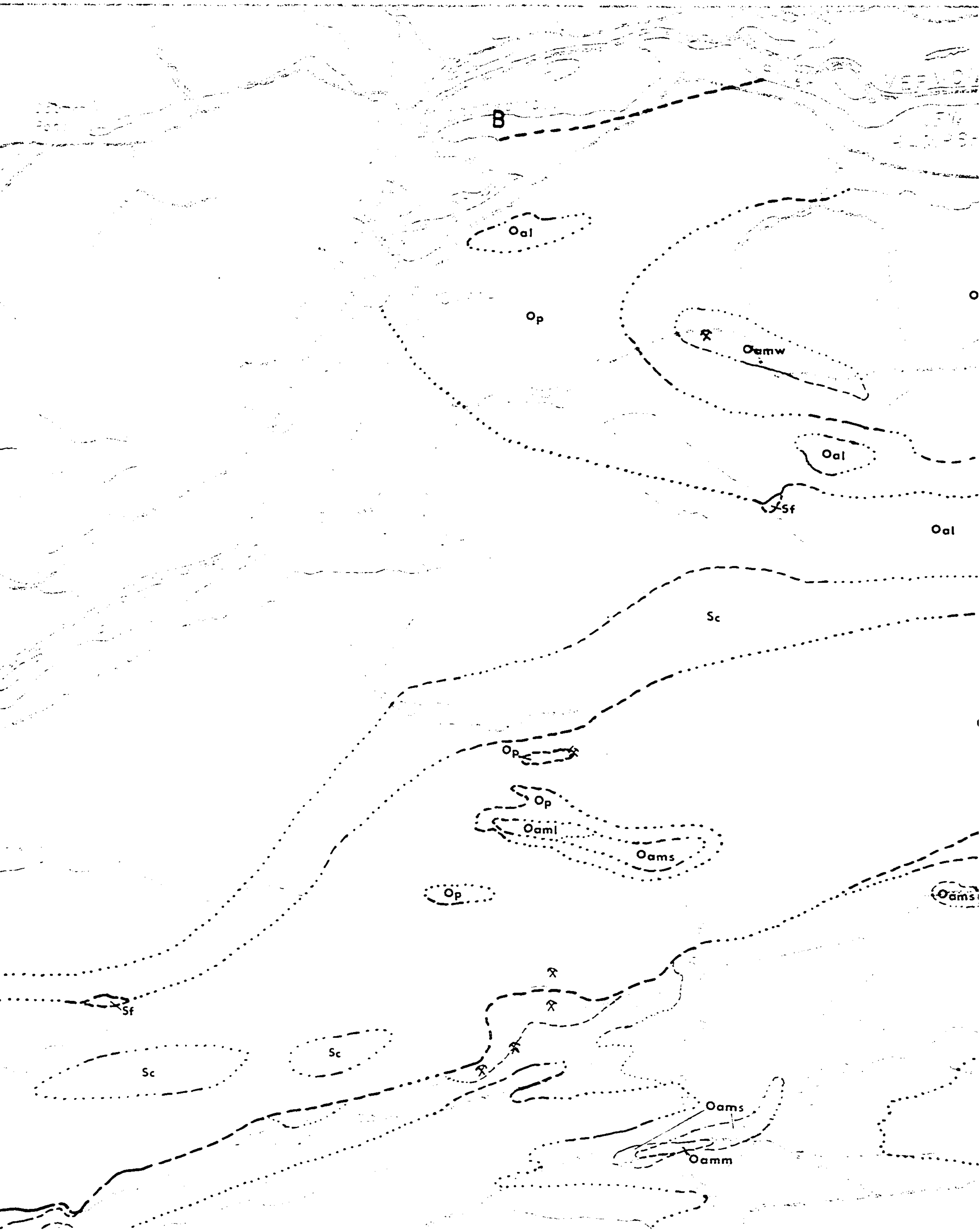
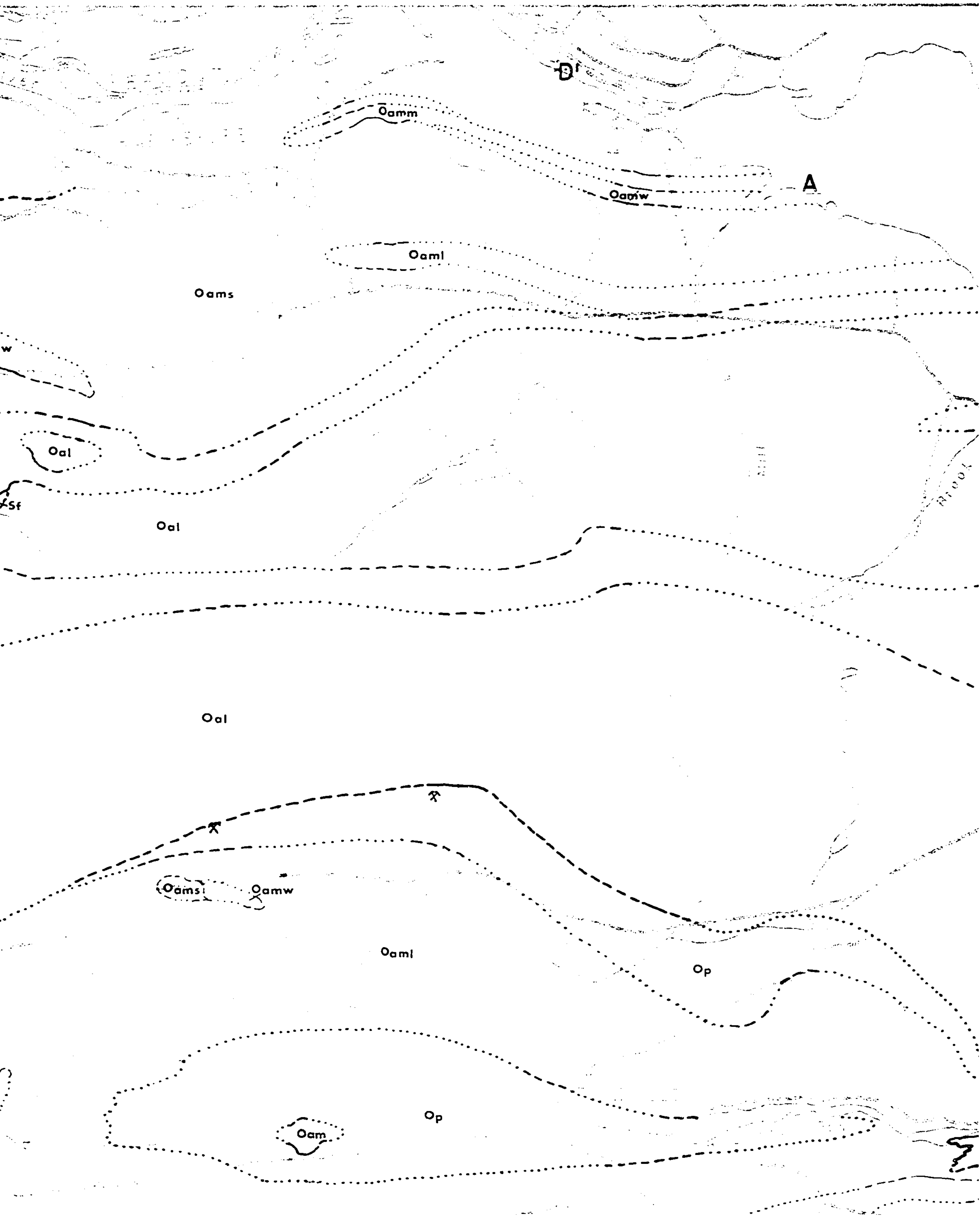

B
Oal
Op
Oamw
Oal
Sf
Oal
Sc
Op
Op
Oaml
Oams
Op
Oams
Sf
Sc
Sc
Oams
Oamm

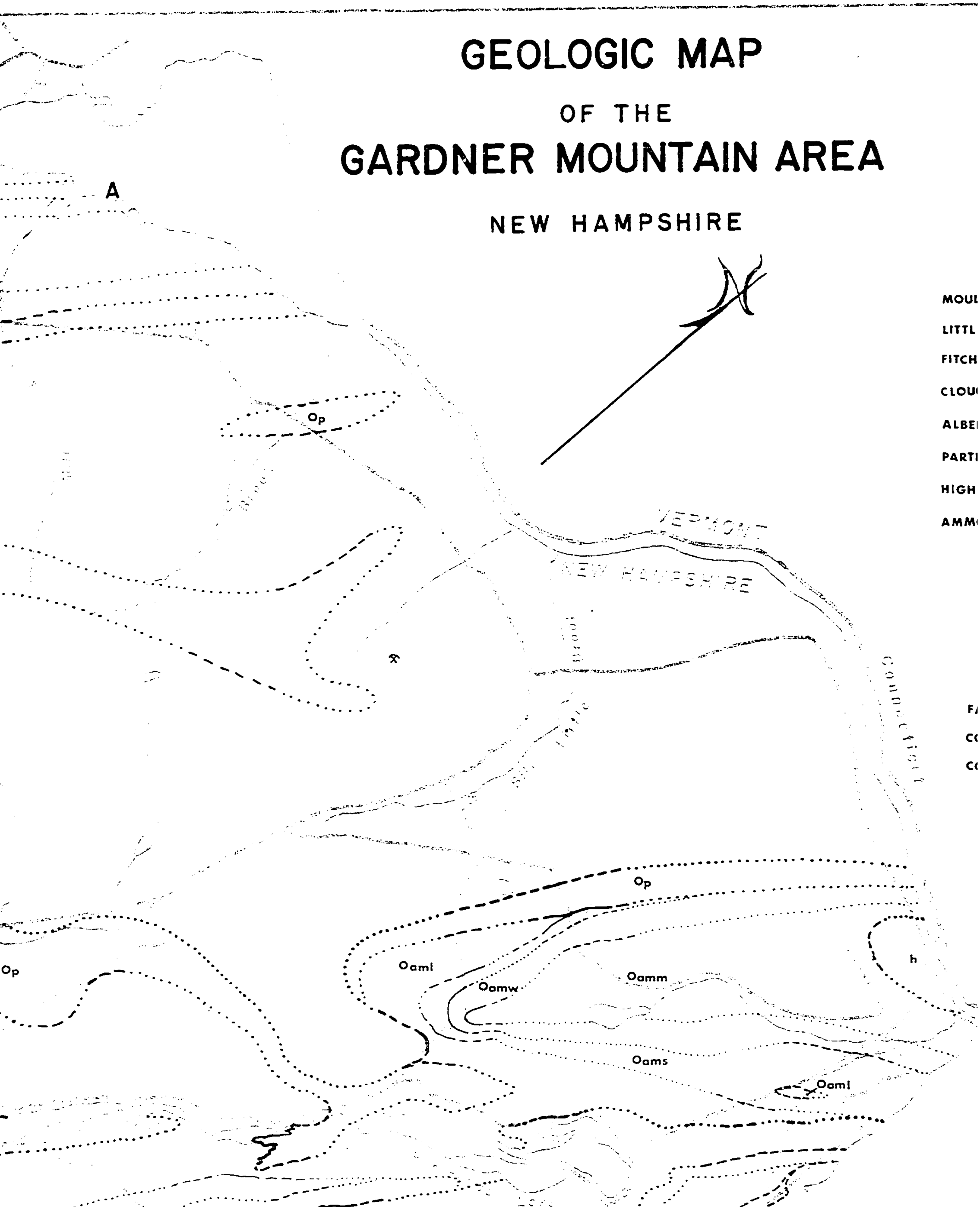

D
Oamm
A
Oamw
Oaml
Oams
w
Oal
Sf
Oal
Oal
Oams
Oamw
Oaml
Op
Op
Oam

GEOLOGIC MAP

OF THE

GARDNER MOUNTAIN AREA

NEW HAMPSHIRE

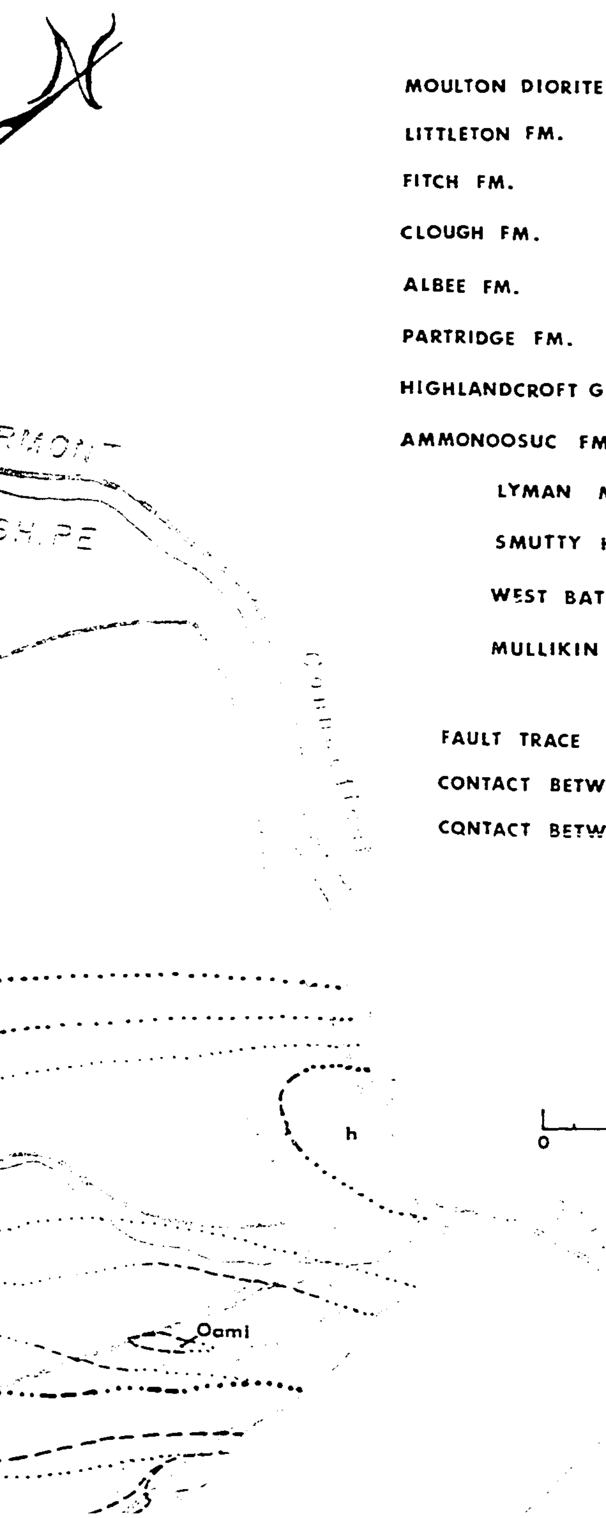


MAP

PLATE I

TAIN AREA

IRE



KEY

MOULTON DIORITE	m
LITTLETON FM.	Dl
FITCH FM.	Sf
CLOUGH FM.	Sc
ALBEE FM.	Oal
PARTRIDGE FM.	Op
HIGHLANDCROFT GRANODIORITE	h
AMMONOOSUC FM.	Oam
LYMAN MBR.	Oaml
SMUTTY HOLLOW MBR.	Oams
WEST BATH MBR.	Oamw
MULLIKIN BROOK MBR.	Oamm

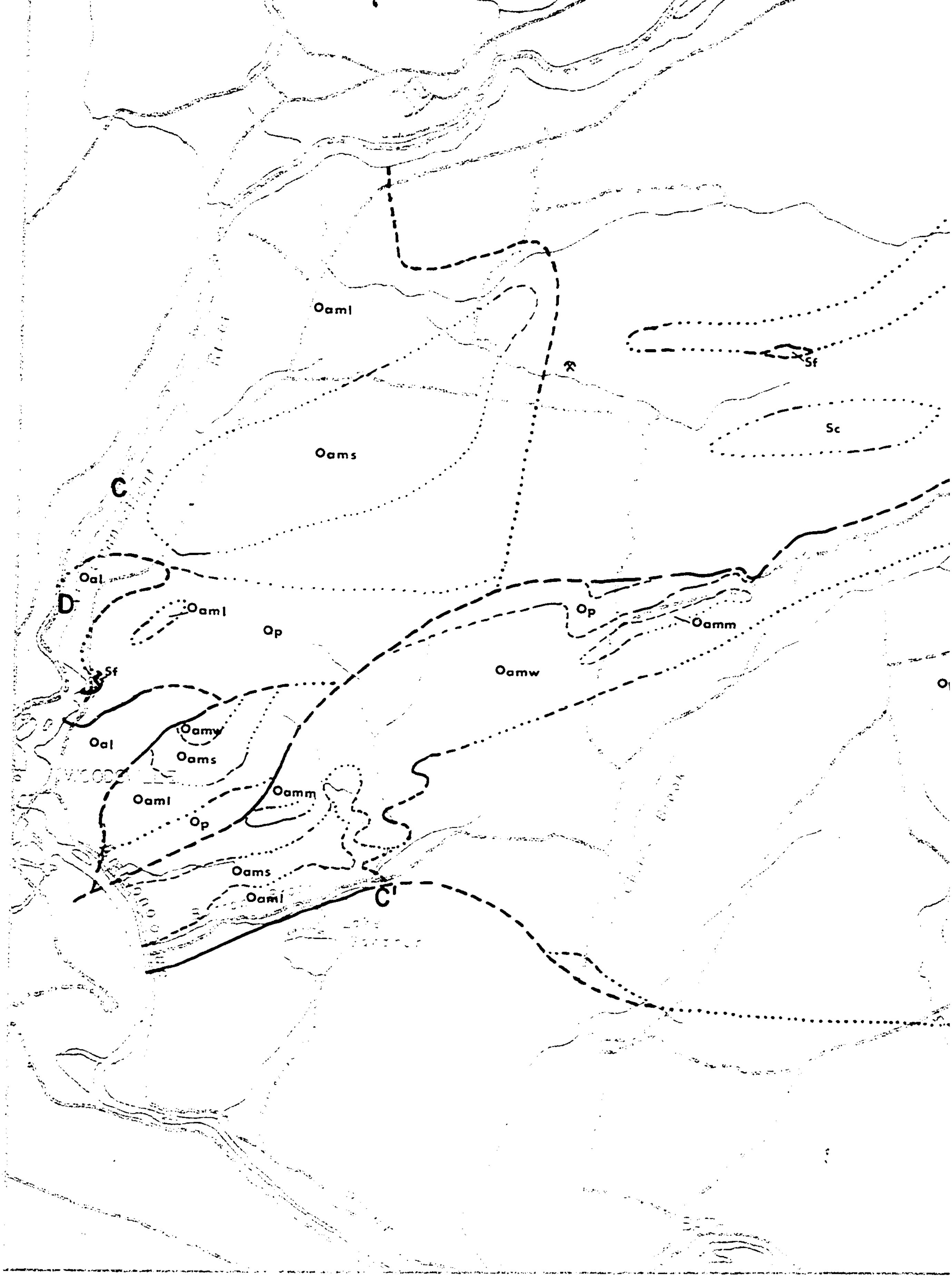
FAULT TRACE

CONTACT BETWEEN FORMATIONS

CONTACT BETWEEN MEMBERS

0 1 2
MILES

SCALE 1 : 38000


Oaml
Oams
C
Sf
Sc
Oal
D
Oaml
Op
Op
Oamm
Oamw
Sf
Oal
Oamw
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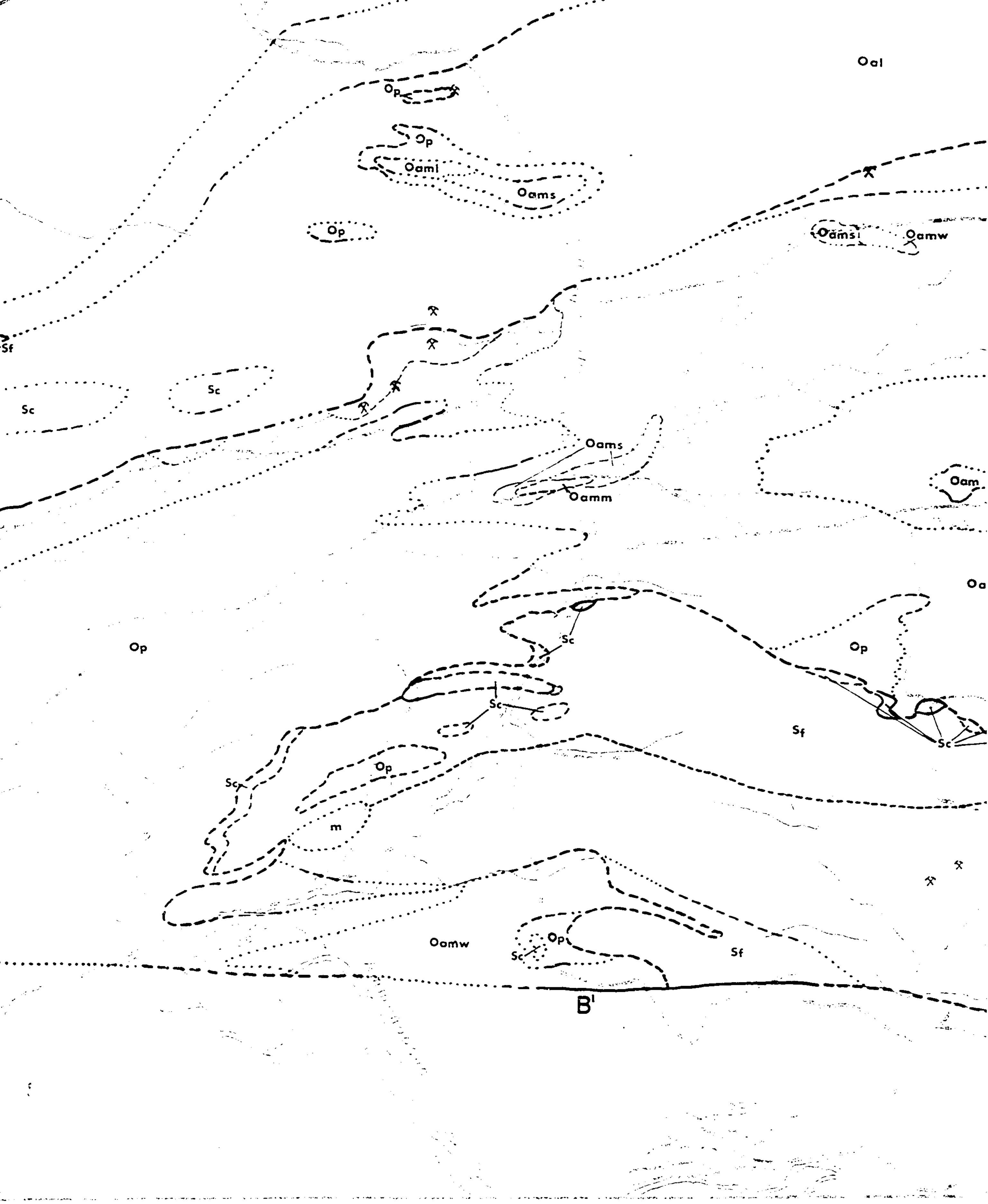
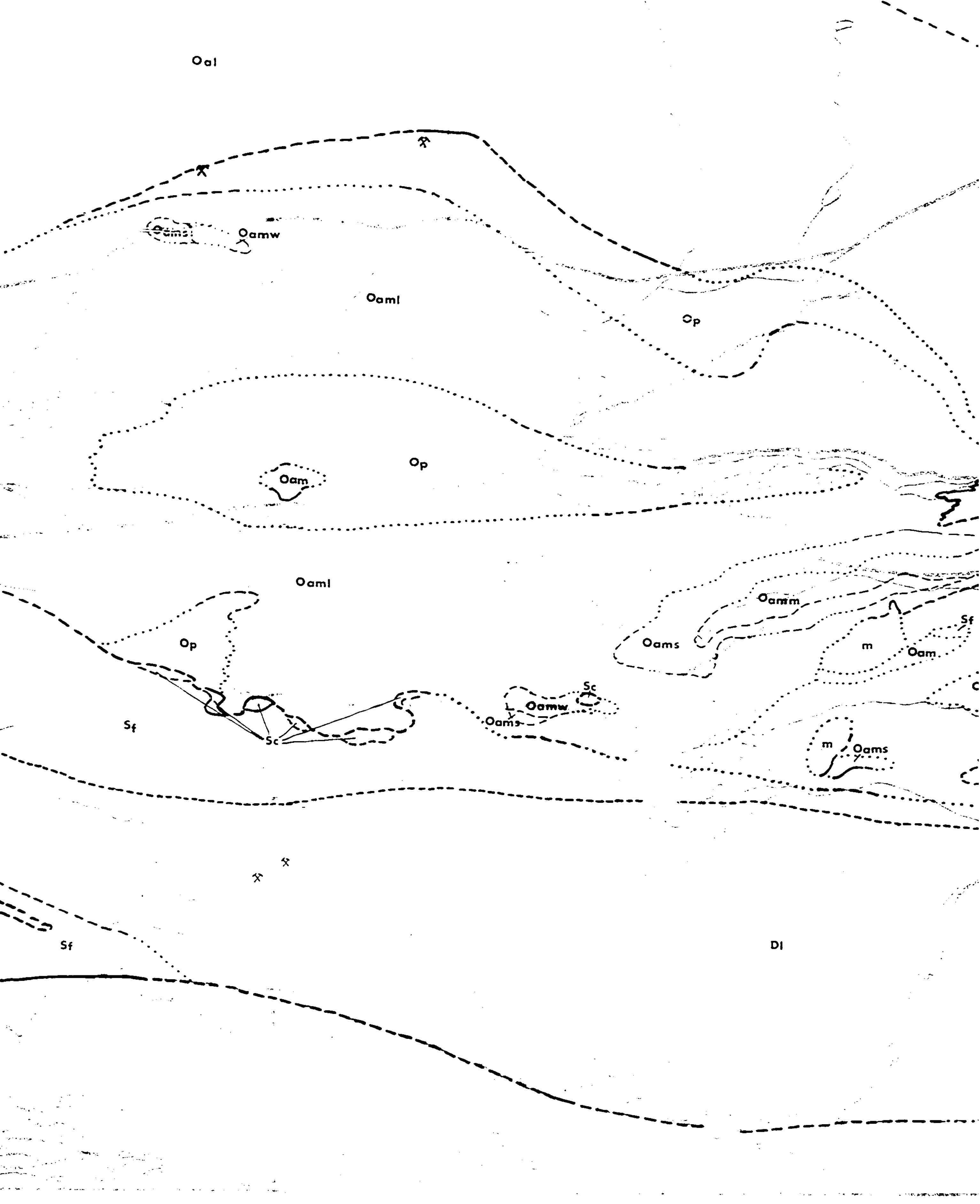
Oaml
Oamm
Op
Oams
Oaml
C'


Oal
Op
Op
Oaml
Oams
Op
Oamsl
Oamw
Sf
Sc
Sc
Oams
Oamm
Oam
Oa
Sc
Op
Op
Sc
Sf
Sc
Sc
Op
m
Oamw
Op
Sc
Sf
B'


Oal
Oams
Oamw
Oaml
Op
Oam
Op
Oaml
Op
Oamm
Oams
Sf
m
Oam
Sc
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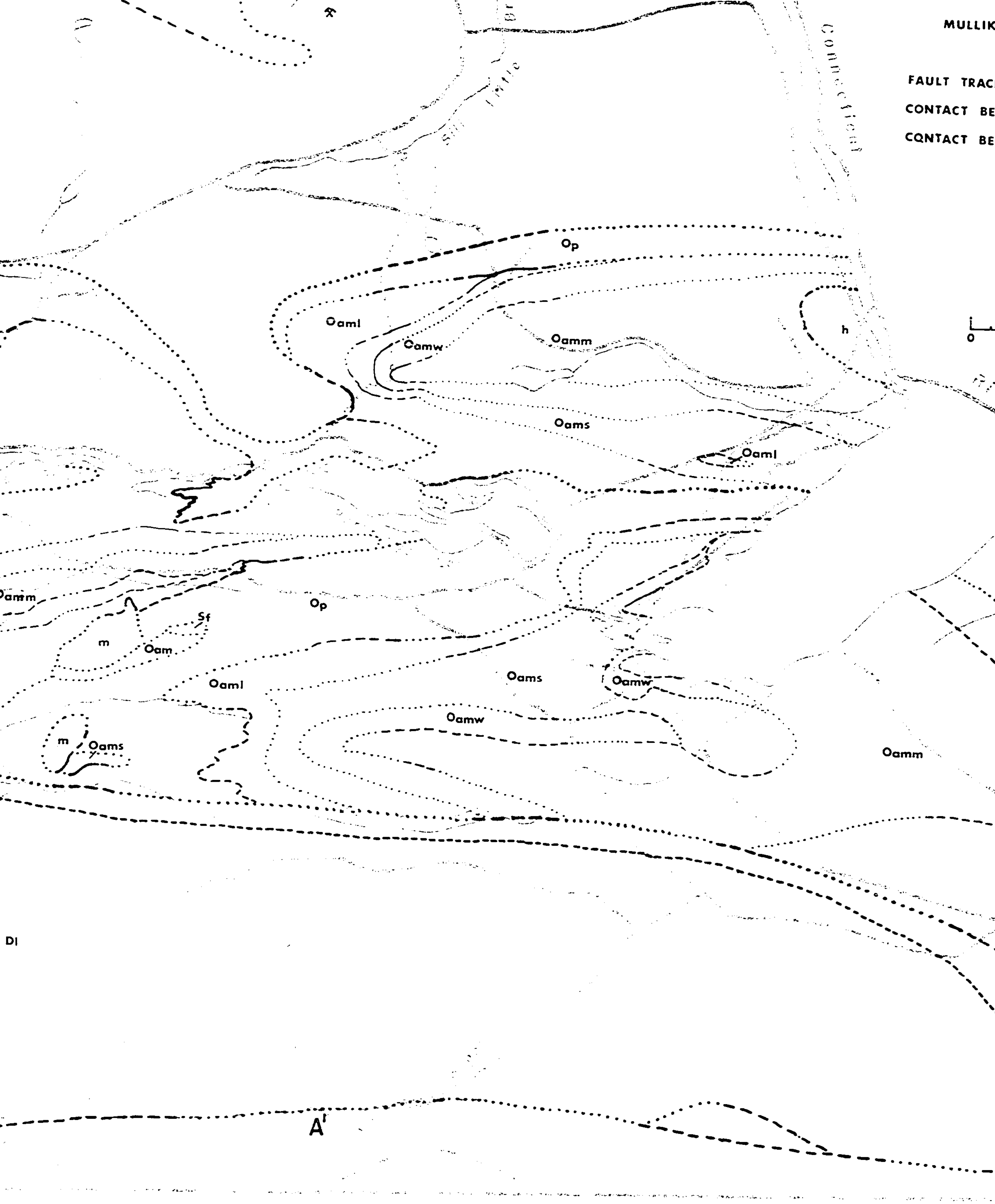
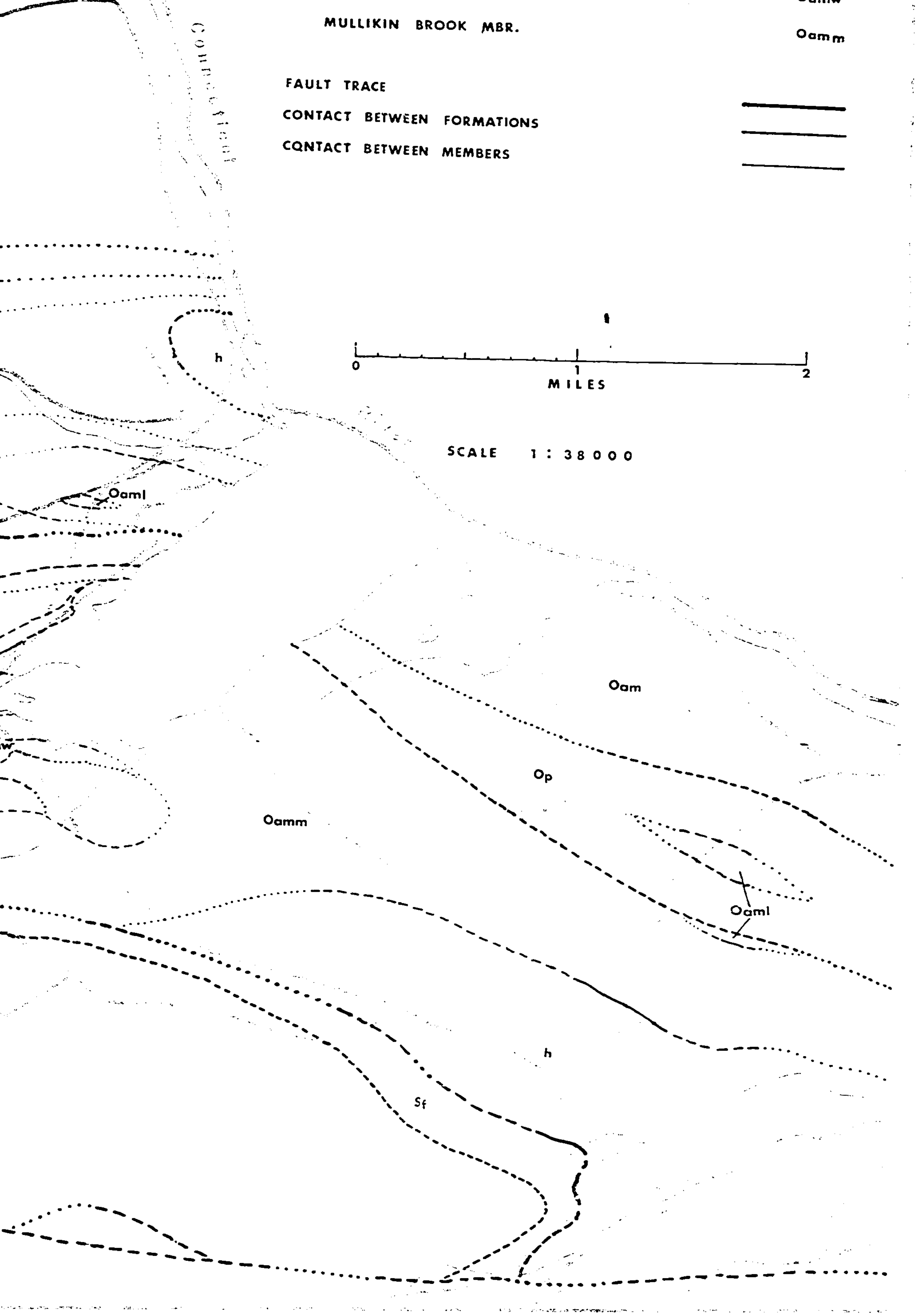
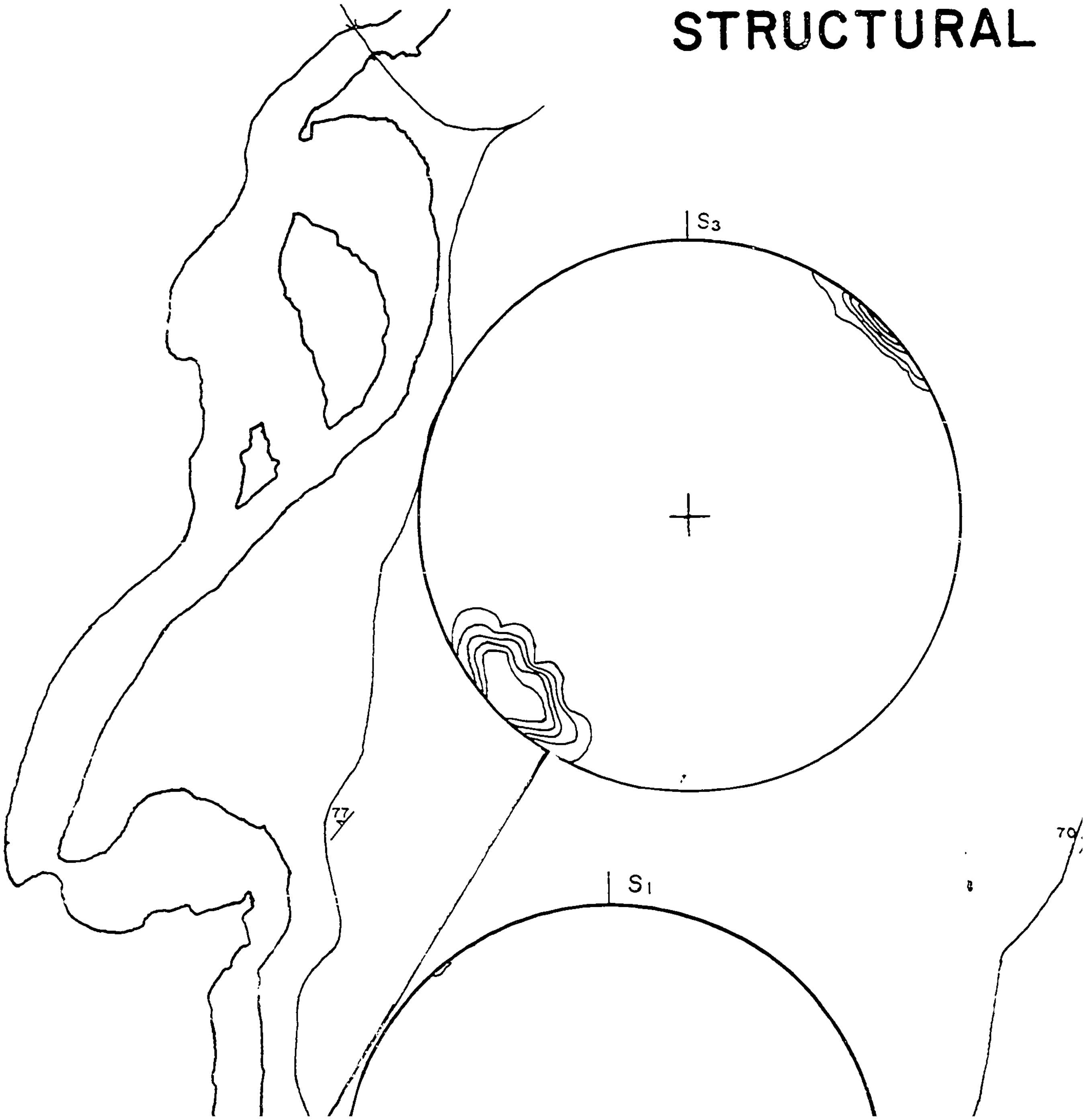
Oams
Sf
Sc
m
Oams
Sf
Dl

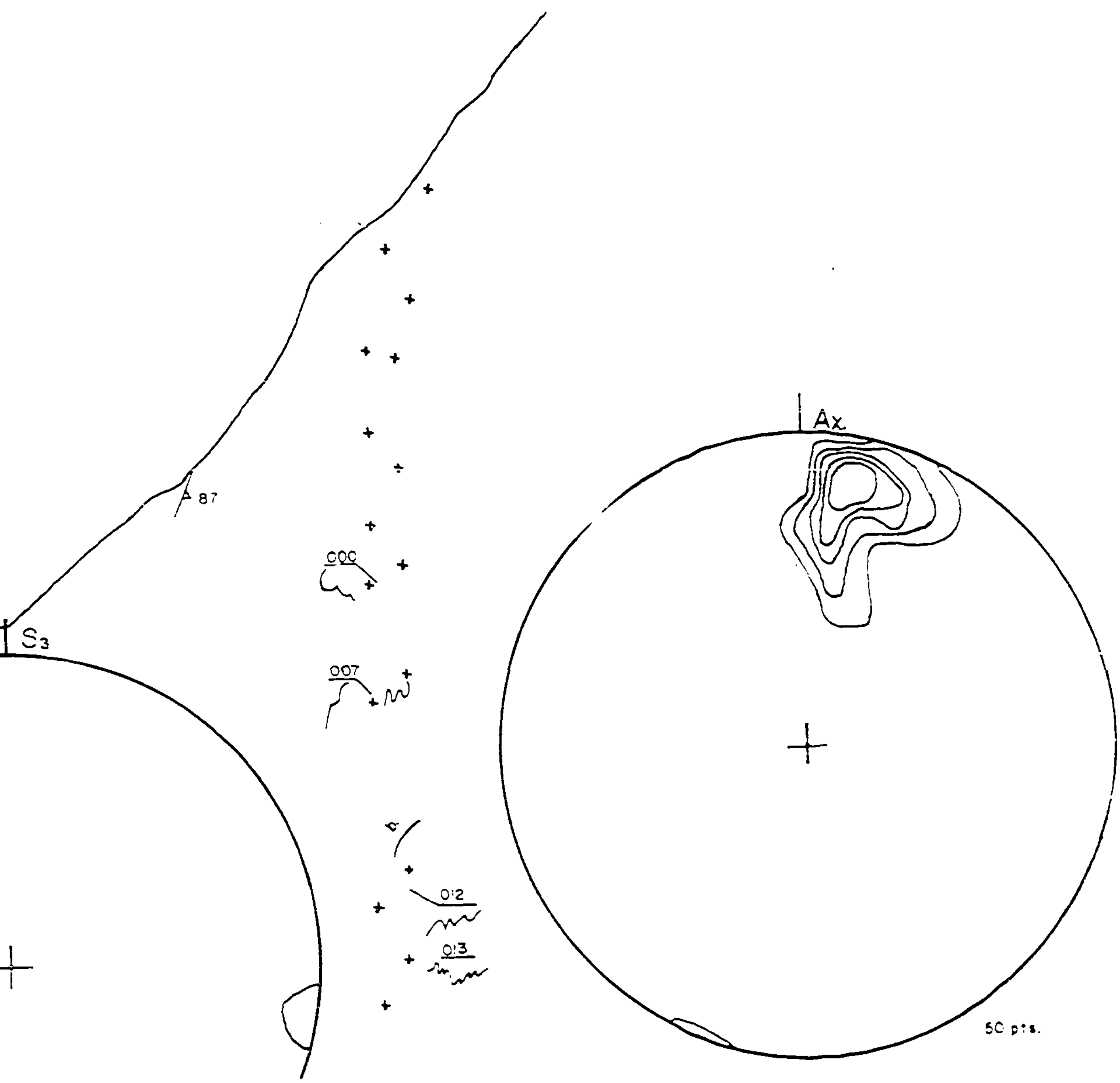

MULLIK
FAULT TRAC
CONTACT BE
CQNTACT BE
0
Op
Oaml
Oamw
Oamm
h
Oams
Oaml
Oamm
Op
Sf
m
Oam
Oaml
Oams
Oamw
Oamw
m
Oams
Oamm
Dl
A'

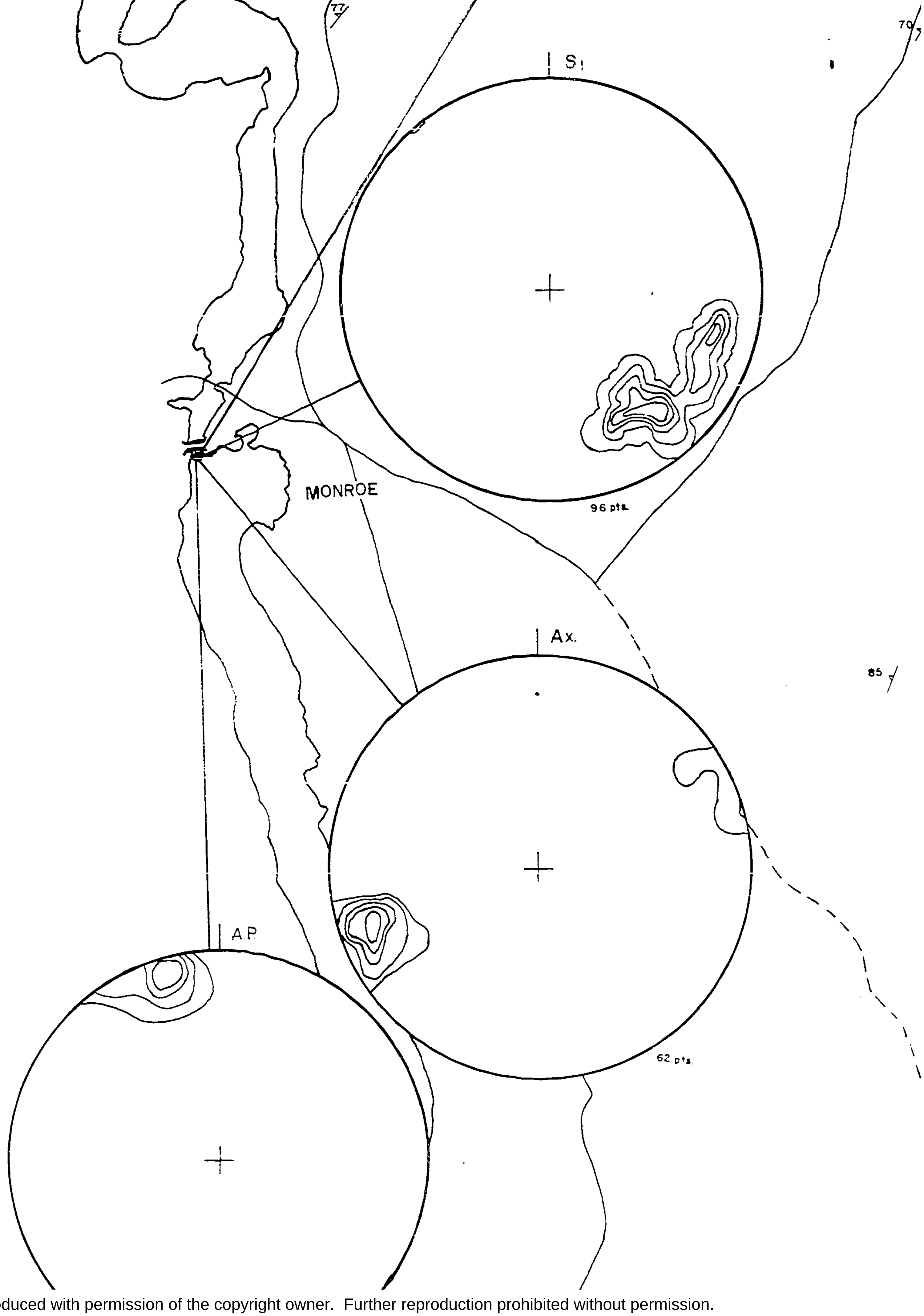

MULLIKIN BROOK MBR.
Oamm
FAULT TRACE
CONTACT BETWEEN FORMATIONS
CONTACT BETWEEN MEMBERS
0
1
2
MILES
SCALE 1 : 38000
h
Oaml
Oam
Op
Oamm
Oaml
h
Sf


STRUCTURAL
S3
S1
77
70

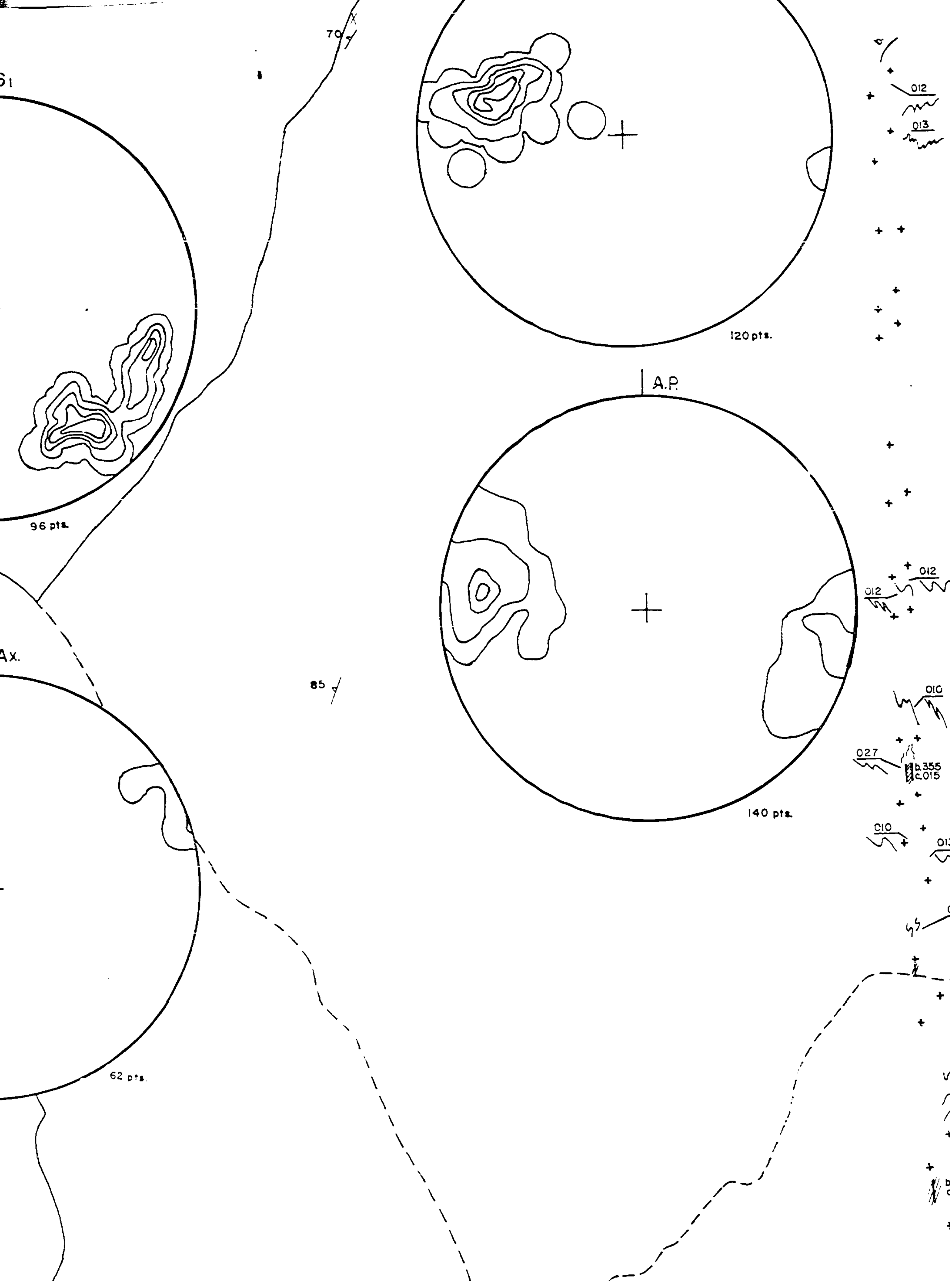
STRUCTURAL INDEX MAP

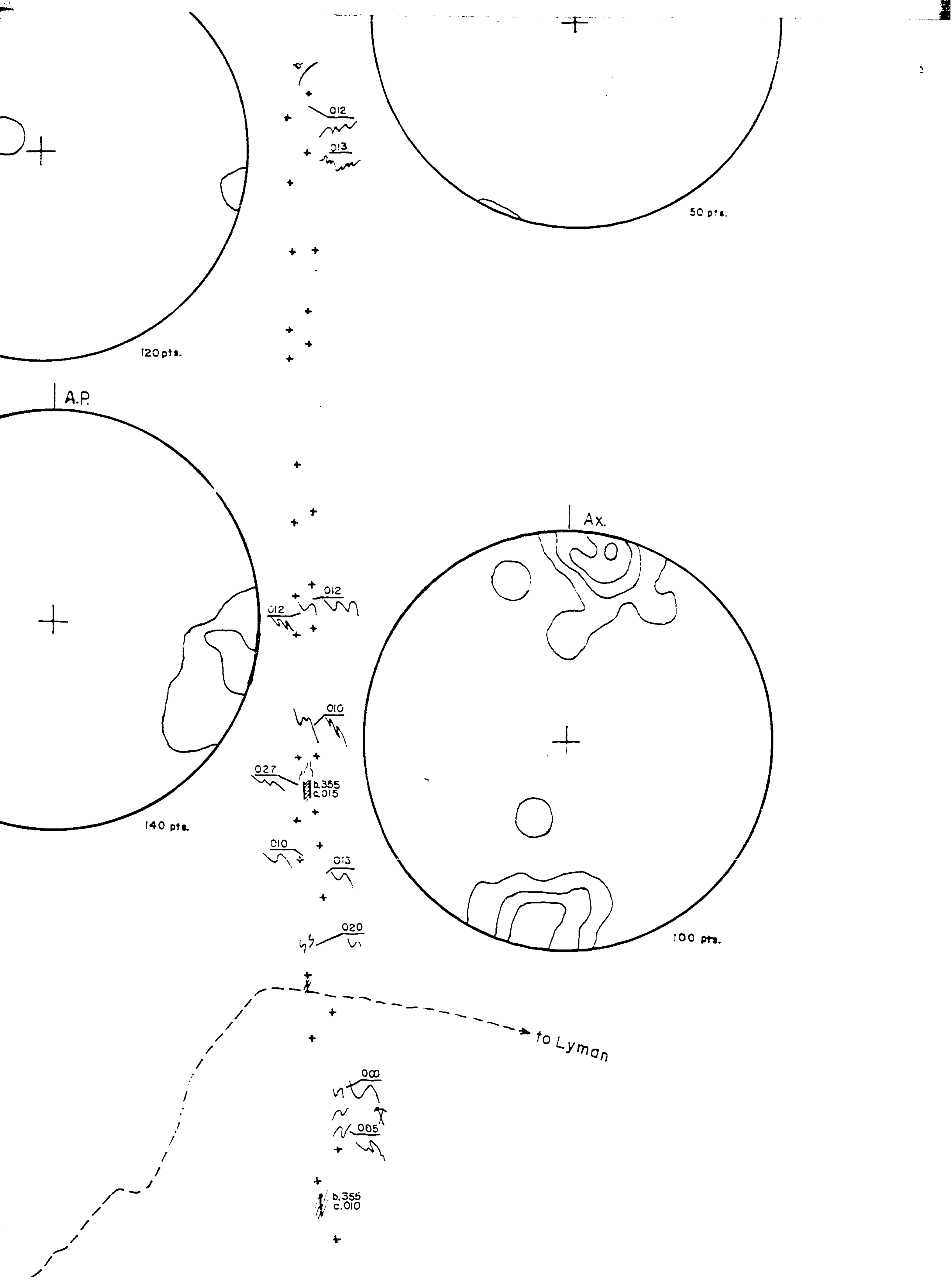
Plate 2

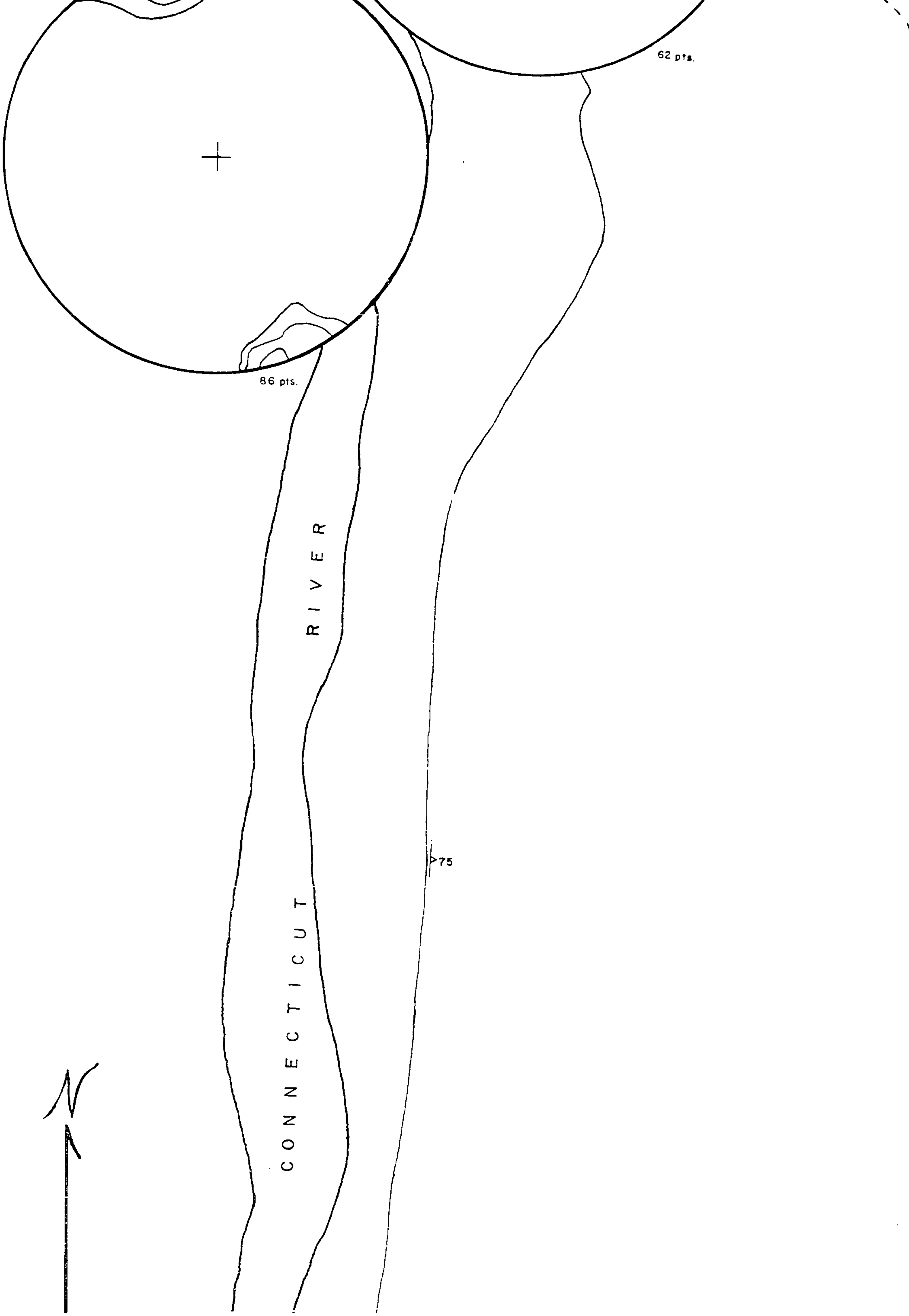


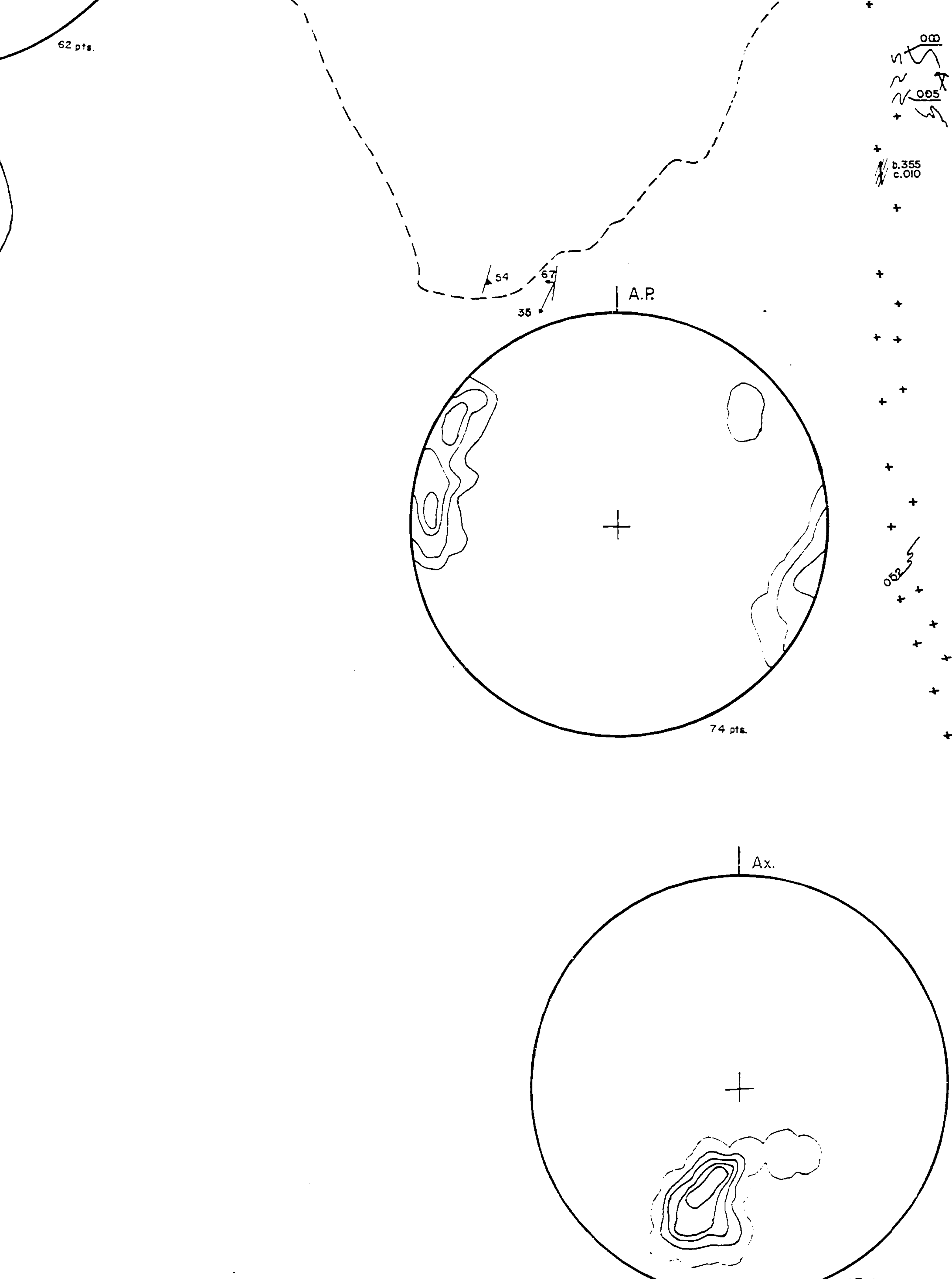


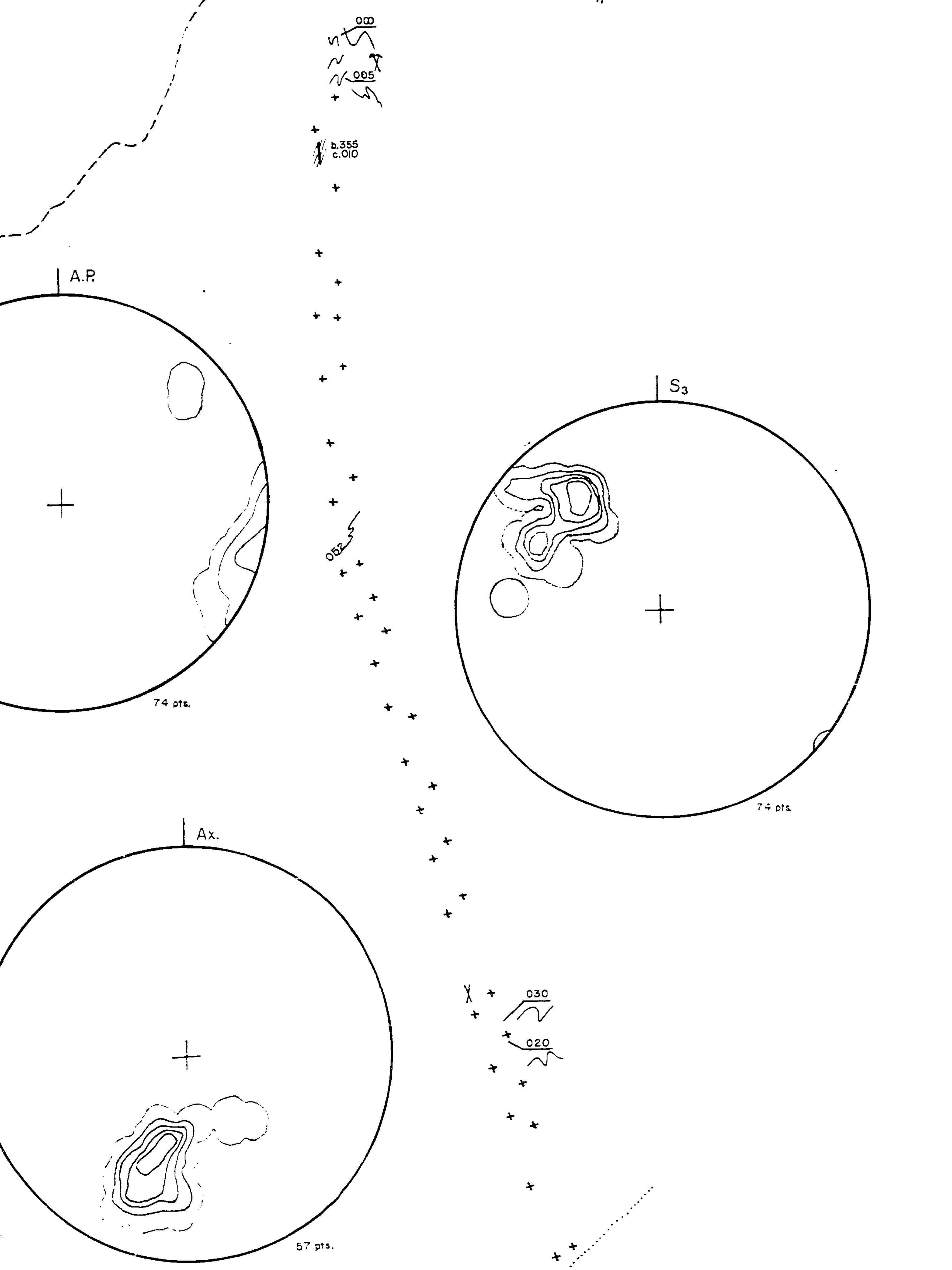
77
70
S1
MONROE
96 pts.
Ax.
85
62 pts.
AP

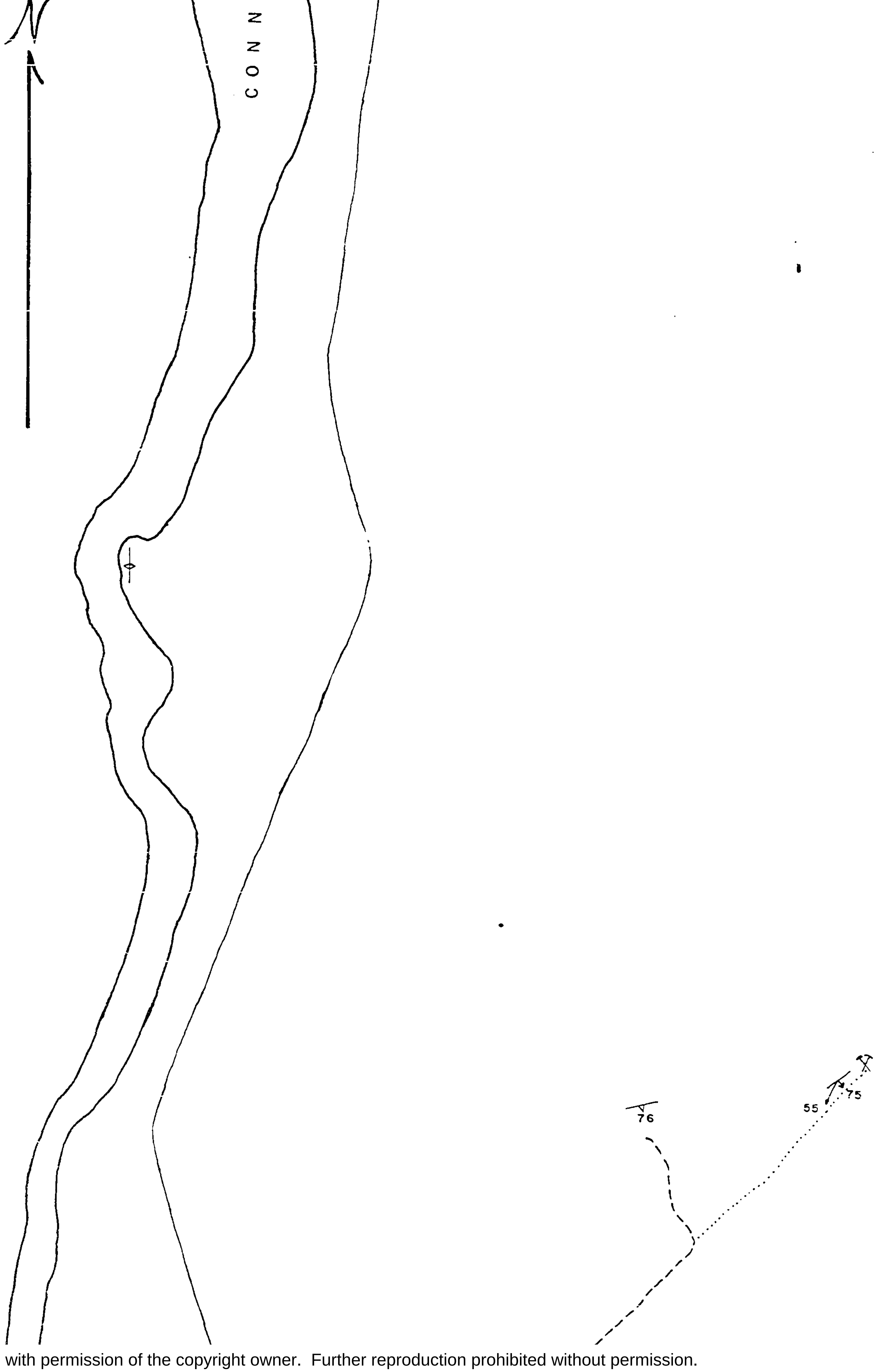

70
96 pts.
120 pts.
A.P.
140 pts.
Ax.
85
62 pts.
012
013
012
012
010
027
b.355
c.015
010

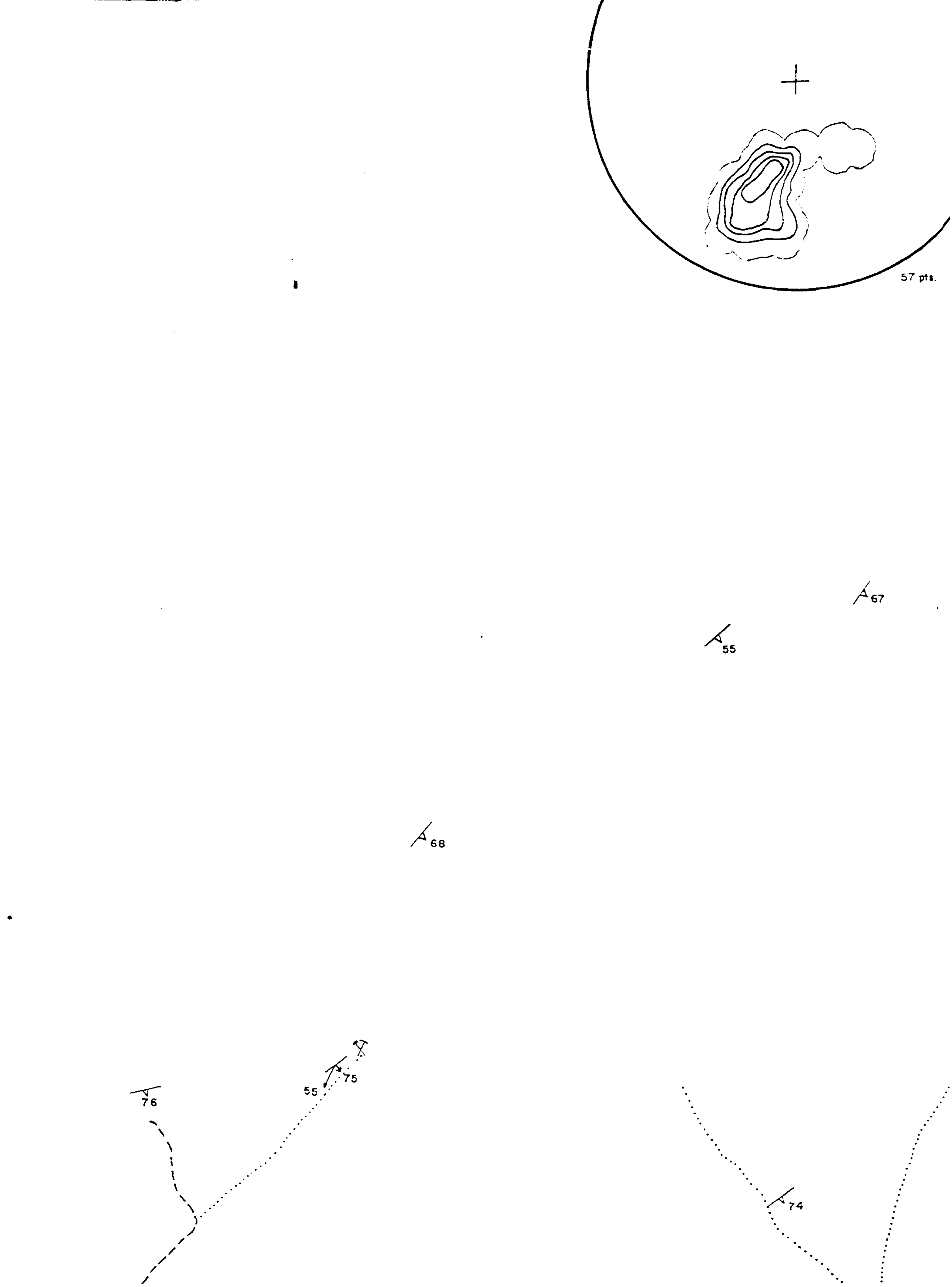

012
013
120 pts.
50 pts.
A.P.
012
012
140 pts.
Ax.
010
027
b.355
c.015
010
013
020
100 pts.
to Lyman
000
005
b.355
c.010

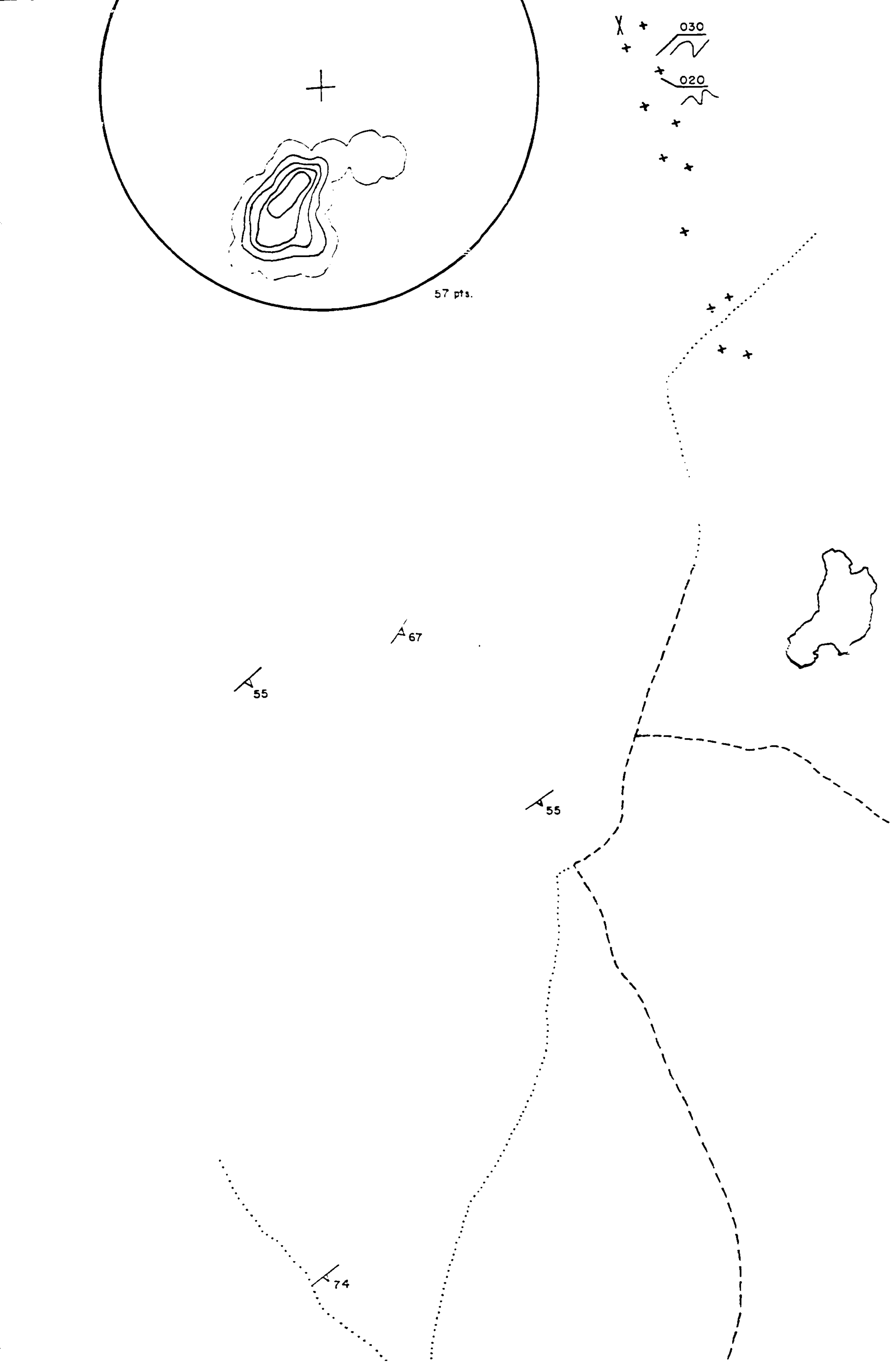

62 pts.
86 pts.
RIVER
>75
CONNECTICUT

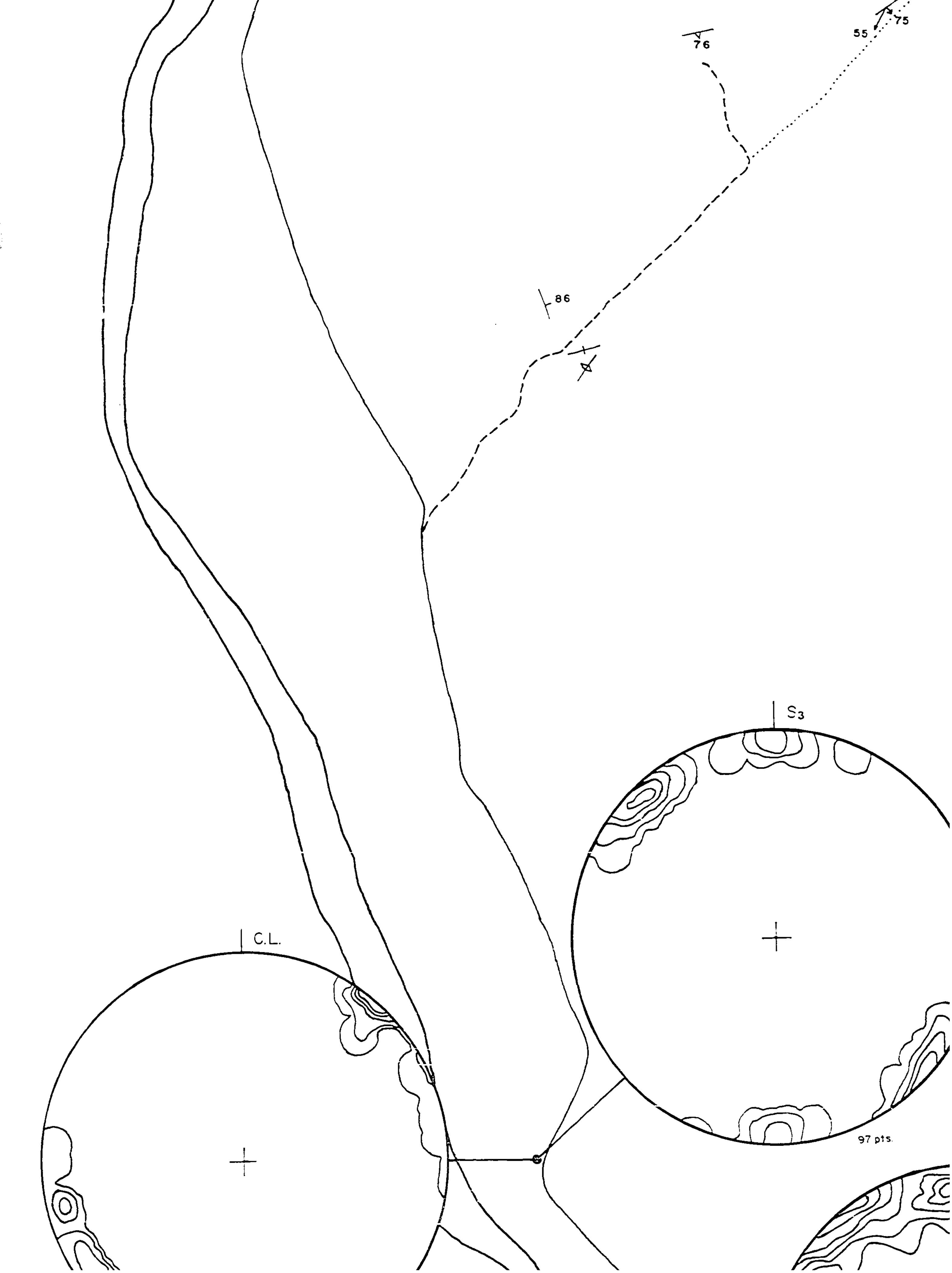

62 pts.
54
67
35
A.P.
74 pts.
Ax.
b.355
c.010
005
052


000
005
b.355
c.010
052
030
020
A.P.
74 pts.
S3
74 pts.
Ax.
57 pts.

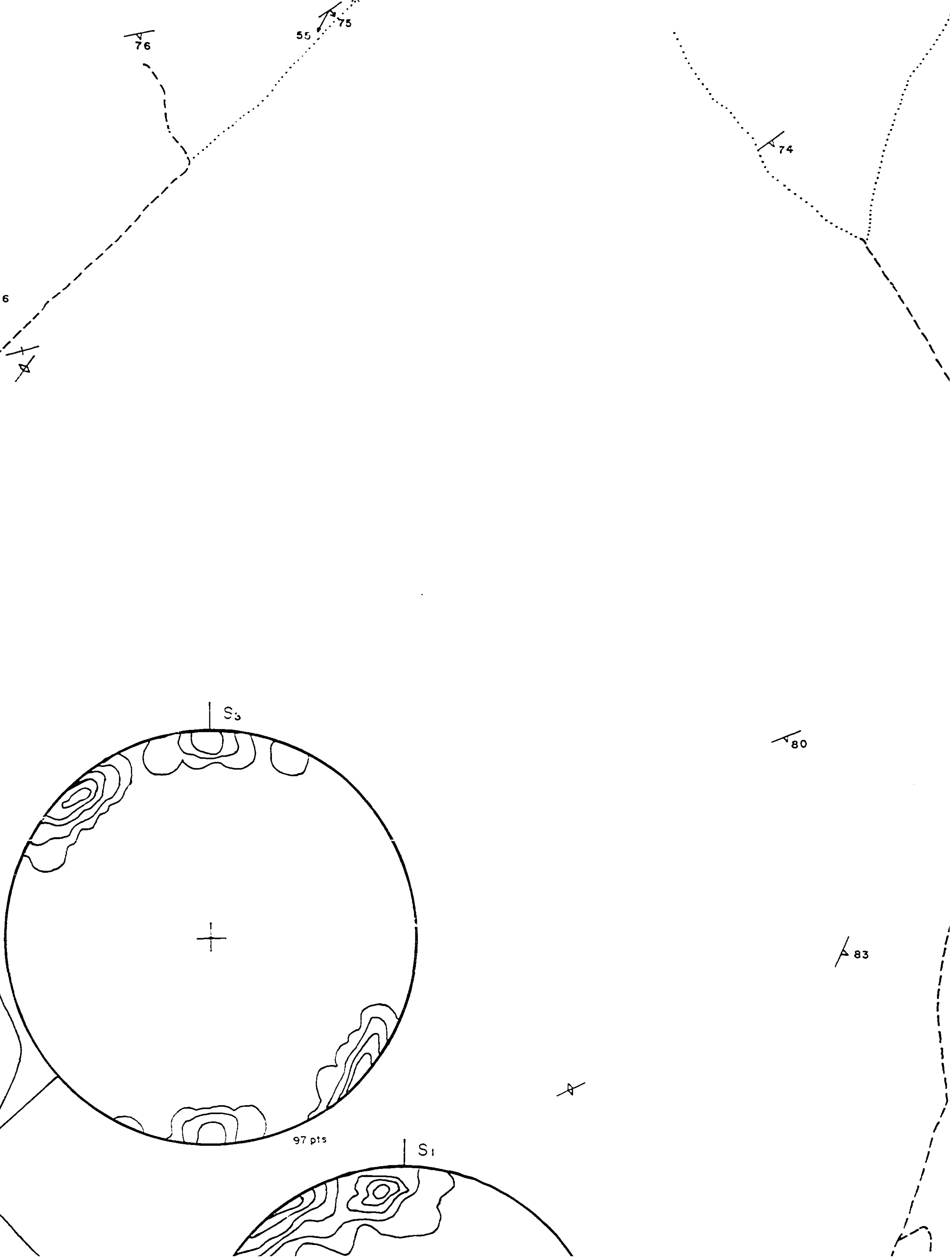

CONN
76
55
75

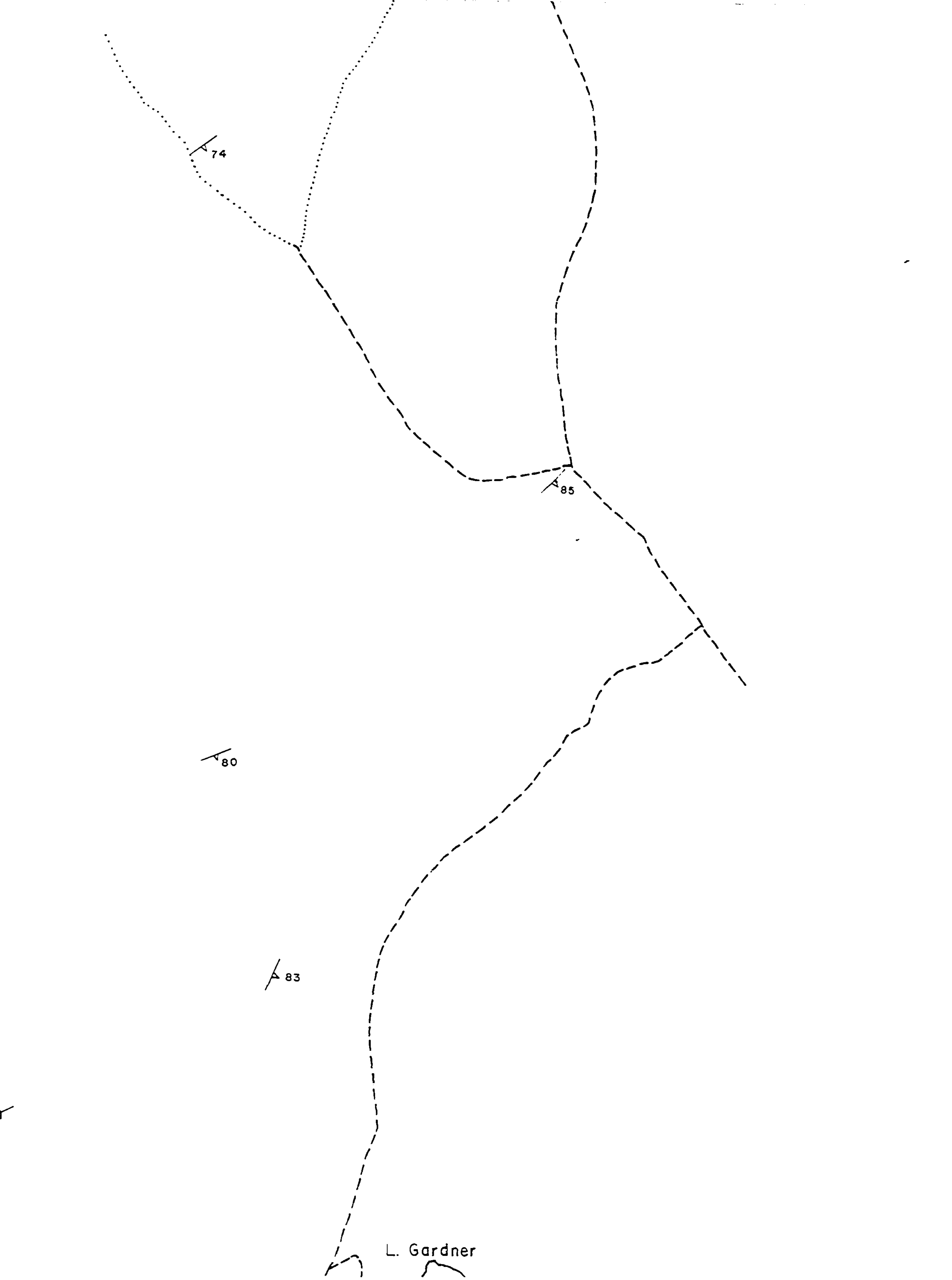

57 pts.
67
55
68
76
55
75
74

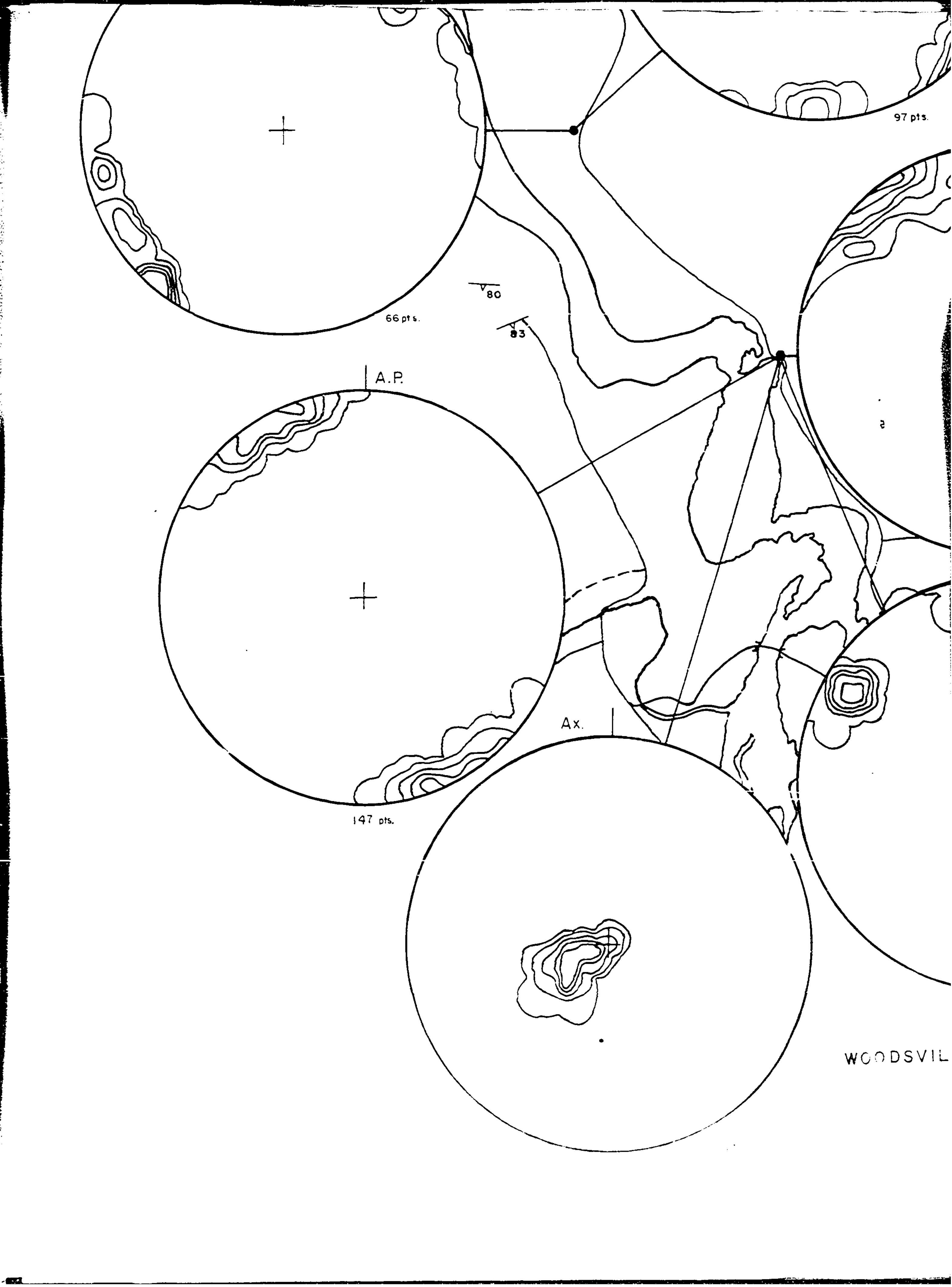

57 pts.
030
020
67
55
55
74

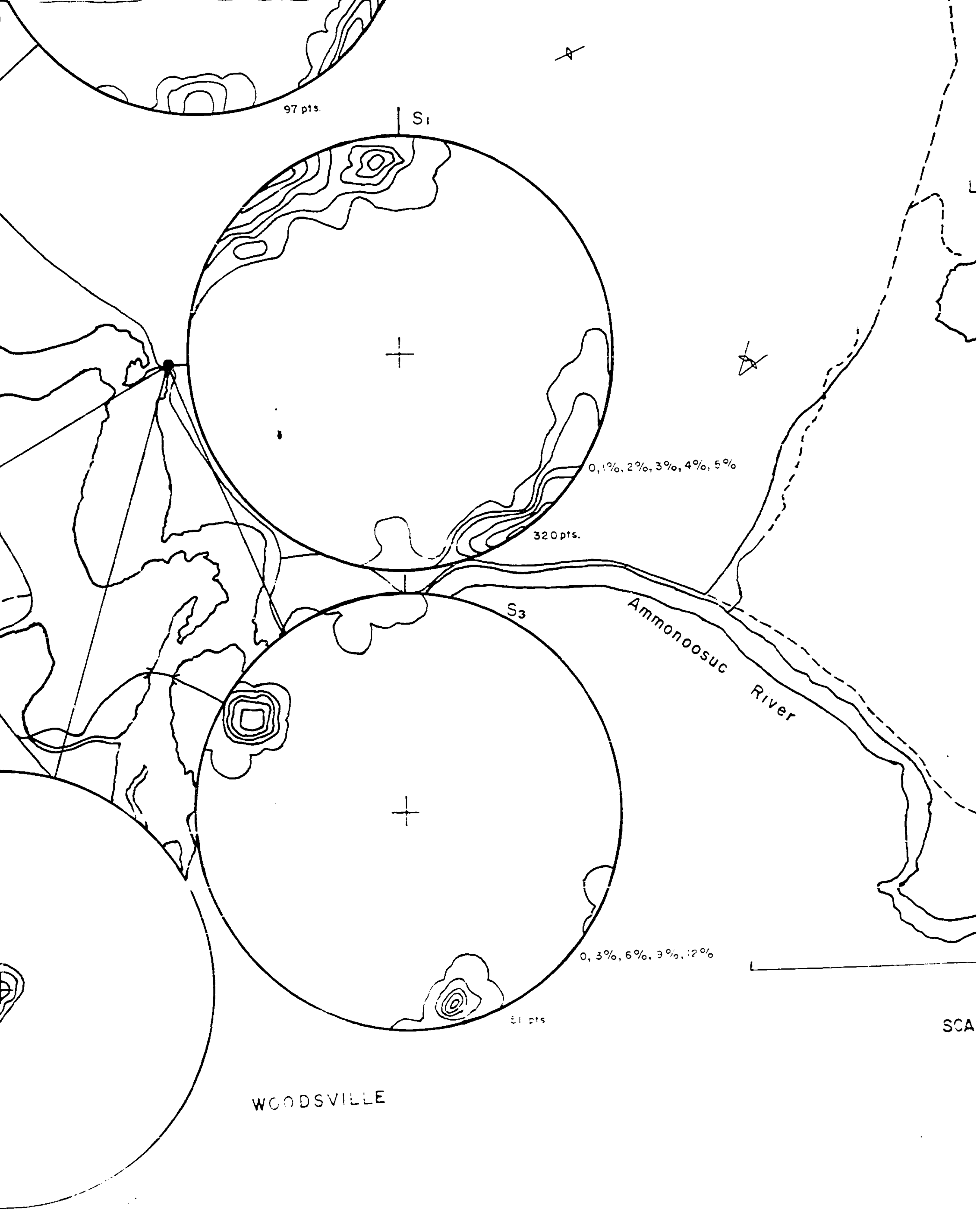


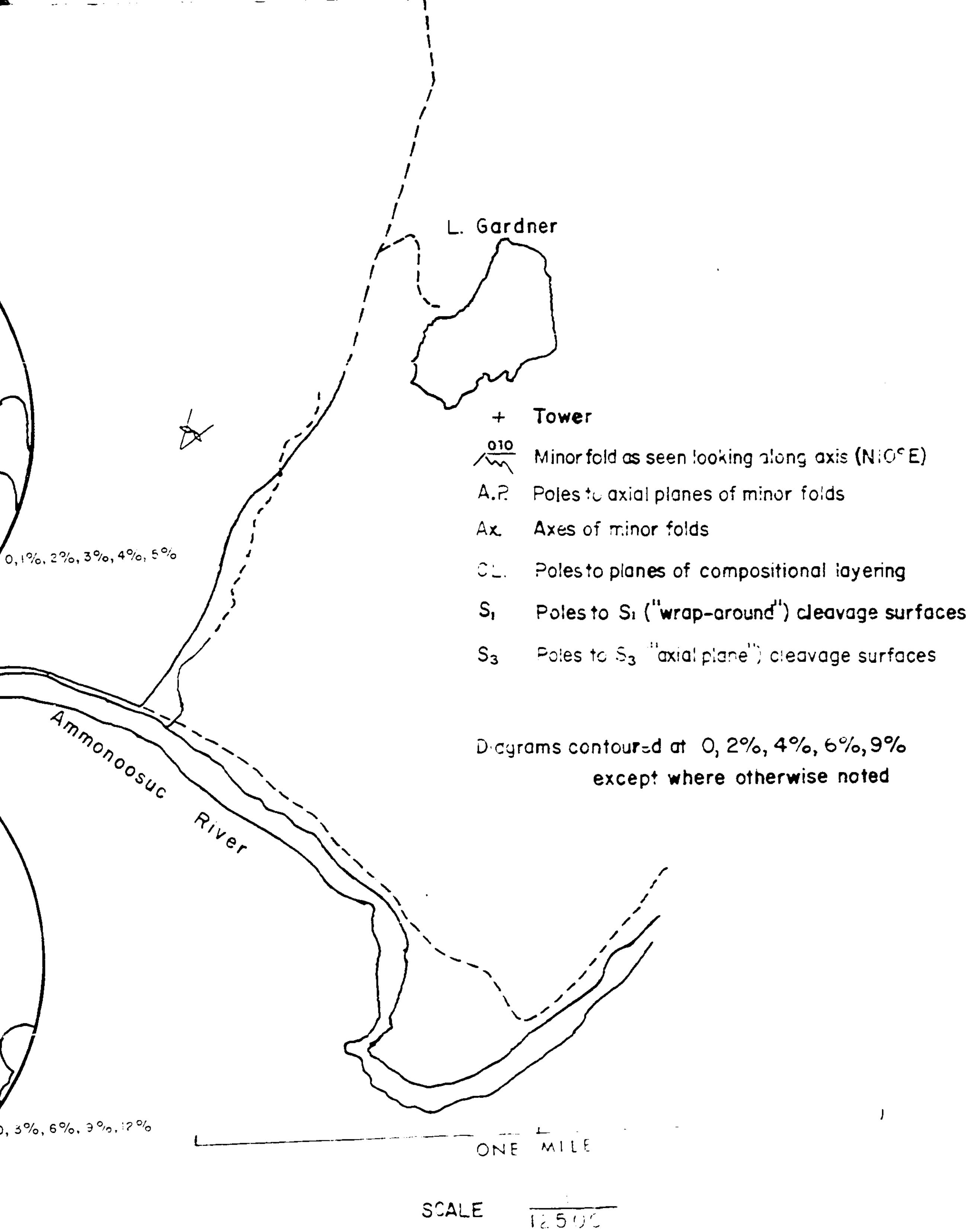
76
55
75
86
S3
97 pts.
C.L.


76
55
75
74
6
S3
97 pts
S1
80
83


74
85
80
83
L. Gardner


97 pts.
66 pts.
80
83
A.P.
147 pts.
Ax.
WOODSVIL


97 pts.
S1
0, 1%, 2%, 3%, 4%, 5%
320 pts.
S3
Ammonoosuc River
0, 3%, 6%, 9%, 12%
SCA
WOODSVILLE


L. Gardner
Tower
010
Minor fold as seen looking along axis
A.P.
Poles to axial planes of minor folds
Ax.
Axes of minor folds
Poles to planes of compositional layering
S_1
Poles to S_1 ("wrap-around") cleavage surfaces
S_3
Poles to S_3 ("axial plane") cleavage surfaces
Diagrams contoured at 0, 2%, 4%, 6%, 9%
except where otherwise noted
0, 1%, 2%, 3%, 4%, 5%
Ammonoosuc River
ONE MILE
SCALE

GENERALIZED

GENERALIZED CROSS SECTIONS

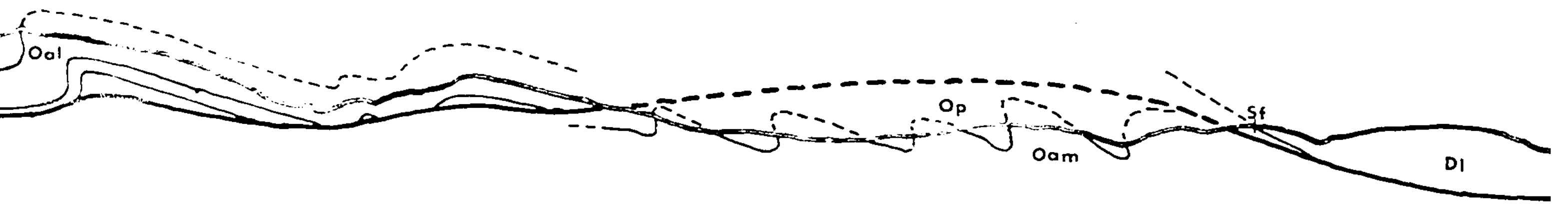
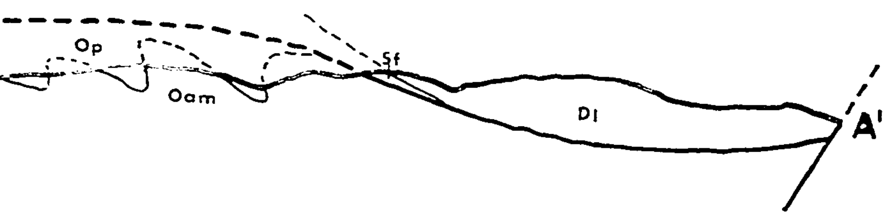
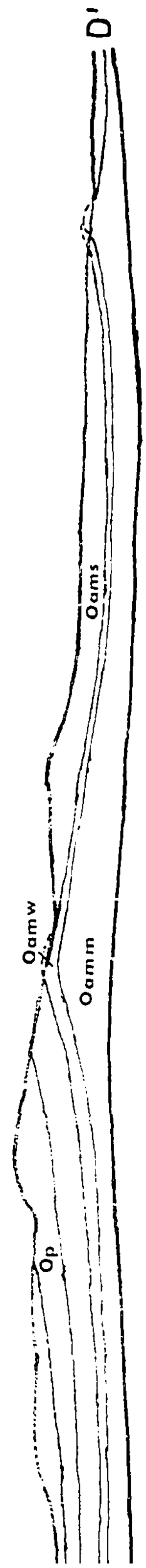


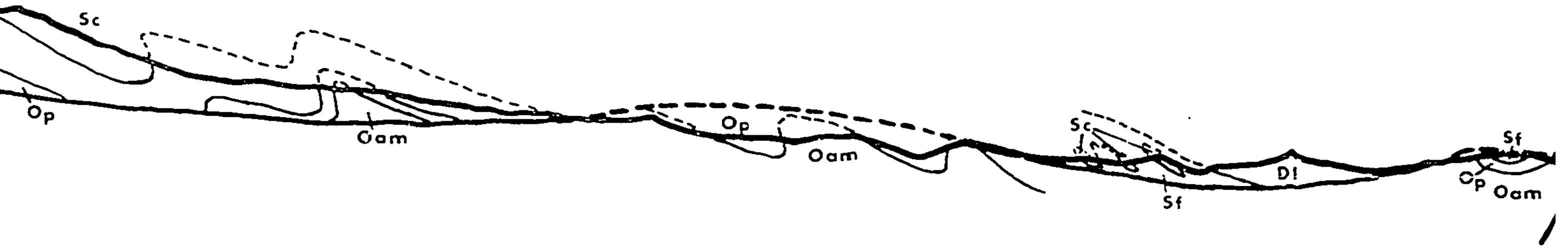
Plate 3

ECTIONS

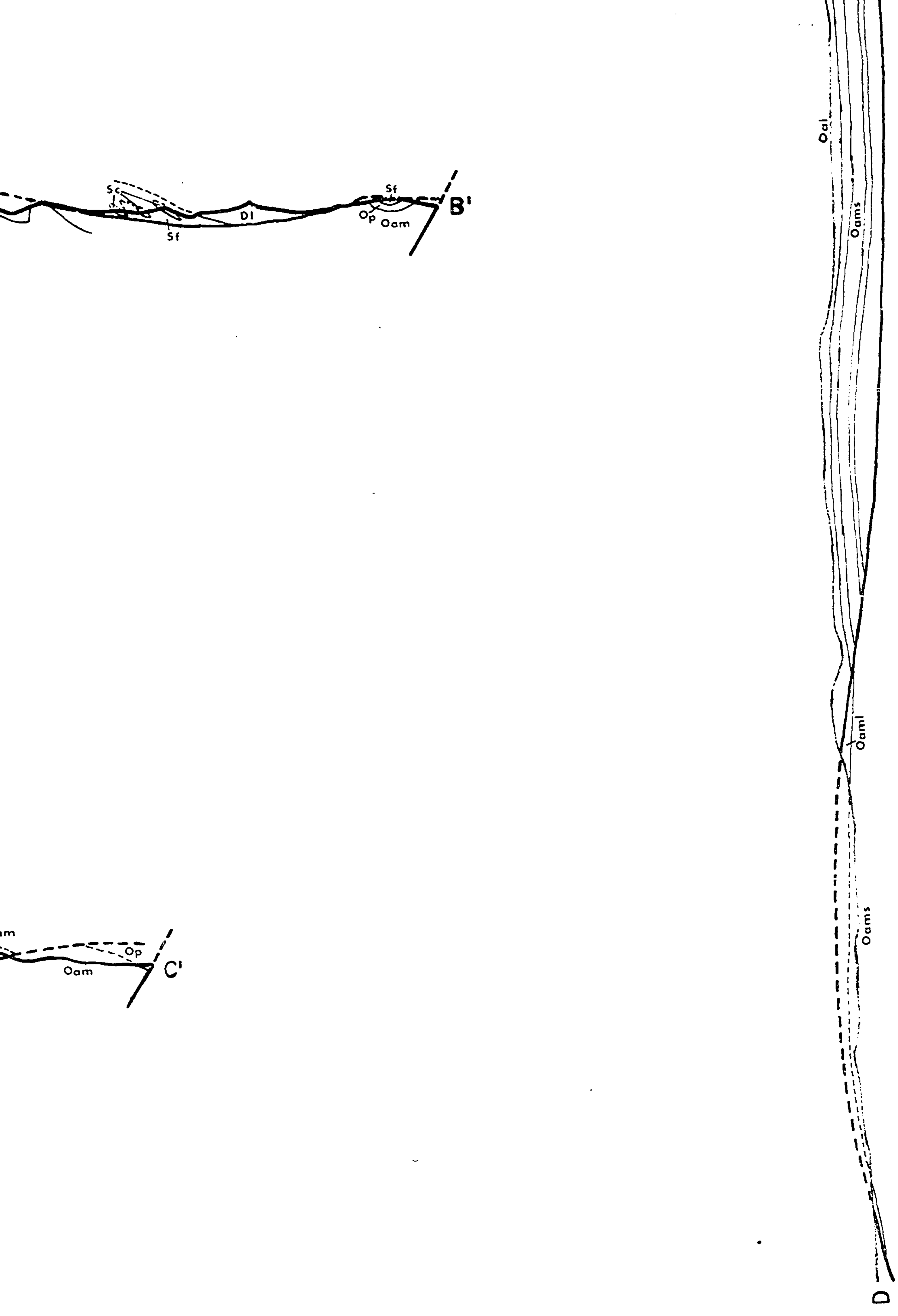





B
Op
Oal
Sc
Op
Oam
Oam
C
0
1
2
MILES


Sc
Op
Oam
Op
Oam
Sc
Sf
Dl
Sf
Op
Oam


Oam
C
Op
Oam
Op
Oam
C'


Sc
Sf
Dl
Op
Oam
B'
Op
Oam
C'
Oal
Oams
Oaml
Oams
D