AN ABSTRACT OF THE THESIS OF

Gayle Ann Ehret for the degree of Master of Science in Geology presented on December 5, 1980.

Title: Structural Analysis of the John Day and Mitchell Fault Zones, North-Central Oregon.

Abstract approved: Redacted for Privacy

Robert D. Lawrence

The John Day and Mitchell faults are large scale, nearly east-west-trending structures which offset both Tertiary and pre-Tertiary rock units in the Blue Mountains geologic province of north-central Oregon. The John Day fault bounds the northern flanks of the Aldrich and Strawberry ranges, and forms a prominent linear physiographic feature which is visible both on the ground and on remote sensing imagery. The Mitchell fault bounds the northern flank of the Ochoco Mountains to the west of the Aldrich Mountains, and is nearly on strike with the John Day fault. Considered together on a regional scale, these faults, and the numerous parallel but smaller scale faults associated with them, form an almost continuous fault zone which nearly bisects the Blue Mountains province at an oblique angle to the overall structural trends of the province. It has been suggested that this zone may provide a significant clue to the Tertiary tectonics of not only the Blue Mountains region but of the

entire Pacific Northwest.

In order to determine the regional structural characteristics of the area adjacent to the John Day and Mitchell fault zones in greater detail, a remote sensing study was undertaken. LANDSAT imagery, high altitude U-2 photography, and side-looking airborne radar imagery were studied. Lineaments were mapped on both LANDSAT and U-2 formats. The LANDSAT imagery showed limited correlation between remotely sensed lineaments and mapped structural featues. The U-2 photography, however, provided enough detailed lineament data to permit a further statistical analysis of U-2 lineament trends, some of which are known to represent regional tectonic joints, particularly in the Columbia River Basalts of north-central Oregon. By assuming that the mapped U-2 lineaments in the thesis area do indeed represent tectonic joints, a tectonic interpretation of the mapped lineament trends was possible.

U-2 lineament data for the thesis area were plotted on rose diagrams, establishing dominant trends in each part of the thesis area. These diagrams indicate that several dominant trends exist within the thesis area. By assuming that these lineament trends in fact represent regional tectonic joints, as their consistent orientations imply, the lineament trends were interpreted in terms of tectonic brittle fracture theory.

The U-2 lineament trends observed in the thesis area suggest two separate deformational episodes. The first was a region-wide episode of compression, oriented approximately N.30°W. This episode is suggested by lineament trends in nearly all parts of the thesis area. The second implied tectonic episode was one in which northeast-southwest-directed compression was dominant. This latter episode appears from the lineament data to have been localized in the eastern part of the thesis area. Both episodes must date to early or middle Pliocene in age, as they are evident in volcanics of middle to late Miocene age.

A joint study was undertaken to attempt to verify remotely sensed lineaments as actual joints in the field. Joint sites were chosen to correspond to U-2 lineament sample areas. The lack of similarity between field mapped joints and remotely sensed lineaments suggests that if U-2 mapped lineaments do represent tectonic fractures, these must be of a more regional scale and are not apparent on the ground.

The regularity of U-2 observed lineament trends in north-central Oregon suggests that they are of regional tectonic significance. The combination of lineament-derived tectonic trends with mapped geologic structures allows for a more complete tectonic synthesis of the areas where these lineaments exist.

Structural Analysis of the John Day and Mitchell Fault Zones, North-Central Oregon

by

Gayle Ann Ehret

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INTRODUCTION

The geology of the Pacific Northwest is dominated by extensive Tertiary volcanic rocks which reflect a period of widespread volcanism and tectonism. Pre-Tertiary rock units are, for the most part, obscured by these younger volcanic rocks, and are exposed only in isolated and structurally discontinuous terranes. Until recently few attempts had been made to tectonically interpret either pre-Tertiary or Tertiary units on a regional basis. As a result, the regional geologic history of much of the Pacific Northwest is incompletely understood.

Gross similarities in the isolated pre-Tertiary terranes of north-central Oregon, northwestern California, and northern Washington suggest that these widely separated outcrop areas may at one time have been part of a single, continuous tectonic belt which paralleled the western margin of the North American plate. Recent studies propose that this pre-Tertiary belt broke up during late Mesozoic and early Cenozoic time, and that the isolated terranes which exist at present behaved as micro-plates which were translated and rotated to their present positions (Hamilton and Myers, 1966). The extensive early and middle Cenozoic volcanics of the region may be genetically related to this major tectonic event.

Because much of the geology of the Pacific Northwest is dominated by middle to late Tertiary volcanic and tectonic features, such as the Columbia Plateau and the Basin and Range provinces, there are only limited areas where direct evidence might be found for large scale structural and tectonic events which involved both pre-Tertiary and early Tertiary rock units. One area which provides excellent exposures of both pre-Tertiary and early Tertiary stratigraphic sections is the Blue Mountains province of north-central Oregon, a structural uplift located between the late Tertiary basalt-mantled Columbia River Plateau to the north and the normal fault-dominated Basin and Range province to the south (Figure 1).

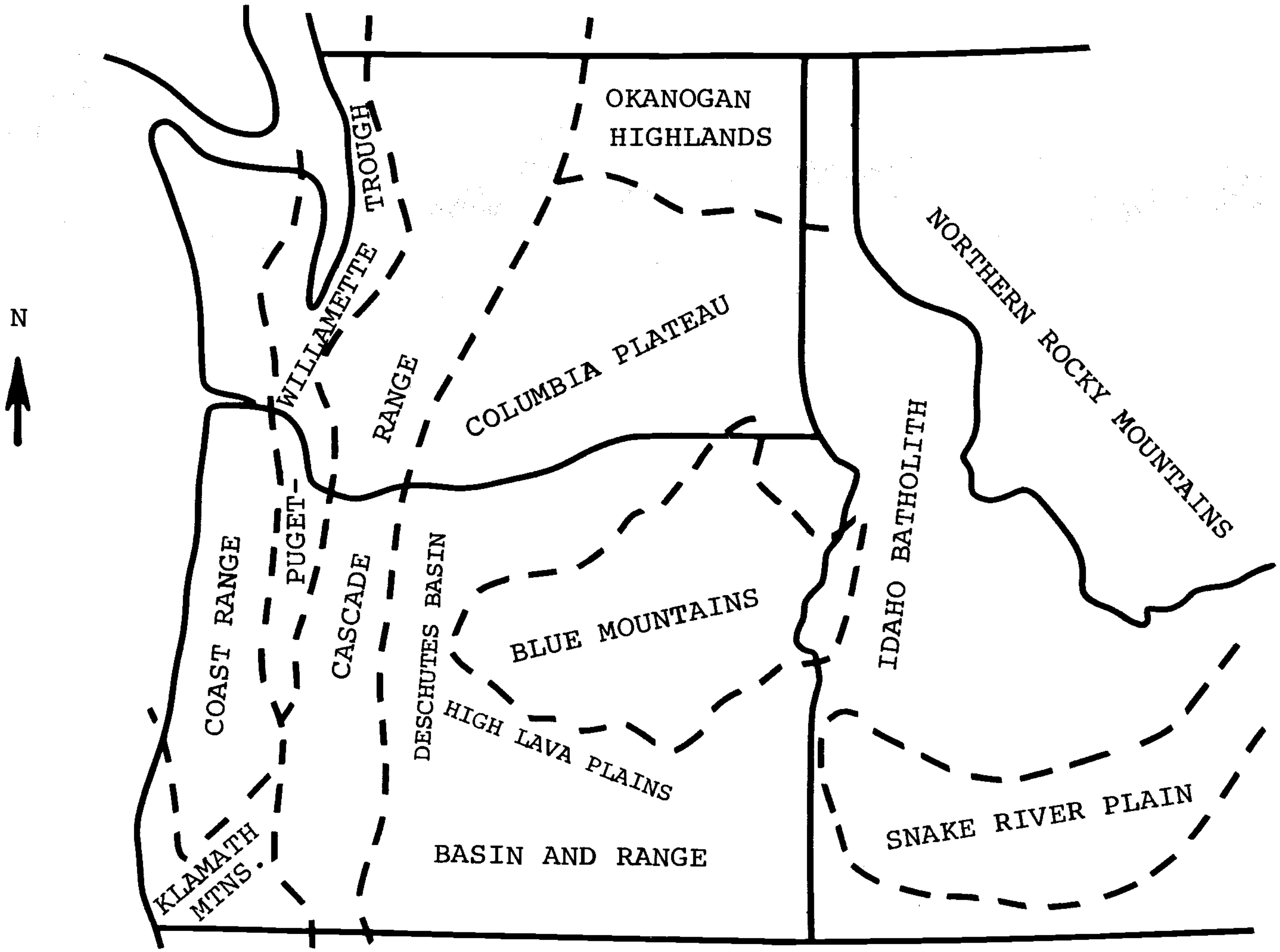


Figure 1. Regional geologic provinces of the Pacific Northwest. (after McKee, 1972)

Basis of Investigation

The John Day and Mitchell faults are large scale, nearly east-west-trending structures which offset both Tertiary and pre-Tertiary rock units in the Blue Mountains geologic province of north-central Oregon. The John Day fault bounds the northern flanks of the Aldrich and Strawberry ranges, and forms a prominent linear physiographic feature which is visible both on the ground and on remote sensing imagery (Figure 2). The Mitchell fault bounds the northern flank of the Ochoco Mountains to the west of the Aldrich Mountains, and is nearly on strike with the John Day fault. Considered together on a regional scale, these faults, and the numerous parallel but smaller scale faults associated with them, form an almost continuous fault zone which nearly bisects the Blue Mountains province at an oblique angle to the overall structural trends of the province. It has been suggested that this zone may provide a significant clue to the Tertiary tectonics of not only the Blue Mountains region but of the entire Pacific Northwest (Thayer and Wagner, 1968). It is one of the major goals of this investigation to examine this possibility.

Figure 2. LANDSAT composite image of Oregon, showing area of study.

With this geologic setting in mind, the immediate objectives of this investigation are (1) to compile and review previous work on the structural geology and tectonic history of the area, (2) to determine the regional structural character of the Tertiary rock units of the area, and (3) from this to interpret the Tertiary tectonic history of the area.

Location

This investigation comprises approximately 12,400 square kilometers in north-central Oregon, encompassing parts of Wheeler, Grant, Crook, Jefferson, and Baker Counties (Figure 3). The area extends from the longitude of Prineville on the west to the longitude of Baker on the east, and includes approximately 25 kilometers to the north and south of the John Day and Mitchell faults. U.S. Highway 26 crosses the area from west to east, and State Highway 19 and U.S. Highway 395 provide north-south access. County maintained dirt and gravel roads and National Forest Service roads provide additional but limited access.

The area of study lies entirely within the Blue Mountains uplift. Topographic relief in the area is greater than 2000 meters, ranging from about 1000 meters elevation along the John Day River to over 3000 meters elevation in the Strawberry Mountains. The climate is semi-arid, with a low annual rainfall. Lower elevations support sagebrush and juniper vegetation, while more dense Ponderosa pine forests thrive at higher elevations. The economy of the region is dominated by cattle ranching, although the John Day

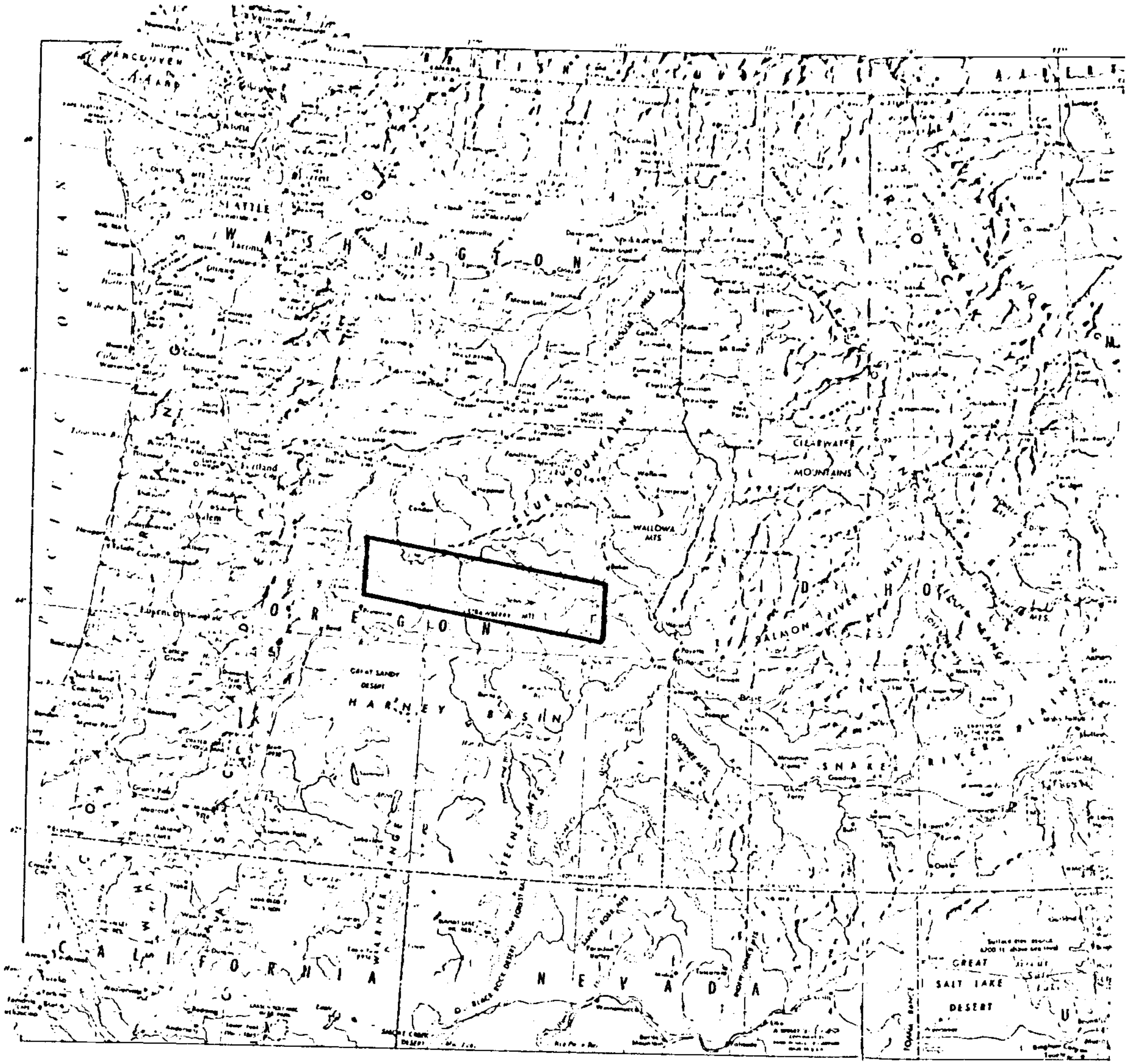


Figure 3. Geographic location map of thesis area.

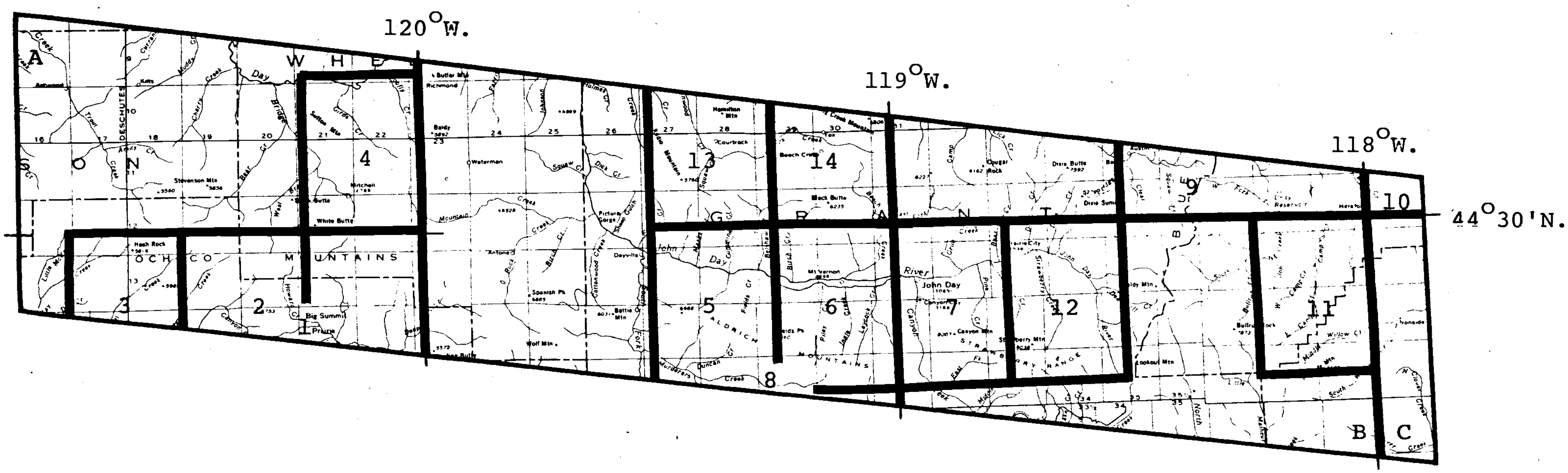
Valley supports limited farming. The higher forests support an active logging industry, and also serve for summer grazing and recreational purposes.

Historic mining in the area recovered gold, silver, and chromium, with minor quantities of asbestos, copper, cobalt, mercury, manganese, antimony, and tungsten. Most of this mining activity occurred near Canyon City and in the Horse Heaven mining district northwest of Mitchell. Hot springs in the John Day Valley and along the southern and eastern margins of the Blue Mountains province have recently aroused interest in the geothermal capabilities of the area.

Previous Work

The geology of north-central Oregon was first described in detail by Merriam (1901), who recognized and named most of the Tertiary volcanic units in the John Day drainage basin, including the Clarno, John Day, Columbia River, Mascall, and Rattlesnake Formations. He also noted the presence of Cretaceous conglomerates and shales, which he correlated with Cretaceous sedimentary strata in northern California. Most of Merriam's formational definitions remain in use today. Calkins (1902) described the petrography of the Tertiary volcanic units in more detail. Merriam's Cretaceous strata were described in greater detail by Packard (1929), who also was the first to note the presence of Paleozoic strata in this part of the Blue Mountains region (Packard, 1928). Gilluly (1937) described the Tertiary and pre-Tertiary rock units found in the eastern part of the thesis area, in the Unity Basin and vicinity. The pre-Tertiary strata of the Aldrich Mountains area was described in detail by Dickinson and Vigrass (1965).

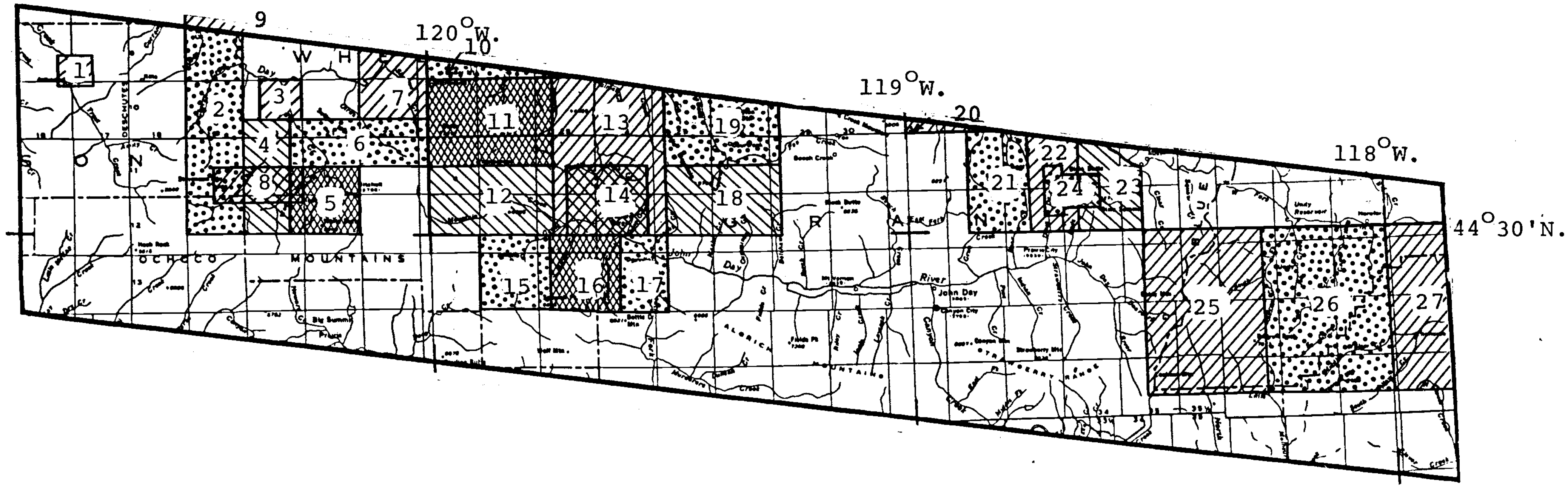
The first regional geologic map of the John Day Basin was published by Hodge (1942). Since then, numerous geologic maps of parts of the area have been



Scale 1:1,000,000

A Swanson, 1969
B Brown and Thayer, 1966a
C Brooks et al., 1976
1 Wilkinson, 1940
2 Waters, 1968a
3 Waters, 1968b
4 Oles and Enlows, 1971
5 Thayer and Brown, 1966a
6 Brown and Thayer, 1966b
7 Thayer, 1956
8 Wallace and Calkins, 1956
9 Pardee, 1941
10 Gilluly, 1937
11 Lowry, 1968
12 Thayer and Brown, open-file
13 Thayer and Brown, open-file
14 Thayer, Brown, and Hay, open-file

Figure 4. Published geologic maps in thesis area.



1	Ojala, 1964	10	Lindsley, 1960	19	Napper, 1958
2	Lukanuski, 1963	11	Snook, 1957	20	Thompson, 1956
3	Huggins, 1978	12	Irish, 1954	21	Humphrey, 1956
4	Swarbrick, 1953	13	White, 1964	22	Mobley, 1956
5	Howard, 1955	14	Coleman, 1949	23	Nelson, 1956
6	Bowers, 1953	15	Dobell, 1949	24	Johnson, 1976
7	Bedford, 1954	16	Dawson, 1951	25	Wray, 1946
8	Owen, 1978	17	Taubeneck, 1950	26	Lowry, 1943
9	Taylor, 1960	18	Cummings, 1958	27	Wolff, 1965

Figure 5. Unpublished geology theses covering parts of thesis area.

published at various scales, primarily by the U.S. Geological Survey as geologic quadrangle maps (Figure 4). In addition, many geologic maps covering parts of the current study area have been completed for M.S. and Ph.D. theses (Figure 5). Reconnaissance geologic maps of the three 1:250,000 quadrangles (Bend, Canyon City, and Baker) which include the thesis area have been published by the U.S.G.S. (Swanson, 1969 and Brown and Thayer, 1966a) and by the Oregon Department of Geology and Mineral Industries (Brooks et al., 1976).

Although much geologic work has concentrated on the John Day and Mitchell areas, there has been limited discussion of the regional structure and tectonics of the area. Only recently have attempts been made to tie the known structural geology of the area to a regional tectonic history of the western margin of the North American plate. Hamilton and Myers' 1966 paper stands out as the basis of subsequent work by Simpson and Cox (1977), Churkin and Eberlein (1977), and others. Recent attempts to relate Tertiary volcanism to plate tectonic models of western North American plate boundary evolution have followed the pioneering work of Dickinson (1968) and Atwater (1970).

Methods of Study

The major emphasis of this investigation is on regional data compilation and synthesis. In addition to a literature compilation, a heavy emphasis has been placed on data obtained from remote sensing imagery. The remote sensing part of the investigation involved examination of LANDSAT, U-2, and SLAR imagery for structural trends, field examination of joints and major structures, and analysis and synthesis of these data into a tectonic picture of the area.

Structural analysis of the area was initially undertaken using LANDSAT multispectral scanner imagery. This imagery is recorded at an altitude of approximately 920 kilometers on seven separate wavelength bands. For geologic purposes, Band 5 (wavelengths 0.6 to 0.7 micrometers) and Band 7 (0.8 to 1.1 micrometers) were found to be most useful. Band 5 highlights vegetation, which is often controlled by geologic and topographic features, while Band 7 shows topographic detail. LANDSAT Band 5 coverage of the thesis area was examined at two scales, 1:1,000,000 and 1:500,000. Lineaments observed at both scales were mapped at 1:1,000,000, and then plotted at the final map scale of 1:250,000 using a Bausch and Lomb Zoom Transfer Scope.

High altitude infrared photography was used to map additional and smaller scale photo-linear features. This photography is recorded by N.A.S.A. U-2 aircraft flying at an altitude of approximately 20 kilometers. The photographs utilized in this study are 22.5 by 22.5 cm. color transparencies at a scale of 1:120,000. Stereoscopic pairs of photos were examined using an Old Delft mirror-type stereoscope with a 4X magnification. Lineaments mapped from U-2 photographs were plotted on a separate map overlay at a scale of 1:250,000, again with the aid of the Zoom Transfer Scope.

Side-looking airborne radar (SLAR) coverage of the area of study was obtained at a scale of 1:2,000,000 from Dr. Charles Rosenfeld, Oregon State University Department of Geography, and the 1042nd Military Intelligence Company (Aerial Surveillance), Oregon Army National Guard. SLAR records long wavelength microwaves reflected from terrain at a set scale which remains constant regardless of differences in flight altitude. Due to the large scale of this imagery, it was used for visual comparison only.

Statistical analysis of the dense U-2 lineament data was undertaken by selecting sub-areas within the thesis area which represent single stratigraphic units. The area of each sub-area was measured using a K&E compensating polar planimeter. Within each sub-area, the orientation and length of each individual U-2 lineament was measured. The data from each sub-area was then plotted on a separate rose diagram, and lineament statistics were tabulated across the entire thesis area.

Field studies were completed over a period of four weeks between August 1977 and April 1978. Field sample sites were selected for the purpose of measuring local joint orientations, for later synthesis with lineament orientations. Sites were chosen to provide field representation of U-2 lineament sub-areas. Joint orientations were measured using a Brunton pocket transit. Joint orientations for each location were plotted both on equal area stereonets and on rose diagrams, for comparison with rose diagrams of the photo-lineament data.

The base map used for the final plotting of observed lineaments includes parts of the Bend, Canyon City, and Baker 1:250,000 topographic quadrangles at that scale, to facilitate comparison of the lineaments with published geologic reconnaissance maps.

Regional Geologic Setting

The Blue Mountains province is a region of mountain ranges and intermontane basins with both structural and stratigraphic complexity, distinguishing it from the surrounding, geologically more straightforward provinces. The inhomogeneous nature of the Blue Mountains province is evident on the tectonic map of north-central Oregon (Figure 6), which displays the wide variety of structural trends found within the province. In contrast, each of the adjacent geologic provinces exhibits internal homogeneity. To the north of the Blue Mountains, the Columbia Plateau province consists of simply deformed, nearly horizontal Tertiary volcanic strata, as does the Deschutes Basin directly west of the Blue Mountains province. Farther west, the Cascade Range and Puget-Willamette provinces are characterized by their definitive north-south trends. To the south and southeast of the Blue Mountains, the geology of the Basin and Range is dominated by extensive Tertiary volcanics which are offset by the north-south-trending normal faults responsible for the topography of the province. Northeast of the Blue Mountains, the mountainous pre-Tertiary volcanic terrane of the Seven Devils area separates the bulk of the Blue Mountains from the Idaho Batholith to the east.

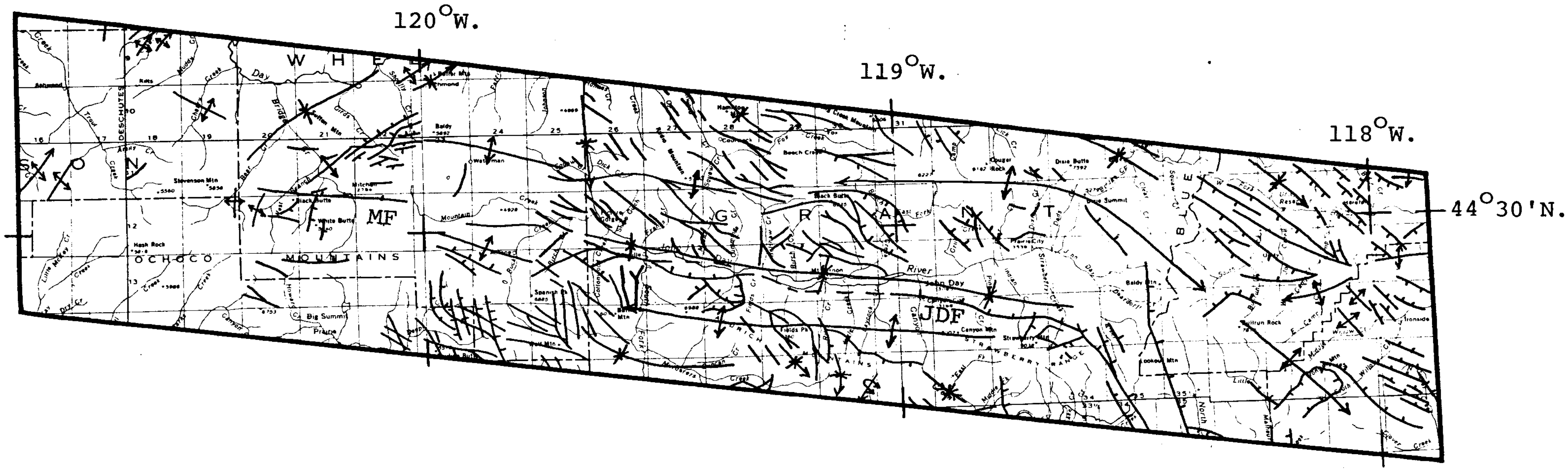


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Figure 6. Tectonic map of the thesis area (after Walker, 1977). MF=Mitchell fault, JDF=John Day fault.

Structural Setting

The Blue Mountains province can be divided into several distinct structural domains according to the age of rocks exposed and by structural style, as shown schematically in Figure 7. These domains are clearly visible on a LANDSAT mosaic of the province (Figure 2). One of the more conspicuous structural domains is characterized by the Blue Mountains Anticlinorium (Domain I), which makes up the northwestern margin of the province. This domain includes the large scale gently folded northeast-trending Blue Mountains anticline, which is slightly oversteepened to the northwest, and the numerous accompanying folds of smaller scale which exist along its flanks. These structures involve the mid-Tertiary Columbia River Basalts, so that the boundary between the Blue Mountains province and the Columbia Plateau to the north can be defined by the northernmost edge of this fold belt.

Another structural domain in the Blue Mountains province which is easily recognized on LANDSAT imagery includes the Wallowa Mountains uplift in the north-eastern corner of the province (Domain II). This domain

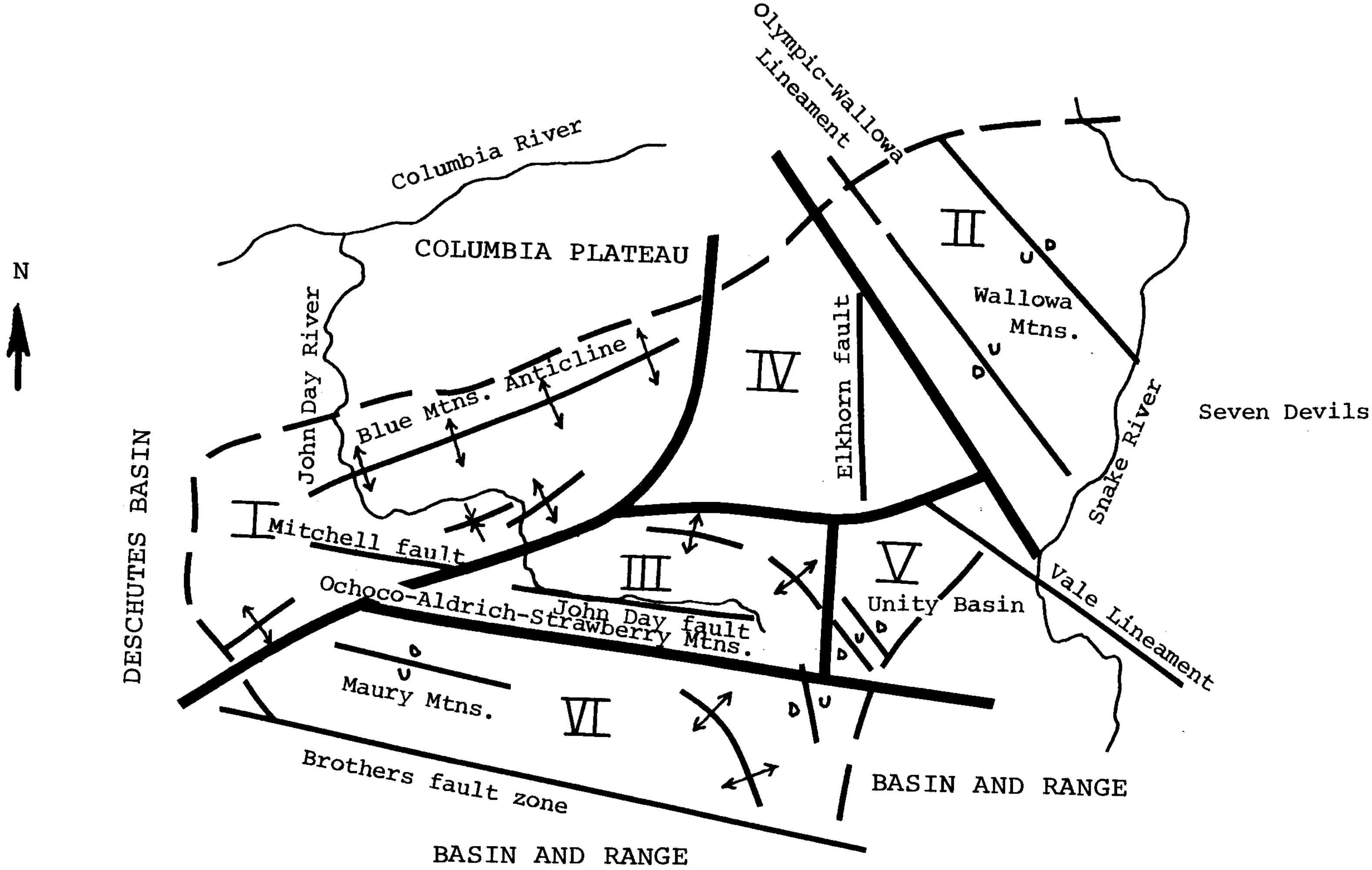

Figure 7. Structural domains in the Blue Mountains province.

is dominated by a northwest-trending normal fault-bounded uplift, or horst, which is deeply dissected, exposing a Mesozoic granitic core. Tertiary volcanics, extensive elsewhere in the Blue Mountains province, are for the most part absent in this domain.

The central part of the Blue Mountains province, Domain III, includes the area directly adjacent to the John Day and Mitchell faults. This domain is characterized by numerous parallel, nearly east-west-trending faults and fold axes. The larger scale Tertiary structures in this domain, in particular the John Day fault and the Aldrich Mountains anticline directly south of it, have resulted in the exposure of Paleozoic and Mesozoic strata which directly underlie the extensive Tertiary formations in the region and which are considered to be the "basement" of the Blue Mountains province.

Domain IV, to the north and east of the John Day fault zone, includes the Elkhorn, Greenhorn, and Blue Mountain ranges. This domain is characterized by north- and northwest-trending fold axes and steeply dipping faults, including the prominent Elkhorn fault. Pre-Tertiary exposures exist scattered throughout this structural domain.

Another distinct structural domain, Domain V, exists to the east of the John Day drainage basin and is separated from it by the north-south-trending Blue Mountains. This domain, which includes the Unity Basin, is characterized by northwest-trending folds and fault blocks which involve Tertiary volcanics. These are similar in structural style to the structures found in the vicinity of the John Day and Mitchell faults; however, the northwest trend of the structures of Domain V is consistent throughout this domain.

South of the John Day and Mitchell faults, the structure of the Blue Mountains province becomes complexly intertwined with the structural style of the Basin and Range province. Although the northwest-trending Brothers fault zone is commonly considered to be the southernmost margin of the Blue Mountains province, north-south-trending Basin and Range-type normal faults exist north of this zone in Domain VI. Within this domain, east-west-trending structures similar to the John Day and other faults bend southeastward and become parallel to the Basin and Range-type structures, particularly near the eastern end of the John Day fault zone. To the west, the two structural trends are superimposed, resulting in an orthogonal fault pattern in the Maury Mountains area.

Stratigraphic Setting

In addition to its unique structural configuration within the framework of the Pacific Northwest, the Blue Mountains province is also set apart stratigraphically from its neighboring provinces. While middle and late Tertiary volcanic strata dominate the geology of adjacent provinces, the structural style of the Blue Mountains has resulted in exposure of underlying pre-Tertiary and older Tertiary rocks as well. Pre-Tertiary rock units are exposed primarily in erosional "windows" through the more extensive Tertiary cover, and are, as a result, difficult to correlate both within the Blue Mountains province and with other geologic provinces in the Pacific Northwest.

The pre-Tertiary rocks in the Blue Mountains province consist of predominantly marine strata which range in age from Devonian (Buddenhagen, 1967) to Cretaceous (Dickinson and Vigrass, 1965). Within the thesis area, the oldest of these are Permian meta-volcanic and meta-sedimentary rocks. Tectonically injected into these Paleozoic strata are serpentinized gabbro and peridotite of the Canyon Mountain Complex, of probable Triassic age (Thayer, 1963). Late Triassic to Early Jurassic marine strata of the Aldrich Mountains Group (Thayer and Brown, 1964) and a sequence of Jurassic marine strata (Dickinson and Vigrass, 1965) overlie the Canyon Mountain Complex and older Paleozoic strata with unconformity. Cretaceous clastic sedimentary strata overlie the older, slightly metamorphosed strata, and represent initial continental deposition in the region.

Continental volcanics dominate the Tertiary stratigraphic section and show a significant variation in chemical composition with time. All of the major Tertiary rock units found in the Blue Mountains region as a whole are represented within the thesis area.

The oldest Tertiary rock unit is the Clarno Formation, a series of primarily andesitic flow and pyroclastic units of late Eocene to early Oligocene age. More silicic tuffaceous rocks of the John Day Formation overlie the Clarno volcanics with slight angular unconformity. The Miocene Picture Gorge Basalt, a member of the extensive Columbia River Basalt Group, unconformably overlies the John Day Formation. In the eastern part of the study area, the Picture Gorge interfingers with contemporaneous andesites and rhyolites of the Strawberry Volcanics. The early

Pliocene Mascall Formation disconformably overlies the Picture Gorge Basalt, and is chiefly volcaniclastic in character. The correlative Ironside Formation overlies the Strawberry Volcanics to the east with similar stratigraphic relationship. The youngest formation in the thesis area is the Plio-Pleistocene Rattlesnake Formation, which consists primarily of fluvial gravel deposits with one or more widespread ignimbrite units. The Rattlesnake represents the last major depositional event in the John Day and Mitchell area.

GEOLOGIC HISTORY

Paleozoic - Triassic

Melange

The oldest rocks exposed in the Blue Mountains province are part of a large scale tectonic melange whose constituents range in age from mid-Paleozoic to early Mesozoic. The geographic extent of this melange is shown in Figure 8. Intact lithologic blocks within the melange unit are generally many kilometers in lateral dimension, and are nearly everywhere in fault contact with other melange members. Because of the large scale of the melange, individual rock types were until recently assigned to numerous separate formations, resulting in a confused geologic conception of the late Paleozoic and early Mesozoic history of the Blue Mountains province. Recent attempts to interpret the geology of the region in terms of plate tectonic theory have resulted in a more coherent picture of the late Paleozoic geologic setting of the area.

The oldest melange members are Devonian fossiliferous limestones and shales, dated paleontologically by Kleweno and Jeffords (1961) and Johnson (1978). These crop out in the Suplee area, south of the Aldrich Mountains, where they are in fault contact with a variety of oceanic sedimentary and volcanic rock units which range in age from Mississippian to Permian (Merriam and Berthiaume, 1943). Common lithologies in this area include chert, argillite, graywacke, limestone, and volcanic rocks (Dickinson and Vigrass, 1965). Rocks of similar lithology and age crop out in several other areas within the Blue Mountains, including the Elkhorn Mountains (Gilluly, 1937) and the Mitchell area (Wilkinson and Oles, 1968). Units now considered to be part of this late Paleozoic to early Mesozoic melange include the Coffee Creek, Spotted Ridge, and Coyote Butte Formations of Merriam and Berthiaume (1943) and the Burnt River Schist and Elkhorn Ridge Argillite of Gilluly (1937). Most of the melange members have been folded and faulted complexly, and metamorphism in the melange unit appears to increase from west to east across the Blue Mountains.

A plate tectonic interpretation of this structural melange is that it represents individual segments of late Paleozoic and early Mesozoic oceanic lithosphere which were juxtaposed and accreted to a subducting arc during Late Triassic eastward subduction (Brooks, 1979, Thayer and Brown, 1976, and Dickinson and Thayer, 1978). This interpretation is supported by the presence of both Asian and American foraminiferal assemblages in the Elkhorn Ridge Argillite (Brooks, 1979). The presence of ultramafic ophiolitic rocks of the Canyon Mountain Complex (Ave Lallement, 1976), including peridotite, gabbro, quartz diorite, and albite granite, lends additional support to the interpretation of the entire assemblage as a melange formed during subduction. Blueschists found in the Mitchell area have been dated by K-Ar methods to be Triassic in age (Hotz et al., 1977), possibly dating subduction and accretion in this area.

The structure of the late Paleozoic-early Mesozoic melange, as previously noted, is complex. However, gross structure seems to be dominated by northeast-southwest-trending fold axes, noted in the Mitchell quadrangle (Oles and Enlows, 1971) and in the Suplee area (Buddenhagen, 1967). These trends, and the structural boundaries found within the melange, may have had an effect on later tectonism in the Blue Mountains region. In addition, extensive serpentinization of the ultramafic members of the melange may have served to lubricate subsequent deformation along pre-existing structures in the vicinity of the Canyon Mountain Complex.

Oceanic Arc Terrane

During subduction and accretion of the melange, an oceanic island arc is postulated to the east of the subduction zone. This paleo-arc is represented in the Blue Mountains region by the Clover Creek Greenstone (Gilluly, 1937) and the Seven Devils Volcanics (Anderson, 1930), assemblages which include submarine volcanic flows, breccia, tuff, and interbedded volcanic-derived sedimentary rocks. These arc assemblages have been dated paleontologically to be Permian to Late Triassic in age (Brooks, 1979). The similarity in geochemistry of these rocks to the present day arc volcanics of the Aleutian Islands led Hamilton (1963) to infer a similar origin.

The island arc assemblage of the eastern Blue Mountains is overlain by a sequence of shallow water marine sedimentary rocks which include the Martin Bridge Limestone, the Hurwal Formation, and the contemporaneous Lucille Slate. The abundance of volcanic detritus within this sedimentary section suggests the possibility of continued tectonic activity during deposition of these units in Late Triassic to Middle Jurassic time.

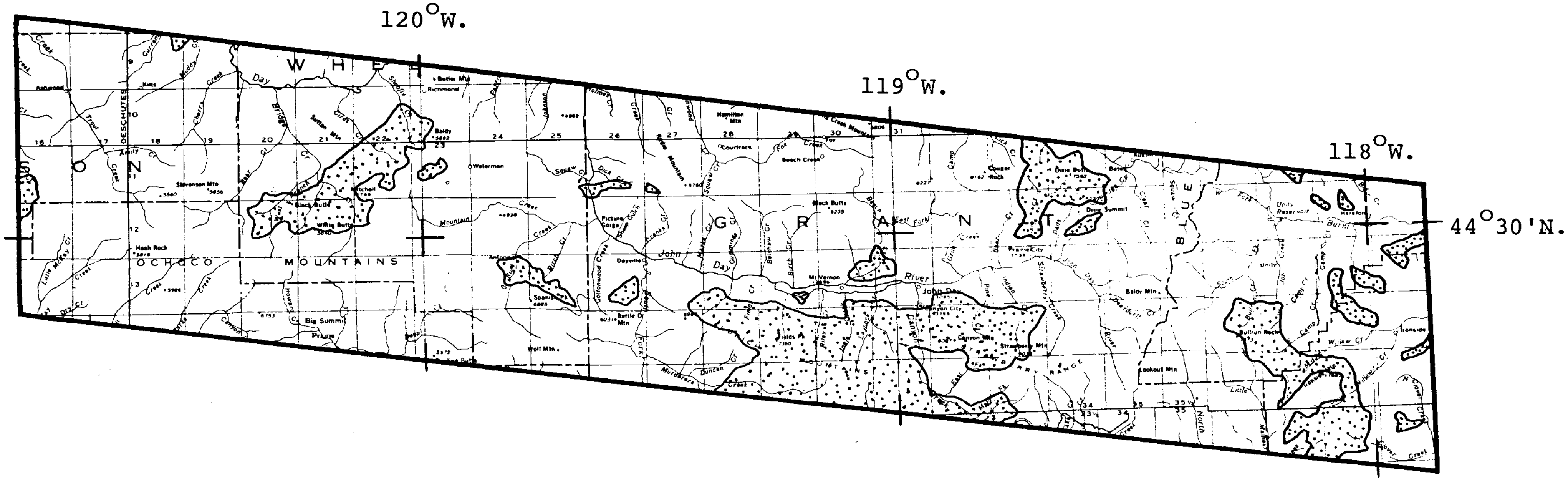

Figure 8. Distribution of pre-Tertiary rocks in the thesis area.

Vester Formation

The accreted late Paleozoic-early Mesozoic melange was overlain during the Late Triassic by clastic strata of the Vester Formation. The Vester is lithologically complex, and includes pebble conglomerate, sandstone, shale, sedimentary breccia, and andesitic tuff. The Begg and Brisbois Formations of Dickinson and Vigrass (1965) are now considered to be members of the Vester (Dickinson and Thayer, 1978).

The Vester Formation has recently been interpreted to be the result of fore-arc sedimentation, primarily because of the presence of identifiable turbidite sequences as well as andesitic components. In support of this interpretation are the juxtaposition and local intermixing of the Vester with melange members (Dickinson and Thayer, 1978), indicating continued tectonic activity subsequent to accretion of the main part of the melange.

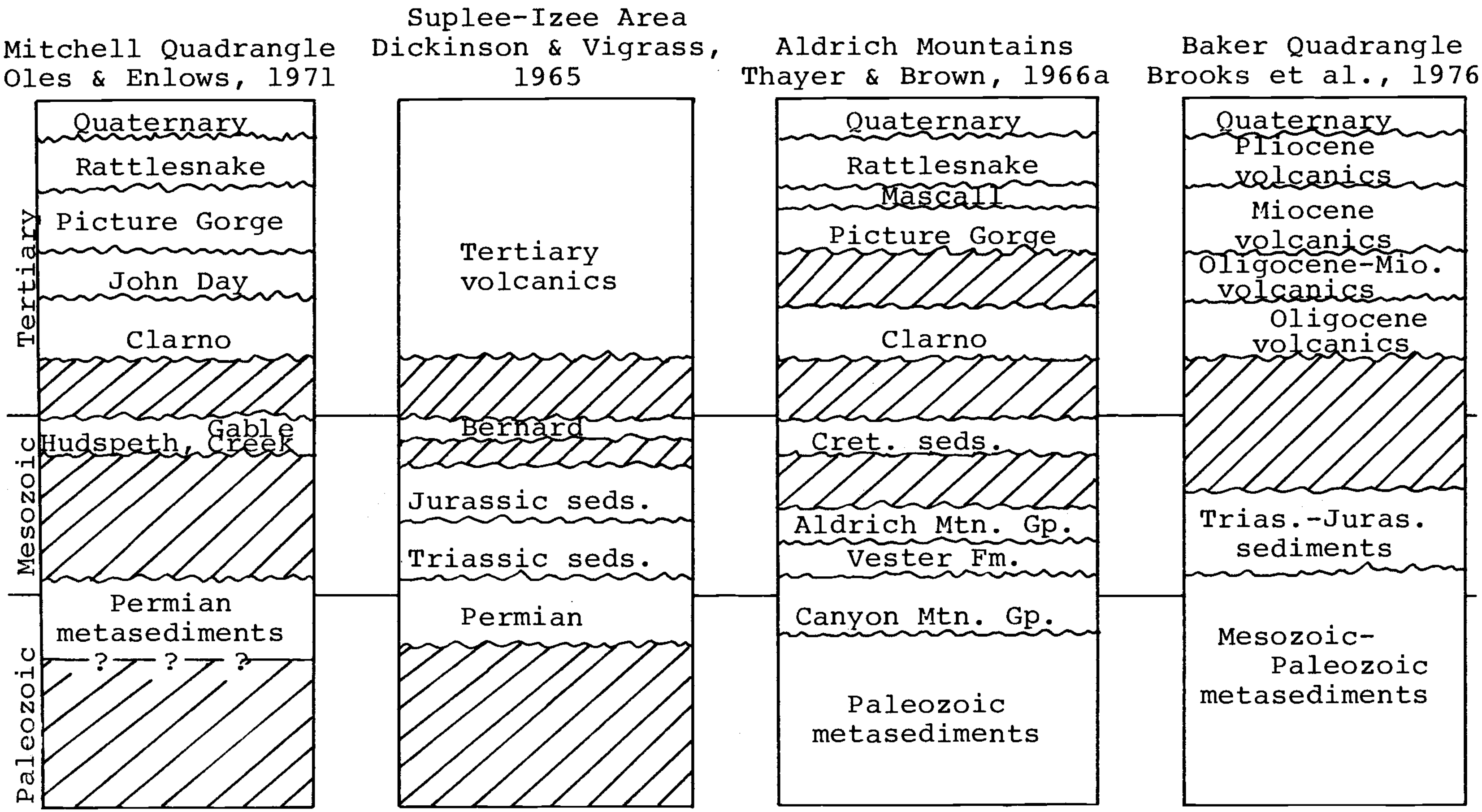

Figure 9. Stratigraphic correlation chart across thesis area.

Late Triassic - Jurassic

The Vester Formation is overlain with erosional and angular unconformity by a thick sequence of marine clastic sedimentary rocks belonging to the Aldrich Mountains Group. This group, exposed in the Aldrich Mountains and in the Suplee-Izee area, includes the Fields Creek Formation, Laycock Graywacke, Murderers Creek Graywacke, Keller Creek Shale, Rail Cabin Argillite, and Graylock Formation (Dickinson and Thayer, 1978). These units consist primarily of coarse- to fine-grained clastics, limestones, shales, and volcaniclastics of andesitic composition. Fossiliferous strata within the units date the group to range in age from Late Triassic to Early Jurassic. Total thickness of the Aldrich Mountains Group is nearly 10,000 meters. Like the underlying Vester Formation, these strata have been interpreted as fore-arc deposits which were shed southeastward into a fore-arc basin located above a west-northwest-dipping subduction zone (Dickinson and Thayer, 1978 and Brooks, 1976).

The Aldrich Mountains Group was folded and faulted, with minor accompanying metamorphism, prior to deposition of the overlying Jurassic sedimentary sequence. Dominant structural trends are northeast-southwest. The tremendous thickness of sediments in the Aldrich Mountains Group suggests continuous tectonism and downwarping during deposition.

A thick sequence of unmetamorphosed Jurassic marine sedimentary strata overlie the Aldrich Mountains Group with marked unconformity in the Suplee-Izee area. The hiatus represented by this angular unconformity may represent a major tectonic event during the Late Triassic to Early Jurassic. This event is supported by the presence of igneous intrusives of similar age (approximately 200 million years before present) in westernmost Idaho, adjacent to the Blue Mountains (Armstrong et al., 1977).

The Jurassic sedimentary sequence is lithologically similar to the underlying Aldrich Mountains Group and the Vester Formation, with the exception that volcaniclastic strata are more abundant and clastics finer grained and better sorted within the younger sequence (Thayer and Brown, 1976). This sequence includes the Mowich Group, the Snowshoe Formation, and the Lonesome Formation (Dickinson and Vigrass, 1965). Total thickness of the sequence may exceed 10,000 meters. Abundant fossil ammonites in each of these formations record a range in age from Early to Late Jurassic.

Like the underlying Mesozoic units, the Jurassic sequence is interpreted to represent fore-arc deposition (Dickinson and Thayer, 1978). The smaller grain size and the lesser degree of deformation as compared with the Aldrich Mountains Group and the Vester Formation may indicate a reduction of tectonic activity during the Jurassic (Thayer and Brown, 1976).

Summary of Pre-Cretaceous Geologic History

The pre-Cretaceous geologic history of the Blue Mountains province is dominated by island arc tectonism. The late Paleozoic to early Mesozoic melange terrane of the southwestern Blue Mountains was formed when pieces of oceanic lithosphere were tectonically mixed and accreted to an oceanic arc, represented by the eastern Blue Mountains-Seven Devils volcanic terrane. The Mesozoic sedimentary deposits of the central Blue Mountains developed during fore-arc basin deposition adjacent to and overlying the melange, and oceanward of the island arc.

Cretaceous

Jurassic and older strata are intruded in the Blue Mountains province by rocks of predominantly granitic composition (Figure 10). Thayer and Brown (1964) reported a date for the westernmost of these intrusive outcrops of from 120 to 150 million years B.P. (before present), based on K-Ar dating techniques. This age closely correlates with K-Ar and Rb-Sr dates of the larger Wallowa and Bald Mountain plutons to the northeast. Within the thesis area, these granitic intrusives are stratigraphically age-bracketed by overlying sediments of middle Cretaceous age (Oles and Enlows, 1971).

The Late Jurassic to Early Cretaceous intrusives of the Blue Mountains province have been thought to be outliers of the Idaho Batholith (Taubeneck, 1957 and 1964). However, the bulk of the Idaho Batholith, to the east, yields dates ranging from 70 to 100 million years B.P. (Armstrong et al., 1977). A possible interpretation for this age disparity is that magmatism may have been initiated to the west in latest Jurassic time and migrated eastward during the Cretaceous, culminating in the vicinity of present day

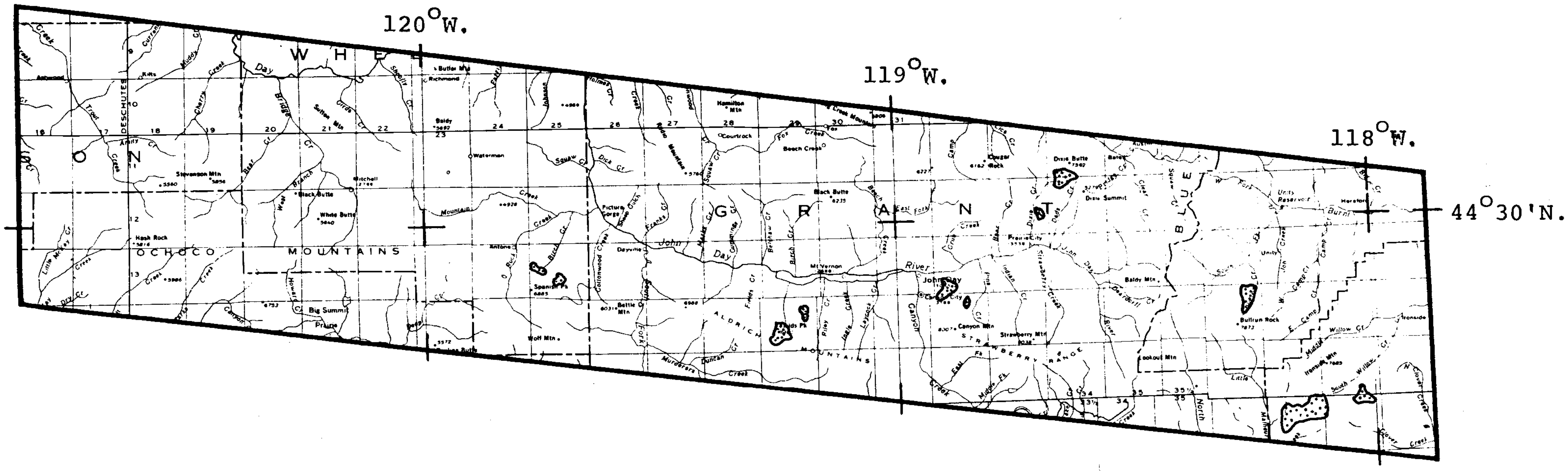

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Figure 10. Distribution of granitic rocks in the thesis area.

Idaho and Montana in Late Cretaceous to early Tertiary time. In the broader tectonic framework of western North America, this episode approximately coincides with the beginnings of the widely recognized Laramide Orogeny. This orogenic event may represent the final closing of an inter-arc basin, and subsequent development of an Andean-type continental margin arc (Hamilton, 1969).

Coarse-grained clastic rocks of Cretaceous age unconformably overlie, and contain clasts derived from, the Early Cretaceous intrusives and older, slightly metamorphosed rocks of the Blue Mountains province. In the thesis area, these post-intrusive sedimentary strata are exposed in three main localities: the Mitchell area, where they include the Hudspeth and Gable Creek Formations (Wilkinson and Oles, 1968), along the John Day River north of Picture Gorge, where they are referred to as the Goose Rock Conglomerate (Thayer, 1972), and in the Suplee-Izee area, where they are termed the Bernard Formation (Dickinson and Vigrass, 1965). The "Chico" and "Knoxville" of Merriam (1901) are included in the above formations.

The Cretaceous stratigraphic section has been studied in detail in the Mitchell area by Wilkinson and Oles (1968) and by Oles and Enlows (1971). In this area, Cretaceous strata consist of deltaic and fluvial clastic rocks ranging from mudstone to conglomerate (Figure 11), and represent the first continentally derived deposits in the Blue Mountains province. Shallow marine fossiliferous zones date these units as middle Cretaceous in age. Paleocurrent studies indicate deposition occurred to the south and southeast (Wilkinson and Oles, 1968). This may reflect local downwarping in a sheltered embayment on the accretionary continental margin (Dickinson and Thayer, 1978).

Figure 11. Cretaceous Gable Creek Conglomerate, northeast of Mitchell near Sutton Mountain.

Early Tertiary

Eocene to Oligocene

The oldest rocks of Tertiary age in the Blue Mountains province are widespread Eocene volcanics of predominantly andesitic composition belonging to the Clarno Formation. The Clarno Formation was first defined by Merriam (1901) to include Eocene to Oligocene volcanic flows and tuffs in the John Day Basin. The Clarno has been described in greatest detail in the Mitchell area (Oles and Enlows, 1971), but extends as far north and west as the Horse Heaven area (Waters et al., 1951), as far south as the Maury Mountains (Swanson, 1969), and eastward beyond the Strawberry Mountains to the Unity Basin (Thayer and Brown, 1966a). The areal distribution of Clarno rock types in the thesis area is shown in Figure 12.

The stratigraphy of the Clarno Formation varies markedly from one locality to another, making regional correlation difficult. However, all localities have in common rocks of primarily andesitic composition deposited continentally, primarily in subaerial and lacustrine environments. Common lithologies include

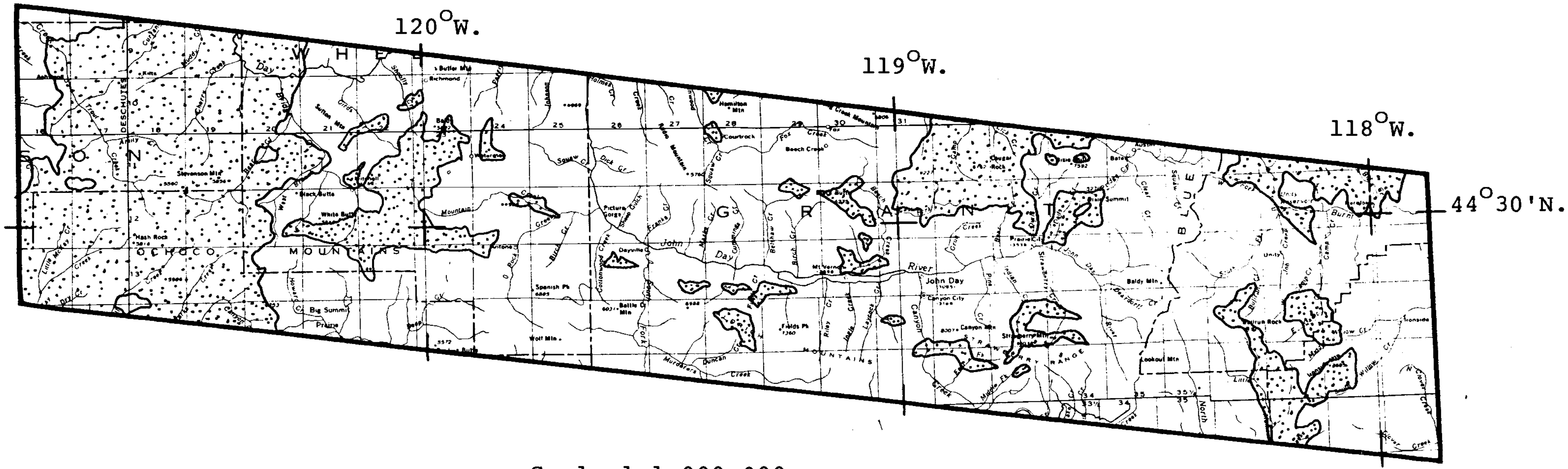

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Figure 12. Distribution of the Clarno Formation in the thesis area.

lava flows, volcanic mudflows, tuffs, and breccias of predominantly andestic composition, although compositions ranging from basalt to rhyolite are present.

The most detailed mapping of the Clarno has been completed in the vicinity of Mitchell by Oles and Enlows (1971) and by theirs and Dr. Edward M. Taylor's students at Oregon State University. In the Mitchell quadrangle, two distinct Clarno volcanic sequences are separated by an obvious angular unconformity and distinguished by degree of deformation. This led Oles and Enlows (1971) to recommend group status for the Clarno, to include both sequences, locally termed Upper and Lower Clarno. However, Clarno sequences described elsewhere in the Blue Mountains lack any prominent unconformity and more closely resemble the Lower Clarno sequence both lithologically and paleontologically. In the eastern part of the thesis area, in the vicinity of the Unity Basin and Ironside Mountain, Clarno-type rocks have been described which are roughly time-equivalent and lithologically similar to the more typical Lower Clarno of the Mitchell area. These include the "andesitic tuff" of Pardee and Hewitt (1914), the "andesite tuff and breccia" of Gilluly (1937), "andesite flows and tuffs" of Pardee (1941), "andesitic flows and agglomerates" of Lowry (1943) and Wray (1946), and "andesitic flows and tuffs" of Brooks et al. (1976).

Modal analyses of Clarno rocks by Enlows and Oles (1973) indicate the following average composition for Clarno andesitic volcanism: 78% plagioclase, 14% augite, 5% magnetite, 2% hypersthene, plus trace components of quartz, hornblende, and volcanic glass. Geochemical analyses by Novitsky-Evans (1974) and by Rogers and Novitsky-Evans (1977) suggest that the Clarno reflects a calc-alkaline compositional trend representative of volcanic arc assemblages. The terrestrial nature of Clarno deposition suggests that this arc developed along the early Tertiary continental margin. Low SiO_2 and strontium content, and the dominance of pyroxene over hornblende, more typical in oceanic arc assemblages, may reflect the predominance of arc- and oceanic-derived strata underlying the Clarno.

K-Ar dates presented by Enlows and Parker (1972) range from 46.0 to 30.0 million years B.P. for Clarno volcanism. The Lower Clarno volcanics directly overlie Cretaceous conglomerates and sandstones with only minor angular unconformity, although the time gap between deposition of these two units is significant. This suggests a lack of major tectonic activity during this period, from Late Cretaceous to Eocene time.

In the Mitchell area, where the Clarno has been studied in detail, Clarno strata exhibit significant structural deformation (Figure 13). In addition to numerous local erosional and angular unconformities, Clarno rocks exhibit complex jointing with accompanying slickensided faces, indicating post-depositional tectonism. Lower Clarno rocks are folded and faulted to a greater degree than Upper Clarno strata. Northeast-southwest fold axes such as the Mitchell anticline are dominant in this area, and involve at least Lower Clarno and Cretaceous strata. Other Clarno outcrop areas in the Blue Mountains have been studied in less structural detail. However, tectonic jointing, folding, and faulting in the Clarno have been noted elsewhere in the thesis area, suggesting that widespread tectonism may have accompanied and closely followed Clarno volcanism, occurring prior to the main part of subsequent John Day volcanism and deposition.

Figure 13. Deformed Lower Clarno volcanics, northwest of Mitchell near the Painted Hills.

Oligocene to Miocene

A thick sequence of poorly indurated volcaniclastics belonging to the Oligocene to early Miocene John Day Formation directly overlies Clarno rocks in the western part of the Blue Mountains province (Figure 14). Stratigraphically equivalent rocks appear to be missing to the east in the upper John Day Basin and in the Unity Basin, where middle Miocene rocks are in direct contact with Clarno strata. Locally, the contact between John Day and Clarno rocks appears to be gradational (Peck, 1961), but elsewhere, a marked angular unconformity exists between the two formations. Fisher and Wilcox (1960) noted that John Day tuffs locally overlie a weathered saprolitic zone above the Clarno, representing at least a brief hiatus between deposition of the two formations. However, the noted angular unconformity may be the result of deposition of the horizontal-lying tuffs of the John Day over the more rugged volcanic topography of the Clarno, rather than the result of tectonic activity occurring prior to John Day deposition. The overlapping of K-Ar dates for the Clarno (46 to 30 myB.P.) and John Day (36 to 23 myB.P.) (Laursen and Hammond, 1974 and Enlows and

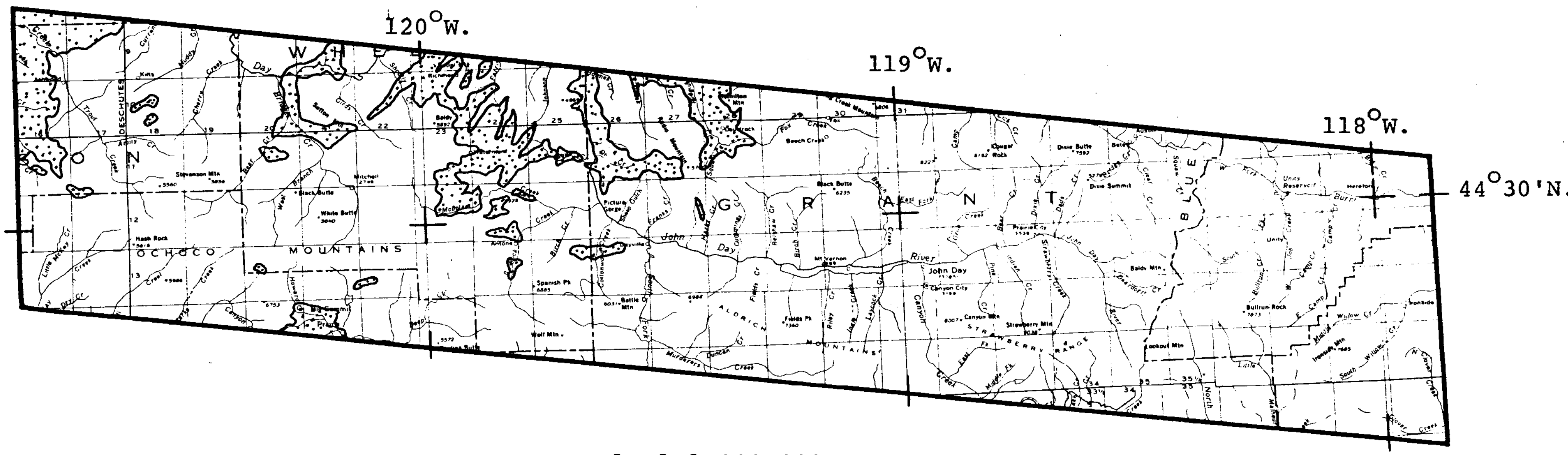

Figure 14. Distribution of the John Day Formation in the thesis area.

Parker, 1972) supports the possibility that volcanism and deposition continued with only minor interruption during Eocene to early Miocene time.

The John Day Formation was first described by Marsh (1875) as a thick sequence of lake bed deposits. Merriam (1901) later identified the unit as being volcanic in origin. Detailed study of the John Day has been accomplished more recently by Fisher and Wilcox (1960) on stratigraphy in the Monument area, by Peck (1961) on the John Day in the Ashwood area, and by Robinson (1966) on facies changes within the John Day.

The John Day Formation is commonly described in terms of an eastern and a western facies (Robinson, 1973). The eastern facies includes the type section of the John Day in the Painted Hills, where it consists of three thick sequences of tuffaceous mudstones and vitric tuffs, separated by resistant ignimbrites (Hay, 1963) which are easily correlated from one locality to another. The western facies of the John Day, in the Clarno-Antelope-Ashwood area, is more complex stratigraphically, and includes at least five separate ignimbrites within the section (Peck, 1964). Within the thesis area, the John Day is better represented by its eastern facies.

The John Day Formation is readily recognizable in the field as a result of its weathering characteristics, forming low, easily eroded hills with numerous gullies and rills, typical of weathering in soft, poorly consolidated materials (Figure 15). Tuffs of the John Day are varicolored, ranging from green to red and buff. Mammalian fossils indicate an Oligocene to early Miocene age for the John Day volcanics, in support of K-Ar dates.

The John Day Formation is characteristically silicic in composition (Robinson, 1966), suggesting that the andesitic arc volcanism of Clarno time had waned and was gradually replaced by the more silicic and episodic eruptions of the John Day tuffs. Contemporaneous andesitic volcanism to the west in what is now the western Cascade province suggests that active plate subduction and concomitant arc volcanism migrated to the west following eruption of the Clarno during the Eocene to early Oligocene (Lawrence, 1979).

Because the John Day tuffs are poorly consolidated, they rarely exhibit joint or fault surfaces in outcrop. As a result, little structural study of the unit has been undertaken. Small scale faults are visible only locally within the tuff sequences, but may indicate some tectonism accompanying John Day volcanism.

Figure 15. John Day Formation at Cathedral Rock, north of Picture Gorge on the John Day River. Note the resistant ignimbrite near the top of the outcrop.

Middle Tertiary

John Day volcanism was followed by a period of erosion and tectonic activity recorded by the regional angular unconformity which separates John Day and Clarno strata from the overlying basalts of the Columbia River Group. Within the thesis area, members of the Columbia River Basalt Group locally lie directly on Clarno rocks, suggesting that the initially widespread John Day Formation was locally stripped away by erosion. Elsewhere, broadly folded and faulted John Day tuffs are overlain by less deformed basalts of the Columbia River Group. A significant radiometric age gap between the two units, from 23 myB.P. for youngest John Day tuffs to 17 myB.P. for oldest Columbia River Basalts, lends additional support to a major tectonic hiatus following John Day deposition.

The Columbia River Basalt Group includes areally extensive Miocene and early Pliocene predominantly basaltic flow units which exceed 3500 meters in aggregate thickness in the Columbia Plateau region. To the south in the Blue Mountains province, the Columbia River Basalt Group is represented primarily by the Miocene Picture Gorge Basalt. The contemporaneous

Strawberry Volcanics and the volcaniclastic Mascall and Ironside Formations are physically contiguous to the Picture Gorge Basalt (Figure 16). Miocene basalts to the south in the Basin and Range province may be genetically related, but are not considered to be part of the Columbia River Group (Goles, oral comm.).

The nomenclature of the Columbia River Basalts remains a subject of considerable controversy. The basalts were first elevated to group status by Waters (1961), to include both the Yakima Basalt of Smith (1903), found along the Columbia River, and the older Picture Gorge Basalt, originally termed the "Columbia Lava" (Merriam, 1901). Waters specifically excluded the Mascall Formation, a volcaniclastic air-fall unit which overlies the Picture Gorge, and also excluded other sedimentary units which are intercalated with basalts of the Columbia River Group. The group has since been broadened to include the Imnaha and Prineville Basalts, as well as several sub-groups of the Yakima.

Although geochemically distinct from the Columbia River Basalt Group, several volcanic units in the central part of the Blue Mountains province were deposited at approximately the same time as basalt flows of the Columbia River Group, and locally interfinger with the

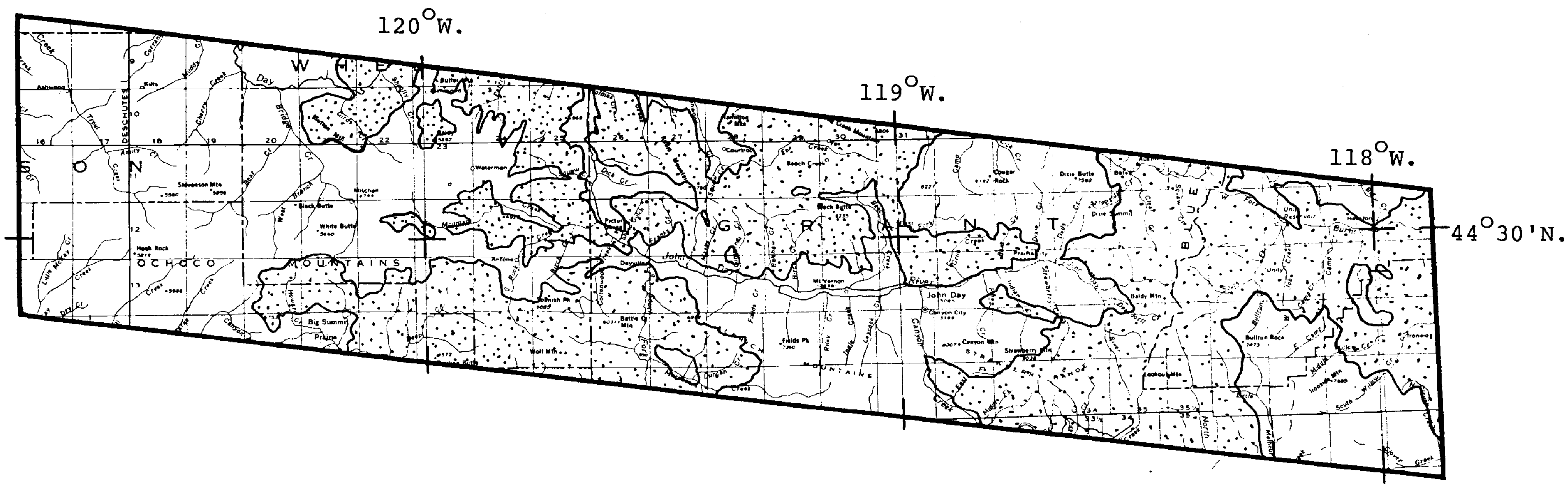

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Figure 16. Distribution of Miocene volcanics in the thesis area.

Columbia River basalt flows. These include the Slide Creek basalts and the Strawberry Volcanics. The volcaniclastic Mascall and Ironside Formations are late Miocene to early Pliocene in age, but are excluded from the Columbia River Group.

Picture Gorge Basalt

The oldest member of the Columbia River Group in the Blue Mountains province is the Picture Gorge Basalt, first defined by Merriam (1901) at its type locality, Picture Gorge. The Picture Gorge consists of a thick sequence of volcanic flows of olivine basalt composition which are believed to have erupted from the Monument Dike Swarm. At the type locality, eighteen individual flows are exposed, from the basal unconformable contact with the John Day Formation to the top of the basalt sequence, where tuffs of the Mascall Formation rest disconformably on the youngest basalt flow. Individual flows generally range in thickness from 15 to 30 meters, resulting in an aggregate thickness of approximately 500 meters. Flows exhibit well-developed columnar jointing, a distinctive characteristic of the Picture Gorge Basalt.

Figure 17. Picture Gorge Basalt at the type locality, Picture Gorge on the John Day River. Note the camper at the entrance to the gorge for scale.

Chemical analyses by Waters (1961) indicate a tholeitic basalt composition for the Picture Gorge. More recent studies by Goles (oral comm.) emphasize the high alumina and olivine normative character of these basalts. A typical sample shows 8% glass, 40% plagioclase, 35% clinopyroxene, 5% olivine, and 5% magnetite and ilmenite, with clay minerals after olivine and chlorophaeite (Swanson, 1969).

Picture Gorge flows have been dated radiometrically to range from 16.6 to 14.5 myB.P. (Laursen and Hammond, 1974). Although age distinction of individual flows by K-Ar means is not available because of the short time span between flows, paleomagnetic studies show that the earliest Picture Gorge flows are normal in magnetic polarity, while the latest flows appear to have been erupted during transitional polarity (Goles, oral comm.)

The similarities in chemistry between basalts of the Picture Gorge and mid-ocean ridge basalts implies that the Picture Gorge may have originated within the mantle, and remained relatively uncontaminated during the migration of magma through the Miocene crust of the Blue Mountains province. Goles (oral comm.) has suggested that these basalts were derived from a large scale mantle diapir. The nearly north-south orientation of the dike swarms from which the Picture Gorge is believed to have erupted suggests that extensional tectonic activity nearly parallel with east-west subduction west of the Cascade volcanic arc occurred during the Miocene. This relationship closely parallels numerous cases of back-arc spreading and related volcanism along present day plate margins.

Slide Creek Basalts

East of Picture Gorge, in the vicinity of the Strawberry Mountains, volcanic flows ranging from basaltic andesite to rhyolite compositions appear to have been extruded approximately contemporaneously with flows of the Picture Gorge Basalt (Robyn, Hoover, and Thayer, 1977). Some of these flows are both geochemically and physically similar to the Picture Gorge flows and appear to interfinger with them (Thayer, 1957). These flows are part of the Slide Creek basalts, variously considered to be part of either the Columbia River Basalt Group or the Strawberry Volcanics. Flows of the Slide Creek member interfinger with more andesitic and rhyolitic flows of the Strawberry Volcanics in the vicinity of the Aldrich and Strawberry Mountains.

Strawberry Volcanics

The Strawberry Volcanics were first described by Thayer (1957) for exposures in the Strawberry Mountains. This volcanic group is divided into two predominantly andesitic flow sequences, separated by a persistent and extensive zone of rhyolitic flows and volcaniclastics. Geochemical analyses of Strawberry Volcanics suggest a calc-alkaline composition (Goles, oral comm.).

The distribution of rhyolitic and dacitic members of the Strawberry Volcanics indicates that they were erupted from localized volcanic centers. The outward dip of flows away from the cirque walls near Strawberry Mountain imply that a large shield volcano in that vicinity was the source of much of the Strawberry Volcanics.

The predominantly andesitic Strawberry Volcanics are chemically dissimilar from the time-correlative Columbia River Basalts. Goles (oral comm.) and other workers have suggested that the geochemical variation of the Strawberry Volcanics may result from crustal contamination of the same basaltic magma which created the Columbia River Group to the north and west, where a thinner continental crust may have existed.

Figure 18. Strawberry Volcanics, exposed on Strawberry Mountain.

Mascall Formation

The Picture Gorge Basalt and the Strawberry Volcanics are overlain by volcaniclastic strata of late Miocene to early Pliocene age. These strata belong to the Mascall Formation to the west and to the Ironside Formation to the east of the Strawberry Mountains.

The Mascall Formation consists of a sequence of air-fall tuffs and water-laid volcaniclastics of rhyolitic composition (Enlows, 1973), first named by Merriam (1901) for exposures at the Mascall Ranch near Picture Gorge. The Mascall is found primarily along the John Day River from Picture Gorge to just west of Mt. Vernon, although erosional remnants are found in Fox Valley to the northeast.

The basal part of the Mascall lies directly on upper flows of the Picture Gorge Basalt, and has in the past been considered to be a part of the Columbia River Group (Thayer and Hay, 1950). However, the wide disparity in geochemistry between the Mascall and the Miocene basalts has led to its subsequent elimination from the group (Goles, oral comm.).

An extensive ignimbrite near the base of the Mascall has yielded a K-Ar date of 15.8 myB.P. (Davenport, 1971). This age is supported by abundant floral and faunal remains which indicate a middle to late Miocene age for Mascall deposition.

The Mascall is believed to have been deposited primarily as air-fall debris from violent rhyolitic eruptions, which gradually replaced the mafic eruptions of the Picture Gorge Basalt in the John Day Basin. Thayer (1957) has suggested that the Mascall may be related genetically to the rhyolitic members of the Strawberry Volcanics to the east.

Ironside Formation

To the east in the Unity Basin, the Ironside Formation appears to be a stratigraphic equivalent of the Mascall Formation. Tuffaceous buff-colored sandstones and mudstones of the Ironside directly overlie flows of the Strawberry Volcanics, and locally appear to be intercalated with them (Thayer and Brown, 1973).

Mammalian fossils in the Ironside Formation indicate a late Miocene to early Pliocene age (Merriam, 1916 and Wray, 1946) for the unit. Much of the clastic material of the Ironside appears to have been derived from the Strawberry Volcanics.

Middle Tertiary Structure

Miocene to early Pliocene volcanism was followed in the Blue Mountains province by a period of increased tectonic activity which may have been responsible for the present day structural character of the region. During this period, prior to deposition of the late Pliocene Rattlesnake Formation, the Miocene to early Pliocene Columbia River Basalts and overlying volcaniclastics were broadly folded and faulted throughout the province. Major structures originating during this period of tectonism include the broad Blue Mountains anticline, the John Day fault, and numerous related smaller scale structures. These post-Miocene structures exhibit a variety of orientations but are dominated by northwest, north, and northeast trends.

Late Tertiary

Following late Miocene to early Pliocene tectonism, the Columbia River Group and related volcanics were unconformably overlain in the central Blue Mountains by the Rattlesnake Formation, a sequence of coarse-grained gravel and cobble conglomerates with at least one ignimbrite member (Figure 19). The Rattlesnake was defined by Merriam (1901) to include "gravels, tuffs, and rhyolite lava" exposed in pediments and bluffs along both sides of the John Day River between Picture Gorge and the Strawberry Mountains. The "rhyolite lava" of Merriam has more recently been defined as an ignimbrite (Wilkinson, 1950).

The Rattlesnake ignimbrite exhibits a rhyo-dacitic composition (Enlows, 1973), with a normative analysis of 40% quartz, 24% orthoclase, and 32% plagioclase, with traces of ilmenite, magnetite, and enstatite. Sedimentary strata in the Rattlesnake contain abundant clasts of Columbia River Basalts.

Mammalian remains found within Rattlesnake sediments indicate a Pliocene age, in agreement with K-Ar dates of 6.4 to 6.0 myB.P. yielded by the ignimbrite

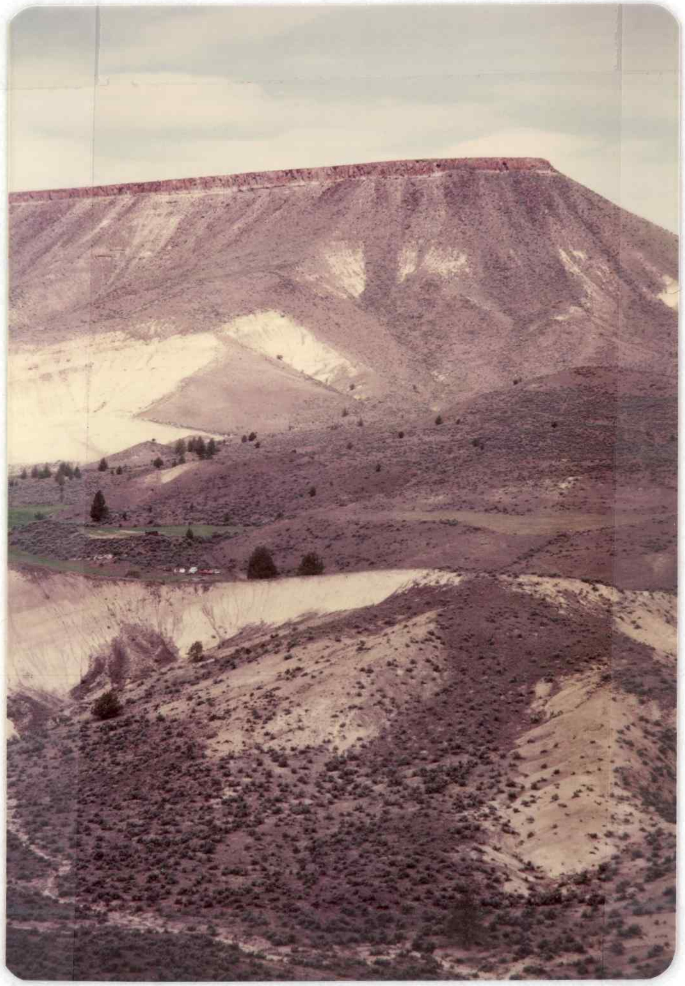


Figure 19. Rattlesnake Ignimbrite, overlying the Mascall Formation, southwest of Picture Gorge.

(Laursen and Hammond, 1974). Reversed magnetic polarity is exhibited by the ignimbrite (Enlows, 1973).

The Rattlesnake Formation is believed to be the result of fluvial and alluvial deposition in an ancestral John Day drainage which developed during the early Pliocene depositional hiatus and following the major tectonic episode which followed Columbia River Basalt volcanism. Studies of late Pliocene volcanism in the Basin and Range province suggest that the Rattlesnake ignimbrite, which occurs in the middle of the Rattlesnake gravel sequence, originated from a single violent eruption which occurred south of the Blue Mountains in the Harney Basin (Enlows, 1973). The ash flow from this catastrophic event flowed northward through Plio-Pleistocene drainages into the ancestral John Day Valley (Enlows, 1976) (Figure 20).

The gravels of the Rattlesnake are poorly consolidated and lithified. Tectonic activity occurred following deposition of the Rattlesnake, as evidenced by normal fault offsets of the ignimbrite in the vicinity of Picture Gorge. However, the more severe tectonism which is responsible for the John Day and Mitchell faults appears to have taken place prior to Rattlesnake deposition, as the ignimbrite is only slightly offset in a vertical sense from one side of

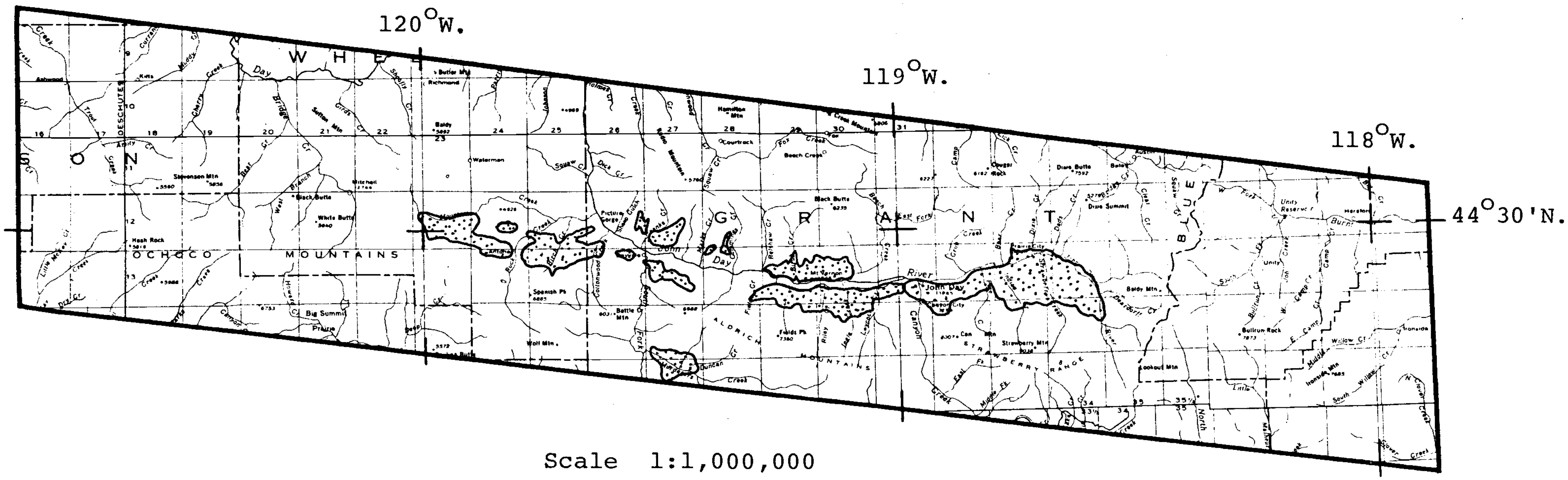


Figure 20. Distribution of the Rattlesnake Formation in the thesis area.

the John Day fault to the other (Brown and Thayer, 1966b). In fact, the major uplift and tectonic activity which followed Columbia River Basalt volcanism may have provided the source material and high energy environment required for Rattlesnake conglomerate deposition.

Since deposition of the Rattlesnake, the central part of the Blue Mountains province has shown relative internal tectonic stability, while the Blue Mountains province as a whole has been arched up between the adjacent Basin and Range and Columbia Plateau provinces. Pediment surfaces developed over Rattlesnake conglomerates, but have subsequently been raised above the present John Day Valley by increased cutting down of the John Day River as a result of regional uplift. Recent landslide debris obscures formation contacts and outcrops in much of the area around Mitchell, and Pleistocene glacial morphology dominates the higher elevations in the Strawberry Mountains. Quaternary basalt flows of limited areal extent are found south of the Aldrich Mountains in the Murderers Creek area (Thayer and Brown, 1966a), and are probably related to the more tectonically active Basin and Range province to the south.

LINEAMENT ANALYSIS

Much geologic study in recent years has centered on the Blue Mountains province of eastern Oregon. However, most of this work has emphasized either the stratigraphy and geochemistry of the widespread Tertiary volcanic units or the complex early Mesozoic melange. As a result, the Tertiary tectonic history of the region has remained an enigma. Attempts to interpret the known Tertiary structure in terms of plate subduction such as that which exists today along the western margin of North America have met with only limited success, and generally suffer from overgeneralization. The great variety of structural trends within Tertiary rocks of similar age make widespread tectonic simplifications insufficient to understand the tectonic history of the Tertiary of eastern Oregon. In addition, the possibility that the province has undergone rotation as a whole during the Tertiary, with respect to the rest of North America (Hamilton and Myers, 1966 and others) increases the need to more completely understand the structure of the area prior to making conclusions regarding the temporal and spatial interrelationships between Tertiary structures and the volcanic units in which they exist.

The numerous fault and fold orientations in the Tertiary volcanics of the central Blue Mountains provide some clues to the forces which were active during Tertiary tectonism. However, many of the earlier Tertiary structures are partially or completely concealed by the widespread middle Tertiary Columbia River Basalts and by other younger units. Because of the complexity of the known Tertiary structures, and because many of them are partially buried by younger strata, a regional study of the structural character of the province may provide insight into Tertiary tectonism that more locallized field studies might not.

One means of studying the regional structure of the Blue Mountains province is to gain additional structural information from the numerous lineaments present, many of which represent faults and tectonic joints (Lawrence, 1979). It is hoped that a study of these linear features, clearly visible on both conventional aerial photography and on more exotic remote imagery, may indicate more detailed tectonic trends and their time and space relationships with the Tertiary volcanic units, thus providing a better understanding of the Tertiary tectonic history of the region.

General Use of Lineaments

Use of the term "lineament" in geology is generally made in reference to a geomorphic feature which displays rectilinear or near-linear characteristics, and which may reflect the linearity of an underlying geologic feature. This broad definition includes features of any scale, ranging from a small lineament, which might represent a single joint, to a large lineament such as the entire John Day Valley, which is actually a composite of many smaller, nearly parallel linear segments. Geomorphic lineaments may represent a variety of geologic features, including joints, faults, fold axes or hinges, or even stratigraphic contacts.

Lineament studies commonly involve the recognition of linear geomorphic or topographic features and the subsequent interpretation of these features in geologic terms. Because such geomorphic lineaments are often large scale features not easily recognizable on the ground, lineament studies commonly use remote sensing techniques such as aerial photography, radar, and airborne geophysical methods, often in conjunction with field studies. One of the earlier studies of lineaments was by Raisz (1945), who noted linear characteristics of parts of northeastern Oregon by studying a three-dimensional (raised) topographic map of the area. The large scale Olympic-Wallowa lineament was first defined in this manner. An example of a study involving smaller scale lineaments is that of coal-cleat orientations by Diamond et al. (1975). This study utilized conventional aerial photographs to determine lineament trends, which were subsequently compared with actual joint (cleat) orientations in coal mines. Examples of other uses of lineaments include studies by Reches (1976) on joint patterns associated with folding, Wise (1963) on continental scale lineaments, and Casella (1976) on lunar fracture orientations.

Approach

In order to study the structure of Tertiary units in the John Day and Mitchell areas in greater detail, a lineament analysis was undertaken using three types of imagery: LANDSAT, U-2 photography, and side-looking airborne radar (SLAR). A comparison of the parameters of these imagery sources is given in Table 1. Lineaments were mapped over the entire thesis area by studying each of these remote sensing sources individually. A statistical study of prominent lineament trends and densities was made from the U-2 data. A field examination of faults, folds, and joints in outcrops of the various Tertiary volcanic units followed, in order to compare the photo-mapped lineaments and their dominant trends with actual mappable structural features.

TABLE 1; Comparison of Remote Sensing Parameters for U-2, LANDSAT, and SLAR.

	U-2	LANDSAT	SLAR
Flight Altitude	19.5 km. (65,000 ft.)	933 km. (580 miles)	low altitude (variable)
Ground Resolution	9 sq.m.	4700 sq.m. (1.16 acres)	variable
Scale	1:120,000	1:1,000.000	1:2,000,000
Image Size	23 x 23 cm.	23.5 x 23.5 cm.	15 x 28 cm.
Format	Color Infrared Transparency	Black and White Infrared Transparency	Black and White Print

LANDSAT Procedure

LANDSAT (formerly ERTS) imagery of the John Day and Mitchell areas was obtained in transparency format at two scales, 1:1,000,000 and 1:500,000. Imagery at the smaller scale (1:1,000,000) was available for use at the Environmental Remote Sensing Applications Laboratory (ERSAL) on the Oregon State University campus. Separate images were available in 23.5 by 23.5 cm. black and white transparencies of Band 4 ("green" band, 0.5 to 0.6 m.), Band 5 ("red" band, 0.6 to 0.7 m.), and Band 7 ("black" band, 0.8 to 1.1 m.). False color composite transparencies combining the three bands were also available through ERSAL. LANDSAT imagery at the scale of 1:500,000 was provided through Dr. Robert D. Lawrence in 39 by 39 cm. black and white transparencies of Bands 5 and 7. LANDSAT coverage of the thesis area is shown in Figure 21.

The LANDSAT imagery utilized in the lineament study was generated by the LANDSAT-1 satellite, which records visible through infrared radiation on digital tape with a ground resolution of approximately 1.16 acres. A lesser resolution is available in imagery format. The LANDSAT system orbits the earth at about 920 kilometers and records radiation in seven bands of overlapping

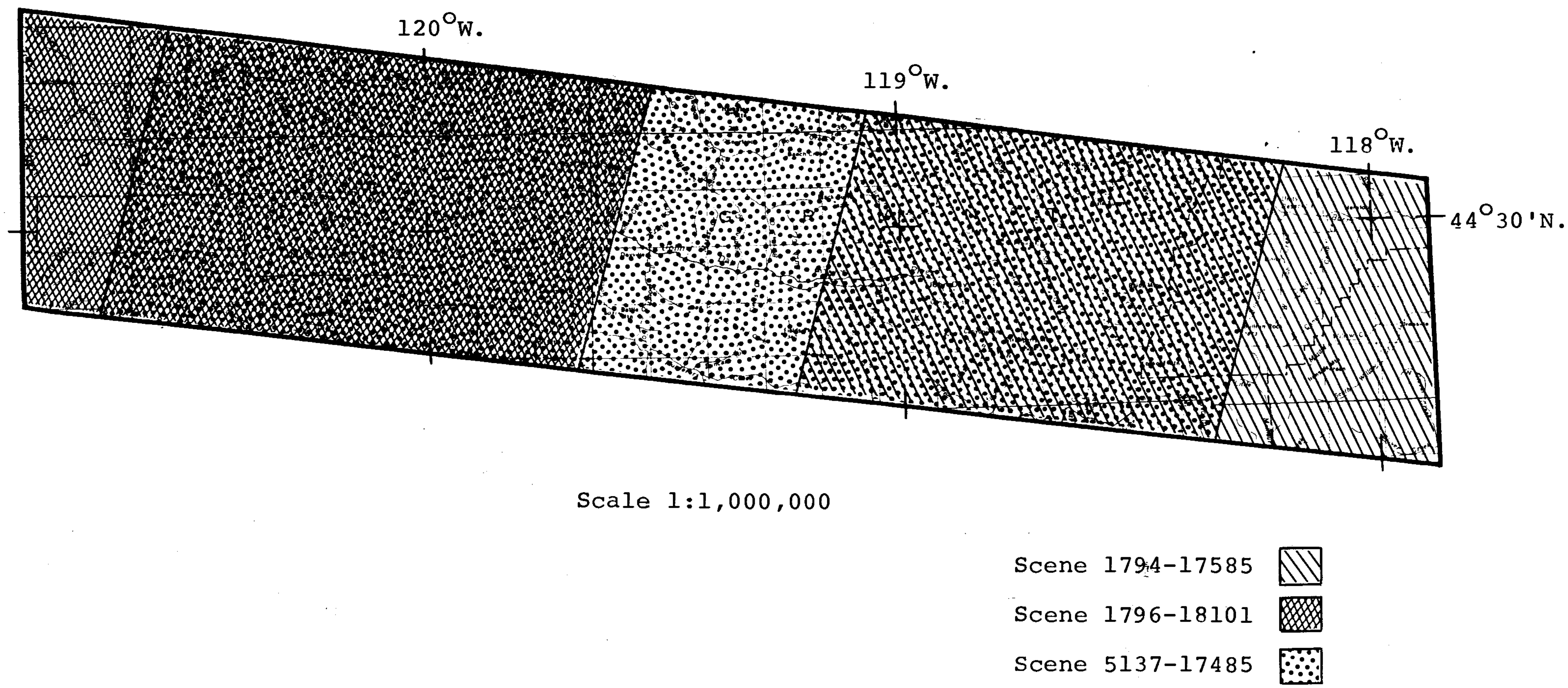


Figure 21. LANDSAT imagery coverage of thesis area.

wavelengths as it is reflected from the earth. The specifications of the LANDSAT system have been published elsewhere, and will not be discussed in further detail here. A more detailed description of the system is given by Williams and Carter (1976).

Lineaments in the vicinity of the John Day and Mitchell faults were identified primarily on LANDSAT Band 5 images at the 1:1,000,000 scale, using Band 5 at 1:500,000 and Band 7 at both scales for visual comparison and additional mapping of lineaments. Lineaments defined on these images were transferred from the initial imagery scale to the final map scale of 1:250,000 using a Bausch and Lomb Zoom Transfer Scope. Major trends and patterns indicated by these LANDSAT lineaments are evident on the resulting LANDSAT lineament map (Plate I). Because of the relative low density of the lineaments visible on LANDSAT imagery, a statistical analysis of these data was not undertaken. Instead, lineaments mapped on this satellite format were compared with published geologic reconnaissance maps of the area which are available at the same scale (Brown and Thayer, 1966a, Swanson, 1969, and Brooks et al., 1976). This enabled a study of any coincidence of mapped geologic features with LANDSAT lineaments.

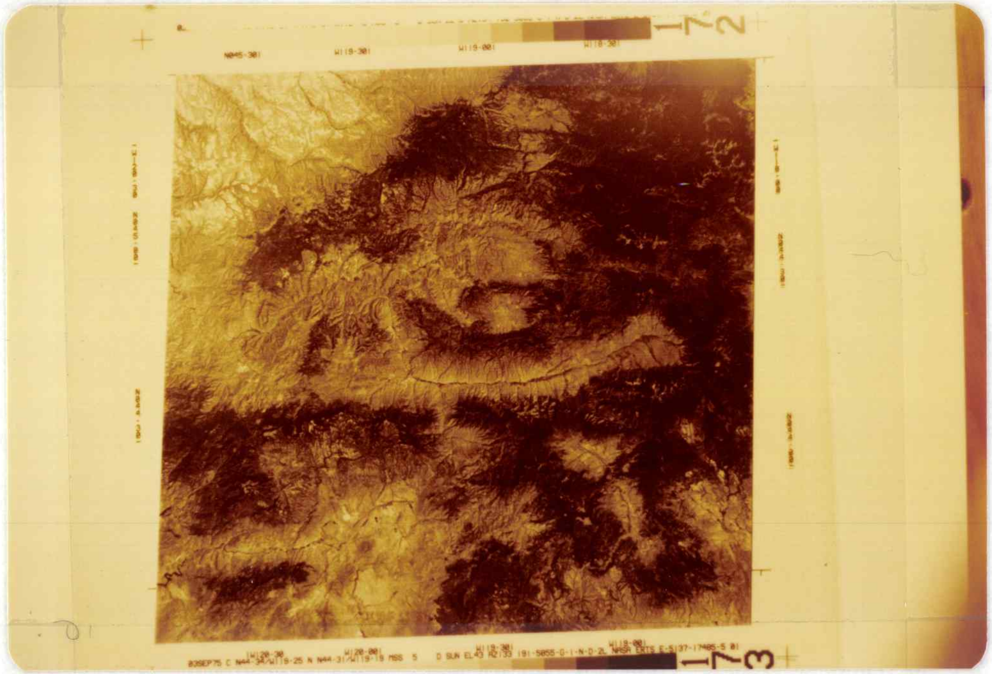
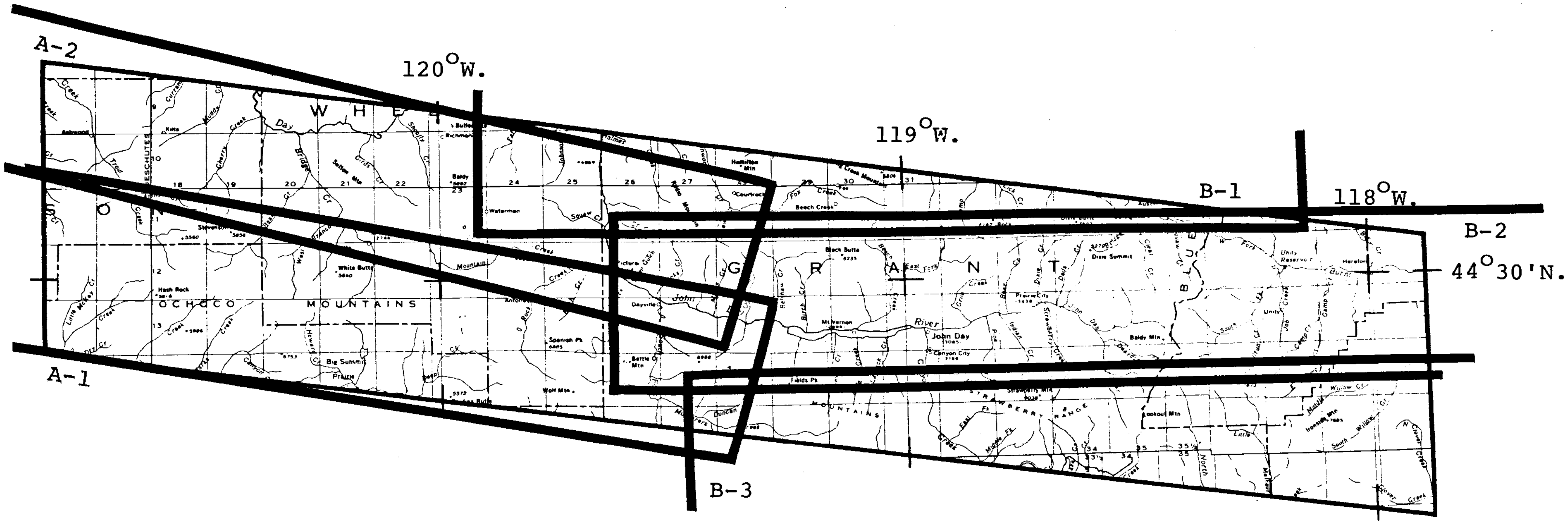


Figure 22. LANDSAT image of the Mitchell area. Note the linear trace of the Mitchell fault (MF) and the geometric pattern of lineaments at Big Summit Prairie (BSP).

U-2 Procedure

High altitude aerial photography coverage of the thesis area was obtained from ERSAL at a scale of 1:120,000 as 23.5 by 23.5 cm. color infrared transparencies. The photos available were taken from a NASA U-2 aircraft at an altitude of approximately 20 kilometers. The high resolution camera system utilized results in a ground resolution of about 5 meters, providing aerial photographs which cover a large area yet are quite detailed for their scale and size. Photo coverage of the area of study is shown in Figure 23. A more detailed discussion of U-2 photographic parameters is given by Gilnett (1975).

U-2 photos were examined stereoscopically, using an Old Delft mirror-type scanning stereoscope with an optional 4 times enlargement lens. In mapping lineaments, an attempt was made to be objective; however, some care was taken to avoid mapping linear segments known to be cultural in origin, such as roads, power line rights of way, and National Forest boundaries. Individual lineament segments were mapped only to the extent visible on the photos, to avoid, as much as possible, bias toward certain trends.



Scale 1:1,000,000

A) Flight 72-114 (1) 3255-3262
(2) 3309-3317

B) Flight 76-126 (1) 6083-6093
(2) 6107-6117
(3) 6121-6131

Figure 23. U-2 photographic coverage of the thesis area.

Lineaments were mapped on clear acetate overlays on the U-2 photos at a scale of 1:120,000, and were subsequently transferred to the final map scale of 1:250,000 using the Zoom Transfer Scope. Plate II shows the lineaments mapped on U-2 photography. These can be compared visually with the LANDSAT lineament map (Plate I) and with known geologic features. In addition, the high density of U-2 lineaments in the John Day and Mitchell areas provides a suitable basis for further statistical trend analyses.

In order to undertake a statistical analysis of the U-2-derived lineament data, fourteen sample areas within the thesis area were selected for detailed study (Figure 25). Boundaries for these sample areas were chosen so that each area represents a single stratigraphic unit, allowing for an eventual correlation of lineament trends with age and rock type. Only areas underlain by the Clarno Formation, Columbia River Basalts, and Strawberry Volcanics were included in the sample areas. Areas underlain by other Tertiary volcanic units lacked well-defined lineament patterns and in general showed low lineament density. Areas underlain by pre-Tertiary rocks in general showed high lineament densities, probably reflecting the

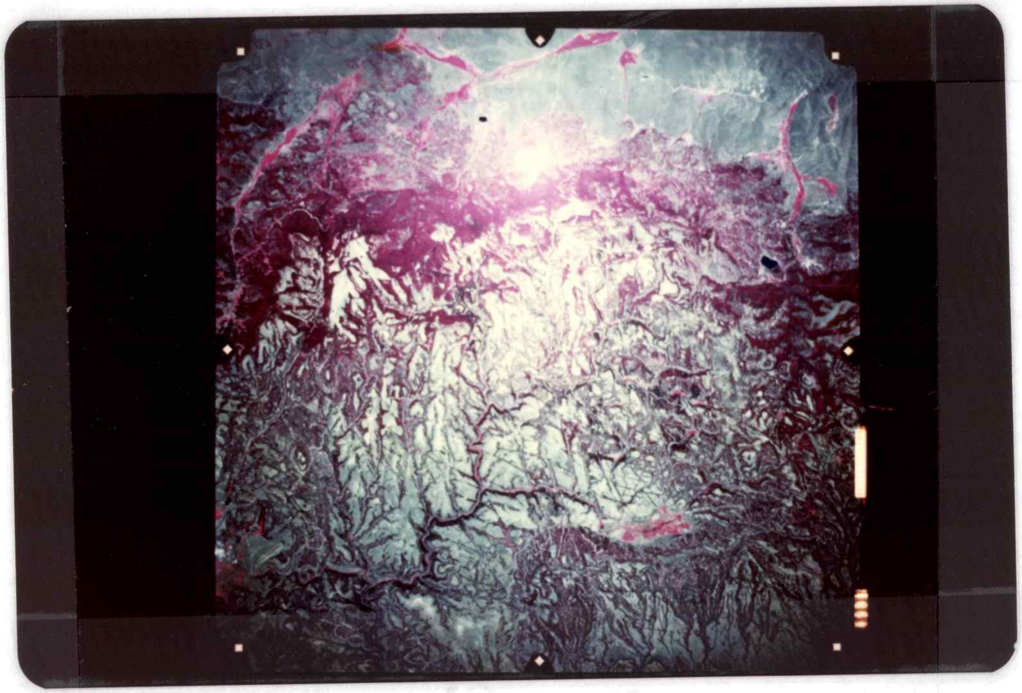
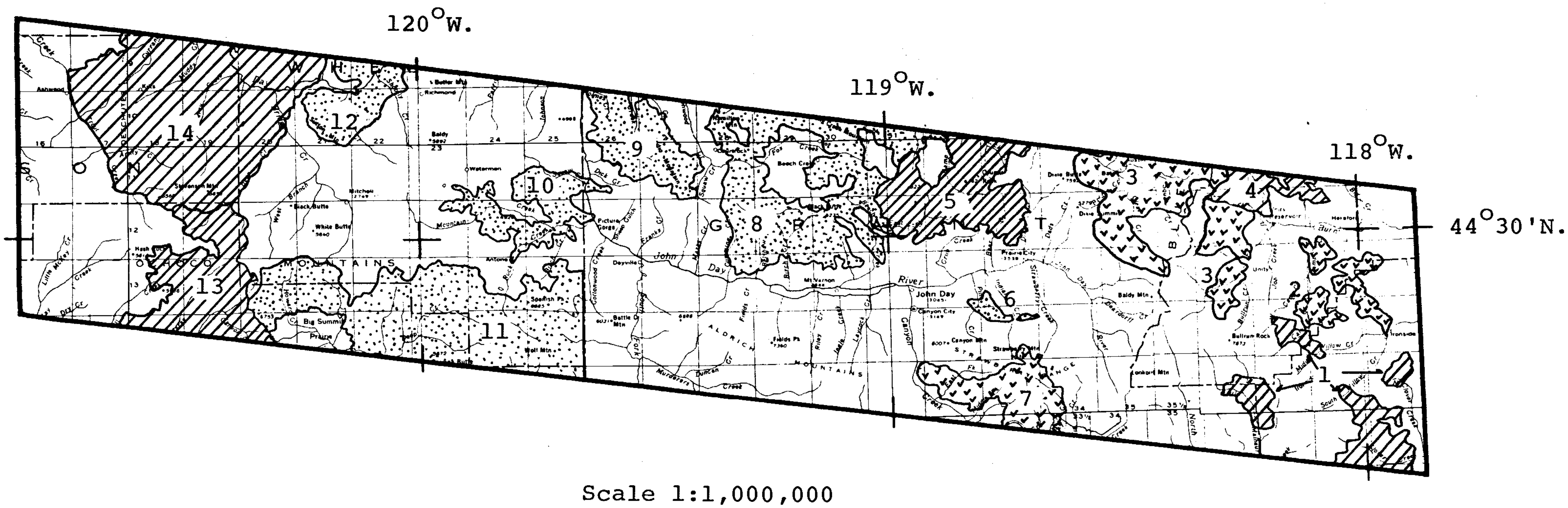


Figure 24. U-2 photograph of the Big Summit Prairie area, southeast of Mitchell. Note the obvious geometric pattern of lineaments.



Clarno Formation

Picture Gorge Basalts

Strawberry Volcanics

Figure 25. Location of U-2 sample areas.

overprinting of numerous tectonic trends and episodes. Two of the larger sample areas were subdivided further to test the continuity of lineament trends and patterns within a single rock unit. The map area of each U-2 lineament sample area was measured using a K&E compensating polar planimeter, allowing for calculations of lineament density per square kilometer.

Within each U-2 sample area, the orientation (from North) and length (in kilometers) for each individual lineament segment in that sample area were compiled, and initial statistical data were calculated (Table 2). The data were plotted on rose diagrams which show total length of lineaments for each 5 degree interval. Only the northern half of each rose diagram is shown; because lineaments represent bidirectional trends, the southern half of the rose diagram shows a symmetrical configuration. A dashed circle on each rose diagram represents the average length of lineament per 5 degree interval for that particular diagram, to enable a judgement as to the significance of any particular size peak. A solid inner circle on each diagram is arbitrary, and was used to avoid drawing the converging lines in the apex of the diagram. Prominent lineament peaks are labelled on each diagram.

The mean trend of each dominant peak was calculated following the method of Diamond et al. (1975). By this method, only those peaks which extend beyond the average length of lineament per interval for that particular rose diagram were considered. A summary of prominent peaks for each sample area calculated by this method is presented in Table 3.

TABLE 2: U-2 Statistics by Sample Area

Area	Rock Unit	Area sq.km.	#Lineaments	Total Length (km)	Avg. Length (km)	Density #/sq.km.	Density km./sq.km.	avg.length per 5° int. (km)
1	Straw. Volc.	188.7	78	149.75	1.92	0.413	0.794	4.16
2	Straw. Volc.	84.9	65	125.5	1.93	0.766	1.478	3.49
3	Straw. Volc.	361.2	231	363.0	1.57	0.640	1.005	10.07
4	Clarno	82.5	77	142.75	1.85	0.933	1.730	3.97
5	Clarno	281.2	169	310.75	1.84	0.601	1.105	8.63
6	Col.Riv.Bas.	16.2	18	37.5	2.08	1.111	2.315	1.04
7	Straw. Volc.	187.5	50	122.25	2.45	0.267	0.652	3.39
8	Col.Riv.Bas.	577.5	363	718.25	1.98	0.629	1.244	19.95
9	Col.Riv.Bas.	197.5	100	203.25	2.03	0.506	1.209	5.65
10	Col.Riv.Bas.	141.3	68	129.00	1.90	0.481	0.913	3.58
11	Col.Riv.Bas.	749.9	589	1181.75	2.01	0.785	1.576	32.83
12	Col.Riv.Bas.	165.0	41	68.25	1.66	0.248	0.414	1.90
13	Clarno	355.0	133	285.25	2.14	0.375	0.804	7.92
14	Clarno	870.2	151	367.75	2.44	0.174	0.423	10.22

TABLE 3: Prominent U-2 Peaks by Sample Area.

Area	Rock Unit										
1	Straw.Volc.	N63°W	N35°W	N35°E	N54°E			N55°W			
2	Straw.Volc.	N63°W	N33°W	N32°E	N62°E			N53°W	N43°W		
3	Straw.Volc.	N60°W	N33°W	N32°E	N60°E				N43°W		
4	Clarno	N60°W	N33°W	N32°E	N62°E	N82°E	N10°W			N78°W	N47°E
5	Clarno	N58°W	N35°W	N27°E	N65°E		N18°W				N47°E
6	Col.Riv.Bas.	N58°W	N33°W	N32°E		N87°E				N73°W	N47°E
7	Straw.Volv.	N63°W	N33°W	N27°E	N55°E			N53°W	N43°W		
8	Col.Riv.Bas.	N58°W	N31°W	N32°E	N55°E	N88°W				N70°W	
9	Col.Riv.Bas.	N58°W	N33°W	N32°E	N55°E		N16°W				
10	Col.Riv.Bas.	N58°W		N34°E	N62°E	N87°E	N 8°W				N52°E
11	Col.Riv.Bas.	N58°W	N30°W	N32°E	N57°E		N10°W				
12	Col.Riv.Bas.	N56°W	N28°W		N62°E	N89°E	N13°W			N73°W	N50°E
13	Clarno	N56°W	N31°W	N32°E	N58°E	N87°E	N18°W			N73°W	N42°E
14	Clarno	N58°W	N30°W	N32°E	N56°E	N87°E	N15°W			N78°W	

SLAR Procedure

Side-looking airborne radar (SLAR) imagery of the thesis area was made available by Dr. Charles Rosenfeld of the Oregon State University Department of Geography and the 1042nd Military Intelligence Company (Aerial Surveillance) of the Oregon Army National Guard in Salem, Oregon. This imagery was provided at a scale of 1:2,000,000. SLAR imagery is recorded from aircraft flying at variable altitude, depending on topography. The radar scanners record radiation on both sides of the aircraft, so that the resulting imagery shows an image to either side of an empty strip representing the flight path. In the thesis area, the flight path of the SLAR imagery obtained coincided with the John Day Valley, resulting in only partial coverage of the area.

The exceptionally small scale of this imagery (1:2,000,000) ruled out detailed study of SLAR lineaments in the thesis area, although major features such as the Mitchell fault zone are clearly visible. Because of the low lineament density and the horizontal distortion of features toward the margins of the SLAR image, no lineaments were mapped from this remote sensing format. A detailed description of the SLAR system is provided by Dellwig et al. (1968).

Field Procedure

An attempt was made to identify individual U-2 and LANDSAT lineaments in the field. However, the lack of rock outcrops in many areas made it difficult to recognize any individual segments except as topographic features such as straight valley segments or slope breaks. An exception to this is the Mitchell fault, which can be identified clearly in places on aerial photos and on LANDSAT, and can be mapped on the ground as a crush zone within the Clarno volcanics and Cretaceous sedimentary rocks.

A detailed study of joint orientations in rock outcrop was undertaken to compare remotely sensed lineament patterns with actual geologic trends. Sample sites for this part of the study were selected and numbered to correspond with the U-2 lineament sample areas. The location of these field sample sites is shown in Figure 26. At each site, a total of 50 joint attitudes were measured using a Brunton pocket transit. The number 50 was chosen so that a stereonet and rose diagram of each site would contain enough points to indicate general trends, and to be consistent from one site to another. The data for each sample site were

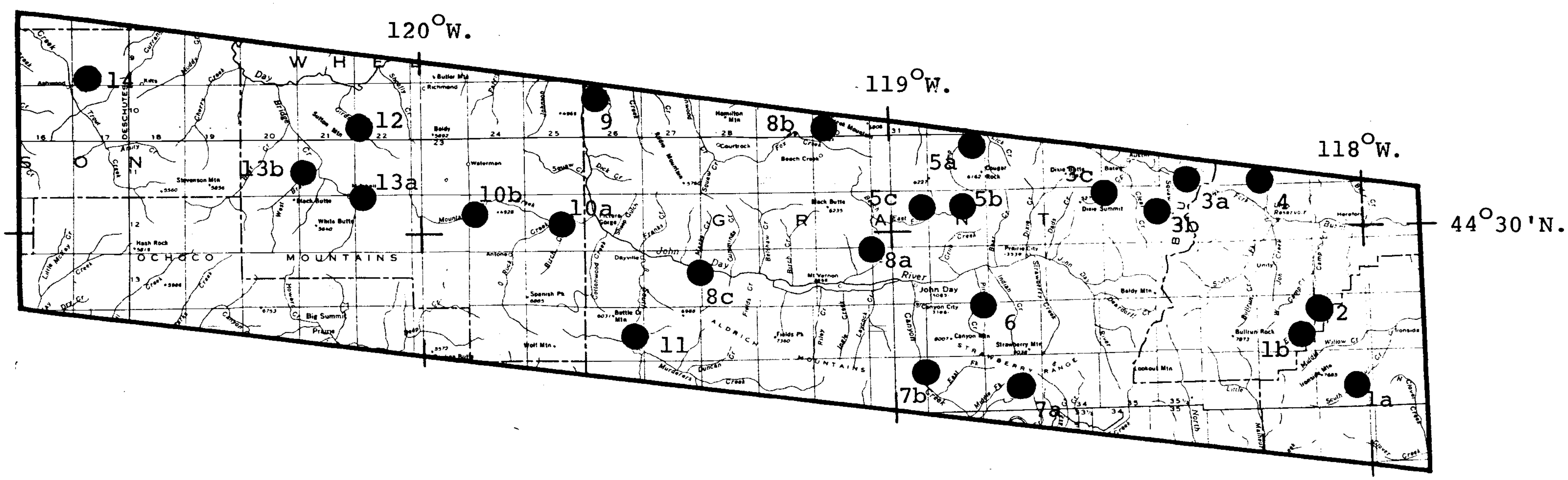


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Figure 26. Field sample site locations.

compiled and plotted on a lower hemisphere equal area stereonet, as poles to joint planes. Each stereonet diagram was subsequently contoured using the Kalsbeek method as described by Ragan (1973). Rose diagrams of the joint data were also plotted, to provide a direct comparison with U-2 lineament rose diagrams. Rose diagrams of the joint data show the number of joints per 10 degree interval. This larger interval was necessitated in the joint study, as compared to the interval used in the lineament diagrams, by the relatively small sample of joints included in each diagram.

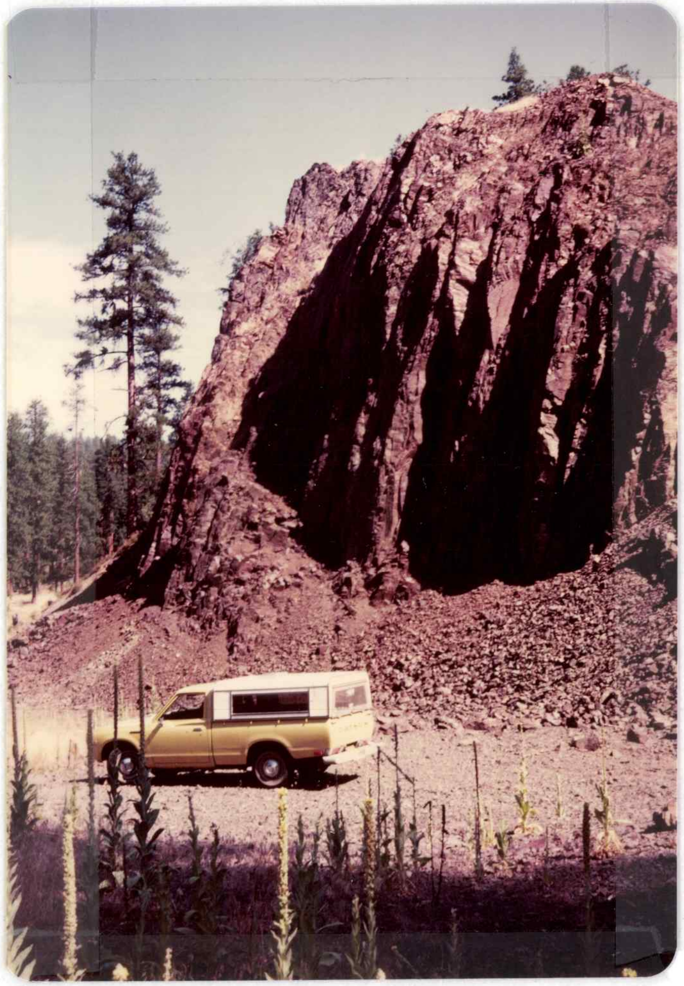


Figure 27. Tectonic joints in the Clarno Formation, west of Mitchell.

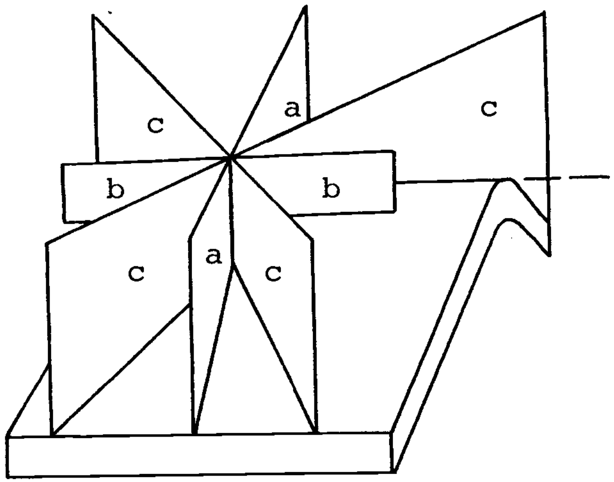
Evaluation of Data

U-2 Results

U-2 lineaments and rose diagrams for each sample area and composite rose diagrams for each rock unit represented are shown in Figures 29 through 49. Lineament trends from these diagrams can be analyzed both in terms of lithology of the rock unit involved and in terms of spatial or areal changes in trend across the thesis area.

The three major rock units in the area which are represented by the mapped U-2 lineaments (the Clarno Formation, Picture Gorge Basalt, and Strawberry Volcanics) consist primarily of relatively thick sequences of volcanic flows. The Clarno and Picture Gorge flow rocks are known to behave as brittle materials under experimentally applied stress conditions similar to those under which these rocks were deformed in nature (Lawrence, oral comm.). This brittle behavior generally results in the development of fractures, either joints or faults, in field conditions. Price (1966) provides a detailed discussion of brittle and semi-brittle behavior in rocks, but a brief summary of his work will aid in the discussions which follow.

Theories of brittle fracture development assume a homogeneous and isotropic material, a description which is approximated by the known physical characteristics of flows in the Clarno, Picture Gorge, and Strawberry volcanic units in the Blue Mountains province. Figure 28 shows the orientation of fractures which commonly develop in a brittle or semi-brittle material in association with broad compressional folds of the type found in the middle to late Tertiary rock units in the thesis area. Three fracture orientations are common: cross joints (a-c joints) are those fractures which are oriented perpendicular to fold axes, longitudinal joints are those which form parallel to fold axes, and conjugate shear joints are those which form symmetrically at approximately 30° to either side of cross joints. The trend of fold axes and their associated joints can be used to predict the orientation of maximum compressive stress, σ_1, which was responsible for generating those structures. In Figure 28, σ_1 would lie along the line perpendicular to the longitudinal joints. Using this relationship as a criterion, principal stress axis orientations can be determined by jointly considering U-2 lineament and fold axis trends.



a=cross joints

b=longitudinal joints

c=conjugate shear joints

Figure 28. Brittle fracture orientations (after Price, 1966).

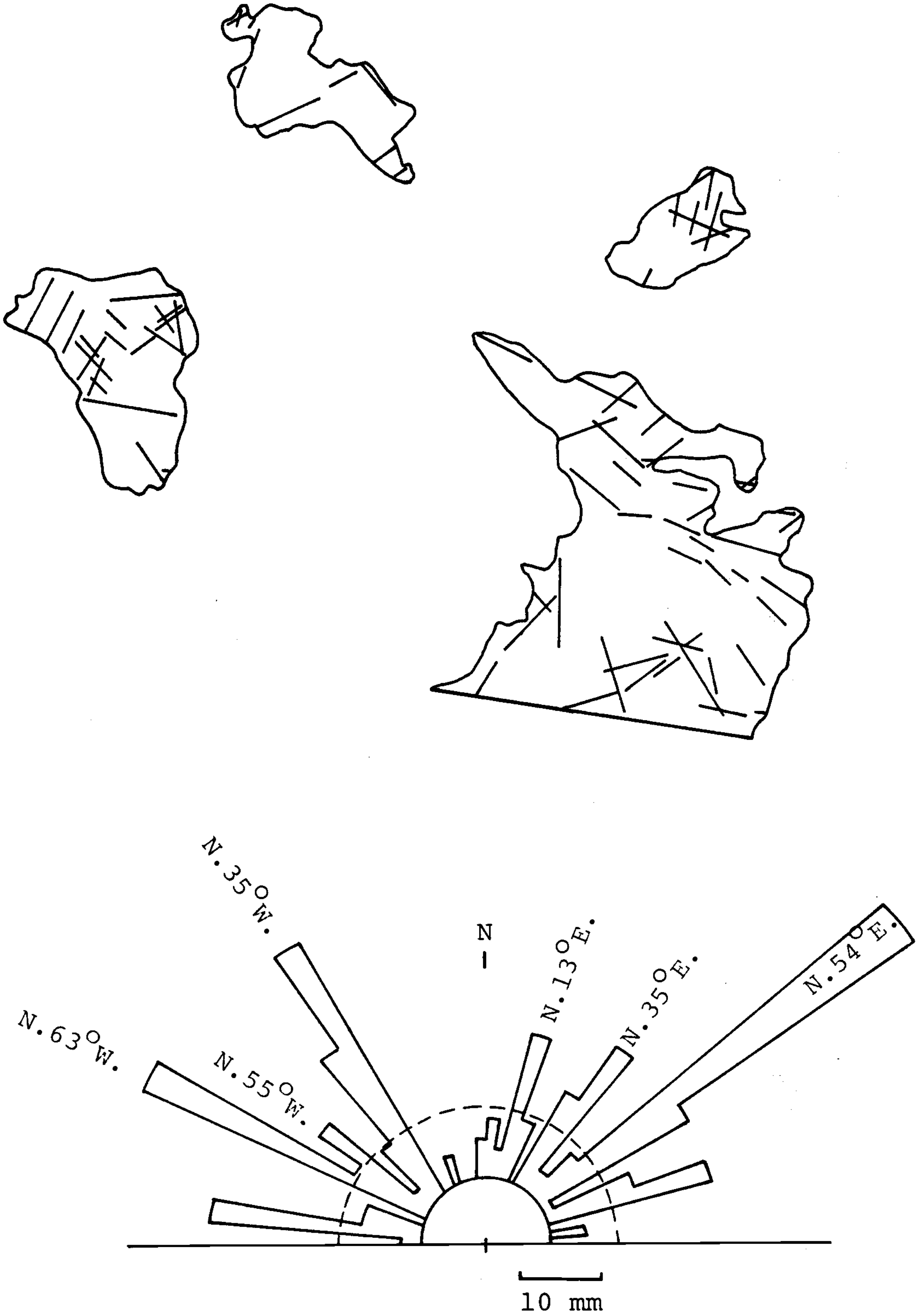


Figure 29. Lineament map and rose diagram for Area 1.

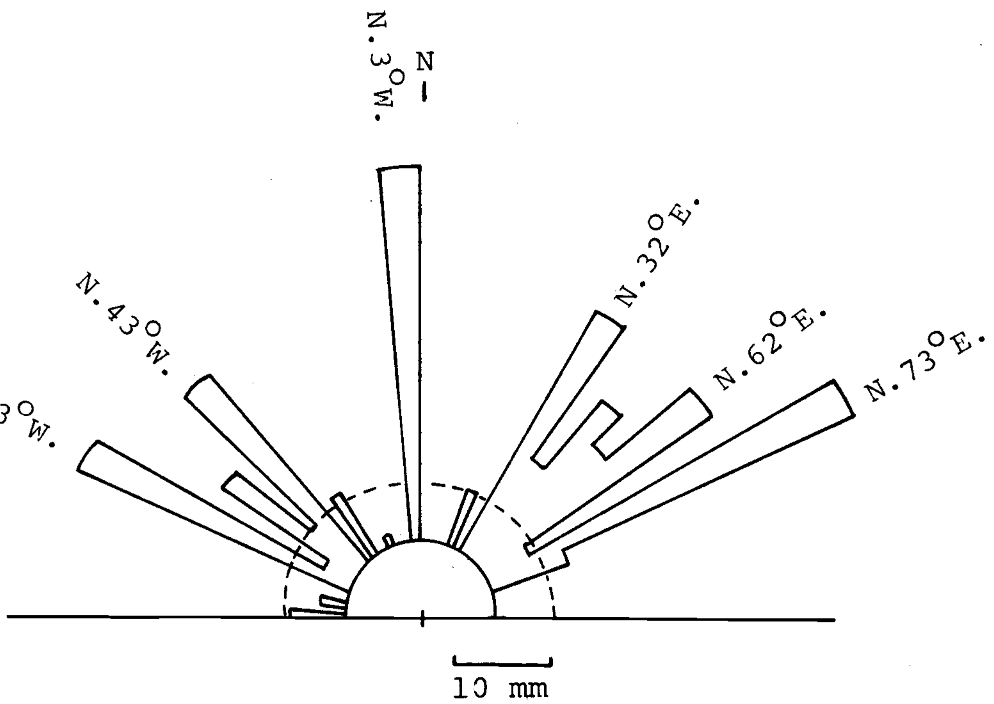


Figure 30. Lineament map and rose diagram for Area 2.

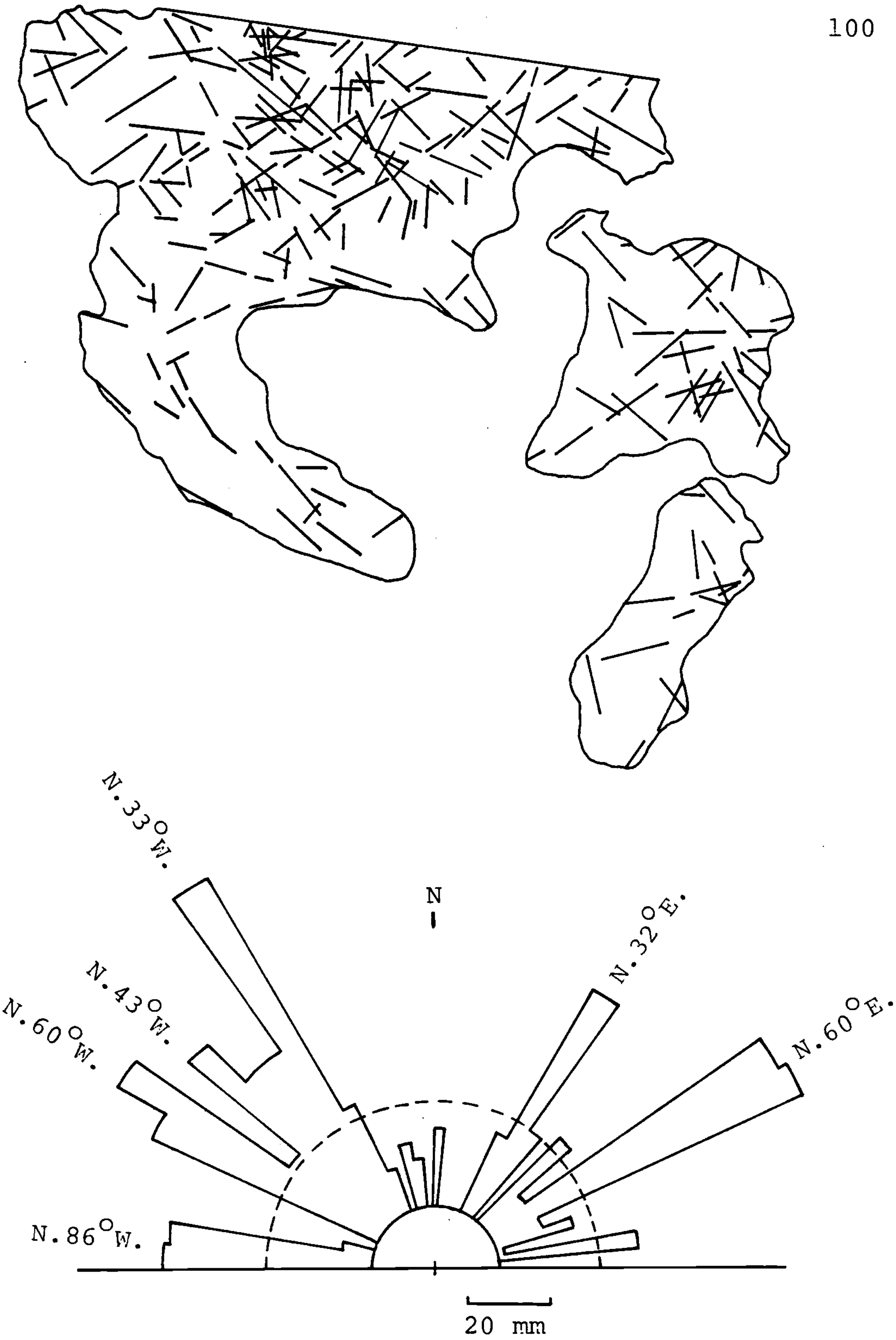
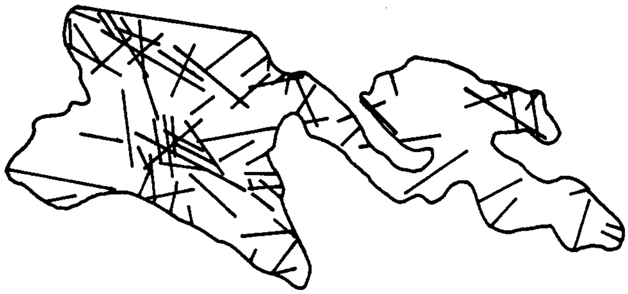


Figure 31. Lineament map and rose diagram for Area 3.



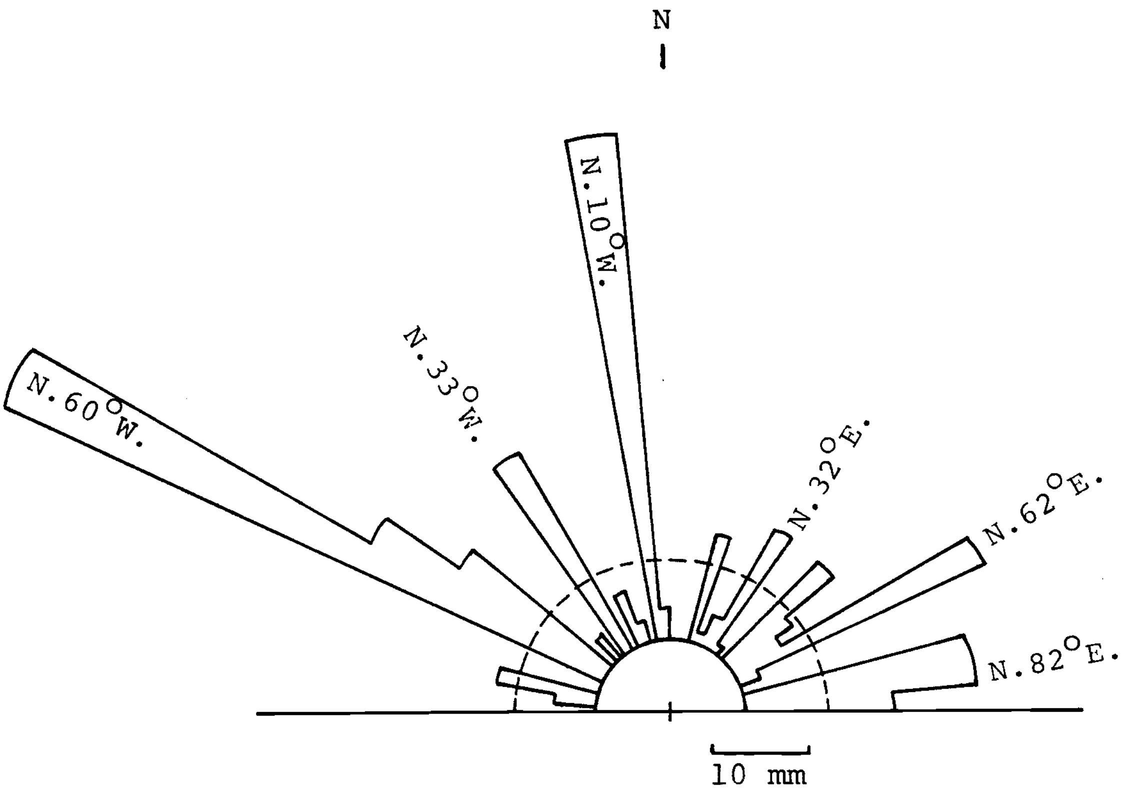
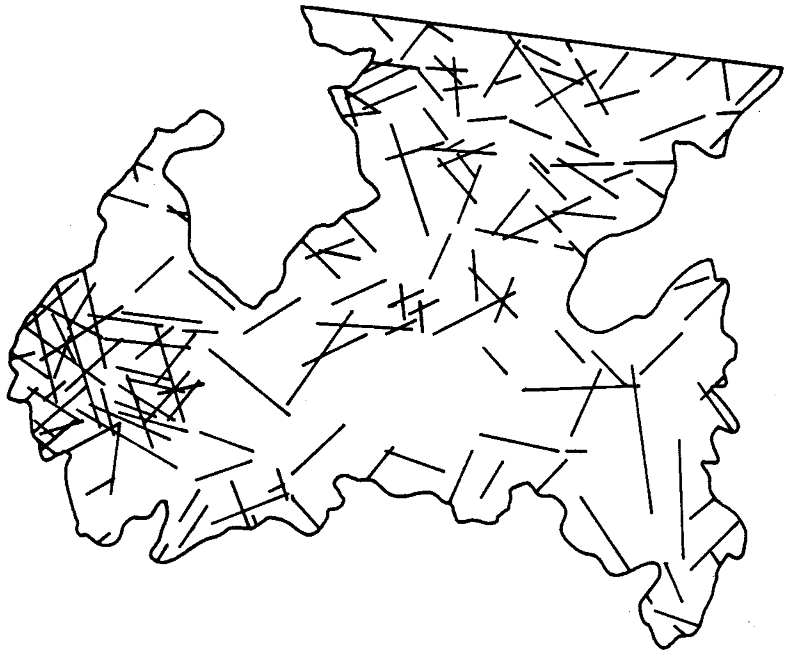


Figure 32. Lineament map and rose diagram for Area 4.



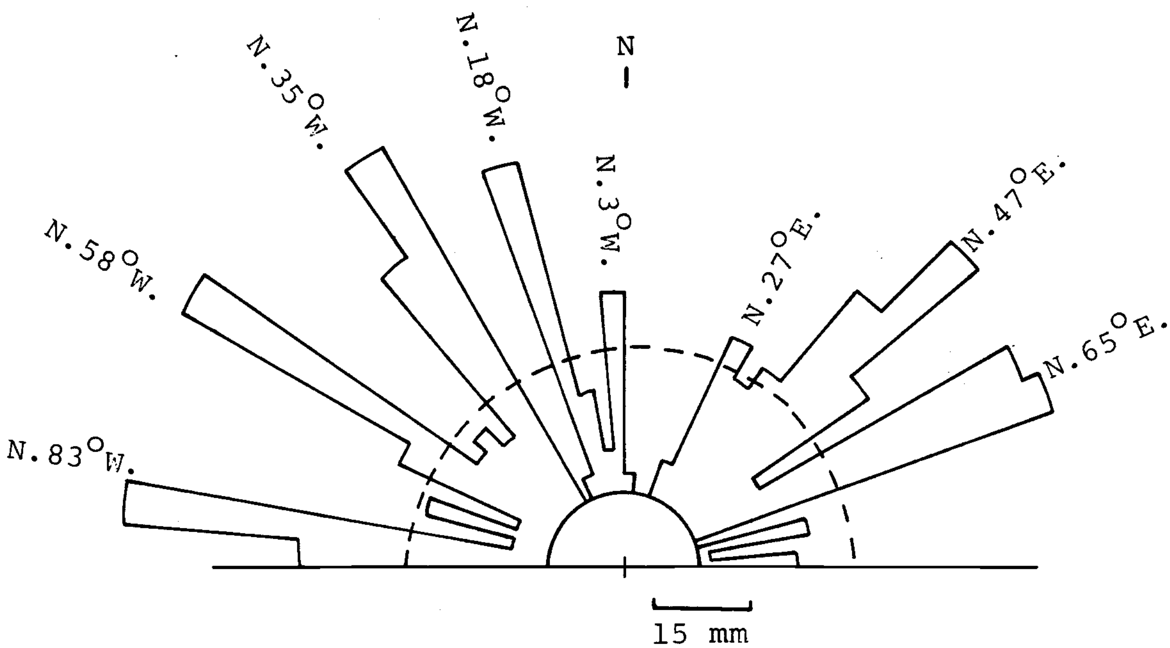
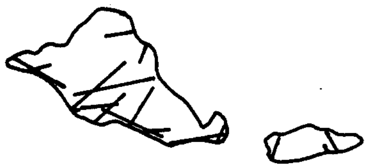


Figure 33. Lineament map and rose diagram for Area 5.



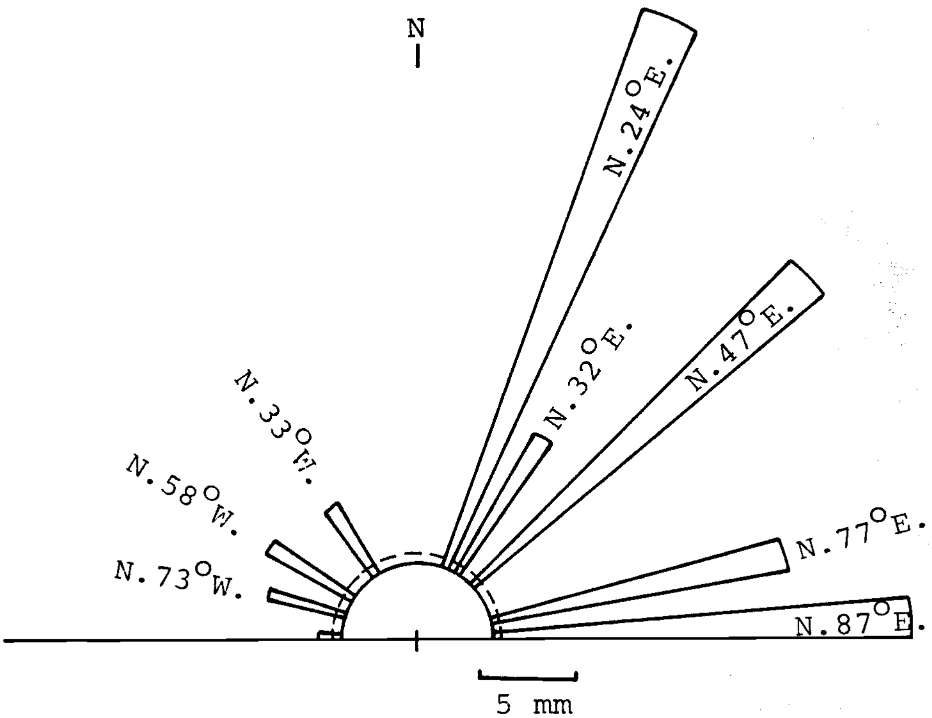
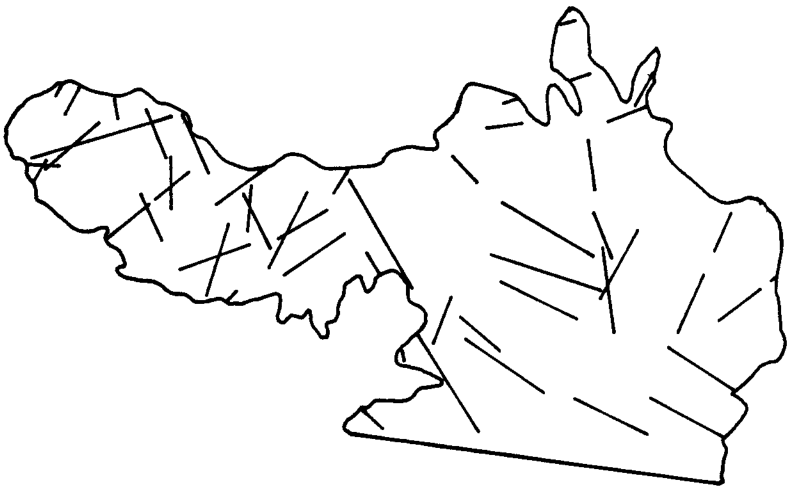


Figure 34. Lineament map and rose diagram for Area 6.



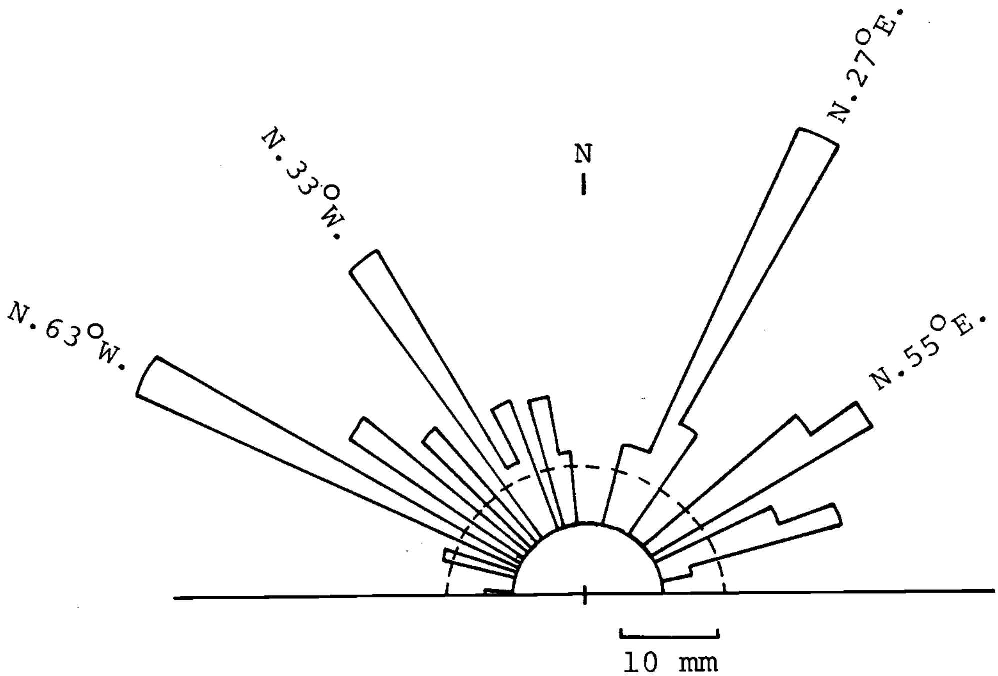


Figure 35. Lineament map and rose diagram for Area 7.

Figure 36a. Lineament map for Area 8.

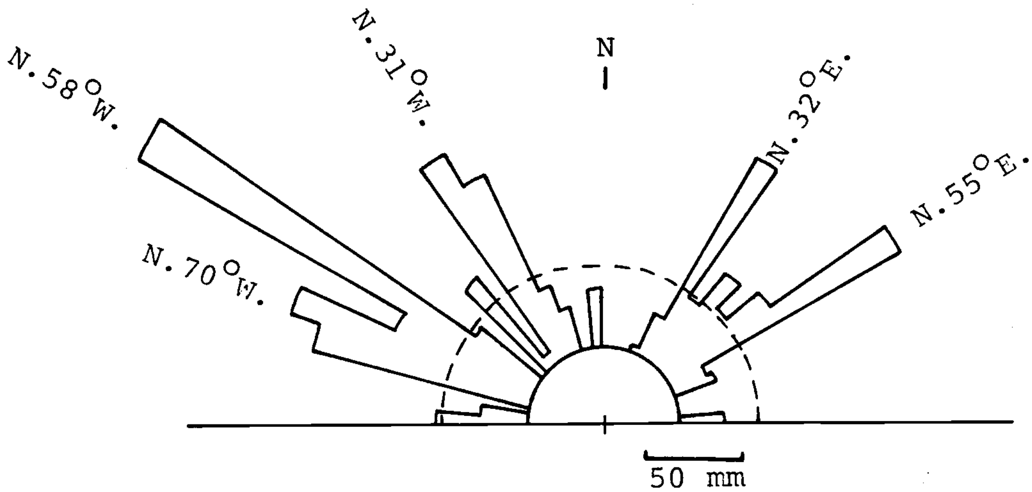


Figure 36b. Rose diagram for Area 8.

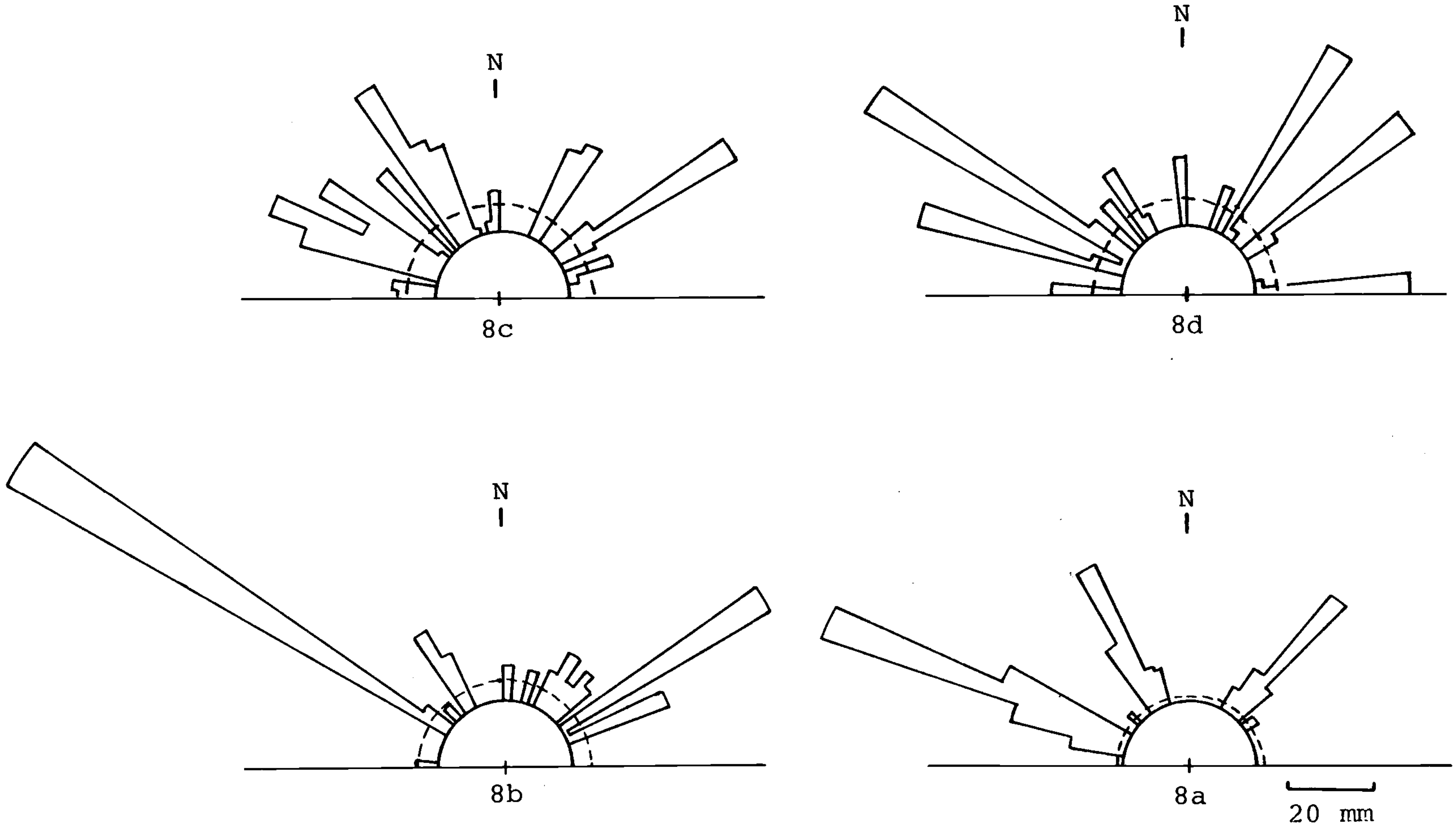


Figure 37. Lineament rose diagrams for subdivisions of Area 8.

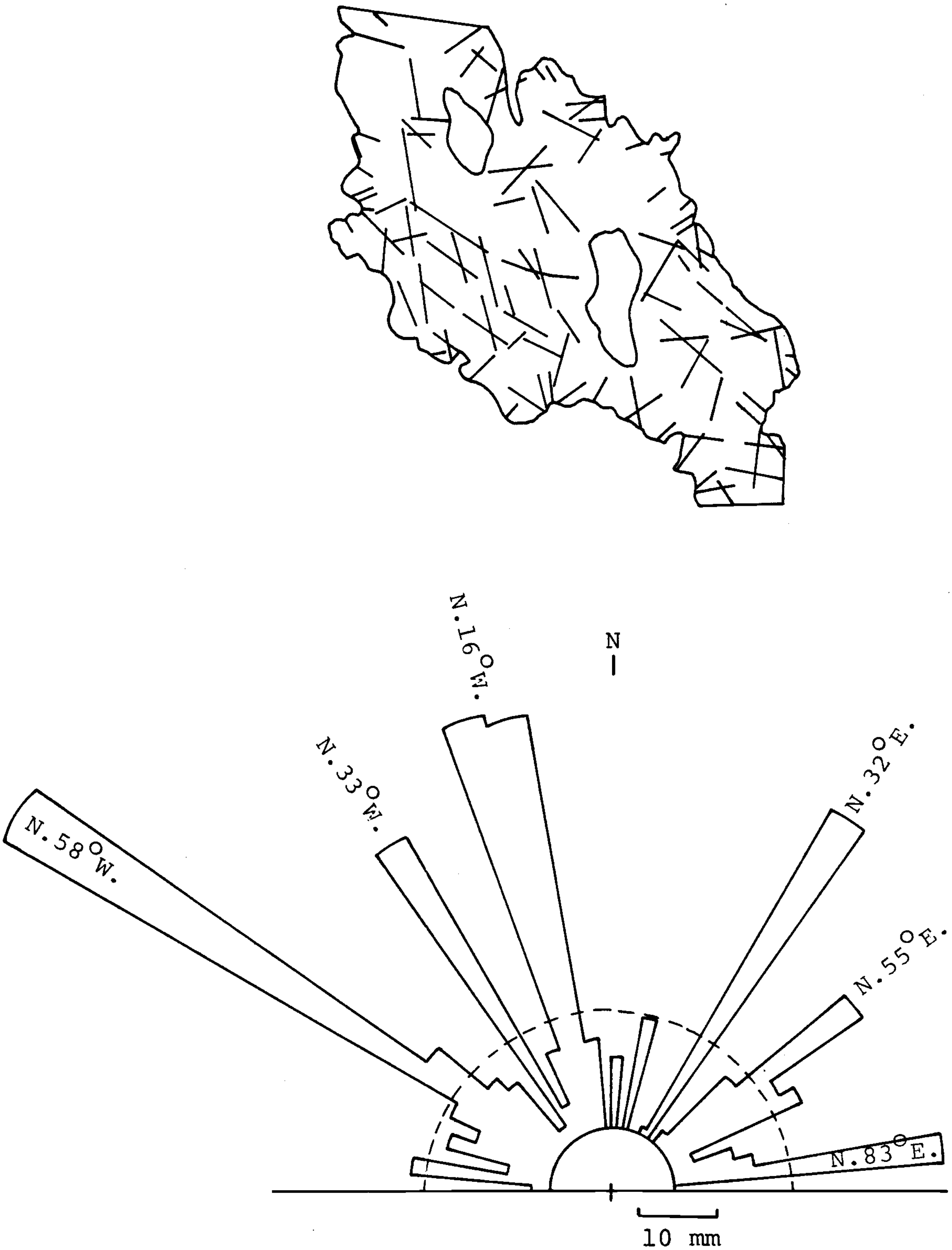


Figure 38. Lineament map and rose diagram for Area 9.

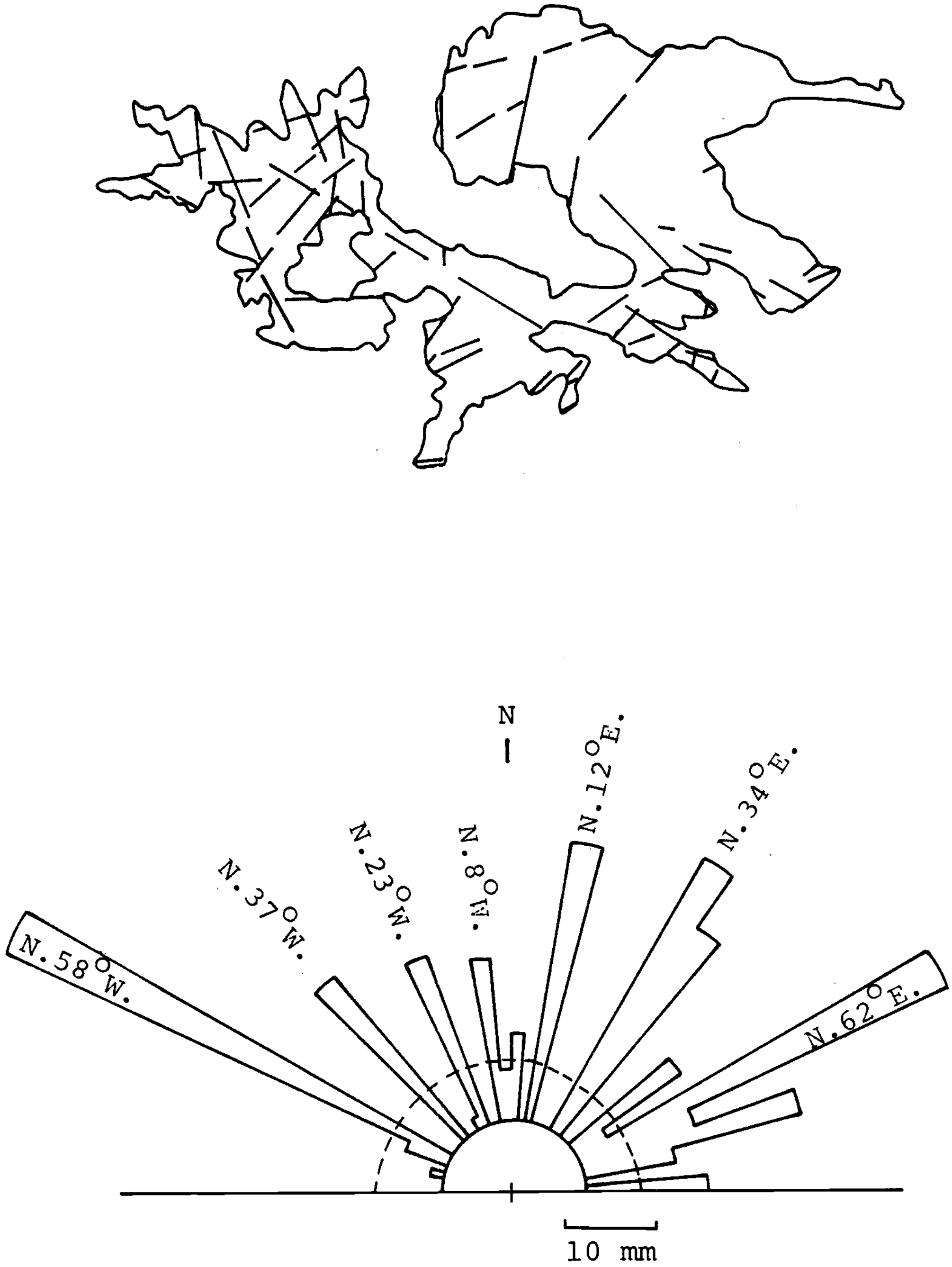


Figure 39. Lineament map and rose diagram for Area 10.

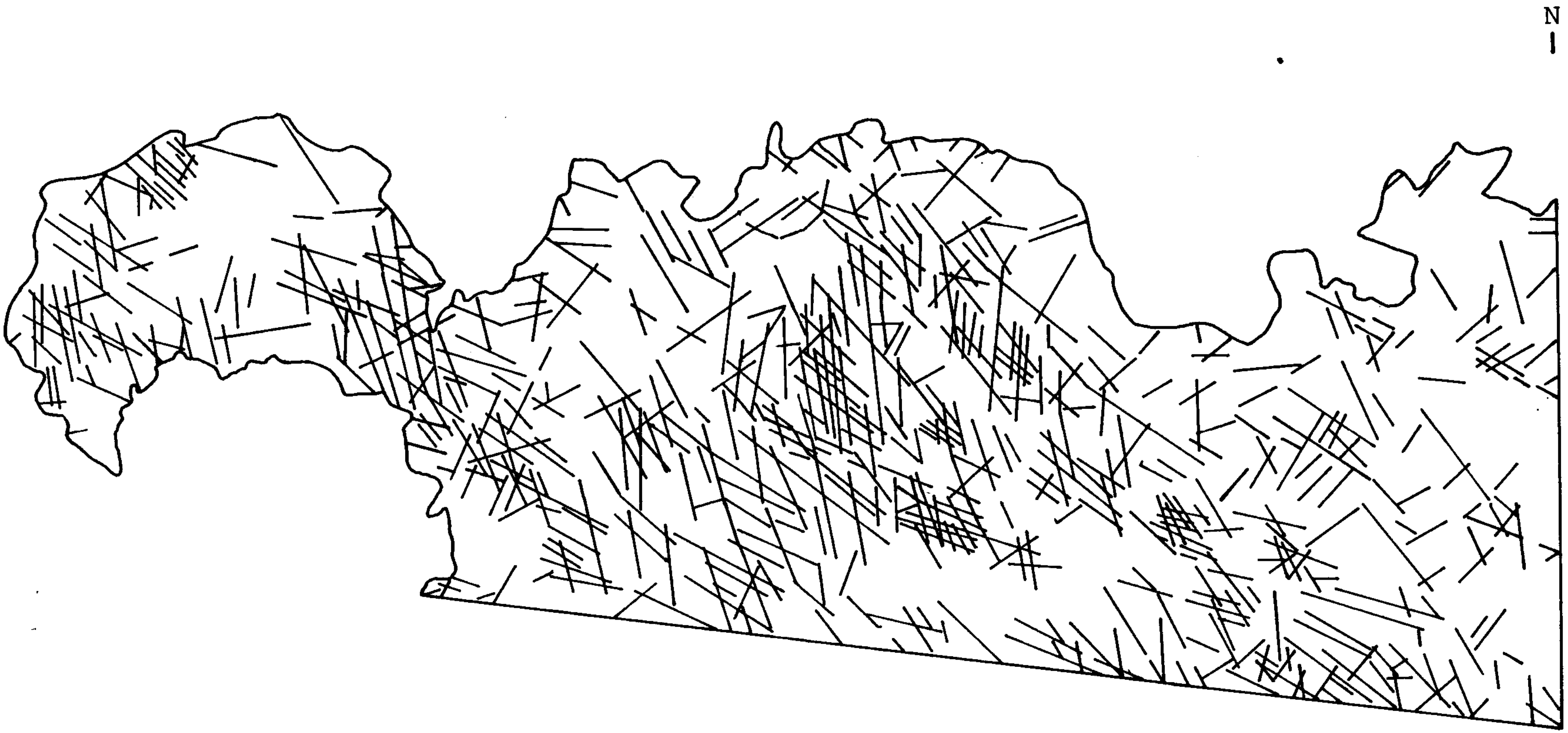


Figure 40. Lineament map for Area 11.

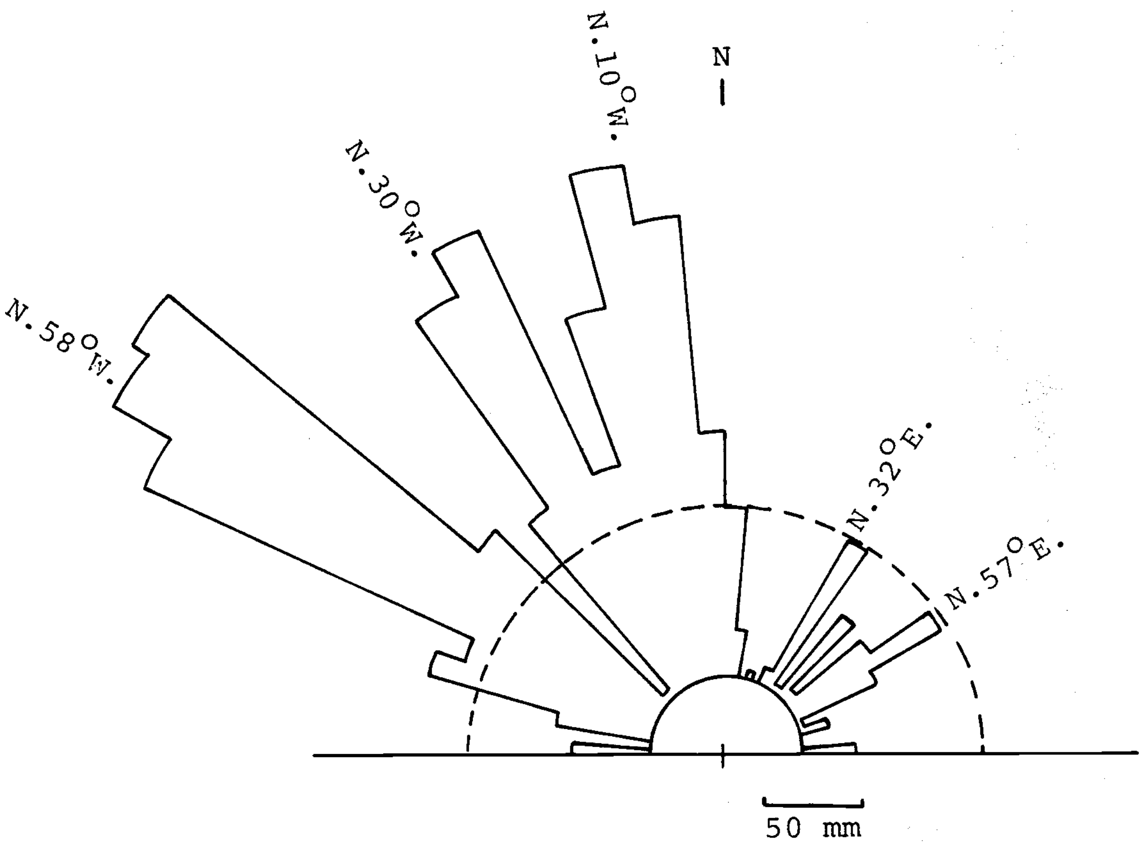


Figure 41. Lineament rose diagram for Area 11.

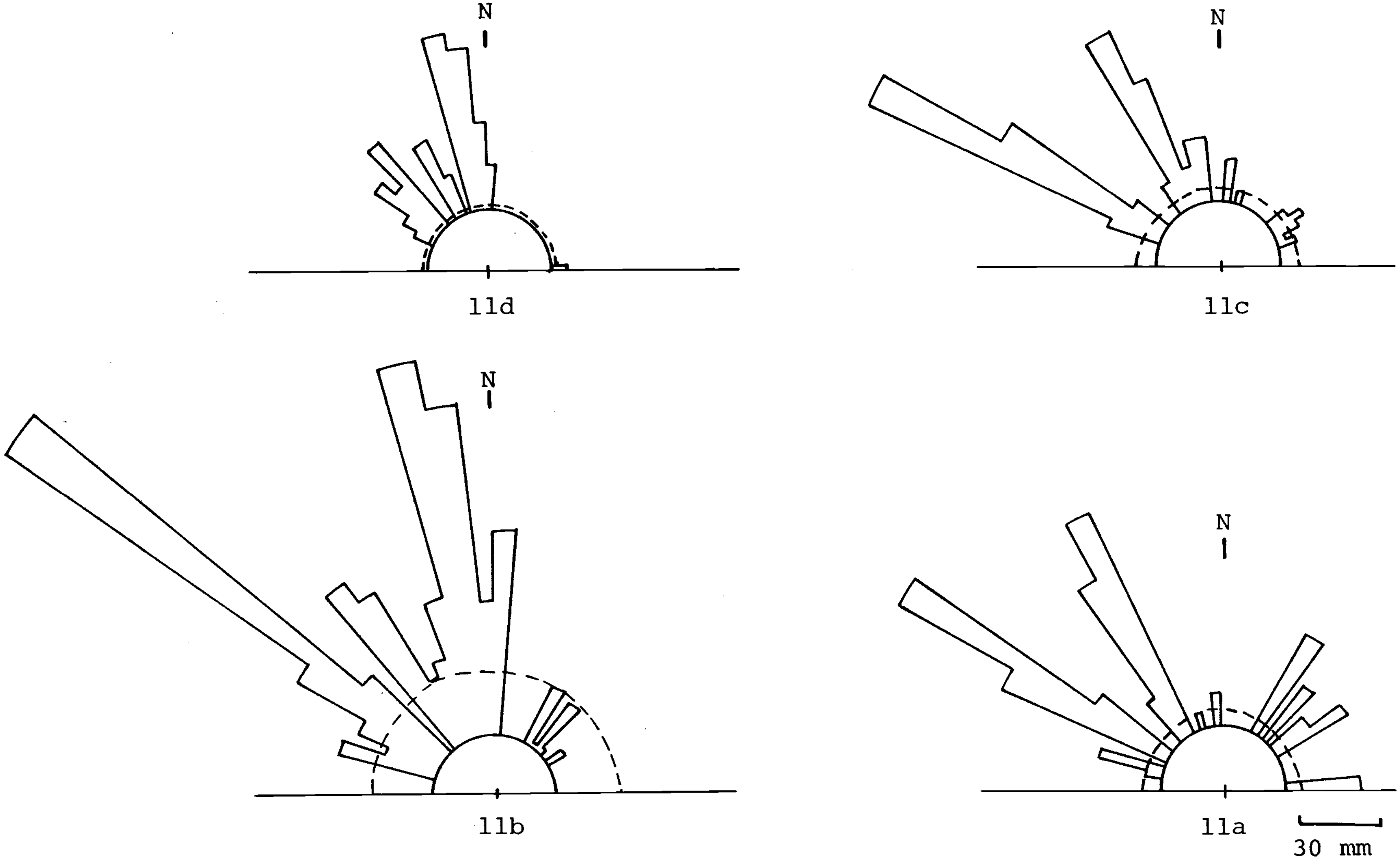
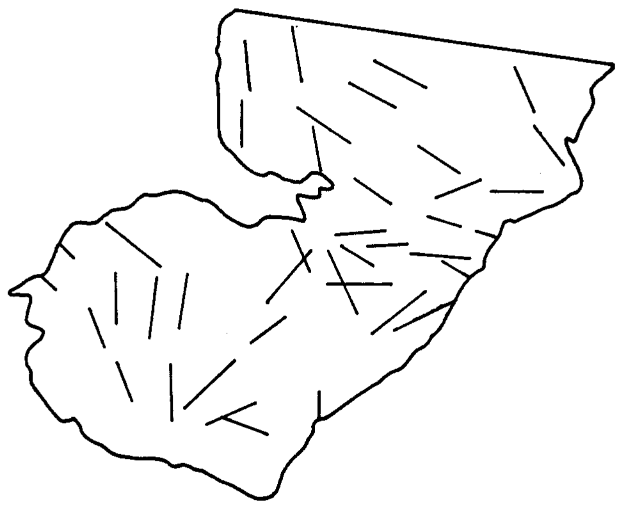


Figure 42. Lineament rose diagrams for subdivisions of Area 11.



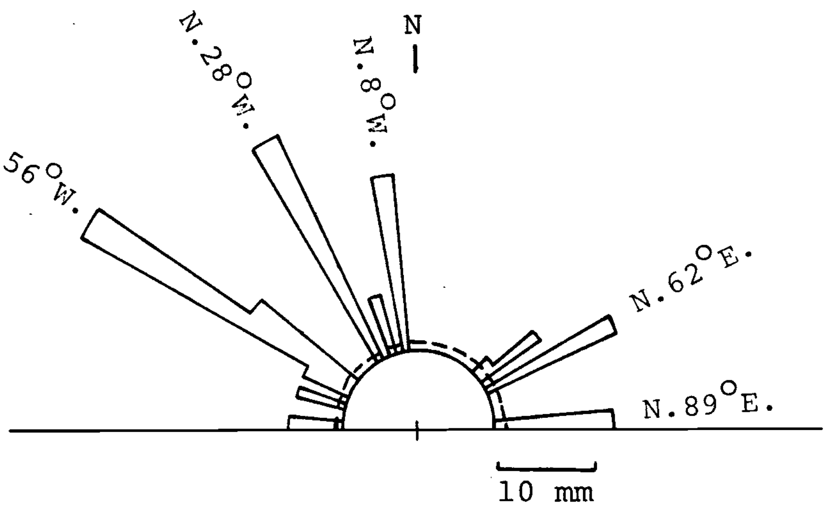


Figure 43. Lineament map and rose diagram for Area 12.

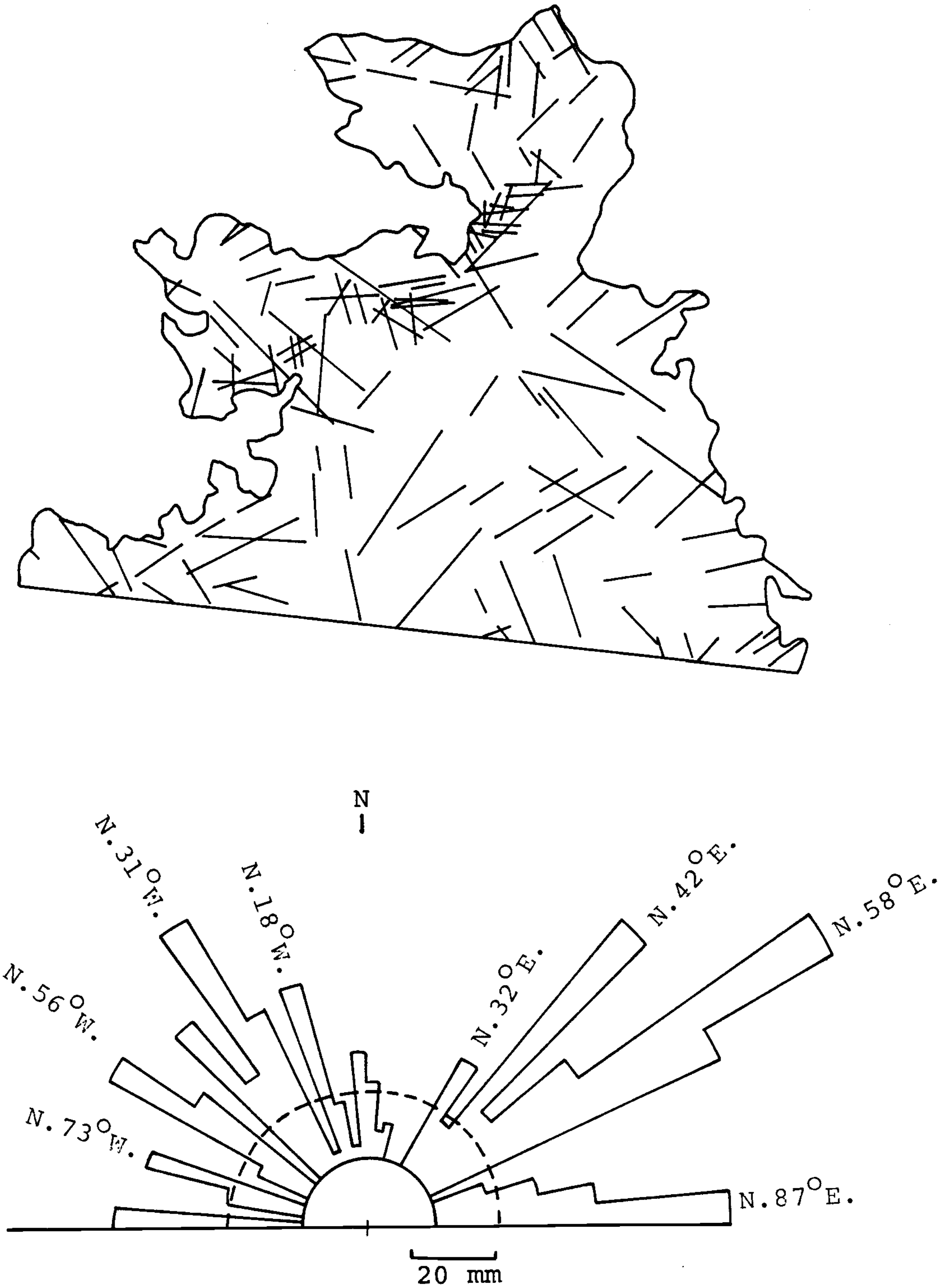


Figure 44. Lineament map and rose diagram for Area 13.

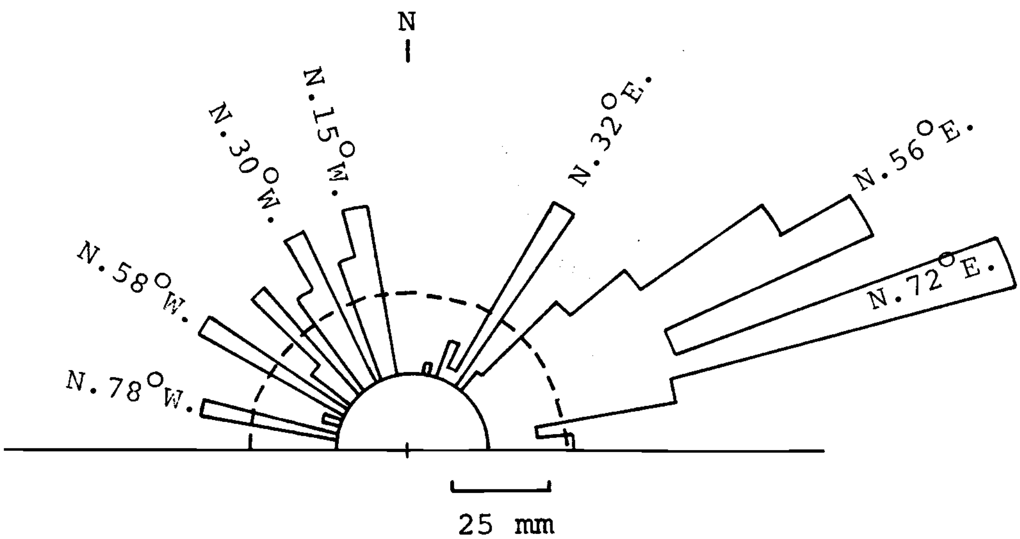


Figure 45. Lineament rose diagram for Area 14.

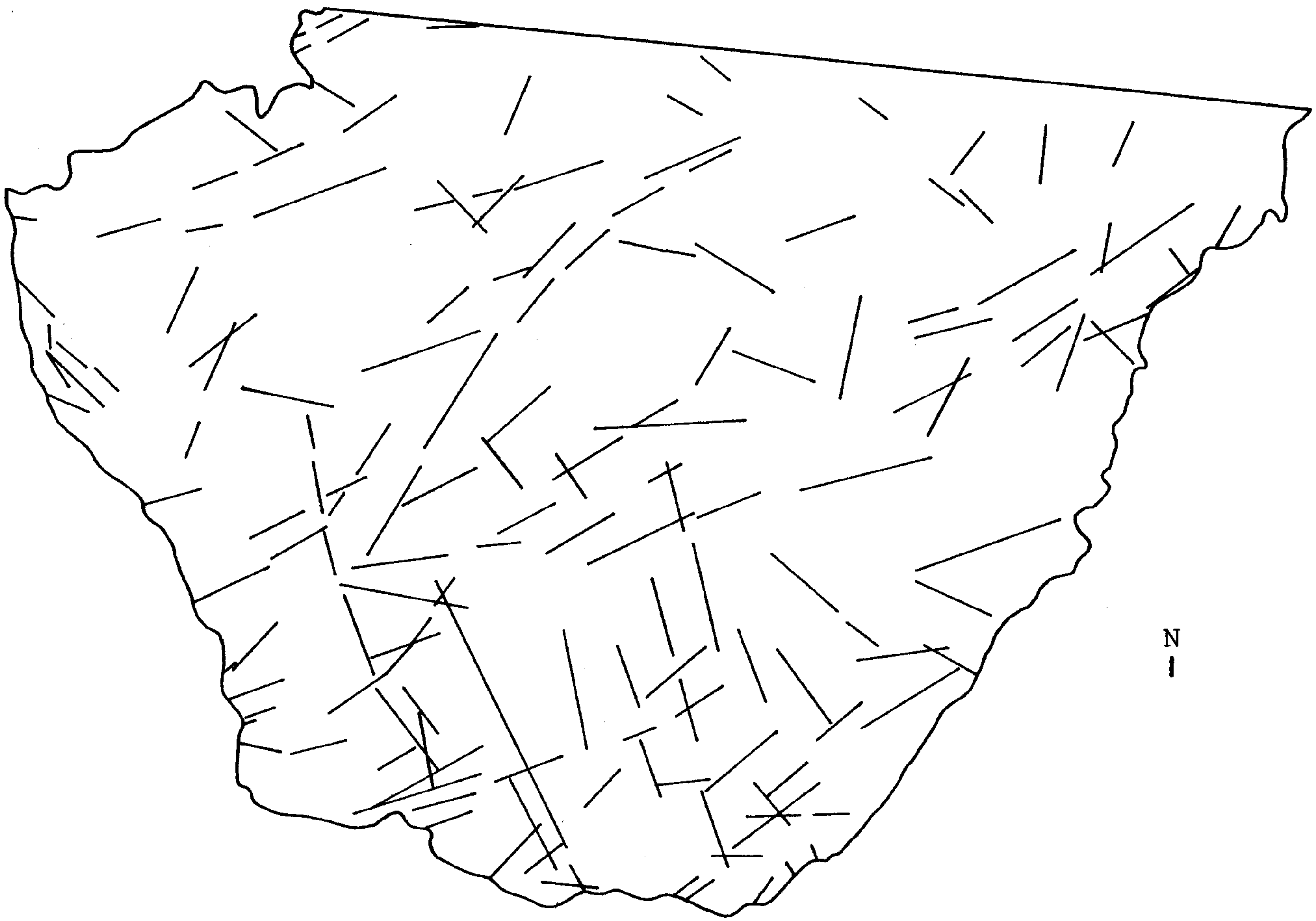


Figure 46. Lineament map for Area 14.

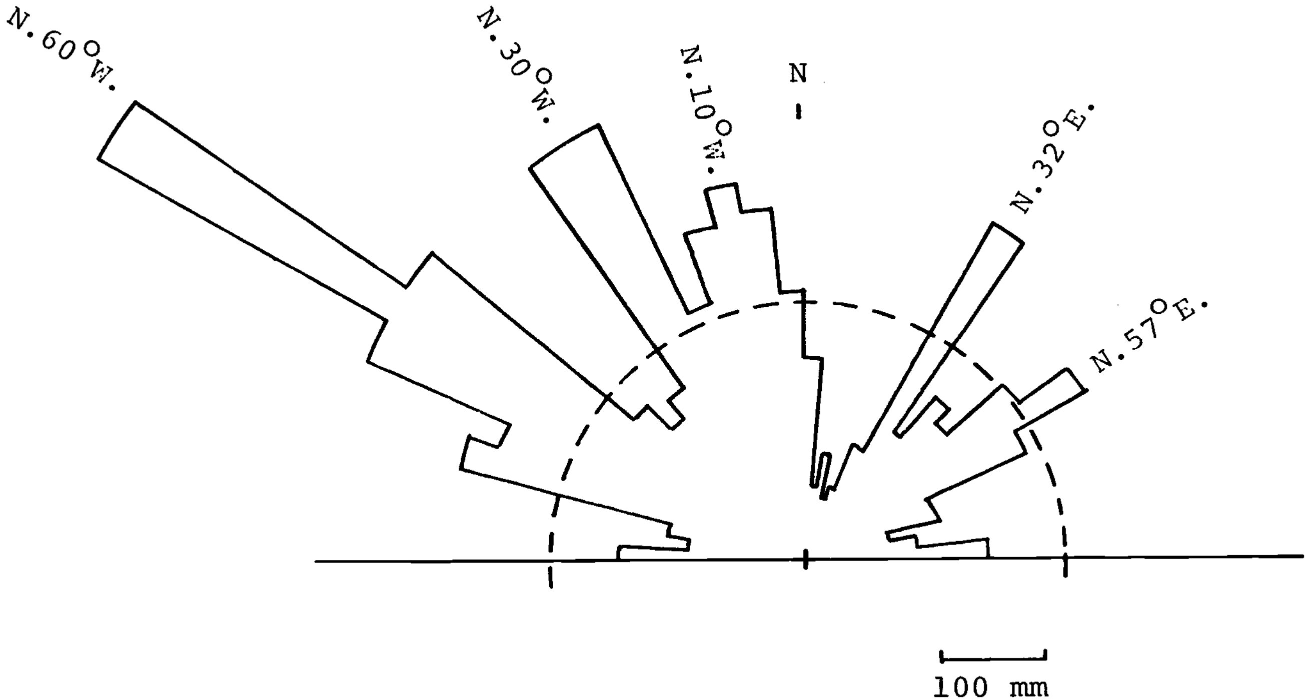


Figure 47. Summary diagram of U-2 lineaments in Columbia River Basalts.

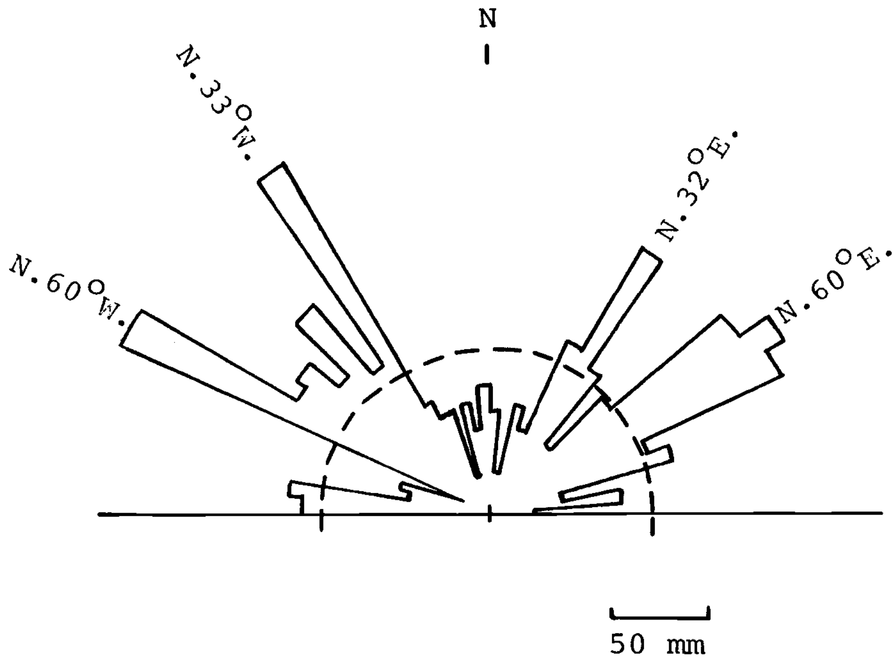


Figure 48. Summary diagram of U-2 lineaments in Strawberry Volcanics.

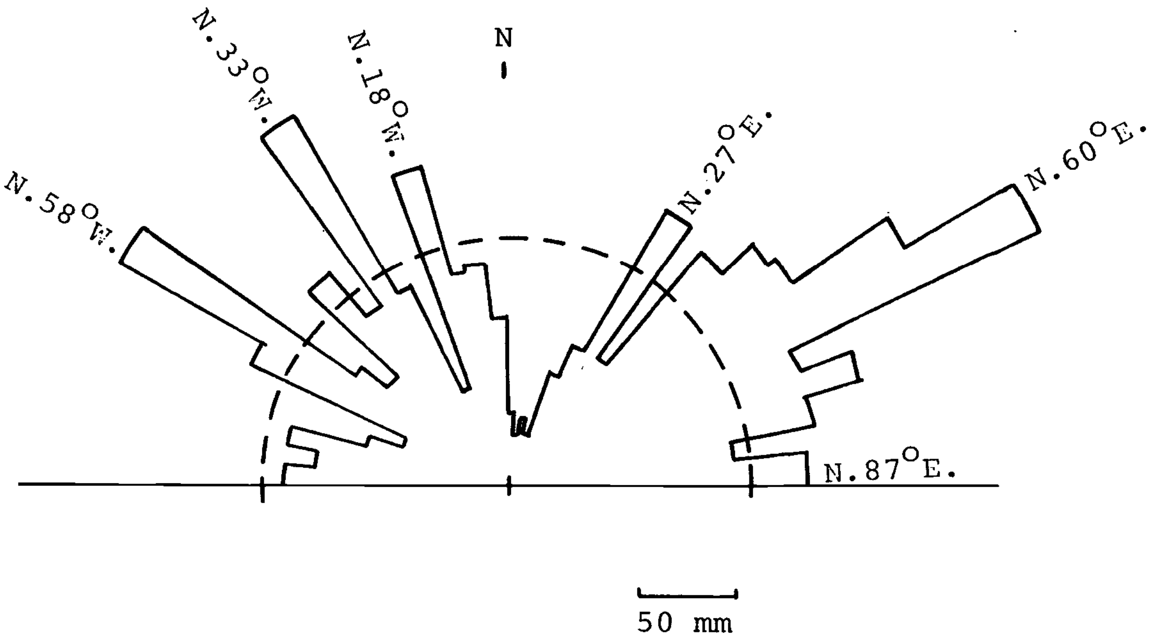


Figure 49. Summary diagram of U-2 lineaments in the Clarno Formation.

Lineaments in Picture Gorge Basalts

One of the least complex U-2 lineament patterns noted in the area of study is the one representing Area 11 (Figure 40), an area where the Picture Gorge Basalt crops out. As previously stated, many of the lineaments seen on U-2 photos and satellite imagery in this area (Big Summit Prairie) are known to represent joints and faults, as mapped by Swanson (1969), Brown and Thayer (1966a), and Walker (1977). As a result, the U-2 lineament pattern of Area 11 can be interpreted to represent joints and faults in the Picture Gorge Basalts of that area.

Examination of the U-2 rose diagram for Area 11 shows that three lineament trends dominate the area: N.58°W., N.30°W., and N.10°W. A less dominant peak, N.57°E., is also present. Using the previously discussed tectonic criteria for determining principal stress axes, the axis of maximum compressive stress, σ_1, which may have been responsible for the observed fracture orientations can be determined. Because broad N.60°E. fold axes have been mapped in this area, the simplest orientation of σ_1 would be perpendicular to those fold axes, or in this case, σ_1=N.30°W. This coincides with the dominant N.30°W. lineament peak, which might thus be interpreted to represent cross joints to the N.60°E. fold axes. The other dominant peaks, N.58°W. and N.10°W., are nearly symmetrically placed at from 20 to 30 degrees to either side of the N.30°W. peak, and can be interpreted to represent conjugate shear fractures related to the same fold axes. The smaller N.57°E. peak parallels the trend of the fold axes in the area, as well as some mapped joints, and may represent longitudinal fractures related to the same fold axes. Thus, using the brittle fracture theory discussed by Price (1966), the U-2 lineament rose diagram for Area 11 can be used to interpret a N.30°W. trend for the axis of maximum compressive stress, σ_1, which was responsible for the orientation of fractures found in the middle Miocene Picture Gorge Basalts in the Big Summit Prairie area.

The same major peak orientations, N.60°W., N.30°W., N.10°W., and N.60°E., are exhibited in the rose diagrams for Areas 9 and 12, which also represent Picture Gorge Basalts. This suggests that, although large scale joint and fault patterns similar to those found in the Big Summit Prairie area (Area 11) have not been mapped in these other areas, the presence of similarly oriented U-2 lineaments in Areas 9 and 12 indicate that the fracture network noted in Area 11 exists over a widespread area in the Blue Mountains province.

The U-2 lineament pattern exhibited by Area 8 also shows markedly similar trends to the previously discussed Areas 9, 11, and 12. Area 8, just north of the town of Mt. Vernon, is also underlain by Picture Gorge Basalts, although rock outcrops are scarce in this area and no fracture orientations have been mapped in the field. In Area 8, major peaks at N.58°W., N.31°W., N.3°W., and N.55°E. closely parallel the prominent peaks of the previously discussed Picture Gorge areas. This similarity suggests that the northwest-southeast compressive episode interpreted for the other areas occurred in Area 8 as well. In fact, a close look at Table 3, which lists major U-2 lineament peaks by area, shows that the dominant peaks of Area 11, N.58°W., N.30°W., and N.10°W., are present in nearly all geographic areas and rock units throughout the thesis area, suggesting that these fracture trends are the result of a major and widespread tectonic event.

Two other prominent U-2 lineament peaks are present in Area 8, N.70°W. and the nearly perpendicular N.32°E. Broad folds in the basalts of this area near the eastern margin of Picture Gorge exposure have been mapped with axes trending northwest-southeast, nearly parallel to the N.70^{o}W. lineament trend. These lineament peaks may be interpreted to represent longitudinal joints (N.70^{o}W.) and cross joints (N.32^{o}E.) to the northwest-trending fold axes of this area, recording a compressive episode in which the direction of maximum compressive stress, σ_1, was oriented approximately N.30^{o}E.

The other two areas which represent Picture Gorge Basalts, Areas 6 and 10, are areally small and contain fewer lineaments than the areas already discussed. This smaller sampling may affect the validity of lineament peaks shown on the rose diagrams for these areas by creating statistically biased results. However, lineament data for these two areas does show some similarity to the data from the larger areas.

The rose diagram for Area 10 (Figure 39) shares several peaks with the larger Picture Gorge sample areas, in particular the N.58^{o}W., N.52^{o}E., and N.8^{o}W. peaks. The presence of these trends supports the interpretation of a major episode of northwest-southeast compression. The N.32^{o}E. peak of Area 10 is also found in most of the areas representing Picture Gorge Basalts, and is of major importance in the interpretation of northeast-southwest compression. The fact that most areas representing the same rock unit share similar lineament trends provides a basis for determining the areal extent, whether regional or local, of tectonic episodes.

Area 6 is a very small sampling of U-2 lineaments in Picture Gorge Basalts. Again, the prominent N.32^{O}E. lineament peak is shared with other Picture Gorge areas. Other mutually shared peaks are N.58^{O}W., N.33^{O}W., and N.47^{O}E. A particularly prominent lineament peak trends E.-W., and nearly parallels the nearby John Day fault.

By combining the U-2 lineament data for all Picture Gorge Basalt sample areas into one rose diagram (Figure 47), dominant peaks are emphasized and less important or random peaks which may have resulted from small lineament samplings are reduced. This composite diagram emphasizes the N.30^{O}W., N.60^{O}W., and N.10^{O}W. peaks, supporting the presence of these peaks throughout the thesis area and supporting the interpretation of a widespread northwest-southeast compressive episode.

To summarize U-2 lineament data from the middle Miocene Picture Gorge Basalts, two major tectonic episodes have been inferred from dominant lineament peaks. The more widespread of these was a northwest-southeast-directed compressive episode (σ_1=N.30^{O}W.) which created longitudinal (N.57^{O}E.), cross (N.30^{O}W.), and conjugate shear fractures (N.60^{O}W., N.10^{O}W.) related to northeast-southwest-trending fold axes. This episode is suggested by lineament data from all Picture Gorge sample areas. The second episode interpreted from the lineament data was a more localized northeast-southwest-oriented compressive episode which resulted in areally limited longitudinal and cross fractures related to northwest-southeast-trending fold axes in the eastern and central part of the thesis area. The latter episode appears to be the younger of the two; structures related to the second episode mask the earlier structures, which show up prominently in the western part of the thesis area where the second set of structures are not present.

Lineaments in Strawberry Volcanics

The four U-2 lineament sample areas which represent Strawberry Volcanics, Areas 1, 2, 3, and 7, exhibit markedly similar lineament trends and patterns within this relatively localized rock unit. The dominant lineament peaks which are common to all four areas are N.60°W., N.33°W., N.32°E., and N.55-60°E. Broad folds in the Strawberry Volcanics outcrop area trend N.30°W., and normal faults generally parallel this trend. The

N.33°W. lineament peak closely parallels this structural trend, and may be interpreted to represent longitudinal fractures related to the N.30°W. fold axes. Similarly, the N.55° to N.60°W. peaks may represent cross fractures to the northwest-southeast-trending fold axes. This implies a maximum compressive stress oriented perpendicular to the N.30°W. fold trend, or σ_1=N.60°E. The other major peaks, N.60°W. and N.32°E., are mutually perpendicular, and may be related to the northwest-southeast compressive episode inferred from the lineament trends in Picture Gorge Basalts. In the Strawberry Volcanics, northeast-trending faults and folds are superimposed on northwest-trending structures, particularly in the Ironside Mountain area (Lowry, 1943 and Thayer and Brown, 1973). This supports the interpretation of a northeast-southwest compressive episode in the eastern part of the thesis area.

Other prominent U-2 lineament peaks in the Strawberry Volcanics are the nearly east-west-trending peaks of Areas 1, 3, and 7, and the nearly north-south-trending peak of Area 2. The east-west trend may be related to the tectonic pattern found to the west where the John Day and Mitchell faults exhibit the same trend. This trend is also dominant in the Ochoco, Aldrich, and Strawberry uplifts. The north-south-trending peak of Area 2 is perpendicular to the east-west trend, and may also be related to the dominant east-west tectonic fabric of this part of the Blue Mountains province.

Figure 48 shows a composite rose diagram including all lineaments mapped in the Strawberry Volcanics sample areas. The four dominant peaks previously mentioned, N.60°W., N.33°W., N.32°E., and N.60°E., are emphasized even more strongly in this diagram, and tend to support the interpretation that at least two tectonic episodes occurred in the Strawberry Mountains area following late Miocene volcanism.

Lineaments in the Clarno Formation

U-2 lineament rose diagrams representing Clarno rocks are considerably more complex than lineament data representing the younger Picture Gorge Basalt and Strawberry Volcanics rock units. This reflects the overprinting of tectonic episodes which occurred after Clarno volcanism but prior to the later tectonic episodes indicated by lineaments and structures in Miocene rocks. This is especially true in the western part of the thesis area, where much of the exposed rock has been mapped as Lower versus Upper Clarno because of its higher degree of deformation (Oles and Enlows, 1971).

Examination of the four areas representing the Clarno Formation, Areas 4, 5, 13, and 14, indicates a more strongly developed east to northeast trend than is evident in lineament data representing younger rock units. The rose diagram for Area 4 is the only one of all Clarno diagrams in which trends from north to west are not numerous and nearly equal. In Area 4, N.60°W. and N.30°W. peaks are prominent. The former trend parallels fold axes mapped in the Clarno near Mitchell, and may be the result of northeast-southwest compression. The N.30°W. peak parallels mapped faults in the area. The similarity of these peaks to those of the Strawberry Volcanics of Area 2 suggests that the structures represented by the mapped lineaments may be genetically related, either to the same tectonic episode or to a widespread structural grain present in the province which controlled different episodes of deformation.

Another prominent lineament peak in the Clarno is the east-west peak of Area 13, in the vicinity of the Mitchell fault. The nearly parallel orientation of the lineament peak with this dominant and large scale structural feature suggests that they may be related to the same tectonic stress field.

The previously discussed strongly developed east-northeast trend in Clarno lineament peaks is difficult to interpret, but may represent the northeast-trending folds evident in the Mitchell area, a part of the strong northeast structural domain represented by the Blue Mountains anticlinorium to the north. The northwest-trending peaks are so numerous that many different interpretations are possible. No structures have been mapped in the eastern part of the Clarno outcrop area which are limited solely to pre-Miocene rocks. However, in the western end of the thesis area, the Lower Clarno is known to be structurally deformed. This deformation has been related to northwest-southeast compression which occurred shortly following Clarno volcanism in the late Eocene to early Oligocene (Oles and Enlows, 1971). The strongly developed northeasterly trends in the area may therefore represent compressional features approximately perpendicular to this direction of maximum compression. The numerous northwest-trending lineament peaks may be interpreted to represent cross fractures (tensional) associated with this tectonic episode.

A composite rose diagram of all Clarno U-2 lineaments is shown in Figure 49. This diagram emphasizes the confusion of fracture trends in the older Clarno rocks. Overprinting of the numerous tectonic events which took place in the central Blue Mountains subsequent to Clarno volcanism is suggested by this confusing array of lineament trends. More detailed field studies of the Clarno are required to distinguish structural features of different ages.

Joint Study Results

Rose diagrams and equal area stereonets of joints measured at each sample site are shown in Figures 50 through 79. Rose diagrams show the strike of all joints measured. Equal area stereonets show poles to joints contoured by the Kalsbeek method (Ragan, 1973). Each diagram represents 50 joint attitudes measured in the field at a single outcrop. Because a statistically small number of samples are included in each diagram, rose diagrams show the number of joint strikes per 10 degree interval rather than the 5 degree interval used in the U-2 lineament analysis. Joint sample site numbers correspond with the U-2 sample areas (for example, sites 1-A and 1-B correspond to lineament Area 1, and so forth). Table 4 presents a list of dominant joint peaks by sample site, and can be compared with the dominant U-2 lineament peaks for each area listed in Table 3.

Joint diagrams for sites 1-A and 1-B represent joints observed in the Miocene Strawberry Volcanics near the eastern end of their exposure in U-2 lineament Area 1. The differences observed between these two joint diagrams, which represent the same rock units

Figures 50 - 73. Equal area stereonets are contoured using intervals of 2, 4, 6, 8, etc. % per 1% of area.

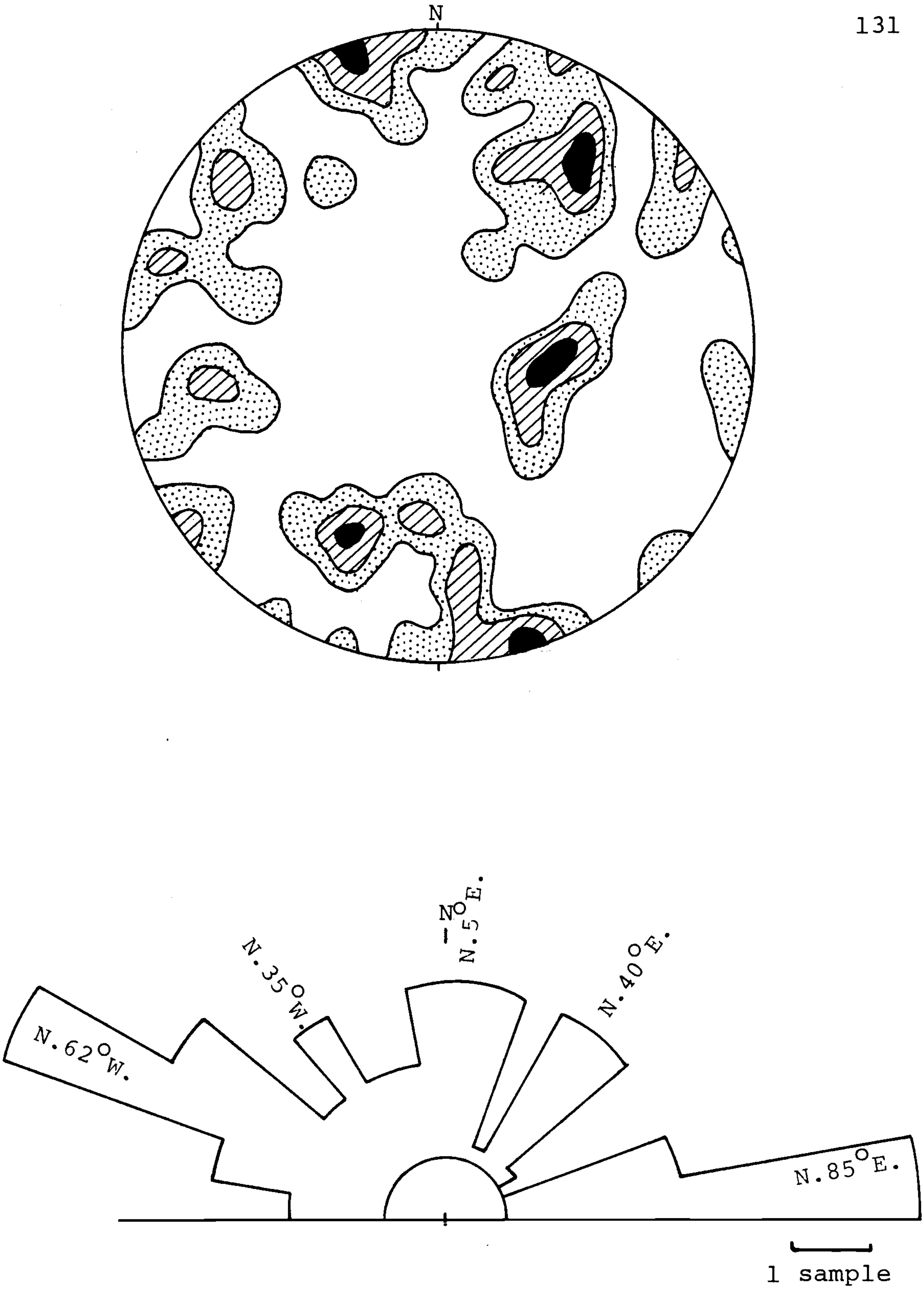
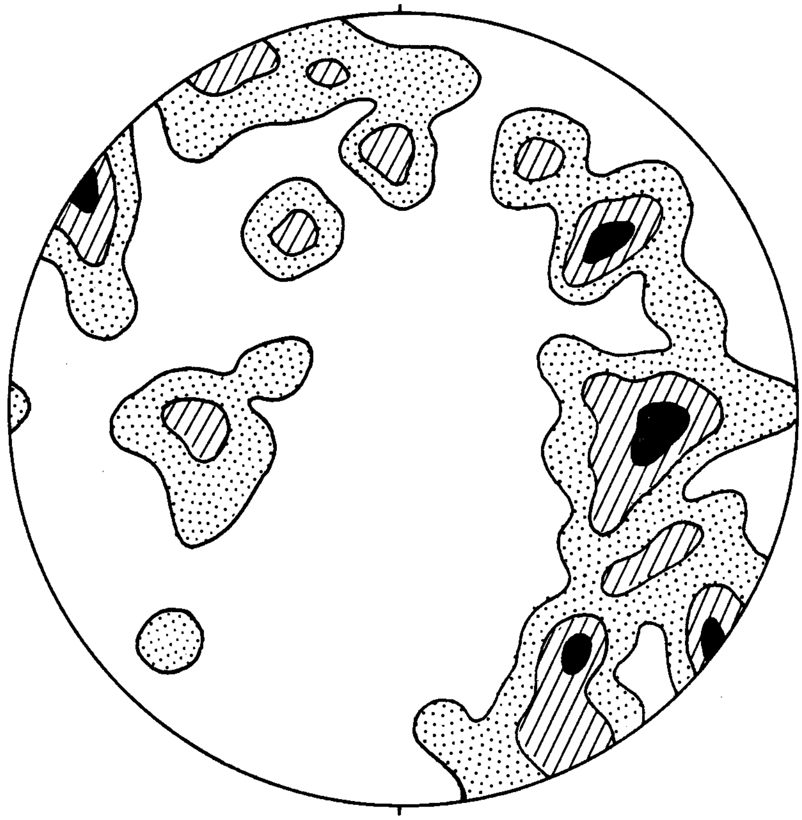


Figure 50. Stereonet and rose diagram of joints measured at Site 1-A.



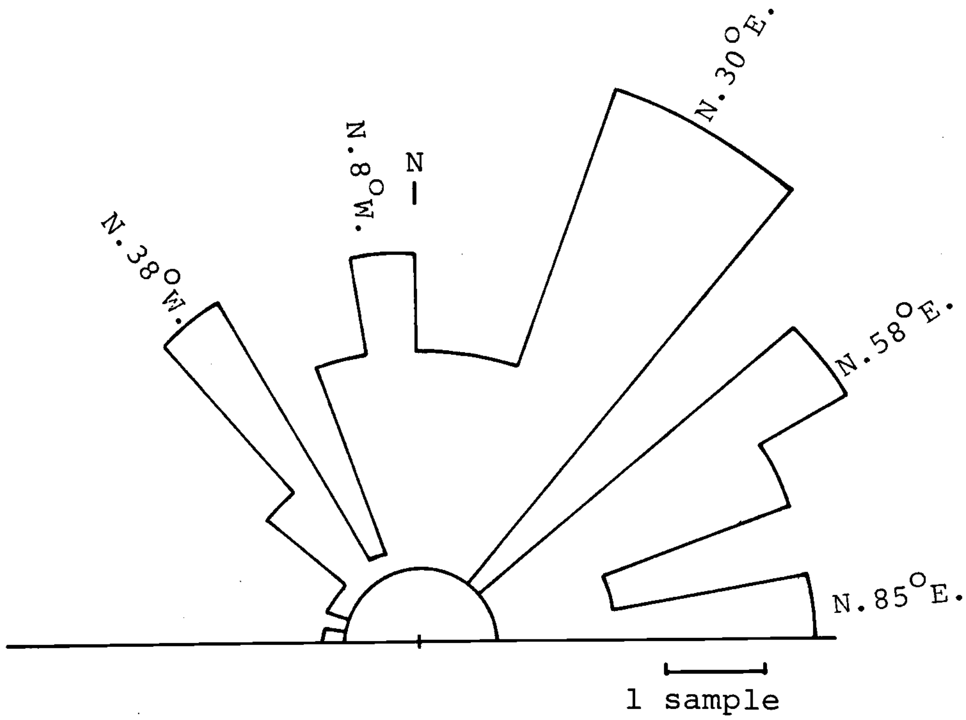
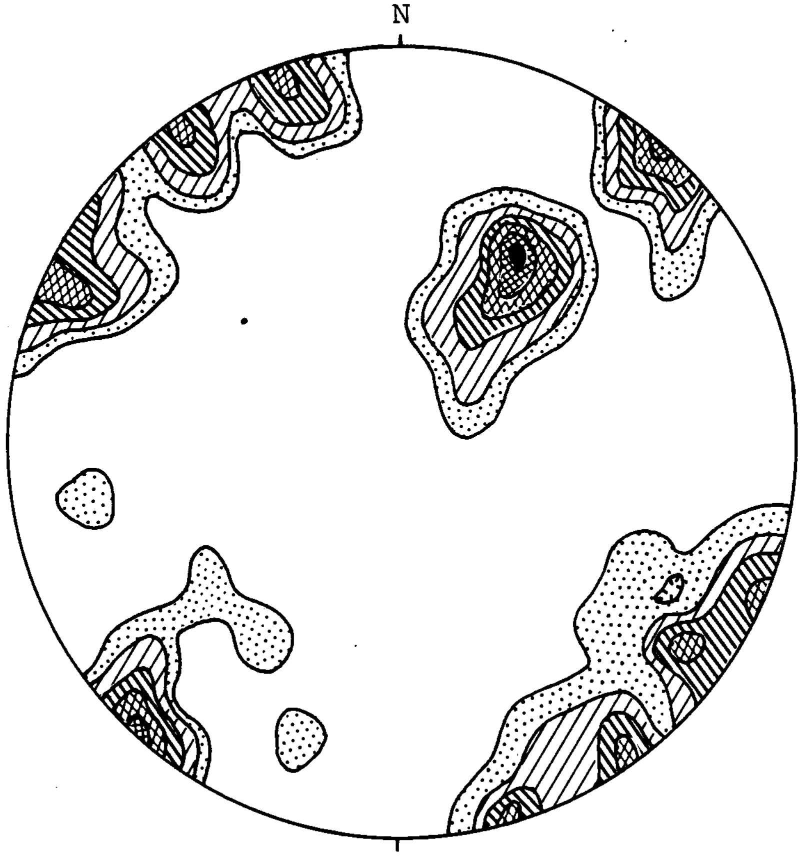


Figure 51. Stereonet and rose diagram of joints measured at Site 1-B.



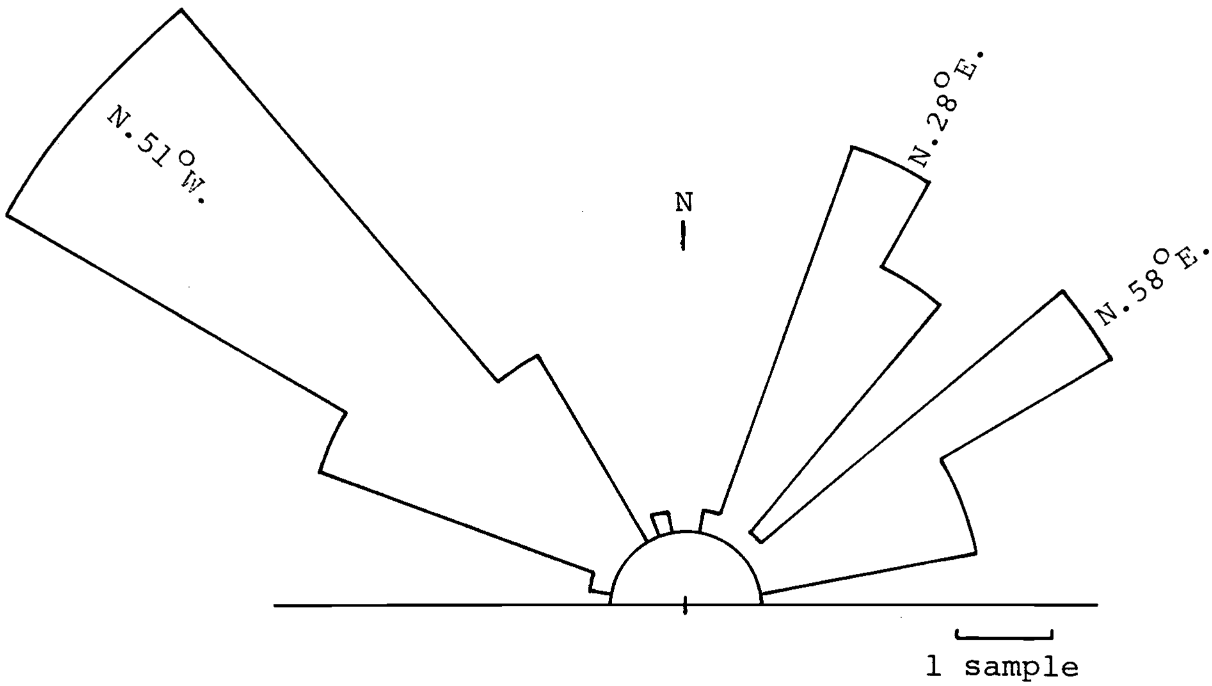
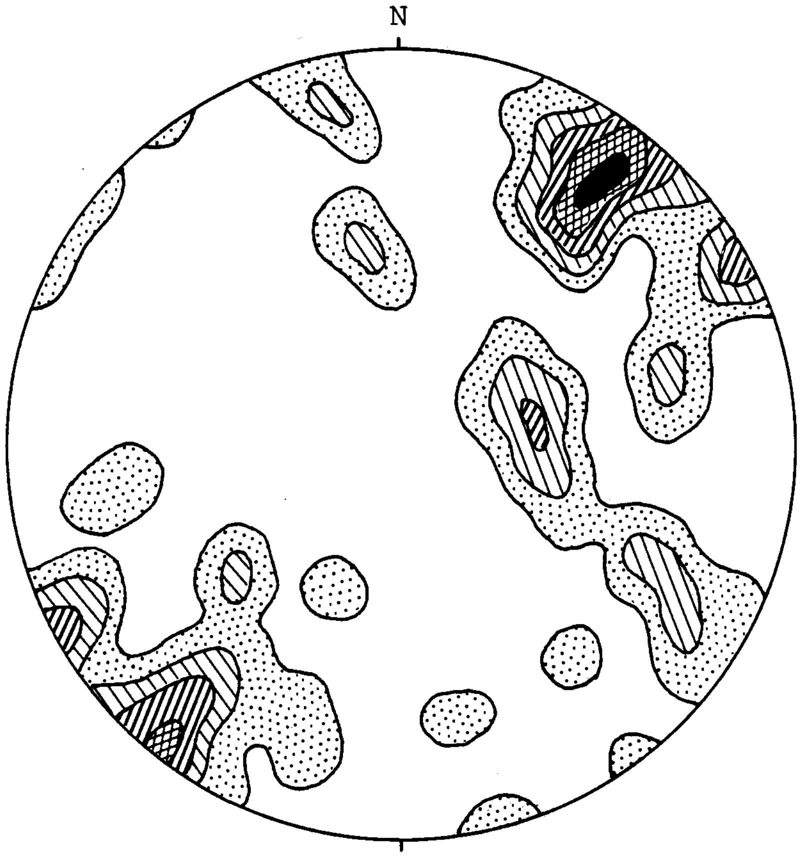


Figure 52. Stereonet and rose diagram of joints measured at Site 2.



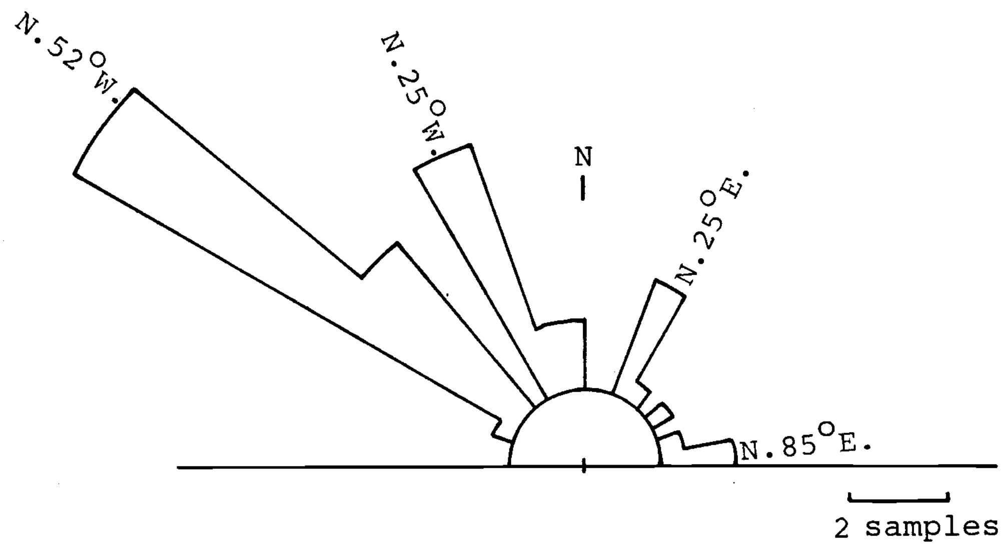


Figure 53. Stereonet and rose diagram of joints measured at Site 3-A.

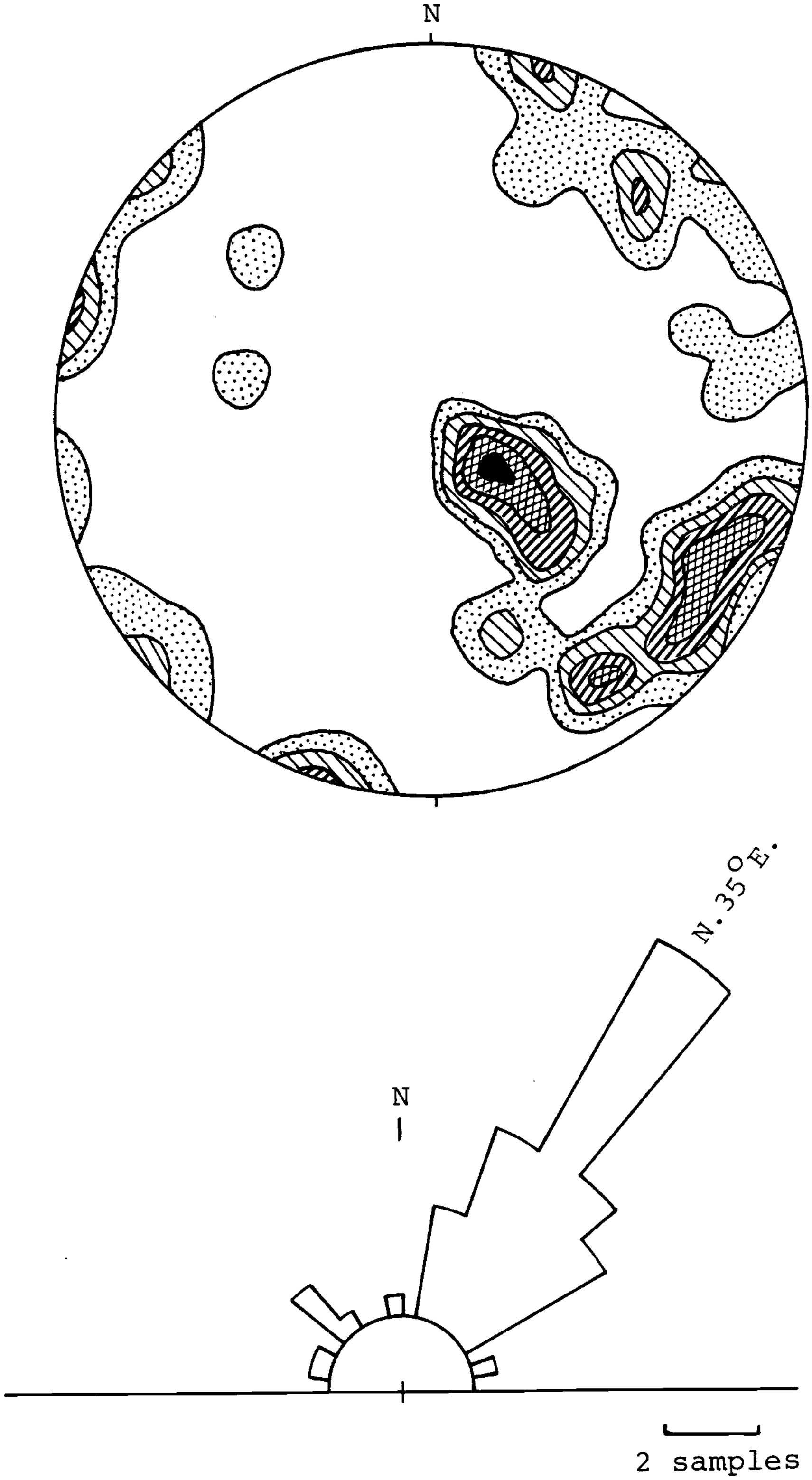


Figure 54. Stereonet and rose diagram of joints measured at Site 3-B.

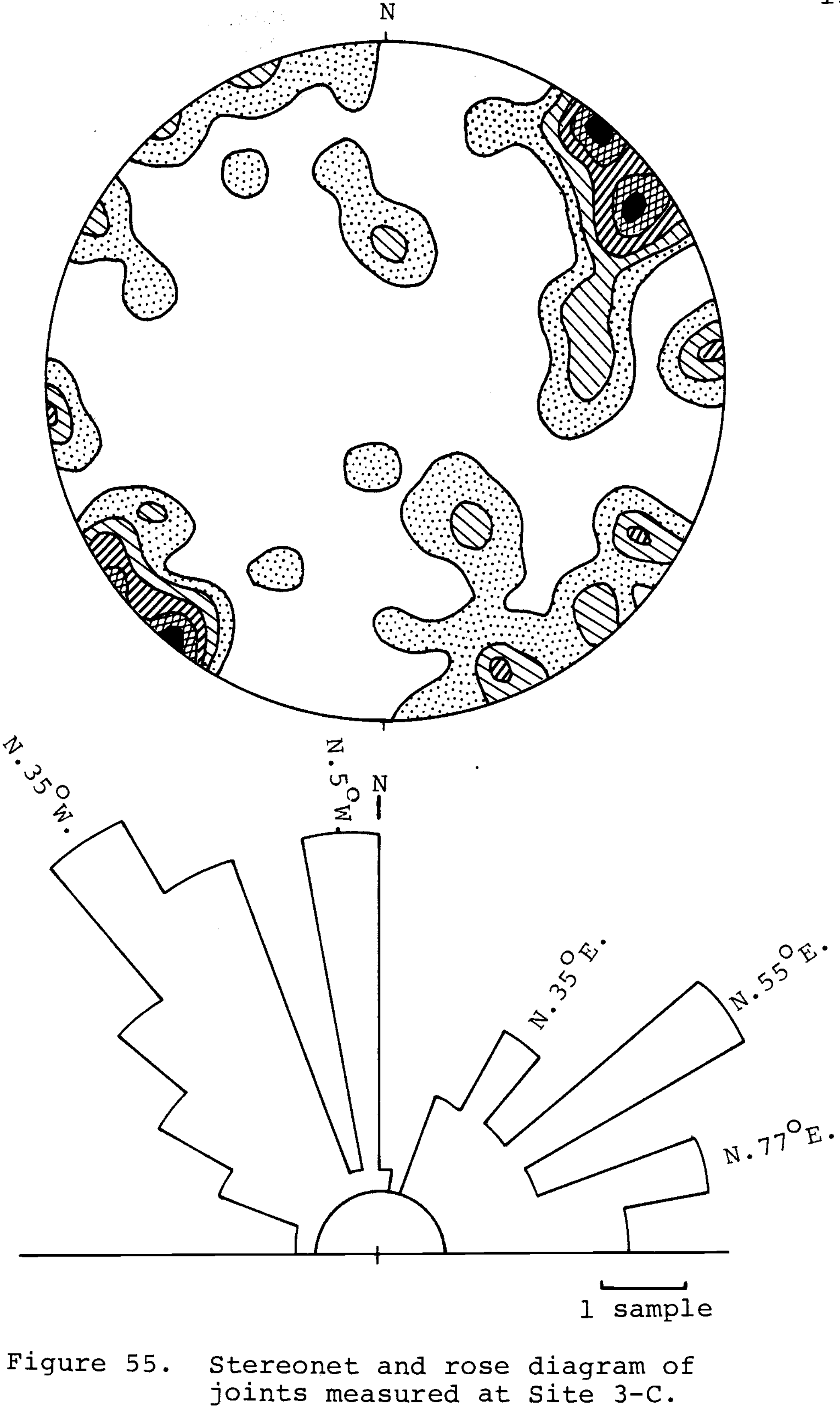
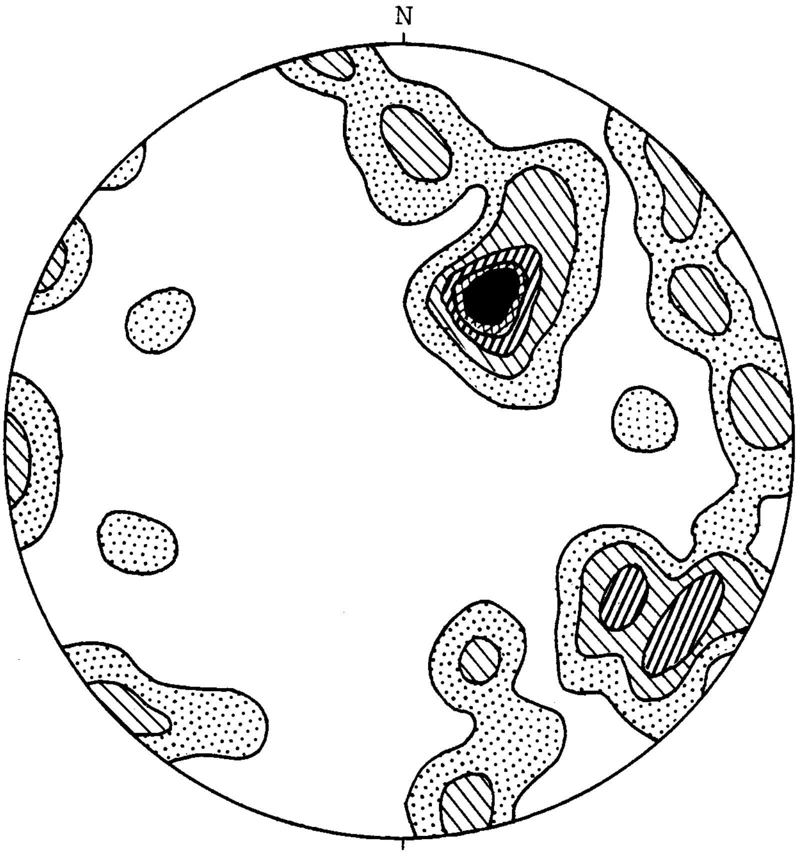


Figure 55. Stereonet and rose diagram of joints measured at Site 3-C.



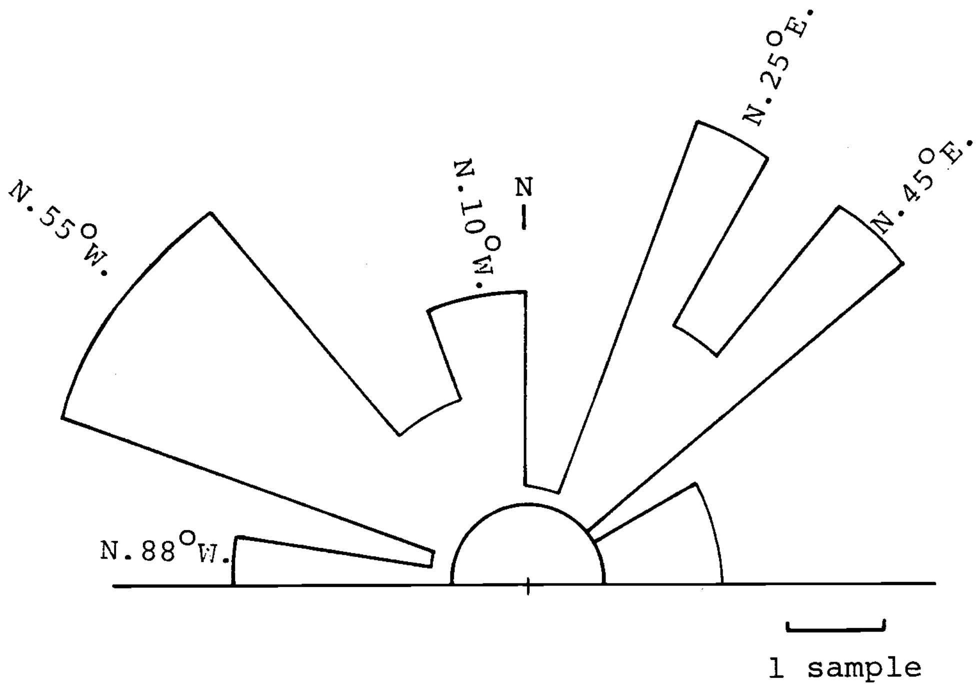
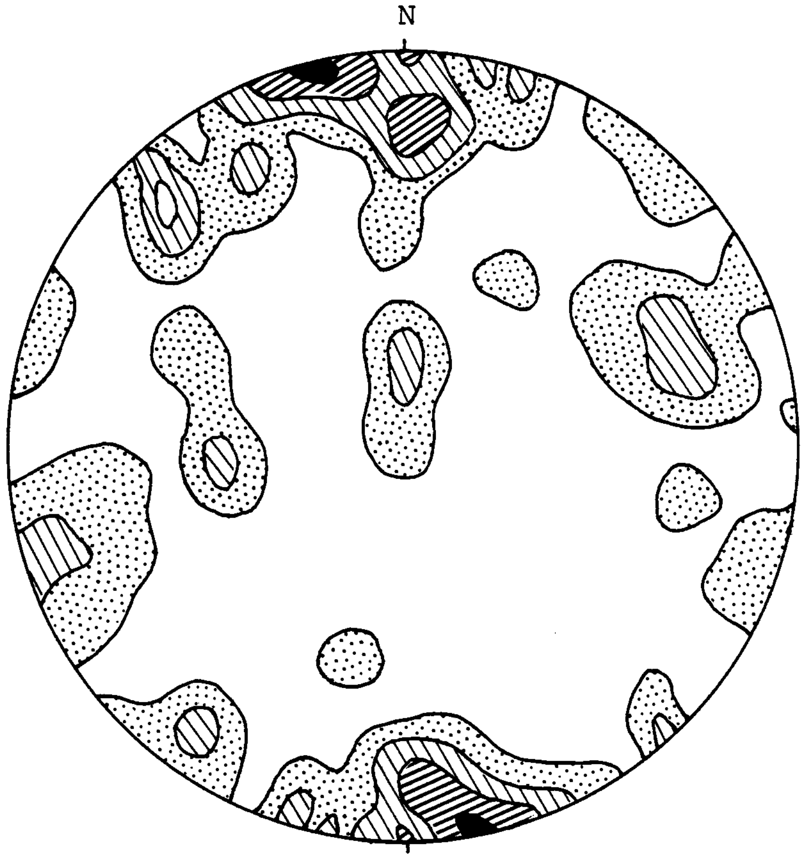


Figure 56. Stereonet and rose diagram of joints measured at Site 4.



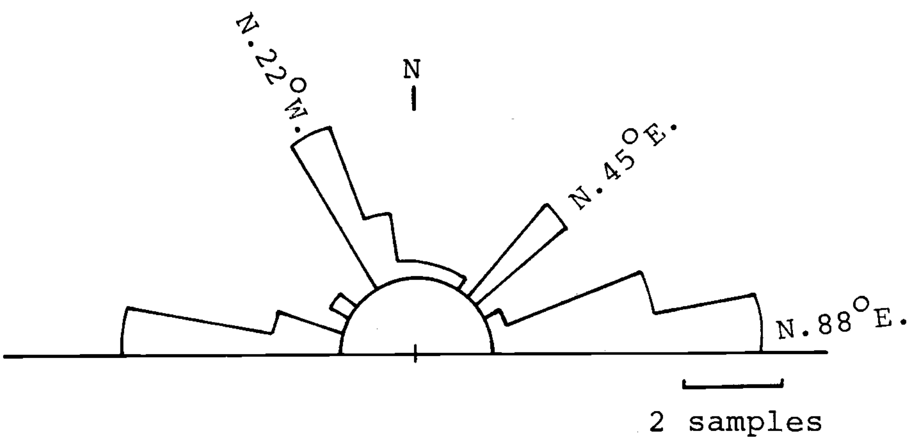


Figure 57. Stereonet and rose diagram of joints measured at Site 5-A.

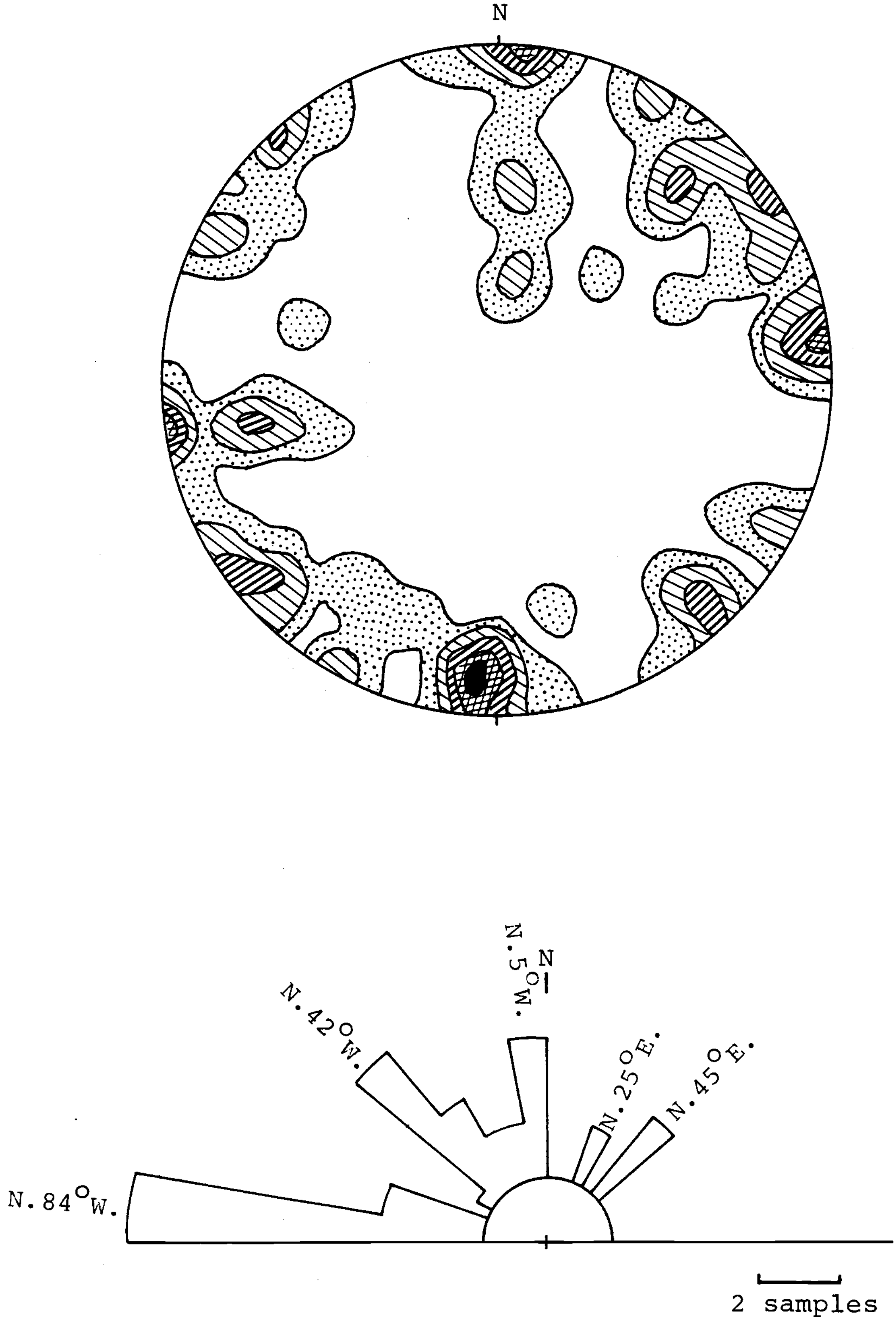


Figure 58. Stereonet and rose diagram of joints measured at Site 5-B.

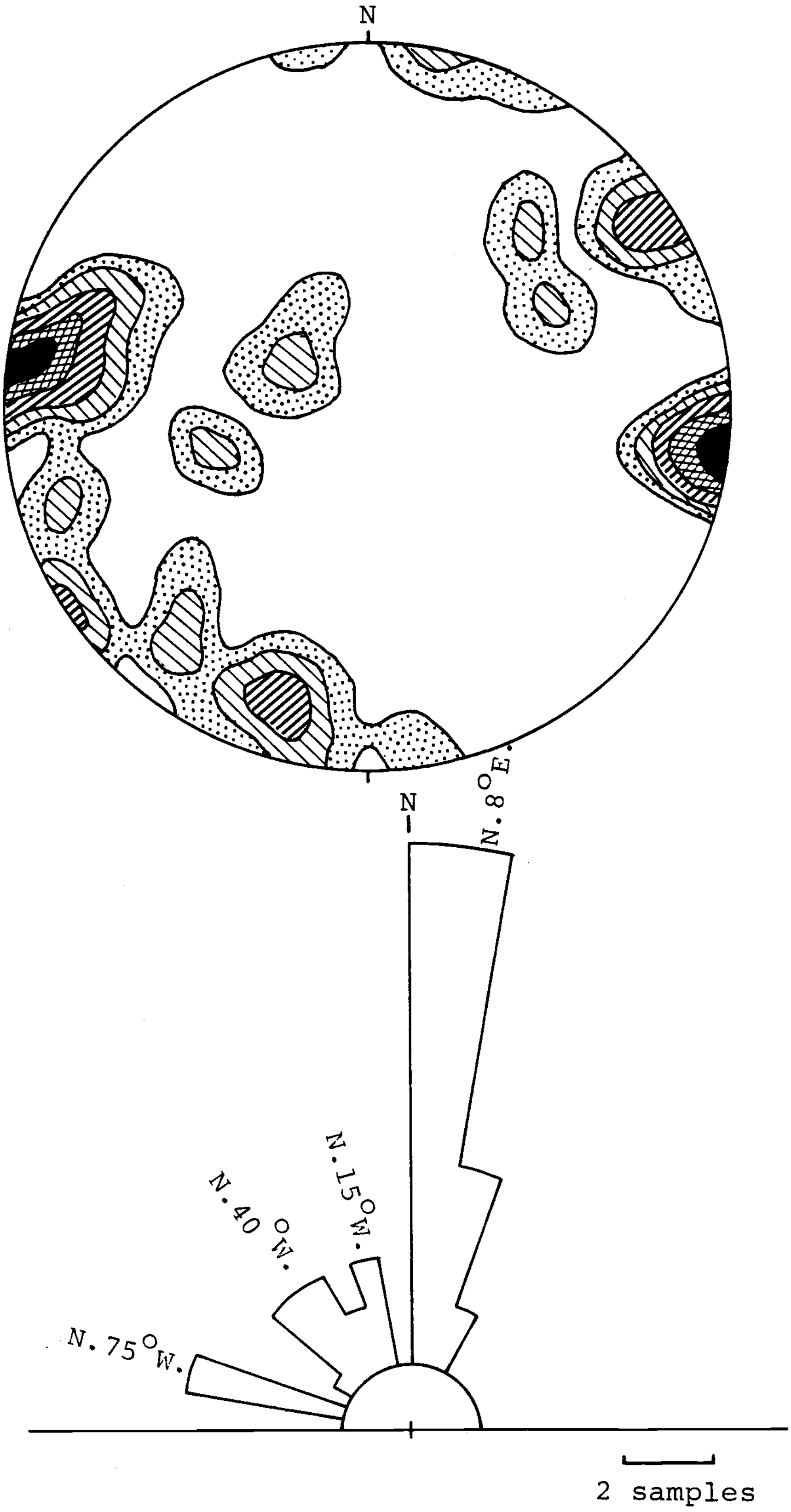


Figure 59. Stereonet and rose diagram of joints measured at Site 5-C.

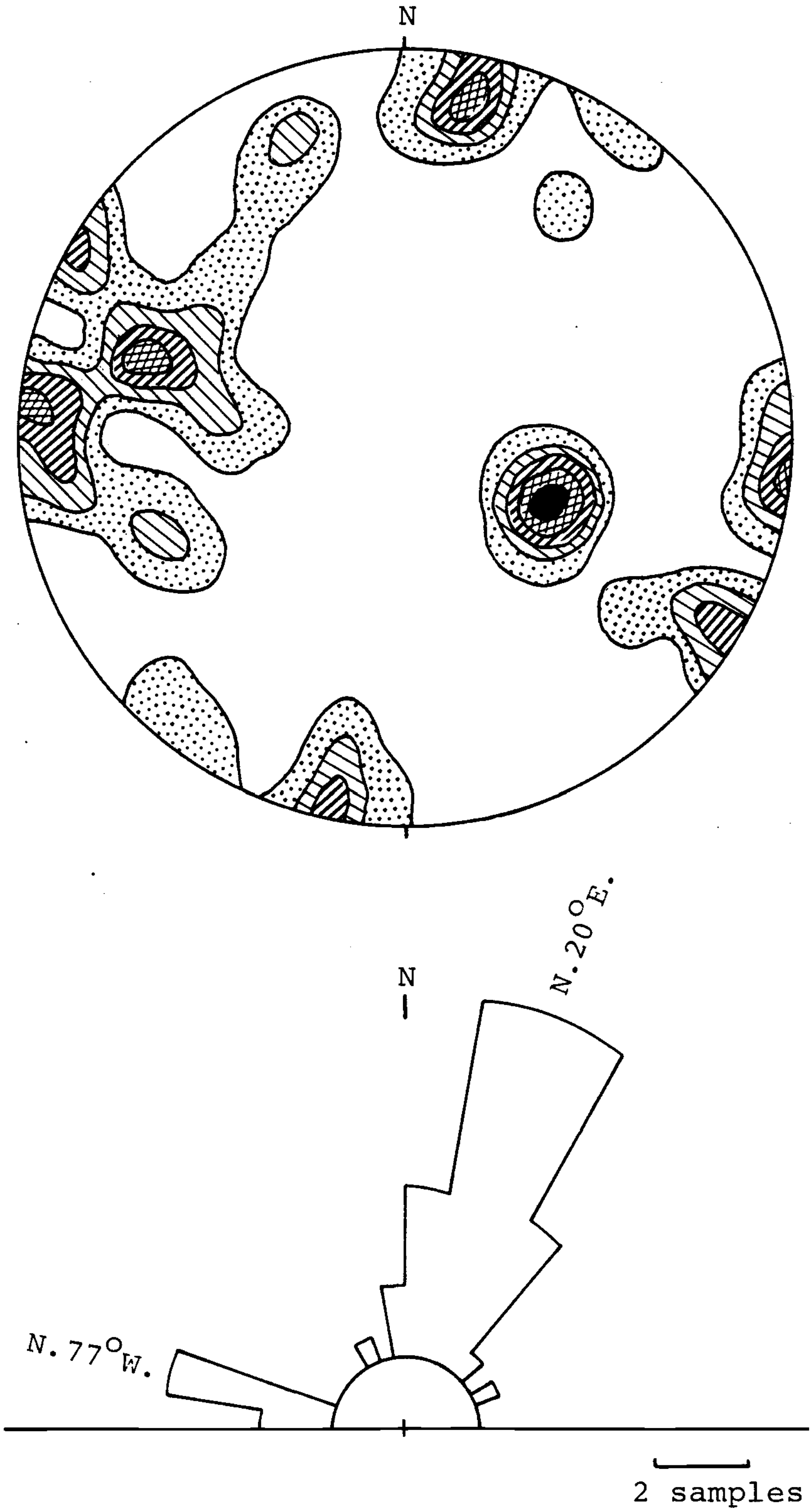


Figure 60. Stereonet and rose diagram of joints measured at Site 6.

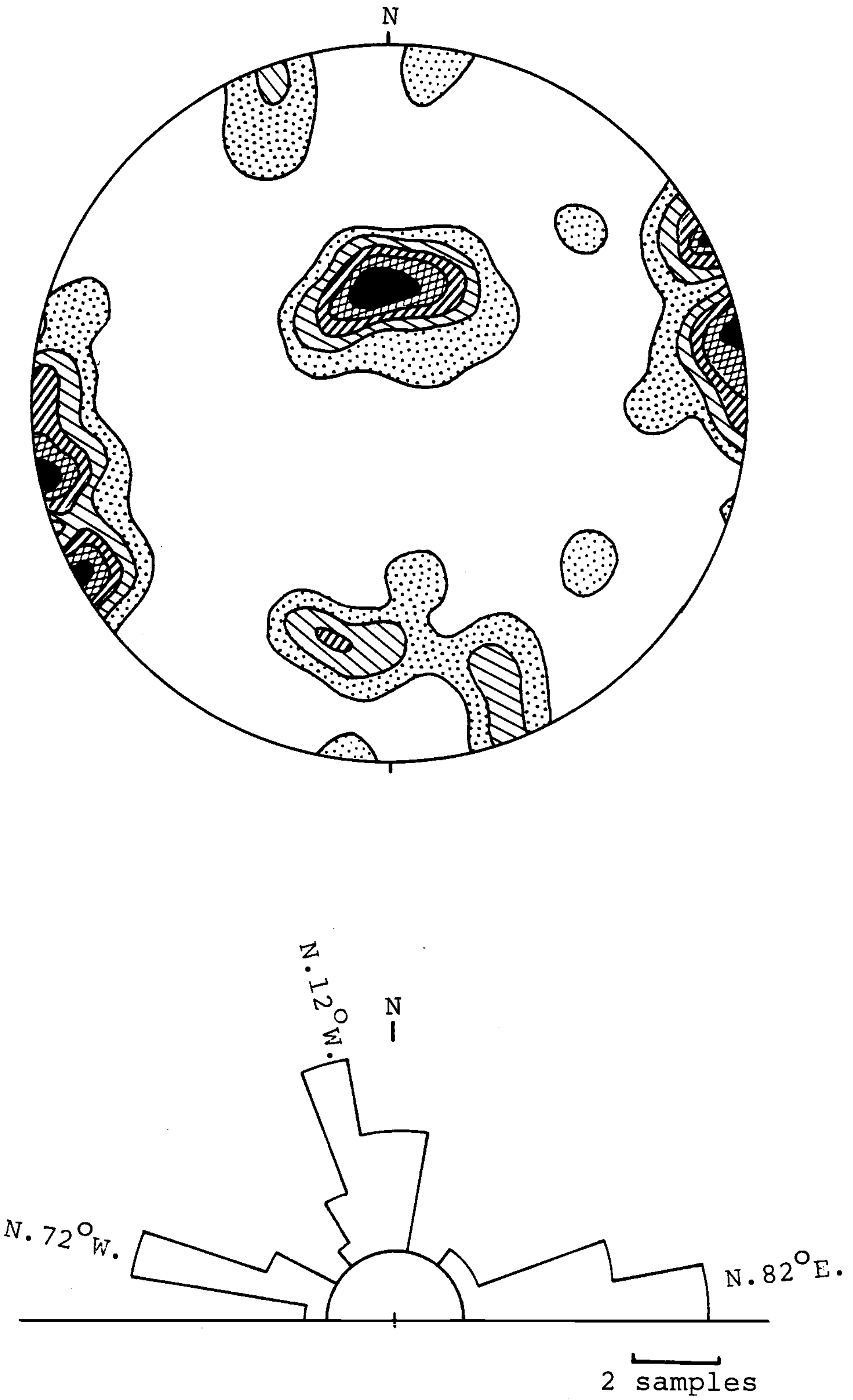


Figure 61. Stereonet and rose diagram of joints measured at Site 7-A.

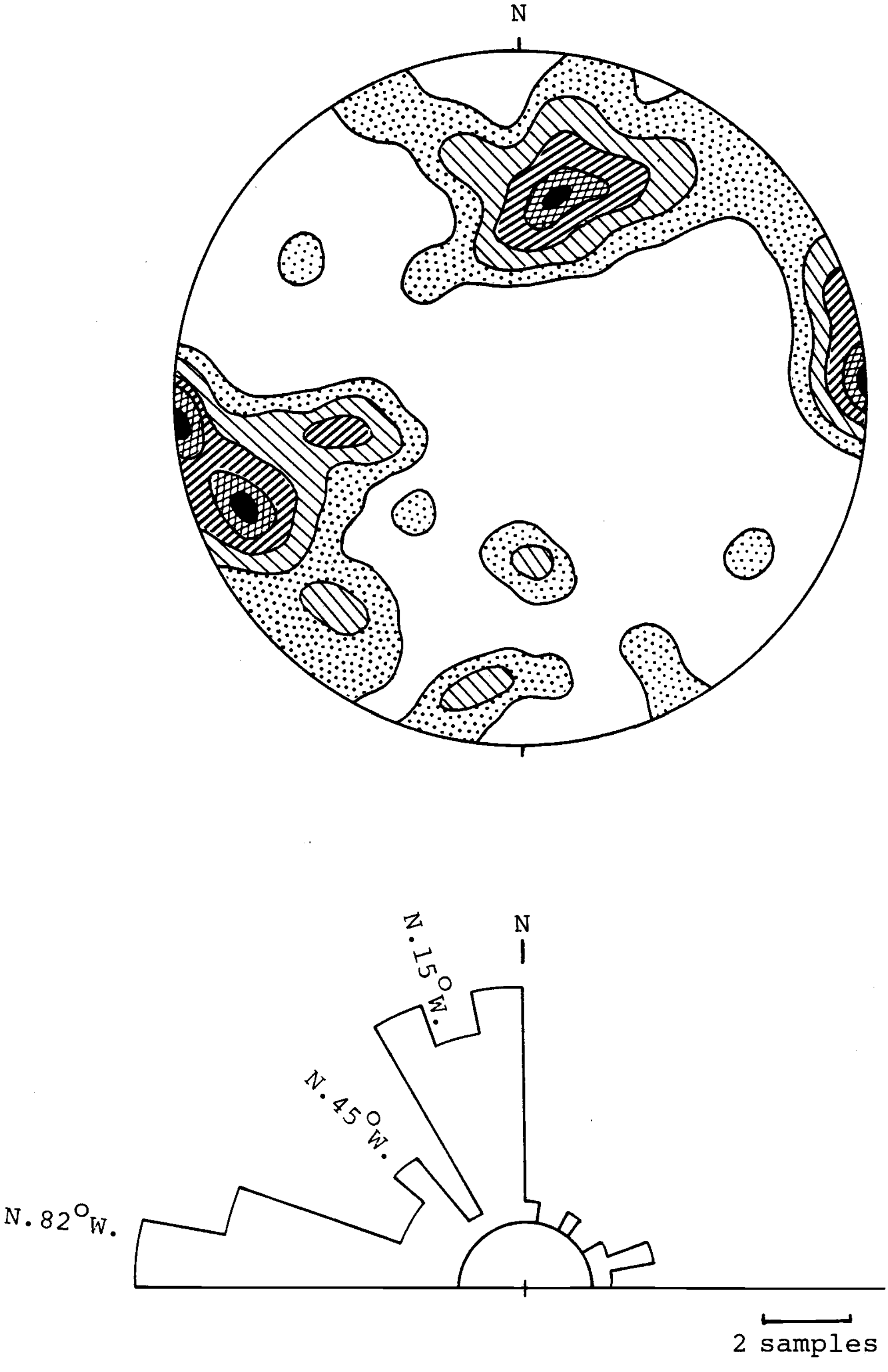


Figure 62. Stereonet and rose diagram of joints measured at Site 7-B.

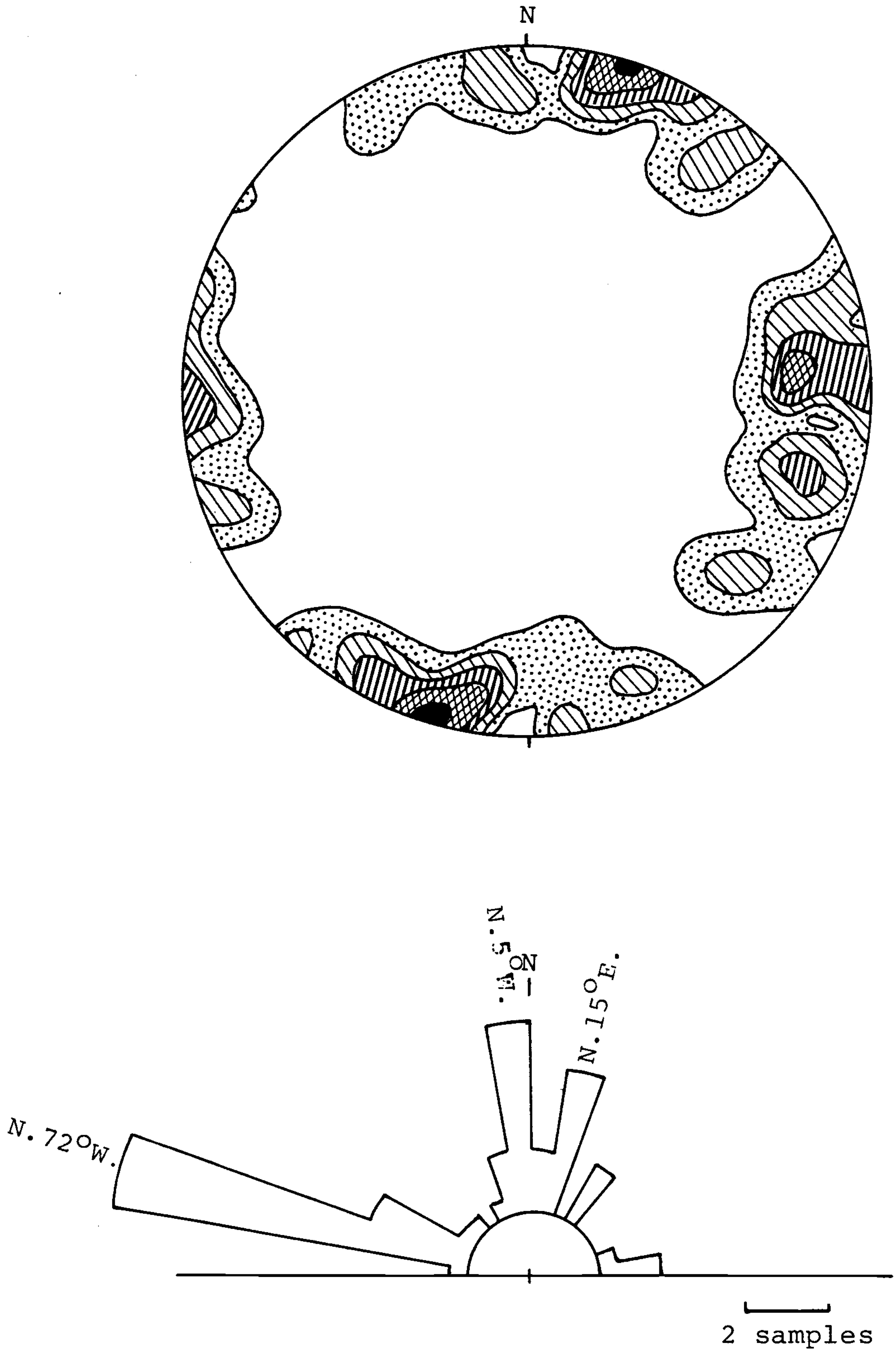


Figure 63. Stereonet and rose diagram of joints measured at Site 8-A.

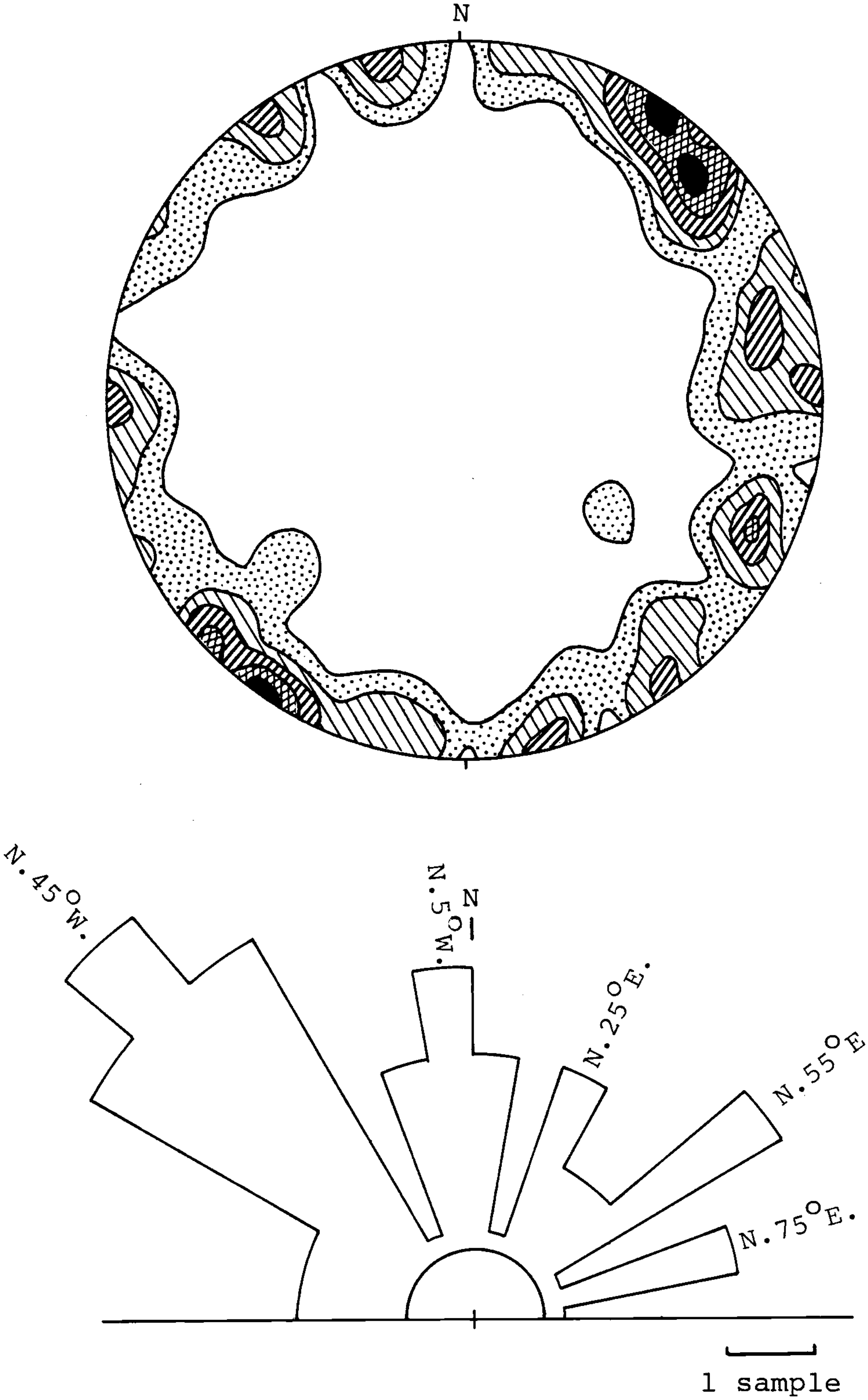


Figure 64. Stereonet and rose diagram of joints measured at Site 8-B.

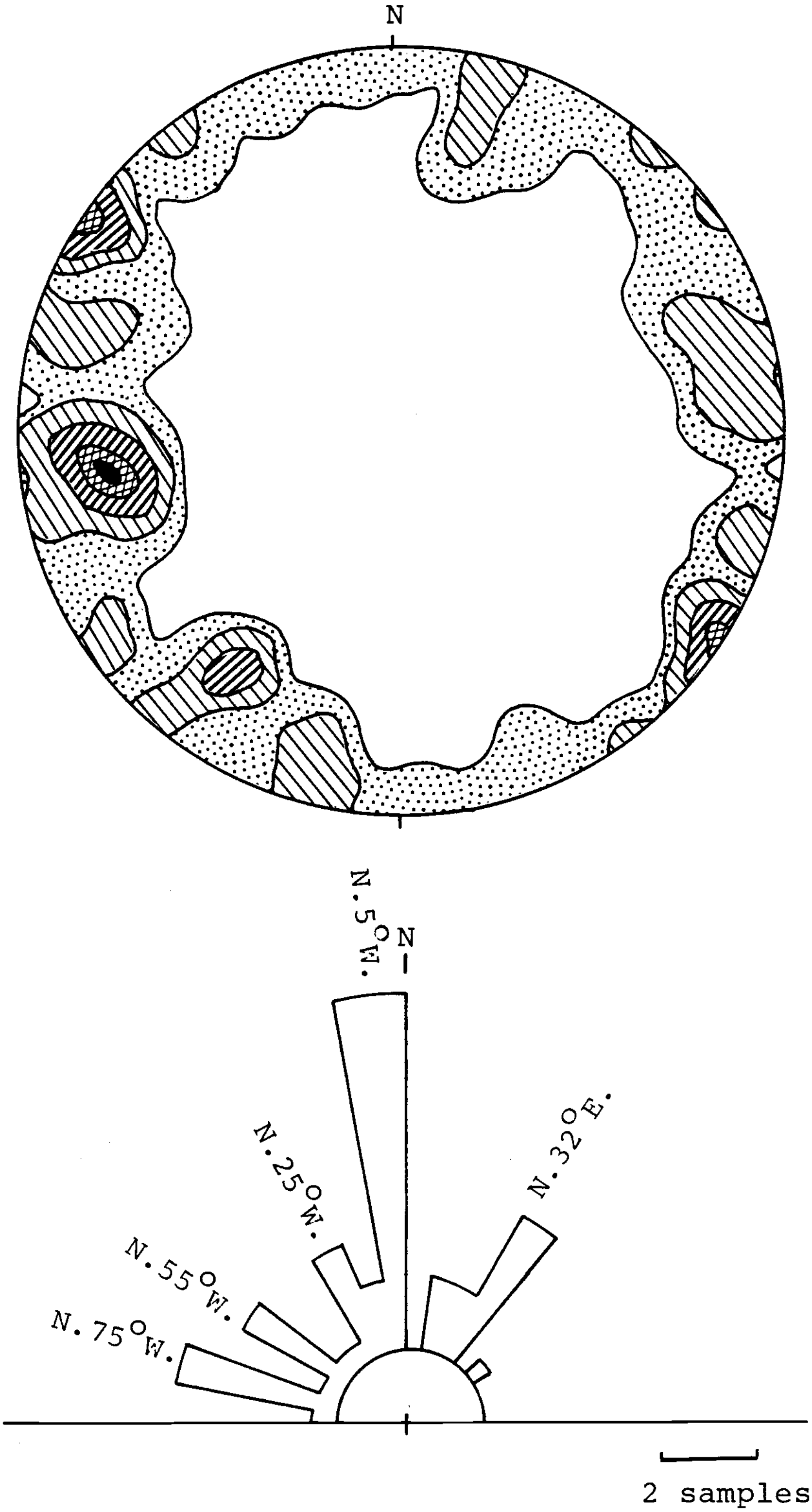
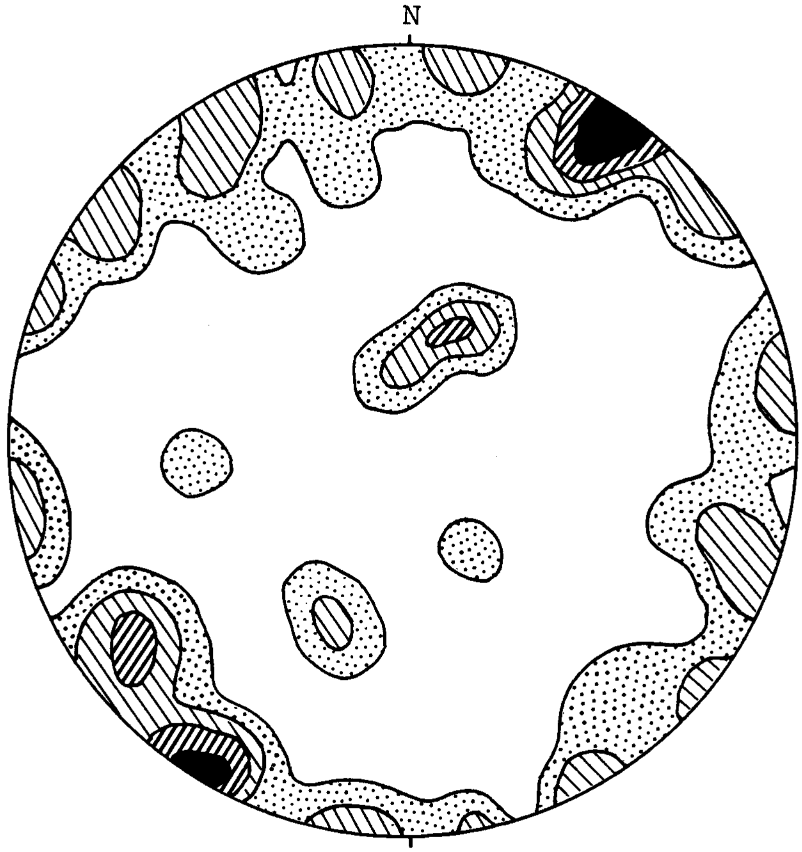


Figure 65. Stereonet and rose diagram of joints measured at Site 8-C.



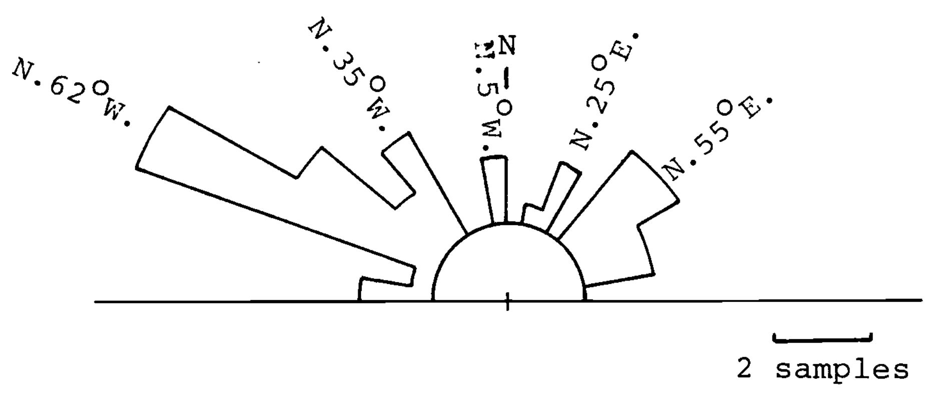


Figure 66. Stereonet and rose diagram of joints measured at Site 9.

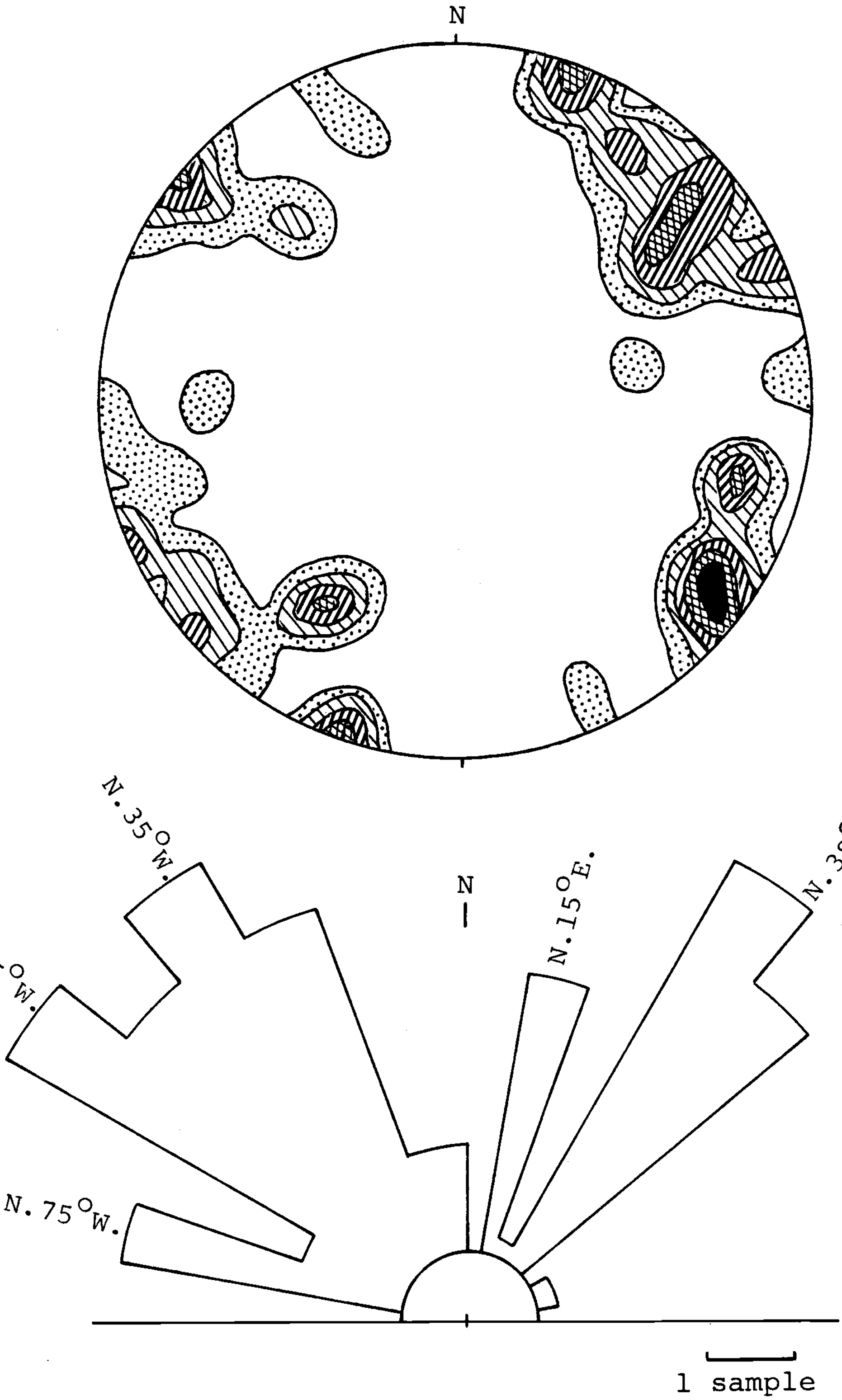


Figure 67. Stereonet and rose diagram of joints measured at Site 10-A.

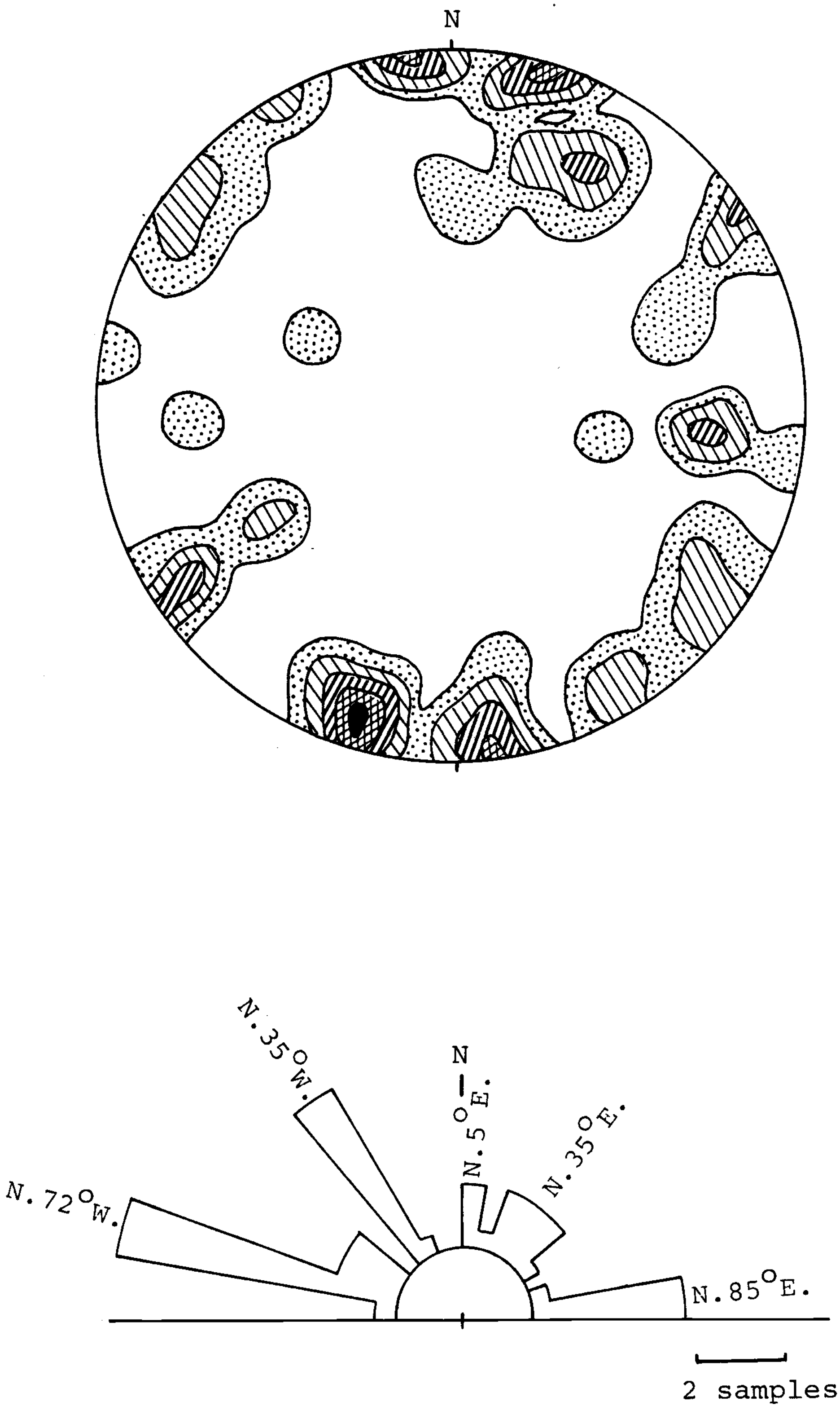
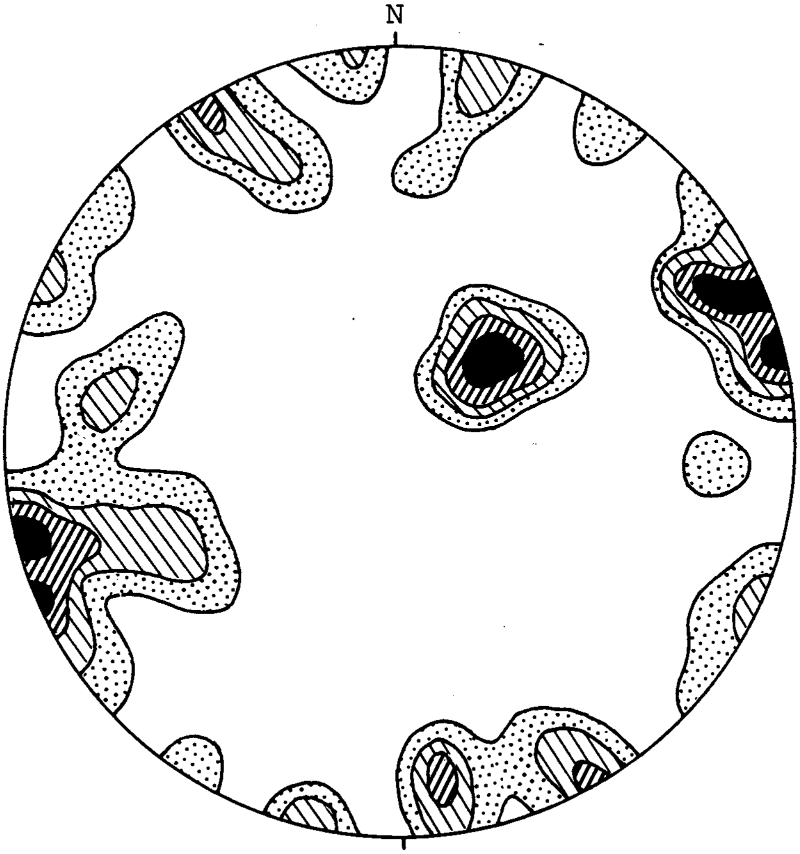


Figure 68. Stereonet and rose diagram of joints measured at Site 10-B.



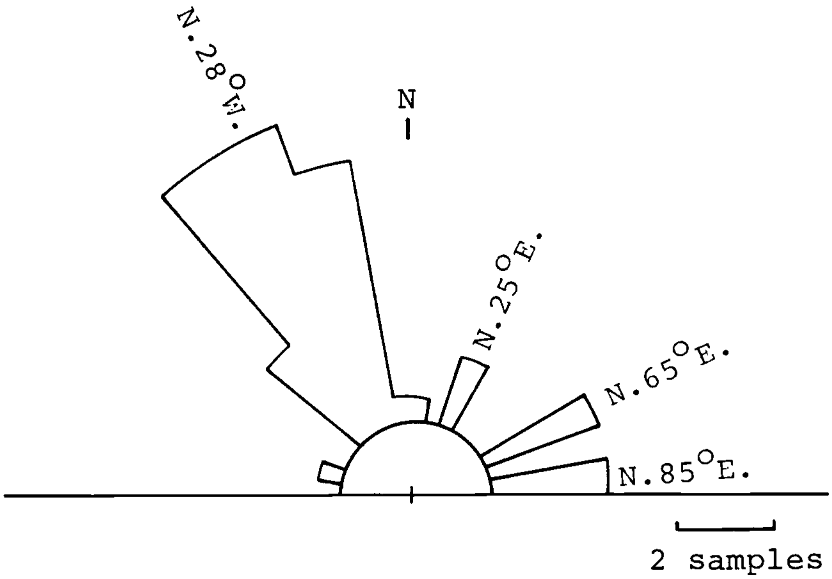


Figure 69. Stereonet and rose diagram of joints measured at Site 11.

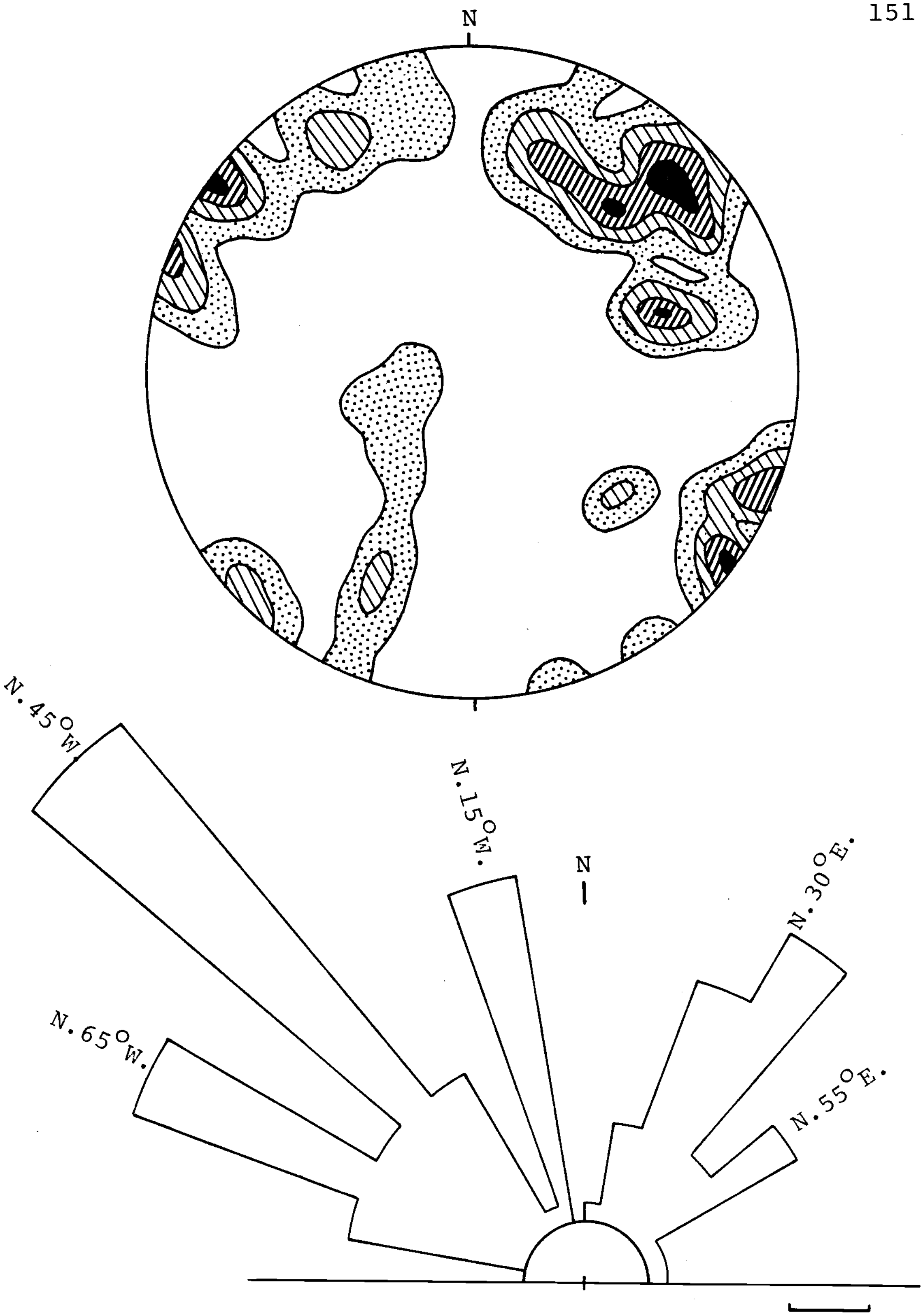


Figure 70. Stereonet and rose diagram of joints measured at Site 12.

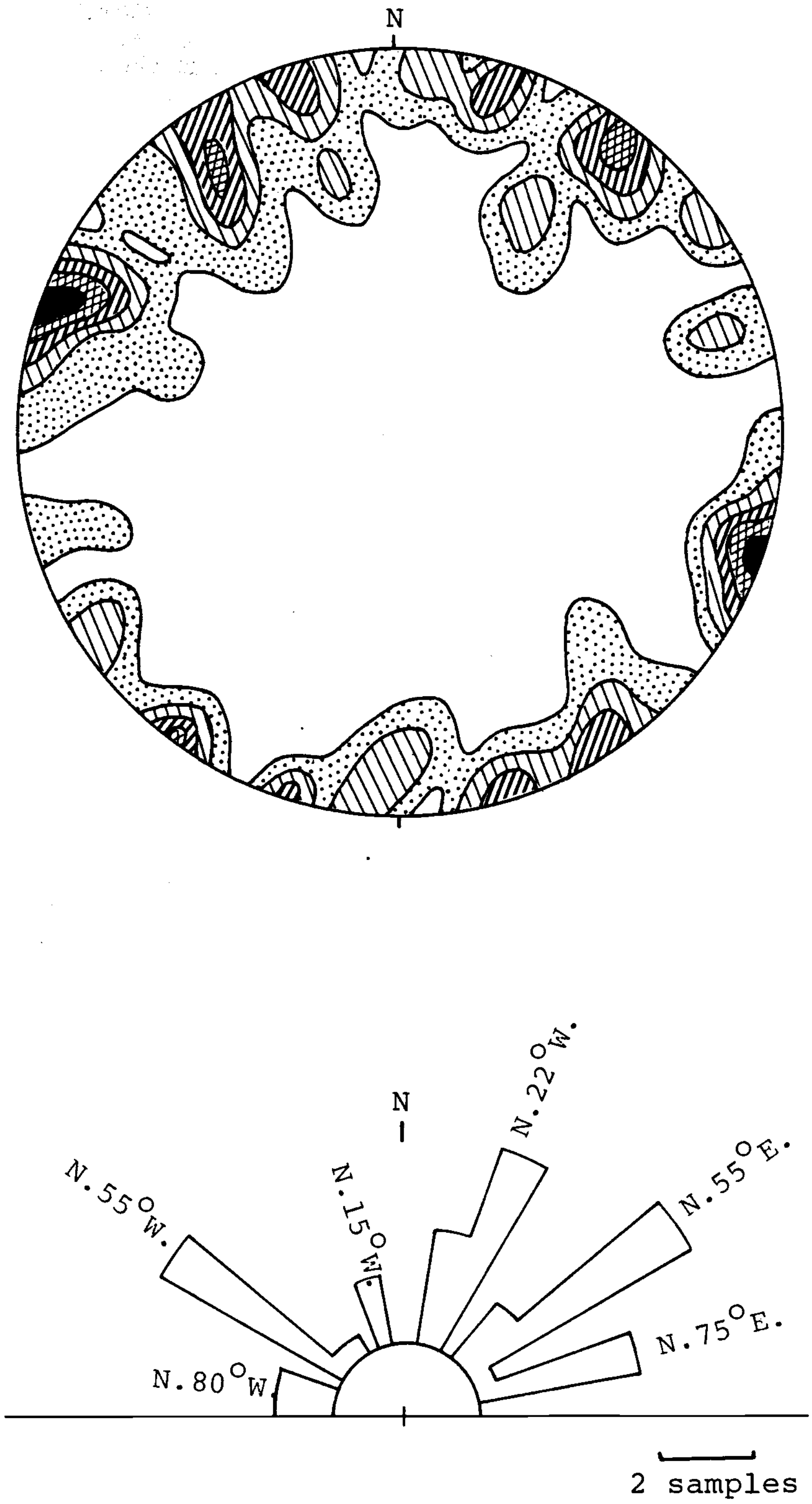


Figure 71. Stereonet and rose diagram of joints measured at Site 13-A.

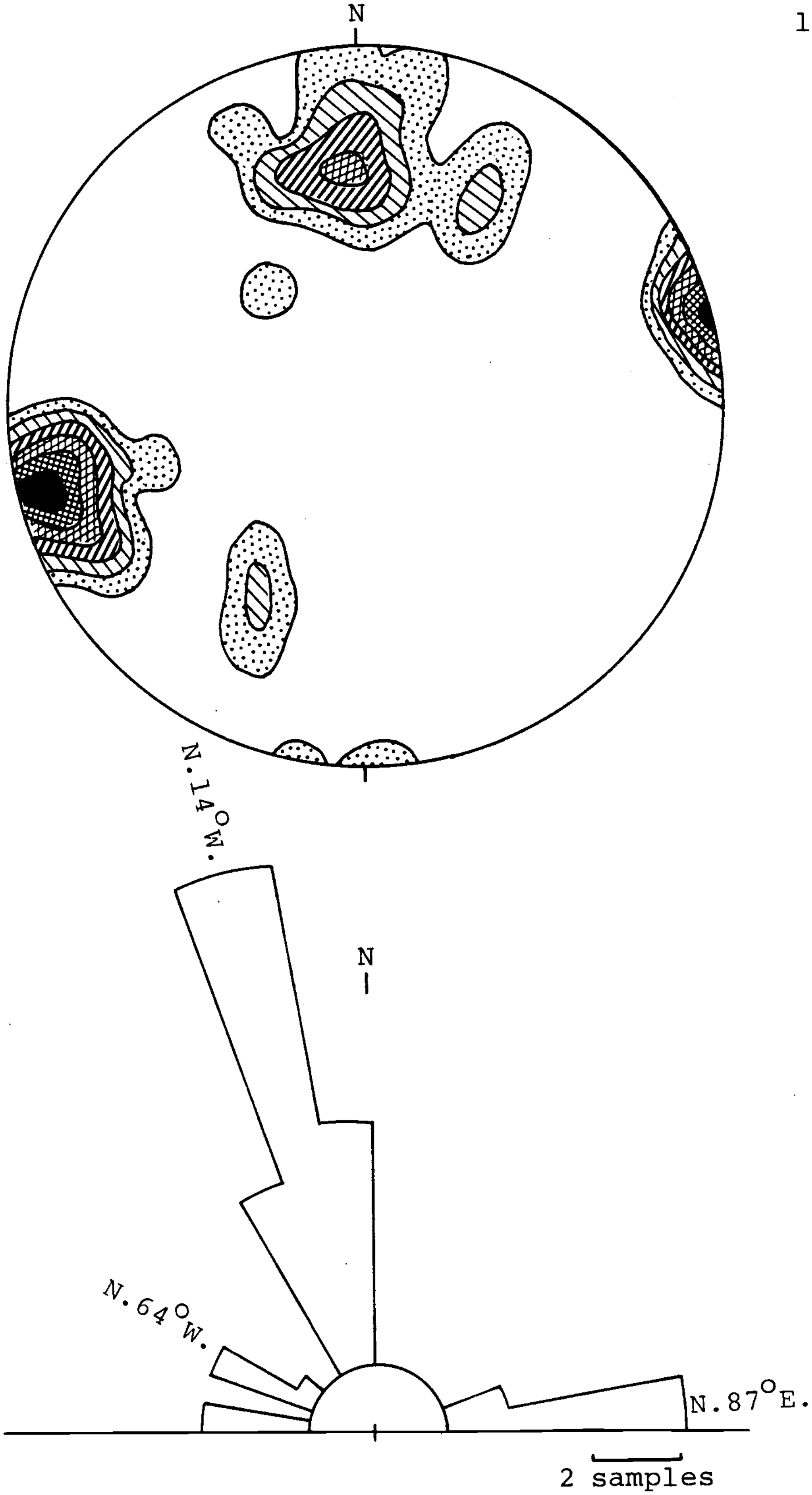


Figure 72. Stereonet and rose diagram of joints meaaured at Site 13-B.

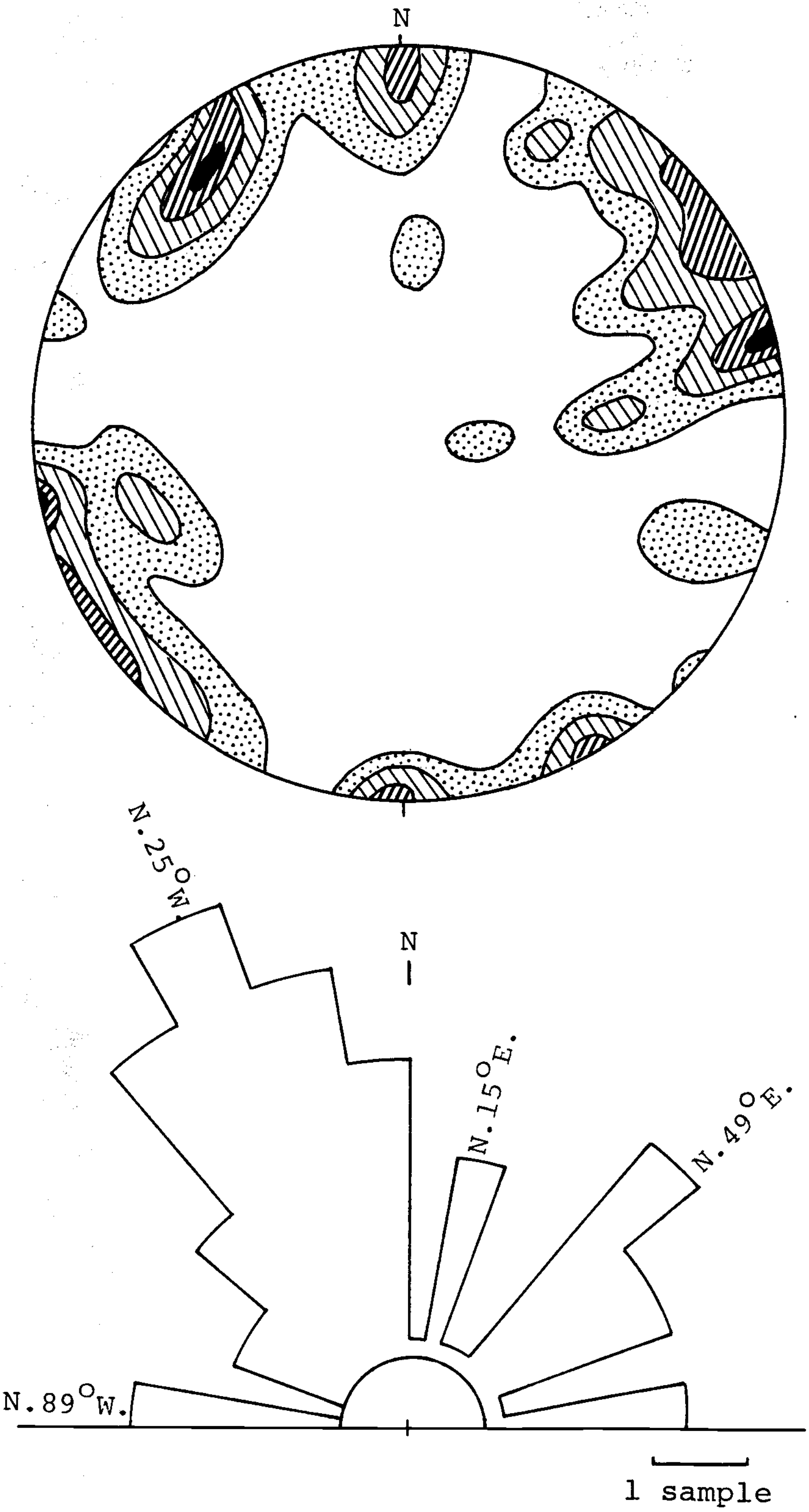


Figure 73. Stereonet and rose diagram of joints measured at Site 14.

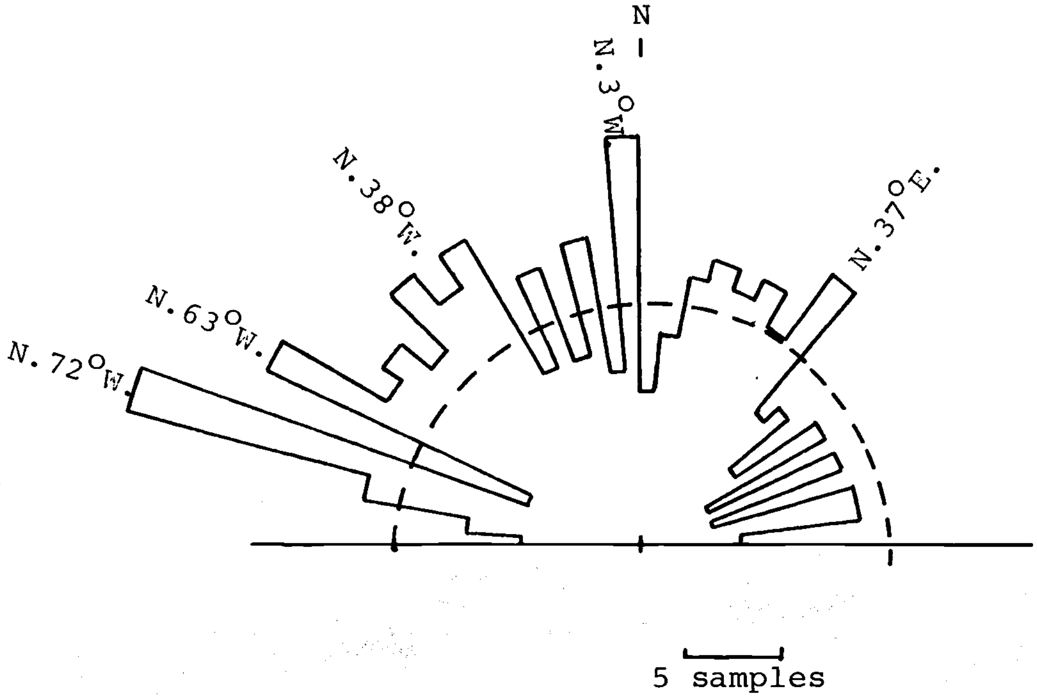


Figure 74. Summary rose diagram of joints in Columbia River Basalts.

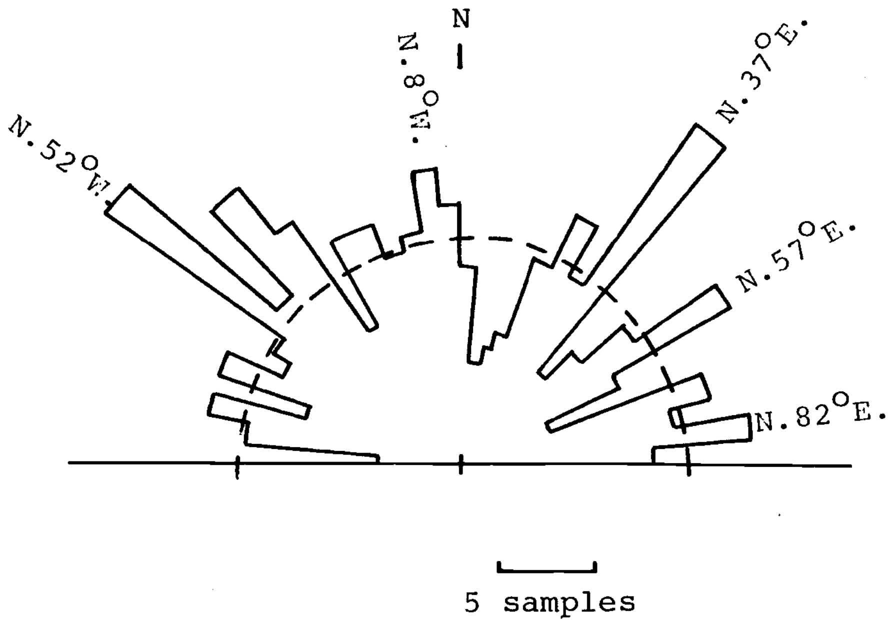


Figure 75. Summary rose diagram of joints in Strawberry Volcanics.

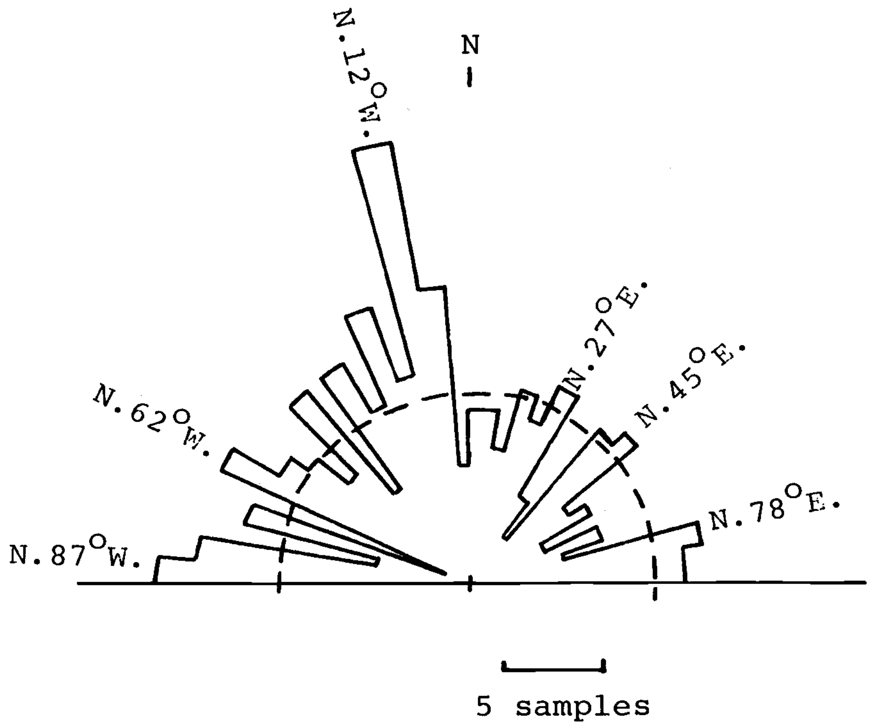


Figure 76. Summary rose diagram of joints in the Clarno Formation.

TABLE 4: Prominent Joint Peaks by Sample Site.

Site	Rock Unit									
1A	Straw.Volc.	N85°E	N 5°E		N35°W	N62°W		N40°E		
1B	Straw.Volc.	N85°E	N 8°W		N38°W			N30°E	N58°E	
2	Straw.Volc.					N51°W		N28°E	N58°E	
3A	Straw.Volc.	N85°E				N52°W		N25°E		N25°W
3B	Straw.Volc.							N35°E		
3C	Straw.Volc.	N77°E	N 5°W		N35°W			N35°E	N55°E	
4	Clarno	N88°W	N10°W			N55°W		N25°E	N45°E	
5A	Clarno	N88°E							N45°E	N22°W
5B	Clarno	N84°W	N 5°W		N42°W			N25°E	N45°E	
5C	Clarno	N75°W	N 8°E	N15°W	N40°W					
6	Col.Riv.Bas.						N77°W	N20°E		
7A	Straw.Volc.	N82°E		N12°W			N72°W			
7B	Straw.Volc.	N82°W		N15°W	N45°W					
8A	Col.Riv.Bas.		N 5°W				N72°W	N15°E		
8B	Col.Riv.Bas.	N75°E	N 5°W		N45°W			N25°E	N55°E	
8C	Col.Riv.Bas.		N 5°W			N55°W	N75°W	N32°E		N25°W
9	Col.Riv.Bas.		N 5°W		N35°W	N62°W		N25°E	N55°E	
10A	Col.Riv.Bas.				N35°W	N55°W	N75°W	N15°E	N38°E	
10B	Col.Riv.Bas.	N85°E	N 5°E		N35°W		N72°W	N35°E		
11	Col.Riv.Bas.	N85°E			N28°W			N25°E	N65°E	
12	Col.Riv.Bas.			N15°W		N45°W	N65°W	N30°E	N55°E	
13A	Clarno	N80°W		N15°W		N55°W		N22°E	N52°E	
13B	Clarno	N87°E		N14°W			N64°W			
14	Clarno	N89°W						N15°E	N49°E	N25°W

and are located relatively close to each other, may represent actual changes in joint attitudes from one outcrop to another, or may merely reflect the relatively small joint sample taken at each site.

A comparison of the composite joint trend data for sites 1-A and 1-B with the corresponding lineament trends shows that some differences in dominant trends exist. For example, a dominant, nearly east-west trend exhibited by joints in the Strawberry Volcanics does not appear to be prominent in the lineament data. However, several peaks do appear equally prominent in both data sets. These are the N.55°E., N.62°W., N.35°W., and N.30°E. peaks. It is these four peaks which are important in the U-2 interpretation of two tectonic episodes, one oriented northwest-southeast and one northeast-southwest.

An example of very close coincidence of U-2 lineament and joint trends is exhibited by Area 2. The broadness of the joint peak at N.50°W. can approximate the closely spaced northwest-trending peaks of the U-2 data. The other two dominant joint peaks, N.28°E. and N.60°E., coincide closely with lineament peaks in this area.

At the other extreme, Area 7 provides an example of an area where little correspondence exists between joint attitudes and U-2 lineament trends. Dominant joint peaks in this area are N.15°W., N.75°W., and East-West, whereas dominant lineament trends are N.63°W., N.33°W., and N.27°E.

Joint trends for the other areas can be compared with lineament trends in the same manner as the above comparisons. The result of such a comparison suggests that, while there is some coincidence between joint and lineament trends, the two data sources do not give closely similar results in most cases. There are several factors to which such differences may be attributed.

Several problems involved in the study of joint orientations may affect the results of a summary of the overall trends of these joints. One problem inherent in the joint data which is included in the present study is the probable inclusion of non-tectonic joints, such as cooling joints, which may have a more random orientation. Cooling joints were visible in many of the outcrops of the three volcanic flow units considered in this study. An attempt was made to ignore joints of obvious cooling origin by avoiding outcrops with columnar jointing. However, it is intrinsically difficult to distinguish between these and tectonic joints.

One means of insuring a purely tectonic sample would have been to include only those joints which display slickensides. This method was initially attempted. However, except in the Clarno outcrop areas, where few cooling joints were observed in any case, most outcrops did not yield a large enough number of slickensided joint planes to enable an adequate sample, and some outcrops did not exhibit any slickensided joints whatsoever. As a result, the probable inclusion of cooling joints in the joint sampling may have created an inaccurate picture of tectonic trends.

Another reason for the noted difference between joint and lineament trends in the area of study may be the difference in scale of the features involved. Although lineaments in the Big Summit Prairie area do correspond with mappable tectonic joints in the Columbia River Basalts in that area (Lawrence, 1979), these joints are much larger in scale than the joints measured in outcrop for the thesis study. The lineaments mapped in other parts of the thesis area may thus represent regional joints that are not readily apparent in terrain in which the volcanics are for the most part masked by vegetation and alluvium.

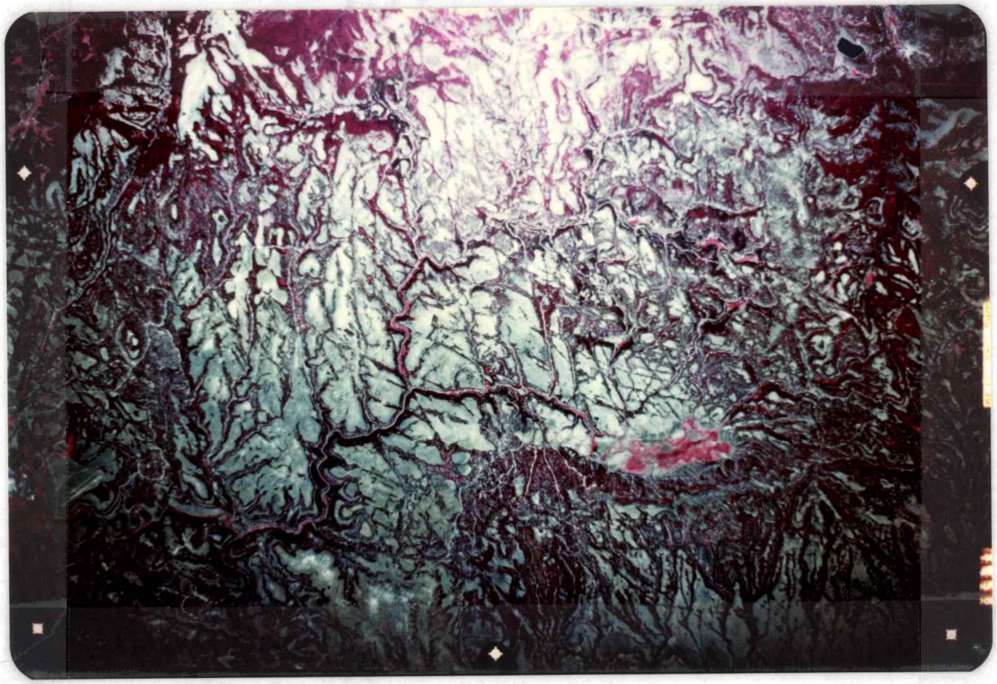


Figure 77. Detail of a U-2 photo showing the geometric pattern of lineaments at Big Summit Prairie. These have been mapped in the field as regional joints or fractures.

CONCLUSIONS FROM LINEAMENT DATA

If it is accepted that the abundant lineament trends noted by remote sensing techniques in the Tertiary volcanics of the central Blue Mountains province are of geologic significance, then it is probable that they represent regional tectonic fractures. The extent and regularity in trend of the observed lineaments, in particular in the Miocene Columbia River Basalts, are not likely to be the result of random or local features such as cooling joints, stratigraphic contacts, or man-made features. In addition, such lineaments can be directly observed as regional fractures in some areas of Columbia River Basalt exposure, such as in the Big Summit Prairie and along the Columbia River (Lawrence, 1979). By reaching the conclusion that these remotely sensed lineament patterns are indeed tectonic in origin, a tectonic interpretation of fracture trends and the stresses to which they are related is made possible.

The area map in Figure 78 displays the marked regularity of lineament trends across the thesis area. A comparison of the areas representing Columbia River Basalts, Areas 6, 8, 9, 10, 11, and 12, shows that very

These lineament trends are present in most areas similar patterns exist in this rock unit throughout the thesis area. The same conclusion can be drawn by examining the Strawberry Volcanics Areas 1, 2, 3, and 7. Clarno areas exhibit much more complex lineament patterns, but even in the case of these older and more tectonically deformed Tertiary volcanics, some regularity exists in lineament trends across the area of study.

The previous area by area discussion of lineament trends pointed out several dominant area-wide or regional trends. These have been interpreted, following general tectonic fracture theory (Price, 1966), to be the result of at least two distinct tectonic events which occurred in post-Columbia River Basalt time (post-middle Miocene) in the central part of the Blue Mountains region. The more dominant and widespread of these is the northwest-southeast compressive episode evident in most of the Columbia River Basalt areas. Lineament trends which may be related to this event include the N.60°W. and N.10°W. trends which may make up a pair of conjugate shears, and the orthogonal N.60°E. and N.30°W. trends which may represent longitudinal and cross joint sets, respectively. These lineament trends are present in most areas throughout the thesis area, and are present in all three rock types represented. The consistency of these trends is exhibited not only by comparing lineament trends in the sub-areas of Area 11, but also by comparing lineament trends in such widely separated areas as Area 11 and Area 8.

The other interpreted tectonic episode is one during which northeast-southwest compression occurred. Lineaments related to this episode include N.30°E., which could represent longitudinal fractures, N.60°W., North-South, and N.60°E. This episode of tectonism does not appear to have been as widespread as the other. Lineament trends which can be traced to this second compressive episode exist primarily in the eastern part of the thesis area, and particularly in the Strawberry Volcanics.

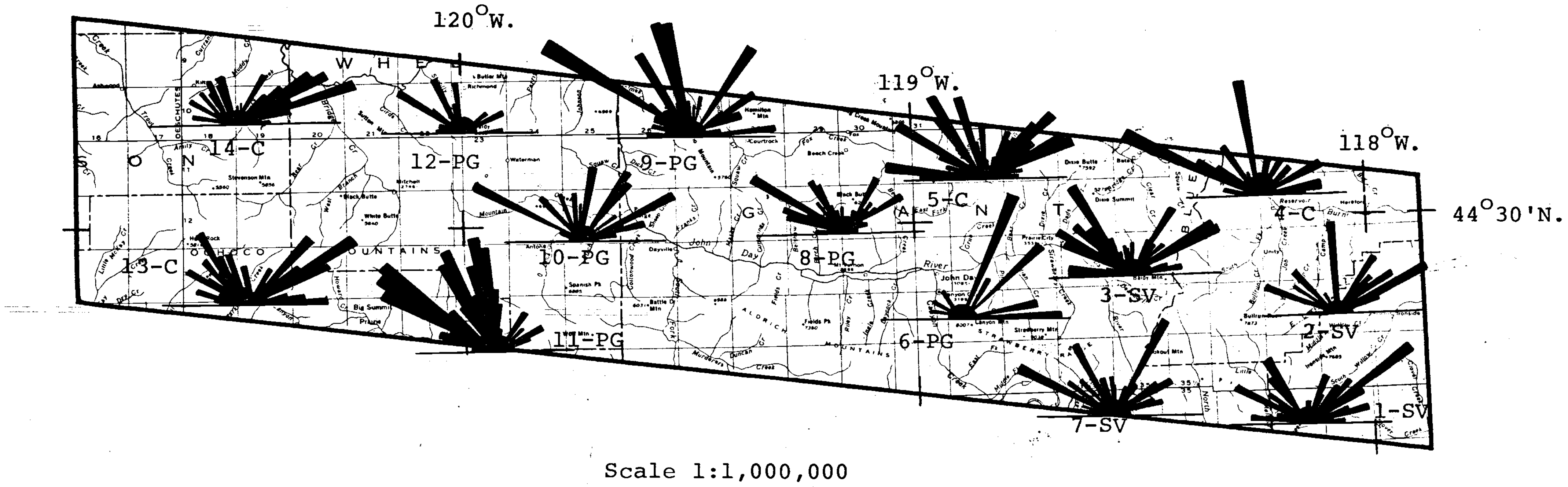


Figure 78. U-2 lineament trends across thesis area. SV=Strawberry Volcanics, PG=Picture Gorge Basalts, and C=Clarno Formation.

SUMMARY OF TERTIARY TECTONIC HISTORY

The Tertiary began in the Blue Mountains province of north-central Oregon during a period of relative tectonic quiescence. A regional unconformity exists between Eocene volcanics of the Clarno Formation and the underlying clastic sedimentary strata belonging to the Cretaceous Gable Creek, Hudspeth, and correlative units. This unconformity represents a significant time gap in the geologic column; however, there is little angular discordance between the two formations. During this depositional hiatus, from Late Cretaceous to early Eocene, westward regression of the Cretaceous ocean margin occurred, with subsequent subaerial exposure of the Cretaceous marine sedimentary strata in the Blue Mountains area. Only minor tectonic activity appears to have accompanied this regression. The westward migration of the marine coastline may have been caused by a shift of active subduction to the west, resulting in the eventual isolation of the Cretaceous depositional basin from the open ocean (Figure 79). Continental sedimentary deposition occurred far to the north in the northern Cascade area of Washington, and to the south-west in the Klamath area during the Late Cretaceous to

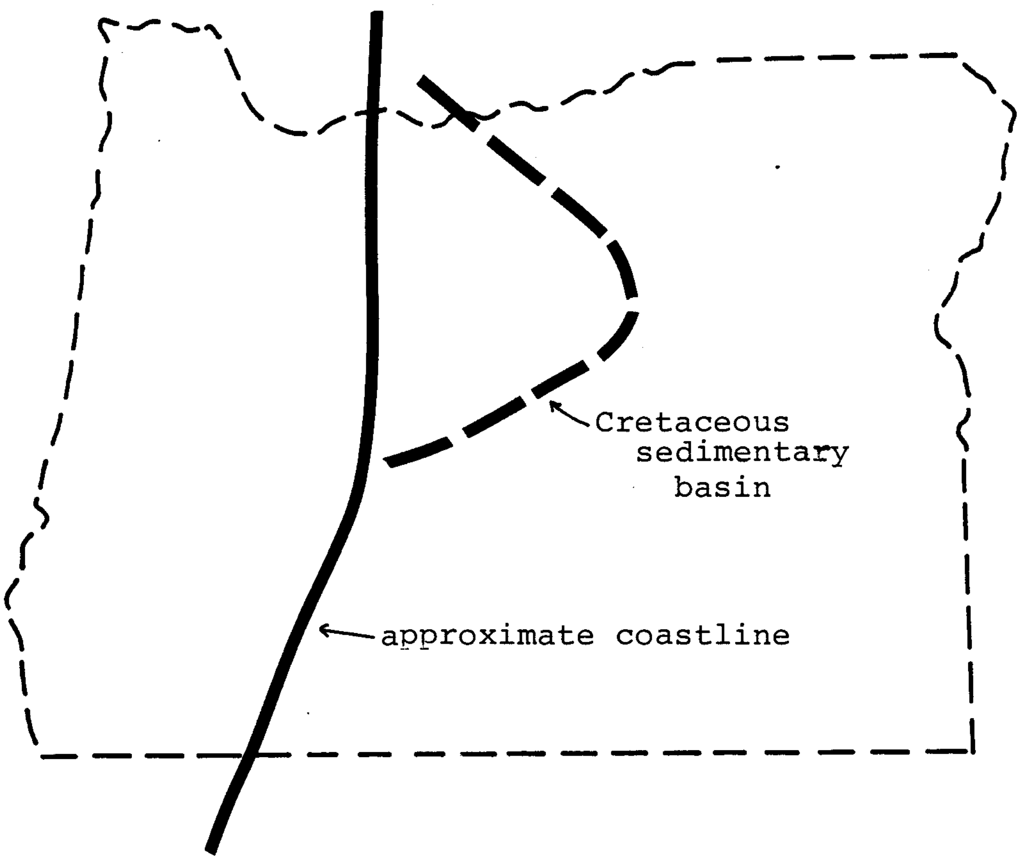


Figure 79. Paleocene to middle Eocene tectonic setting of the thesis area.

early Eocene, where subduction probably continued relatively unchanged.

Andesitic volcanism began in the Blue Mountains province during the middle Eocene, contemporaneous with continental volcanism to the north in northern Washington and submarine basaltic volcanism and turbidite sedimentation to the west. This volcanic activity corresponds to the "Challis" episode of Armstrong (1978). In the Blue Mountains area, volcanic activity was solely continental and subaerial. Geochemistry and deposition of the Clarno rocks suggest that these rocks were extruded as part of a volcanic arc environment, located along the early Tertiary continental margin.

Tectonic activity accompanied Clarno volcanism. A particularly strong tectonic episode occurred at least locally in the Mitchell area, where the Clarno has been divided into a lower, more tectonically deformed member and an unconformably overlying less deformed upper member. Northeast-southwest-trending fold axes, including the Mitchell anticline, affect Lower Clarno but not Upper Clarno strata, and suggest the existence of a northwest-southeast-oriented maximum compressive stress axis during Eocene time, approximately parallel to the direction of subduction (Figure 80). In

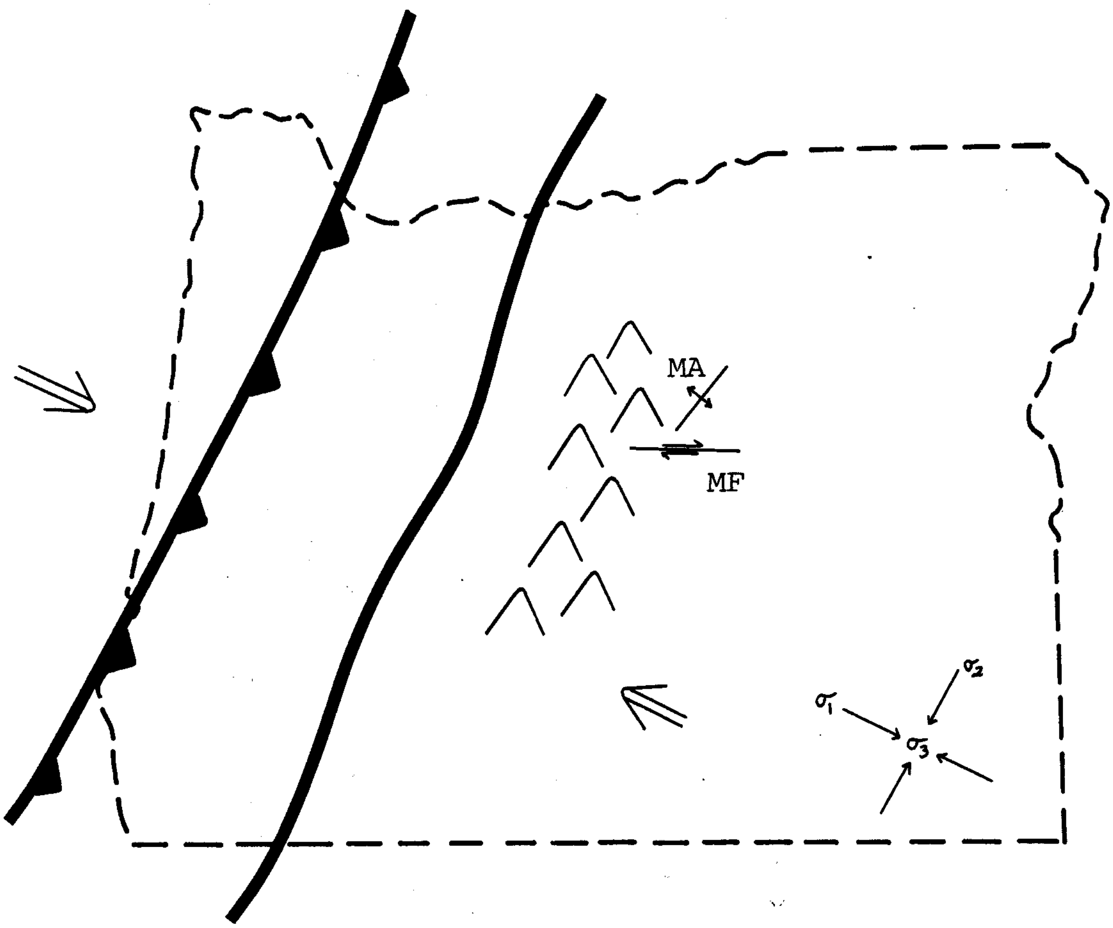


Figure 80. Middle Eocene to early Oligocene tectonic setting of the thesis area. MF=Mitchell fault, MA=Mitchell anticline.

addition, numerous more localized angular and erosional unconformities exist within the Clarno section.

The Mitchell fault may have been active during Clarno volcanism, with possible right-lateral strike-slip motion accommodating the spreading direction of the Juan de Fuca plate to the west. A significantly thicker Upper Clarno section exists directly south of the Mitchell fault than occurs just north of it (Oles and Enlows, 1971), suggesting that volcanic material may have piled up against an active fault face. However, this relationship might also be explained in terms of thicker basinward deposition to the south of the fault and farther away from the volcanic source, which is located just north of the Mitchell fault. Only Cretaceous and Clarno rocks appear to be displaced along the Mitchell fault, which does not appear to offset Picture Gorge Basalts where they crop out to the east of the town of Mitchell, on strike with the Mitchell fault. This might possibly date the fault to be late Eocene or early Oligocene. However, the Mitchell fault might simply die out to the east of Mitchell before it reaches the Picture Gorge outcrop area, so that the age of the fault is not necessarily dated by the fact that it does not offset Miocene and younger rocks.

During Oligocene time, andesitic volcanism waned in the Blue Mountains area. A period of relative quiescence followed, from about 30 to 18 myB.P. During this period, arc volcanism was initiated to the west in the incipient Cascade province along a north-south orientation which exists today. Explosive volcanic events in this early Cascade Range resulted in deposition of the John Day ash-fall tuffs to the east in the Blue Mountains area.

The tectonic activity noted in Clarno volcanics seems to have died out by this time. A local erosional unconformity exists between Clarno and John Day rocks, but there are no significant unconformities found within the John Day sequence. The John Day Formation consists primarily of reworked volcaniclastics and volcanic air-fall debris. Several widespread ignimbrites occur within the western part of the John Day outcrop area, supporting the occurrence of violent eruptive episodes to the west (Figure 81). No volcanic sources have been found within the outcrop area of the John Day Formation.

A period of quiescence followed John Day deposition in the Blue Mountains province, while arc volcanism

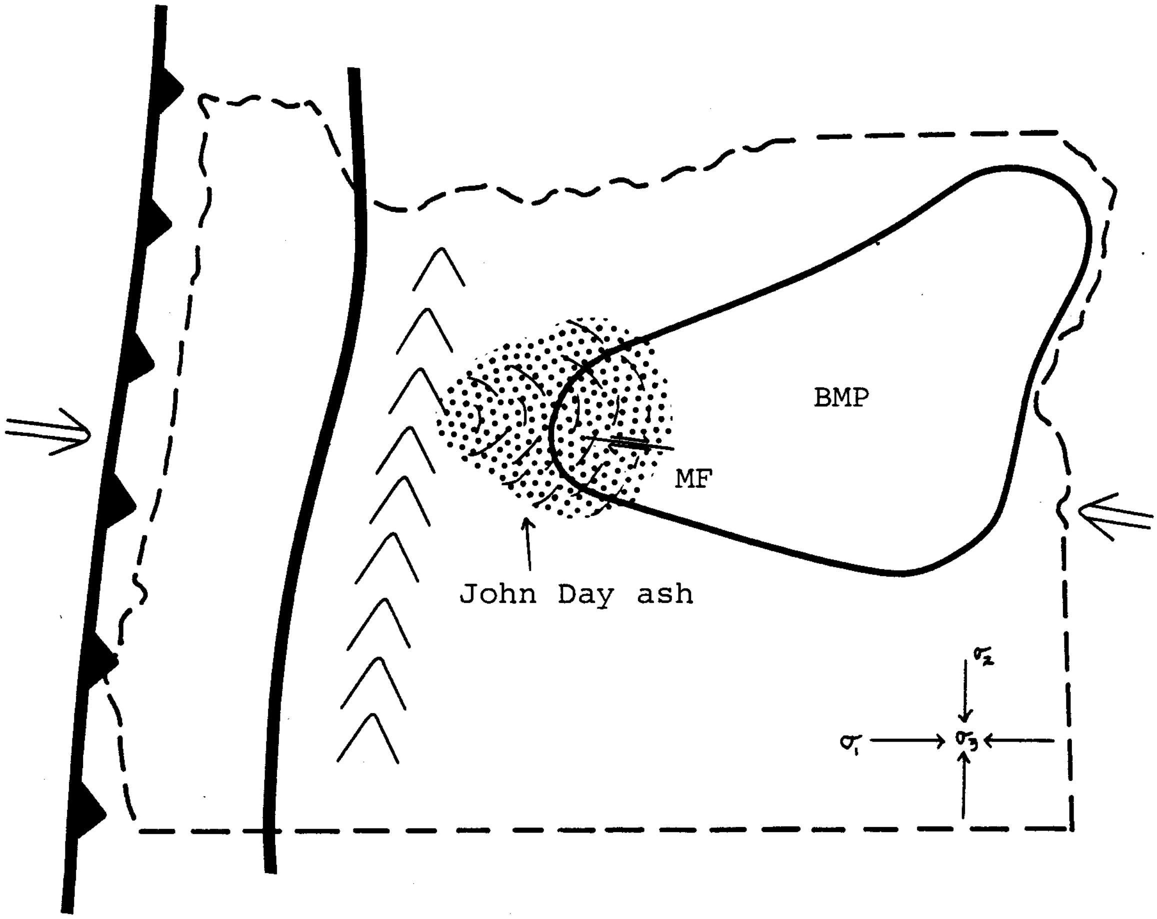


Figure 81. Oligocene to early Miocene tectonic setting of the thesis area. BMP= Blue Mountains Province, MF=Mitchell fault.

continued to the west in the Cascade arc, and fore-arc sedimentation occurred to the west of the arc. A significant time gap exists between youngest John Day and oldest Picture Gorge Basalts, which are also separated by a widespread erosional and slightly angular unconformity. Minor faulting, limited to the John Day tuff sequence, may have occurred during this hiatus. Northeast-southwest-trending folds which involve the John Day are present, particularly in the Painted Hills area. However, this deformation may date to younger tectonic events.

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Eruption of the extensive Columbia River Basalts began during the early to middle Miocene, contemporaneous with renewed volcanism to the south in the Basin and Range area and during continued arc volcanism to the west (Figure 82). In the Blue Mountains region, the Picture Gorge Basalts were extruded from north-south-trending fissures, some of which are preserved in the Monument Dike Swarm. This basaltic volcanism, located behind the volcanic arc complex of the Cascades, may be the result of back-arc spreading such as exists today in other areas of the world (e.g. Sea of Japan).

Initiation of Columbia River Basalt volcanism ("Columbia" episode of Armstrong, 1978) occurred at the

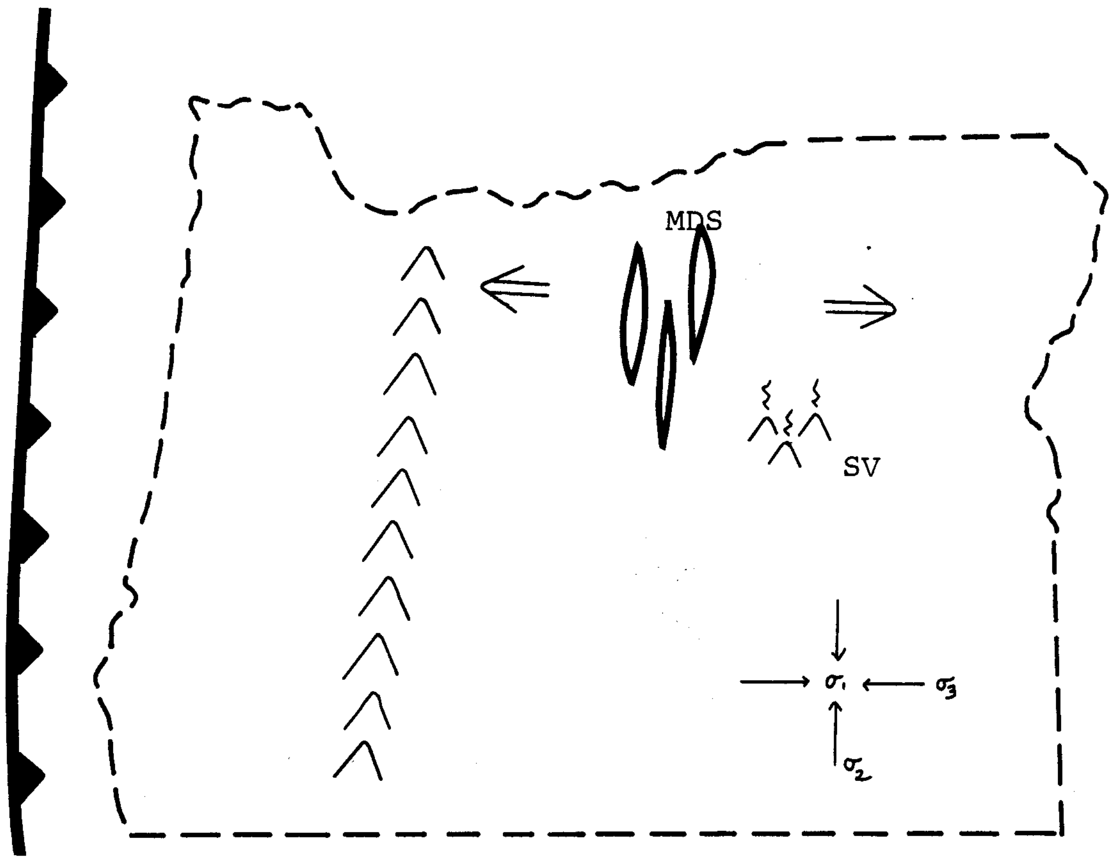

Figure 82. Miocene tectonic setting of the thesis area. MDS=Monument Dike Swarm, SV=Strawberry Volcanics.

same time that bimodal volcanic activity began to the south in the Basin and Range province. This renewed volcanism throughout the back-arc area may be related genetically to the changing plate margin framework to the west (Christiansen and McKee, 1978). As the transform plate boundary between the North American plate and the Pacific plate began to interact with the Juan de Fuca system to the north, the subduction rate along the Cascade arc may have slowed enough to initiate back-arc spreading by reducing the east-west stress axis to a minimum compressive stress, allowing east-west extension. This extension, supported by the north-south trend of fissures in the Monument Dike Swarm, may mark the initiation of Basin and Range expansion.

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During the middle to late Miocene, volcanism of a more silicic composition took place to the east of the Monument fissures at a volcanic center located in what are now the Strawberry Mountains. Andesitic flows and breccias of the Strawberry Volcanics were emplaced locally about this volcanic center, which consisted of a single shield volcano (now exposed in the Strawberry Mountain cirque) with minor surrounding flank vents. Western flows of the Strawberry Volcanics are locally interbedded with eastern flows of younger Picture Gorge eruptions in the vicinity of Prairie City and John Day.

Near the end of the Miocene, explosive silicic eruptions resulted in the voluminous ash deposits of the Mascall and Ironside Formations which overlie the flows of the Picture Gorge and Strawberry Volcanics with local unconformity. These ash deposits were erupted from the Strawberry volcanic center, around which geochemically similar volcanic plugs are found. These ash eruptions mark the final volcanic episode in the central Blue Mountains region.

Volcanic activity ceased in the Blue Mountains region following eruption of the Mascall and Ironside ash, but tectonic activity increased. During the late Miocene to early Pliocene, a major tectonic episode occurred, creating many of the large scale structures which dominate the terrain we see today in the central Blue Mountains, including the Blue Mountains Anticlinorium (Figure 83).

Some clockwise rotation of the Blue Mountains region may have occurred in late Miocene to early Pliocene time, contemporaneous with major uplift of the province along a northeast-southwest axis. This axis, represented by the Blue Mountains anticline and the parallel-trending Mitchell anticline and related folds,

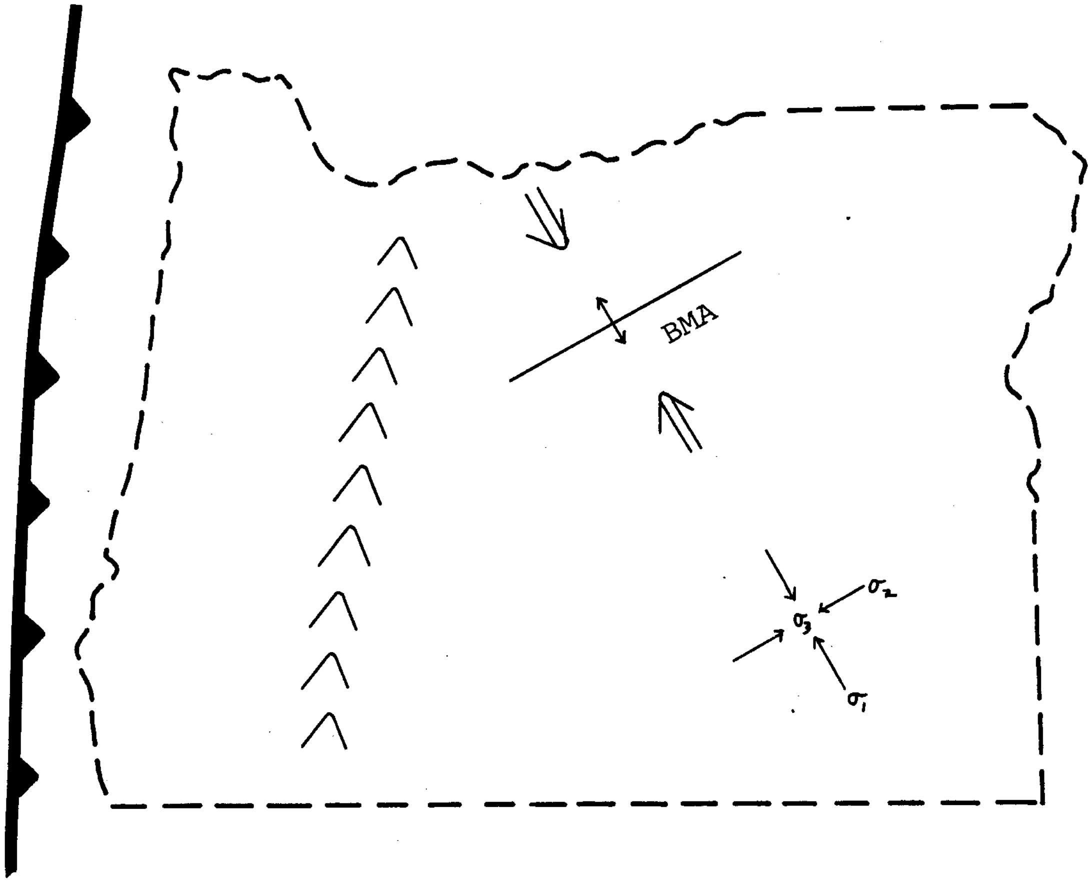

Figure 83. Late Miocene to early Pliocene tectonic setting of the thesis area. BMA=Blue Mountains Anticlinorium.

is supported by the widespread and consistent lineament patterns which indicate northwest-southeast compression. Rotation may be the result of interaction between the expanding Basin and Range province to the south and continued subduction to the northwest, effectively creating a large scale right-lateral shear couple in the Blue Mountains area. However, the north-south orientation of the Monument Dike Swarm does not allow for any substantial post-Miocene rotation.

Following this major northwest-southeast-directed regional tectonic episode in late Miocene to early Pliocene time, subsequent tectonism occurred within the Blue Mountains province. Structures which resulted from an early to middle Pliocene episode include the nearly east-west-trending John Day fault, with a maximum vertical displacement estimated to exceed 1000 meters, the Aldrich Mountain anticline, bounded by the John Day fault, and the numerous nearly east-west-trending faults and fold axes north of the John Day Valley. The uplift of the Ochoco Mountains fault block also occurred during this tectonic episode, with normal faulting on the north side of the mountain range which may have included vertical movement along the Mitchell fault. The particularly large scale

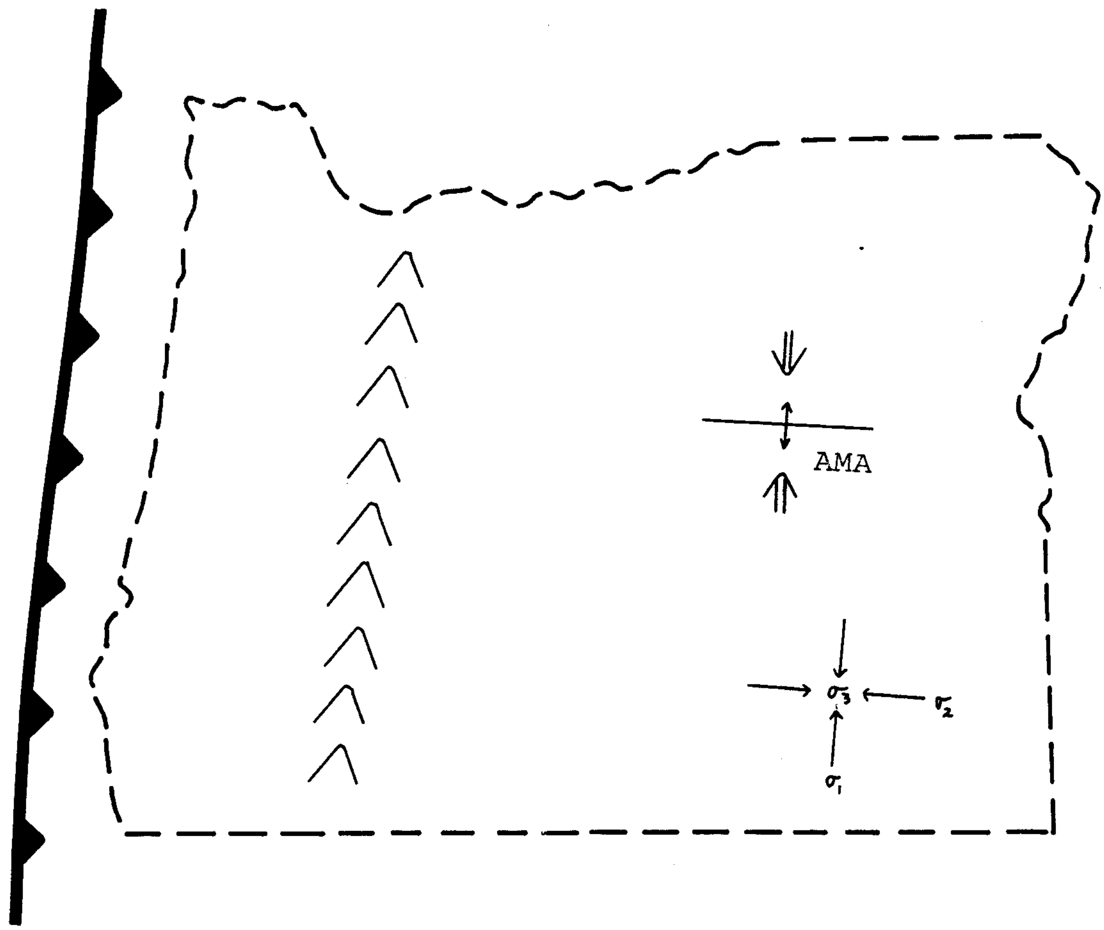

Figure 84. Early to middle Pliocene tectonic setting of the thesis area. AMA=Aldrich Mountain anticline.

displacement which occurred along the John Day fault may indicate that this displacement took place along a pre-existing zone of weakness possibly related to an Eocene-Oligocene shear zone on trend with the Mitchell fault. Near the end of this episode, northeast-southwest compressive tectonics were localized in the eastern part of the Blue Mountains province, as evidenced by folds, faults, and lineament orientations in that area.

Following these tectonic events, the terrain of the central Blue Mountains probably looked much as it does today. Coarse stream gravels were deposited along an ancestral John Day drainage controlled by the John Day fault zone. This period of erosion and relative quiescence occurred in the Blue Mountains region while arc volcanism in the Cascades and bimodal volcanism in the Basin and Range continued with little interruption. During this period, a particularly violent volcanic event far to the south in the Harney Basin sent an ignimbrite flow northward into the John Day drainage through a low pass between the Aldrich and Strawberry Mountains, resulting in deposition of the Rattlesnake Ignimbrite.

Regional tectonic activity occurred following

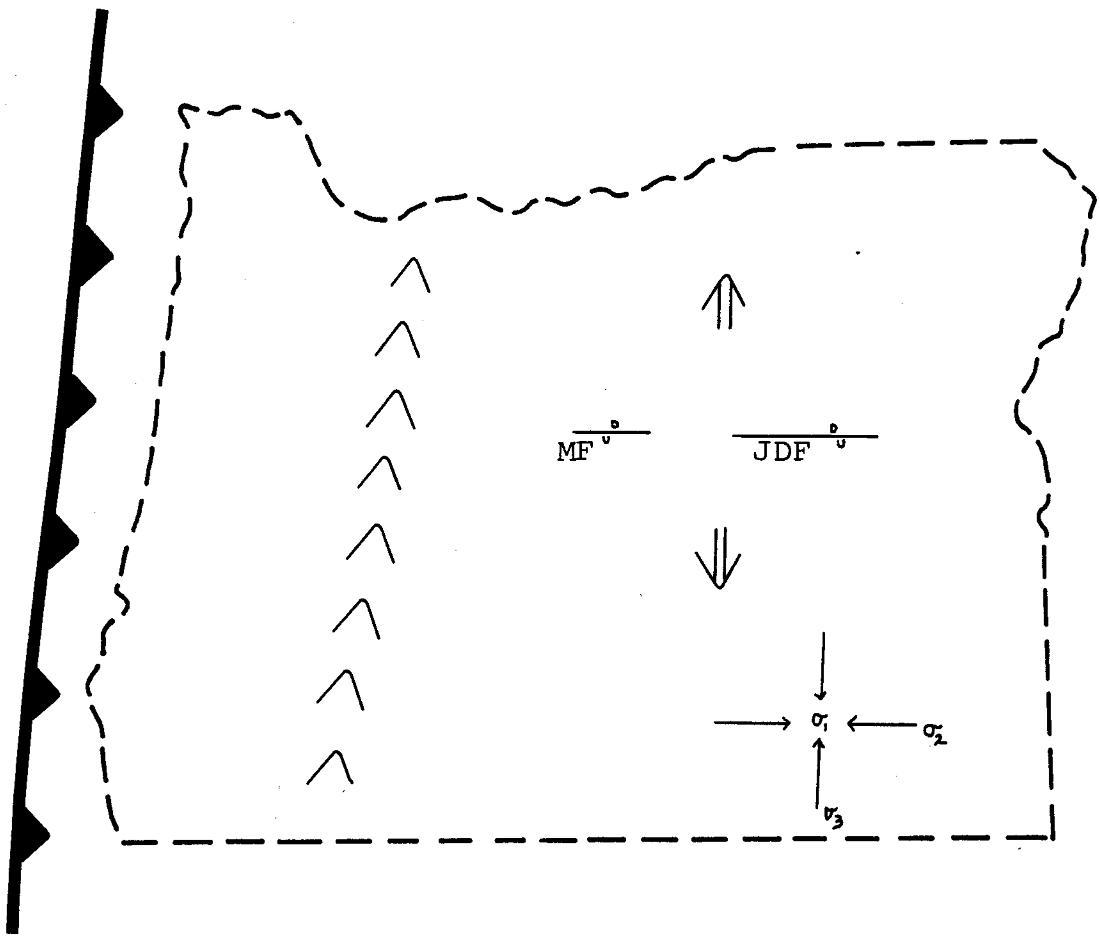

Figure 85. Late Pliocene tectonic setting of the thesis area. MF=Mitchell fault, JDF=John Day fault.

deposition of the Rattlesnake Ignimbrite in late Pliocene time (Figure 85). Terraces cut into the Rattlesnake conglomerates are slightly offset vertically across the John Day River in the vicinity of John Day, suggesting that additional movement may have occurred along the John Day fault zone. In addition, Rattlesnake outcrops near Picture Gorge have clearly been displaced vertically along normal faults.

Following this latest tectonic episode, the central Blue Mountains region has remained relatively inactive tectonically. Local Quaternary basalt flows found south of the Aldrich Mountains in the Murderers Creek area are probably related to continued bimodal volcanism in the tectonically active Basin and Range province.

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