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REGIONAL TECTONIC SYSTEMS OF THE PACIFIC NORTHWEST
DELINEATED FROM ERTS-1 IMAGERY

by

Linda K. Wackwitz

B.A. Colby College, 1972

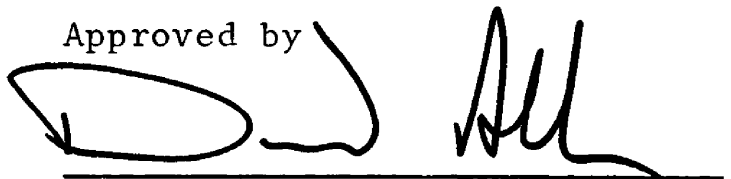
Presented in partial fulfillment of the
requirements for the degree of

Master of Arts

UNIVERSITY OF MONTANA

1975

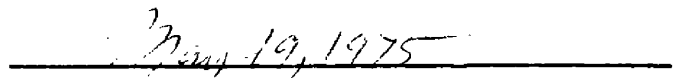
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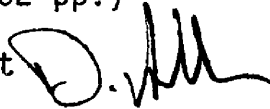
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Geology

Regional Tectonic Systems of the Pacific Northwest Delineated
from ERTS-1 Imagery (62 pp.)

Director David D. Alt



An Earth Resource Technology Satellite mosaic of the Pacific Northwest, at a scale of 1:1,000,000 and covering 1.5×10^6 square kilometers, was annotated to extend the technique of lineament delineation to a large area and to test whether a correlation with known tectonic elements would still be valid at that scale.

Illumination direction and dense ground cover were shown to be two limitations of the imagery for geologic interpretation. Rose diagrams proved useful in testing lineament reliability and domain homogeneity. A map of southeastern Oregon was drawn which met the requirements for a reconnaissance geologic map. A lineament map representing the Lewis and Clark line and adjacent regions was compiled defining several major tectonic domains and the structural patterns within those domains. Three megalineaments were annotated which have divided the Pacific Northwest into several large blocks from Tertiary to Recent times.

High quality space imagery of a quality comparable to the ERTS imagery is at least a fundamental tool in all reconnaissance work. It provides a valuable new large scale view of the Earth which will lead to new channels of thought and major new discoveries.

ACKNOWLEDGMENTS

I wish to give special thanks to Dave Alt whose patience, understanding and genuine interest throughout the preparation of this paper were invaluable. I also wish to thank Bob Weidman who kindled my initial interest in the ERTS project and provided technical guidance, and Tom Margrave of the Physics Department who provided fresh insight on several occasions. Thanks to Ruth Badley whose friendship helped me maintain my sanity and who helped proof-read and critique successive drafts of the paper. Finally I thank Michael Collins for his special contribution and it is to him that this manuscript is dedicated.

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PREFACE

The Pacific Northwest as discussed below includes the states of Washington, Oregon, Idaho and western Montana and embraces some 1.5×10^6 square kilometers of the country. It is a region of spectacular scenery which has overwhelmed travelers since the days of Lewis and Clark. The variety of elements that make up its landscape seems endless: majestic mountains, vigorous rivers, large lakes, icy glaciers, formerly fiery volcanoes, parched deserts and dense rain forests - truly a melting pot.

Since before the turn of the century when C.F. Calkins and his colleagues were roaming the countryside, theories have come and gone to explain the seemingly unrelated tectonic patterns. Geologists have spent many a sleepless night trying to fit the pieces of this complex puzzle together. Even today there are many areas which have not been adequately mapped, leaving large holes in regional geologic compilations.

Today a satellite scanning the earth is sharing its unique vantage point with us. It is transmitting images on a scale never before imagined and the whole Pacific Northwest has been condensed in photographic mosaic form at the scale of a regional map. (See plate A) Finally the myriad complexities of this region are assembled and can be viewed as a whole.

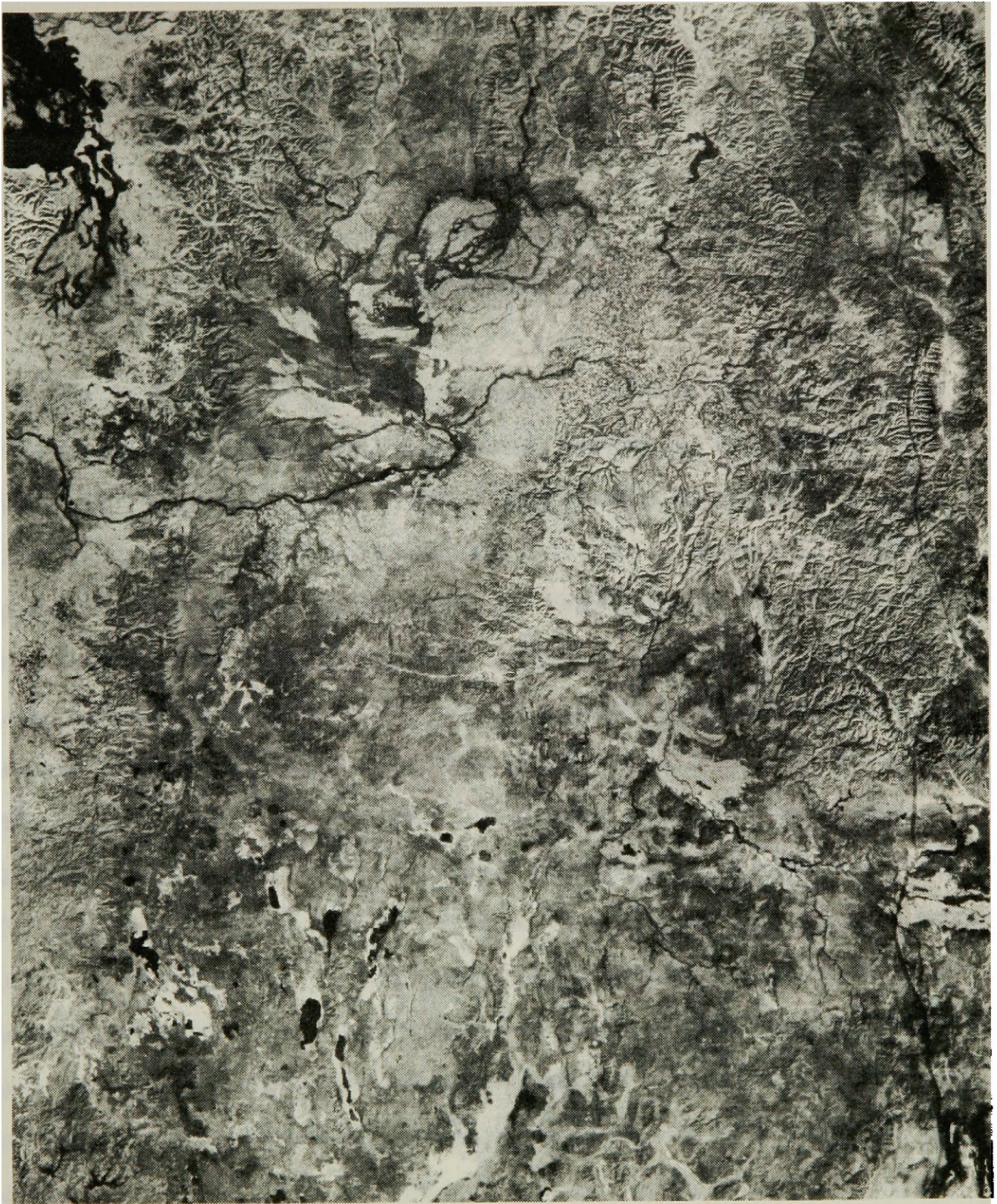


Plate A. An ERTS eye view of the Pacific Northwest

CHAPTER ONE

INTRODUCTION

On July 23, 1972, the National Aeronautics and Space Administration launched the Earth Resource Technology Satellite (ERTS) into orbit. The satellite's mission was to electronically record images of the Earth from 906 km up in space, beam them back to several receiving stations to be unscrambled by computers then printed and distributed to researchers throughout the world. The satellite is in a nearly polar, sun-synchronous orbit, and it completes each orbit in about 103 minutes. Adjacent orbits are 24 hours apart. As a result, the Pacific Northwest is imaged over the course of nine days at close to ten o'clock in the morning. Covering the entire earth once every 18 days, the satellite provides a new cycle of high angle images, each one covering a very large area; and it provides a means of continuously monitoring dynamic systems on the face of the earth.

The imagery has proven to be a very useful tool for scientists in many disciplines, notably: hydrology, forestry, agronomy, meteorology, oceanography and geology. Geo-

logists are especially impressed with the new look they perceive from 900 km up in space. What used to be formidable mountain ranges look as rough as tree bark, large rivers are opaque black ribbons across a mottled landscape and lakes look like drops of jet black ink accidentally spilled by a careless draftsman. In short, wide open spaces are condensed onto small pieces of paper, so that the whole country can be seen at a glance and it is this aspect that most geologists find spectacular. They are no longer hindered by myriad surface complexities, natural and man-made. Whole towns are lost, engulfed by the vast scope of the imagery. Only the bolder features stand out - masses of rock, soil, vegetation and water.

Another advantage of the imagery is that it is multispectral. Data in four different bands of the electromagnetic spectrum (green .500 - .600 nanometers, red .600 - .700 nm, infrared .700 - .800 nm and infrared .800 - 1.100 nm) are recorded separately. The multispectral scanner separates the light so that four images, one in each wavelength are recorded from the same scene. Although all of the imagery is printed in black and white, comparison of features in each of the color bands often leads to interesting observations in certain types of determinations.

Success of the ERTS program can be measured by the quantity of new and useful information gleaned from the imagery. Geologic applications of the imagery include: map editing, landforms analysis, structural geology, lithologic

identification, mineral exploration and engineering and environmental geology (Short and Lowman, 1973). Each of these applications is being carefully investigated by various geologists.

ERTS IN MONTANA

Here at the University of Montana, work on NASA grant NAS-21826 began in August of 1972. With the arrival of the first imagery of Montana in October, countless traditional interpretations were immediately undertaken to test their usefulness on the very small scale of the new imagery. These included all phases of photogeologic interpretation ranging from lithologic identification of the rock units to detailed structural interpretations. Of the many individual projects undertaken, the greatest failure reported was a concerted effort to identify rock types. One concrete observation did emerge from this effort; in most cases where the vegetation is not too dense, it is possible to distinguish layered rocks from non-layered rocks.

During the course of the investigations a procedure from aerial photo interpretations was adapted to the satellite imagery. Reasonably straight linear features were seen in all rock types and in all degrees of credibility. These features are termed lineaments. Overlays were annotated on images enlarged to 1:500,000 for all of western Montana and

northern Idaho by five researchers. These annotations were then superimposed and compiled onto a large master sheet. In this way trends of all lineaments could be evaluated, and lineaments could be grouped into several distinct regions on the basis of their trend. The master lineament map was then compared with geologic maps of the same area and in places a surprising correlation with known structural features emerged. Statistically, through the construction of rose diagrams, it was shown that lineament trends and known tectonic trends compared favorably in magnitude and orientation.

Promising results of the preliminary investigation and arrival of a new U.S. Department of Agriculture mosaic of the Pacific Northwest¹ led to my thesis problem: to extend the technique of lineament delineation to a much larger area and test whether a similar correlation with known tectonic elements would still be valid. The Pacific Northwest seemed an ideal testing ground due to the complexity of the geologic relationships therein. Although the entire mosaic was carefully annotated only two sample areas, one in southeastern Oregon and the other in eastern Washington, northern Idaho and western Montana, were analysed. The purpose of this

¹This is the Earth Resource Technology Satellite - 1 mosaic, sheet A, scale 1:1,000,000, imagery .8 - 1.1 nm band, July 23 to October 31, 1972; prepared by the USDA - Soil Conservation Service.

study is not to answer the many geologic questions of the area; but instead, to offer a different perspective, perhaps a new tool to future researchers and hopefully to suggest a few interpretations of my own and raise new questions.

CHAPTER TWO

LINEAMENTS DEFINED IN THE ERTS CONTEXT

For this study, the term lineament was used to denote any straight or slightly curved alignment of topographic or photogeologic features. More specifically, ERTS lineaments represent faults and fault scarps, straight segments of stream channels, straight stream valleys, ridge crests, elongate lakes, edges of topographic highs and alignment of vegetation (Short and Lowman, 1973). Only those lineaments thought to be due to bedrock conditions were actually annotated. Those annotated included: straight range-front scarps; very long, straight river valleys and alignments of shorter segments of straight stream channels; sequences of ridge crest offsets; linear trends in vegetation; and tonal boundaries between areas of different looking features.

In haste, these features are easily equated with such structural features as faults, joints and inclined strata. Many lineaments do test out when field checked, but others prove to be artifacts created by random alignments of cultural or topographic features and enhanced by illumination effects. The term lineament is not genetic, connoting geo-

logic structures; instead it is a very general term describing any linear feature based on image topography, tone, texture or stream pattern. Although lineaments and faults are extensively compared in this study, do not assume that lineament and fault are equivalent terms, they are not.

In our previous study of lineaments in western Montana, some interesting figures emerged. Approximately 40% of all lineaments mapped could be equated with faults, contacts, fold axes and other geologic features on published ground truth maps. 32% were not actually shown on the maps but were compatible in trend with known faults and could easily be added to tectonic maps without disrupting the pattern. Only 28% were inconsistent with available ground truth and admittedly many of these were probably not of a structural geologic origin (Weidman, Alt, et al; 1974).

A field check of all lineaments annotated is not within the scope of this study. I have instead accepted the data with a sort of blind faith, the way most data is trusted. I accepted it with full knowledge that a certain percentage of the lineaments are meaningless¹. A large number of lineaments recognized are features never before noticed - a fact

¹Interesting studies have been conducted on human perception. Random patterns of dots when viewed at a distance, cease to appear as discrete dots and definite linear patterns emerge. (Personal communication, D.D. Alt, November 1974)

of which investigators are increasingly aware. As Short and Lowman (1973) so succinctly stated, "The interplay between underlying structure, topography, vegetational distributions, and solar illumination commonly enhanced the appearance of structural elements, so that the subtle relationships were disclosed that were not apparent in the maps."

Even the most casual observer cannot help but notice the abundance of linear features expressed on ERTS imagery. These features are certainly not unique to high altitude space imagery, they have been used for years in interpretations of conventional aerial photography. Until recently the scale of the ERTS imagery was unheard of. When a single image covers almost 18,000 square kilometers of the earth's crust, lineaments are easily recognized that otherwise would require synthesizing large quantities of more traditional geologic data before they could be detected. Another important asset of the ERTS imagery results from the ease with which large regional mosaics can be produced. Through-going linear features can be quickly and accurately traced over tens and sometimes hundreds of kilometers. This leads to compilation of a regional network of lineaments that probably represents a fundamental tectonic system in the earth's crust. With surface topographic and geologic details obscured (due to resolution limitations) structural data can be viewed in a very broad continental framework and interpreted in terms of plate tectonics.

CHAPTER THREE

PROCEDURE

Geologic mapping from aerial photographs has long been recognized as an excellent means of doing reconnaissance work and techniques of interpretation of low altitude photography are well established. Often because of poor resolution certain criteria used in these techniques are ill-suited to analysis of high altitude photography, and almost useless in the interpretation of the ERTS imagery. From the beginning, one major objective of all ERTS researchers was to decide exactly what to do with the imagery and how to do it. During the last two years, many new approaches to imagery interpretation have been tried, providing researchers with new tools to evaluate conditions on the earth's surface. Unique features of the imagery, its year round cyclic coverage and its regional or synoptic multispectral coverage, offered new insights to investigators. Geologists were quick to capitalize on large linear features found extensively on the imagery for regional interpretations. Hence the art of lineament annotation blossomed.

The following is a discussion of annotation and interpretation procedures developed and used at the University of Montana. They are perhaps not the best, and certainly not the only techniques of lineament annotation which have evolved. They did adequately and expediently serve our purpose - to extract regional tectonic patterns from the imagery.

LINEAMENT ANNOTATION

Proper equipment for lineament annotation includes a sheet of clear acetate at least the size of the image(s), and several colored marking pens. Annotation involves staring at the image until the various physiographic and photogeologic features appear to form straight or slightly curved lines at their boundaries. Then it is a simple matter to trace them onto the overlay. Some discretion must be used in selecting a lineament for tracing because while many lineaments are readily identifiable by all investigators, others are seen by only one. The first category usually includes very straight river and stream segments, straight mountain-front scarps and obvious offsets in layered rocks. The latter includes subtle color changes that can be denoted by a line, subtle mountain ridge or drainage offsets which are aligned and any other "funny linear feature".

All investigators are biased in one way or another. Either they go wild and mark up the entire overlay, or they consider each linear feature carefully and trace only those which seem indisputable, in which case very few lines appear on the overlay. Some are willing to reorient the image to try and see a different set of lineaments from a different angle, others are content to look at it with the north end at the top. My own annotation style falls somewhere in between the two extremes.

Another important source of bias is the direction of solar illumination. Images are always recorded within a few minutes of the same solar time in the morning, so the sun is consistently in the southeast. Topographically expressed lineaments oriented northeast-southwest tend to be perpendicular to the sun's rays and are highlighted by shadowing effects, whereas northwest-southeast trending lineaments being nearly parallel to the direction of illumination are very poorly revealed. At the present time there is no established method of directly evaluating the effect of this bias on lineament data from the ERTS imagery. It is anticipated that significant numbers of northwest-southeast striking lineaments remain undetected. Necessarily this bias must be carefully considered in a study (such as this one) where numbers of lineaments as well as their orientation are critical factors for a statistical evaluation. An indirect method of evaluating the extent of the bias is possible

through the use of side looking radar or the comparison of evening and morning low sun angle, high altitude photography or perhaps a comparison between ERTS and the new Skylab imagery. Such an evaluation was not within the scope of this thesis since the additional imagery is very difficult to obtain.

Compiling the final lineament map is a matter of superimposing all overlays of the same area, and tracing off those lineaments seen by two or more persons. Hopefully this excludes most of the imaginary lineaments, products of an overzealous or tired annotator.¹ Blueprints, useful in further interpretation are then made from the final acetate master map.

INTERPRETATION METHODS

Generally the interpretation procedure involves comparing ERTS lineaments with previously mapped linear tectonic features. Data must be compiled from the maps. For this, the length and strike of every lineament from ERTS and corresponding ground truth maps must be carefully measured. Much confusion can be eliminated by assigning a number to each lineament, and then measuring them sequentially. Up to

¹When fatigue sets in, lineaments miraculously appear everywhere on the imagery, and even on the floor and ceiling of the office!!

this point, the whole procedure is fairly mechanical, requiring only a great deal of patience; hereafter, a vivid imagination is almost a necessity.

Lineaments must be grouped into domains. A domain will be defined as the areal extent of a given tectonic environment. On the ERTS imagery, domains appear as areas of sub-parallel lineaments, which can be delineated from surrounding lineament swarms. There is no prescribed size for a domain, although the size is generally influenced by the scale of the entire Pacific Northwest, domains selected were quite large, including more than one dominant lineament trend in some cases. The domains were chosen very subjectively by simply studying the ERTS lineament map, and then outlining those areas which seemed to exhibit a coherent regional lineament trend. Another method developed for lineament analysis involves superimposing a grid over the map and measuring the lines within each grid square separately. These squares then become mini-domains, which can be added together to produce the final domain boundaries. This latter method is very efficient over small areas where individual lineaments are highly significant, but over a very broad region it is much too cumbersome.

Rose diagrams, statistically representing the lineaments in each domain, are then compiled. Lineaments are divided into groups, with each group representing five degrees of

trend, then the lengths of all the lineaments in each group are totaled and plotted. Validity of the domains is quickly determined. Rose diagrams plotted for poorly chosen domains will exhibit a random scatter of petals, whereas those plotted for well-founded domains will exhibit one or two strong peaks.

For a sound correlation with ground truth, domains established on the lineament map must be transferred to the geologic map. Then rose diagrams can be constructed in the manner described above from structural data taken from the published maps. Care should be exercised to plot all of the rose diagrams to the same scale to facilitate their comparison.

Construction and comparison of rose diagrams is not an end in itself. Some conclusions must be drawn. The correspondence or lack of correspondence of ERTS lineament data and patterns from geologic maps must be explained. Lineaments could be compared on a one to one basis with known geologic features, a course not followed due to the regional scale of this study. Otherwise, entire domains can be compared with each other, a method especially well suited to far-reaching regional interpretations. Inherent to this type of analysis, is a synthesis of the geology of very large areas, a little practiced art in today's world of overspecialization.

CHAPTER FOUR

LINEAMENT VALIDITY

A Statistical Test in Southeastern Oregon

Before proceeding with an interpretation of lineaments mapped from the ERTS imagery, it is important to first establish their validity with respect to known features on published geologic maps. The southeastern corner of Oregon was selected for the comparison because of its very distinctive geology and corresponding lineament patterns. The arid climate in this region can support a sparse grass, sage and juniper flora which provides excellent rock exposures. The lack of ground cover facilitates lineament annotation so that numerous lineaments can be drawn and with great confidence, two requisites to a valid statistical analysis.

BACKGROUND GEOLOGY

I.C. Russel (1884) published the first account of the geology of southcentral Oregon in a reconnaissance report for the Geological Survey. Later, regional geologic structures were summarized by Fuller and Waters (1929). Individual quadrangles were mapped in the ensuing years with most of the

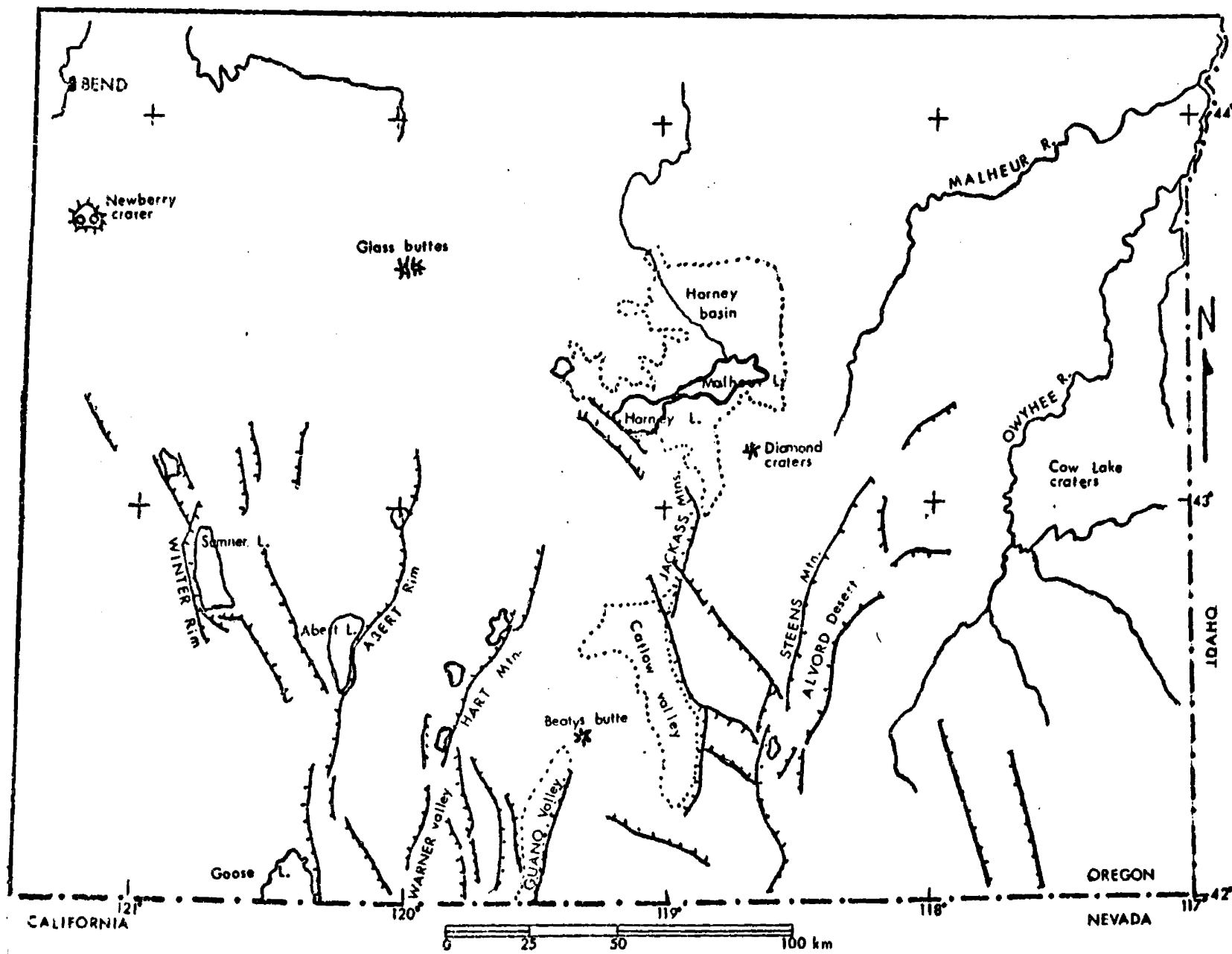


Figure 4.1. Map of Southeastern Oregon Showing Faults (from Baldwin)

emphasis on economic geology. The first regional geologic synthesis was not published until 1959 (Baldwin), and the preliminary state geologic map of eastern Oregon was not published until 1973 (Walker et al). The paucity of geologic information concerning southeastern Oregon is astounding since it is a region of spectacular volcanics and major structures which pose tectonic questions within the continental framework. Figure 4.1 should be referred to during the following discussions for geographic details.

THE HIGH LAVA PLAINS

Southeastern Oregon can really be divided into two geomorphic provinces: the high lava plains and the basin and range (Raisz, 1945). (See figure 4.2.) The high lava plains extend east from the Cascade Range to the Harney basin and south of the Blue Mountains. This province can be distinguished from the basin and range by the absence of normal faulting and the presence of a wide variety of recent volcanic features.

Here is a landscape created during late Quaternary time in a setting of explosive volcanoes, vast lakes and alpine glaciers. Fresh cinder cones, explosion craters and calderas dot the landscape breaking the monotony of the level plateau surface. Miocene and Pliocene rocks correspond stratigraphically with major formations to the south and east

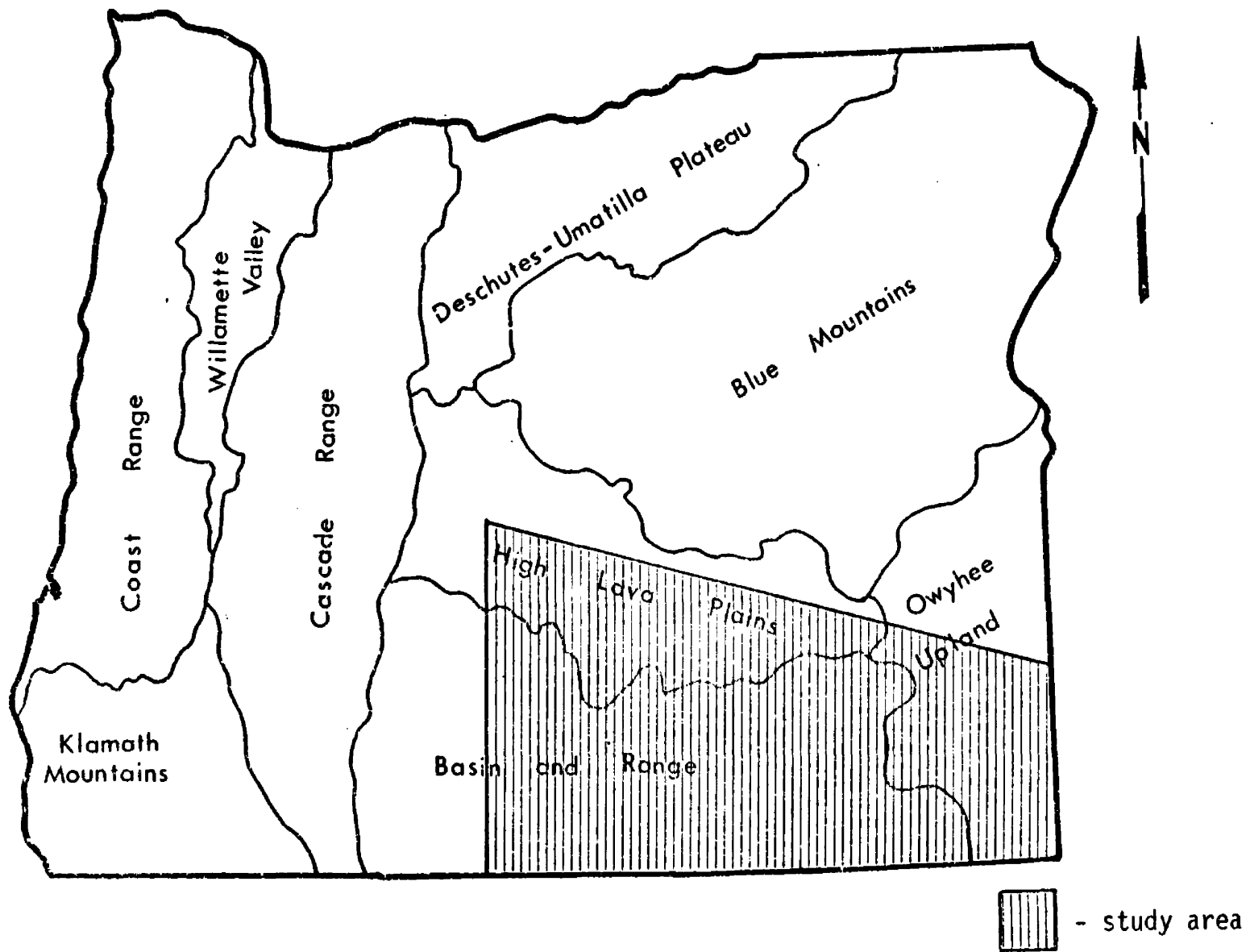


Figure 4.2. Physiographic Provinces of Oregon

and consist of massive flood basalts and nonmarine sediments. Pleistocene and post Pleistocene units are chiefly volcanic - basaltic and rhyolitic lavas, tuffs and pyroclastics; and, valley fill - lake deposits and eolian sediments (Baldwin, 1959). Newberry Crater on Paulina Mountain, a large shield volcano 25 miles South of Bend, is the most striking feature on the plateau. Two large lakes fill the caldera where twin cinder cones were built by subsequent eruption following the collapse of the original volcanic summit (McKee, 1972).

THE BASIN AND RANGE

The basin and range, south of the high lava plains and east of the Cascades, is part of a much larger physiographic province of the same name extending all the way south to Arizona and New Mexico. In Oregon, it is characterized by major north trending normal faults which break the massive flood basalts into horst and graben structures, and by many playa-type lakes.

Here the Mesozoic metamorphosed basement - pyroclastics, flows and nonmarine sediments, is related to similar Triassic rocks in the Blue Mountains. The basement is overlain unconformably by a thick Miocene volcanic sequence including stratified volcanics interbedded with nonmarine sediments, tuffaceous sediments and that great pile of lava known as the Steens basalt (Smith, 1927; Russel, 1903). Throughout south-

eastern Oregon, the Miocene was a time of quiet effusion of basalt from large fissures in the crust. Time and again lava flooded the countryside covering thousands of square miles east of Albert Rim and burying all but the peaks of older mountains. More than 100 flows have been identified with local accumulations up to 4000 feet thick (Baldwin, 1959). East of the Alvord desert, on the Owyhee upland, these flood basalts are referred to as the Owyhee basalts. Both the Owyhee and Steens basalt are contemporaneous with the late Miocene Columbia River basalt of Washington and northern Oregon, and may be genetically related by a common magma chamber (McKee, 1972). Pyroclastics, thin basalts and nonmarine sediments form the bulk of sediments accumulated during the Pliocene.

During the late Cenozoic, after deposition and solidification of the flood basalts, there was a period of tectonism resulting in an east-west lengthening of the crust and the formation of many north trending normal faults. Near vertical movement on these faults with displacements up to several thousand feet (Donath, 1962) created the horst and graben structures so typical of the basin and range (Stewart, 1971). Major fault scarps in the area from west to east are: Winter Rim, Albert Rim, Hart Mountain, Jackass Mountain, Catlow Rim and Steens Mountain. Immense lakes occupied the basins in the Pleistocene, filling and draining with each glacial stade. Contemporaneously with the normal faulting,

a second set of faults developed.

This is a set of pervasive northwest trending faults which in places appear to offset the normal faults (Donath, 1962). These faults are present on the high lava plains as well as in the basin and range, and unlike the normal faults in that area, they are not buried by recent volcanics. Pease (1969) observed that these northwest trending faults "...lack vertical construction, have shallow linear depressions due to erosional weakness, show evidence of lateral offset and may represent orientations of shear movement in more recent time." Right lateral strike slip movement has been verified on many of the faults in this set (Donath, 1962; Pease, 1969) making these faults very similar in orientation and sense of movement as the majority of non-normal faults throughout the basin and range. Stewart (1971) has proposed a model consisting of a rigid crust underlain by a plastically deforming substrate which is extending in an east-west direction, to explain the rhombic pattern created by intersecting normal and wrench faults.

THE ERTS LOOK

The region is very distinctive on the ERTS imagery. (See figure 4.3.) When viewed on the infrared mosaic of the entire Pacific Northwest, southeastern Oregon stands out because of its very smooth surface texture and medium grey

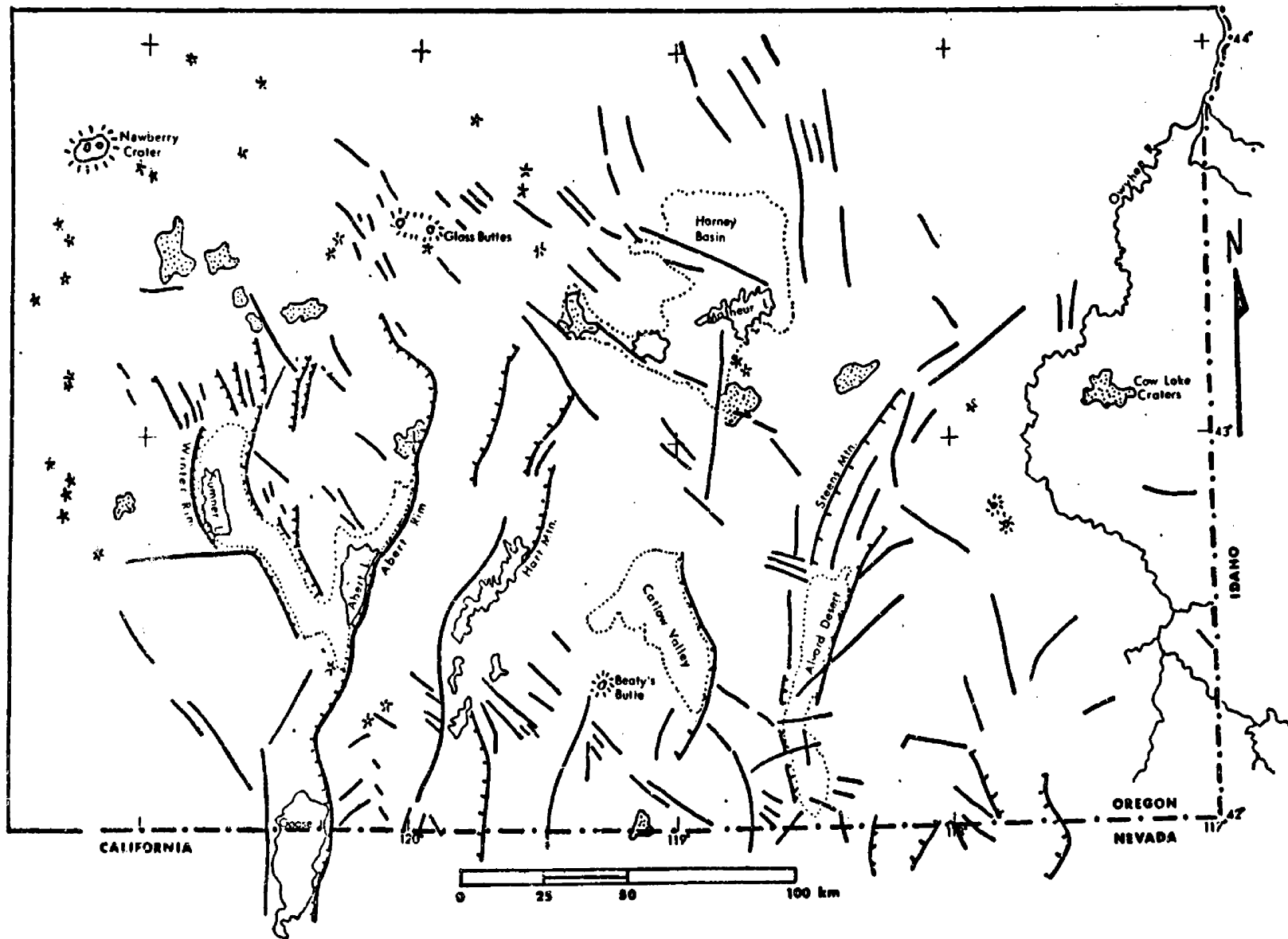


Figure 4.3. ERTS Lineament Map of Southeastern Oregon

tone, quite a contrast to the rough texture and light tone of the nearby Blue and Cascade Mountains. The overall medium grey tone of the basalt blanket appears mottled in places with irregular lighter and darker grey patches. These are the more recent volcanics which erupted on top of the flood lavas leaving cinder cones and basaltic or rhyolitic lava flows scattered across the basalt plain. On the imagery at a scale of 1:1,000,000, individual cinder cones are difficult to distinguish but many were identified due to their characteristic circular shape. Those identified included Newberry Crater, Glass Buttes, Diamond Craters and several others which were topographically prominent. On the imagery these cones range from .5 to 1.5 cm in diameter representing 5 to 15 km on the ground. Recent lava flows are quite easily annotated by carefully observing changes in tone and following these tonal boundaries.

For the most part streams in the area are seasonal with poorly defined channels, the Owyhee River on the eastern edge of the region is the only exception. Slight differences in the petrology of the Owyhee basalt may make the ground more susceptible to stream erosion, thus allowing the development of a consolidated drainage system. Otherwise there is no well consolidated drainage network to dissect the surface of the basalt.

A very striking feature on the imagery is the presence of several large lakes in the fault basins. Abert, Sumner,

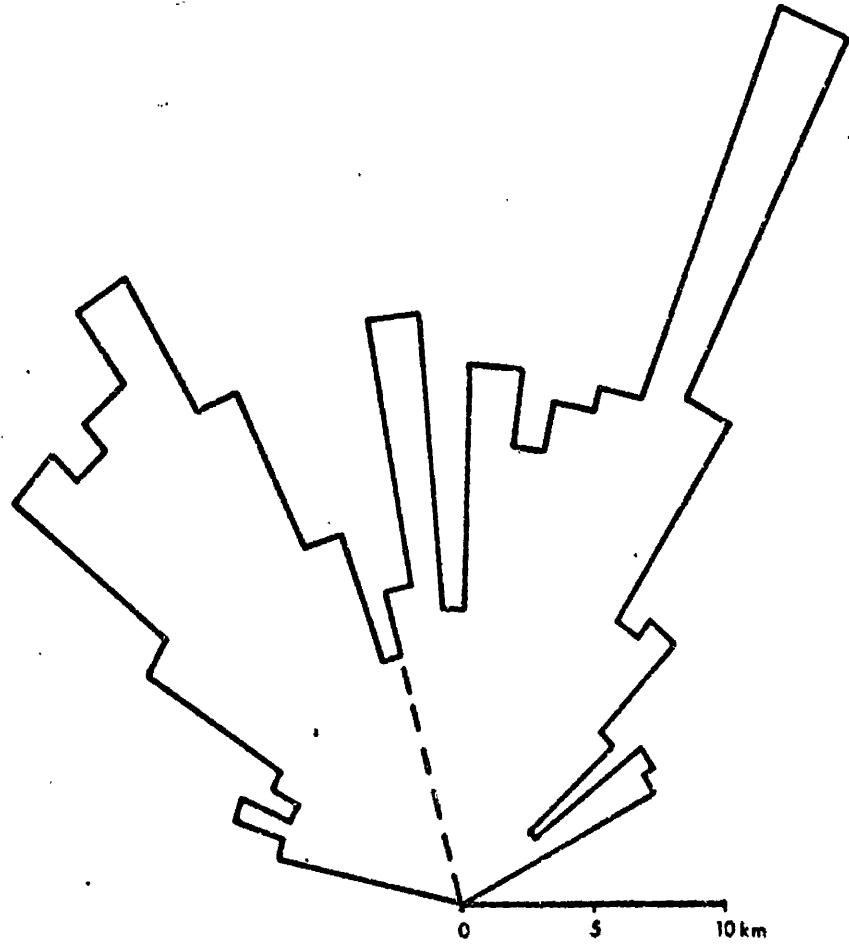
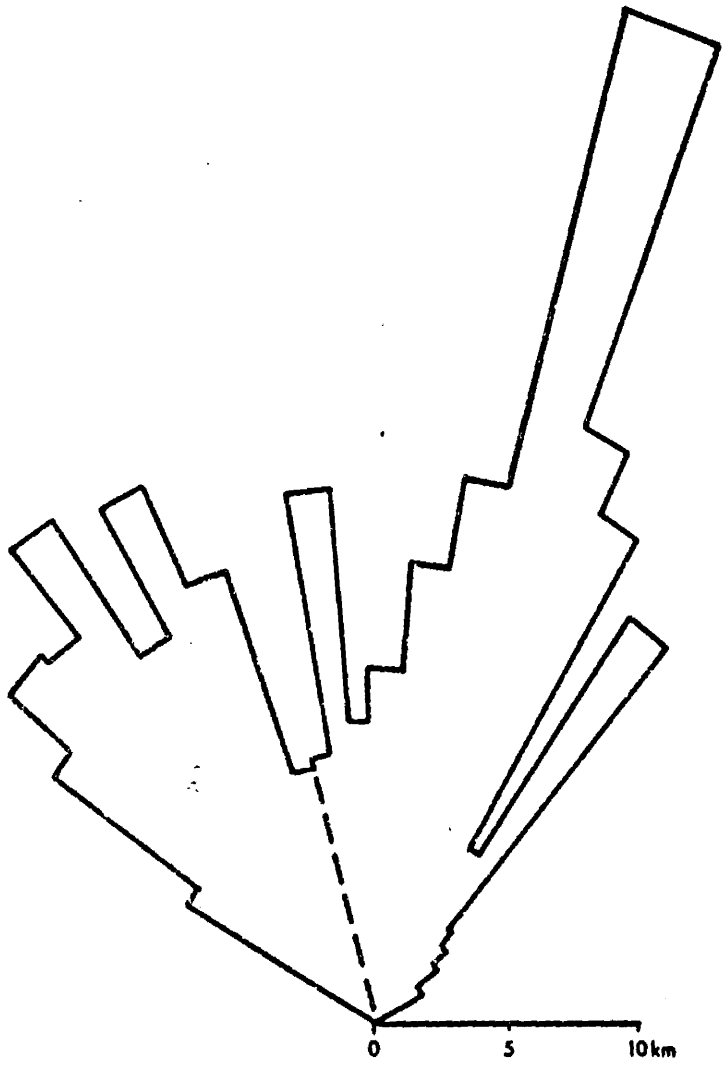
Goose, Silver, Harney and Malheur, seasonal remnants of the great Pleistocene lakes, appear as jet black spots. Bright toned evaporite deposits surround these lakes making them even more prominent. Very bright toned playas occupy other basins, notably Catlow Valley and Alvord Desert. Conceivably several of the very dark toned lavas could be mistaken for lakes since their general shape is similar to the outline of a lake. The very bright haloes encircling the lakes, therefore, serve to set them apart from the lavas, which obviously have no associated evaporite deposits.

Normal faulting, responsible for the basin and range type topography, produced many north-northwest trending scarps. They are easily identified from the imagery and appear as long, sinuous, dark grey lineaments. Due to their orientation relative to the direction of solar illumination, these faults are much more easily identified than the northwest striking set. Also, those faults with their downdropped block to the west cast a shadow, and are more easily seen than their reciprocals with downdropped blocks to the east directly facing the morning sun. A second set of lineaments, striking northwest, cuts across and in places offsets the normal faults. These faults are less distinct features on the ERTS imagery for two reasons. They have little dip-slip displacement (Pease, 1969) to produce recognizable scarps; and they are oriented more nearly parallel to the illumination direction which minimized their photographic

relief. A rose diagram compiled from the lineament data in this region reveals the two trends very clearly. (See figure 4.4)

GROUND TRUTH

As was previously mentioned, little work has been done in southeastern Oregon beyond the initial reconnaissance work and what was necessary to develop isolated ore deposits. Fortunately the preliminary map of eastern Oregon was accompanied by a tectonic map at a scale of 1:1,000,000, the same scale as the ERTS mosaics, drawn by G.W. Walker (1973). This tectonic map was used for the comparison with the ERTS lineament map. Strike and length of all faults - inferred and recognized, and all major fold axes in an area coincident with the region defined on ERTS imagery were measured. The northern tip of California, present on the imagery, and the western edge of the basin and range in Oregon, west of Winter Rim, were excluded from the comparison because they did not fall within the boundaries of Walker's map. To include these areas would have meant using ground truth of inferior quality and possibly introducing substantial error into the data. All data obtained from the ground truth map was organized into a rose diagram drawn to the same scale (1cm = 1km) as the one constructed from the ERTS lineament data. (See figure 4.5)



ROSE DIAGRAMS FROM LINEAMENT DATA IN SOUTHEASTERN OREGON

Figure 4.4. From USGS Map MF-495

Figure 4.5. From ERTS Lineament Map

ERTS LINEAMENTS V.S. USGS FAULTS

A superposition of the two rose diagrams reveals a striking similarity between them. (See figure 4.6) A large percentage of the total petal area of the two diagrams matches, although this is not the best test of correspondence. A very long peak adds much more petal area for each increment of lineament length at its outside end than it does near the origin. So having a small angular discrepancy between the two diagrams, in the trend of the main petal, can add considerable area of mismatch. It is better to observe the distribution of peaks, and note their astonishing correspondence.

A line striking N 15 W, separating the two major petal clusters, can be drawn on both of the diagrams. This line represents the boundary between the two principal lineament sets. There is a 5 degree discrepancy between the two diagrams on the main peak of the northeast quadrant. Their total lengths only differ by 2.6 cm and the slight angular difference is acceptable when the scale of the imagery and map is considered. On the scale of 1:1,000,000, a felt tipped pen makes lines obviously much wider than the width of the feature being traced. Small mistakes in the exact measurement of the strike of the lineaments are easily made. Hopefully most of these errors are self correcting as there should be no built in bias for the direction in which they

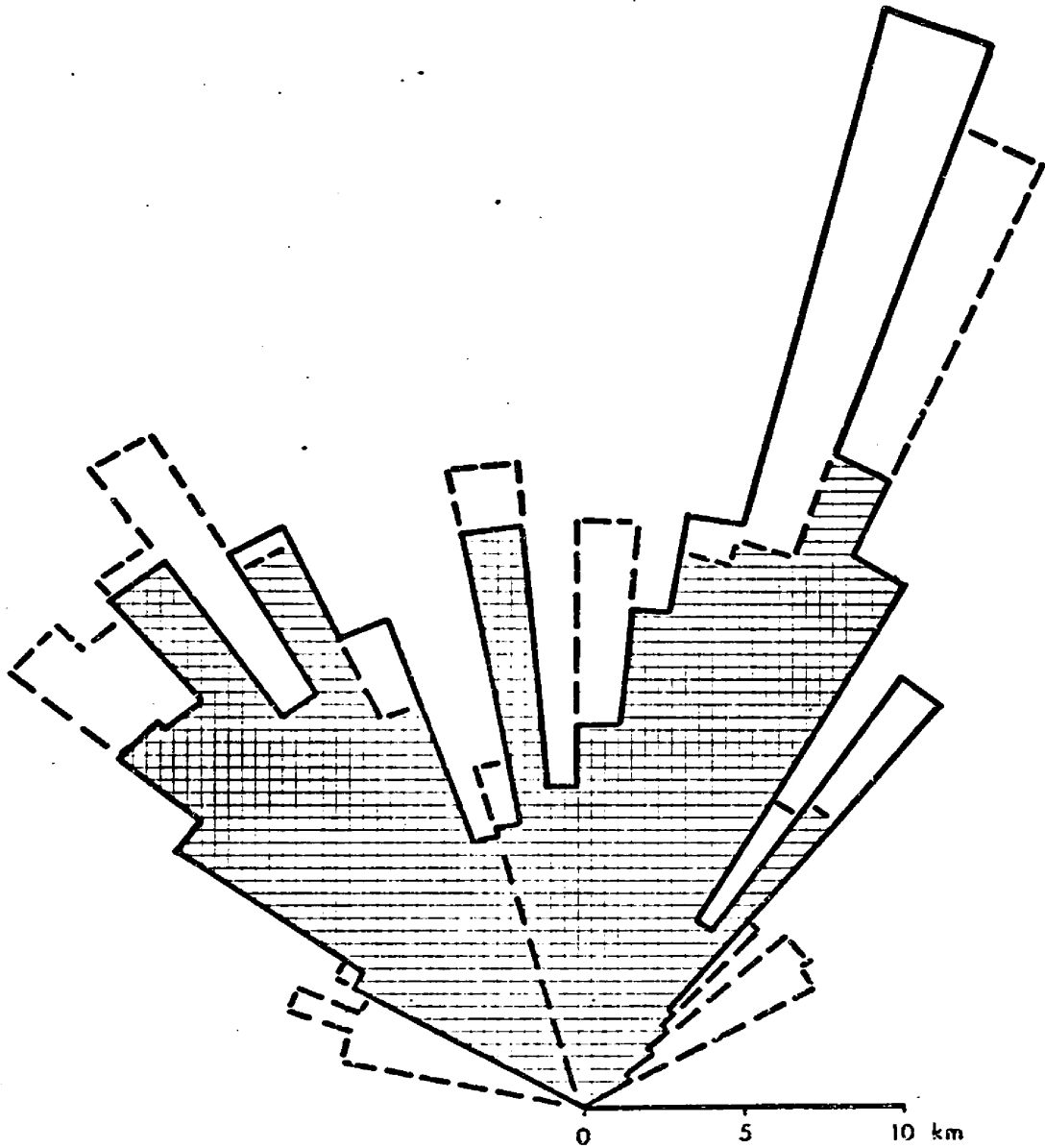


Figure 4.6. Superposition of Figures 5.4 and 5.5
Dashed line outlines data from the USGS map,
solid line outlines data from the ERTS map,
and the hatched area represents the area of
correspondence between the two diagrams.

occur. Another way of introducing error in either ground mapping or lineament annotation is through the generalization of intersecting fault sets of small angular difference to create one main trend rather than distinguishing two trends. It is easy to see how several angular mistakes could accumulate to produce angular discrepancies between the two diagrams of five to ten degrees. For the above reasons, the diagrams were plotted in five degree rather than one degree increments although ten degree intervals might have been also justified. The important consideration is that most of the other peaks do coincide, and where so many measurements make up the largest peak, there is a much greater chance of erring.

As was anticipated, the magnitude of total petal area in the northeast quadrant of the diagrams is greater than that in the northwest, on both the ERTS and the USGS compilations. This substantiates the predominance of northeast trending normal faults in the area. Interestingly, detailed mapping of small areas (Donath, 1962; Pease, 1969) has revealed that the extent of northwest trending faults is actually much greater than previously thought and should be the dominant trend in the area on the basis of total length and density of faults. On a regional scale the converse is true. Northeasterly trending lineaments are significantly enhanced in ERTS imagery by the direction of solar illumination, while those trending northwest are obscured. On the ground, northeast striking normal faults are easily rec-

ognized by large scarps whereas those striking northwest are usually wrench faults with little or no dip-slip displacement making them very subtle features.

CONCLUSIONS

The close similarity of the rose diagrams should provide ample proof of the statistical validity of a lineament map relative to published ground truth from the following observations.

1. A large percentage of the total peak area of the two diagrams matches.
2. All of the peaks on both diagrams match closely in length.
3. The trends of all but one peak on both diagrams coincide.
4. The major discontinuity in strike between the two lineament sets can be placed at N 15 W on both of the diagrams.

Even with the above lines of reasoning, it is still not permissible to conclude that this is proof that lineaments can be compared on a one to one basis with known faults. Lineament and fault are not synonymous terms. The rose diagram test shows that over a broad region, the trend of lineaments drawn from ERTS imagery closely resembles the trend of regional tectonic elements as they have been inter-

preted on geologic maps. Interestingly, the fact is that in many cases the match is so close that a lineament map is a valid substitute for the geologic map should the need for substitution arise. Clearly, southeastern Oregon is one such case.

CHAPTER FIVE
LINEAMENT ANALYSIS
The Lewis and Clark Line

AN HISTORICAL INTRODUCTION

Since the days of F.C. Calkins, one of the earliest geologic explorers in the Pacific Northwest, mention has been made in the literature of a peculiar linear topographic feature between Spokane, Washington and Deer Lodge, Montana. First described by Calkins and Jones in 1914 as the "old valley", it has been the subject of much debate among northwest geologists and is not completely understood even today. Early in the development of northwest geologic thinking the Lewis and Clark line was established as a major structural feature. Umpleby (1924) in describing the Osburn fault, mapped for some 150 km east of Coeur d'Alene Lake in Idaho, said that it coincided with the "old valley" and was the most pronounced tectonic feature of northern Idaho crossing the prevailing structural axes of the region. Billingsley and Locke (1941) first referred to the lineament as the Lewis and Clark line, describing it as a tear fault zone of

continental scale. Smedes (1958) first introduced the idea that the Lewis and Clark line might be evidence of movement between major crustal blocks during the Laramide deformation. Few authors of local geologic treatises have been able to disregard the lineament as a major tectonic element in the structural framework of the Pacific Northwest. Others who have contributed to geologic knowledge of the Lewis and Clark line include Anderson (1948), Campbell (1960), McMannis (1965), Weidman (1965), Smith (1965) and Harrison (1963, 1974).

A BIRD'S EYE VIEW OF THE LEWIS AND CLARK LINE

There seems to be some debate over the exact placement of the Lewis and Clark line, depending on how it is defined (Weidman, 1965). Most authorities would agree that it cannot be drawn as one discrete continuous line between Spokane to the west and Deer Lodge or Helena to the east but instead must be represented by a zone of variable width. For the purpose of this study the boundaries of the Lewis and Clark line were drawn on the ERTS lineament map on the basis of major discontinuities in lineament trend. The area was thus divided into three domains: Region A - the Lewis and Clark line, Region B - a Precambrian Belt terrain north of the line and Region C - A late Cretaceous-Tertiary igneous terrain south of the line. (See figure 5.1) Geologic valid-

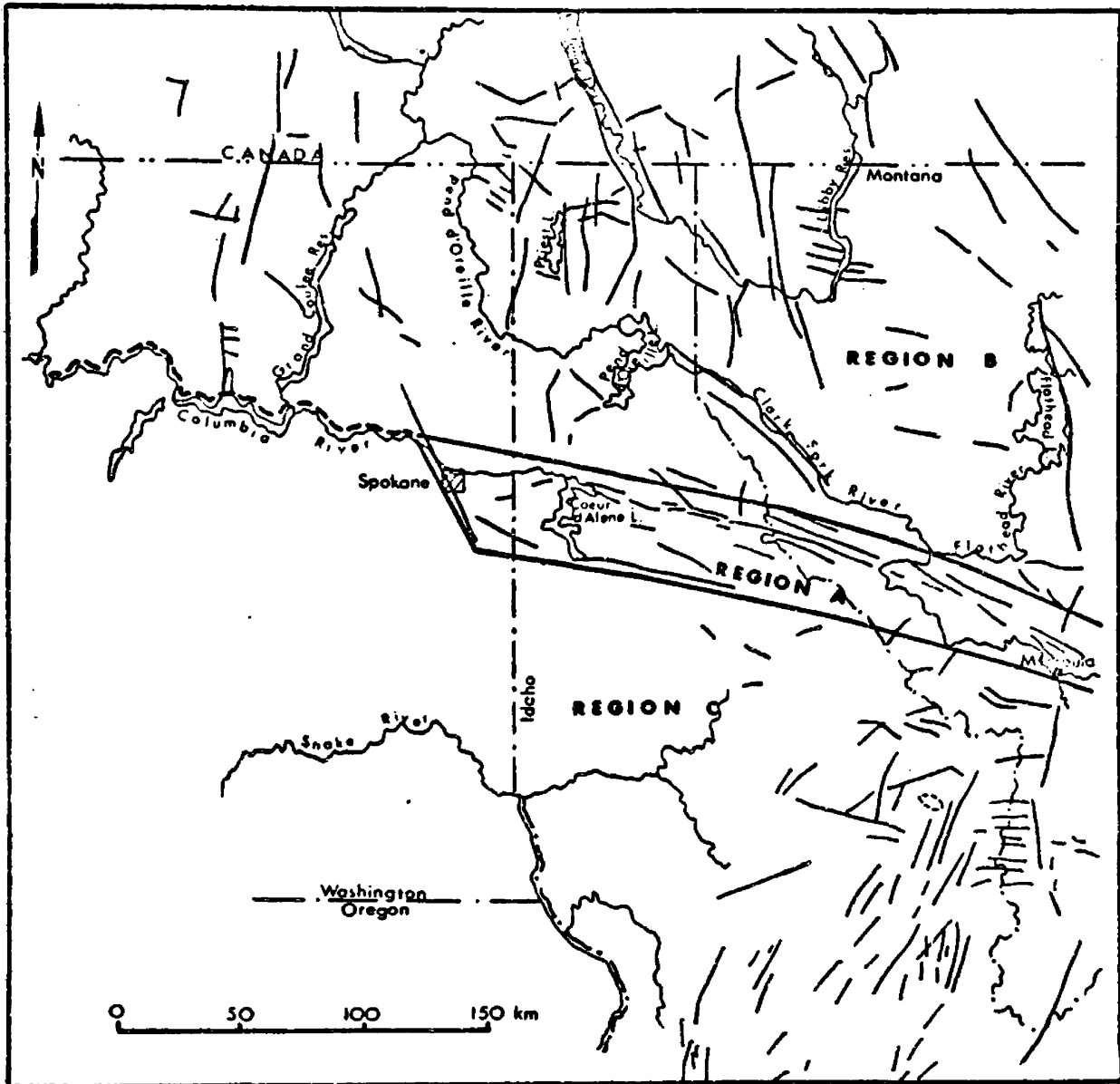


Figure 5.1. Lineament map of western Montana, northern Idaho and eastern Washington showing Regions A,B and C

ity and tectonic coherency of these three domains was then tested statistically by compiling rose diagrams to verify the contrasting lineament trends between the regions, and by comparing those diagrams with rose diagrams constructed from ground truth maps.

REGION A - The Lewis and Clark Line

From the vantage point of the ERTS satellite 900 km high, the Lewis and Clark line is a very prominent linear feature across the northwest between Missoula, Montana and Grand Coulee, Washington¹, a distance of some 400 km. It is a broad zone of west-northwest trending lineations which sharply divides the topographic features and related geologic structures to the north and south. (See figure 5.2) The zone itself can be divided into two segments, east and west of Coeur d'Alene lake in Idaho.

Between Coeur d'Alene and Missoula, the Lewis and Clark line is easily recognized as a very high concentration of transverse mountain ranges and range front scarps with lineaments up to 65 km long. The widest and most dense lineament pattern lies between Coeur d'Alene and Superior Montana.

¹I have extended the line past Spokane for reasons to be explained below, and have terminated it at Missoula, not because I believe that it ends there, but because Missoula is the extreme eastern edge of the imagery with which I was working.

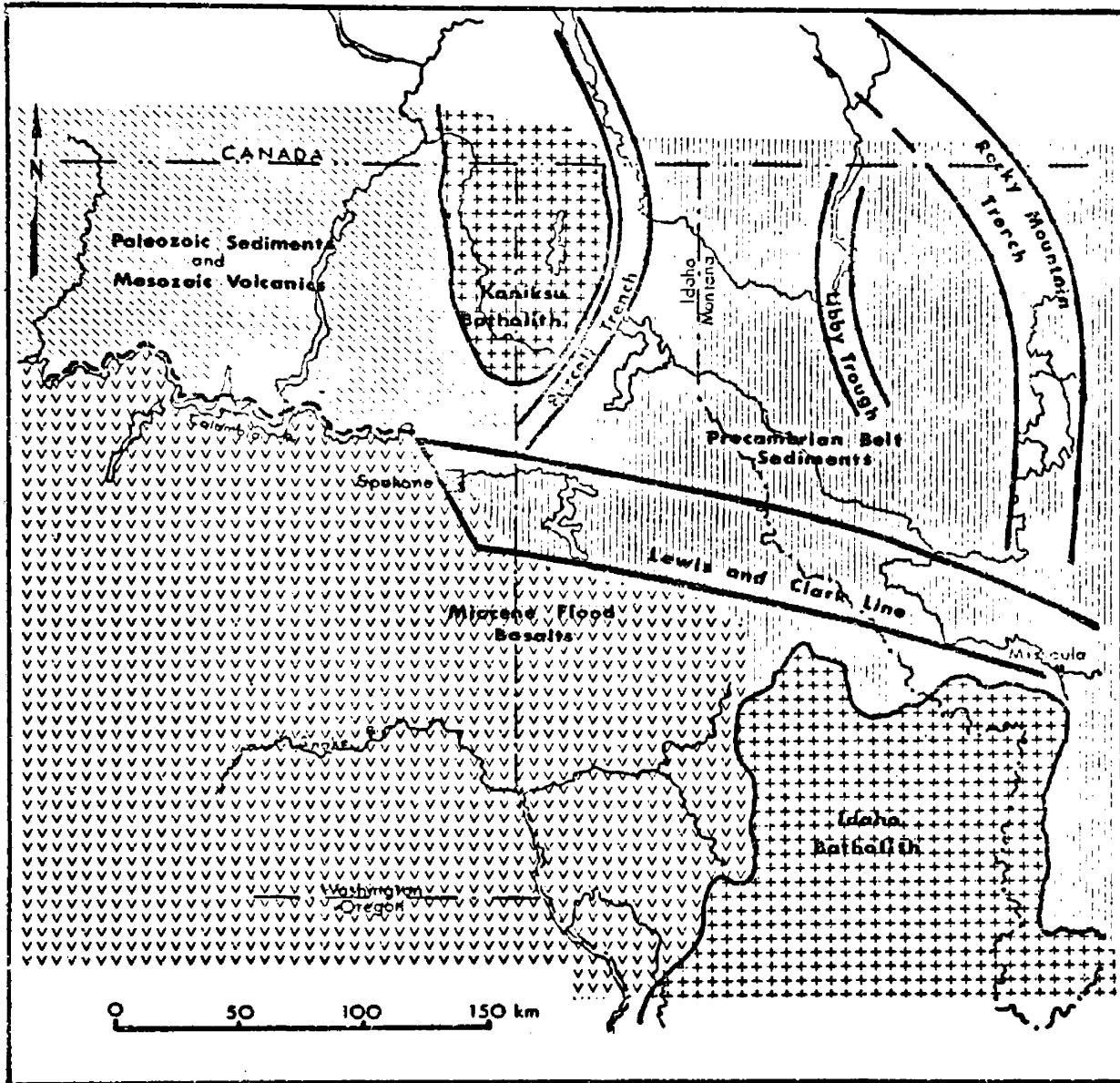


Figure 5.2. Generalized geologic map showing major tectonic provinces

Here in the famed Coeur d'Alene silver, lead and zinc mining district the zone bulges from 30 to 50 km wide. In this area very thick accumulations of moderately folded Precambrian Belt rocks have been rearranged by numerous wrench faults. Ground truth is very well established due to the extreme economic importance of the district, literally hundreds of faults have been mapped and described in detail (Calkins and Jones, 1914), (Umpleby, 1924), (Billingsley and Locke, 1941), (Wallace et al, 1960), (Campbell, 1960), (Hobbs et al, 1965).

In a previous study (Weidman, Alt, et al, 1973), this segment of the Lewis and Clark line was mapped in great detail from 1:500,000 enlargements of the ERTS imagery. An exhaustive comparison was made between all lineaments mapped and all known faults and related tectonic features from a recent ground truth compilation (Kleinkopf, Harrison, Zartman; 1972). Major faults including the Hope and Osburn among others, matched almost identically on both maps, and the two rose diagrams derived resembled each other very closely. As stated by Weidman et al:

"Both (diagrams) show a strong set of north-west-trending structures and very much weaker sets trending in other directions. Rose diagrams derived from the lineament and geologic maps in this domain are so similar that they are virtually interchangeable and the lineament map would appear to be a statistically valid substitute for the geologic map insofar as linear structures are concerned."
(See figure 5.3)

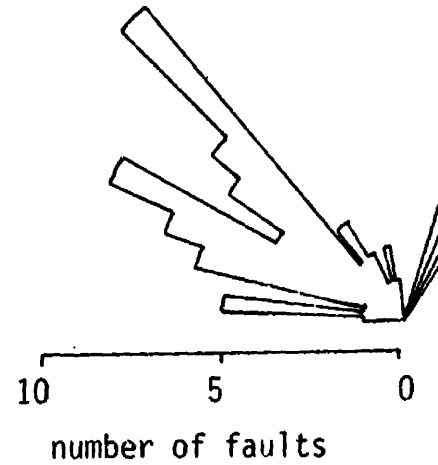
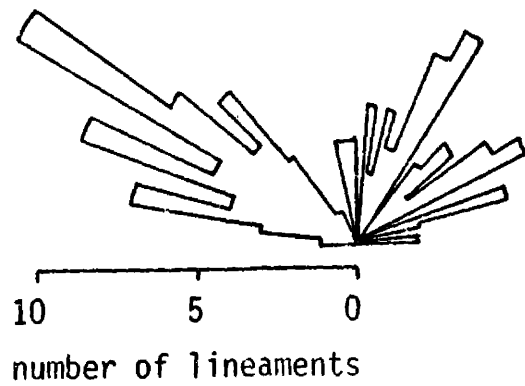
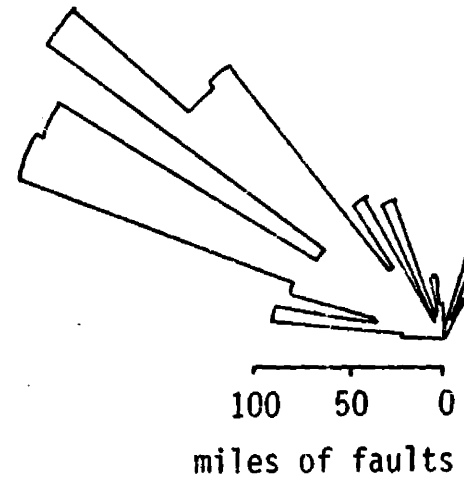
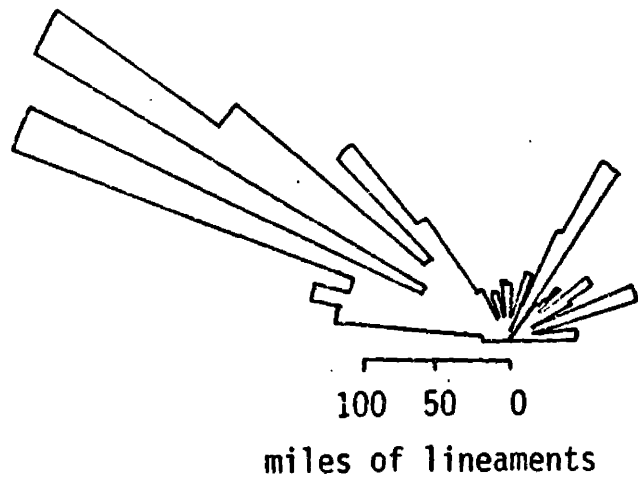


Figure 5.3. Rose diagram for the Western Lewis and Clark lineament structural domain. ERTS lineaments from imagery, scale 1:500,000; mapped faults from Kleinkopf and others, 1972. (from Weidman, Alt et al; 1973)

West of Coeur d'Alene quite a different geologic situation exists, and the Lewis and Clark line is a very subtle feature. Between Coeur d'Alene and Spokane the line is obscure. Careful examination of the imagery reveals that the area of dense agricultural activity on the plains to the south terminates abruptly along a western extension of the Osburn fault, north of which is an area of mountainous looking topography. From Spokane to Grand Coulee and on to the eastern edge of the Cascade Mountains, the line is very narrow, largely represented on ERTS by the jet black serpentine path of the Columbia River. Here the Lewis and Clark line is no longer a wide zone, but a narrow line. West of Spokane, in fact, the line hardly fits the geometric requirements of a lineament. It is extended out into Central Washington however, on the basis of topographic inconsistencies seen on ERTS imagery on either side of the Columbia River which marks the trace of the main Lewis and Clark line.

Region A then, comprising the western part of the Lewis and Clark line, is internally inhomogeneous insofar as it is defined by numerous photogeologic criteria along its 400 km length. A common feature of the entire zone, is the striking topographic and geologic discrepancy north and south of the "Line".

REGION B - A Precambrian Belt Terrain

Geologically, this region should be divided into two tectonic provinces. The Purcell Trench marks the western boundary of a block fault terrain. Pardee (1950) described an area of broad, open, north-trending folds, block faulted during late Cenozoic times to create a basin and range-type structure and topography. There are three main basins: the Purcell Trench, forming the western boundary; the Libby Trough, not a pronounced topographic feature, but including downdropped Cambrian blocks; and, the Rocky Mountain Trench, a graben-like feature bounded on both sides by normal faults (Harrison, Kleinkopf, Obradovich; 1972). The eastern edge of this province is the Montana disturbed belt, a zone of imbricate Cretaceous thrust faults (Mudge, 1970). There is widespread opinion at the University of Montana that the basin and range structures west of the thrusts are actually pull-apart grabens, or large extensional fractures that opened up when the thrust plates were sliding eastward. From the literature (Calkins and MacDonald, 1909), (Pardee, 1950), (McMannis, 1965) and (Harrison and others, 1974), it is evident that the main structures of northern Idaho and western Montana do not continue south of the Lewis and Clark line. This southward termination corresponds well with lineament patterns seen on the ERTS imagery, and would indicate that the structural domain previously defined as Region B is a valid domain.

West of the Purcell Trench is an area "... sieved by Cretaceous batholiths..." and partly covered by Tertiary volcanics (Harrison et al, 1972). It has been called the Kootenay Arc mobile belt (Yates, 1973), an area of complex faulting, intrusion, extrusion and intense deformation. Cretaceous time witnessed the emplacement of the Kaniksu batholith and the rising Selkirk Mountains.

A major dichotomy in topographic expression within this region is also evident on the ERTS imagery. East of the Pend d'Oreille River in Washington is an area of mountainous terrain with high tonal contrast. Well established drainage systems dissect the Belt surface. Drainage textures are fine grained south of Pend d'Oreille Lake becoming progressively more coarse grained toward the Canadian border. This corresponds with an increasing density of lineaments approaching the Hope and Osburn fault zones. Prominent features easily recognizable on ERTS are the high angle fault scarps and adjacent basins of the Purcell and Rocky Mountain Trenches. The Libby Trough is practically indistinguishable save for the long sinuous reservoir to the north, and a system of obvious though heretofore unmapped cross faults across the valley. These are the only real structural breaks in an otherwise homogenous albeit highly corrugated mountainous terrain. Several large lakes also serve to distinguish the eastern half of Region B. These appear as very irregularly

shaped opaque black spots and all are elongated in a north-south direction. They include Flathead Lake and Libby Reservoir in Montana, Pend d'Oreille, Coeur d'Alene and Priest Lakes in Idaho, and Kootenay Lake in British Columbia, Canada.

East of the Pend d'Oreille River the structural province referred to as the Kootenay Arc Mobile belt is not distinguishable from the Belt province east of the Purcell Trench. On the ERTS imagery the Selkirk Range appears quite similar to the mountains in northern Idaho. This is unusual since Igneous rocks predominate in the Selkirks whereas northern Idaho is almost exclusively a metasedimentary terrain. Both areas have in common an extensive fault system which may have some relationship to the similar lineament patterns. I would suggest however that similar climatic conditions, a very dense coniferous forest and deep soil cover over the entire area are the keys to the likeness. In previous ERTS lineament studies (Weidman, Alt, et al, 1973) heavy ground cover was recognized as a serious detriment to an accurate evaluation of the underlying photogeologic units. Under these conditions even a basic discrimination between layered and non-layered rocks cannot always be made.

West of the Pend d'Oreille River there is a striking topographic change. Here Paleozoic sediments and Mesozoic intrusives predominate creating a medium grey surface of moderate relief with a random though well developed drainage

pattern. Cenozoic volcanics in the extreme west of the region produce a smoother surface with an unconsolidated drainage system, and large patches of darker toned rocks.

REGION C - A late Cretaceous-Tertiary Igneous Terrain

None of the topographic or geologic features described in Region B can be traced past the Lewis and Clark line, south into Region C. A quick glance at even the most generalized geologic map serves to point out the major incongruencies in geologic terrains north and south of the line (See figure 5.2). Likewise, even a casual inspection of the ERTS imagery reveals the differing physiography between these two regions (See figure 5.1). Region C should be divided into two tectonic provinces, east and west of a line projected southeast of Coeur d'Alene Lake.

The Batholith province (McMannis, 1965) in the eastern half of this region is an area characterized by Cretaceous-Tertiary igneous rocks. The Idaho Batholith, a Cretaceous quartz monzonite intrusive, outcrops over much of the area in east-central Idaho. To the north it is fringed by a zone of complexly folded regional metamorphic rocks. The batholith's northeastern margin, known as the frontal zone gneiss of the Bitterroot Range, Montana, is thought to represent a zone of gravitational sliding (Talbot, Hyndman; 1973).

On the ERTS imagery, the area appears to have much less relief than Region B. The drainage pattern is fine grained, characteristic of many granitic rocks, and is well developed along what might be interpreted as prominent joint sets in the batholith which create the only prominent lineament set in the region. (See figure 5.1). Photographic contrast is subdued with an overall light grey tone. Regional metamorphic rocks to the north are distinguishable only by their slightly darker grey tone, and cataclastic rocks of the Bitterroot Mountains are identified on the basis of a textural change. Here range front scarps form north-south lineaments, and a well developed drainage system forms prominent east-west lineaments, the majority of which do not continue past the divide. Absent are the large lakes of Region B. Only scattered glacial tarns are present, they show up as very minute black dots on the mountain tops.

A very fertile agricultural plain stretches west from the Idaho Batholith all the way to the Cascade Mountains in west-central Washington. This is a Cenozoic landscape of Miocene volcanics and Quaternary eolian and lacustrine sediments. During the Miocene, fissure basalts flooded the area time and again, building up layer upon layer of lava flows. A third great pile of late Miocene lava, the Columbia River Basalt is commonly more than 2,000 feet thick but locally exceeds 5,000 feet. (Baldwin, 1959) The upper surface is generally scoriaceous and well weathered which

may account for the absence of any well developed drainage systems other than the Columbia River and its tributaries. During the Pleistocene, central and southeastern Washington were in the path of a gigantic braided river, created by repeated catastrophic draining of glacial Lake Missoula. This scabland stands out distinctly on the ERTS imagery. The abundance of loess deposits makes the soil ideal for agriculture, evidenced by expansive wheat fields creating a checkerboard pattern of bright grey tones in rectangular shapes against the dark surface of the basalt plateau.

Two types of domain boundaries can be distinguished along the Lewis and Clark line. East of Spokane it is a hard boundary represented by a set of parallel west-north-west trending lineaments separating two distinct tectonic settings: that of the folded and faulted Belt terrain to the north and the well jointed Idaho Batholith to the south. West of Spokane it is a soft boundary identified primarily on the basis of a change in geology and not on a change in lineament trend across the line of the Columbia River.

THE ROSE DIAGRAM TEST

In the preceding sections, major differences in the regional geology of three tectonic domains were discussed. Even from these very general geologic considerations it appears quite obvious that the original tentative boundaries

drawn on the ERTS lineament map closely correspond with real tectonic domains. The three regions are easily delimited on the ERTS lineament map on the basis of widely divergent strike trends in the three areas. In an attempt to graphically demonstrate the existence of the Lewis and Clark line and adjacent structural domains, rose diagrams were prepared from ERTS lineament data.

The diagram for Region A, the Lewis and Clark line, displays an astounding homogeneity of lineament strike-trend. (See figure 5.4) Prominent petals are at N 60-75 W, corresponding with the general trend of major faults, notably those of the Osburn fault zone, in the Coeur d'Alene district previously discussed. It is also one of the least prominent trends in both Regions B and C. Region A thus forms a well defined transverse structural boundary between the other two regions.

In Region B, a block faulted Precambrian Belt terrain north of the Lewis and Clark line, the major lineament trend is N 10 E to N 40 W with the main peak at N 20-25 W. (See figure 5.5) This is the orientation of lineations that correspond with structures parallel to the Purcell, Libby and Rocky Mountain Trenches, and which end abruptly at the boundary of Region A. A less prominent peak at N 50-55 W is revealed by the rose diagram. This appears to correspond with the several lineaments mapped southeast from Pend d'Oreille Lake, in the Hope Fault Zone. This is a zone of

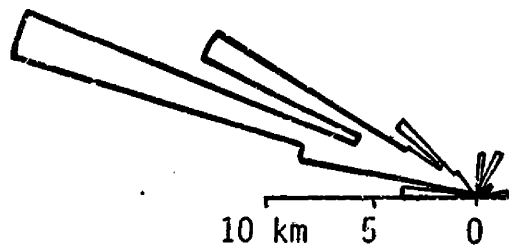


Figure 5.4. Region A

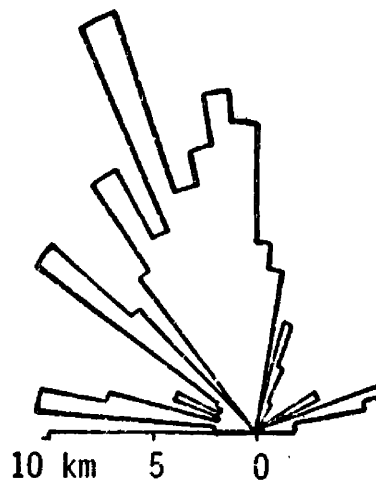


Figure 5.5. Region B

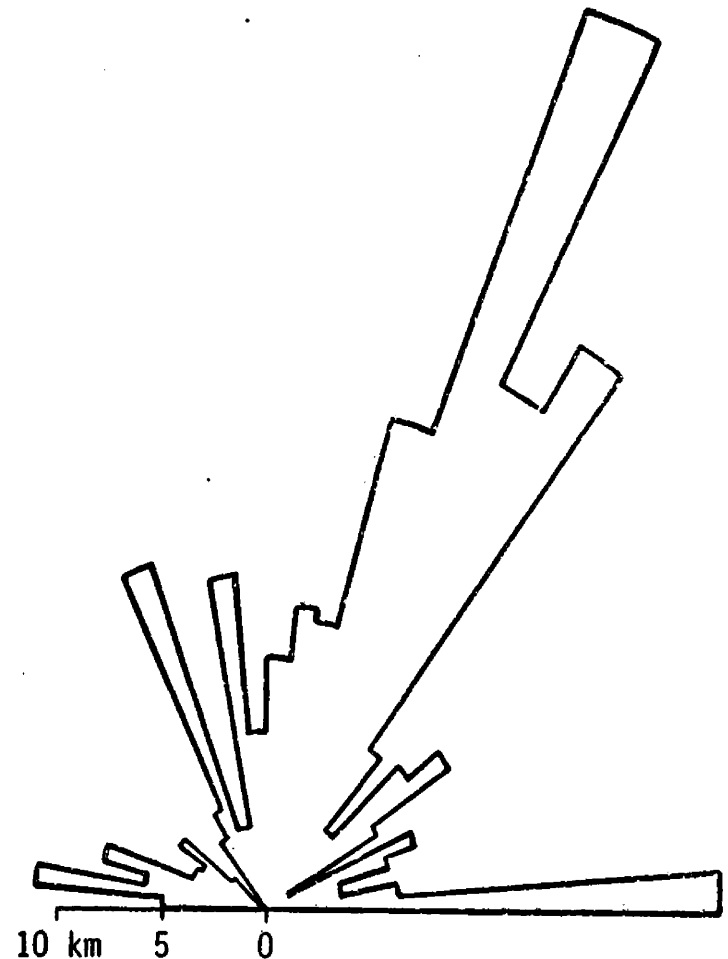


Figure 5.6 Region B

ROSE DIAGRAMS FROM DATA ON USDA MOSAIC LINEAMENT MAP

extensive Precambrian to Cenozoic right lateral wrench faulting, somehow related to faulting in the Osburn zone (Harrison et al, 1972). A third distinct trend on the diagram, N 75-85 W, most likely represents the series of transverse faults across the Libby Trough, already mentioned.

The average lineament trend in Region C, a Tertiary igneous terrain south of the Lewis and Clark line, is N 0-40 E. (See figure 5.6) Most of the lineaments observed in this region are in Idaho within the outcrop area of the Idaho Batholith. They probably reflect the general strike of a prominent joint set in the granite. A major peak at N 85-90 E represents an isolated set of east-west trending lineaments mapped in the Bitterroot Mountains in Montana. These are possibly glacially scoured and straightened valleys. West of the batholith, in southeastern Washington, there is a pronounced absence of lineaments on the Columbia basalt plateau. Blanketed by loess and fluvial glacial deposits, any structural features in the lavas might easily be hidden.

Although all three rose diagrams were plotted to the same scale, the one for Region C is almost twice as large as the other two. This indicates that either more lineaments were mapped, or those mapped were generally longer than those in Regions A and B. A quick glance at figure 5.1 reveals that the average length of lineaments in the three regions is comparable, although B seems to have the longest ones, but Region C does contain a greater number. I would

suggest that this might be a good example of how the bias of illumination angle can influence numbers of lineaments mapped. General trend in Regions A and B is northwest-southeast, so that some lineaments are probably not visible. In fact, the small number of lineaments mapped in these regions does not agree with reports in the literature of a complexly faulted terrain.

In spite of this last complication with illumination bias, each region does exhibit a characteristic lineament trend, and there is very little overlap between prominent trends. This is the final proof that the subjective domains drawn on the ERTS lineament map, with little prior knowledge of regional geological relationships, adequately portray the tectonic situation.

CHAPTER SIX

SUMMARY

During the course of my research actual progress was very difficult to measure and it is only in retrospect that I can objectively evaluate the products of my research.

Results of this study are four-fold.

1. Illumination direction and dense ground cover were shown to be two limitations of the imagery for geologic interpretation. Of primary concern is the problem of illumination direction which enhances structural features in a particular orientation while obscuring others. Caution is urged in all statistical analyses of ERTS structural data unless the extent of the bias is first evaluated. Difficulty in annotating the imagery in regions of dense ground cover were also encountered. For this reason, one test site was chosen in an area of sparse vegetation in southeast Oregon, and the other in the heavily timbered slopes of northern Idaho and western Montana. Lineament - ground truth correlations were markedly closer in Oregon than in Idaho and Montana and vegetation differences between the two areas are interpreted to be the main cause.

2. Rose diagrams were shown to be useful in testing lineament reliability and domain homogeneity. In the southeast Oregon study, rose diagrams were constructed from both lineament and ground truth maps. The favorable comparison between the diagrams seems to justify the lineaments as reliable indicators of regional bedrock structure. A less favorable comparison would indicate major discrepancies between the data from the two maps in which case a one-to-one comparison of lineaments and mapped structures would be recommended. Rose diagrams were also used to test the homogeneity of tectonic domains subjectively drawn on the ERTS lineament map. Comparison of diagrams representing three domains in Idaho and Montana revealed a distinct lineament trend in each domain with little significant overlap.

3. A lineament map of southeastern Oregon was drawn which more than met the requirements for a reconnaissance geologic map. Excellent correlation of topography and bedrock structures, homogeneity of bedrock, and sparse vegetation, combined to make the area ideal for ERTS annotation. Although for the purpose of this study linear features were emphasized, other geologic elements including fold axes, lava flows and cinder cones were easily annotated. The map drawn could easily have been substituted for a preliminary ground truth map.

4. A lineament map representing the Lewis and Clark line and adjacent regions was compiled. Coupled with a general knowledge of the bedrock geology this map represents a reasonable tectonic map of the area, defining several major domains and the structural patterns within those domains. In an area of less dense vegetation I feel certain that a very reliable tectonic map could be produced.

I have tried to demonstrate that high altitude space imagery of a quality comparable to the ERTS imagery, is at least a fundamental tool in all reconnaissance work. Lineament maps of broad regions can be produced quickly and inexpensively in the office. In addition, a cursory field check to identify lithologies would enable the annotator to expand the skeletal lineament map into a full blown geologic map with little additional effort. However, the lineament map is valuable in itself since it represents the regional tectonic picture.

CHAPTER SEVEN

CONCLUDING REMARKS

Months of staring at the Pacific Northwest from my window in the sky have convinced me that ERTS imagery is precisely what is needed to complete a revolutionary interpretation of Cenozoic tectonics. Naturally I cannot refrain from speculating on the role of ERTS in the context of recent theories of continental tectonism.

Many isolated studies have led geologists to postulate that the West has been a very broad zone of right lateral movement since the beginning of Cenozoic time. Several deal specifically with structures in the Northwest. Donath (1962) demonstrated a right lateral sense of movement on many northwest striking faults in southeast Oregon. Hamilton and Myers (1966) reconfirmed the right lateral movement along the Lewis and Clark line, suggesting that the large fault troughs north of the line are extensional features resulting from this motion. Pease (1969) described several northwest trending zones of right lateral deformation in southern Oregon and northeastern California. He attributed them to shear strain with concomittant north-south crustal short-

ening and east-west crustal extension.

Atwater (1970) finally considered the evidence in terms of plate tectonics. In her analysis differential motion between the Pacific and North American plates created a broad belt of right lateral movement throughout western North America. Much of the movement is taken up along the entire length of the San Andreas fault zone, the remainder is distributed as extensional fragmentation of the crust (including the basin and range structures) throughout the West (Stewart, 1973). She suggests that the right lateral deformation initiated when the North American plate overrode the East Pacific Rise, has not yet ceased (as evidenced by very recent movements in the San Andreas fault zone and intermountain seismic belt; Smith and Sbar, 1974).

ERTS observations seem to support the theory in the Pacific Northwest. Almost every major geologic element in the photo is Cenozoic in age, this includes the Cascade volcanoes, the great flood basalts, basin and range structures both north in Idaho and Montana and south in Oregon, igneous intrusives (Idaho and Kaniksu batholiths) and even the Lewis and Clark line (most recent movement is Laramide; Kleinkopf et al, 1972). This is glaring proof that a dramatic reorganization of the landscape must have taken place since the Cretaceous to obliterate almost every trace of older tectonism.

A pervasive system of northwest trending structures annotated from Vancouver Island across to western Montana and south to northern California seems to indicate a broad belt of deformation although sense of movement is hard to define. Northwest striking lineaments are more dense in certain zones including Vancouver Island and the Olympic Peninsula, the Lewis and Clark line and broad belt north of the basin and range province in Oregon. These appear to fit into the total picture as major zones of shear strain and right lateral adjustment similar to the San Andreas, although perhaps no longer active, but the sense of movement is indeterminate on the ERTS imagery.

Giant stretch marks across southern Oregon south of the shear zone, and large structural trenches in Idaho and Montana, north of the Lewis and Clark line may be related. They are certainly both evidence of east-west crustal extension. Stewart (1973) has demonstrated that horst-graben structures in the Great Basin are surface evidence of right lateral deformation of a plastic substrate, this argument might be extended to the horst graben terrain north of the Lewis and Clark line. In any case there seems to be a piece of relatively uneffected crust between these two lines of northwest shearing, including a large expanse of essentially undeformed basalts and batholithic granite. And of course the thousands of square miles of massive basalts which

dominate the photo must be evidence of crustal extension and fragmentation when large fissures ripped open a thin crust allowing an incredible volume of subcrustal basalt to flood the surface. Possibly, interaction between the North American plate and the East Pacific rise would provide a source for the basalts.

Three megalineaments crisscrossing the Pacific Northwest are visible on the ERTS imagery. (See figure 7.1) The most prominent is a north-south trending line connecting the major volcanic peaks in the Cascade Mountains from northern Washington to northern California. This is a line of Tertiary volcanism 900 km long which sharply divides the landscape. A second lineament can be drawn from Vancouver Island, B.C. to Missoula, Montana, 750 km apart. It is a line of north-northwest trending transverse structures. East of the Cascades it coincides with the Lewis and Clark line which could be drawn all the way to the coast were it not for the discontinuity created by the mountains. The Lewis and Clark line therefore appears to be an older tectonic feature than the Cascade volcanoes.

A third line can be drawn from southeastern Idaho northwest across Oregon up to the Cascades but not across them, a total of 700 km. This lineament is defined by a chain of recent volcanics stretching across central and eastern Oregon becoming younger to the east, and by a giant rift in

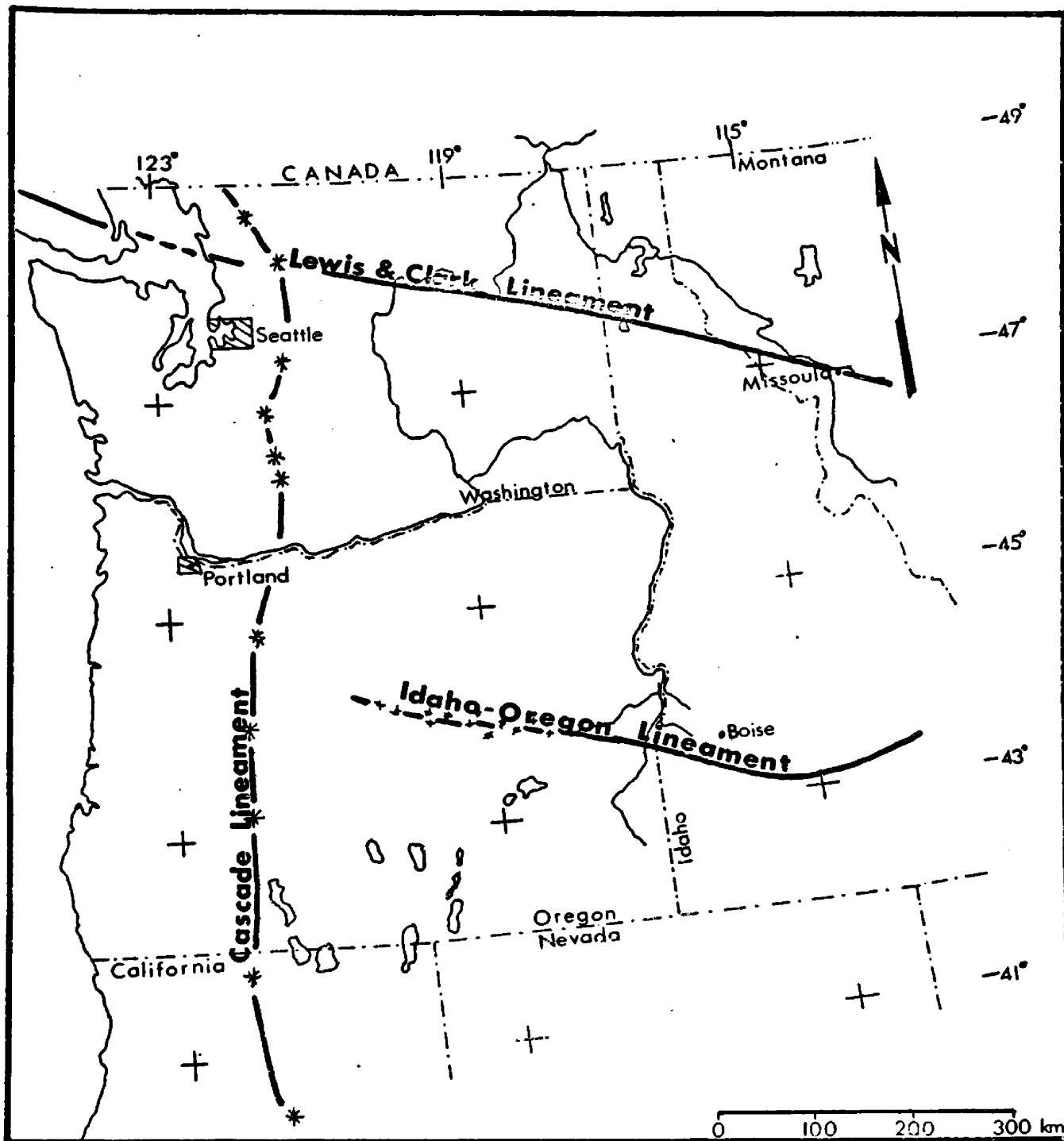


Figure 7.1. Megalineaments as seen from ERTS

the crust - the Snake River plain in southern Idaho. This lineament, the youngest of the three, seems to mark the northern limit of the basin and range province as discussed above.

These three lineaments have divided the region up into several large blocks from Tertiary to recent times and should be critically considered in any tectonic analysis of the western United States.

From the preceding comments, I only wish to conclude that ERTS imagery has one final asset. It provides a dramatic new view of the Earth. Such a large scale panorama can only help jolt the scientific community into radical new channels of thought which eventually will lead to major new discoveries.

BIBLIOGRAPHY

- Anderson, A.L., 1948, Role of the Idaho Batholith during the Laramide orogeny: *Econ. Geol.*, v. 43, p. 84-89.
- Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: *Geol. Soc. America Bull.*, v. 81, p. 351-3536.
- Baldwin, E.M., 1959, *Geology of Oregon*: Edwards Brothers Inc., Ann Arbor, Michigan, 136 p.
- Beaulieu, J.D., 1972, Plate tectonics in Oregon: *Ore Bin*, v. 34, p. 129-143.
- Billingsley P., and Locke, A., 1941, Structure of ore districts in the continental framework: *American Inst. Min. and Met. Eng. Trans.*, v. 144, p. 9-64.
- Calkins, F.C. and MacDonald, D.F., 1909, A geological reconnaissance in northern Idaho and northwestern Montana: *U.S. Geol. Survey Bull.*, v. 384, 112p.
- _____, and Jones, E.L., 1914, Economic geology of the region around Mullen, Idaho and Salt Lake, Montana: *U.S. Geol. Survey Bull.*, v. 540, p. 167-211.
- Campbell, A.B., 1960, Geology and mineral deposits of the St. Regis - Superior area, Mineral Co., Montana: *U.S. Geol. Survey Bull.*, v. 1082-I.
- Clark, S.H.B., 1973, Interpretation of a high-grade Precambrian terrain in northern Idaho: *Geol. Soc. America Bull.*, v. 84, p. 1999-2004.
- Donath, F.A., 1962, Analysis of basin and range structure, south-central Oregon: *Geol. Soc. America Bull.*, v. 73, p. 1-16.
- Fuller, R.E., and Waters, A.C., 1929, The nature and origin of the horst and graben structure of southern Oregon: *Jour. Geol.*, v. 37, p. 204-238.
- Griggs, A.B., 1973, Geologic map of the Spokane Quadrangle, Washington, Idaho, Montana - scale 1: 250,000: *U.S. Geol. Survey Map*, I-768.

Hamilton, Warren and Myers, W.B., 1966, Cenozoic tectonics of the Western United States: Rev. Geophysics, v. 4, p. 509-549.

Harrison, J.E. and Jobin D.A., 1963, Geology of the Clark Fork Quadrangle, Idaho - Montana: U.S. Geol. Survey Bull., 1141-K 38p.

_____, 1972, Precambrian Belt basin of northwestern United States and its geometry, sedimentation and copper occurrences: Geol. Soc. America Bull., v. 83, p. 1215-1240.

_____, Kleinkopf M.D., and Obradovich, J.D., 1972, Tectonic events at the intersection between the Hope fault and the Purcell trench, northern Idaho: U.S. Geol. Survey Prof. Paper 719, 24p.

X _____, Griggs, A.B., and Wells, J.D., 1974, Tectonic features of the Precambrian Belt basin and their influence on past Belt structures: U.S. Geol. Survey Prof. Paper 866, 15 p.

Hobbs, S.W., Griggs, A.B., Wallace, R.E., and Campbell, A.F., 1965, Geology of the Coeur d'Alene district, Shoshone Co., Idaho: U.S. Geol. Survey Prof. Paper 478, 159 p.

King, P.B., 1969, The tectonics of North America - a discussion to accompany the tectonic map of North America, scale 1: 5,000,000: U.S. Geol. Survey Prof. Paper 626, 95 p.

Kleinkopf, M.D., Harrison, J.E. and Zartman, R.E., 1972, Aeromagnetic and geologic map of part of northwestern Montana and northern Idaho: U.S. Geol. Survey Map GP - 830.

McMannis, W.J., 1959, Salient tectonic features of western Montana: Guidebook to field trips, Geol. Soc. America Rocky Mtn. Section, P. 71-75.

X _____, 1965, Resumé of depositional and structural history of western Montana: Am. Assoc. Petroleum Geologists Bull., v. 49, p. 1801-1823.

Melhase, John, 1936, The saline lakes of eastern Oregon: Mineralogist, v. 4, p. 9-10, 26-28.

Moody, J.D. and Hill, M.J., 1956, Wrench-fault tectonics: Geol. Soc. America Bull., v. 67, p. 1207-1246.

- Mudge, M.R., 1970, Origin of the disturbed belt in western Montana: Geol. Soc. America Bull., v. 81, p. 372-392.
- Pardee, J.T., 1950, Late Cenozoic block faulting in western Montana: Geol. Soc. America Bull., v. 61, p. 359-406.
- Pease, R.W., 1969, Normal faulting and lateral shear in northeastern California: Geol. Soc. America Bull., v. 80, p. 715-720.
- Raisz, E., 1945, The Olympic - Wallowa lineament: Am. Jour. Sci., v. 243 - A, p. 479-485.
- Russell, I.C., 1884, A geological reconnaissance in southern Oregon: U.S. Geol. Survey 4th Ann. Report, p. 435-464.
- _____, 1903, Notes on the geology of southwestern Idaho and southeastern Oregon: U.S. Geol. Survey Bull., v. 217, 83 p.
- Short, N.M. and Lowman, P.D., 1973, Earth observation from space: Outlook for the geological sciences: Goddard Space Flight Center, Greenbelt Md., 115 p.
- x Smedes, H.W., 1958, Interpretation of geologic structure of western Montana and northern Idaho (abst): Geol. Soc. America Bull., v. 69, p. 1745.
- Smith, J.G., 1965, Fundamental transcurrent faulting in northern Rocky Mountains: Am. Assoc. Petroleum Geologists Bull., v. 49, pp. 1398-1409.
- x Smith, R.B. and Sbar, M.L., 1974, Contemporary tectonics and seismicity of the western United States with emphasis on the intermountain seismic belt: Geol. Soc. America Bull., v. 85, p. 1205-1218.
- Smith, W.D., Contributions to the geology of southeastern Oregon, Steens and Pueblo Mountains: Jour. Geol., v. 35, p. 421-440.
- x Stewart, J.H., 1971, Basin and range structure - a system of horsts and grabens produced by deep seated extension: Geol. Soc. America Bull., v. 82, p. 1019-1043.
- x _____, 1972, Initial deposits in the Cordilleran geosyncline - Evidence of a late Precambrian (<850 my) continental separation: Geol. Soc. America Bull., v. 83, p. 1345-1360.

- ✓ Talbot, J.L. and Hyndman, D.W., 1973, Relationship of the Idaho batholith structures to Montana lineament: Northwest Geol., v. 2, p. 48-52.
- Umpleby, J.B., 1924, The Osburn fault, Idaho: Jour. Geol., v. 32, p. 601-614.
- ✗ Walker, G.W., 1973, Tectonism and silicic volcanism of eastern Oregon (abst): In Cordilleran Sect., 69th Ann. Meeting Geol. Soc. America Abst., v. 5, p. 119.
- _____, et al, 1973, Preliminary geologic and tectonic maps of Oregon east of the 121st meridian: U.S. Geol. Survey Map MF - 495.
- Wallace, R.F., Griggs, A.B., Campbell, A.B., and Hobbs, S.W., 1960, Tectonic setting of the Coeur d'Alene District, Idaho: U.S. Geol. Survey Prof. Paper 400-B, p. 25-27.
- Weidman, R.M., 1965, The Montana lineament: Billings Geol. Soc., 16th Ann. Field Conf., Billings Mont., 1965 Guidebook, p. 137-143.
- _____, Alt, D.D. et al, 1973, Applicability of ERTS-1 to lineament and photogeologic mapping in Montana - a preliminary report: NASA SP-327, v. 1, p. 539-543.
- _____, _____, et al, 1974, Applicability of ERTS-1 to Montana Geology: Final report to NASA
- Williams, H., 1962, The ancient volcanoes of Oregon: Univ. Oregon Press, Eugene, Oregon, 68 p.
- ✓ Wise, D.U., 1963, An outrageous hypothesis for the tectonic pattern of the north American Cordillera: Geol. Soc. America Bull., v. 74, p. 357-362.
- Yates, R.G., 1973, Significance of the Kootenay arc in Cordilleran tectonics, (abst): Geol. Soc. America Abs. with Programs, v. 5, p. 125.

