PRECAMBRIAN GEOLOGY AND ORE DEPOSITS NEAR POLAND JUNCTION, YAVAPAI COUNTY, ARIZONA

by

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ABSTRACT

The area of Poland Junction, Yavapai County, Arizona, consists of a series of tholeiitic mafic-to-felsic metavolcanic, metapyroclastic, and metasedimentary rocks. Contained within the layered sequence are syngenetic massive sulfide bodies. The sulfide bodies include both volcanogenic bodies in environments proximal to volcanic centers and volcanic exhalative deposits in environments distal to volcanic centers. All rocks were subjected to at least one period of intense deformation resulting in isoclinal folding, transposition of original bedding, and development of penetrative axial plane foliation with contemporaneous regional metamorphism to greenschist grade. During Laramide time, a granodiorite intrusion imparted a hornfelsic texture to the adjacent rocks. Laramide mineralization is also present in the form of vein and fracture-filling deposits.

The original site of deposition of the Proterozoic volcanics is believed to be a volcanic proto-island arc because of the tholeiitic chemistries and the abundance of mafic and felsic rocks. Mapping has further disclosed a close relationship between volcanogenic massive sulfide deposits and rhyolites. The Lone Pine, Boggs, Iron Queen, and Upshot mines all occur at approximately the same stratigraphic horizon. At least two other rhyolite horizons are

also mineralized but exact stratigraphic relationships between the various felsic horizons could not be determined due to complex folding and lensoidal nature of the original units.

INTRODUCTION

The relatively recent recognition of the volcanogenic, syngenetic origin of widespread but, as far as is known to date, small massive sulfide bodies in the Precambrian rocks southeast of Prescott, Arizona, suggested that an understanding of the volcanic stratigraphy of these rocks might help to guide future exploration. An excellent example of the application of this idea can be found in the work of Spence and de Rosen-Spence (1975) in the Noranda District in Quebec, Canada. The Noranda District occurs in the Abitibi Greenstone Belt, a thick pile of Archean metavolcanic rocks. Spence and de Rosen-Spence mapped five distinct rhyolitic zones representing five successive cycles of andesite to rhyolite volcanism. Volcanogenic massive sulfide ore bodies in the Noranda district were found to occur almost exclusively at the time-stratigraphic horizons marking the ends of the third and fourth volcanic cycles. These two horizons thus become the most favorable areas for exploration for future deposits.

Purpose

The goal of the present study southeast of Prescott, Arizona, was to determine the stratigraphic position of massive sulfide deposits within the volcanic and sedimentary sequence. Recognition of the fact that the orebodies may have occurred at a restricted number of favorable horizons would greatly increase the efficiency of future exploration work to find similar deposits.

Modern work in the Arizona Proterozoic utilizing recent tectonic and petrochemical ideas is in a fledgling state, although recent work (P. Anderson and Guilbert, 1978) has defined several metavolcanic belts in the central and western parts of the state, some of which are known to contain massive sulfide deposits. The present study involves only a small part of one of these belts. Because of the restricted area of study in relation to the entire belt, the complex state of deformation found, and difficulty in distinguishing primary lithologic features, it was not possible positively to define projectable favorably mineralized horizons. A close relationship between rhyolites and volcanogenic massive sulfide deposits was found with at least two and possibly more rhyolite horizons mineralized. Both proximal and distal deposits were found, an indication of the complexity and variability of environments in a volcanic belt of this nature.

The petrography, petrology, geochemistry, and structure of the rocks will be described, followed by a description and discussion of the economic geology. A discussion and interpretation will then attempt to integrate all aspects of the area geology.

Methods

Regional geologic mapping, at 1 inch = 500 feet, was done on an enlarged topographic map base, greatly assisted by color aerial photography supplied by American Selco, Inc. One hundred and two thin sections were examined to determine basic petrology and metamorphic grade, and 25 major and selected trace-element whole rock analyses were done in hopes both of being able to trace selected horizons along strike and to see if igneous differentiation patterns could be detected in the area.

Location

The study area (Fig. 1) is located in north central Arizona about 21 km southeast of Prescott and about 117 km north-northwest of Phoenix. The area is centered about the now-abandoned railroad stop of Poland Junction and comprises about 20 km^2. The area is located primarily in the Poland Junction 7 1/2 minute quadrangle, but parts extend to the Mayer and Prescott Valley South 7 1/2 minute quadrangles.

Access is generally good with State Highway 69 running conveniently through the area. Rough but usually passable mine and ranch roads provide further access. The area enjoys a high elevation, and semi-desert climate and vegetation. Terrain is moderately rugged with hills separated by dry washes and intermittent streams. The area is

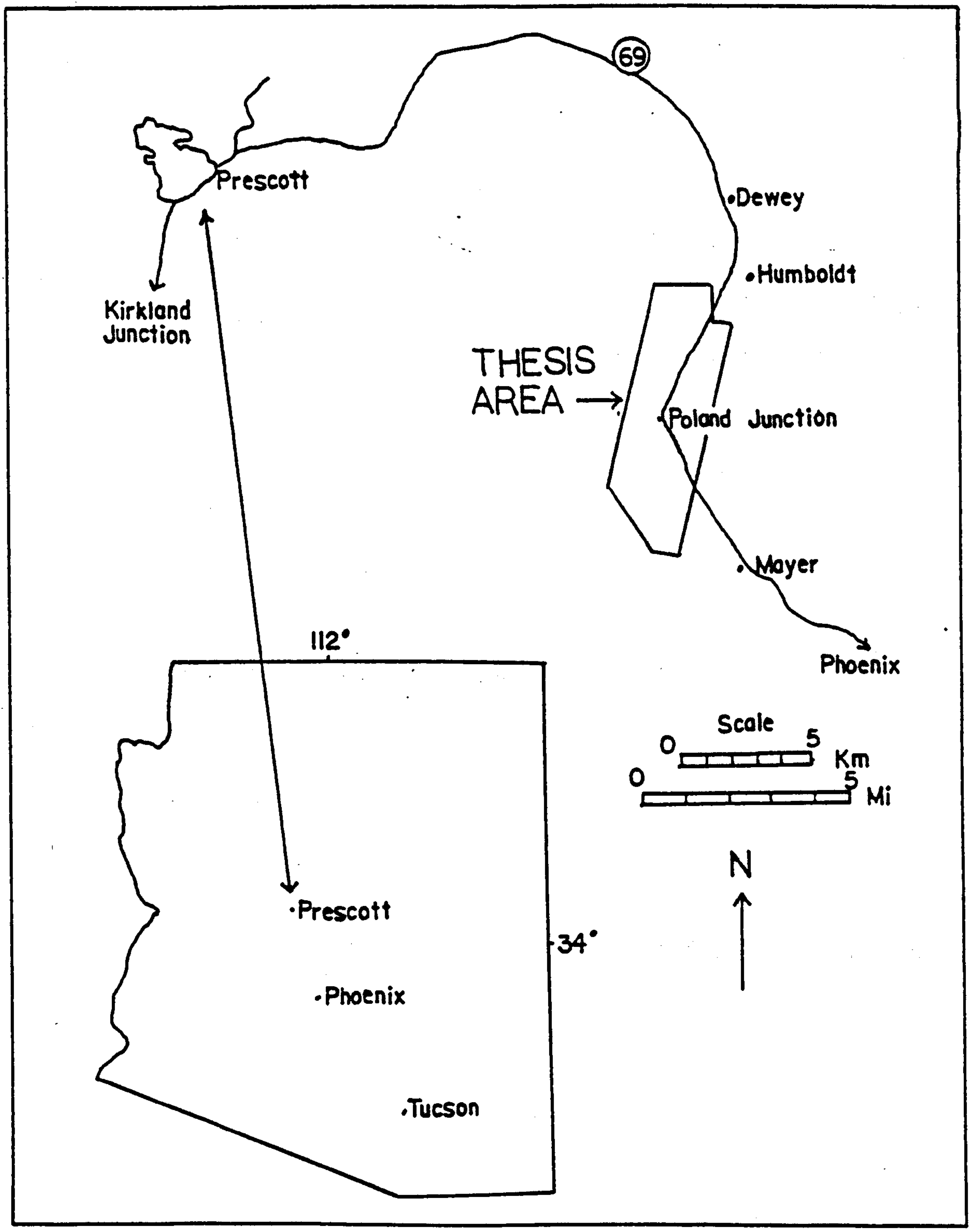

Figure 1. Location map, Poland Junction area, Yavapai County, Arizona

located in the extreme northeast corner of the Bradshaw Mountains. Vegetation is primarily scrub oak, grasses, and cactus.

Previous Work

Jaggar and Palache (1905) performed the earliest reconnaissance work in the area. Lindgren (1926) studied the numerous mines of the Bradshaws and the Jerome area. C. A. Anderson (1968), C. A. Anderson and Creasey (1958), and C. A. Anderson and Blacet (1972a, b, c) covered an extremely large and complex area in a very thorough manner, although some of their conclusions are now open to reinterpretation. Gilmour and Still (1968) published a pioneering paper establishing the syngenetic origin of the Iron King Mine, which caused previous workers to reexamine similar bodies elsewhere in Arizona (C. A. Anderson and Nash, 1972). Important age dating was reported in C. A. Anderson et al. (1971). Sturdevant (1975) studied the Laramide Big Bug pluton, which intrudes this study area. Recent studies outside this area, but in similar terrain, by Brook (1974) and DeWitt (1976) suggested this study. An overview of the ore deposits of this area, and their stratigraphic positions and occurrence characteristics, establishes these Proterozoic rocks and ores as a metallogenic unit (P. Anderson and Guilbert, 1979).

PETROGRAPHY AND PETROLOGY

The standard U. S. Geological Survey formational nomenclature established for this area by C. A. Anderson et al. (1971) will not be followed in this study because this author believes that this nomenclature artificially separates the rocks into formational units that are not distinctly different from adjacent units. One exception is that the term "Texas Gulch Formation" will be retained because this unit has been shown to be younger than the surrounding volcanics and to be a distinctly mappable unit. The other rocks in the area were mapped on a lithological basis. The prefix "meta" will not be used in describing the rocks because in most areas enough relict textures are preserved to permit determination of the original rock type. It must be remembered, however, that the rocks are now dominantly phyllites, have undergone regional metamorphism to greenschist grade, and are locally severely deformed. Therefore, some interpretations are uncertain, although overall conclusions are not compromised.

The Precambrian volcanic rocks of the Prescott area have been dated by C. A. Anderson et al. (1971) at 1770 ± 10 m.y. and are thus Proterozoic. Intrusive rocks south of the thesis area that intrude the volcanics have also yielded ages of 1770 m.y.

No attempt will be made to describe the granodiorite body exposed in the west-central part of the study area (Figs. 2 and 3, in pocket) because this body has been dated at 70 m.y. (C. A. Anderson and Blacet, 1972c) and has been described by Sturdevant (1975).

Proterozoic Rocks

Mafic and Intermediate Rocks

Mafic and intermediate flows and pyroclastic units make up about 60 percent, by area of outcrop, of the rocks in the study area (Figs. 2, 3 and 4, in pocket). Basalts predominate, with minor andesites and dacites identified. Petrochemistry will be described in a later section. In outcrop, the rocks range in color from greenish black to light greenish brown or yellow. Outcrops may be very massive with poorly defined foliation, or they may exhibit intensively developed foliation with few relict primary textures, a difference in part a function of the original depositional texture of the rock. Massive, thick-bedded flows and tuff-breccia units now form massive, poorly foliated units while originally thin-bedded, fine-grained tuffs now form easily weathered, highly foliated units.

The units are dominantly pyroclastic, with fragment size ranging from tuff-breccia with one-meter-diameter blocks (Fig. 5) down to fine tuffs. Flows are subordinate in the area, but that they do occur is evidenced by the

Figure 5. Mafic tuff-breccia with rhyolitic and andesitic clasts. -- These tuff-breccias probably formed on the flank of submarine volcanoes. The location is sec. 8, T. 12 N., creek bed about 500 meters south of the Butternut mine.

presence of vesicular zones, flow breccias, and possible poorly formed pillows (Fig. 6). Flows are difficult to trace along strike, however, as are all units, due to original lateral variability and the highly foliated nature of the area.

Microscopically, the mafic to intermediate rocks are seen to consist chiefly of albite, actinolite, chlorite, clinozoisite, and epidote, with lesser amounts of quartz and calcite. Textures are commonly lepidoblastic with albite and quartz forming a granoblastic groundmass (Fig. 7).

Plagioclase is a major component of the mafic rocks and has two main habits. Untwinned albite, along with lesser amounts of quartz, clinozoisite, and calcite, occurs as a granoblastic groundmass in most of the tuffaceous and flow rocks. Because of the untwinned and very fine grained nature of this plagioclase, exact compositions are hard to determine. Variously altered relict plagioclase phenocrysts or crystal fragments, ranging in size from less than 1 mm to 8 mm, are also common in the mafic rocks. Unaltered fragments give compositions, by the Michel-Lévy method, from An_{10} to An_{54}, with most in the An_{40-50} range. A complete gradation in degree of alteration was observed, from fresh crystals to ones completely altered to clinozoisite-albite-calcite.

The possibility exists that some of the unaltered twinned plagioclase crystals may not be relict phenocrysts

Figure 6. Pillow lava. -- The lensoid mass on which the hammer rests is a possible pillow in a mafic flow. The location is the railroad cut, sec. 16, T. 12 N., about 230 meters northeast of the Hackberry mine.

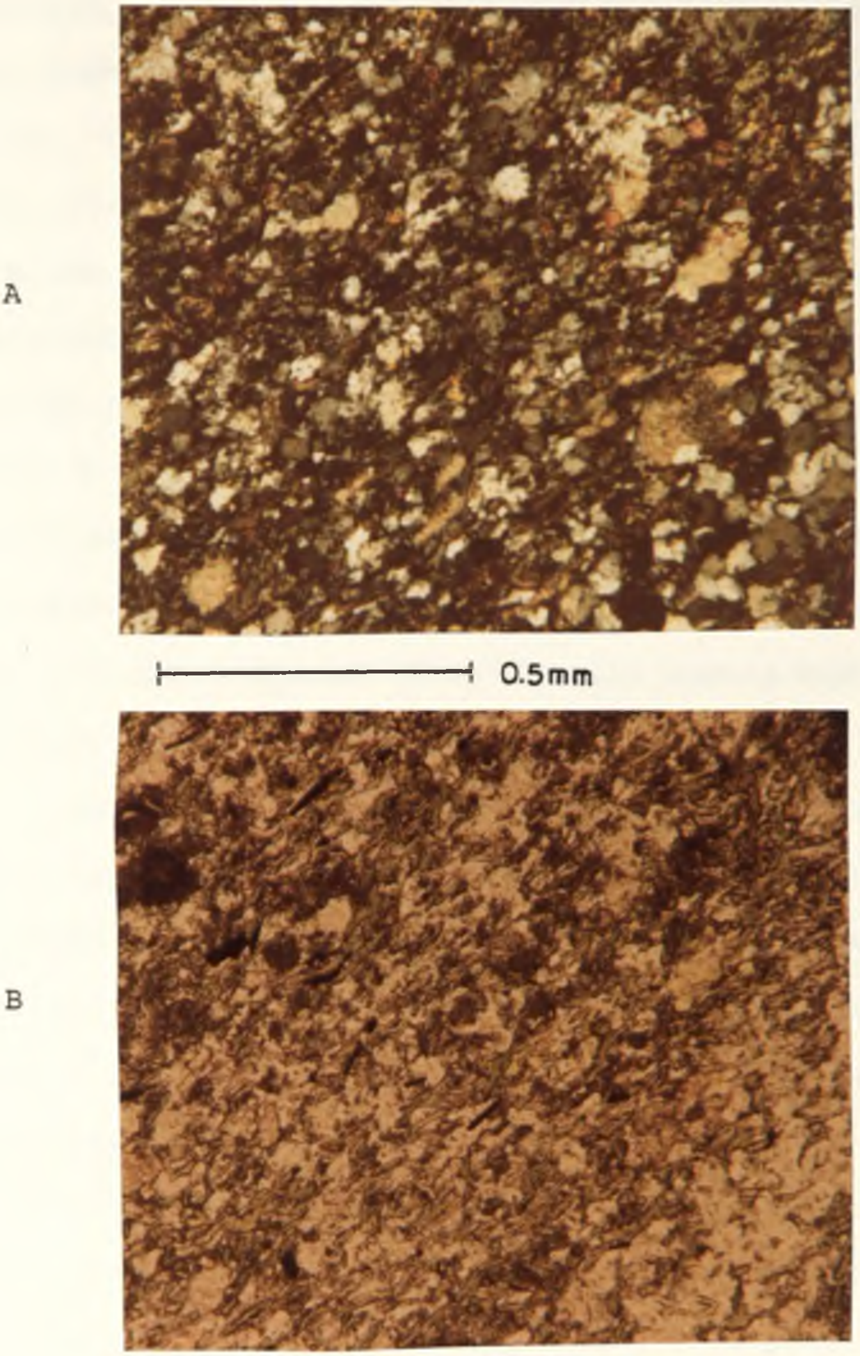

Figure 7. Photomicrographs of foliated basalt.

A. Crossed nicols. The sample is dominantly plagioclase (yellowish white), actinolite (green, prismatic), calcite, chlorite.

B. Plane light. Same sample. Note prisms of actinolite. The black opaque mineral is ilmenite. Thin-section number 167 from north of the Carbine prospect.

or crystal fragments, but rather are metamorphic porphyroblasts formed at the expense of albite, clinozoisite, and calcite. Winkler (1976) mentions that at lower greenschist grade, calcic plagioclase is unstable, breaking down to form albite and clinozoisite. But if uppermost greenschist temperatures are approached, calcic plagioclase may be restabilized and appear again. This recrystallization would explain the very fresh, unaltered appearance of some of the plagioclase porphyroblasts. The reappearance of calcic plagioclase is also a metamorphic grade indicator which suggests that the rocks at least locally approached upper greenschist grade.

Several mafic minerals characterize these units. Actinolite is common in the rocks. It occurs as small, idioblastic needles and prisms with long axes parallel to foliation. Because of this oriented habit, it is interpreted as a metamorphic mineral formed at the expense of preexisting pyroxenes. Actinolite is blue-green in color and pleochroic. Chlorite is a major constituent of the mafic rocks. It is pleochroic from dark green to yellowish green or colorless and commonly shows a purplish interference color, although lesser quantities show a blue interference color. It occurs as tiny flakes, which may be disseminated through the groundmass, or may form larger wispy concentrations usually aligned parallel to foliation. This parallel alignment defines the foliation in most of the rocks of the area. Epidote and clinozoisite are major components of the rocks. Clinozoisite occurs dominantly as very tiny grains within altered plagioclase crystals. Less commonly, it occurs as wispy clots parallel to foliation. Epidote occurs either as tiny granoblastic grains scattered through the groundmass or as concentrations of grains rimming relict plagioclase crystals.

Quartz is among the common but usually minor constituents of the mafic rocks. It commonly occurs with albite in a granoblastic groundmass texture. Rarely, clusters of tiny quartz grains occur that give the appearance of quartz phenocrysts or crystal fragments. Calcite is present from a trace up to 15 percent in some rocks. It occurs as tiny disseminated grains, clusters of grains around relict feldspars, and as microveinlets cutting the rocks. Sericite is present up to 20 percent in some of the rocks that evidently were more dacitic in composition. It occurs as tiny flakes disseminated through the rock or as concentrations parallel to foliation. Minor accessory minerals are magnetite, leucoxene, rutile, sphene, and stilpnomelane.

Felsic Rocks

Felsic pyroclastic units occur throughout the area of study and make up about 20 percent of outcrop area of the rocks. They range in fragment size from medium-grained crystal tuffs with 5-mm quartz crystals down to fine-grained tuffs which further grade into tuffaceous sediments. Only one questionable flow unit was found in the area, and its considerable lateral extent suggests that it may instead be a shallow, subvolcanic sill. This unit is very important in the structural interpretation and will be discussed at length later in this paper.

The felsic rocks are light gray to creamy white in outcrop and vary from essentially nonfoliated to strongly foliated, a variation, as in the mafic rocks, interpreted as a function of the original rock texture. Massive-bedded, coarsely crystalline, crystal-lithic tuffs show weak foliation development. Originally thin-bedded, fine-grained tuffs show strongly developed foliation. The color contrast between the felsic and mafic units is a great aid in following units in the field, and for massive units this color contrast shows up well on aerial photographs. The more massive felsic units, in addition, tend to form prominent ridges.

Microscopically, felsic rocks are made up dominantly of quartz, sericite, and feldspar (Fig. 8). Quartz has two habits in the rocks. It occurs as porphyroblasts interpreted as relict crystal fragments in a crystal tuff, which range in size from 1 to 5 mm and are anhedral to subhedral. Most show resorption features on their rims. Quartz fragments commonly show undulatory extinction and about 25

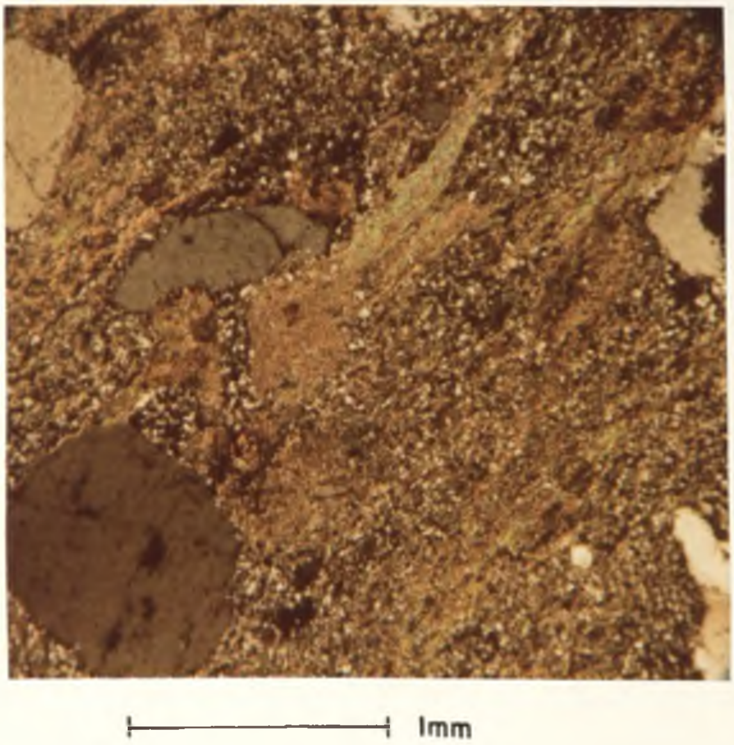

Figure 8. Photomicrograph of rhyolitic crystal tuff.

The quartz crystal fragments are in a fine-grained matrix of quartz, sericite, plagioclase, chlorite, calcite, and epidote. Crossed nicols. Thin section number 216 from the east central part of sec. 33, T. 13 N.

percent have been reduced to clots of granoblastic quartz grains. Quartz also occurs in fine-grained granoblastic groundmass material intermixed with albite and sericite. Feldspar occurs in the same two habits as quartz. About half of the units contain albite porphyroblasts, but they are always subordinate in number to quartz and are euhedral to subhedral and twinned. Albite also occurs, in the groundmass, subordinate in amount to quartz, but exact proportions are hard to determine because of very small grain size.

Potassium feldspar was observed in the matrix but only in subordinate amounts. Presumably much of it has altered to sericite. Sericite is a major component in the felsic rocks and occurs either as tiny flakes scattered through the groundmass or as larger wispy ribbons oriented parallel to foliation. In the felsic rocks, the oriented sericite is the primary cause of foliation. It is present in widely variable amounts from 10 to 50 percent, evidently depending on the original presence of potassium feldspar or potassium-bearing clays in the very fine grained tuffaceous felsic rocks.

Minor amounts of chlorite and epidote occur in the felsic rocks in habits similar to those in the mafic rocks. Magnetite is present in some of the rhyolites as a trace mineral, but in at least one specimen it constitutes 5 percent by volume. Sphene and leucoxene are present as traces.

Tuffaceous Sedimentary Rocks

The identity of these rocks is based primarily on field occurrence and appearance. Sediments are various shades of brown or gray in outcrop or on a fresh surface and are all fine grained and well foliated. When first encountered in the field, they were mapped as dacitic tuffs because their brown color suggested a composition intermediate between the green andesites and creamy-white rhyolites. They are typically fine grained; therefore, mineralogical determinations in the field were difficult. In thin section, they were found to be a mixture of rhyolitic and andesitic detritus, and thus they are better termed "tuffaceous sediments." They are gradational into the fine-grained andesitic and rhyolitic tuffs. In outcrop, they also commonly show a higher sheen than other units, suggesting a higher chlorite and sericite content, probably derived from original clay minerals, further suggesting a sedimentary origin. Because of their fine-grained and highly foliated nature, these units typically form poor outcrops in covered areas of valleys and slopes of ridges. They are widely interbedded with the mafic and felsic units in addition to being the predominant rock type in some areas. They occupy about 20 percent by area of outcrop of the thesis area.

With the microscope, they are seen to consist of the same minerals as the mafic and felsic rocks (Fig. 9),

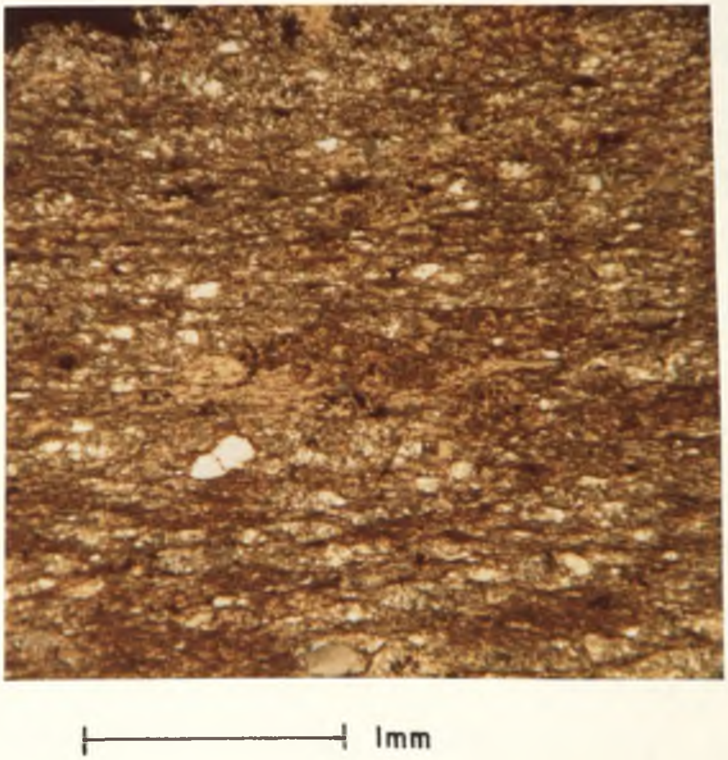

Figure 9. Photomicrograph of tuffaceous sedimentary rock. -- Small fragments of quartz and feldspar, actinolite, and sericite. Note graded bedding from bottom to top of photograph. Crossed nicols. Thin section number 123 from the northwest corner of sec. 34, T. 13 T.

only in proportion varying according to whether a local basin of deposition was receiving dominantly felsic or mafic detritus. The most common characteristic under the microscope is a fine grain size with a well-developed foliation defined by chlorite, actinolite, and sericite. Since these rocks contain the same minerals as the previously described mafic and felsic rocks in the same habit, no detailed description of the minerals will be given. The rocks are texturally uniform, suggesting that they are well sorted texturally although not mineralogically.

Texas Gulch Formation

The Texas Gulch Formation is the only established formational unit used in this study. It was named by C. A. Anderson and Creasey (1958) and later used by Blacet (1968) and C. A. Anderson and Blacet (1972a, b, c). In the area of study, it occurs as a thin sliver between volcanic units, widening to the south. In outcrop, the rocks are highly foliated slates and phyllites, purple to gray to creamy white in color. They have a high, silvery sheen suggesting a high clay mineral or mica content.

Under the microscope, the dominant minerals are quartz and sericite (Fig. 10). Quartz is fine grained with occasional coarser-grained (1 mm) crystals. Sericite is scattered through the groundmass as tiny flakes and also as ribbony plates oriented parallel to foliation. Chlorite

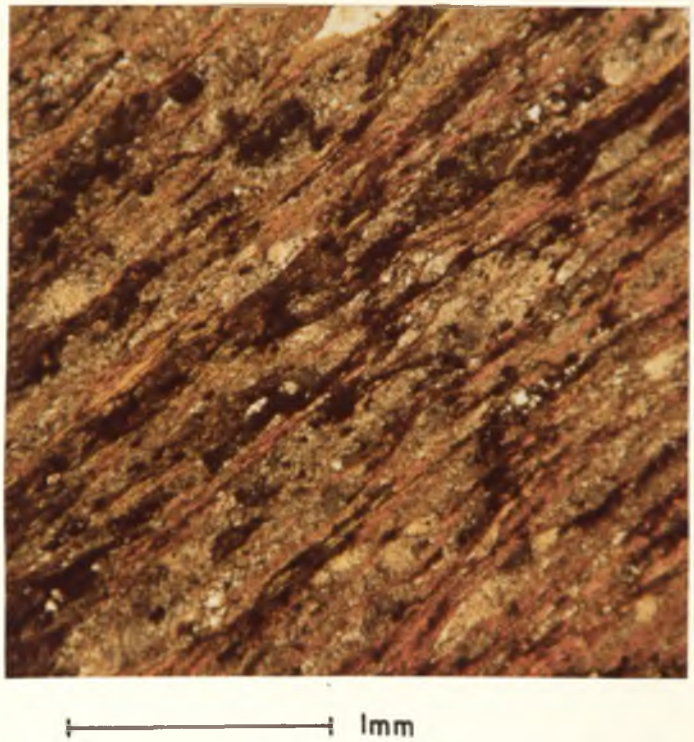

Figure 10. Photomicrograph of highly foliated Texas Gulch Formation rock. -- Sample is dominantly quartz and sericite with lesser amounts of chlorite and limonite. Note larger percentage of sericite as compared with sample 123 in Figure 9 indicating a more felsic provenance for the Texas Gulch Formation. Crossed nicols. Thin section number 111 from the northwest quarter of sec. 33, T. 13 N.

and magnetite are common accessory minerals. Specular hematite flakes are common accessories in the more purple phases of the unit. Several conglomerate beds occur within the unit. Chert, jasper, and a fine- to medium-grained leucocratic plutonic rock make up most of the pebbles which range from one centimeter up to about four centimeters in length. They commonly have a stretched appearance with the longest dimension parallel to regional foliation. This elongation of pebbles will be discussed more fully in the structure section of this thesis. The Texas Gulch Formation differs from the previously described tuffaceous sedimentary rocks in having more quartz and sericite. It apparently was derived from a dominantly felsic to intermediate provenance.

Ferruginous Cherts

A ferruginous siliceous rock is found throughout the area, but it is primarily concentrated in areas and sections of felsic volcanic or sedimentary rocks. In outcrop, it is reddish or purplish in color and is essentially nonfoliated but jointed (Fig. 11). The rocks occur as discontinuous pods varying in size from one meter to several hundred meters long and from one centimeter to several meters thick. The long axis is always subparallel to regional foliation. Pods are concentrated along

Figure 11. Outcrop of ferruginous chert. --Photograph shows typical prominent lensoidal occurrence of ferruginous chert. Outcrop, approximately 1 meter high by 1 meter wide, is in the northeast quarter of sec. 33, T. 13 N.

preferential horizons, although isolated pods can be found anywhere in the section.

In thin section, these rocks are seen to consist of quartz and specularite (Fig. 12). The specularite may range from 1 to 30 percent by volume. The quartz occurs as a fine-grained granoblastic mosaic with the specularite flakes either disseminated in the groundmass or concentrated in bands subparallel to regional foliation. The quartz does not show a detrital texture, even allowing for recrystallization due to metamorphism. The fine-grained quartz suggests, considering the widespread yet apparent stratigraphic positioning, that the rock was a chemical sediment, probably having been a ferruginous chert. Such ferruginous chemical sediments are a common constituent of volcanic terrains elsewhere in the world, such as the Canadian Shield (Goodwin, 1973), the Great Lakes in the United States (James, 1954), and Precambrian shields in Brazil, India, Australia, and Scandinavia (Stanton, 1972).

Quartz Veins

Present throughout the area are white quartz veins or pods. These veins are usually small, from 1 to 5 meters long and less than 0.5 meter thick, and are usually subparallel to regional foliation. They can occur in any rock type in the area. The veins are predominantly quartz with no feldspar. At several places the quartz carries very

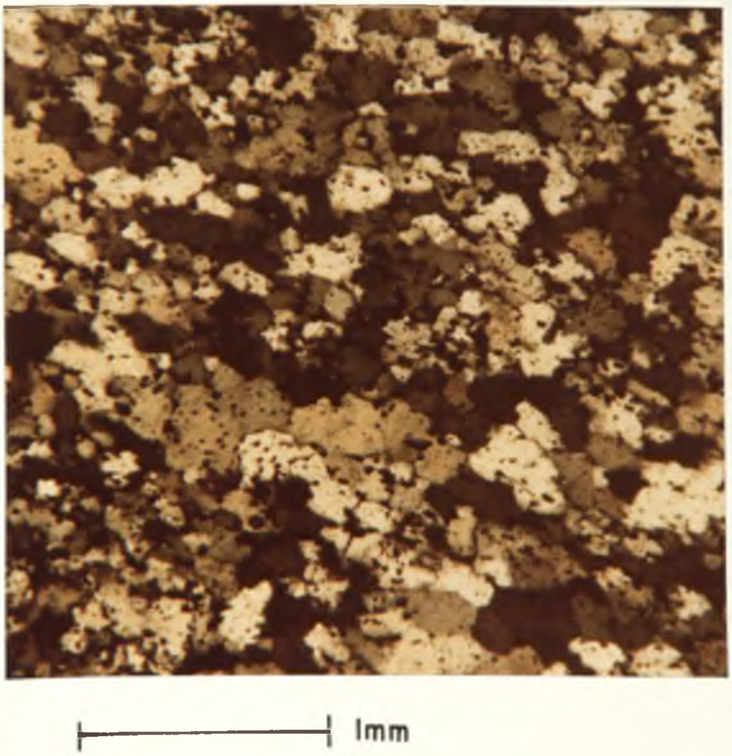

Figure 12. Photomicrograph of recrystallized ferruginous chert. -- Sample is primarily quartz with a lesser amount of specular hematite (black specks). Crossed nicols. Thin section number 230 from north of the Carbine prospect.

minor pyrite and chalcopyrite. For this reason, every quartz vein or pod in the area has a prospect pit on it. Early prospectors in the area evidently attributed the veins to hydrothermal activity.

Phanerozoic Rocks

Hornfels

If one walks along the strike of any rock unit, except the massive felsic units, toward the 70-million-year-old, Laramide-age pluton exposed in Big Bug Creek (Fig. 3), one sees a definite change in the physical character of the rocks. The units become finer grained and darker. The foliation becomes less pronounced until in some areas it is destroyed entirely, leaving a blocky, jointed rock. Since rocks with these characteristics are found only around the Laramide intrusion and its smaller apophyses, this physical change is interpreted as a thermal effect due to contact metamorphism. Since it is clearly a Laramide overprinting on Precambrian rocks, no detailed studies of it were undertaken. Under the microscope, the rocks can be seen to consist of the same minerals as rocks along strike farther from the pluton. The minerals are typically finer grained, however. The only units that do not respond to this contact metamorphism are massive felsic units and ferruginous cherts, probably because their quartz-rich mineralogy was stable at the elevated temperatures and because they never developed a pervasive foliation during regional deformation. It is this pervasive foliation that the contact metamorphism has destroyed in all the other rock units.

Intrusive Rocks

The granodiorite body exposed in Big Bug Creek (Fig. 3) will not be described in this study, the reader being referred to a dissertation by Sturdevant (1975) on this body.

Two other types of Phanerozoic intrusive rocks occur in the thesis area. Several tan to creamy-white felsic dikes, 1 to 6 meters thick, intrude the Precambrian rocks parallel to regional foliation. These dikes, unfoliated and considered by all previous workers to be post-Precambrian, were best described by C. A. Anderson and Blacet (1972c). Several black diabase dikes, 0.5 to 1 meter wide, were also found within the thesis area. They trend at right angles to regional foliation and are unfoliated and appear very fresh. They are considered to be post-Precambrian in age. They were possibly feeders for basalt flows in the Hickey Formation, which caps mesas outside the thesis area, considered to be late Miocene to early Pliocene in age (C. A. Anderson and Blacet, 1972c).

Metamorphic Rank

The mineralogy of the Precambrian rocks of this area, namely albite, chlorite, actinolite, epidote, and clinozoisite, is considered to be the classic assemblage of greenschist-grade metamorphism (Winkler, 1976; Turner and Verhoogen, 1960). Most of the albite, particularly in the mafic rocks, is probably metamorphic, formed in part by the breakdown of calcic plagioclase. Calcic plagioclase present is dominantly a relict igneous mineral in the form of partially altered phenocrysts or crystal fragments in flows and tuffs. However, the presence of very fresh appearing, twinned, unaltered oligoclase and andesine (An_{10}-An_{54}) in some samples suggests that at least some of the plagioclase may be metamorphic, formed at the expense of albite, epidote, and calcite. There is debate in the literature as to the use of the reaction from albite to oligoclase (An_{18}) as the upper limit of greenschist metamorphism. Turner and Verhoogen (1960) proposed it, while Winkler (1976) considers the temperature of the reaction to be too low to be diagnostic.

Actinolite is a metamorphic mineral in these rocks, formed at the expense of earlier pyroxenes. The oriented habit of actinolite and other prismatic and platy minerals suggests that metamorphism and deformation took place at approximately the same time. Chlorite is present as a metamorphic mineral, some formed at the expense of earlier mafics and some formed from iron- and magnesium-rich clays in the sedimentary rocks. Epidote and clinozoisite were formed from the breakdown of preexisting mafics and calcic plagioclase. Winkler (1976) considers clinozoisite as a mineral diagnostic of greenschist grade. Actinolite, chlorite, and epidote may all be present at lower grades, but the formation of clinozoisite is diagnostic of greenschist metamorphism.

Quartz is present dominantly as a relict igneous and chemical sedimentary mineral except for some quartz veins and pods, which may be metamorphic remobilizations of preexisting quartz. Sericite present was formed by the breakdown of preexisting potassium feldspars and from potassium-rich clays in sediments. Calcite was formed from both the breakdown of calcic plagioclase and from carbonate beds in sediments.

The lack of hornblende, garnet, staurolite, sillimanite, and biotite show that the rocks of this area have not progressed to amphibolite grade metamorphism and, as mentioned previously, the presence of clinozoisite shows them to be above very low grade. They fall within the classic greenschist or low-grade zone of Winkler (1976). Temperature limits of about 350°C to 500°C are put on this zone; Winkler did not place pressure limits on it, but Turner and Verhoogen (1960) suggested P_{H_2O} = 3 to 8 kilobars.

Observations in greenstone belts elsewhere in the world and studies of submarine weathering and metamorphism have provided new ideas and information on regional greenschist metamorphism. Studies in the Precambrian rocks of the Canadian Shield (Thurston and Breaks, 1978; Jolly, 1978; Nielsen, 1978) tended to use the Winkler (1976) transition from prehnite-pumpellyite to zoisite-clinozoisite to mark the lower limit of greenschist grade; they use the change from blue-green actinolitic amphiboles to brown amphiboles, the change from sodic to calcic plagioclase, and the disappearance of chlorite and appearance of biotite to mark the upper limit of greenschist grade in mafic metavolcanic rocks. Nielsen (1978) suggested temperatures less than 400°C and pressures around 2 kilobars for greenschist-grade zones. Windley (1977), discussing the Dharwar Greenstone Belt in India, suggested 300-350°C and 3 kilobars pressure for greenschist facies. Low pressures and temperatures to produce greenschist facies rocks are further supported by the presence of typical greenschist mineralogies in ocean-floor basalts near rift zones (Humphris and Thompson, 1978). Geothermal systems in these rift zones elevate temperatures to several hundred degrees centigrade, but pressures do not get above 2 kilobars, showing that greenschist-grade metamorphism is primarily a thermal event.

GEOCHEMISTRY

Twenty whole-rock analyses were done on rocks from the thesis area both to discern differentiation trends and to better classify the rocks. Samples were taken wherever possible in creek beds to obtain the least-weathered, and hopefully least-altered, rocks. The samples were analyzed by X-Ray Assay Laboratories, Toronto, Ontario, using X-ray fluorescence. No duplicate samples were submitted because of cost limitations. Table 1 gives the results of the analyses. Twelve additional analyses from this area have been reported by C. A. Anderson and Blacet (1972c) and Sturdevant (1975). These are shown in Tables 2 and 3. Figures 13 through 18 show the general similarity of the samples for various oxides from the three studies. Gelinas et al. (1977) suggested discarding any sample which has greater than 3.8% volatiles as probably being altered. Using this criterion samples 167 (3.85%), 209 (4.08%), 225 (7.00%), and 228 (4.38%) from Table 1, samples 7-5 (7.79%) and 6-8 (4.8%) from Table 2, and sample 374 (5.23%) from Table 3 should be discarded. This writer has elected not to completely discard the samples, but rather to plot them with the others on the various diagrams to follow and to bear in mind that the samples may be altered.

Table 1. Whole-rock chemical analyses. -- Done by X-Ray Assay Laboratories for the Poland Junction area.

Oxide Wt. %	Sample number 135	167	177	191	193	197	209	212	214	215
SiO_2	45.1	50.6	66.1	68.4	80.5	73.1	47.5	70.0	75.2	69.0
Al_2O_3	14.9	16.8	15.4	10.4	8.69	12.2	14.8	13.2	11.2	20.5
CaO	10.8	8.56	2.13	0.12	0.10	0.45	2.22	0.08	0.92	0.10
MgO	8.35	4.42	0.94	4.69	0.30	0.18	6.30	1.45	0.36	0.00
Na_2O	1.84	1.49	5.85	0.28	0.64	4.91	2.41	0.02	1.84	0.00
K_2O	0.10	0.11	0.84	0.90	1.53	0.87	0.13	3.36	1.75	0.21
FeO[a]	11.9	11.0	4.17	8.76	3.29	4.29	16.7	3.31	4.66	3.05
MnO	0.25	0.34	0.19	0.31	0.10	0.21	0.39	0.14	0.20	0.41
TiO_2	0.83	0.75	0.37	0.13	0.13	0.48	1.93	0.19	0.30	0.82
P_2O_5	0.12	0.14	0.15	0.07	0.06	0.19	0.29	0.05	0.12	0.09
L.O.I.[b]	2.46	3.85	1.00	2.62	1.54	0.69	4.08	2.46	1.08	- 0.85
Sum	98.0	99.3	97.6	97.6	97.3	98.0	98.6	94.6	98.1	93.7
Rock Type	Basalt	Basalt	Rhyo-dacite	Rhyo-dacite	Rhyo-lite	Rhyo-lite	Basalt	Rhyo-dacite	Rhyo-lite	Rhyo-dacite

Table 1. Continued

Oxide Wt. %	Sample number									
	216	217	218	220	221	222	223	225	226	228
SiO	73.0	71.0	64.6	52.1	49.1	50.7	70.1	46.1	75.1	51.9
Al_2O_3	11.1	21.9	27.1	14.6	19.5	13.5	15.2	15.9	10.8	15.7
CaO	1.22	0.20	0.40	8.94	8.29	5.20	0.11	11.0	0.84	6.75
MgO	0.78	0.01	0.00	2.36	2.56	3.72	0.18	4.56	1.22	4.71
Na_2O	2.15	0.05	0.12	1.21	3.60	1.66	0.56	0.87	1.87	2.72
K_2O	1.75	0.12	0.29	0.09	0.54	0.05	3.43	0.23	1.35	0.31
FeO	4.30	0.62	1.10	13.7	11.5	14.7	4.29	9.72	3.76	8.66
MnO	0.30	0.09	0.15	0.36	0.30	0.27	0.17	0.17	0.16	0.24
TiO_2	0.16	0.76	1.44	1.56	1.11	2.17	0.63	0.64	0.19	0.74
P_2O_5	0.07	0.19	0.35	0.26	0.14	0.60	0.18	0.11	0.05	0.24
L.O.I.	1.62	2.62	1.92	2.00	1.85	2.92	2.46	7.00	2.23	4.38
Sum	97.0	97.6	97.6	98.6	99.7	97.1	97.8	97.4	98.0	97.3
Rock Type	Rhyolite	Rhyolite	Dacite	Basalt	Basalt	Basalt	Rhyolite	Basalt	Rhyolite	Basalt

[a] Total Fe

[b] L.O.I. = Loss on ignition

Table 2. Selected chemical analyses reported by C. A. Anderson and Blacet (1972c) for Poland Junction area

Oxide Wt. %	Sample number				
	5-2	7-5	1-6	7-7	6-8
SiO_2	52.0	53.8	65.0	78.5	53.8
Al_2O_3	17.4	15.0	14.3	11.5	15.5
Fe_2O_3	2.7	1.0	3.4	1.6	3.7
FeO	8.2	8.7	3.6	0.18	4.8
MgO	4.5	5.6	2.2	0.35	4.7
CaO	7.6	4.6	5.8	1.4	7.1
Na_2O	2.6	2.4	1.5	0.10	3.1
K_2O	0.45	0.10	2.4	3.5	0.49
H_2O_t	3.03	4.79	1.0	1.0	3.6
TiO_2	0.94	0.68	0.52	0.17	0.65
P_2O_5	0.17	0.11	0.09	0.03	0.21
MnO	0.24	0.12	0.11	0.00	0.19
CO_2	0.05	3.00	0.05	0.88	1.2

Sample 5-2 = sample 5, table 2, andesite
Sample 7-5 = sample 7, table 5, basaltic andesite
Sample 1-6 = sample 1, table 6, rhyolitic tuff with admixed mafic detritus
Sample 7-7 = sample 7, quartz porphyry
Sample 6-8 = sample 6, table 8, gabbro

All samples from C. A. Anderson and Blacet (1972c).

Table 3. Selected chemical analyses reported by Sturdevant (Appendix C, 1975) for Poland Junction area

Oxide	Sample number						
Wt. %	308	326	328	374	409	526	528
SiO_2	52.0	52.0	65.0	62.0	48.0	53.0	55.0
Al_2O_3	18.1	13.7	14.3	14.6	15.6	17.2	18.0
Fe_2O_3	10.9	11.0	6.9	8.4	12.4	10.3	10.2
MgO	4.6	3.9	1.7	2.1	2.4	3.8	4.3
CaO	9.05	10.8	5.1	4.35	13.2	3.6	3.45
Na_2O	2.17	4.0	1.88	4.92	2.77	3.80	3.30
K_2O	0.16	0.29	1.72	0.72	0.53	1.04	1.03
TiO_2	0.76	1.92	0.68	1.08	0.90	0.86	0.76
MnO	0.23	0.19	0.11	0.12	0.36	0.16	0.16
$-H_2O$	2.79	0.74	1.46	5.23	1.10	3.48	3.66
Total	100.8	98.0	98.9	103.5	97.3	97.2	99.9

All samples reported by Sturdevant as greenschist.

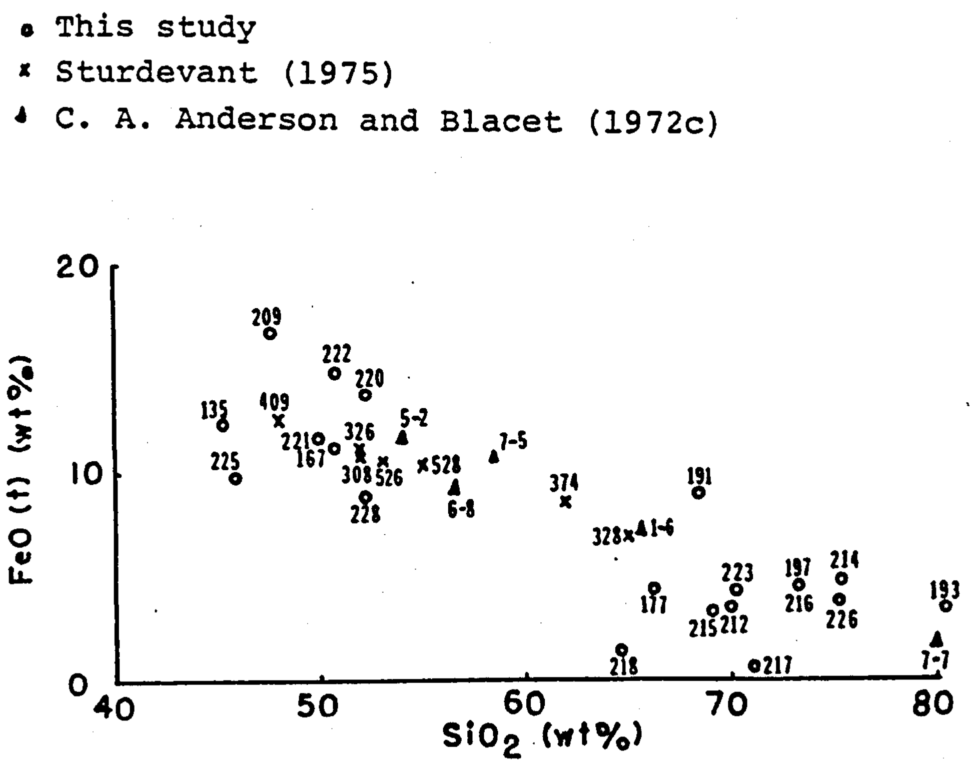

Figure 13. Plot of FeO (total Fe) versus SiO_2

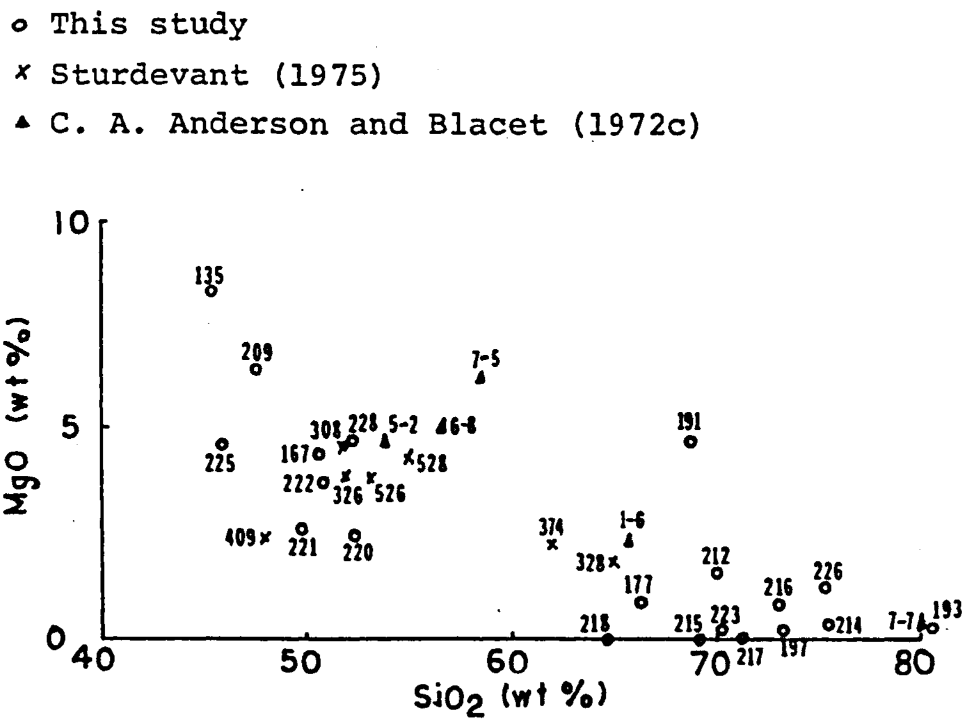

Figure 14. Plot of MgO versus SiO_2

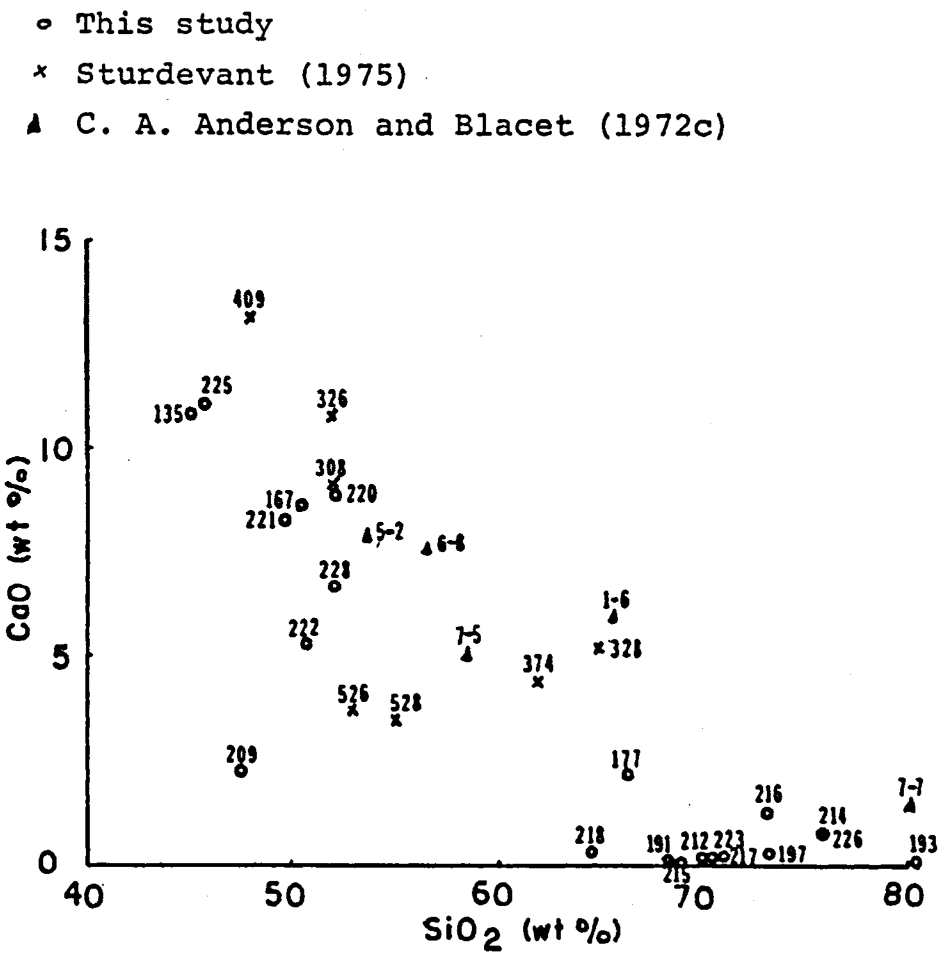

Figure 15. Plot of CaO versus SiO_2

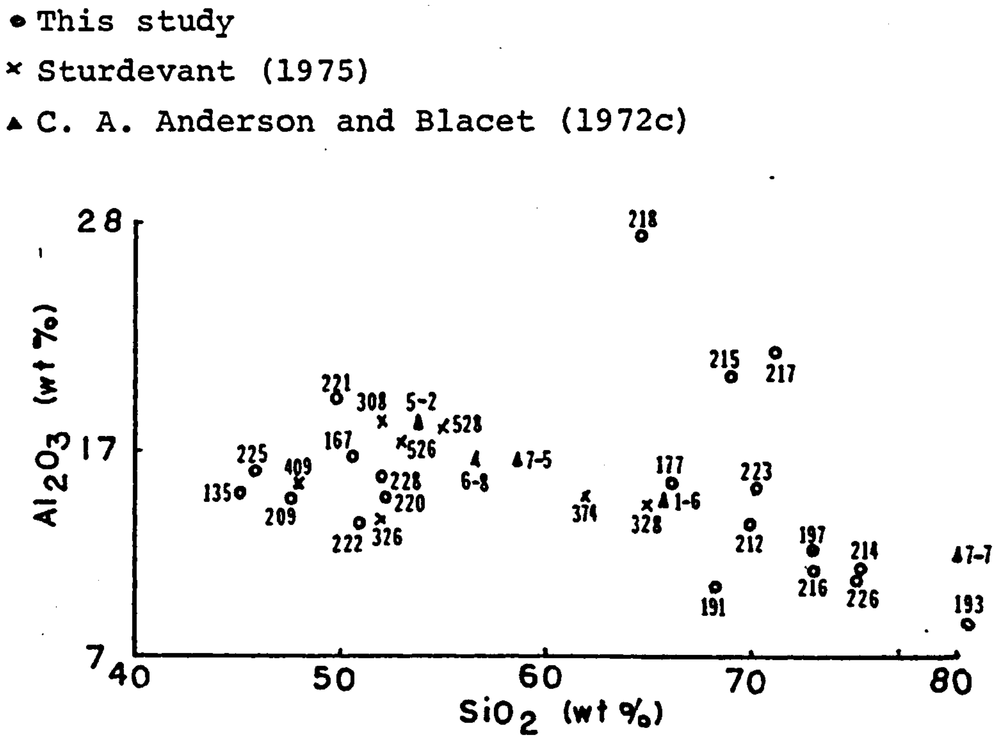

Figure 16. Plot of Al_2O_3 versus SiO_2

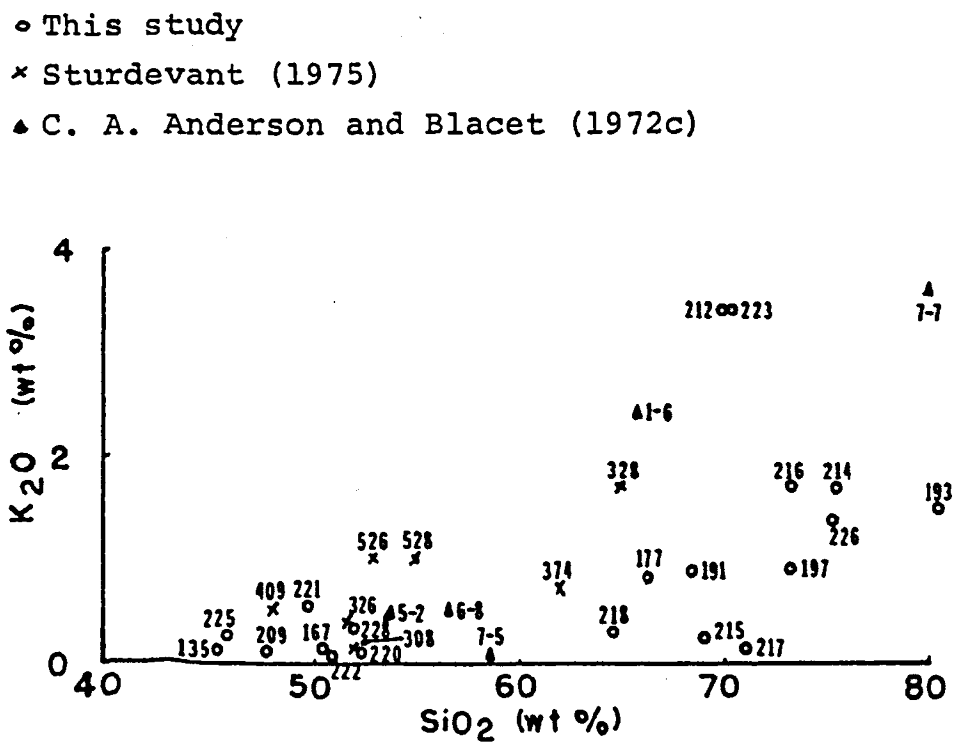

Figure 17. Plot of K_2O versus SiO_2

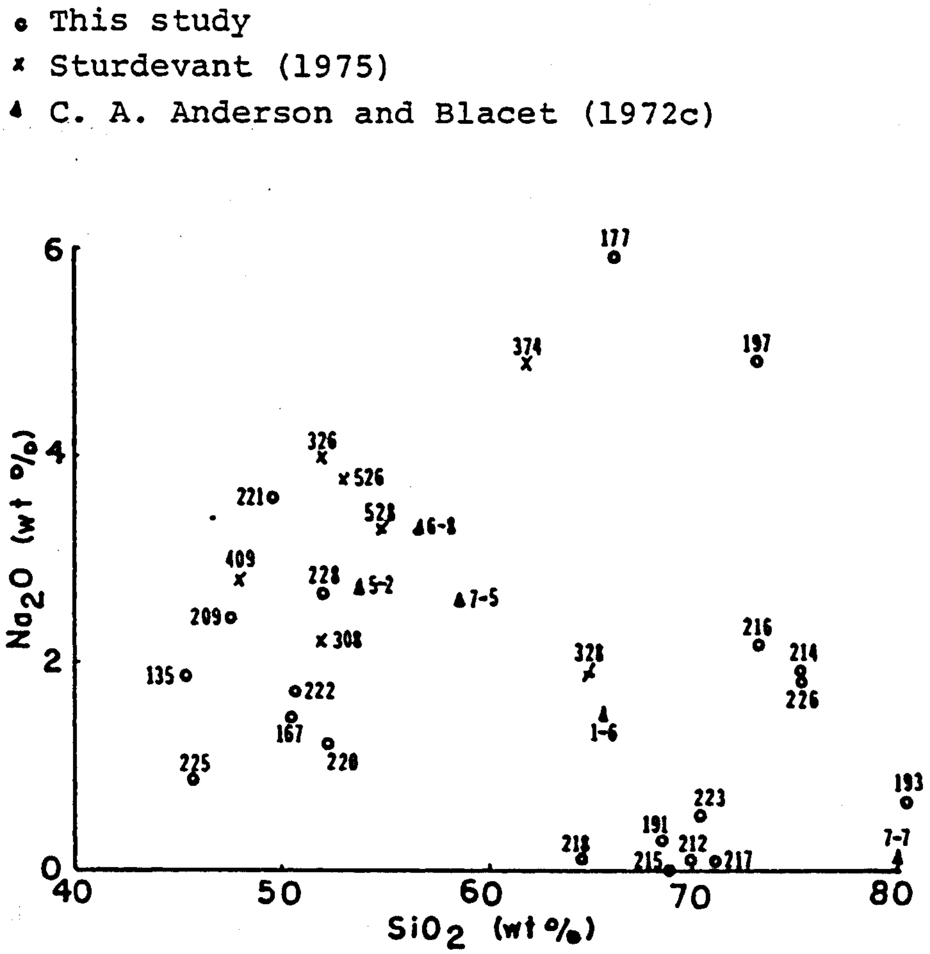

Figure 18. Plot of Na_2O versus SiO_2

Discussions to come later in this section are based on the assumption that there was no major redistribution of elements during submarine weathering and metamorphism. Miyashiro (1975) has provided a discussion of this assumption. Miyashiro gives a plot of Na_2O/K_2O versus $Na_2O + K_2O$ for fresh, late-Cenozoic volcanic rocks from a variety of geologic environments. All fresh unaltered volcanics plot below his line V-V, so he proposed that any sample that plots above line V-V has undergone redistribution of its alkali elements. Samples from this thesis area were plotted on Figure 19 and only one, 177, plots above line V-V.

Another more indirect way to look for possible alteration is a comparison of the series of plots of Figures 13 through 18 with similar ones prepared by Descarreaux (1973) showing Archean metavolcanics from the Abitibi Belt in eastern Canada and also typical magmatic series rocks from Japan. The comparison showed no apparent alteration of FeO, MgO, and CaO. Samples 215, 217, and 218 show a strong enrichment of Al_2O_3 (Fig. 16); K_2O shows an enrichment in samples 7-7, 1-6, 212, and 223 (Fig. 17). The K_2O versus SiO_2 plot of Descarreaux only shows samples from the Abitibi Belt and not from the Japanese magmatic series so it is hard to say how abnormal the samples from this study area really are. The Na_2O versus SiO_2 plot of Descarreaux is also inconclusive because the Japanese magmatic series rocks are not plotted on it either. When compared with

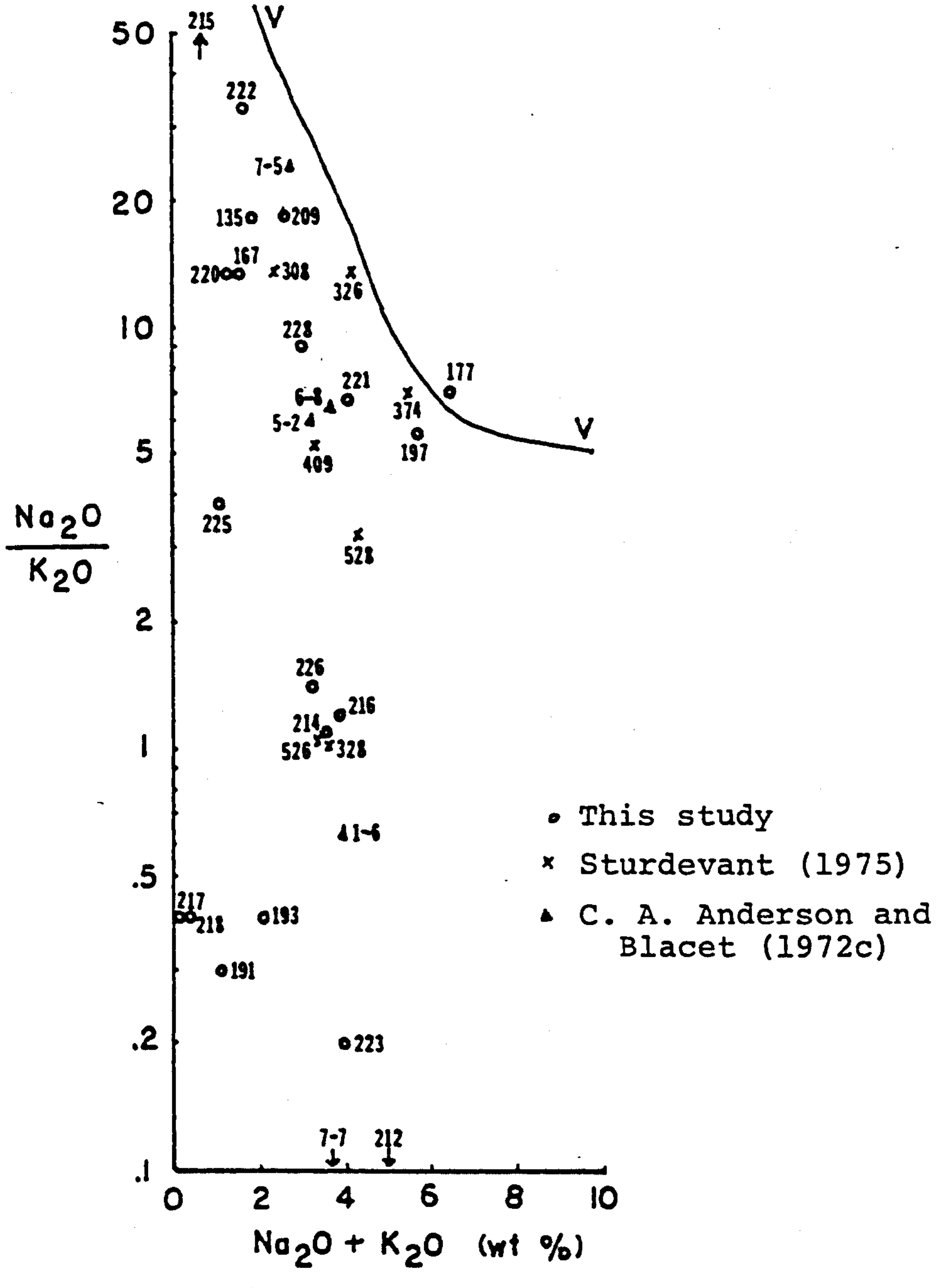

Figure 19. Plot of Na_2O/K_2O versus $Na_2O + K_2O$. -- Samples 215, 212, and 7-7 plot off the graph as shown by arrows at top and bottom.

only the Abitibi Belt samples, the rhyolitic rocks from the Poland Junction area appear to be depleted in Na_2O except for samples 374, 177, and 197, which are enriched in Na_2O (Fig. 18). The basalts from this thesis area are similar to the Abitibi rocks in Na_2O, and so if the rocks are altered in Na_2O it must be a selective and local process restricted to the intermediate and felsic rocks rather than the result of a regional metasomatism affecting all the rocks. Going back to the Miyashiro (1975) plot (Fig. 19) one sees that sample 177 falls within Miyashiro's altered zone and samples 197 and 374 are very close to the boundary so these rocks are evidently enriched in Na_2O. Samples 7-7, 193, 215, 217, 218, 191, 223, and 212 do not fall within Miyashiro's altered zone, but neither do they fall within the zones containing the bulk of his samples, so there is a strong possibility that they are truly depleted in Na_2O as suggested by Figure 18. In summary, the major alteration seems to be in Na_2O, although it is attributed to a local, selective process rather than to regional metasomatism. Therefore the whole rock analyses presented here will be used to attempt to classify the rocks but the reader is urged to keep in mind the possible effects of Na_2O alteration in some of the following diagrams.

The analyses were plotted on an alkali-iron-magnesia (AFM) triangular diagram to determine calc-alkaline or tholeiitic trends (Fig. 20). Most samples fall within the tholeiitic field, with a suggestion of an iron enrichment trend.

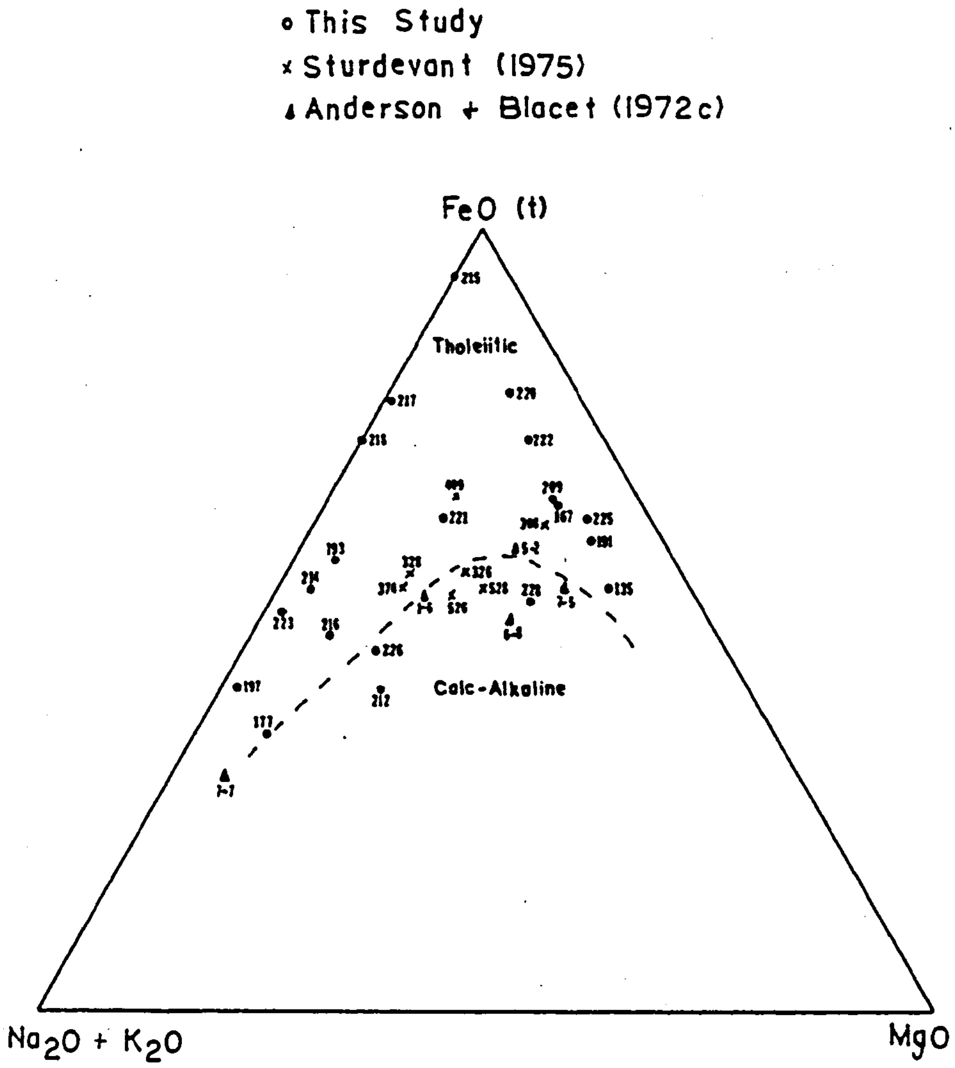

Figure 20. AFM plot of thesis data. -- Tholeiitic, calc-alkaline dividing line from Irvine and Baragar (1971).

X-Ray Assay Laboratories provided a plot of the samples on a Jensen cation plot (Fig. 21), which is basically an AFM plot with the alkali corner replaced by Al_2O_3. Jensen believes this to be a better plot because Al_2O_3 is more stable during deuteric and other possible alteration and remobilization periods than Na_2O and K_2O. Jensen also uses cation molecular percentages rather than weight percentages of the oxides. Again the samples plot dominantly in the tholeiitic field with a clear iron enrichment trend. A plot of weight percent $Na_2O + K_2O$ versus weight percent SiO_2 has been used by Kuno (1966) to show differences in alkaline, high-alumina calc-alkaline basalt and tholeiitic rock series. Plotting the values (Fig. 22) from this area again shows tholeiitic trends. Irvine and Baragar (1971) state that Al_2O_3 content is a particularly useful oxide to use for differentiating between tholeiitic and calc-alkaline rocks, particularly for mafic rocks. Therefore they have devised a plot of weight percent Al_2O_3 versus normative plagioclase composition (100 An/[An + Ab + 5/3 Ne]). Samples from Poland Junction were plotted (Fig. 23) and again fall dominantly in the tholeiitic field.

Thus the evidence is strong that the rocks from this thesis area are dominantly tholeiitic with some calc-alkaline tendencies. The evolutionary picture is not as clear as was hoped, however, because complex folding makes structural and stratigraphic reconstruction difficult. The iron enrichment trend suggested on the AFM (Fig. 20) and

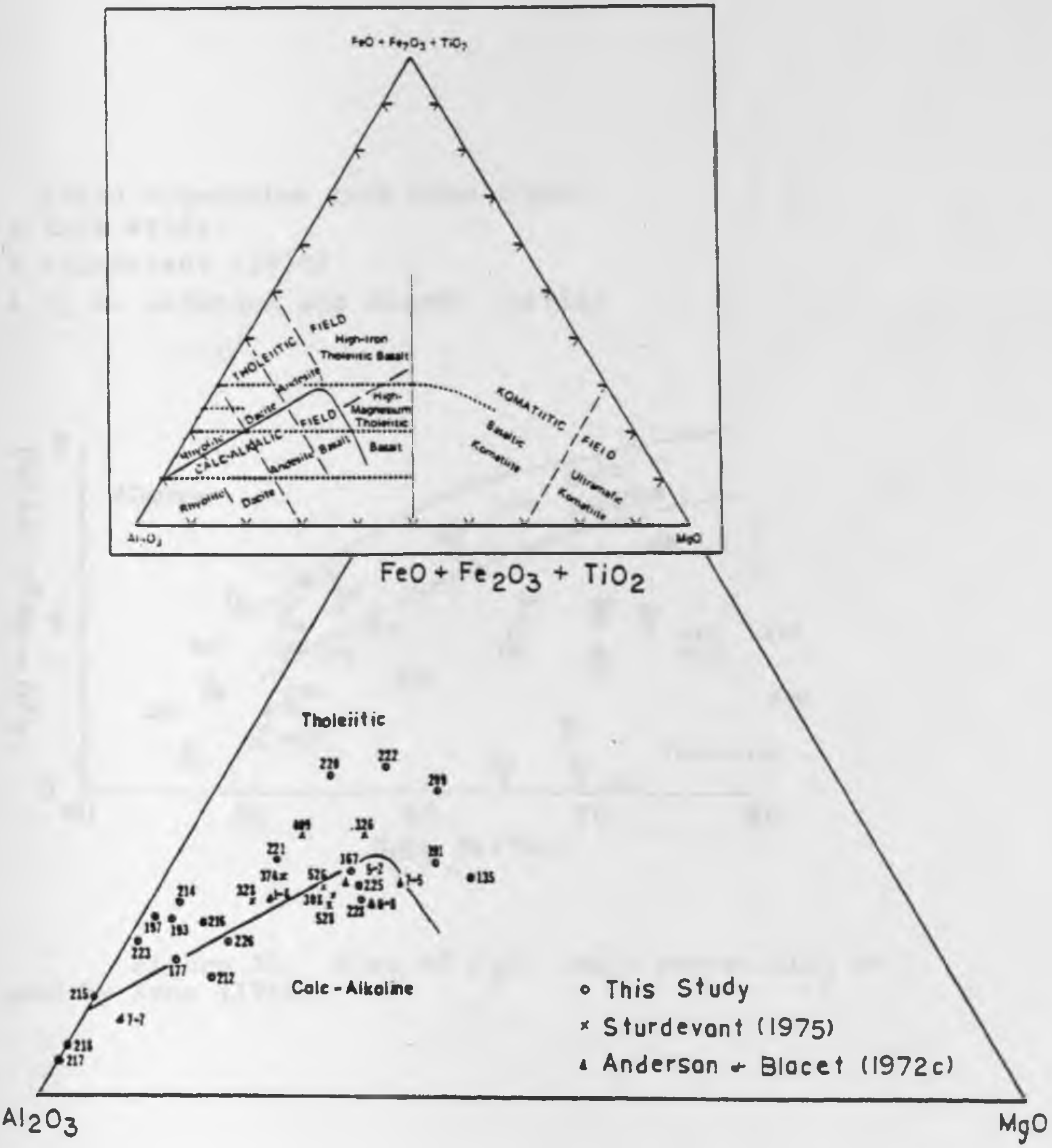

Figure 21. Jensen plot of thesis data. -- Inset shows dividing lines proposed by Jensen (1976). All values in cation molecular percent.

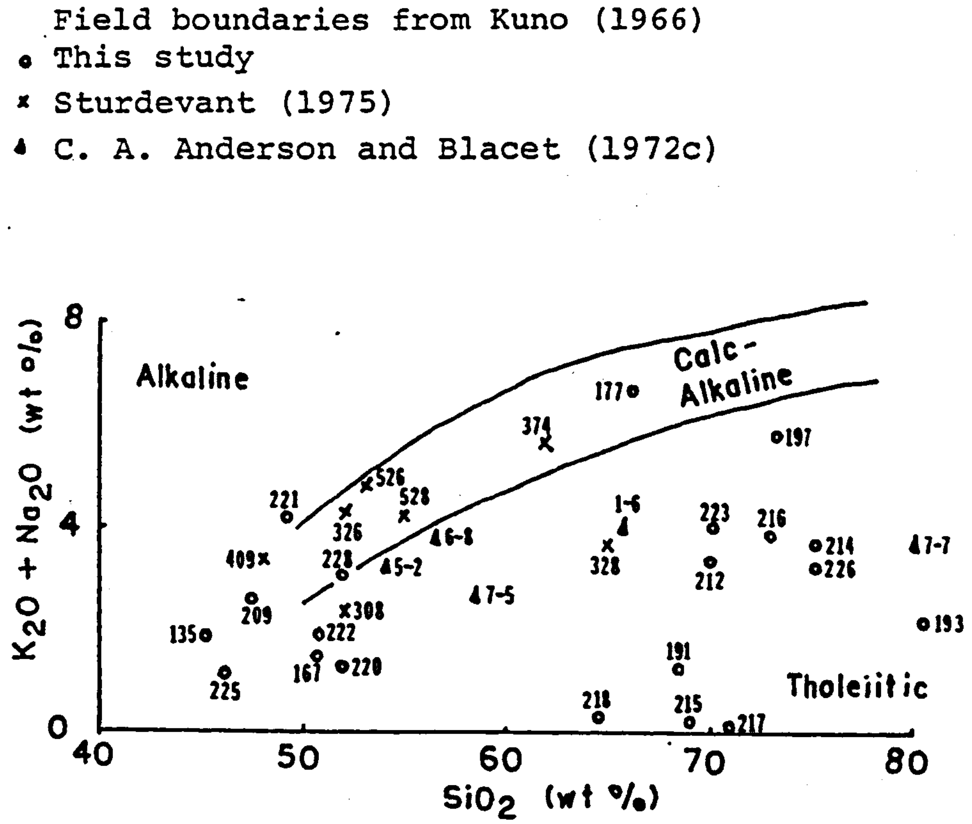

Figure 22. Plot of $K_2O + Na_2O$ versus SiO_2 as used by Kuno (1966).

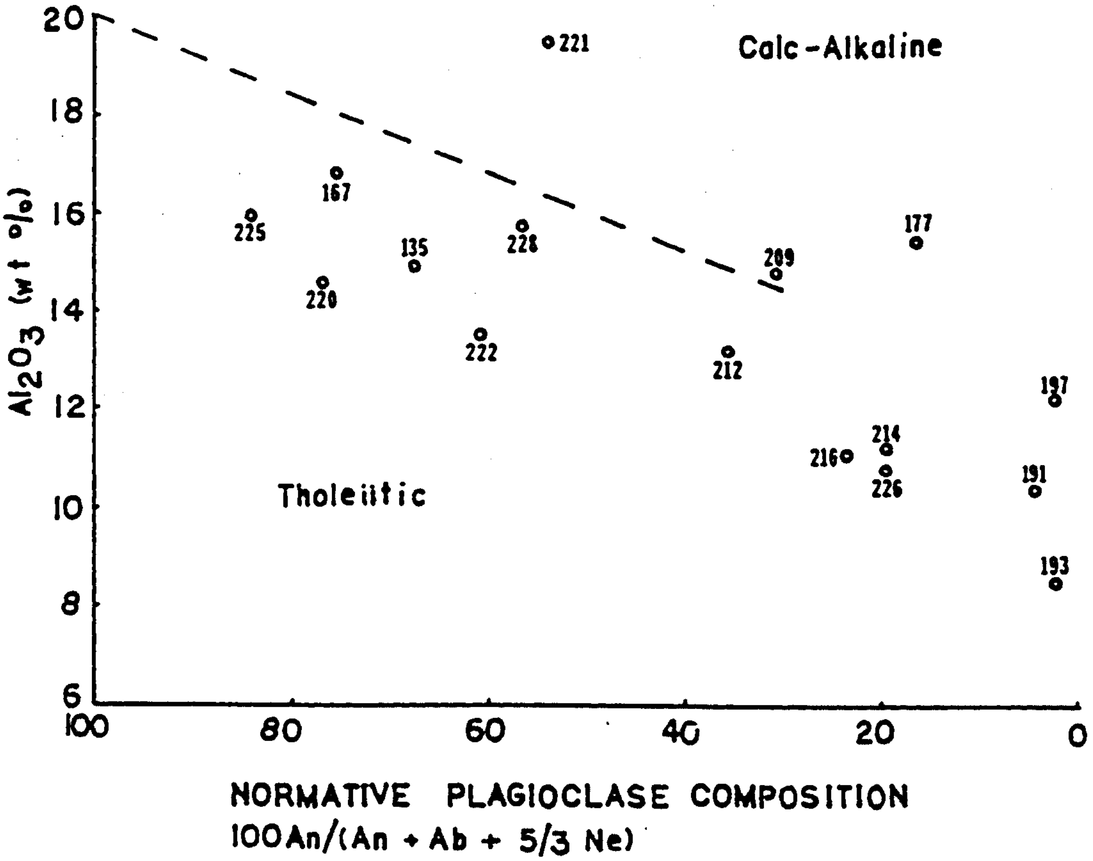

Figure 23. Normative plagioclase composition plot. -- Plot of Al_2O_3 versus normative plagioclase composition (100 An/(An + Ab + 5/3Ne)) as proposed by Irvine and Baragar (1971).

Jensen (Fig. 21) plots is not apparent when studying the sample locations on Figures 2 and 3. The samples fall in an apparently random manner over the mapped area, so no vertical differentiation trends are identified. This is attributed to the complex folding present in the area. Most previous studies of the Archean metavolcanic rocks of the Canadian Shield (Sangster, 1972; Descarreaux, 1973) have suggested that the volcanogenic massive sulfide deposits are found principally in the calc-alkaline upper parts of volcanic piles. The tholeiitic lower parts of the pile, while they may contain nickel-copper deposits, do not contain copper-zinc-lead deposits. This makes the presence of copper-zinc-lead deposits in this thesis area seem abnormal. However, a recent paper by Fox (1979) based on a worldwide sampling of massive sulfide host rocks suggests that an equal number of copper-lead-zinc deposits occurs in tholeiitic rocks as in calc-alkaline rocks. Another interesting point made by Fox is that quartz-phenocryst-bearing porphyries should be more abundant in tholeiitic rocks than in calc-alkaline rocks. Results of this thesis study support this idea because the rocks in this area are tholeiitic and quartz-porphyries are abundant.

Spitz and Darling (1975) suggested, based on the study by Nockolds (1954), on volcanic rocks, that the following SiO_2 values be used to subdivide volcanic rocks:

Rhyolite	> 70% SiO_2
Rhyodacite	65-70% SiO_2
Dacite	59-65% SiO_2
Andesite	53-59% SiO_2
Basalt	< 53% SiO_2

Using this scheme, most of the rocks from this study area fall within the basaltic and rhyolitic fields, with few andesites, dacites, or rhyodacites. A submarine site of deposition and the presence of abundant rhyolites would suggest a volcanic island arc environment of formation for the rocks rather than an abyssal oceanic or continental tholeiitic province.

Summary

Whole-rock geochemical data produced for this study was determined to show some degree of Na_2O alteration but was deemed suitable for attempts to classify the rocks into magmatic series. After plotting the thesis data on AFM, Jensen, Kuno, and normative plagioclase composition plots, it is concluded that the rocks are dominantly of tholeiitic affinity but with some calc-alkaline tendencies. No vertical differentiation patterns were detected primarily because the complex folding made structural reconstruction very difficult. Studies in volcanic piles in the Canadian Shield (Gelinas et al., 1977) show typical vertical igneous differentiation trends from tholeiitic at the base to calc-alkaline higher in the pile and sometimes to alkaline rocks at the top. Because the present thesis study involved only a small part of the whole volcanic belt, larger regional studies may yet detect such differentiation patterns. It is suggested the rocks under study here formed in a volcanic island arc environment. Whether these ancient island arcs, if they existed, were components of Proterozoic plate tectonic systems is an interesting question for future studies.

STRUCTURAL GEOLOGY

The Poland Junction area is west of the Shylock fault zone of C. A. Anderson and Creasey (1958), a zone of such intense foliation development that it is visible on Landsat photographs. The Poland Junction area is also intensely foliated and this foliation has contributed to the obliteration of earlier planar features, thus making the structural history of this area difficult to resolve.

Foliation

Pervasive north-northeast foliation (Fig. 24) is the most obvious structural element one sees when working with these rocks. It is defined by the parallel orientation of chlorite, sericite, and actinolite within the rocks. Rocks vary from pervasively foliated to almost nonfoliated. As explained earlier, the variation is thought to be a function of the original texture, grain size, and bedding thickness of the units. The dominant foliation trend is N. 15°-35° E. The only major departure from this trend is at Spud Mountain (Fig. 3) on the extreme northwest edge of the area where trends are north-northwest. All foliation dips steeply, both east and west.

The plane of foliation has also been a plane of movement. Transposition of bedding (Whitten, 1966; Hobbs,

Figure 24. Lower hemisphere pole-density diagram of poles to foliation for the Poland Junction area.

A. Data west of the Texas Gulch Formation, primary direction N. 32° E., contour intervals of 5%, 10%, 15%, and 20%. 49 points.

B. Data between the Texas Gulch Formation and Highway 69, primary direction N. 33° E., contour intervals same as in A. 46 points.

C. Data between Highway 69 and the major eastern fold axis, primary directions N. 17° E. and N. 35° E., contour intervals of 5%, 10%, and 15%. 67 points.

D. Data east of the major eastern fold axis, primary direction N. 24° E., contour intervals of 5%, 10%, 15%, and 20%. 53 points.

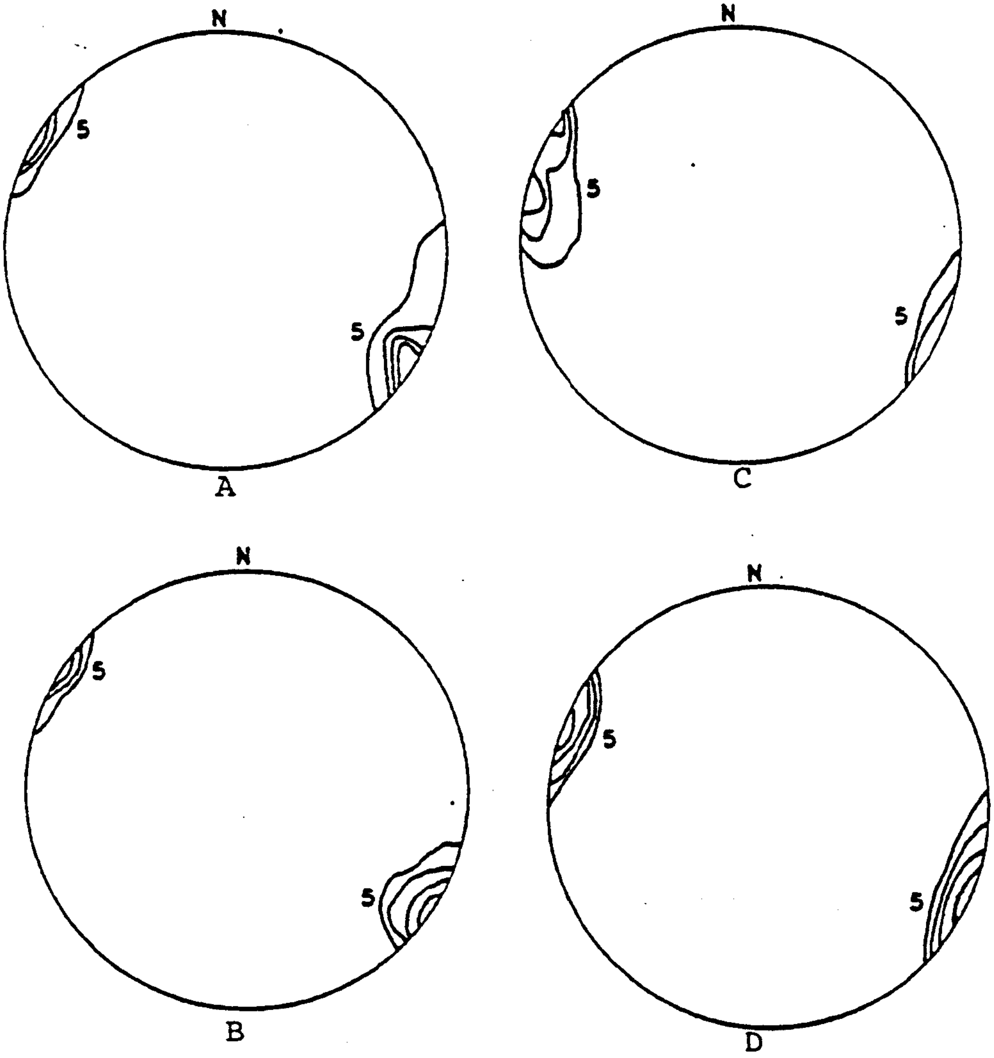

Figure 24. Lower hemisphere pole-density diagram of poles to foliation for the Poland Junction area

Means, and Williams, 1976) is widespread in the thesis area. One of the first problems the author encountered in this study was to determine whether the metamorphic foliation (S_1) importantly coincided with original bedding (S_0). On a typical outcrop, foliation looks identical to bedding. However, in places where bedding can be positively identified, either through tracing pebble zones or by distinct lithological or mineralogical differences, it was seen that bedding and foliation are not necessarily parallel (Fig. 25), diverging from as little as 5 degrees on fold limbs to a full 90 degrees at fold closures. In most of the places where bedding and foliation could both be identified on the same outcrop, bedding tended to trend more to the north than foliation. As will be discussed in the section on folds, the foliation appears to be an axial plane foliation.

Lineations

Lineations within the area are defined by elongate pebbles and breccia fragments, orientation of prismatic minerals, intersection of bedding and foliation, fold plunges, and plunges of massive sulfide orebodies. Fragments within breccia units are commonly stretched parallel to regional foliation (Fig. 26). The maximum elongation, which is in the plane of foliation, plunges steeply north. The intermediate axis of elongation is in the plane of foliation, and the minor axis is perpendicular to foliation.

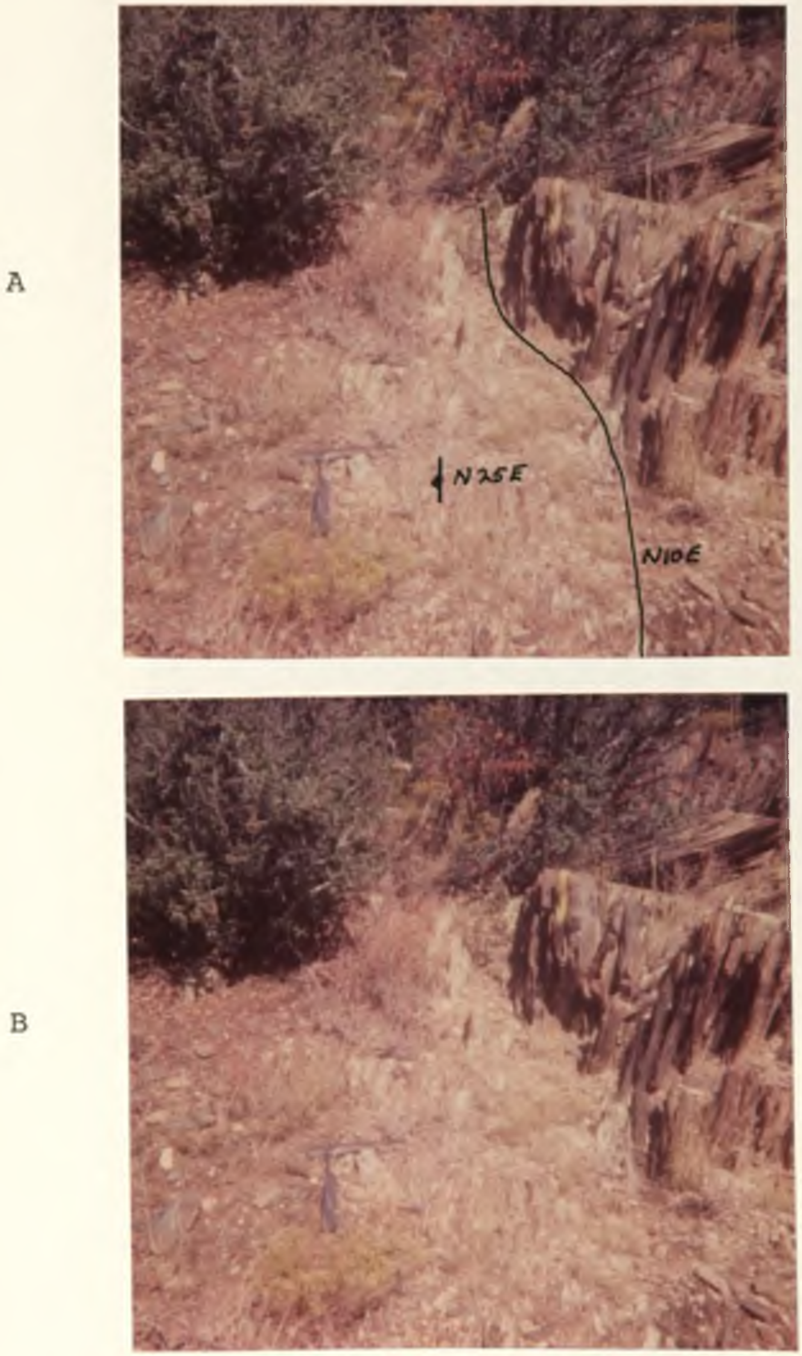

Figure 25. Foliation cutting bedding.

A. Hammer handle parallels foliation, N. 25° E. Contact, N. 10° E., is marked with ink. Note the color contrast between the andesitic unit on the right and the rhyolitic unit on the left.

B. Unmarked photograph of the above showing the contact. The location is the northeast quarter of sec. 33, T. 13 N. Parallel foliation in both lithologies cuts contact.

Figure 26. Stretched clasts in mafic tuff-breccia. -- The elongate light-colored clasts generally parallel to the hammer handle are stretched clasts in a mafic tuff-breccia in the creek bed between Spud Mountain and the Lookout mine, sec. 20, T. 13 N.

Elongation ratios range from 8:4:1 to 16:6:1. Maximum elongation ratios typically were found in monomictic breccias where a similarity between fragments and matrix meant that both were affected equally by the strain. In polymictic breccias the elongation ratios are typically smaller at 4:2:1 because the dissimilarity in texture and composition of matrix and fragment meant that the typically finer grained matrix was more affected by the strain than the more compact pebbles or fragments.

One of the most eloquent expressions of lineation within the study area is reflected in the shape of massive sulfide bodies. These bodies typically have a lensoidal form very similar to the stretched fragments in a breccia. Unfortunately, only enough data were available to determine plunges for three orebodies. The Gilmour and Still (1968) study of the Iron King mine showed conclusively that the lenses there plunge about 45° to 60° N. The major and intermediate axes of elongation of the orebodies are subparallel to regional foliation and the minor axis is perpendicular to foliation. Mine maps in open-file reports of the Arizona Department of Mineral Resources in Phoenix show that the Hackberry deposit is also in the form of overlapping lenses with their maximum length subparallel to foliation and plunging steeply north. A sketchy mine map of the Lone Pine mine also strongly suggests a north plunge with the longest dimension subparallel to foliation, although the data are less complete. C. A. Anderson and Blacet (1972c) gave an orientation for the Boggs mine deposits which parallels regional foliation, but they did not report a plunge direction or amount.

Lineations caused by elongate minerals such as actinolite and occasionally feldspar also trend parallel to foliation and plunge steeply north. In the few instances where isoclinal (F_1) fold closures could be identified, they plunge from 45° to 70° N. The only major lineation that does not plunge north is that defined by the plunge of kink bands (F_2 folds). They usually plunge steeply west, a fact discussed more fully in the next section.

Folds

Good, clear evidence for folding is surprisingly difficult to find within the thesis area, a function of the slip type of folding (Whitten, 1966) and the effect of transposition on the folds. Folds are tight to isoclinal or overturned and similar (Whitten, 1966), as shown by thinning of the limbs and thickening of crests and troughs. Isoclinal folds of this type within the area represent F_1 folds. A generation of kink bands (F_2) will be discussed later in this section.

Isoclinal F_1 folds are present in the area on a mesoscopic to megascopic scale. None were observed on a microscopic scale, although with the slip-type folding involved they are probably present but inconspicuous. Mesoscopic F_1 folds have amplitudes of 0.5 to 30 meters and wavelengths of 0.25 to 8 meters. Megascopic F_1 folds have wavelengths of 0.25 to 1 km and unknown amplitudes. F_1 folds trend subparallel to regional foliation at N. 15°-35° E., and plunge 45° to 70° N. The subparallelism of foliation and F_1 fold axes strongly suggest that they are genetically related and that the foliation is an axial-plane foliation. The current debate on the origin of axial-plane foliation with regard to its cause by compression with maximum shortening perpendicular to foliation or by shearing parallel to foliation is summarized well by Hobbs, Means, and Williams (1976).

Transposition in the plane of foliation is one of the main factors that made fold recognition difficult in the thesis area. Transposition tends to stretch fold limbs and completely obliterate fold closures. The closures are stretched parallel to the limbs until all that remains are two parallel lenses of similar lithology. If bedding indicators within the units have also been destroyed or never existed, the units may be interpreted as two separate lensing units. This interpretation is completely reasonable in a volcanic-sedimentary pile such as the one under study here, where lensing of units and rapid vertical and lateral facies changes are to be expected. The author interpreted several units as separate lenses before more detailed study showed them to be fold limbs. The rhyolites in sections 5 and 8 of Figure 2 are limbs of a fold and at least some of the rhyolites in section 33 of Figure 3 are limbs of a fold.

Kink bands (F_2) fold S_1 foliation and are thus considered to be younger than the F_1 folds associated with S_1. They are present throughout the area, but are best developed in thin-bedded tuffaceous and sedimentary units. They have amplitudes of 1 to 5 cm and wavelengths of 1 to 3 cm. They are formed by flexural slip (Whitten, 1966) rather than pure slip as shown by a constant thickness of the limbs and hinge lines. Slippage occurred along the S_1 foliation. Kink bands trend generally east-west and plunge steeply west, usually within the plane of S_1. Associated with them is a joint set which in some areas also progresses to small displacement microfaults.

Since F_2 folds are typically very small in scale they are not believed to represent a major deformation event. They were probably formed during a minor readjustment at the end of major F_1 deformation after S_1 foliation had been well developed, but they may represent a small deformation event well after the main deformation.

Faults

Faults are not readily detectable within the area. If they occur parallel to foliation, they are essentially impossible to detect on a typical weathered outcrop.

Several faults parallel to foliation were seen in roadcuts or prospect pits, but none could be traced on the surface. Amount of displacement could not be judged due to similarity of units on both sides of the fault plane. Faults of this nature are probably widespread but difficult to discern.

Several east-west trending faults were detected, primarily because they offset the Laramide(?) rhyolite dike that parallels the Texas Gulch Formation. Displacement on these faults is on the order of a few meters to 10 meters parallel to strike. Dip displacements are not known, nor is it known whether these faults had a Precambrian origin.

Joints

Sturdevant (1975) reported a detailed and extensive study of fracturing within and around the Laramide intrusion exposed in Big Bug Creek (Fig. 3). His study showed a close correlation between joint orientations within the intrusion and in the surrounding country rocks, suggesting that the joints are related and probably Laramide to post-Laramide in age. For this reason, they will not be discussed further in this paper.

Summary of Structural Geology

North-northeast-trending axial plane foliation is extensively developed in the area. Transposition of bedding is also widespread parallel to S_1 foliation. Isoclinal, steeply north plunging folds (F_1) present throughout the area are hard to recognize due to obliteration of fold closures by transposition. East-west-trending F_2 folds represent a minor readjustment at the end of F_1 deformation. Faults are probably widespread throughout the area but are impossible to detect if parallel to foliation.

The deformation causing F_1 folds probably occurred during the Mazatzal Revolution of Wilson (1939; 1962). He described this event as producing northeast-trending foliation and folding, which matches that found in the thesis area. Silver (1965) and C. A. Anderson and Silver (1976), using Pb-U dates from pre- and postdeformational rocks in the Mazatzal Mountains, determined that the Mazatzal revolution occurred between 1715 ± 15 m.y. years and 1660 ± 15 m.y. years ago.

ECONOMIC GEOLOGY

There are eight mines in the thesis area which have previously produced from Precambrian massive sulfide-type mineralization (Fig. 27). It is this type of deposit that this study is primarily interested in. There are also several mines which produced from epigenetic vein-type mineralization. Most deposits were found and mined during the period from 1875 to 1920, when gold and silver were taken from the oxidized upper zones (Lindgren, 1926). Later, starting in the 1930s and particularly during World War II, several of the mines produced copper, lead, and zinc (C. A. Anderson and Blacet, 1972c).

It was not the intent of this thesis to do a detailed study of any individual mine in the area but rather to look at their regional distribution. All of the mines are flooded or caved, so underground access is nil to limited. Any detailed studies would have to be based on surface and dump samples, surface mapping and underground records, which, for most of the mines, are scanty. Therefore, the descriptions which follow are not detailed and exhaustive. They are generalized from the literature and the author's regional mapping, with a few special notes on certain features. The author would again like to thank

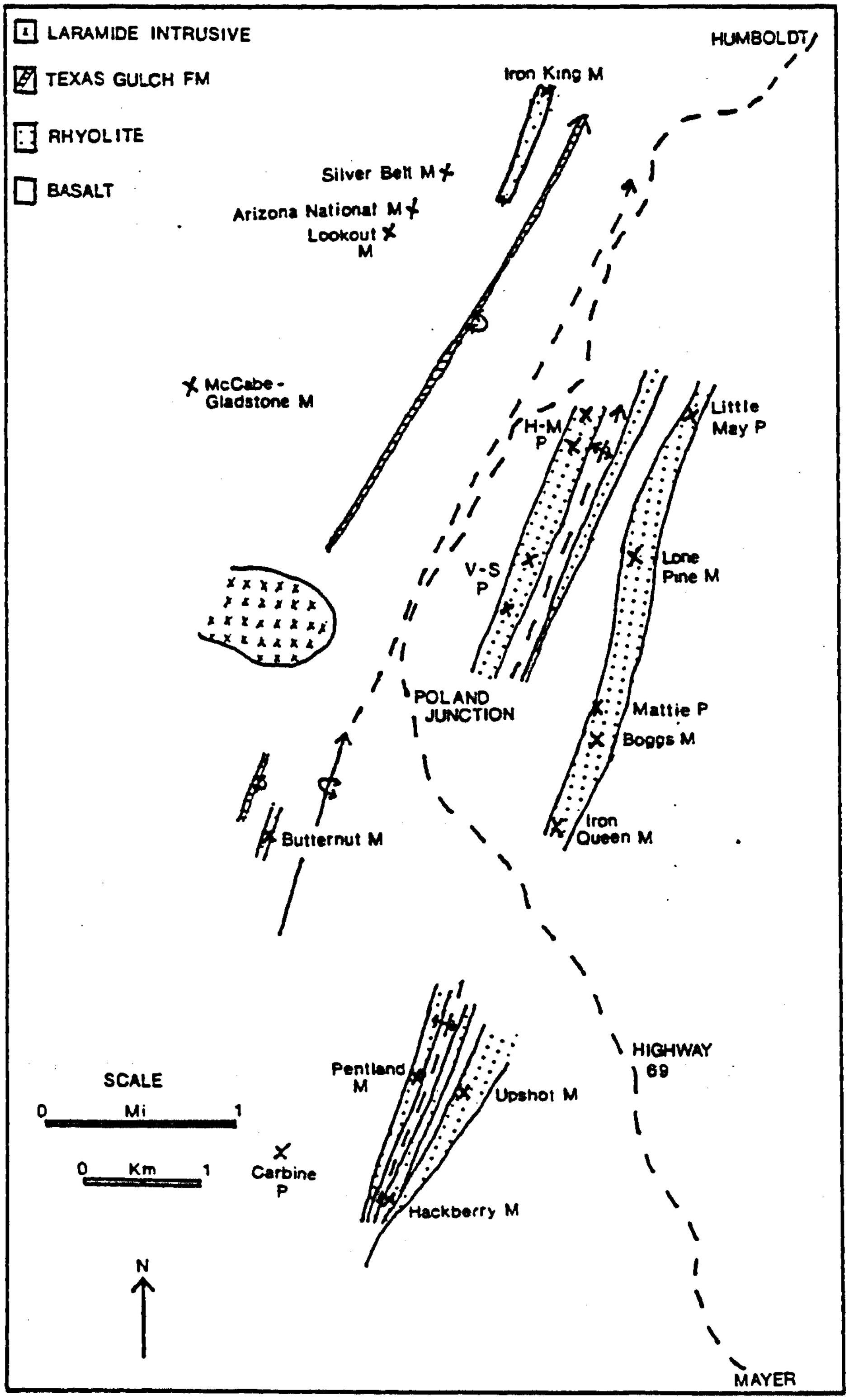

Figure 27. Simplified geologic map showing gross lithologies, major fold axes, and mine and prospect locations.

American Selco, Inc., which controls most of the area, for access to these properties.

Vein-type Mineralization

There is a major, 2-to-5-meter-wide vein system in the northwest part of the thesis area along which are distributed the McCabe-Gladstone, Lookout, Arizona National, and Silver Belt mines (Fig. 3, sec. 20 and 21, T. 13 N., and Fig. 27; Lindgren, 1926; C. A. Anderson and Blacet, 1972c). They show vuggy and drusy textures of quartz and exhibit evidence of being fracture-filling deposits. A smaller vein system, the Kit Carson, lies about 500 meters west of the Silver Belt-McCabe vein (Fig. 3, sec. 20 and 21, T. 13 N.). The mafic volcanic rocks surrounding both vein systems have been bleached for 1 to 3 meters and are very fissile, suggesting movement which cannot be ascertained. The fracture trend varies from N.30° E. on the north end of the vein to N. 60° E. on the south end, crosscuts foliation, and probably crosscuts bedding. Dips vary from steeply east to steeply west. There is also a zoning of metals along the vein. The McCabe-Gladstone mine at the south end, west of the area of Figure 3, produced primarily gold and copper, while the Arizona National and Silver Belt mines, on the north end, produced silver and lead (C. A. Anderson and Creasey, 1958). The Lookout mine in the central part of the vein produced a mixture of gold, silver, copper, lead, and zinc (C. A. Anderson and Creasey, 1958). This zoning is probably related to the Laramide intrusion exposed in the Big Bug Creek area (Figs. 2 and 3), immediately south of the south end of the McCabe-Gladstone vein. The high gold-copper values are found close to the intrusion with the lead, zinc, and silver values farther removed. Therefore, these deposits are believed to be also Laramide in age and formed by a hydrothermal system generated by the Laramide pluton.

Massive Sulfide-type Mineralization

Volcanogenic massive sulfide deposits were mined at the Iron King, Lone Pine, Boggs, Iron Queen, Upshot, Pentland, Hackberry, and Butternut mines (Figs. 2, 3, and 27). The following mine descriptions will be in more detail than those for the vein-type deposits because the stratigraphic positions of the massive sulfide deposits was the main area of study of this thesis.

Iron King Mine

One can hardly do better than to read the Gilmour and Still (1968) paper for a detailed discussion of the Iron King mine (Fig. 3, sec. 16, T. 13 N., and Fig. 27). The discussion by Creasey in C. A. Anderson and Creasey (1958) and in Creasey (1952) is dated in interpretation but still good for descriptive purposes. The Iron King is a massive sulfide deposit consisting of 12 en echelon lenses parallel to foliation and plunging steeply north. The deposit was mined primarily for zinc, lead, and silver and was the main producer of zinc and lead in Arizona during the late 1950s and 1960s (Arizona Dept. of Mineral Resources, 1961). Average assays were 0.123 ounce per ton Au, 3.69 ounces per ton Ag, 2.5% Pb, 7.34% Zn, and 0.19% Cu (Gilmour and Still, 1968). The deposit occurred at the contact of a rhyolitic tuffaceous sedimentary unit and andesitic tuffs and flows. The rhyolitic tuffs and sedimentary rocks are very fine grained and extremely well foliated. They probably represent a distal tuff and tuffaceous sedimentary deposit. This writer agrees with the Gilmour-Still interpretation that the orebodies are exhalative sedimentary in origin, presumably formed by submarine fumaroles.

The Copper Shaft dump (Fig. 28), in particular, still carries numerous samples of cellular, porous siliceous sinter with 2-mm pyrite cubes disseminated through it. This writer also found that the Copper Shaft area shows particularly good evidence of chloritic alteration on the west side of the present shaft, perhaps representing one of the fumaroles presumed to have fed the deposit. The silica- and heavy-metal-bearing waters flowed north from the vent for 100 to 1,000 meters where there were depressions in the presumed sea floor in which the silica and heavy-metal sulfides formed. The north end of the ore zone is covered by dumps and alluvium, but there may be other fumarolic centers in

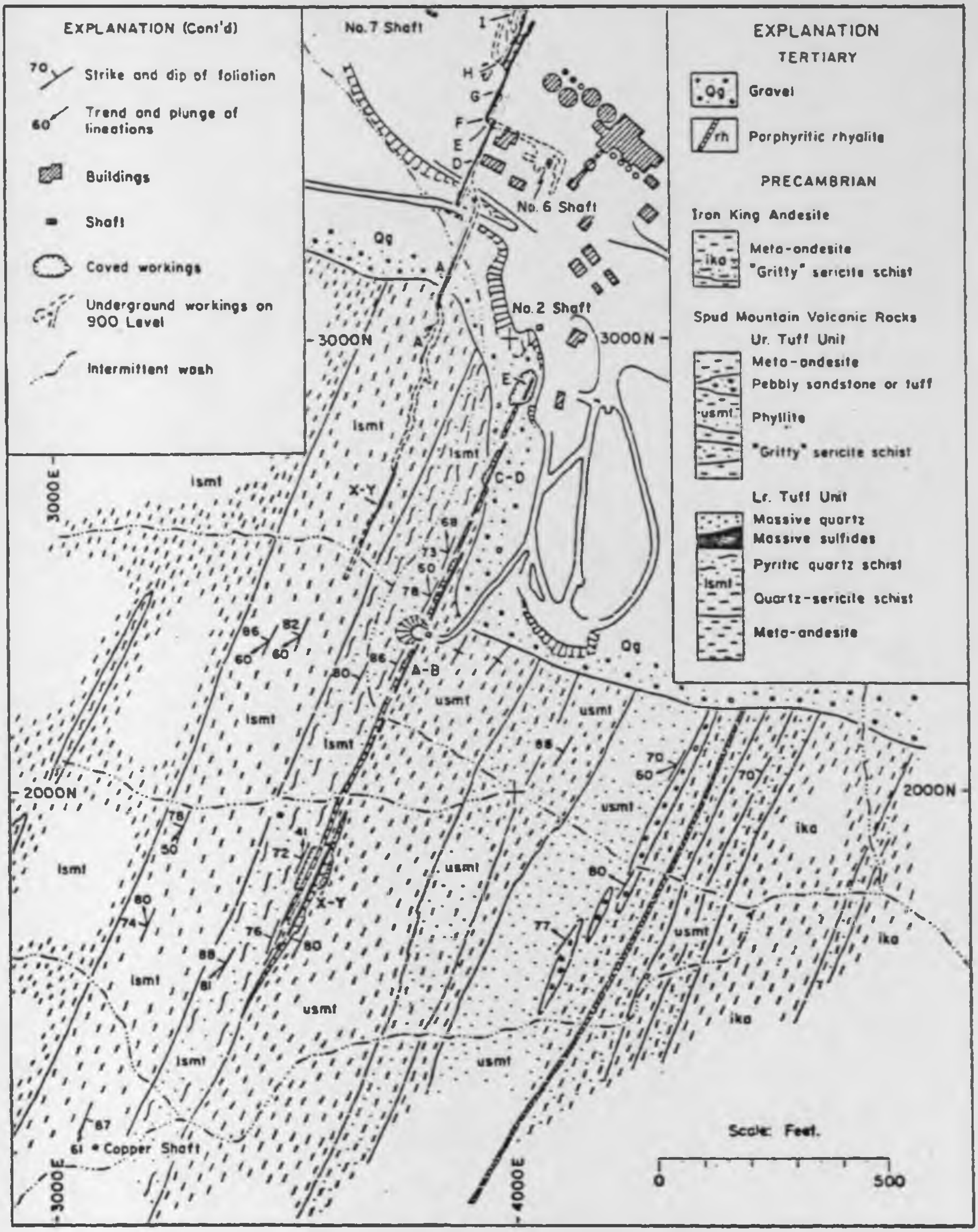

Figure 28. Geologic map of the Iron King mine area. -- From Gilmour and Still (1968).

the area. The ore lenses overlap each other to the east as one comes south (Fig. 28), so assuming the fumarole at the Copper Shaft to have been a main supplier, and that the rocks young to the east, then the northwest or I lens (Fig. 28) was the first to form and each succeeding lens formed in a basin a little farther south, suggesting that there was a slight tilting of the area to the south as the deposit formed.

There is considerable disagreement over certain geologic details in the Iron King mine area. The rhyolitic rocks here are among the most highly foliated in the region, a foliation that can mask primary deposition features or folding so that they are impossible to detect. The copper zone on the west side of the main ore zone at the Iron King is considered excellent evidence, however, that the general younging direction of the rocks here is to the east (Gilmour and Still, 1968).

Lone Pine Mine

The Lone Pine mine is found in the northeast-central part of the thesis area in sec. 34, T. 13 N. (Figs. 3 and 27). It was mined in the early part of this century for gold and silver, and after World War II Fred Gibbs of Prescott, Arizona mined oxidized copper ore. C. A. Anderson and Blacet (1972c) reported, from incomplete records, that 2,763 tons of ore grading 0.2 ounce per ton Au, 3.16 ounce per ton Ag, and 5.35% oxidized copper were mined from 1907 to 1957. Records on file in Phoenix at the Arizona Department of Mineral Resources give assays of 1.5% Pb, 5% Zn, 5% Cu, 0.2 ounce per ton Au, and 3 ounces per ton Ag. Samples found are noticeably less siliceous than those from the Iron King and some other mines in the area. The rocks in the area are slightly hornfelsic owing to contact metamorphism by Laramide granodiorite to the northwest and southeast of the mine. The orebody strikes subparallel to regional foliation, dips steeply east, and is believed to plunge north.

The orebody occurs on the east side of a rhyolitic tuff and tuff-breccia unit. West of the ore zone is a monomictic rhyolitic breccia about 5 meters thick which lenses out about 300 meters north and an unknown distance south of the mine. Sample 226 (Table 1) is a fragment from this breccia. The main difference between fragments and matrix is in the SiO_2 content. The matrix appears to be more mafic, possibly due to admixed andesitic mud. East of the breccia is a zone of chloritically altered rhyolite about 5 meters thick. Sample 191 (Table 1) is from this zone and is the altered equivalent of sample 193 which was collected distally about 50 meters south of the altered zone. The altered zone has been leached of Na, K, and Si and enriched in Fe and Mg. This alteration is similar to that noted by Roberts and Reardon (1978) at Mattagami Lake, Quebec, Canada, and known at numerous other volcanogenic massive sulfide deposits (Spence and de Rosen-Spence, 1975; Spence, 1975; Gilmour, 1965; Sangster, 1972). A heavily chloritized sample was found on the dump that closely resembles the "black schist," or altered zone material, from the United Verde mine, Jerome, Arizona. Unfortunately, the sample's exact location underground is not known, but an X-ray diffraction pattern of the chlorite is identical to that reported by Franklin, Kasarda, and Poulsen (1975) from the Mattabi deposit, Canada, namely a magnesian ripidolite, according to Hey's (1954) classification. An iron-rich carbonate mineral, giving an X-ray diffraction pattern similar to ankerite, was also noted as an abundant gangue mineral in this sample from the Lone Pine mine.

Immediately overlying the altered zone is the ore zone, which is a few meters thick and, in turn, is overlain by a massive lens of ferruginous chert. This lens, about 20 meters long and 10 meters wide in outcrop, is of unknown vertical extent. The west, or probable footwall, side of the lens contains cubic voids after pyrite or magnetite. This unit is overlain by a sedimentary unit of mixed composition which is about 15 meters thick, followed by a series of mafic flows and tuffs. Thus this small orebody exhibits classic massive sulfide form and zoning. It occurs at a break between felsic and mafic volcanism and consists stratigraphically from bottom to top of a rhyolite breccia, then a chloritically altered zone, then the ore zone, and finally a zone of iron oxide and silica deposition. C. A. Anderson and Blacet (1972c) further report that a zone about 35 meters thick of disseminated pyrite and chalcopyrite occurs on the west or footwall side of the deposit, evidently a "stringer" zone corresponding to the chloritic alteration zone on the surface but much wider. The Lone Pine orebody has all the characteristics of a proximal massive sulfide deposit.

Boggs Mine

The Boggs mine is in sec. 4, T. 12 N. (Figs. 3 and 27), about 1,800 meters south of and in approximately the same stratigraphic position as the Lone Pine mine. The Boggs originally produced primarily gold and silver, but during 1905 to 1909 it produced considerable copper (Lindgren, 1926). Again during World War II it was mined for copper. C. A. Anderson and Blacet (1972c) report a shipment from 1943 which assayed 0.45 ounce per ton Au, 5.2 ounces per ton Ag, 1.07% Cu, and 4.3% Zn. Minerals found on the dump were major sphalerite with lesser pyrite, chalcopyrite, and arsenopyrite. The dump material here also has a hornfelsic texture, again due to contact metamorphism by the Laramide intrusion. Two 1-meter-wide Laramide granodiorite dikes trending parallel to regional foliation are exposed in the pit here. C. A. Anderson and

Blacet (1972c) give an attitude for the deposit of N. 20° E., dipping steeply northwest with an unknown plunge. This writer found mostly vertical and steeply east dipping rocks in this area, but the units are so nearly vertical that east and west dips can be found in the same area. This variability is a function of the passive slip nature of deformation and the isoclinal folding.

The deposit occurs within a rhyolitic crystal tuff unit which is in the same relative position as that at the Lone Pine mine. It is near the break between felsic and mafic volcanism, although not precisely on it as is the Lone Pine body. There is another rhyolitic unit to the east of the one containing the Boggs mine. This easternmost rhyolite contains several ferruginous chert lenses. Farther east a sedimentary unit is found, and still farther east the mafic units are superposed.

Iron Queen Mine

The Iron Queen mine is in sec. 4, T. 12 N. (Figs. 2 and 27), about 450 meters south and west of the Boggs. It is probably in the same stratigraphic position as the Boggs and Lone Pine, although this cannot be proven because the area between the Boggs and Iron Queen mines is covered. The production history of the Iron Queen is similar to that of the Boggs, but it was not mined during World War II for copper. C. A. Anderson and Blacet (1972c) quote Lindgren

(1926) as saying that ore minerals were the same as at the Boggs mine, but of lower grade; 0.025 ounce per ton Au, 1 ounce per ton Ag, and 2%-2.75% Cu. Sphalerite and pyrite were noted on the dump. A most impressive feature of the Iron Queen dump material is the amount of cellular, pyritic, siliceous sinter. If one equates this sintery material with fumaroles or hot springs, then the Iron Queen mine area definitely was a vent.

Lindgren (1926) makes note of the presence of garnets, epidote, and other contact metamorphic minerals at the Boggs and Iron Queen mines. During this thesis study this writer found garnets in outcrop immediately west of the Iron Queen dumps, and considers them to be a Laramide effect, like the hornfels, and related to the Big Bug intrusion. The area of these two mines, known as Boggs Flat, is a topographic low and is probably underlain by an eastern extension of the Big Bug intrusion. The Iron Queen mine occurs within a rhyolitic unit, succeeded to the east by a sedimentary unit, and then the same mafic flows encountered 450 meters to the north at the Boggs mine. Thus these mines all occur at approximately the same horizon.

Upshot Mine

The Upshot mine is in sec. 16, T. 12 N. (Figs. 2 and 27), about 2.5 km south of the Iron Queen mine. Very little published material could be found on the Upshot, but some records in the Arizona Department of Mineral Resources in Phoenix suggest its production was primarily lead-zinc with some copper, silver, and gold. Dump samples show abundant massive sphalerite and galena. The ore is very siliceous, similar to that found at the Iron King mine, and a few sintery specimens were found. The deposit strikes subparallel to foliation and dips steeply west. Plunge is unknown.

The deposit occurs at about the same stratigraphic horizon as the Iron Queen, Boggs, and Lone Pine mines (Fig. 27), although as at the Boggs there is another rhyolite to the east of the Upshot before the sedimentary horizon and mafic flow units are reached. There is a 5-meter-wide chloritic zone to the west of the ore zone and a zone of ferruginous chert lenses to the east of the ore zone (Fig. 29). Sample 212 (Table 1) is from the northern extension of the rhyolite which contains the ore zone. This rhyolite is a fine-grained, highly foliated unit similar to that at the Iron King mine. This fine grain size suggests that it may be a distal rhyolite. Thin sections show it to be about 60% quartz and 40% sericite, with few accessory minerals. Similar high-sericite, fine-grained rhyolites were found in thin sections from the Iron King and Pentland ore zones.

Hackberry Mine

The Hackberry mine is in sec. 17, T. 12 N. (Figs. 2 and 27), about 1,200 meters southwest of the Upshot. It was

Figure 29. Geologic relationships at the Upshot mine. -- Massive outcrop at right center is ferruginous chert, which appears to overlie the ore-bearing horizon. The string of outcrops to the left are the ore zone in which the adit in lower center of picture has been driven. An alteration zone to the left of the ore zone is not detectable on the photograph. Facing north. Drill road is about 3 meters wide.

originally located about 1880 and was mined for gold, silver, and oxidized copper until 1909. It lay idle until 1929 when it was mined sporadically by various groups for gold, silver, copper, lead, and zinc. This production ended in 1947. Composite assays over the period from 1929 to 1947, compiled by Gibbs (1964), are 0.113 ounce per ton Au, 5.18 ounces per ton Ag, 2% Cu, 3.5% Pb, and 9% Zn from 13,000 tons of ore. The dump contains abundant massive sphalerite, pyrite, and galena with lesser chalcopyrite. The ore is typically very siliceous, similar to that found at the Iron King and Upshot mines. Quartz and an ankeritelike carbonate were the major gangue minerals noted in thin section.

The deposit occurs in a fine-grained rhyolitic tuff unit which is in contact on its western side with a coarser grained rhyolitic quartz crystal tuff. The east side of the ore deposit is covered by dumps, but farther north and south of this area lies a mixed andesitic tuff and sedimentary unit, succeeded to the east by a major rhyolitic unit. This unit then is succeeded farther east by the mafic flow units, which can be traced north past the Upshot, Iron Queen, Boggs, and Lone Pine mines (Fig. 27). Thus the Hackberry does not appear to occur at the same stratigraphic horizon as the previously mentioned mines.

The Hackberry occurs as five en echelon lenses striking about N. 35° E., which dip steeply west and plunge steeply north, subparallel to regional foliation and lineation. The lenses average about 25 meters long along strike, 2 meters wide perpendicular to strike, and 100 meters long parallel to plunge according to maps at the Arizona Department of Mineral Resources in Phoenix. Three of the five lenses crop out.

Pentland Mine

The Pentland mine is in sec. 17, T. 12 N. (Figs. 2 and 27), about 1,200 meters north of the Hackberry mine and only about 500 meters west of the Upshot. No published information could be found on the Pentland. The dumps are moderately extensive, however, with a variety of material. Pyritic and chalcopyritic material, disseminated and in stringers in a chloritic matrix, was abundant. This rock strongly resembles "stringer" ore from the altered footwall zone of numerous Canadian volcanogenic massive sulfide deposits. Cellular, pyritic siliceous sinter was present, suggesting that there had been a fumarolic vent here. Massive pyritic material with lesser sphalerite and chalcopyrite was also found. Much of the dump material is strongly chloritic, and this, plus the sintery material, strongly suggests that a geothermal circulation system vented here and probably chloritically altered at least some of the rocks.

The deposit occurs within a fine-grained, highly foliated rhyolitic tuff or tuffaceous sediment. A thin-section shows the unit to be highly siliceous and sericitic, similar to units containing the Iron King and Upshot deposits. This unit is probably the same as the one that contains the Hackberry mine, only occurring on the opposite limb of an inferred antiform.

Butternut Mine

The Butternut mine is located in sec. 8, T. 12 N. (Figs. 2 and 27), in the south central part of the thesis area. Production of gold, silver, and oxidized copper transpired during the early part of this century. It is not known whether or not it produced any copper during World War II. The New Jersey Zinc Company drilled two holes in the area in 1953, and the following composite assays were obtained from open-file reports of the Arizona Department of Mineral Resources in Phoenix: 0.025 ounce per ton Au, 1.16 ounces per ton Ag, 1.1% Pb, 4.9% Zn, and 1.6% Cu. Dump material shows abundant fine-grained, massive, and banded sphalerite and chalcopyrite with lesser pyrite and minor arsenopyrite. A few scattered pieces of cellular, pyritic siliceous sinter were also found. The rock here is very hornfelsic because the mine is only 750 meters south of the Big Bug intrusion. This hornfelsic texture tends to obliterate original rock textures unless they were very prominent. There is also a fracture zone trending N. 37° E. through the collapsed shaft at the Butternut. Rocks on the east side of the shaft dip vertically, while those on the west side dip steeply to the west. Displacement could not be determined due to lack of exposure. The fracture zone could not be traced north or south but is assumed to trend subparallel to foliation.

The deposit occurs within a fine-grained rhyolitic tuff or tuffaceous sedimentary unit, a siliceous, sericitic unit similar to those containing the Pentland, Upshot, and Iron King mines (Fig. 27). Several small ferruginous chert pods immediately west of the ore zone suggest a west-facing stratigraphy here. This supports the view that the mine occurs on the east limb of a major synform.

Cross sections constructed from the New Jersey Zinc Company drill logs on file at the Arizona Department of Mineral Resources, Phoenix, show that both holes intersected mineralized zones, but that the zones are not at the same stratigraphic position. This difference in position suggests that the ore occurs in at least two different lenses or stratigraphic positions.

Carbine Prospect

The Carbine prospect is 1 km west of the Hackberry mine in sec. 17, T. 12 N. (Figs. 2 and 27). No published data were found pertaining to it, and the small dump there shows that no major work has been done. Several samples from the dump show chalcopyrite in a moderately chloritized, siliceous rock. Minor pyrite was present, and several samples consisted of the only massive magnetite found in the thesis area.

Exact rock relationships at the prospect are not well known because of complex lensing and intertonguing or folding and heavy brush cover, but the mineralization appears to occur in a fine-grained rhyolitic tuff or tuffaceous sedimentary unit about 25 meters east of a coarse-grained rhyolitic quartz crystal tuff unit. Immediately east of the mineralization are several pods of ferruginous chert.

Victor-Swindler and Huron-Montezuma Prospects

These claims occur in secs. 28 and 33, T. 13 N. (Figs. 3 and 27), between the Lone Pine mine and Highway 69. The mineralized zones occur as three subparallel discontinuous zones, almost 2 km long, within rhyolitic rocks, which include both coarse-grained quartz crystal tuffs and tuffaceous sedimentary units. There are at least 11 small- to medium-size prospect pits occurring along the zones. Most of these are small, showing that production was minor. No published data were found. Probably gold and silver were recovered from the oxidized zones. Dump samples show pyritic, siliceous sinter with no other sulfides. Several zones of weakly chloritized rhyolitic crystal tuff were found, which, with the sintery material, suggests that fumaroles vented here and altered the rock.

Mattie and Little May Prospects

The Mattie is a small prospect in sec. 4, T. 12 N. (Figs. 3 and 27), about 500 meters northwest of the Boggs mine. Several small dumps were found with no evidence of mineralization, although there are several small limonitic zones and a weakly chloritized rhyolitic zone. Significant is the fact that a monomictic rhyolitic breccia runs through the claim and then north to the ridgeline (Fig. 3). The limonitic zones occur on the eastern edge of a rhyolite with an andesite to the east. No published data could be found although drill road access to the property suggests that it has been drilled.

The Little May prospect occurs in sec. 27, T. 13 N. (Figs. 3 and 27), at the extreme northeast corner of the thesis area. A small propsect pit was found with no evidence of mineralization. Numerous ferruginous chert lenses occur here, and an outcrop of weakly disseminated pyrite in rhyolite was found. There is a rhyolitic breccia here also. This zone is at the same stratigraphic horizon as the Lone Pine mine to the south.

Unnamed Prospects

No attempt will be made in this paper to describe all of the prospects scattered over the area, but several warrant some discussion.

A prospect pit in limonitic, sericitic, fine-grained rhyolitic tuff or tuffaceous sediment occurs in the northwest corner of sec. 33, T. 13. N. (Fig. 3). Up to several percent disseminated pyrite was found in siliceous sinter on the prospect dump. This rhyolitic horizon, plus another to the west, can be traced south into the hornfelsic zone in sec. 32. Here two more prospect pits occur. One is within a dark hornfelsic rock, which is not believed to be rhyolitic. Disseminated pyrite and siliceous rock is found on a small dump. The other prospect pit is plainly within the western rhyolite horizon. This dump has pyritic siliceous sinter with copper oxide staining. The dump at this site is of very fine grained material, so it may have been the site of a small mill for treating ore from several pits to the west. These western pits occur in extremely fine grained, dark-colored hornfelsic rocks, so it is impossible to say what they were originally. They are not believed to be rhyolitic, however, and this zone may represent an epigenetically mineralized fracture zone related to the Laramide intrusion. The two rhyolitic horizons to the east of this zone are probably northern extensions of the rhyolites found at the Butternut mine (Fig. 2). It is impossible to trace the rhyolites through the hornfelsic zone related to the Big Bug pluton, but they appear to occupy similar positions on the eastern limb of the major synform (Figs. 2 and 3).

Two small pits occur in the southwestern part of sec. 27, T. 13 N. (Fig. 3). These pits are in an andesitic unit with no rhyolites. There is a quartz vein with minor oxide copper stain. There are two possible origins for these quartz veins and others in the thesis area. One is that they are quartz segregations formed during regional metamorphism. Silica taken into solution during metamorphism commonly migrates to local areas of lower pressure where quartz may precipitate in veins and pods. Ramberg (1952) discusses the mobility of silica during metamorphism and gives numerous examples of segregations in even low-grade metamorphic rocks. These veins might also be hydrothermal and associated with either Precambrian or Laramide ore-forming processes. However, because the veins and pods show no distribution preferential to mineralized areas, a metamorphic origin for them is favored. Some copper was evidently also extracted during metamorphism from the rocks, and when the quartz was redeposited the copper came out of solution with it.

Two small pits occur in sec. 8, T. 12 N. (Fig. 2), south of Big Bug Creek. These pits are within a rhyolitic unit, although outcrop is poor and the unit could not be positively traced to the north or south. This rhyolite is believed to be a northern extension of the rhyolite that contains the Pentland mine. The dumps contain abundant limonitic rhyolite with a trace of oxide copper stain.

An extensive zone of limonitic stain occurs in sec. 20, T. 12 N. (Fig 2), south of the Hackberry mine. Only one small pit was found in this zone and no sulfides or copper oxides were observed, but the iron oxide is most impressive in places and is definitely after sulfides. Weakly chloritized rhyolites were observed in several spots. This zone is apparently a southern extension of the Hackberry and Pentland zones.

Summary of Economic Geology

The most significantly and consistently mineralized horizon would seem to be the one on the eastern edge of the area (Figs. 2, 3, and 27) separating the rhyolitic units on the west from the mafic flows on the east. Starting at the north (Figs. 3 and 27), this horizon contains the Little May prospect, the Lone Pine mine, the Boggs and Iron Queen mines (Figs. 2 and 27), and the Upshot mine. There seems to be a facies change also from proximal to volcanic centers at the Lone Pine mine (Figs. 3 and 27) to distal to them at the Upshot (Figs. 2 and 27). The Boggs and Iron Queen mines are intermediate, and the Little May area has too little mineralization exposed to permit its classification.

The Huron-Montezuma and Victor-Swindler claim areas (Fig. 3) are considered to be proximal because of the many massive, coarse-grained rhyolitic tuffs. This zone can then be traced south through the Pentland zone (Fig. 2) and just west of the Hackberry mine. The Pentland shows both proximal and distal characteristics. The Hackberry mine occurs in a rhyolite unit between the Pentland and Upshot zones (Fig. 2). This rhyolite unit may be the same as that containing the Pentland because of its position on the opposite limb of an inferred antiform from the Pentland. The Hackberry mine shows definite distal characteristics.

The Butternut mine (Figs. 2 and 27) occurs on the limb of a major synform opposite to the limb containing the Iron King mine (Figs. 3 and 27), although the distance separating them is too great to suggest any clear relationship. The Iron King mine shows distal characteristics while the Butternut is also considered to be distal but with less clear characteristics.

DISCUSSION AND INTERPRETATION

As was stated in the structural section of this paper, it is believed that the thesis area has been subjected to extreme isoclinal folding. However, the overprinting of transposition in approximately the same plane as the fold axes has resulted in obscuring fold closures and other direct evidence of folds. This has made it impossible to reconstruct the original stratigraphy of the area and so the oldest unit can only be inferred. Therefore, in the following section the discussion will proceed from the northwest corner of the thesis area to the southeast corner, a progression moving across the section as now exposed in a direction thought to be perpendicular to stratigraphy and foliation except at fold closures.

The tuff-breccia exposed on Spud Mountain (Fig. 3) and to the southwest was probably formed as a subaqueous pyroclastic flow breccia as described by Parsons (1969) and Fiske and Matsuda (1964). Material appears to have flowed off of submarine volcanic highs by a turbidity current process. Coarse, graded bedding found in Galena Gulch in sec. 29, T. 12 N. (Fig. 3), gives contradictory facing directions in different places, a phenomenon probably caused either by mesoscopic folding, which is widespread in the area, or by reverse graded bedding. Tasse, Lajoie, and Dimroth (1978) performed a detailed study of a volcaniclastic sequence at Noranda, Quebec, Canada, and found that reverse graded bedding is quite common. Lajoie (1977) reports the same in a general discussion of "mill rock." Porphyritic andesite clasts with feldspar phenocrysts are the most abundant fragments in the breccia in the thesis area, although rhyolitic clasts are also present. Clasts range from less than one centimeter up to one meter long in a direction parallel to regional foliation. As one moves east down the slope of Spud Mountain (Fig. 3), the clasts become smaller and fewer in number. The same is true as one moves southwest along foliation until south of Galena Gulch in sec. 29, T. 13 N. (Fig. 3), where there are few breccia beds left and the unit is predominantly feldspar crystal tuff. The rocks forming Spud Mountain would thus seem to have been deposited in a basin on the flank of a submarine andesitic volcano.

East of Spud Mountain, the rocks continue to become finer grained until the fine-grained rhyolitic tuffs and tuffaceous sedimentary units of the Iron King ore horizon are reached in sec. 21, T. 13 N. (Fig. 3). These rocks are believed to be distal because of their very fine grain size and well-foliated nature. As the Iron King ore horizon is traced to the southwest, it loses its rhyolitic character and becomes a mix of rhyolitic and andesitic debris, which suggests a source to the north for the rhyolitic material in the Iron King ore horizon. Just how far north would be hard to judge, but certainly not as far as Jerome, as suggested by Bouley and Hodder (1976). Their suggestion that the Iron King area is a distal equivalent of the Jerome area is much too simplistic, as pointed out by P. Anderson (1977). Attempts to trace the actual ore-bearing horizon at the Iron King mine to the southwest along strike revealed several limonitic zones in secs. 28 and 29, T. 13 N. (Fig. 3), but they were much too discontinuous to connect with the zone at the Iron King mine.

The southwest corner of sec. 29 and the northwest corner of sec. 32, T. 13 N. (Fig. 3), contain abundant rhyolites interbedded with andesites and sedimentary units, suggesting that there may have been a rhyolitic center somewhere farther southwest that would probably coincide with the area now occupied by the main mass of the Big Bug intrusion. This area was not mapped in this study but probably should be looked at in more detail because of the presence of these rhyolites.

Between the Iron King ore horizon (Fig. 3) and the Texas Gulch Formation is a sequence of mafic tuffs and flows and interbedded sediments. One possible pillow was found in this zone and the presence of numerous limy beds attests to the submarine nature of deposition. Most of the units are lapilli tuffs and tuffaceous sediments, with feldspar crystals the dominant lapilli-size fragments.

The Texas Gulch Formation (Fig. 3) is considered to be the youngest Precambrian rock unit in the thesis area. This age is based on stratigraphic-structural relics in the thesis area and on evidence outside the area to the south where the Texas Gulch Formation is in depositional contact with the Brady Butte Granodiorite (C. A. Anderson and Blacet, 1972c). The Brady Butte intrusion cuts Precambrian volcanic rocks similar to those in this study area such that the Texas Gulch Formation at Brady Butte must be younger than the volcanics. This writer did not personally trace the Texas Gulch unit north to the thesis area, but other investigators (C. A. Anderson and Blacet, 1972a, b, and c) have found the lithologies to be nearly identical such that the Texas Gulch lithologies within this thesis area can be demonstrated to be the same as those at Brady Butte and therefore to be younger than the volcanics.

C. A. Anderson and Blacet (1972a, b, and c) considered the Texas Gulch Formation to be in fault contact with neighboring rocks. As seen in the field, within this thesis area, there is no evidence of faulting along either the east or west contacts. However, since contacts generally parallel foliation, it is possible that evidence of shearing would be destroyed, although such obliteration is not believed to be the case. The Texas Gulch lithology is believed to be in depositional contact with the underlying volcanics such that the contacts represent a regional unconformity. Recent mapping in the region by others (O'Hara et al., 1978; DeWitt, 1976) confirms this view.

Stratigraphic facing indicators to confirm the synclinal character of the synform, with the Texas Gulch Formation as the axis, are unfortunately not compelling. The sequence of units at the Iron King mine (Fig. 3) suggests an east-facing mode, while the sequence at the Butternut mine on the opposite limb (Fig. 2) appears to be west-facing. The general decrease in size and abundance of fragments from Spud Mountain (Fig. 3) to the Iron King mine also suggests an east-facing stratigraphy on the west limb. It was hoped that whole rock geochemistry would help solve this problem but no coherent pattern was apparent from the samples collected on both limbs of the fold.

The rocks between the Texas Gulch Formation and Highway 69 (Fig. 3) are a series of interbedded mafic tuffs, flows, and sediments. The rocks 100 meters west of Highway 69 in secs. 21, 22, and 28, T. 13 N., contain abundant tuff-breccia beds with clasts of porphyritic andesite similar to those on Spud Mountain. These tuff-breccias may be correlatable with those on Spud Mountain, although they would seem to be farther from the source because of their generally thinner-bedded occurrence and smaller fragment size. It is not known how far north the antiformal axis (Figs. 2 and 3) projects through this area because the lithologies are too similar and intertonguing for reliable differentiation. The rocks here contain numerous interbedded fine-grained sedimentary rocks probably derived, based on their dark color, from a dominantly mafic provenance.

As this sequence of rocks is traced to the southwest, they become finer grained and more sedimentary. Two rhyolitic horizons also appear (Fig. 3, northwest corner of sec. 33, T. 13 N.), which grade into the sedimentary units to the north. These rhyolitic tuffs or tuffaceous sedimentary rocks are abundantly limonite stained and several prospect pits show weak disseminated pyrite. It is not known whether these rhyolites occupy the same or opposite limbs of the projected antiform. Farther south below Big Bug Creek (Fig. 2), rhyolites believed to be stratigraphically the same are mineralized at the Butternut mine, and the Texas Gulch Formation passes about 300 meters west of the Butternut mine. The presence of a volcanic center to the south is suggested because the dominantly sedimentary area in the northwest corner of sec. 33, T. 13 N. (Fig. 3), is supplanted south and east of the Butternut mine (Fig. 2) by an area of dominantly mafic lapilli tuffs and tuff-breccias. These units contain porphyritic andesite and rhyolite clasts similar to those on Spud Mountain and west of Highway 69 in secs. 21, 22, and 28, T. 13 N. (Fig. 3).

The area of secs. 5 and 8, T. 12 N. (Fig. 2), contains a north-plunging antiform, which is defined by the convergence of the rhyolites at the Butternut and a major rhyolite to the east. Parasitic folds found in the northwest corner of sec. 17, T. 12 N. (Fig. 2), which indicate an antiformal axis to the west, are further evidence of the presence of this fold. The west-facing stratigraphy at the Butternut mine and east-facing breccia beds in the south part of sec. 8, T. 12 N. (Fig. 2), also suggest a fold. C. A. Anderson and Blacet (Plate 1, 1972c), show an east-facing bulge on the east contact of the Texas Gulch Formation in sec. 18, T. 12 N., west of the Hackberry mine. C. A. Anderson and Blacet show a north-plunging fold axis trending northeast out of this bulge which corresponds to the above-described fold. Exactly how far north this fold continues is not known. The lack of any distinctive lithologies to the north between the Texas Gulch Formation and Highway 69 (Fig. 3) precludes tracing units around closures. It is also not known whether the rhyolites in the northwest corner of sec. 33, T. 13 N. (Fig. 3), are the two exposed on the west limb of the fold at the Butternut mine or whether they are a transposed closure of the same rhyolite horizon on opposite fold limbs.

East of Highway 69 (Fig. 3), a major change occurs in the form of greatly increased rhyolitic volcanism. There is at least one major fold, and possibly others which were undetected, trending through this area such that it is hard to determine just how many discrete rhyolite horizons are present. Whole rock chemical analyses of samples 215, 217, and 218 (Table 1) strongly suggest the presence of a major fold. Figures 13-18 show the chemical similarity of these three samples. Samples 217 and 218 are from opposite limbs of the fold (Fig. 3, northeast corner of sec. 33, T. 13 N.). In the field they appear to be very similar massive rhyolite flows or shallow sills (Fig. 30). The sill occurrence is favored because identical rocks can be traced discontinuously in the same horizon south past the Hackberry mine (Figs. 2 and 27) to where sample 215 was collected. It is not believed that a rhyolite as siliceous as this unit could be widespread for 7 km on the surface as a thin flow. As a sill, however, it could retain most of its volatile elements and heat and thus maintain sufficient fluidity. The fold causing the duplication of this sill is believed to be antiformal because of east-facing flowtop breccia exposed at sample site 218 (Fig. 3) and east-facing graded bedding elsewhere on this east limb (Fig. 3).

The horizon on the west limb of the fold, which contains samples 215 and 217, can be traced south confidently for 7 km partly because of the rhyolite occurrence but also because of extensive and characteristic limonite stains along it. It was evidently a horizon marked by abundant fumarolic activity which resulted in the widespread deposition of pyrite, which, in turn, produced the

Figure 30. Outcrop of massive rhyolite sill (?). -- The outcrop is approximately 10 meters thick at base. Facing north. Northeast corner of sec. 33, T. 13 N.

limonite. At certain places such as the Pentland mine (Fig. 2) there was also base-metal mineralization, although this horizon has not been as profitable as others. The rhyolites on the east limb of this fold have also not been profitable with the exception of the Hackberry mine (Fig. 2) on the south end. Unquestionably, the most productive rhyolite horizon, except for that at the Iron King, has been the easternmost one, which contains the Lone Pine, Boggs, Iron Queen, and Upshot mines (Fig. 27). These mines are all on approximately the same horizon. This horizon also shows a lateral facies change from proximal at the Lone Pine mine southwesterly through the Boggs and Iron Queen area to distal at the Upshot mine (Fig. 27).

Attempts were made to use the characteristics of rhyolite breccias to locate volcanic centers. A breccia consisting of rhyolite and chert clasts in an andesitic matrix occurs in the western central part of sec. 27, T. 13 N. (Fig. 3) near the Little May prospect. The largest fragments, 1.5 meters long, were found about 150 meters southwest of the Little May. This breccia is polymictic and was probably deposited in a basin near the flank of a volcano. There is a monomictic rhyolitic breccia exposed in the footwall of the Lone Pine mine (Fig. 3). The fragments decrease in size to the north and could not be traced to the south so they seem to center on the Lone Pine mine, which was evidently a site of explosive rhyolitic volcanism. Another monomictic, rhyolitic breccia was found at the Mattie prospect in the northeast corner of sec. 4, T. 12 N. (Fig. 3). This breccia increases in fragment size to the north up the hill until the largest fragments are found on the ridgeline. Thus the Mattie is also on the flank of a rhyolitic center. There are undoubtedly many more local volcanic centers in this area as suggested by the widespread occurrence of rhyolitic tuff-breccias and coarse-grained crystal tuffs (Fig. 3, north and east of Highway 69). These other units could not be followed to their sources, however, because of poor outcrop or complications due to folding. There is, nonetheless, a general tendency in this particular part of the section toward more distal rocks as one goes southwest along strike (Fig. 2). This is not to say that there are no small, local volcanic centers south of Big Bug creek, but that the most extensive ones are north and east of Highway 69 (Fig. 3). The general thinning and pinching together of the rhyolitic units toward the southwest also suggest this, although part of this pinching effect may be due to fold closures. It is not believed that all of this pinching together is a folding effect, however, because the mafic flows east of the thesis boundary are definitely different than the dominantly intermediate tuffs and breccias west of this boundary. This contact seems to mark a significant change from andesitic and felsic explosive volcanism and sedimentation to one of mafic flow volcanism. The structure is apparently more complex than just an overturned syncline as interpreted by C. A. Anderson and Blacet (1972c, Plate 1).

Two rock units are interpreted differently in this study than they were by C. A. Anderson and Blacet (1972c). On their Plates 1 and 2 they show many bodies of quartz porphyry in the area suggesting the intrusive nature of these rocks. In this study, these units have been interpreted as extrusive quartz and feldspar crystal tuffs, primarily because they are conformable with other rock units. At least one was found that also shows graded bedding of quartz crystals. C. A. Anderson and Blacet (1972c) also show several large bodies of gabbro, again suggesting an intrusive origin. In this study, these rocks are interpreted as massive basalt flows, not only because of their conformable nature but also because of the presence of interbedded sedimentary rocks that do not show up at the mapping scale of C. A. Anderson and Blacet, nor, in many places, at the mapping scale of this study.

An observation that impressed this writer throughout this study was the general similarity between the massive sulfide deposits of Proterozoic age in this study area and the Archean deposits of the Canadian Shield. A more detailed comparison of the deposits in the two areas shows interesting features. The most striking similarity noted between both areas was the close association between massive sulfide deposits and submarine felsic volcanic rocks or tuffaceous sediments derived from felsic rocks. The Canadian deposits show a more direct association with rhyolitic tuffs and breccias, while the deposits in this study area, with the exception of the Lone Pine mine which occurs in a definite rhyolitic tuff-breccia, seem to be associated more with finer grained felsic tuffs or tuffaceous sediments. This contrast may be more a function of a distal character of the deposits in this study area rather than a real fundamental difference between the Canadian and Arizona deposits because when one includes other Arizona Proterozoic deposits not in this study area such as the United Verde (C. A. Anderson and Nash, 1972), Copper Queen (Brook, 1974), and DeSoto and Bluebell Mines (DeWitt, 1976) there is seen to be a close association with proximal felic volcanics. In the Canadian deposits, the enclosing volcanic stratigraphy has been studied in enough detail to show that the massive sulfide deposits generally occur at the stratigraphic top of felsic units. In many areas it is possible to follow these horizons for many kilometers and find ore deposits occurring at the same stratigraphic level. It was hoped that the volcanic stratigraphy of this study area could be worked out in enough detail to show a similar relationship, but complex folding prevented determination of sufficiently detailed stratigraphic relationships. The author believes however that the Iron King, Lone Pine, and Butternut mines occur at the tops of different felsic units, and that certain other mines, such as the Lone Pine, Boggs, Iron Queen, and Upshot, occur at approximately the same stratigraphic position.

Another similarity between the Canadian Archean deposits and the Arizona Proterozoic deposits is their occurrence within greenstone belts which are probably metamorphosed and deformed volcanic island-arc environments. A composite Canadian greenstone belt includes a tholeiitic base with predominantly ultramafic or mafic volcanism, grading up through a calc-alkaline zone with intermediate to felsic volcanism, capped by either an alkaline volcanic top or a dominantly sedimentary top. The Canadian Archean sulfide deposits typically occur within the calc-alkaline middle to upper part of the volcanic pile. A similar picture has been suggested by P. Anderson and Guilbert (1979) for the Arizona Proterozoic. Their work has shown that the Arizona greenstone belts have a tholeiitic-mafic base, calc-alkaline intermediate to felsic center, and sometimes an alkaline felsic top. A notable difference is the lack of ultramafic komatiites in the Arizona belts.

Going from a regional to local scale also shows many similarities between the two regions. Both Canadian and Arizona deposits typically occur as tabular lenses or cigar-shaped pods. Their present attitude may vary from flat lying to nearly vertical, depending on the degree of regional deformation. A common characteristic of the Canadian deposits is the presence of a chloritically enriched root projecting stratigraphically below the ore lense. In the thesis area, only one chloritically altered zone was positively identified, that at the Lone Pine mine, and it seems to be more like a flat lens than a true root, although detailed mapping may change this picture. The apparent lack of positively identified chloritic zones at other mines and prospects in this thesis area may be due to a lack of detailed mapping, a result of their more distal character, or, less likely, their absence. Other proximal Proterozoic massive sulfide deposits in Arizona, the United Verde, DeSoto and Bluebell, and the Bruce and Old Dick deposits (Collins and Clayton, 1977), are all characterized by chloritic alteration zones. The chloritic zone detected by this author at the Lone Pine mine shows the same iron and magnesium enrichment and alkali and silica depletion reported for numerous Canadian deposits.

Texturally and mineralogically there are similarities and differences between the Canadian and Arizona deposits. Both contain "stringer" and massive and banded sulfide ores. This writer noted a lack of sulfide breccia ores in this study area but again this may be due to a more distal origin with less direct explosive volcanism during ore formation. Sulfide breccia ores may be present at the United Verde and other proximal Arizona deposits.

Mineralogically the Arizona and Canadian deposits show some differences. Canadian deposits usually have as much pyrrhotite as pyrite, while the Arizona deposits have very little pyrrhotite. This pyrrhotite-pyrite distinction has been attributed to both differences in availability of sulfur in the original depositional environment (Pilmer and Finlow-Bates, 1978) and to varying degrees of metamorphism (Sangster, 1972). The Canadian Archean deposits are characterized by a zinc-copper rich mineralogy. This chalcopyrite-sphalerite dominance is true for the Arizona Proterozoic deposits classed as proximal such as the United Verde; however, Arizona deposits classed as distal such as the Iron King have a sphalerite-galena-rich mineralogy. Canadian Archean deposits typically show a metal zoning from copper to zinc from the footwall to the hanging wall of the deposit. Only the Iron King mine in this study area has enough detailed information published to determine metal zoning, and it does have a copper-rich zone at the base and a zinc-lead-rich zone at the top. Copper to zinc zoning from footwall to hanging wall is also reported from the United Verde deposit and from the Old Dick and Copper Queen deposits near Bagdad, Arizona (Collins and Clayton, 1977). Thus the above discussion, summarized in Table 4, shows far more similarities than differences between the Canadian Archean deposits and the Arizona Proterozoic deposits.

Table 4. Comparison of features of Canadian Archean massive sulfide deposits and Arizona Proterozoic massive sulfide deposits

Feature	Arizona	Canada
Association with submarine fragmental rhyolites	common	common
Occurrence at top of rhyolite units	some	common
Occurrence at a restricted number of horizons	some	common
Volcanic Piles show gradation from tholeiitic mafic base to calc-alkaline felsic top	probable	yes
Tabular lense shaped orebody	common	common
Chloritically enriched root	proximal--yes distal--no	proximal--yes distal--no
Alteration zone enriched in Fe and Mg, depleted in Si, Na, and K	yes	yes
"Stringer" ore present	yes, in proximal bodies	yes
Massive and banded sulfide ores present	common	common
Ratio of pyrite (Py) to pyrrhotite (Po)	Py > Po	Py = Po
Ore metals	Proximal Zn-Cu Distal Zn-Pb	Zn-Cu
Metal zoning: Cu-rich base, Zn-rich top	some	common
Association with Fe-rich chemical sediments	common	common
Siliceous hanging wall lithology	common	common

CONCLUSIONS

A series of dominantly tholeiitic, mafic to felsic volcanic, volcaniclastic, and sedimentary rocks was deposited along with interbedded syngenetic massive sulfide bodies and ferruginous cherts in what was to become the Poland Junction area, Arizona. Vertical and lateral facies changes over short distances produced a complexly intertongued group of rock units. Areas proximal and distal to volcanic centers can be determined by primary rock characteristics and associated massive sulfide bodies. A close relationship between volcanogenic massive sulfide deposits and rhyolites was found. Mapping also succeeded in defining several horizons that are favorable for the occurrence and discovery of further ore deposits.

The most important of these is the horizon on the east boundary of the thesis area which runs from the Little May prospect in the north (Fig. 3) to south of the Hackberry mine (Figs. 2 and 27). This horizon includes the Lone Pine, Boggs, Iron Queen, and Upshot mines (Figs. 2, 3, and 27) and has been a significant producer of metals in the past. Another horizon with potential is that which contains the Hackberry mine (Figs. 2 and 27). Weak to extensive limonitic zones on strike for about 1 km north and south of the Hackberry exist. The rhyolite horizon containing the Hackberry continues northeast past Highway 69 onto Figure 3. In this area, however, no limonites were found along this particular rhyolite horizon, so its potential may be confined to terrain south of the highway. Another potential mineralized horizon is the one containing the Pentland mine (Figs. 2 and 27). This horizon can be traced from southwest of the Hackberry mine (Fig. 2), through the Pentland zone, northeast past Highway 69 to the areas of the Victor-Swindler and Huron-Montezuma claims (Fig. 3). Limonitic zones exist along the entire length of this horizon. The rhyolite zones containing the Pentland and Hackberry mines (Figs. 2 and 27) are believed to be the same, repeated by isoclinal folding, and the possibility exists that the horizon containing the Upshot, Iron Queen (Figs. 2 and 27), Boggs, and Lone Pine mines (Figs. 3 and 27) is continuous. No major fold axes could be defined between the Upshot and Hackberry horizons, but detailed mapping in the future may disclose one.

The rhyolitic horizon hosting the Butternut mine (Figs. 2 and 27) has been shown to be the same as the next rhyolite to the east between the Butternut mine and Big Bug creek (Fig. 2) repeated by folding. The limonitic rhyolites in the northwest corner of sec. 33 and east part of sec. 32, T. 13 N. (Fig. 3), are also believed to be the same as those containing the Butternut. The section of this rhyolite horizon between the Butternut mine and the limonitic zones noted above in Figure 3 might have had economic potential at one time but it is now intruded by the Laramide Big Bug pluton (Fig. 3), which destroyed any existing deposits. The main potential of the Iron King ore horizon (Fig. 3) is believed to be northeast of the Iron King mine under the alluvial gravels of the Agua Fria River valley. According to open-file records of the Arizona Department of Mineral Resources in Phoenix, several companies have tested the area with electromagnetic systems and found conductors. Drilling has been done with unknown results.

Both proximal and distal massive sulfides have been found in the thesis area. Proximal ones, showing chloritic alteration zones and intimate association with rhyolitic breccias, include the Lone Pine mine and possibly the Pentland mine. Distal bodies, showing zinc-, lead-, and silver-rich mineralogies, association with fine-grained rhyolitic tuffs and tuffaceous sediments, and sintery quartz indicating fumarolic activity, include the Hackberry, Upshot, Iron King, and Butternut mines. The Boggs and Iron Queen mines are intermediate between the two end-members.

Unconformably overlying the older volcanic units is the Texas Gulch Formation, which represents sediments deposited after granodiorite intrusion domed the area and exposed the rocks to erosion.

The Mazatzal revolution, of 1715 to 1660 million years ago, produced steeply plunging isoclinal folds, extensive transposition of bedding, and development of penetrative axial-plane foliation. A minor readjustment presumably at the end of the major deformation produced a second generation of folds represented by foliation kink banding. The classic greenschist mineralogy of albite, chlorite, epidote, clinozoisite, and actinolite is present. Greenschist-grade metamorphism at approximately 350-500°C and 3-8 kilobars pressure was produced during the major deformation event.

Laramide events included intrusion of the Big Bug pluton, which produced a hornfelsic halo in the rocks surrounding it. Laramide mineralization was introduced as crosscutting, fracture-filling veins such as the McCabe-Gladstone, Arizona National, Lookout, and Silver Belt mines.

The Arizona Proterozoic represents a tremendous potential for regional and detailed mapping projects, and not until many such projects are done will a full understanding of the complex geology be possible.

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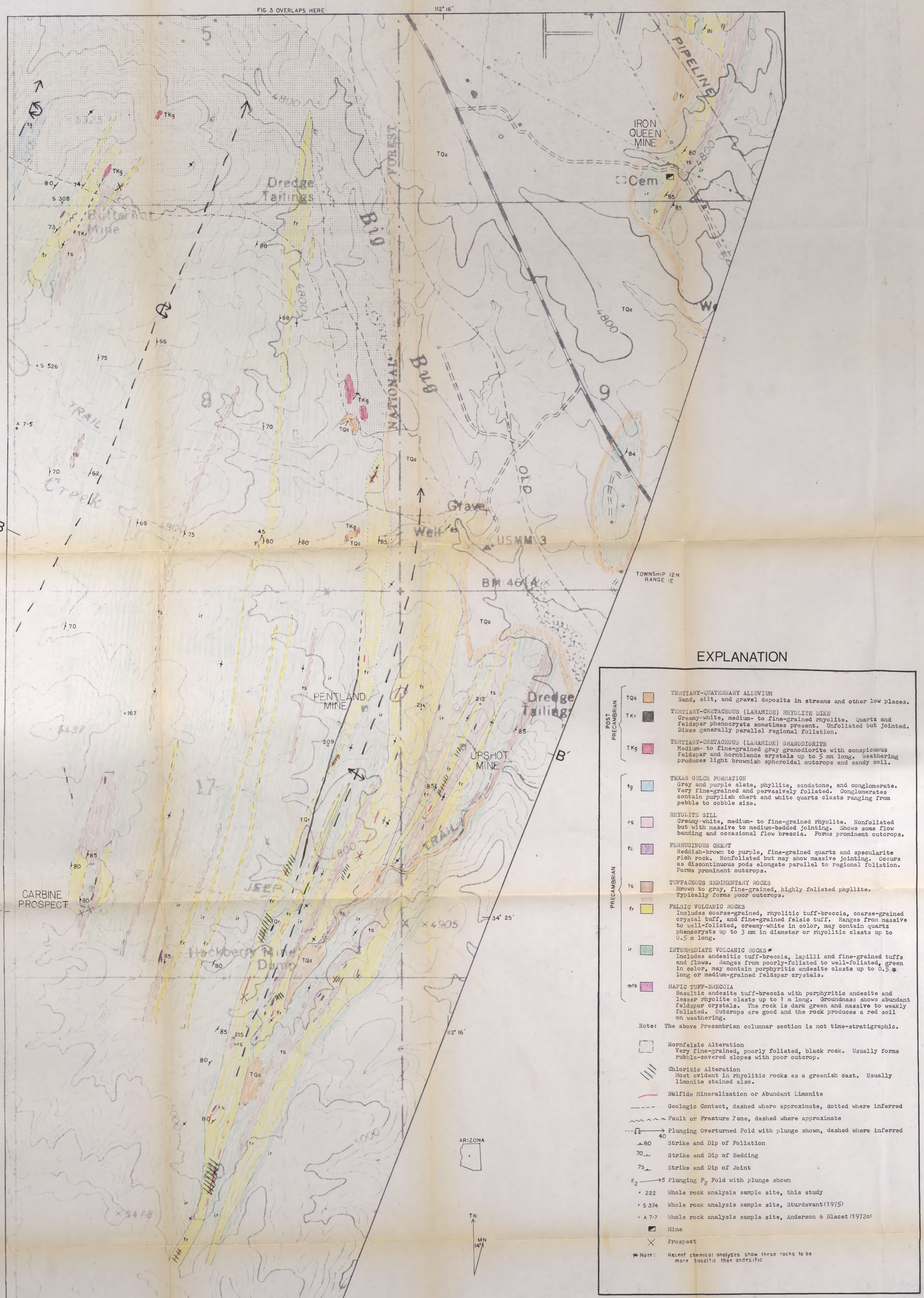

EXPLANATION

POST PRECAMBRIAN	TQa	🟧	TERTIARY-QUATERNARY ALLUVIUM Sand, silt, and gravel deposits in streams and other low places.
	TKr	⬛	TERTIARY-CRETACEOUS (LARAMIDE) RHYOLITE DIKE Creamy-white, medium- to fine-grained rhyolite. Quartz and feldspar phenocrysts sometimes present. Unfoliated but jointed. Dikes generally parallel regional foliation.
	TKg	🟥	TERTIARY-CRETACEOUS (LARAMIDE) GRANODIORITE Medium- to fine-grained gray granodiorite with conspicuous feldspar and hornblende crystals up to 5 mm long. Weathering produces light brownish spheroidal outcrops and sandy soil.
PRECAMBRIAN	tg	🟦	TEXAS GULCH FORMATION Gray and purple slate, phyllite, sandstone, and conglomerate. Very fine-grained and pervasively foliated. Conglomerates contain purplish chert and white quartz clasts ranging from pebble to cobble size.
	rs	⬜	RHYOLITE SILL Creamy-white, medium- to fine-grained rhyolite. Nonfoliated but with massive to medium-bedded jointing. Shows some flow banding and occasional flow breccia. Forms prominent outcrops.
	fc	🟪	FERRUGINOUS CHERT Reddish-brown to purple, fine-grained quartz and specularite rich rock. Nonfoliated but may show massive jointing. Occurs as discontinuous pods elongate parallel to regional foliation. Forms prominent outcrops.
	ts	🟫	TUFFACEOUS SEDIMENTARY ROCKS Brown to gray, fine-grained, highly foliated phyllite. Typically forms poor outcrops.
	fr	🟨	FELSIC VOLCANIC ROCKS Includes coarse-grained, rhyolitic tuff-breccia, coarse-grained crystal tuff, and fine-grained felsic tuff. Ranges from massive to well-foliated, creamy-white in color, may contain quartz phenocrysts up to 3 mm in diameter or rhyolitic clasts up to 0.5 m long.
	ir	🟩	INTERMEDIATE VOLCANIC ROCKS* Includes andesitic tuff-breccia, lapilli and fine-grained tuffs and flows. Ranges from poorly-foliated to well-foliated, green in color, may contain porphyritic andesite clasts up to 0.5 m long or medium-grained feldspar crystals.
	mtb	🟪	MAFIC TUFF-BRECCIA Basaltic andesite tuff-breccia with porphyritic andesite and lesser rhyolite clasts up to 1 m long. Groundmass shows abundant feldspar crystals. The rock is dark green and massive to weakly foliated. Outcrops are good and the rock produces a red soil on weathering.

Note: The above Precambrian columnar section is not time-stratigraphic.

▨	Hornfelsic Alteration Very fine-grained, poorly foliated, black rock. Usually forms rubble-covered slopes with poor outcrop.
////	Chloritic Alteration Most evident in rhyolitic rocks as a greenish cast. Usually limonite stained also.
—	Sulfide Mineralization or Abundant Limonite
——---···	Geologic Contact, dashed where approximate, dotted where inferred
~~ ^^^	Fault or Fracture Zone, dashed where approximate
---→ 40	Plunging Overturned Fold with plunge shown, dashed where inferred
⊥80	Strike and Dip of Foliation
70⊥	Strike and Dip of Bedding
75⊥	Strike and Dip of Joint
F_2 →5	Plunging F_2 Fold with plunge shown
• 222	Whole rock analysis sample site, this study
• S 374	Whole rock analysis sample site, Sturdevant (1975)
• A 7-7	Whole rock analysis sample site, Anderson & Blacet (1972c)
◩	Mine
×	Prospect

*Note: Recent chemical analyses show these rocks to be more basaltic than andesitic

FIG. 2 GEOLOGIC MAP OF POLAND JUNCTION AREA, YAVAPAI CO., ARIZONA

BASE FROM POLAND JUNCTION 7.5' QUAD

SOUTH HALF

SCALE 1:6000

GEOLOGY BY W. WEBB, 1977 + 78

500' 0 500'

0 .25 MI

0 .25 .5 KM

CONTOUR INTERVAL 40 FEET

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FIG. 3 GEOLOGIC MAP OF POLAND JUNCTION AREA, YAVAPAI CO., ARIZONA

NORTH HALF

BASE FROM POLAND JUNCTION 7.5' QUAD
MAYER 7.5' QUAD
HUMBOLDT 7.5' QUAD
PRESCOTT VALLEY SOUTH
7.5' QUAD

TN
MN
14°

SCALE 1:6000
500' 0 500'
0 .25 MI
0 .25 .5 KM
CONTOUR INTERVAL 40 FEET

ARIZONA

GEOLOGY BY W. WEBB, 1977 + 78
EXPLANATION SAME AS ON FIG. 2

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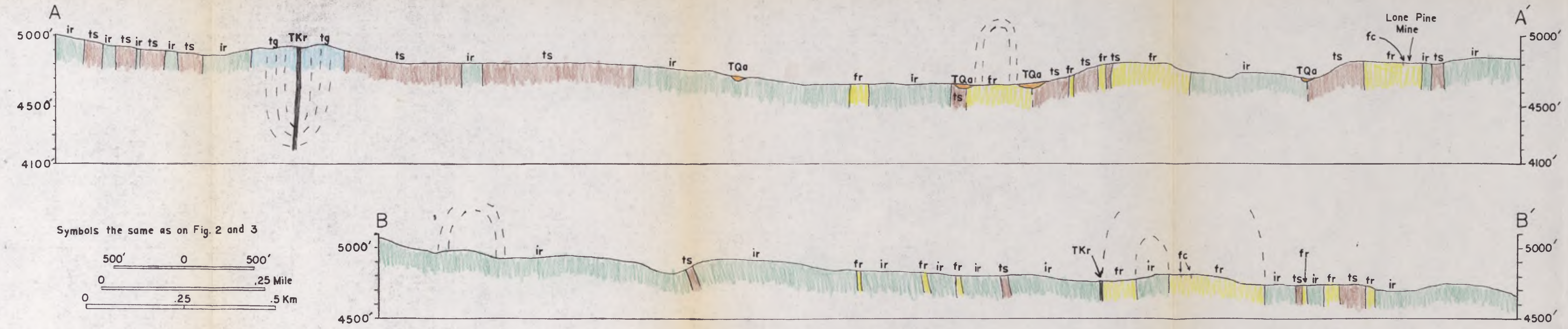

FIG. 4 CROSS SECTIONS FOR FIGURES 2 AND 3

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