DEPARTMENT OF THE INTERIOR

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A Geologic Investigation of the Early Proterozoic Irving Formation, Southeastern Needle Mountains, Colorado

by

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ABSTRACT

The Early Proterozoic Irving Formation in the southeastern Needle Mountains consists chiefly of a bimodal assemblage of subalkaline basaltic to rhyolitic flows and tuffs with associated submarine sedimentary rocks, that are locally intruded by mafic plutonic rocks. Irving lithologies record upper-greenschist to lower-amphibolite facies prograde regional metamorphism and polyphase deformation, retrograde recrystallization, and local contact metamorphism. Field evidence and petrochemical signatures of volcanogenic rocks in the Irving Formation argue for deposition in an oceanic-arc or continental margin-arc. These results agree with regional models that relate Early Proterozoic volcanogenic rocks in Colorado to arc volcanism and related sedimentation.

East of Table Mountain, fluvial siliciclastic rocks of the Vallecito Conglomerate rest unconformably upon previously deformed basement rocks of the Irving Formation. In the canyon of Vallecito Creek, basite clast-rich conglomerate and minor sandstone of the conglomerate of Fall Creek are exposed in a strongly deformed sliver that is faulted against siliciclastic rocks of the Vallecito, and appears to lie in contact with the Irving along a sheared angular unconformity. The conglomerate of Fall Creek is here interpreted as a basal and proximal facies of the Vallecito that was derived largely from erosion of the metamorphosed Irving volcano-plutonic complex.

The Irving Formation and overlying sequence of clastic sediments are deformed into a series of macroscopic, south-plunging folds that are cut by north-northeast and east-west trending faults. On its western and eastern margins, this folded succession of stratified rocks is intruded by batholithic masses of the ca. 1.45 Ga Eolus Granite.

The basement-cover sequence in the study area appears to represent a juvenile magmatic arc-crust complex and overlying continental supracrust. This succession is analogous to other Proterozoic volcano-plutonic basement complexes and overlying siliciclastic successions exposed in north-cental New Mexico and central Arizona.

INTRODUCTION

General Setting

The San Juan Mountains of southwestern Colorado are a spectacular series of glaciated peaks and canyons that lie along the western margin of the southern Rocky Mountains. Covering an area of nearly 10,000 square kilometers, they expose a spectrum of rock types ranging from Precambrian to Tertiary in age.

Early to Middle Proterozoic metamorphic and plutonic rocks exposed in the Needle Mountains, West Needle Mountains, and Grenadier Range form the core of a broad, deeply eroded, domal uplift along the southwestern edge of the San Juan Mountains. This Precambrian complex is blanketed by Tertiary volcanic rocks of the San Juan Volcanic Field to the north and east and Phanerozoic sedimentary strata to the south and west. No substantial exposures of Proterozoic rocks occur between the Precambrian complex in southwestern Colorado and other extensive Proterozoic terranes in Colorado and north-central New Nexico (Figure 1).

Precambrian Rocks of the Needle Mountains

Precambrian rocks in the Needle Mountains and adjacent ranges are exposed over an area of approximately 1100 square kilometers and record a geologic history that spans nearly 400 million years. Deformed and metamorphosed basaltic to rhyolitic volcanogenic and plutonic rocks of the ca. 1.8-1.76 Ga Irving Formation and Twilight Gneiss (Table 1) form the base of Proterozoic terrane in southwestern Colorado. In the West Needle Mountains the Irving Formation is intruded by ca. 1.7 Ga (Table 1) granitoid plutons of the Tenmile Granite and Bakers Bridge Granite (Figure 2). Overlying this ca. 1.8-1.7 Ga crystalline basement complex are thick successions of fluvial to marine, largely siliciclastic, sedimentary rocks of the Vallecito Conglomerate and Uncompahgre Formation (Barker, 1969c; Burns and others, 1980; Harris and Eriksson, 1987; Harris and others, 1986, 1987; Gibson, 1987b; Gibson and others, 1987; this study). Absolute ages of the Vallecito and Uncompahgre have not been obtained, and these units are nowhere in contact. Their stratigraphic relationship is therefore uncertain. Volcano-plutonic basement rocks and siliciclastic cover sequences in the Needle Mountains region record several episodes of greenschist to amphibolite grade regional metamorphism and polyphase deformation (Barker, 1969c; Tewksbury, 1981, 1982, 1984, 1985; Harris and others, 1986, 1987; Gibson, 1987b; Gibson and others, 1987; this study). The basement-cover complex is intruded by ca. 1.45-1.3 Ga (Table 1) granitic to gabbroic plutons and dikes of the post-tectonic Eolus Granite, Electra Lake Gabbro, quartz diorite of Pine River, and Trimble Granite (Figure 2).

Statement of Problems and Objectives of Study

The Irving Formation in the southeastern Needle Mountains is a metamorphosed and deformed complex composed of basaltic to rhyolitic lava flows and tuffs and associated submarine sedimentary rocks, that

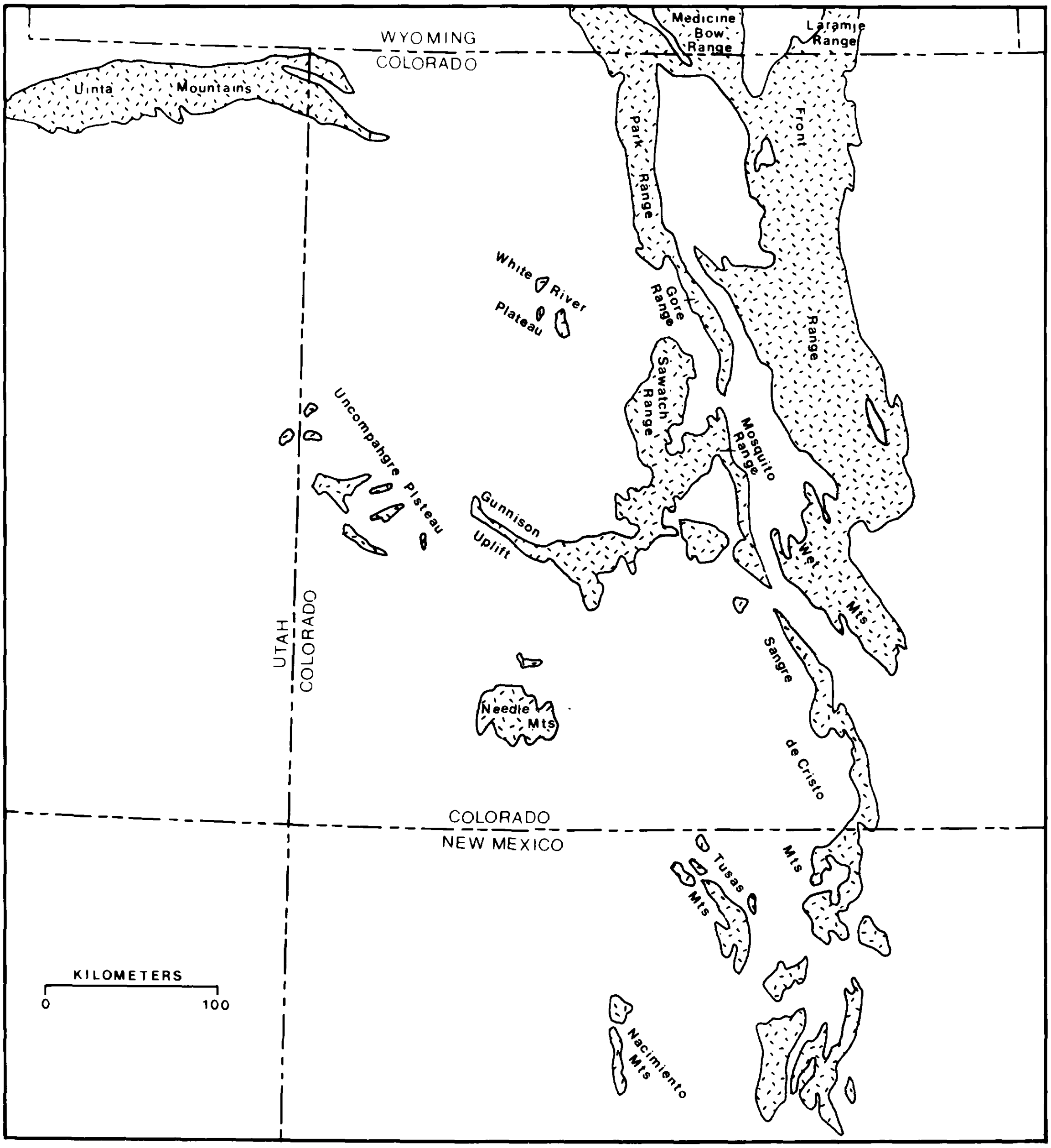
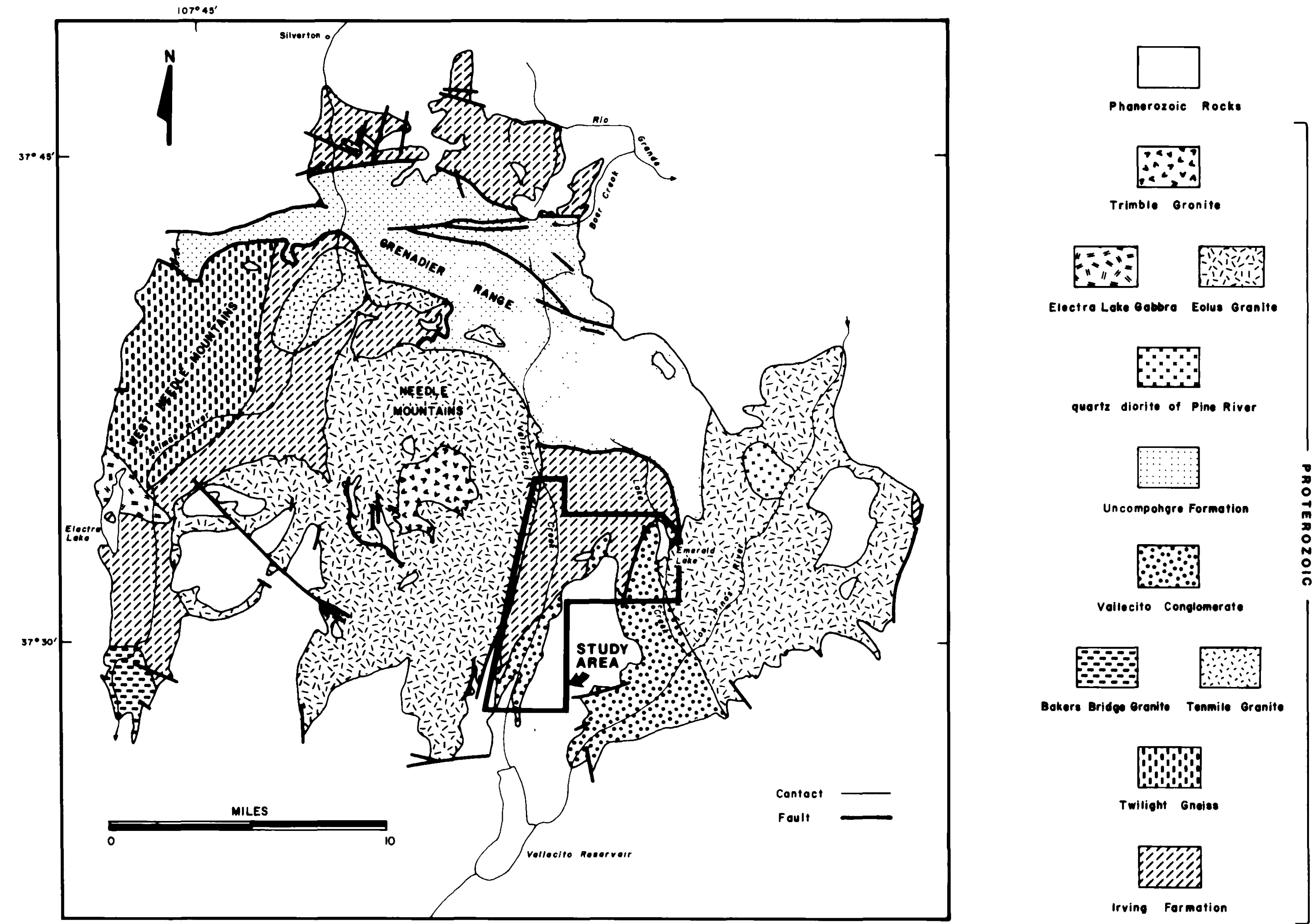


Figure 1. Map of southern Rocky Mountains in Colorado and northern New Mexico showing the distribution of Proterozoic rocks (stippled). Modified after King (1976).

Figure 2. Geologic sketch map of the Proterozoic complex in southwestern Colorado (modified after Barker, 1969c). Placement of the Irving Formation beneath the Vallecito Conglomerate in the stratigraphic column reflects results of this study. The inference that the Vallecito was deposited after intrusion of the Tenmile Granite and Bakers Bridge Granite is not constrained by field or isotopic evidence.



107° 45′
37° 45′
37° 30′
N
Silverton
Rio Grande
Bear Creek
GRENADIER RANGE
NEEDLE MOUNTAINS
WEST NEEDLE MOUNTAINS
Electra Lake
Vallecito Creek
Emerald Lake
STUDY AREA
Vallecito Reservoir
MILES
0
10
Contact
Fault
Phanerozoic Rocks
PROTEROZOIC
Trimble Granite
Electra Lake Gabbro
Eolus Granite
quartz diorite of Pine River
Uncompahgre Formation
Vallecito Conglomerate
Bakers Bridge Granite
Tenmile Granite
Twilight Gneiss
Irving Formation

Table 1

Summary of Precambrian geochronology in the Needle Mountains region.

Data Source:	Bickford & others (1968)*	Silver & Barker (1968)*	Bickford & others (1969)*	Barker & others (1969)*	Barker (1969c)*	Bickford (1987, unpub.)
Method:	Rb-Sr	U-Pb	Rb-Sr	Rb-Sr	K-Ar	U-Pb
Unit:						
Irving Formation	.....	.....	.....	.....	.....	1828 ± 31 Ma
Twilight Gneiss	.....	1762 ± 20 Ma	.....	1767 ± 35 Ma	.....	.....
Bakers Bridge Granite	1656 ± 78 Ma	1702 ± 20 Ma	1675 ± 80 Ma	.....	.....	.....
Tenmile Granite	1688 ± 55 Ma	1702 ± 20 Ma	1684 ± 50 Ma	.....	.....	.....
"Whitehead Granite"	1659 ± 65 Ma	1762 ± 20 Ma 1702 ± 20 Ma	1640 ± 74 Ma	.....	.....	.....
Eolus Granite	1435 ± 27 Ma	1445 ± 20 Ma	1435 ± 27 Ma	.....	1465 ± 70 Ma [1] 1396 ± 40 Ma [2]	.....
Electra Lake Gabbro	1423 ± 50 Ma	1445 ± 20 Ma	1423 ± 50 Ma	.....	.....	.....
Trimble Granite	.....	.....	1321 ± 50 Ma	.....	.....	.....
Rhyolite Porphyry Dikes	1286 ± 38 Ma	1445 ± ? Ma	1321 ± 50 Ma	.....	.....	.....

* Ages cited are adjusted to reflect the decay constants recommended by the IUGS Subcommission on Geochronology (Steiger and Jager, 1977). Correction procedures applied are outlined by Harland and others (1982, appendix 1); U-Pb ages — standardized age = published age x 0.99; Rb-Sr ages — standardized age = published age x (old decay constant/1.42 x 10^{-11}); K-Ar ages (correction tables applied).

[1] Hornblende used in calculation.
[2] Biotite used in calculation.

locally are intruded by small masses of mafic plutonic rocks. General petrographic descriptions of some of these rocks exist, but their outcrop distribution and stratigraphic relationships, geochemical characteristics, and structural history have received little attention in previous investigations (Howe, 1904; Cross and others, 1905b; Cross and Larsen, 1935; Larsen and Cross, 1956; Steven and others, 1969; Barker, 1969c).

Controversy over the nature of contacts and stratigraphic relationship of the Irving Formation in the southeastern Needle Mountains and the Vallecito Conglomerate has not been satisfactorily resolved (Cross and others, 1905b; Cross and Larsen, 1935; Larsen and Cross, 1956; Barker, 1969c; Burns and others, 1980; Ellingson and others, 1982; Gonzales and Ruiz, 1982). A detailed discussion of previous workers interpretations regarding these issues is found on pages 9-16 of this report.

The Irving Formation (Figure 2) was originally divided into the Archean schist and gneiss (Animas River-Bear Creek area) and Irving Greenstone (Vallecito Creek-Lake Creek area) by Cross and others (1905b). The validity of the correlation of these units by Barker (1969c) has since been questioned (Ellingson and others, 1982; Scott, 1983; Van Loenen and Scott, 1983; Baars and Ellingson, 1984; and Van Loenen, 1985). In my opinion, no strong evidence either in favor or against this correlation is presented.

Principal objectives of this study are to combine detailed mapping with petrographic and geochemical studies to determine: 1) the lithologies and possible protoliths, stratigraphic relationships, general geologic history, and paleotectonic setting of rocks in the Irving Formation of the southeastern Needle Mountains; 2) resolve the controversy regarding the nature of the contacts between Irving Formation and Vallecito Conglomerate and determine the relative age of these units; and 3) to obtain some preliminary data necessary to evaluate the correlation of the Archean schist and gneiss and Irving Greenstone of Cross and others (1905b), as proposed by Barker (1969c).

Location and Access

The area investigated during this study lies within LaPlata and Hinsdale Counties approximately 30 to 40 miles north-northeast of Durango, Colorado and covers nearly 16 square miles (Figure 3).

A large portion of the area in Vallecito Creek-Los Pinos River region was included in the Weminuche Wilderness in 1975, thus prohibiting the use of motorized vehicles in the area and limiting the means of travel to foot or horseback. Access within the study area is made possible by well maintained pack trails along Los Pinos River-Lake Creek, Vallecito Creek, and the broad ridge (Middle Mountain) between these major drainages (Figure 4).

Travel above timberline is usually difficult from late fall to early spring due to long and severe winters which are common in the Needle Mountains. Even during the warmer months of June through August, access can be impeded by deep perennial snow fields along higher ridges and basins. Melting snow in the high country commonly causes streams to swell to many times their normal size, forming major obstacles to travel from late March until the end of June.

Figure 3. Photograph of part of a 3-D topographic map of the Durango 1° x 2° quadrangle showing the approximate location of Plate 1.

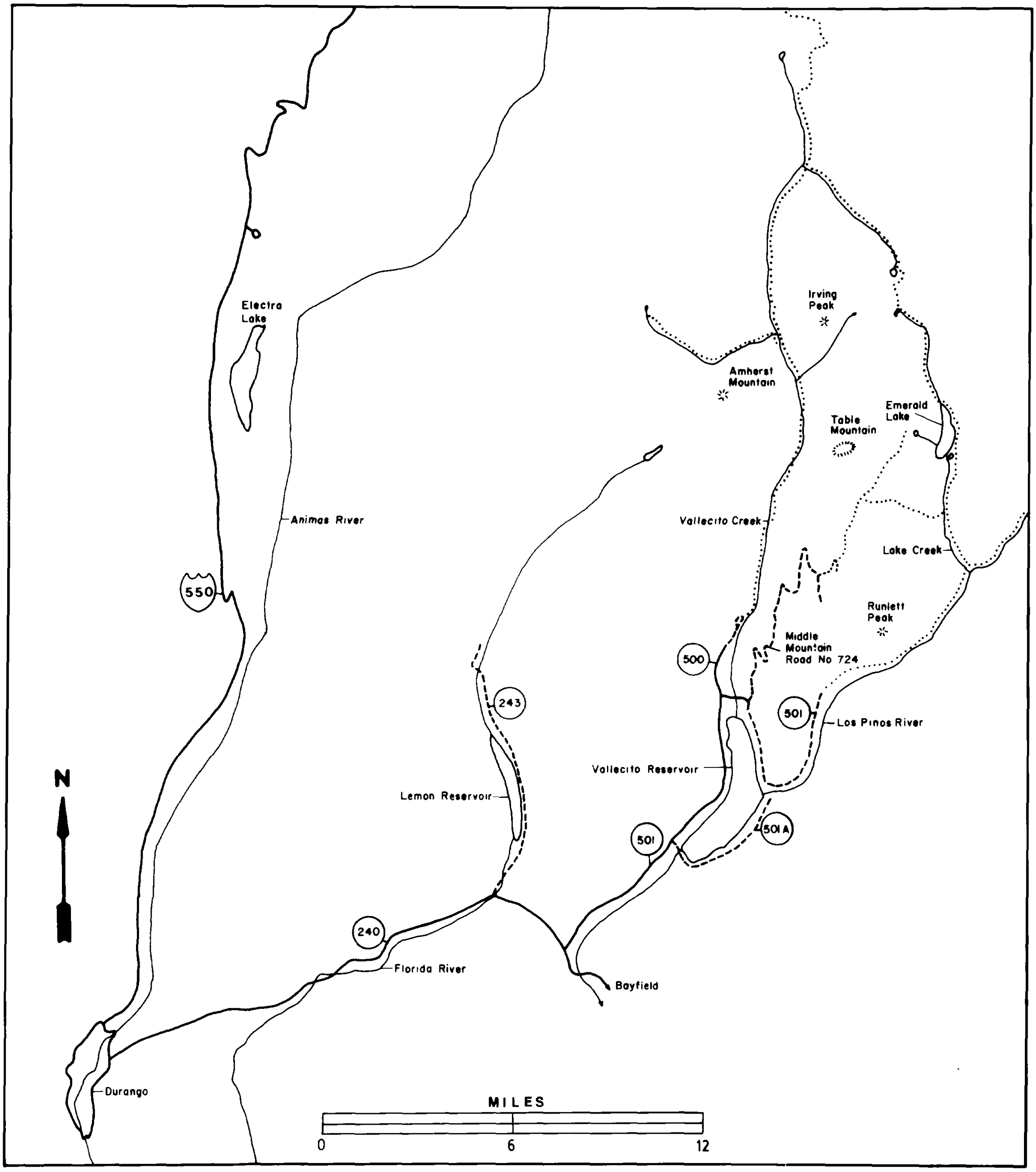


Figure 4. Access map; solid lines are paved roads (shield = U.S. Highway; circle = County Road). Long dashed lines are maintained roadways, short dashed lines signifiy unmaintained roadways, and dotted lines represent maintained trails.

Terrain, Vegetation, and Climate

Steep walled canyons and alpine crags occur throughout the Needle Mountains. Many peaks rise above 13,000 feet and the central mass of the range is marked by four peaks that rise over 14,000 feet. Elevations along Middle Mountain and the sharp ridges which form northern border of the study area range from 11,000 feet to just over 13,000 feet. The flanks of this higher terrain descend steeply into the valleys of Vallecito Creek, Lake Creek, and the Los Pinos River where elevations vary from around 8,000 feet to just over 10,000 feet.

Timberline lies between approximately 11,500 feet and 12,000 feet. Dense forests harboring spruce, fir, pine, and aspen, accompanied by a wide variety of shrubs, grasses, and wildflowers blanket the ridges and gentle benches below this point. This heavy cover often results in poor and limited outcrop exposure. Grass, lichen, flowers, and alpine shrubs form thin, discontinuous carpets between barren, and often extensive, rock surfaces above timberline.

Cold nights and cool days are characteristic of this area during the summer months. Temperatures during the day rarely exceed 80° F and at night commonly drop below 40° F. June is usually a month of low precipitation and fair weather. July and August are characterized by numerous afternoon thundershowers, occassionally accompanied by snowflurries. By late September nighttime temperatures consistently fall below freezing and significant accumulations of snowfall may occur.

Previous Investigations

Early Studies

The Precambrian rocks of the Needle Mountains were first studied (Endlich, 1876) during reconnaissance surveys by the United States Geological and Geographical Survey between 1869 and 1875 (Endlich, 1876). Early cursory descriptions of Precambrian rocks in the Needle Mountains were provided by Comstock (1883, 1887) and Van Hise (1890).

Comprehensive geologic studies in the San Juan Mountains were initiated by the United States Geological Survey in 1895 under the direction of Whitman Cross. By 1910 Cross and his colleagues had compiled 1:62,500 geologic maps for seven 15-minute quadrangles and published the results in a series of folios in the Geological Atlas of the United States. Results of their work on Precambrian rocks in the Needle Mountains region are provided in descriptions of the Silverton (Cross and others, 1905a), Needle Mountains (Cross and others, 1905b), and Engineer Mountain (Cross and Hole, 1910) quadrangles (Figure 5).

Figure 6, column 1, shows the Precambrian stratigraphic succession presented by Cross and others (1905b). Cross and his associates placed metamorphosed mafic to felsic igneous rocks in the Animas River-Bear Creek area at the base of their Precambrian succession, referring to them as Archean schists and gneisses. The name Irving Greenstone was applied to a "complicated series of schists, greenstone, and subordinate quartzite" exposed on Irving Peak and in the Vallecito Creek-Lake Creek area. Initial descriptions of the Irving Greenstone were made by Howe

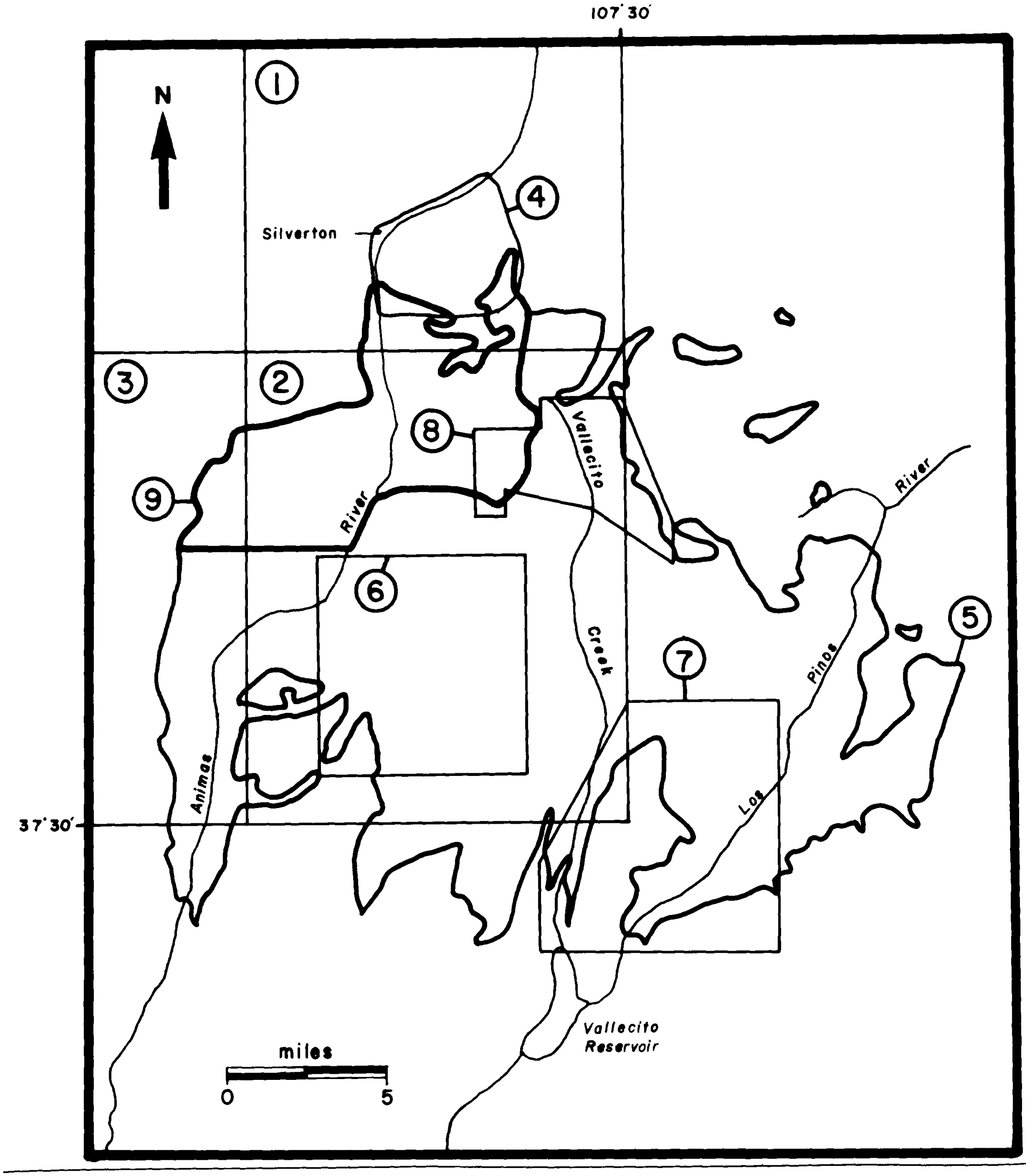
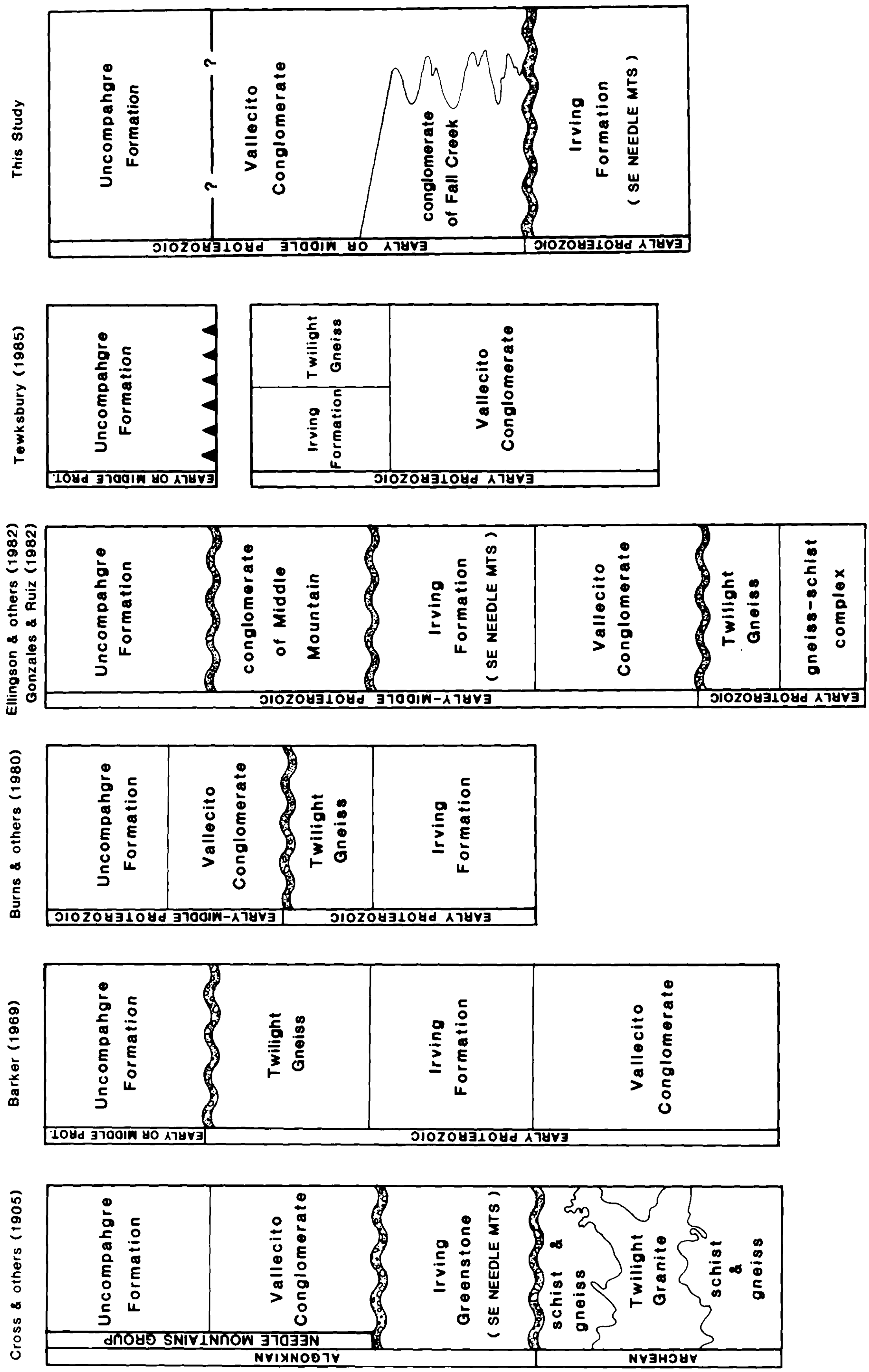


Figure 5. Index map of previous studies in the Needle Mountains. Circled numbers refer to studies in chronological order: 1 - Cross and others (1905a)--part of Silverton Quadrangle; 2 - Cross and others (1905b)--Needle Mountains Quadrangle; 3 - Cross and Hole (1910)--part of Engineer Mountain Quadrangle; 4 - Varnes (1963); 5 - Barker (1969c)--outline of Needle Mountains complex; 6 - Schmitt and Raymond (1977); 7 - Burns and others (1980)--Plate 1; 8 - Tewksbury (1981)--main map area; 9 - Harris and others (1987). Needle Mountains Precambrian complex is also shown on geologic maps of San Juan Mountains by Cross and Larsen (1935) and Larsen and Cross (1956).

Figure 6. Proposed successions of layered Proterozoic rocks in the Needle Mountains region. The Irving Formation in columns 2,3, and 5 consists of the Archean schist & gneiss (same as gneiss-schist complex in column 4) and Irving Greenstone of column 1. Wavy gaps mark periods of erosion. Sawtooth symbol in column 5 denotes that the Uncompahgre Formation is in thrust contact with 1.8-1.76 Ga crystalline basement rocks and that its stratigraphic position is uncertain.



1
Cross & others (1905)
Uncompahgre Formation
Vallecito Conglomerate
NEEDLE MOUNTAINS GROUP
Irving Greenstone (SE NEEDLE MTS)
schist & gneiss
Twilight Granite
schist & gneiss
ALGONKIAN
ARCHEAN
2
Barker (1969)
Uncompahgre Formation
Twilight Gneiss
Irving Formation
Vallecito Conglomerate
EARLY OR MIDDLE PROT.
EARLY PROTEROZOIC
3
Burns & others (1980)
Uncompahgre Formation
Vallecito Conglomerate
Twilight Gneiss
Irving Formation
EARLY-MIDDLE PROTEROZOIC
EARLY PROTEROZOIC
4
Ellingson & others (1982)
Gonzales & Ruiz (1982)
Uncompahgre Formation
conglomerate of Middle Mountain
Irving Formation (SE NEEDLE MTS)
Vallecito Conglomerate
Twilight Gneiss
gneiss-schist complex
EARLY-MIDDLE PROTEROZOIC
EARLY PROTEROZOIC
5
Tewksbury (1985)
Uncompahgre Formation
Irving Formation
Twilight Gneiss
Vallecito Conglomerate
EARLY OR MIDDLE PROT.
EARLY PROTEROZOIC
6
This Study
Uncompahgre Formation
? ?
Vallecito Conglomerate
conglomerate of Fall Creek
Irving Formation (SE NEEDLE MTS)
EARLY OR MIDDLE PROTEROZOIC
EARLY PROTEROZOIC

(1904). In regards to their division of the Archean schists and gneisses and Irving Greenstone, Cross and others (1905b, p. 2) state:

"In many respects similar to the Archean schists of the Animas Canyon, the Irving greenstone must, nevertheless, be distinguished from them, on the account of the distinctive character of certain of the more massive members of the series and presence of sedimentary rocks."

With respect to their placement of the Irving Greenstone stratigraphically above the Archean schists and gneisses they note (Cross and others, 1905b, p. 2-3):

"It is impossible to tell what the relations may have been between the Archean rocks of the Animas Canyon and the Irving greenstone, because the space between them is occupied by the great mass of Eolus Granite. That they are petrographically distinct there can be no question, and the presence of sedimentary rocks in the Irving formation is a good reason for believing it is of later age."

The Vallecito Conglomerate and Uncompahgre Formation were designated by Cross and others (1905b, p. 3) as the lower and upper sections, respectively, of the Needle Mountains Group. This thick succession of quartzite and conglomerate was placed stratigraphically above the Irving Greenstone because of the occurrence of numerous metabasite clasts in what Cross and others (1905b, p. 2-3) interpreted as the base of the Vallecito Conglomerate in Vallecito Creek (conglomerate of Fall Creek in this report). The contact between the Vallecito Conglomerate and Irving Formation in Vallecito Creek is mapped as a fault by Cross and others (1905b).

The work of Cross and his associates established a nomenclature and stratigraphy of the Precambrian rocks in the Needle Mountains and provided information on their petrography, structure, and economic potential. Regional investigations of the entire San Juan Mountains by Cross and Larsen (1935) and Larsen and Cross (1956) summarize much of the early work conducted by Cross and his colleagues.

Results presented by Cross and Larsen (1935) and Larsen and Cross (1956) regarding the nature of the Vallecito-Irving contacts and the relative age of the "Irving Greenstone" that had not been noted in earlier investigations were: 1) all contacts between the Vallecito Conglomerate and Irving Greenstone were shown as faults; and 2) the Irving Greenstone was considered "much less metamorphosed" than the Archean schist and gneiss which Cross and Larsen (1935) and Larsen and Cross (1956) suggested was support for division of these units, as proposed by Cross and others (1905b). The idea that the Irving greenstone had been "less affected by dynamic metamorphism" than the Archean schist and gneiss was first pointed out by Howe (1904). It was not until the work of Cross and Larsen (1935) and Larsen and Cross (1956), however, that this apparent difference in degree of metamorphic deformation was used to imply relative ages of these units.

Contemporary Studies

In 1964 a 1:250,000 scale mapping project of the Durango 1° x 2° quadrangle was initiated by the United States Geological Survey (Steven and others, 1974). A comprehensive study of the Precambrian rocks in the Needle Mountains was carried out by Barker (1968a, 1968b, 1969a, 1969b, 1969c) in conjunction with this investigation. Rb-Sr and U-Pb radiometric ages were obtained (Table 1) for the Twilight Gneiss and intrusive bodies as part of this research. Based on these radiometric dates and his reinterpretation of contacts between the major units, Barker revised the Precambrian stratigraphy, established by Cross and others (1905b) for the Needle Mountains. The most significant changes proposed include: 1) incorporation of the Archean schist and gneiss complex and Irving Greenstone of Cross and others (1905b) into a single unit called the Irving Formation; and 2) abandonement of the Needle Mountains Group and placement of the Vallecito Conglomerate at the base of the Precambrian succession in the Needle Mountains (Figure 6, column 2). Barker (1969c) introduced the name Irving Formation for the Irving Greenstone of Cross and others (1905b) because of the lack of "true greenstone" in this unit. In regards to his inclusion of the Archean schist and gneiss of Cross and others (1905b) into the Irving Formation, Barker (1969c, p. A5) states:

"From their lithologic similarity to the type Irving rocks, their common but not ubiquitous retrograde metamorphism, their structural trends, and their position under the major unconformity, I have grouped all these rocks under the name Irving Formation."

Barker (1969c) interpreted the Irving-Vallecito contacts in Vallecito Creek and the Table Mountain-Dead Horse Creek area as conformable depositional surfaces. Based on well-preserved west facing cross-stratification in the Vallecito Conglomerate in the Vallecito Creek area, he suggested that it was older than the Irving Formation and therefore was not the basal member of the Needle Mountains Group as Cross and others (1905b) had proposed.

Within the Irving Formation in the southeastern Needle Mountains, Barker (1969c) describes a wide variety of lithologies including: "amphibolite, biotite and epidote bearing schist and gneiss, graywacke, biotite-bearing metavolcanics, feldspathic plutonic rocks, andesite, siltstone, quartzite and feldspathic quartzite, muscovite-quartz-biotite schist, and banded iron-formation". The outcrop distribution, and details of the stratigraphic and structural relationships of these rocks, however, were not given.

During the same period as the Durango quadrangle study, a mineral survey was conducted by the U.S. Geological Survey and the U.S. Bureau of Mines in the San Juan and Upper Rio Grande Primitive Areas to evaluate these areas for inclusion into the National Wilderness Preservation System (Steven and others, 1969). As part of this work a special reconnaissance survey was carried out on the Irving Formation in the southeastern Needle Mountains to evaluate reports of potential iron formation (Cross and others, 1905b, page 2). Locations of "magnetic iron formation" and "laminated greenstone" were recorded and geochemical analyses of some lithologies were obtained. None of the iron-rich exposures found by Steven and his associates were considered to have commercial potential because of their small size and low grade.

A National Uranium Resource Evaluation study was conducted by Burns and others (1980) on the quartz-pebble conglomerates in the Vallecito Conglomerate and Uncompahgre Formation. Results of this study suggest a low potential for fossil-placer uranium deposits in these units. Work on the Vallecito Conglomerate during this study is summarized by Ethridge and others (1984). Burns and others (1980, Plate 1) intepreted contacts between the Irving and Vallecito, at the head of Dead Horse Creek, as angular unconformities, and suggested that all additional contacts between these units were faults or fault zones. Based on sedimentary structures observed in the Vallecito Conglomerate at inferred depositional Irving-Vallecito contacts, they placed the Irving Formation beneath the Vallecito Conglomerate (Figure 6, column 3). In agreement with Barker (1969c), Burns and others (1980) concluded that the Uncompahgre Formation was deposited unconformably upon metamorphosed rocks of the Irving Formation and Twilight Gneiss. Based on their post-Irving age assignments for the Vallecito Conglomerate and Uncompahgre Formation they suggest (Burns and others, 1980, p. 75) that a continuous stratigraphic sequence between these units might exist, as reported by Cross and others (1905b).

Column 4 of Figure 6, summarizes the work of Ellingson and others (1982) and Gonzales and Ruiz (1982). During this investigation the Irving-Vallecito contacts exposed in Vallecito Creek and the Table Mountain-Dead Horse Creek areas (Plates 1 and 2) were examined and interpreted as depositional in nature. Based on this, and stratigraphic facing indicated by sedimentary structures in the Vallecito Conglomerate at the contacts in both areas, these workers: 1) placed the sequence of siliciclastic conglomerate and sandstone in the Vallecito Creek-Los Pinos River area conformably beneath the Irving Formation, retaining the name Vallecito Conglomerate for these rocks; and 2) concluded that the Irving Formation was unconformably overlain by the conglomeratic succession in the Table Mountain-Dead Horse Creek area, and the latter representing either basal Uncompahgre or a new unit, informally referred to as the "conglomerate of Middle Mountain".

In addition, Ellingson and others (1982) proposed that the correlation of Cross and others (1905b) Irving Greenstone and Archean schist and gneiss, by Barker (1969c), was not justified. They suggested that based on apparent differences in "parent rocks compositions" and metamorphic grade that: 1) the name Irving Formation be retained for the "greenschist facies" volcanogenic rocks in the Vallecito Creek-Lake Creek area; and 2) the amphibolite-grade, volcano-plutonic complex in the Animas River-Bear Creek area be referred to as the "gneiss-schist complex" (corresponds to Archean schist and gneiss of Cross and others, 1905b), and placed stratigraphically beneath the Vallecito Conglomerate and Irving Formation in the southeatern Needle Mountains. Results of the work by Ellingson and others (1982) and Gonzales and Ruiz (1982) are summarized in Baars and Ellingson (1984). Regarding the relative age of the Irving Formation in the Vallecito Creek-Lake Creek and Animas River-Quartzite Creek area, Baars and Ellingson (1984) state:

"Until more chemical data and age dates are available, the Irving Formation of the eastern Needles should not be correlated with, or the name applied to, gneisses/schists and amphibolites of the Animas Valley. The present study clearly shows differences between these units in mineralogy, sequence, grade of metamorphism, and history."

Tewksbury (1981, 1982, 1984, 1985, 1986) conducted an extensive study of the Uncompahgre Formation in the Grenadier Range, concluding that it was a complexly folded mass which was thrust southward over the Irving Formation and Twilight Gneiss (Figure 6, column 5). She presents the possibility that, because of its allochthonous nature, the age of the Uncompahgre protolith could not be constrained and might be pre-, syn-, or post-Irving/Twilight.

Recently, a detailed examination of the Proterozoic succession on the northwest margin of the Needle Mountains complex has been conducted

(Harris and others, 1986, 1987; Harris and Eriksson, 1987; Gibson, 1987a, 1987b; Harris, 1987; and Gibson and others, 1987). Results of this work suggest that the Uncompahgre Formation "(cover sequence)" was deposited on a basement complex composed of previously deformed and metamorphosed rocks of the Irving Formation and Twilight Gneiss, and ca. 1.7 Ga granitoid plutonic rocks. "Cuspate infolding" of the Uncompahgre into the crystalline basement, subsequent to "limited north-directed thin-skinned thrusting" in the cover sequence, resulted in the localization of ductile deformation along the unconformable basement-cover contacts. The structural evolution presented by these workers for the Uncompahgre Formation is contrary to the fold and thrust belt model of Tewksbury (1981, 1982, 1984, 1985), however, their idea that the Uncompahgre was deposited on an older crystalline complex, and is not an allochthonous mass whose age is entirely unconstrained (Tewksbury, 1985), is consistent with the results of most other previous workers (Cross and others, 1905b; Barker 1969c; and Burns and others, 1980; Gonzales and Ruiz, 1982; Baars and Ellingson, 1984).

Additional Published Work

Table 2 is a comprehensive list of publications that discuss Proterozoic rocks of the Needle Mountains. In addition to the published works mentioned above, this table includes many other early and contemporary works.

Table 2

Published work on Precambrian rocks of the Needle Mountains.

Author(s)	Date of Publication	Form of Publication *	Precambrian Units Discussed	Nature of Study
Endlich	1876	R	granite, quartzite, and schist of the Needle Mtns (then referred to as the Quartzite Mtns)	Cursory descriptions.
Comstock	1883	R	granitic and quartzite series in Animas Canyon	" " "
Comstock	1887	R	" " "	" " "
Van Hise	1892	R	gneiss, granite, schist, and quartzite in Animas Canyon	" " "
Howe	1904	R	Irving Fm in the Vallecito Creek-Lake Creek area	Petrology and petrography with brief discussion of structure and relative age of unit.
Cross, Howe, & Ransome	1905a	RM	Irving Fm (Animas River-Bear Creek area), Uncompahgre Fm, and Whitehead Granite	" " "
Cross, Howe, Irving, & Emmons	1905b	RM	All units except quartz diorite of Pine River	Comprehensive discussion covering mineral deposits, metamorphism, petrology and petrography, stratigraphy of metasedimentary rocks, structural geology, and the sequence of Precambrian events.
Cross & Hole	1910	RM	Irving Fm (Animas River canyon), Twilight Gneiss, Uncompahgre Fm, Electra Lake Gabbro, and Eolus Granite	" " "
Cross & Larsen	1935	RM	All units except Bakers Bridge Granite	Cursory review and descriptions based on largely 1905-1910 publications of Cross and others.
Hinds	1936	RS	Irving Fm, Uncompahgre Fm, Vallecito Conglomerate, and Eolus Granite	General discussion of Needle Mountains Precambrian based largely on the 1905-1910 publications of Cross and others. Summarizes previous investigations and correlates Needle Mountains Group with the Mazatzal Quartzite of Arizona and Cottonwood Group of Utah.
Larsen & Cross	1956	RM	All units except Bakers Bridge Granite	General review and comprehensive descriptions based largely on 1905-1910 publications of Cross & others.
Kelley	1957	RM	All units except quartz diorite of Pine River and Bakers Bridge Granite	Synopsis of Precambrian events and their chronology.
Varnes	1963	RM	Irving Fm (Animas River-Bear Creek area)	Cursory description based on work of Cross, Howe, & Ransome (1905).

Table 2 (continued)

Barker	1968a	A	Irving Fm, Vallecito Conglomerate, Twilight Gneiss, Tenmile Granite, and Eolus Granite	Summarizes his revised version of the Precambrian geologic history in the Needle Mountains and briefly describes units.
Barker	1968b	RS	All Units except quartz diorite of the Pine River	" " "
Bickford & others	1968	A	All plutonic masses except Trimble Granite and quartz diorite of the Pine River	Rb-Sr geochronology.
Silver & Barker	1969	A	" " "	U-Pb geochronology; briefly summarize geologic history of Needle Mountains Precambrian.
Barker	1969a	RS	Vallecito Conglomerate and Uncompahgre Fm	Assesses placer gold potential of units.
Barker	1969b	A	" " "	Interpretes genesis and origin of hematite.
Barker	1969c	RS	All Units	Comprehensive discussion including geochemistry, grade and nature of metamorphism, geochronology, petrology and petrography, sedimentology and stratigraphy, and structural geology.
Barker & Friedman	1969	RS	Pelitic rocks of the Uncompahgre Fm	Describe carbon isotope abundances and discuss probable factors controlling their variability.
Barker & others	1969	RS	Twilight Gneiss	Rb-Sr analysis; discuss petrology and petrography, genesis, geochemistry, as well as possible protoliths and environment of depostion; presents Rb-Sr age determination and briefly summarizes Precambrian events in the Needle Mountains.
Bickford & others	1969	RS	All units except quartz diorite of the Pine River	Rb-Sr geochronology; summarize Precambrian history of the Needle Mountains as reported by Barker (1968a).
Steven & others	1969	RM	Primarily Vallecito Conglomerate, Irving Fm, and Uncompahgre Fm	Assess economic potential of Precambian through Tertiary rocks of the Needle Mountains mining district.
Barker, Peterman, & Marvin	1970	RS	melasyenite of Ute Creek	Geochemistry, geochronology, petrology, and petrography, Rb-Sr isotope characteristics and significance.
Barker & Peterman	1974	R	Twilight Gneiss	Briefly describe lithologies (petrology, chemistry, relationships, and origin); propose models to explain the occurrence of metamorphosed tholeiite and high-silica, low-potash, dacite in Precambrian greenstone belts.
Steven & others	1974	M	All units	Geologic map of the Durango 1° x 2° quadrangle.
Barker & Arth	1976	R	Twilight Gneiss	Discusses various models for generation of trondhjemitic-tonalitic liquids; briefly discusses geochemical character of Twilight Gneiss.
Barker & others	1976	R	Twilight Gneiss	Geochemistry and genesis.
Hutchinson	1976	R	Bakers Bridge Granite, Tenmile Granite, Whitehead Granite, and Eolus Granite	Summarizes geochronologic history of Precambrian rocks in Colorado and parts of Wyoming.

Table 2 (continued)

Van Loenen & Scott	1983	RM	" " "	Mineral resource potential survey of the West Needle Wilderness Study Area. Discuss geology, geochemistry, geophysics, and mineralization in study area. Review previous works and history of mining districts; assess mineral resource potential of units.
Baars	1984	A	Mentions Uncompahgre Fm	Characteristics and evolution of Precambrian fault systems of the Needle Mountains.
Collier	1984	A	Eolus and Trimble Granites	Geochemical characteristics, genesis, and history of parent magmas of the Eolus Granite.
Baars & Ellingson	1984	R	All units except Trimble Granite and quartz diorite of Pine River	General discussion of units and summary of Precambrian events and history incorporating the results of Gonzales & Ruiz (1982) and Ellingson & others (1982)
Ethridge & others	1984	R	Vallecito Conglomerate	Discuss sedimentology and stratigraphy, and possible depositional environment of unit. Based on the study of Burns & others (1980).
Tewksbury	1984	A	All units except Quartz Diorite of Pine River and Electra Lake Gabbro	Gives a short summary of geologic history and reviews timing of deformation in the Uncompahgre Fm and problems regarding origin of these rocks.
Tewksbury	1985	RS	All Units	An in depth discussion of the polyphase deformation in the Uncompahgre Fm. Describes structural features especially along the Irving-Uncompahgre contacts; discusses the timing and history of deformation. Reviews previous ideas of Barker (1969c) and proposes revised stratigraphic succession.
Van Loenen	1985	M	Twilight Gneiss (incorporates Irving Fm of West Needle Mountains in this unit), Tenmile Granite, Uncompahgre Formation, Eolus Granite	Geologic and geochemical maps of the West Needle Wilderness Study Area; includes descriptions of units and a review of Precambrian events and their chronology; summarizes results of geochemical survey described in report of Van Loenen & Scott (1983).
Harris & others	1986	A	Uncompahgre Formation, gneiss/schist/granite of West Needle Mountains, and Tenmile Granite	A chronology of structural events recorded in the Precambrian succession of the West Needle Mountains and description of structures developed.
Tewksbury	1986	R	Uncompahgre Fm	Conjugate crenulation cleavage: Characteristics, origin, timing, and significance.
Wagg	1986	A	Uncompahgre Fm	Summarizes structural history recorded in the Lime Creek area: describes types of structures developed, their features, and timing.
Gibson	1987a	A	basement gneisses in the West Needle Mountains and Uncompahgre Formation	Describes "broken formation" in basement gneisses, and discusses its origin and significance.

Table 2 (continued)

King	1976	RS	All units	Cursory description of the Needle Mountains complex and its history after Barker (1969c).
Tweto	1977	R	All units except quartz diorite of Pine River	Appraises the validity of formally named Precambrian stratigraphic units in Colorado and classifies these units into five major groups based on their chronology and mode of origin.
Schmitt & Raymond	1977	R	Eolus Granite	Economic potential of a composite Tertiary stock and associated alteration of Precambrian wallrock in the Chicago Basin area.
Barker (editor)	1979	R	Twilight Gneiss	A compilation of multi-author works on trondhjemites and other felsic igneous rocks; mentions the Twilight Gneiss in discussions of trondhjemites, referring largely to the geochemical characteristics of the unit.
Burns & others	1980	R	Vallecito Conglomerate and basal conglomerate of Uncompahgre Fm	National Uranium Resource Evaluation study; discusses petrology and petrography, stratigraphy and sedimentology, history and provenance of clastic units; cursory descriptions of structural features and metamorphic history are also provided.
Tewksbury	1981	R (Ph.D. Thesis)	All units mentioned with emphasis on the Uncompahgre Fm	A detailed and comprehensive discussion that focuses on the structural history of the Uncompahgre Fm. Other topics discussed include lithologies, protoliths, metamorphic history, depositional system, age of unit, and mineralization.
Ellingson & others	1982	A	Irving Fm, Twilight Gneiss, Vallecito Conglomerate, Uncompahgre Fm, 1.7-1.4 Ga granitic masses.	Propose a new stratigraphic sequence for layered Proterozoic rocks in the Needle Mts complex. Suggest that Irving Fm in the Animas River-Bear Creek area, and Twilight Gneiss comprise the base of the section, followed by the Vallecito Conglomerate, Irving Fm of the southeastern Needles, and Uncompahgre Fm.
Gonzales & Ruiz	1982	A	Irving Fm, Vallecito Conglomerate, Uncompahgre Fm, Eolus Granite, and "conglomerate of Middle Mountain"	Summarize history and revise Precambrian succession in the southeastern Needle Mountains; propose new unit.
Tewksbury	1982	A	Uncompahgre Fm	Describes structural features including their chronology and evolution.
Houston	1983	A	Uncompahgre Fm	Briefly summarizes lithologies, structural features and history, and discusses possible tectonic evolution.
Scott	1983	M	Twilight Gneiss (Irving Fm of West Needle Mtns included as part of this unit), Tenmile Granite, Uncompahgre Fm, and Eolus Granite	Mine and prospect map of the West Needle Wilderness Study Area.
Birmingham & Van Loenen	1983	R	" " "	Geochemical data for the West Needle Wilderness survey of Van Loenen & Scott (1983).

Table 2 (continued)

Gibson	1987b	R Ph.D. Thesis	1) volcano-plutonic basement composed of ca. 1.75 Ga gneiss complex (Irving Fm and Twilight Gneiss, and ca. 1.69 Ga granitoid plutonics (Tenmile Granite); 2) and siliclastic cover sequence (Uncompahgre Fm)	A comprehensive study of the basement-cover sequence in the northwestern Needle Mountains. Discusses lithologies (e.g. petrology & protoliths); structural features and histories of units; 3) nature of basement-cover contacts and constraints on relative ages of units; 4) grade and nature of metamorphism.
Harris & Eriksson	1987	A	Uncompahgre Fm	Discuss the sedimentology, stratigraphy, environment of deposition, and structural controls on sedimentation.
Gibson & others	1987	A	1,750 Ma felsic to mafic basement gneisses (Twilight Gneiss and Irving Formation); 1,690 Ma granitoids (Tenmile Granite); and cover sequence (Uncompahgre Formation)	Discuss the: 1) structural evolution and contact relationships of Proterozoic basement and cover sequence in the western and northern Needle Mountains; and 2) depositional environment and and stratigraphy of the Uncompahgre Formation. Note similar rock sequences in northern New Mexico and central Arizona and comment on regional implications of supracrustal deformation in these areas.
Harris & others	1987	R	" " "	A detailed discussion of data outlined in Gibson and others (1987).
Tweto	1987	R	Irving Fm, Twilight Gneiss, Tenmile Granite and Bakers Bridge Granite, Vallecito Conglomerate, Uncompahgre Fm, Eolus Granite, Electra Lake Gabbro, Trimble Granite	Extensive review of Proterozoic rocks in Colorado. Discusses general characteristics and regional distribution of major group of layered and plutonic rocks. Briefly describes the features and stratigraphy of Precambrian units in the Needle Mountains.

* R = Report, A = Abstact, M = Map, S = Sketch Map.

RELATIVE AND ABSOLUTE AGE OF THE IRVING FORMATION

Resolution of the age of the Irving Formation in the southeastern Needle Mountains, relative to the Vallecito Conglomerate, is essential for establishing the Proterozoic succession in southwestern Colorado. The absolute age of the Irving in the Vallecito Creek-Lake Creek area is important for assessing its proposed correlation (Barker, 1969c) to Cross and others (1905b) schist and gneiss complex in the Animas River-Bear Creek area (Figure 6), and for broader regional comparisons. Field evidence for the age of the Irving Formation relative to the Vallecito Conglomerate, and a preliminary U-Pb zircon age for the Irving in the southeastern Needles are presented in this section.

Irving-Vallecito Contacts

Quandary over the nature of the contacts and relative stratigraphic age of the Irving Formation and Vallecito Conglomerate is due to the diverse interpretations of previous workers (pages 9-16). Contacts between these units have been interpreted as faults and/or depositional surfaces. In addition, previous investigators (Cross and others, 1905b; Cross and Larsen, 1935; Larsen and Cross, 1956; Barker, 1969c; Burns and others, 1980; Ellingson and others, 1982; Gonzales and Ruiz, 1982; Ethridge and others, 1984) have placed the Irving beneath, between, and upon fluvial siliciclastic rocks of the Vallecito (Figure 6).

Table Mountain-Dead Horse Creek Area

In the Table Mountain-Dead Horse Creek area (Plates 1 and 2), a west-dipping succession of quartz-pebble conglomerate, sandstone, and minor siltstone is unconformably overlain by Paleozoic strata to the south, and elsewhere lies in contact with the Irving volcano-plutonic complex. Most previous workers concluded that this sequence was part of the Vallecito (Cross and others, 1905b; Cross and Larsen, 1935; Larsen and Cross, 1956; Barker, 1969c; Burns and others, 1980; and Ethridge and others, 1984). Gonzales and Ruiz (1984), however, proposed that these rocks comprised a new unit called the "Middle Mountain conglomerate" (Figure 6, column 4).

Contacts between siliciclastic sedimentary rocks in the Table Mountain-Dead Horse Creek area and the Irving Formation have been interpreted as faults (Cross and Larsen, 1935; Larsen and Cross, 1956) and conformable or unconformable depositional surfaces (Barker, 1969c; Gonzales and Ruiz, 1982). In contrast, Burns and others (1980) and Ethridge and others (1984) propose that while the eastern contact between the Irving and Vallecito is depositional, these units lie in fault contact to the west and north.

At several locations, near the head of Dead Horse Creek (Plates 1 and 2), contacts between the siliciclastic sequence and the Irving Formation are clearly depositional (Figure 7). Cross-stratification and grading in beds and lenses of quartz-rich conglomerate and sandstone of this sequence indicate that it was deposited upon the volcano-plutonic complex of the Irving Formation (Figures 8-9), as reported by Burns and others (1980) and Ethridge and others (1984).

Figure 7. Depositional contact between the Irving Formation and the Vallecito Conglomerate near the headwaters of Dead Horse Creek. Contact strikes north-northwest and dips approximately 45° to the west-southwest (photo taken looking northwest).

Figure 8. Cross-stratified lense of sandstone in the Vallecito Conglomerate approximately 60 m west of the Irving-Vallecito contact at the head of Dead Horse Creek (looking west). Truncation of cross-strata indicates that stratigraphic tops face west, away from the Irving.

Figure 9. Bed of feldspathic-sandstone in the Vallecito Conglomerate at the head of Dead Horse Creek (looking west). Grading in this bed, suggests tops west, away from the Irving-Vallecito contact.

Locally, along the depositional Irving-Vallecito contact at the head of Dead Horse Creek, 3-5 m thick lenticular deposits of conglomerate with pebble- to cobble-sized clasts of metabasite and chert, occur in the Vallecito. Clasts in these deposits are petrologically identical to metamorphosed basalt and intercalated chert in adjacent exposures of the underlying Irving Formation. Pebble conglomerate of the Vallecito with clasts of chert, jasper, vein quartz, and lesser proportions of intermediate to mafic schist, in a fine-grained greenish-gray matrix, is also exposed along the contact. Some of the mafic clast-rich conglomerates present along the Irving-Vallecito depositional contact in this area apparently correspond to "scour channel" deposits of Burns and others (1980, p. 29), which they interpret as remnants of an erosional surface. In addition to the intermediate to mafic clasts in conglomeratic deposits at the contact, clasts of amphibolite, felsic to intermediate schist, gneiss, greenstone, phyllite, and meta-argillite have been observed within the siliciclastic succession in the Table Mountain-Dead Horse Creek area (Barker, 1969c; Burns and others 1980, pages 25, 31, and 75; Ethridge and others, 1984; this study). Clast lithologies noted above in the Vallecito are interpreted here, and by Burns and others (1980) and Ethridge and others (1984), as debris that was produced by erosion of the underlying Irving Formation. This evidence suggests that the siliciclastic sequence in the Table Mountain-Dead Horse Creek area was deposited unconformably on previously deformed and metamorphosed rocks of the Irving volcano-plutonic complex.

At its eastern contact with the Irving Formation, bedding in the conglomerate, sandstone, siltstone sequence in the Table Mountain-Dead Horse Creek area strikes north-northwest and dips approximately 45°-50° to the west-southwest. Further west, bedding dips between approximately 65°-85° west-southwest. Cross-stratification in this siliciclastic sequence consistently show west facing stratigraphic tops. Therefore, while this sequence clearly rests upon the Irving Formation at the east bounding contact, it appears to face into the Irving to the west and north. In addition, bedding is truncated by the northern contact of these units. These relationships argue that the west and north bounding contacts are faults, as proposed by Cross and others (1905b), Cross and Larsen (1935), Larsen and Cross (1956), Burns and others (1980), and Ethridge and others (1984). Furthermore, the trend of bedding and stratigraphic facing indicates that the siliciclastic sequence in the Table Mountain-Dead Horse Creek area is exposed either in the eastern limb of a south-plunging syncline, or a homocline.

Collectively, the results of this study preclude the notion of Barker (1969c) that siliciclastic rocks in the Table Mountain-Dead Horse Creek area are older than the Irving, and exposed in an "inverted anticline". In addition, field evidence obtained during this investigation (refer to next section), argues against a pre-Irving age for the Vallecito Conglomerate in Vallecito Creek, contrary to the conclusions of Barker (1969c), Ellingson and others, (1982), Gonzales and Ruiz (1982). Based on evidence presented above, the siliciclastic sequence in the Table Mountain-Dead Horse Creek area is here considered part of the Vallecito Conglomerate. This conclusion agrees with the work of Cross and others (1905b), Cross and Larsen (1935), Larsen and Cross (1956), Barker (1969c), Burns and others (1980), and Ethridge and others (1984).

Vallecito Creek Area

In the canyon of Vallecito Creek, a 50-500-m-thick, north-northeast trending, deposit of basite clast-rich conglomerate and minor sandstone is bound on the west by rocks of the Irving Formation, and by siliciclastic conglomerate and sandstone of the Vallecito Conglomerate to the east (Plate 1). Conglomerate in this deposit is compositionally distinct from volcaniclastic conglomerate in the Irving, and the quartz-rich conglomerate of the Vallecito (refer to pages 44-48 and 56-60). It is therefore mapped as a separate unit in this study, and called the conglomerate of Fall Creek, for its excellent exposures in the vicinity of Fall Creek.

In previous investigations, the conglomerate of Fall Creek is interpreted as basal Vallecito Conglomerate (Cross and others, 1905, page 3) or as a wedge-shaped deposit at the base of the Irving Formation (Barker, 1969c, page A6). It has been proposed that bounding contacts of the conglomerate of Fall Creek are depositional surfaces (Barker, 1969c; Ellingson and others, 1982; Gonzales and Ruiz, 1982; Baars and Ellingson, 1984), or a combination of depositional surfaces and faults (Cross and others, 1905b; Cross and Larsen, 1935; Larsen and Cross, 1956; Burns and others, 1980).

The steep to vertical, east bounding contact of the conglomerate of Fall Creek and is marked by the abrupt appearance of siliciclastic rocks in the Vallecito Conglomerate. An angular discordance of 10°-40° is apparent between this contact and bedding in the Vallecito Conglomerate (Plate 1). Barker (1969c) noted this discordance and suggested that is might reflect "local tilting an erosion of the Vallecito before the Irving" or " folding along the contact". However, he suggested that their was no evidence that is was due to faulting.

Lenses of cross-stratified sandstone in the conglomerate of Fall Creek, west of Vallecito Creek, exhibit east facing stratigraphic tops, while strata in the Vallecito Conglomerate consistently face west (Plate 1, Figures 10-11). Opposing tops directions and strongly contasting lithologies in these units, and the apparent truncation of bedding in the Vallecito, indicates that the contact is a fault. In addition, this evidence suggests that the Vallecito Conglomerate and conglomerate of Fall Creek comprise opposing limbs of a syncline that are juxtaposed along the fault contact of these units.

Intense ductile deformation in the conglomerate of Fall and adjacent exposures of the Vallecito provides further evidence of faulting between these units. A prominent penetrative foliation and highly attenuated clasts (Figure 12) are observed in the conglomerate of Fall Creek, while gneissic banding is locally displayed by siliciclastic rocks of the Vallecito near the contact. Boudinaged veins and deformed cross-stratification occur in some outcrops of the conglomerate of Fall Creek and Vallecito Conglomerate, respectively. Asymmetrically stretched pebbles recording a near vertical, west side up, sense of shear were observed in both units (Figures 13-14).

Interpretation of the contact between the Vallecito Conglomerate and conglomerate of Fall Creek as a fault is contrary to the conclusions of Cross and others (1905b), Cross and Larsen (1935), Larsen and Cross (1956), Barker (1969c), Ellingson and others (1982), and Gonzales and Ruiz (1982). These workers suggested that the contact between these units was a conformable depositional surface.

Figure 10. Cross-stratified lense of sandstone in the conglomerate of Fall Creek approximately 20 m west of its contact with the Vallecito Conglomerate (looking east). Stratigraphic tops face to the east, into the Vallecito.

Figure 11. Trough cross-stratification in the Vallecito Conglomerate 10 m east of its contact with the conglomerate of Fall Creek (looking west). Tops are facing west, into the conglomerate of Fall Creek.

Figure 12. Highly attenuated mafic clasts in the conglomerate of Fall Creek, just north of the Fall Creek-Weasel Skin Creek confluence. Long axis of clasts are subparallel to foliation in the surrounding matrix.

Figure 13. Asymmetrically stretched quartz pebble in the Vallecito Conglomerate near the Irving-Vallecito contact, west of Vallecito Creek campground (looking north-northeast).

Figure 14. Sheared quartz clast in the conglomerate of Fall Creek near the conglomerate of Fall Creek-Vallecito Conglomerate contact, west of Vallecito Creek (looking northeast).

The north-northeast trending contact of the Irving Formation and conglomerate of Fall Creek is discordant to the north-trending contact of mafic and felsic units of the Irving Formation. Foliation in the Irving is also discordant to the contact (Plate 1). This argues that the contact between the conglomerate of Fall Creek and Irving Formation is is either an angular unconformity or a fault.

The high proportion of incompetent clasts, and textural immaturity, of the conglomerate Fall Creek suggests that it was deposited close to the source terrane, and that its coarse debris were transported over a short distance with minor reworking. Most clasts in this unit are petrologically identical to rocks in the Irving Formation, implying that the Irving may have been a major source of debris in the conglomerate of Fall Creek, as noted by Cross and others (1905b). Interestingly, clasts of Irving-type lithologies in the conglomerate of Fall Creek are similar to those that are occur locally in the basal section of the Vallecito in the Table Mountain-Dead Horse Creek area (pages 25 and 59).

East facing cross-strata in the conglomerate of Fall Creek west of Vallecito Creek indicate that while it could either rest upon or lie in fault contact with the Irving Formation, it does lie not at the base of the Irving as suggested by Barker (1969c). Furthermore, this conclusion implies that the conglomerate of Fall Creek could represent basal Vallecito, as noted by Cross and others (1905b), Cross and Larsen (1935), and Larsen and Cross (1956), or a new unit.

Based on observations discussed above, the contact between the conglomerate of Fall Creek and Irving Formation is here interpreted as an unconformable depositional surface which experienced shearing during deformation. In addition, the conglomerate of Fall Creek is regarded as basal and proximal facies of the Vallecito Conglomerate (Figure 6) that was derived largely from erosion of the Irving Formation.

U-Pb Zircon Age

Radiometric ages are reported for the Twilight Gneiss and Early to Middle Proterozoic plutonic rocks in the Needle Mountains complex (Table 1). Tewksbury (1981, page 288) tried unsuccessfully to determine, using Rb-Sr isotopic analyses, the timing of regional metamorphism recorded in pelitic rocks of the Uncompahgre Formation. No isotopic ages for rocks in the Irving Formation or Vallecito Conglomerate are reported in previous studies.

A U-Pb zircon age was obtained (M.E. Bickford, 1987, written communication) for a sample of felsic schist (QFB-1-86) that was collected from the Irving Formation during this investigation. This sample yields an age of 1828 ± 31 Ma based on analyses of four zircon fractions (Figure 15). Analytical data from these analyses are given in Table 3.

On the basis of field and petrographic observations, and geochemical characteristics (refer to page 76), a volcaniclastic protolith is strongly favored for felsic schist and gneiss of the Irving Formation (Plate 1). In this case the 1,828 ± 31 Ma age for QFB-1-86 is probably a good estimate for the time of volcanism. Conclusive field evidence of a volcanic protolith (e.g. relict phenocrysts), however, was not obtained. Thus, the possibility that Irving felsites originated as epiclastic sediments can not be entirely ruled out. If felsic rocks of

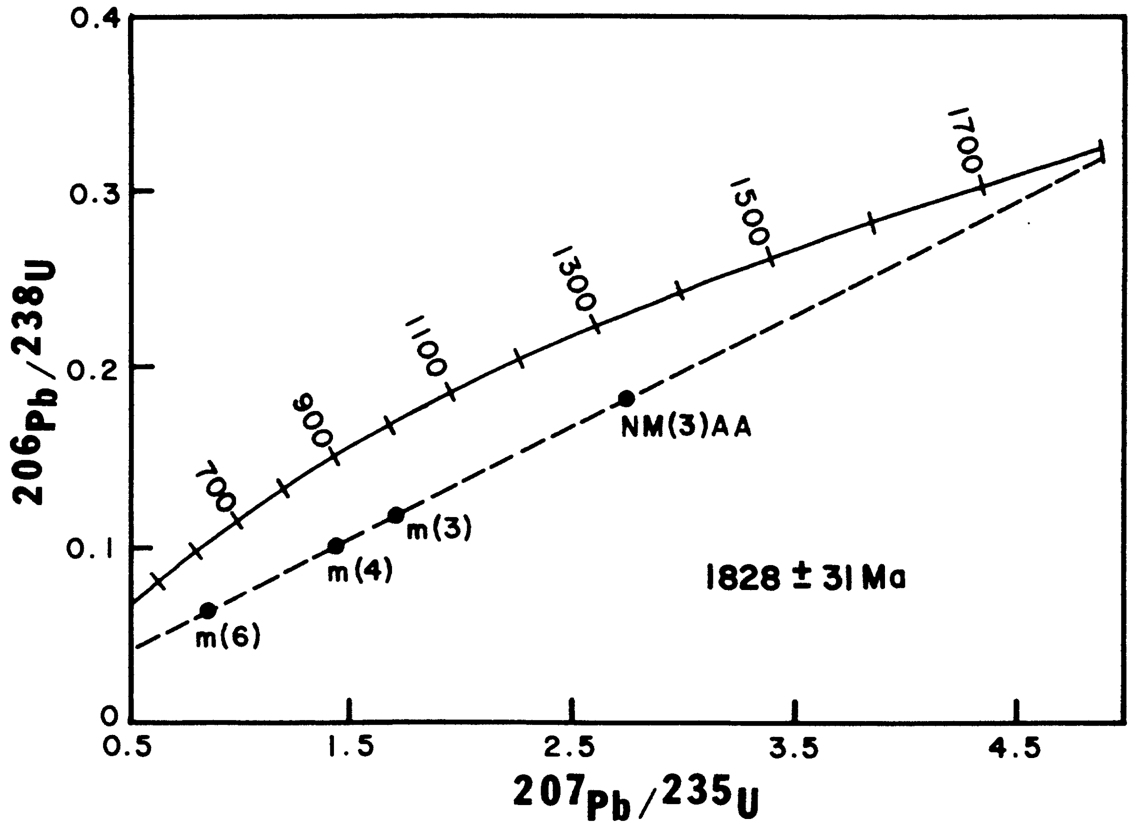


Figure 15. Concordia plot for sample QFB-1-86.

Table 3

Analytical data for zircon fractions obtained from sample QFB-1-86.

Fraction	Concentrations		Pb Isotopic Composition			Radiogenic Ratios			Ages (Ma)		
	U (ppm)	Pb (ppm)	Pb-204/Pb-206	Pb-207/Pb-206	Pb-208/Pb-206	Pb-206/U-238	Pb-207/U-235	Pb-207/Pb-206	Pb-206/U-238	Pb-207/U-235	Pb-207/Pb-206
m(3)	1096.07	141.24	0.000997	0.118574	0.13575	0.11757	1.70123	0.104946	716.6	1009.0	1713.3
m(4)	1205.41	133.85	0.001196	0.120549	0.14637	0.09999	1.43640	0.104187	614.4	904.2	1700.0
m(6)	1578.20	113.63	0.002016	0.129064	0.18109	0.06193	0.86579	0.101393	387.4	633.3	1649.6
NM(3)AA	801.38	155.66	0.000534	0.116672	0.12058	0.18159	2.73947	0.109413	1075.7	1339.2	1789.8

the Irving Formation originated as arkosic sediments they might contain detrital zircons from several different source terranes so that the 1,828 ± 31 Ma age can only be taken as a maximum age for the protolith. Given the lack of conclusive field evidence of a volcanic protolith for these rocks and the slight possibility of an epiclastic origin, the 1,828 ± 31 Ma age obtained should be applied cautiously.

The Irving Formation: One Unit or Two Units ?

The Irving Formation in the Animas River-Bear Creek area has not been examined in detail by this author (Figure 2). A thorough discussion regarding the correlation of these rocks to Irving lithologies in the Vallecito Creek-Lake Creek area is therefore not possible. Results of this study, however, provide valuable insights on the regional correlation problems associated with these rocks (Cross and others, 1905b; Cross and Larsen, 1935; Larsen and Cross, 1956; Barker, 1969c; Ellingson and others, 1982; Baars and Ellingson, 1984).

The petrography, geochemistry, grade of metamorphism, deformational history, and inferred origin of lithologies of the Irving Formation in Vallecito Creek-Lake Creek area are similar in many respects to those of the Irving Formation in the Animas River-Bear Creek area, and Twilight Gneiss (Tables 4 and 5). The U-Pb zircon age obtained during this study, however, indicates that volcano-plutonic rocks (1,828 ± 31 Ma) in the southeastern Needle Mountains may be considerably older than those in the northern and western parts of the Needle Mountains Precambrian (1,762 ± 20 Ma U-Pb zircon age for Twilight Gneiss). This might imply that basement volcano-plutonic rocks in the Needle Mountains comprise several broadly similar complexes of different age, rather than a single contemporaneous terrane as implied by Barker (1969c). Additional isotopic data is required to fully evaluate this possibility.

Regional Comparisons

The Irving volcano-plutonic complex is part of an extensive Early Proterozoic volcanogenic terrane, designated the "Colorado province" by Bickford and others (1986), that is exposed south of the Archean Wyoming craton. This terrane was generated largely by arc volcanism and associated sedimentation. It includes 1,800-1,730 Ma metavolcanic rocks in northern and central Colorado (Reed and others, 1987; Tweto, 1987), the 1,790-1,740 Ma Yavapai Series of central Arizona (Anderson and others, 1971; Conway and others, 1987; Karlstrom and others, 1987), and 1,760-1,720 Ma volcano-plutonic complexes in north-central New Mexico (Robertson and Moench, 1979; Wobus, 1985). This volcanogenic terrane is part of a 1,300-km-wide orogenic zone that was accreted to the Wyoming craton between ca. 1.8-1.6 Ga (Van Schmus and Bickford, 1981; DePaulo, 1981; Stacey and Hedlund, 1983; Bennett and DePaulo, 1984; Nelson and DePaulo, 1984, 1985; Aleinikoff and others, 1987). Models proposed for evolution of the "Colorado province" volcano-plutonic terrane typically involve accretion of volcanic arc and back arc basin suites resulting in a general decrease in age to the south (Anderson, 1978, 1986; Condie and Budding, 1979; Van Schmus and Bickford, 1981; Condie, 1982; Silver, 1984; Bickford and others, 1986; Reed and others, 1987).

Table 4

Resume of the Irving Formation in the Animas Canyon-Bear Creek area and Twilight Gneiss.

UNIT	Irving Formation in the Animas River-Bear Creek area	Twilight Gneiss	
RADIOMETRIC AGE	Not determined; predates intrusion of the Tenmile Granite at around 1,702 ± 20 Ma (Silver and Barker, 1968, corrected).	1,767 ± 35 Ma (Barker and others, 1969, corrected) 1,762 ± 20 Ma (Silver and Barker, 1968, corrected)	
LITHOLOGIES	"Amphibolite", "plagioclase-quartz-biotite ± garnet ± hornblende gneiss", and minor "sericite-biotite-chlorite schist" (Barker, 1969c).	"Metadacite" and minor "amphibolite" (Barker, 1969c, Barker and others, 1969; Barker and Peterman, 1974), and quartzite (Baars and Ellingson, 1984; Van Loenen and Scott, 1983; and Van Loenen, 1985).	
MINERALOGY	Amphibolite: Hornblende, oligoclase-andesine, biotite, garnet and epidote ± quartz ± rare clinopyroxene (Barker, 1969c). Gneiss: Plagioclase, quartz, biotite, ± calcite, chlorite, epidote, garnet, hornblende, microcline, magnetite, and and pyrite (Barker, 1969c).	Gneiss: Oligoclase-andesine, microcline, quartz, biotite and accessory epidote, garnet, and hornblende, muscovite, and opaque oxides (Barker, 1969c). Grain size varies from 0.1-3 mm (Barker and others, 1969).	
INFERRED PROTOLITHS	Mafic to intermediate igneous rocks, predominantly volcanogenic in origin (Barker, 1969c).	Dacitic tuffs, rhyodacite, and minor tholeiitic flows (Barker, 1969c; Barker and others, 1969; Barker and Peterman, 1974; Barker and others, 1976).	
PRIMARY FEATURES OBSERVED	Pillow lava (Barker, 1969c, page A10)	Original fabric is generally obliterated; locally contains quartz aggregates which Barker (1969c) interprets as relict phenocrysts.	
METAMORPHIC GRADE	Amphibolite facies (Barker, 1969c)	Amphibolite facies (Barker, 1969c, page A21)	
AVERAGE CHEMISTRY*			
	Amphibolite (1 sample)	Metadacite (9 samples)	Amphibolite (2 samples)
SiO_2	51.66	73.20	50.93
TiO_2	0.35	0.18	1.47
Al_2O_3	12.77	13.50	13.40
Fe_2O_3	2.04	0.73	3.34
FeO	8.01	2.50	11.37
MnO	0.17	0.10	0.24
MgO	8.44	0.70	5.22
CaO	11.41	1.90	8.92
Na_2O	3.31	4.00	2.15
K_2O	1.26	2.00	0.71
P_2O_5	0.09	0.06	0.15
H_2O	1.26	1.79	1.65
CO_2	0.06	0.08	0.05

* Data from Barker (1969c) and Barker and others (1976).

Table 5

Resume of the Irving Formation in the Vallecito Creek-Lake Creek area.

UNIT	Irving Formation in the Vallecito Creek-Lake Creek area: Felsic Section	Irving Formation in the Vallecito Creek-Lake Creek area: Mafic Section
RADIOMETRIC AGE	1,828 ± 31 Ma (This Study)	Not determined
LITHOLOGIES	Quartzo-feldspathic schist and gneiss with minor amphibolite.	Metamorphosed basaltic to andesitic flows, mafic tuff, graywacke and siltstone chert, conglomerate, and minor mafic intrusive rocks.
MINERALOGY	Quartzo-feldspathic schist and gneiss: Quartz, oligoclase-andesine, biotite, muscovite, and microcline with accessory hornblende, epidote, and garnet; all grains typically < 2 mm in length.	Mafic flow rocks: hornblende, oligoclase-andesine, biotite, epidote with accessory accessory quartz, sphene, muscovite, and rare clinopyroxene. Graywacke and siltstone: Quartz, plagioclase, biotite, epidote, hornblende, lithic fragments, and minor tourmaline. Mafic intrusive rocks: Composed chiefly of varying proportions of hornblende, plagioclase, epidote, and biotite. Refer to text for descriptions of conglomerate, tuff, and chert.
INFERRED PROTOLITHS	Rhyolitic tuffs or reworked tuffs; origin of amphibolite uncertain.	Noted above.
PRIMARY FEATURES OBSERVED	None observed.	Porphyritic, ophitic, and trachytic textures, and pillow lava and breccia in mafic flow rocks; grading, bedding, and cross-stratification in graywacke and siltstone; ophitic and porphyritic textures in mafic intrusive rocks.
METAMORPHIC GRADE	Epidote-amphibolite to lower amphibolite facies	Epidote-amphibolite to lower amphibolite facies

AVERAGE CHEMISTRY

	Rhyolitic Schist and Gneiss (7 samples)	Mafic Volcanic Rocks* A (9)	B (2)	C (3)	D (2)	Graywacke & Siltstone (4)	Mafic Intrusive Rocks+ E (2)	F (1)	G (2)
SiO2	71.71	48.7	53.1	56.8	48.7	59.1	45.8	49.5	47.6
TiO2	0.35	0.85	0.73	0.78	1.10	0.72	0.46	0.88	0.62
Al2O3	12.63	15.1	16.1	17.4	20.7	17.4	13.9	17.0	14.4
Fe2O3	1.41	3.21	2.92	4.47	4.88	4.45	4.35	2.24	4.17
FeO	3.37	8.14	5.74	3.68	5.12	4.04	6.80	7.80	6.11
MnO	0.08	0.21	0.15	0.12	0.16	0.12	0.19	0.18	0.19
MgO	1.60	7.7	6.0	3.4	3.4	2.60	10.3	6.5	9.9
CaO	1.42	9.8	8.5	5.8	8.0	3.2	12.5	10.9	12.1
Na2O	3.24	2.61	3.85	< 2.20	2.90	3.30	< 1.15	2.4	< 1.45
K2O	2.53	0.63	0.86	2.11	2.64	2.87	1.36	0.78	1.17
P2O5	0.08	0.17	0.21	0.25	0.29	0.21	0.11	0.14	0.39
H2O+	0.80	1.66	1.55	1.55	1.50	1.56	2.31	1.92	1.37
H2O-	0.05	0.08	0.10	0.08	0.07	0.11	0.09	0.11	0.06
CO2	0.14	0.17	0.28	0.10	0.09	0.14	1.06	0.09	0.90

* A = < 52% SiO_2; B = 52-56% SiO_2; C = > 56% SiO_2; D = < 52 % SiO_2, > 20 % Al_2O_3; (#) = number of samples.
\+ E = medium- to coarse-grained amphibole-rich rocks; F = metagabbro; G = coarse-grained amphibole-rich rocks with amphibole pseudomorphs of primary pyroxene phenocrysts.

The 1,828 ± 31 Ma U-Pb age reported here is roughly 30 m.y. older than any U-Pb age yet published for supracrustal rocks in the "Colorado province", and appears to reflect a reversal in the general southward decreasing age pattern displayed by Early Proterozoic volcano-plutonic terrane in this province (Tweto, 1977; Condie, 1981; Van Schmus and Bickford, 1981; Bickford and others, 1986; Karlstrom and others, 1987; Reed and others, 1987). The significance of this apparent age reversal is uncertain. One possibility is that the Irving volcano-plutonic complex is part of a collage of crustal blocks of various ages and histories that were accreted to form the volcanogenic terrane in the "Colorado province", similar to a recently proposed model for Early Proterozoic rocks in Arizona (Karlstrom and Bowring, 1987).

The stratigraphic succession in the southeastern Needle Mountains, defined by the Irving Formation and overlying clastic sedimentary rocks of the Vallecito Conglomerate and conglomerate of Fall Creek, is analogous to that in the northern and western Needles where siliciclastic rocks of the Uncompahgre Formation rest upon the Irving Formation and Twilight Gneiss (Barker, 1969c; Harris and others, 1986; Gibson, 1987b; Harris and Eriksson, 1987; Gibson and others, 1987). The stratigraphic position of the Vallecito Conglomerate relative to the Uncompahgre Formation is not constrained by radiometric data or definitive field evidence. Interpretations (Figure 6, pages 11-12) of previous investigators in regards to the relative ages of these units are therefore entirely conjectural. The Vallecito Conglomerate could represent a distinct unit that rests beneath the Uncompahgre Formation, as originally presented by Cross and his colleagues (Cross and others, 1905b; Cross and Larsen, 1935; Larsen and Cross, 1956), or it could conceivably be a lateral facies of the Uncompahgre.

Proterozoic fluvial to marine sediments in the Needle Mountains are also similar to deformed, ca. 1,700 Ma siliciclastic cover sequences of the Mazatzal Group in central Arizona (Conway and Silver, 1984, in press; Conway and others, 1987), and Ortega Group in the Tusas Mountains of north-central New Mexico (Grambling and Codding, 1982; Burns and Wobus, 1983; Soegaard and Eriksson, 1986). These siliciclastic successions appear to reflect a regional episode of continental sedimentation, subsequent to formation of underlying juvenile-arc crust complexes.

DESCRIPTION OF MAP UNITS

Irving Formation

The Irving Formation in the southeastern Needle Mountains is exposed over an area of nearly 65 square kilometers. It contains a variety of metamorphosed igneous and sedimentary lithologies whose diverse origins and histories are reflected in a spectrum of primary and metamorphic textures and structures. Lithologies exposed within the study area include mafic to felsic volcanic and associated sedimentary rocks, and mafic intrusive rocks.

Mafic Volcanic Rocks

Extensive exposures of mafic metavolcanic rocks occur between Vallecito Creek and Lake Creek, and a smaller belt is exposed west of Vallecito Creek. Chemical compositions and well preserved textures and structures indicate that these rocks are largely metamorphosed basaltic to andesitic lava flows, with local intercalations of mafic lapilli tuff (Plates 1 and 2).

Basaltic and Andesitic Flows. Mafic flow rocks in the Irving Formation are grouped into two map units (ba and ap on Plates 1 and 2). Massive, fine- to medium-grained, basalt and basaltic andesite (ba), containing sparse to abundant crystals of amphibole and relict phenocrysts of plagioclase (.1-2 mm) are most common. Porphyritic flow rocks (ap), chiefly andesitic in composition, with abundant (.5-8 mm) lath- and tabular-shaped phenocrysts of plagioclase are widely exposed in the Dead Horse Creek-Dollar Lake area (Figure 16).

Mafic flow rocks in the Irving Formation possess a uniform mineral composition (Table 6). Bluish-green hornblende, plagioclase, and Fe-rich epidote are principal constituents together with minor apatite, biotite, clinozoisite, opaque oxides, quartz, sphene, and tourmaline. Hornblende and biotite are commonly altered to chlorite. Veinlets of calcite ± chlorite ± epidote ± quartz occur locally.

Basaltic and andesitic rocks of the Irving Formation contain from 0-40 (Table 6) volume percent relict phenocrysts and microphenocrysts of plagioclase (An_{20}-An_{50}), which locally define a prominent trachytic texture. Plagioclase crystals in these rocks commonly exhibit albite twinning and rarely, Carlsbad-albite twinning or compositional zoning (Figure 17). They typically are partially to completely sericitized and/or saussaritized, and rarely are recrystallized to very-fine grained, granular and untwinned aggregates of plagioclase.

Locally, particularly in basaltic lithologies, hornblende occurs as 1-5 mm crystals in which the outline of original pyroxene is preserved (Figure 18). In some outcrops these hornblende pseudomorphs partially envelope relict plagioclase defining a blasto-subophitic texture.

Locally, andesitic to basaltic flows of the Irving contain sub-oval to irregular-shaped amygdules and vesicles, up to 2-3 mm in maximum dimension. Amygdule assemblages observed include aggregates of anhedral untwinned plagioclase + decussate biotite, or quartz.

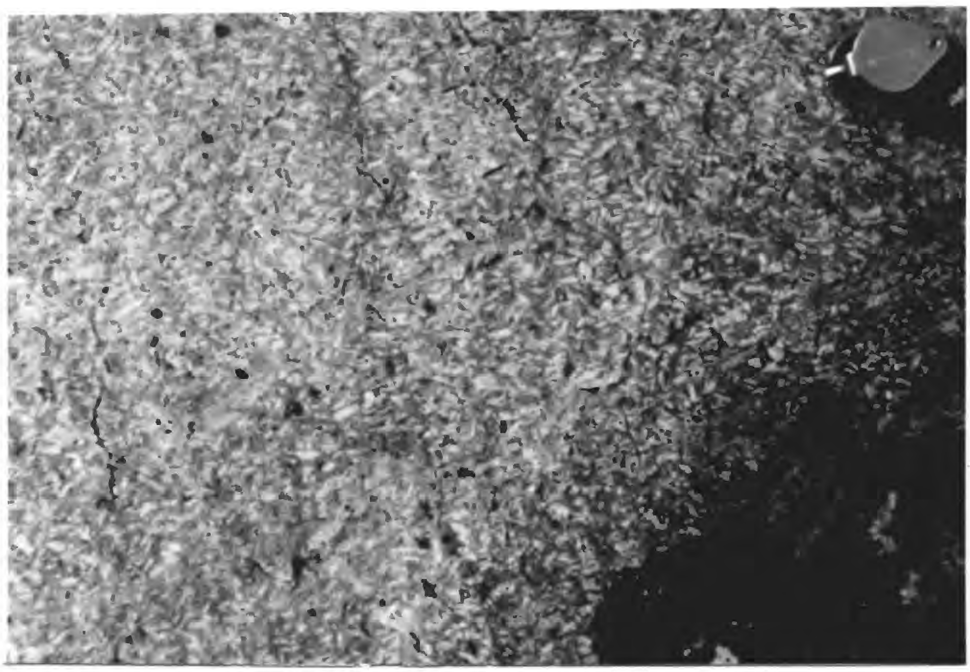


Figure 16. Outcrop of andesite porphyry with abundant relict phenocrysts of plagioclase; Irving Formation between Dead Horse Creek and Second Creek, east of Table Mountain.

Table 6

Modal analyses of mafic volcanic rocks of the Irving Formation.

Map Unit	ba	ba	ba	ba	ba	ba	ba	ba	ba	ba	ba	ba	ap	ba	ba	ap	ba	ba	ba	ba	ba	ap	ap	ap	ap	ap	ap	ba	ap
Sample No.	8a	13	18a	46	48	53	55	56	60	61	63	66	68+	69	76	80a	80b	83	93	97	98	116	125	127	129	131	133	134	154
amygdules	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	P	...	...	...	...	...	...	...	...	...	...	4	...	...
apatite	P	P	...	P	...	...	...	P	...	...	P	...	...	P	P	...	P	...	P	...	P	...	P	...	...	...	...	...	...
biotite	1	< 1	P	...	14	12	18	3	3	P	< 1	2	32	39	P	34	P	...	2	...	20	...	45	24	3	P	31	2	22
calcite	P	< 1	...	< 1	...	...	...	...	...	...	...	...	P	...	...	...	P	...	< 1	...	...	...	...	P	...	...	P	...	...
epidote	1	2	2	1	12	15	15	6	7	22	3	11	2	9	22	P	19	2	8	43	5	36	20	38	8	11	15	43	15
hornblende	73	72	74	74	39	19	27	75	58	64	60	54	11	...	57	...	36	67	44	50	45	...	P	...	34	36	< 1	44	...
muscovite	...	...	...	...	...	...	...	...	...	...	...	...	...	11	2	...	...	...	...	...	...	...	...	...	...	...	...	...	...
opaque oxides	2	1	1	2	2	2	4	P	10	4	< 1	< 1	9	9	11	19	26	4	4	P	2	14	2	5	P	11	3	6	18
plagioclase (1)	...	...	...	...	30	44	20	P	...	...	...	32	41	12	...	26	10	16	21	1	18	17	16	30	53	25	33	...	32
plagioclase (2)	20	24	18	20	2	4	14	12	22	5	32	P	4	20	4	16	9	10	13	6	7	6	17	3	P	17	10	5	8
plagioclase (3)	3	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
pyroxene	...	...	2	P	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
quartz	...	...	...	1	< 1	...	...	...	...	...	4	...	...	...	...	...	...	...	1	...	...	...	...	...	...	...	< 1	...	...
quartz (4)	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	P	...	...	...	...	...	...	...	...	...	...	2	...	...
sphene	P	P	...	...	...	...	...	...	...	...	P	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
tourmaline	...	P	...	...	...	...	...	...	...	...	...	...	...	P	...	P	...	...	...	...	...	P	...	...	...	...	...	...	...
Retrograde:																													
chlorite	P	< 1	P	< 1	P	P	2	3	P	5	< 1	< 1	...	P	4	...	P	1	6	P	3	25	P	< 1	2	P	< 1	P	P
sericite	P	P	3	1	P	P	P	< 1	P	P	P	P	P	P	P	5	P	P	< 1	P	P	2	...	P	P	P	P	P	4
Veinlet minerals (not counted):																													
calcite	...	...	P	...	P	P	P	P	...	P	P	P	...	...	P	...	...	P	...	...	...	...	P	...	P	...	...	P	...
chlorite	...	...	...	...	P	P	...	P	...	P	...	P	...	...	P	...	...	...	P	...	...	P	P	...	P	...	P	P	...
epidote	...	...	...	...	P	...	...	...	...	...	P	P	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	P
plagioclase	...	...	...	...	...	...	...	...	...	P	...	P	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
quartz	...	...	P	...	P	...	P	P	...	P	...	P	...	P	...	...	...	...	...	P	...	P	P	P	P	...	P	P	...
sericite	...	...	...	...	...	...	...	...	...	P	P	P	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Points Counted	200	500	1200	500	200	200	200	500	200	200	200	500	200	200	200	200	200	200	200	200	200	200	200	500	200	200	1000	200	500

1 = plagioclase phenocrysts; includes unaltered fractions and those recrystallized or altered to epidote and sericite.
2 = matrix plagioclase
3 = polycrystalline aggregates of plagioclase; amygdules or recrystallized plagioclase phenocrysts.
4 = polycrystalline aggregates of quartz; most are interpreted as recrystallized amygdules.

Figure 17. Zoned plagioclase phenocrysts in medium-grained mafic volcanic rock; cores of crystals are recrystallized to epidote (photomicrograph with nicols crossed).

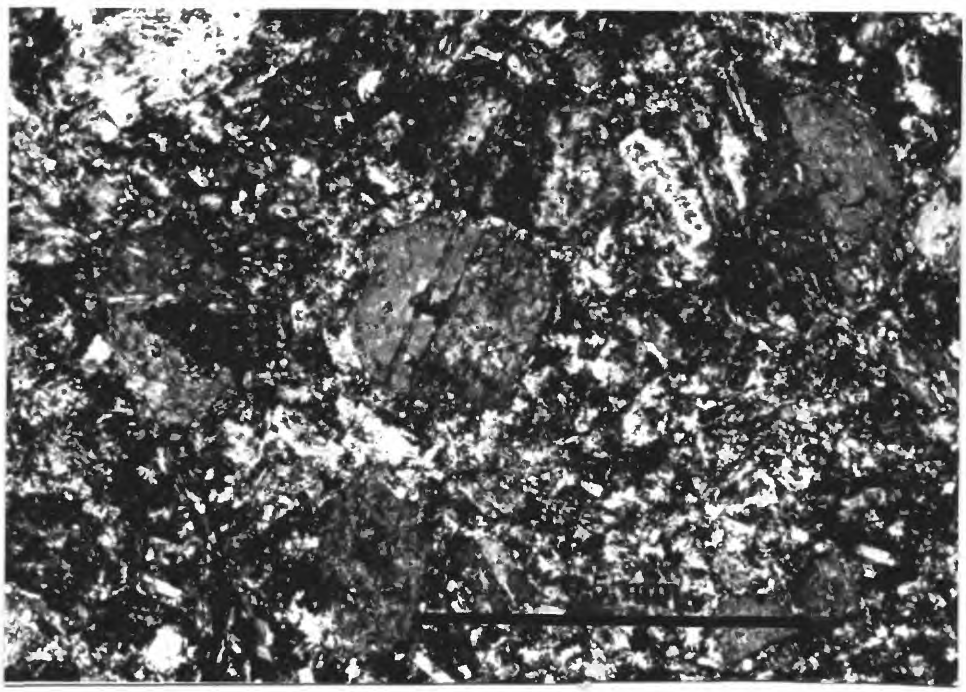


Figure 18. Hornblende pseudomorphs of pyroxene; note that original outline of pyroxene is preserved (photomicrograph with nicols crossed).

Mafic volcanic rocks in the Irving Formation occur in thick successions in which individual flows are rarely mappable. Relict textures are exhibited in many outcrops. Static metamorphic textures (i.e. decussate biotite and hornblende) are commonly developed, while a weak to strong schistosity and gneissic texture are displayed locally.

Pillow breccia, composed of subspherical to ellipsoidal,.1-.5 m, unbroken and broken pillows in very fine grained, dark colored matrix, is exposed approximately .8 km east of Table Mountain (Plate 2, Figure 19). Roughly 400-800 m farther to the northeast, small outcrops of pillow lava are exposed (Figure 20). The occurrence of pillow lava and breccia in the Irving Formation indicates that at least some of the mafic volcanic rocks were deposited in a subaqueous environment.

Lapilli Tuff. Metamorphosed lapilli tuff (Figure 21) is exposed approximately 300-400 m east of the Vallecito-Irving contact in Dead Horse Creek basin (Plate 2). No other exposures of this lithology were observed.

Mafic lapilli tuff in the Irving Formation contains a poorly sorted assemblage of subrounded to angular fragments of gray to black, aphyric to porphyritic mafic volcanic rock, that range from .5-8 cm in maximum dimension. Abundant, subrounded, aphyric fragments composed of plagioclase microlites in a microcrystalline mat of hornblende, occur locally. These are interpreted here as recrystallized scoriaceous lapilli that originally were composed principally of glass.

Clasts in mafic tuff in the Irving are typically dispersed in a very fine grained, black to grayish-black matrix that comprises 60-65% of most outcrops. Matrix assemblages are composed primarily of hornblende with minor calcite, chlorite, epidote, muscovite, plagioclase, and quartz. Foliation is absent in most outcrops and clasts are undeformed.

Volcanic debris in mafic lapilli tuff of the Irving do not appear to have undergone extensive reworking by sedimentary processes, however, redeposition and minor reworking may have occurred. No stratification or primary sedimentary structures were observed, which together with size, shape, composition, and sorting of clasts suggests that this is either a primary pyroclastic deposit or a debris flow.

Volcaniclastic Sediments

In the Dead Horse Creek-Dollar Lake area, volcaniclastic sediments are intercalated with mafic volcanic rocks of the Irving Formation (Plates 1 and 2). Accumulations of these clastic sediments extend up to 1 km along strike and locally are up to 300 m thick. Interstratified graywacke and siltstone, and conglomerate are the two types of volcaniclastic sedimentary rocks that were observed.

In addition to the volcaniclastic sedimentary rocks in the Irving Formation, beds and irregular-shaped deposits of chert and jasper crop out within the volcanic successions in the Dead Horse Creek and Fall Creek areas. Locally, beds of chert in the Irving are exposed discontinuously along strike for more than 1 km and are up to 30 m thick (Plate 1).

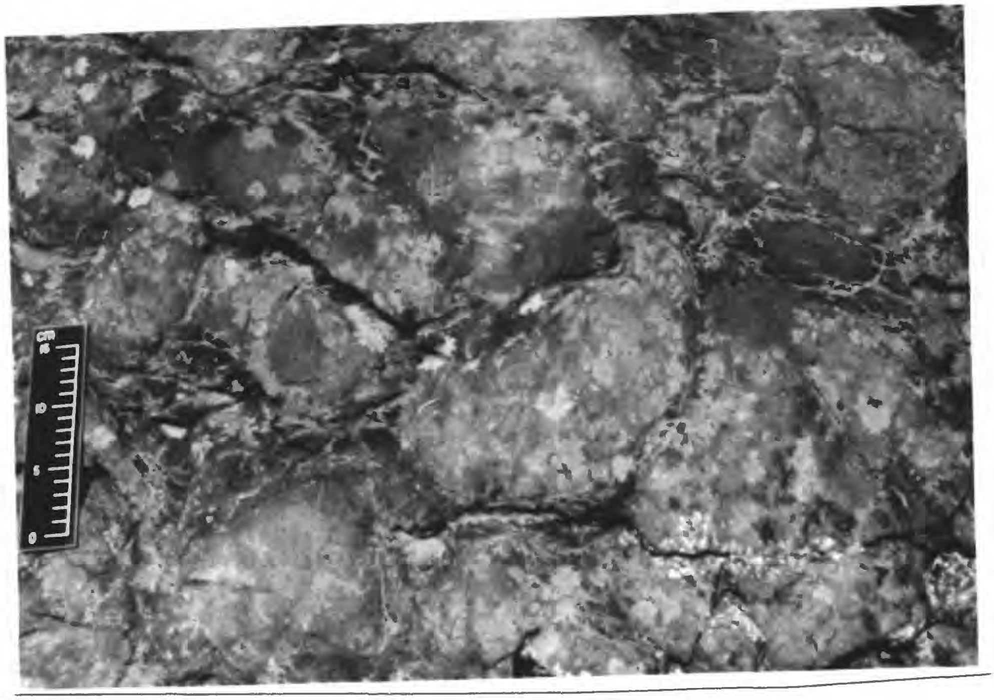


Figure 19. Pillow breccia.

Figure 20. Pillow lava.

Figure 21. Lapilli tuff with abundant sub-oval clasts of mafic volcanic rock; Irving Formation east of Dead Horse Creek basin.

Graywacke and Siltstone. Barker (1969c) noted the occurrence of graywacke and siltstone in the Irving Formation of the southeastern Needle Mountains, but did not give locations or detailed descriptions of these rocks. Steven and others (1969, page F44) briefly describe and cite locations of what they refer to as "laminated greenstone" in the Irving. Laminated rocks observed by Steven and others (1969) on the sharp ridge northwest of Dollar Lake were mapped as volcaniclastic sediments during this study (Plate 1 and 2).

Interbedded successions of thinly laminated (< 1 cm) to thin (>1-8 cm) and medium bedded (10-30 cm) graywacke and siltstone (Figure 22), several meters to tens of meters thick, are exposed south and east of upper Dead Horse Creek (Plates 1 and 2). Laminae and beds in these exposures are typically 3 mm to 8 cm thick. They are generally ungraded and massive, however, well preserved ripple cross-lamination and grading (Figures 23-24) are exhibited locally. Sedimentary structures observed are similar to the Bouma $_{A-D}$ divisions of turbidity current deposits (Bouma, 1962). The frequency and stratigraphic order of bed types in these outcrops, however, were not determined.

Beds and laminae of sandstone and sandy siltstone commonly contain abundant, 1-4mm, detrital crystals of plagioclase (An_{25}-An_{40}). These crystals are rarely zoned and are partially to completely sericitized or saussaritized. Lithic fragments are abundant in some layers and include polycrystalline quartz ± opaque oxides, and quartzo-feldspathic grains. Framework crystals and grains are subangular to subrounded and poorly sorted. They are set in a fine-grained (.01-.1 mm), recrystallized matrix assemblage composed largely of Fe-rich epidote and clinozoisite with varying proportions of apatite, biotite, chlorite, hornblende, plagioclase, muscovite, opaque oxides, and quartz (Table 7). This fine matrix assemblage may have consisted partially or entirely of highly deformed mafic volcanic fragments (pseudomatrix of Dickinson, 1970). Except for significantly lower abundances of rock fragments, siltstone laminae and beds are compositionally similar to the layers of sandstone to silty sandstone.

Original clastic textures are well preserved in silty to sandy volcaniclastic sedimentary rocks in the Irving Formation. Foliation is rarely apparent in outcrop, but a weak to moderate lepidoblastic and nematoblastic texture was observed in a few thin sectioned samples.

Interbedded graywacke and siltstone successions in the Irving Formation are interpreted as submarine gravity flow deposits that were derived by the remobilization of tuffaceous volcanic debris, via turbidity currents. The preservation of Bouma-type sedimentary structures suggests that deposition occurred below storm wave base (commonly a water depth of tens of meters) and that extensive reworking by tidal, storm, long-shore or semi-permanent ocean currents did not take place (Walker and Mutti, 1973).

Conglomerate. Unstratified beds and discontinuous layers of polymictic conglomerate, 10-100 m thick, are exposed in the Irving Formation near the head of Dead Horse Creek. This lithology has not been documented in any previous work. It is typically clast-supported and contains a poorly sorted assemblage of subrounded to subangular, pebble to boulder sized clasts of aphyric to porphyritic mafic volcanic rock (Figure 25). Clasts are up to .5 m in maximum dimension and

Figure 22. Thinly laminated to thinly bedded graywacke and siltstone in the Irving Formation immediately north of the Irving-Vallecito contact, near the head of Second Creek.

Figure 23. Cross-laminated volcaniclastic sedimentary rock, Irving Formation, Dollar Lake-Dead Horse Creek area.

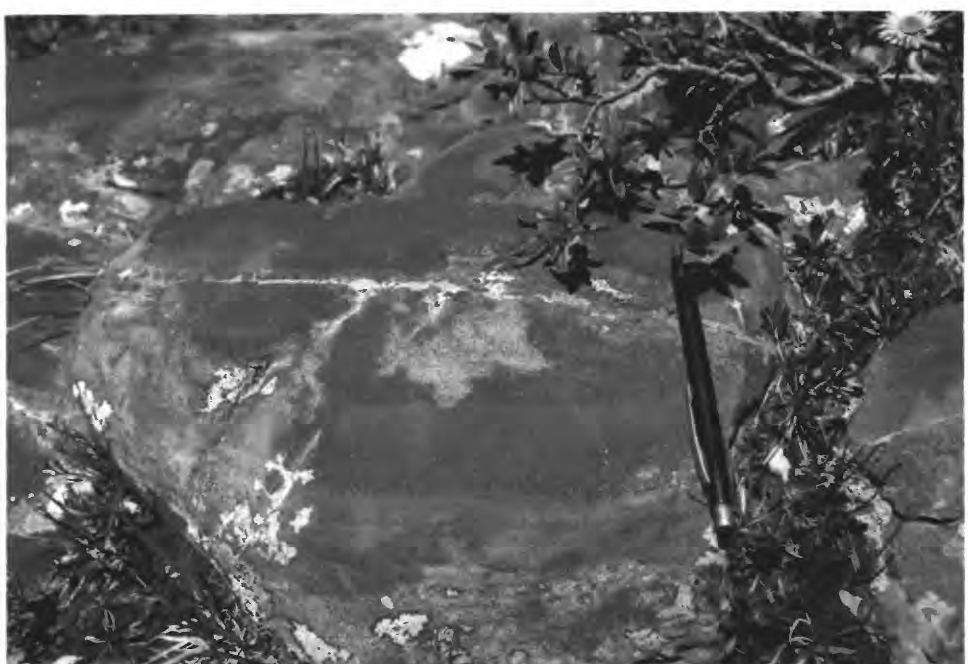


Figure 24. Graded beds of tuffaceous sandstone in the Irving Formation, east of Dead Horse Creek basin.

Table 7

Modal analyses of graywacke and siltstone, Irving Formation.

Sample No.	57a-1*	57a-2*	57a-3*	57a-4	67	81	128*	130
apatite	...	...	...	...	...	...	P	P
biotite	40	22	20	2	69	60	14	8
epidote	20	47	41	70	4	13	28	20
hornblende	...	...	...	...	...	P	30	1
muscovite	...	3	3	...	< 1	...	...	...
opaque oxides	1	7	9	8	2	3	10	14
plagioclase	22	10	12	< 1	13	15	18	30
quartz	< 1	3	1	< 1	11	6	P	7
rock fragments	12	7	8	< 1	...	...	...	...
tourmaline	...	...	...	...	P	P	...	...
Retrograde:								
chlorite	2	1	6	3	< 1	2	P	20
sericite	< 1	P	P	16	...	...	P	...
Veinlet minerals (not counted):								
calcite	...	...	...	...	...	P	...	...
quartz	...	...	...	...	P	P	P	P
Points Counted	400	200	200	200	200	200	200	200

P indicates mineral is present but not encountered; leader indicates mineral not present.
* = graywacke

consist largely of: 1) light gray to grayish-black porphyry with abundant, 1-5 mm, euhedral to subhedral, crystals of amphibole and/or relict plagioclase; and 2) grayish-tan to black, aphyric mafic volcanic rock which is locally epidote-rich.

Most clast lithologies in conglomerate of the Irving Formation are texturally and compositionally identical to surrounding deposits of mafic volcanic rock, and probably represent reworked lapilli tuffs and tuff breccias. Although subordinate to the clast assemblage, a very fine-grained, grayish-black matrix is apparent in most outcrops and locally, intercalated lenses of massive to cross-stratified graywacke or siltstone, up to 10 m in length, were observed. A crude foliation is rarely visible in the fine grained interbeds and matrix of Irving conglomerate, and locally the clasts are highly flattened and define a prominent lineation.

The close spatial association of graywacke and siltstone with conglomerate in the Irving argues that the latter was also deposited in a subaqueous environment. The lack of stratification together with the large size, subangular shape, and poor sorting of clasts in conglomerate of the Irving Formation suggests that it originated as dense, cohesive debris flows (Lowe 1979, 1982). The clast-supported fabric and low proportion of matrix material which this lithology exhibits is also characteristic of some Phanerozoic debris flow deposits (Curry, 1966; Lewis, 1976; Rodine and Johnson, 1976; Winn and Dott, 1977; and Lowe, 1979, 1982).

Chert. Beds of massive, fine- to coarse-grained, bluish-gray to grayish-white, chert are exposed in at least two locations (Plates 1 and 2): 1) east of Fall Creek near the Eolus-Irving contact (Figure 26); and 2) in the basin at the head of the north fork of Dead Horse Creek. In addition to chert beds, irregular-shaped deposits chert and jasper, from 3 cm to 1.5 m in maximum dimension, occur in mafic flow successions in the Dead Horse Creek area (Figure 27).

Chert in the Irving Formation is composed essentially of subequant grains of quartz (90-92 %; largely .4-.6 mm in maximum dimension) and opaque oxides (8-10 %) with traces of apatite, biotite, calcite, chlorite, epidote, muscovite, and opaque oxides. Characteristic features of the quartz grains include: 1) strong undulatory extinction; 2) well developed deformation lamellae ; and 3) interpenetrating contacts with adjacent grains.

Chert deposits in the Irving Formation are interpreted here as siliceous material that was deposited during periods of volcanic quiescence. The apparent lack of marine biota with siliceous tests in the Early Proterozoic requires that these deposits formed by inorganic processes. Inorganic silica may originate by alteration of volcanic glass, volcanic emanations, and hydrothermal action associated with volcanism (e.g. Williams and others, 1982, p. 401) and direct precipitation from restricted lake waters (e.g. Peterson and von der Borch, 1965; Surdam and others, 1972). The close temporal and spatial association with volcanic and volcaniclastic rocks implies that chert in the Irving Formation is volcanic-related.

Figure 25. Metaconglomerate of the Irving Formation containing abundant pebble- to boulder-sized clasts of mafic volcanic rock.

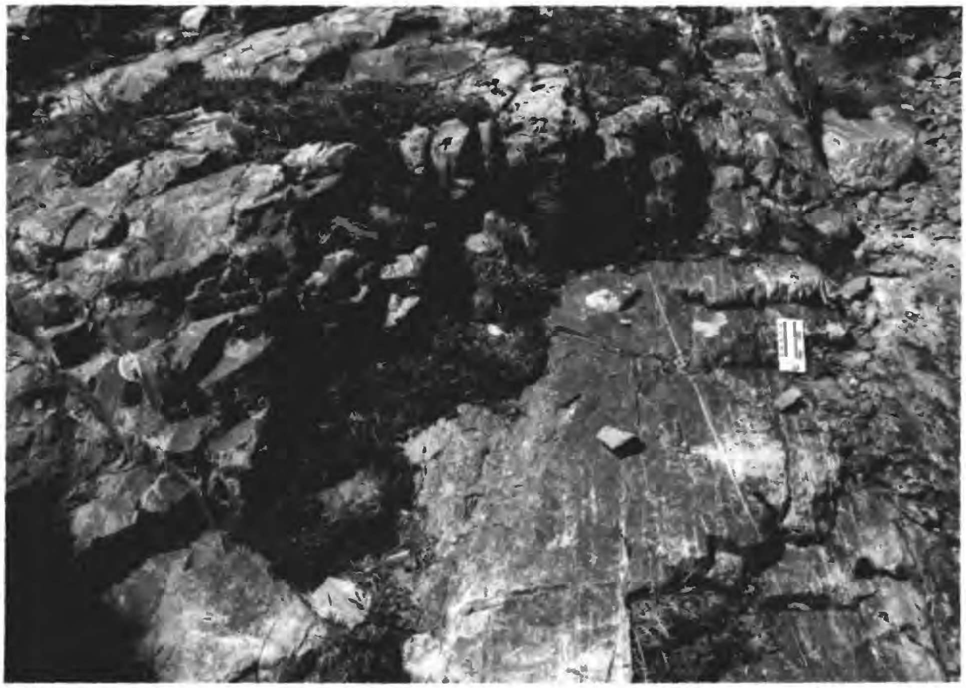


Figure 26. Chert bed in the Irving Formation, along the contact between mafic and felsic volcanic rocks, east of Fall Creek.

Figure 27. Irregular-shaped chert deposits in the Irving Formation, south of Dead Horse Creek basin; 8 x 13 cm index card for scale.

Felsic Volcaniclastic Rocks

The widespread occurrence of felsic rocks in the Irving Formation in the southeastern Needle Mountains has not previously been documented. Howe (1904), Cross and others (1905, Needle Mountains folio), Larsen and Cross (1956), and Barker (1969c) report the occurrence of felsic schist and gneiss, but suggest metamorphosed mafic plutonic and volcanic rocks are the principal lithologies. Observations made during this investigation, however, indicate that an extensive belt of felsic schist and gneiss is exposed in the Irving Formation in the Vallecito Creek area (Plate 1).

Fine-grained, muscovite and biotite bearing quartzo-feldspathic schist displaying a weak to prominent schistosity is the dominant felsic lithology in the Irving Formation, within the study area (Figure 28). Banded gneiss composed of alternating quartzo-feldspathic and amphibole- or quartz-rich layers, up to 3 cm thick, crops out locally (Figure 29). Well-preserved palimpsest textures and structures were not observed in felsic schists and gneisses of the Irving. Outcrops are monotonous and typically do not exhibit pronounced variations in color, composition, texture, or structure. They are typically grayish-white to dark grayish-brown on fresh and weathered surfaces and commonly contain small lenses, streaks, and stringers of quartz which lie subparallel or obliquely to foliation.

Felsic schists in the Irving Formation exhibit a uniform mineralogy and grain size. They are generally composed of an equigranular assemblage of quartz, plagioclase (oligoclase and andesine), microcline, biotite, and muscovite. Accessory minerals include apatite, calcite, Fe-rich epidote, hornblende, opaque oxides, perthite, sphene, tourmaline, and zircon (Table 8). Locally, garnet was identified in outcrops and talus blocks of biotite schist. Steven and others (1969) also report the occurrence of garnet in "iron-formation" on the southwest side of Sheep Draw (Plate 1). Retrograde alteration of biotite to chlorite and plagioclase to sericite is common. Mineral assemblages in gneissic rocks of this unit are similar to those in samples of felsic schist, except that the former commonly contain higher concentrations of hornblende in mafic bands.

Crystals of quartz and feldspar in Irving felsic schist and gneiss are typically $<$ 0.1-0.5 mm in maximum dimension and anhedral, whereas biotite and muscovite commonly form subhedral blades up to 1.5 mm long. Mineral constituents larger than 1.5 mm in maximum dimension were not observed in any of the samples. The fine grain size of these rocks probably largely reflects the original grain size of the protoliths. No evidence (i.e. porphyroclasts or broken and displaced crystals) of extensive granulation and grain reduction due to deformation and recrystallization was observed.

The monotonous petrography, lack of recognizable primary features, and pervasive penetrative foliation of felsic rocks in the Irving Formation precludes a precise determination of parent lithologies. Felsic schist and gneiss exposed in the study area are compositionally and texturally similar to metamorphosed quartzo-feldspathic rocks derived by recrystallization and deformation of fine-grained protoliths such as felsic tuffs or reworked tuffs, rhyolitic lava flows, or arkosic sediments. There is no textural evidence that protoliths were medium- to coarse-grained granitic plutonic rocks. Contacts between felsic and

Figure 28. Felsic schist in the Irving Formation, approximately 100 m west of first footbridge over Vallecito Creek. Note folded foliation and axial plane cleavage.

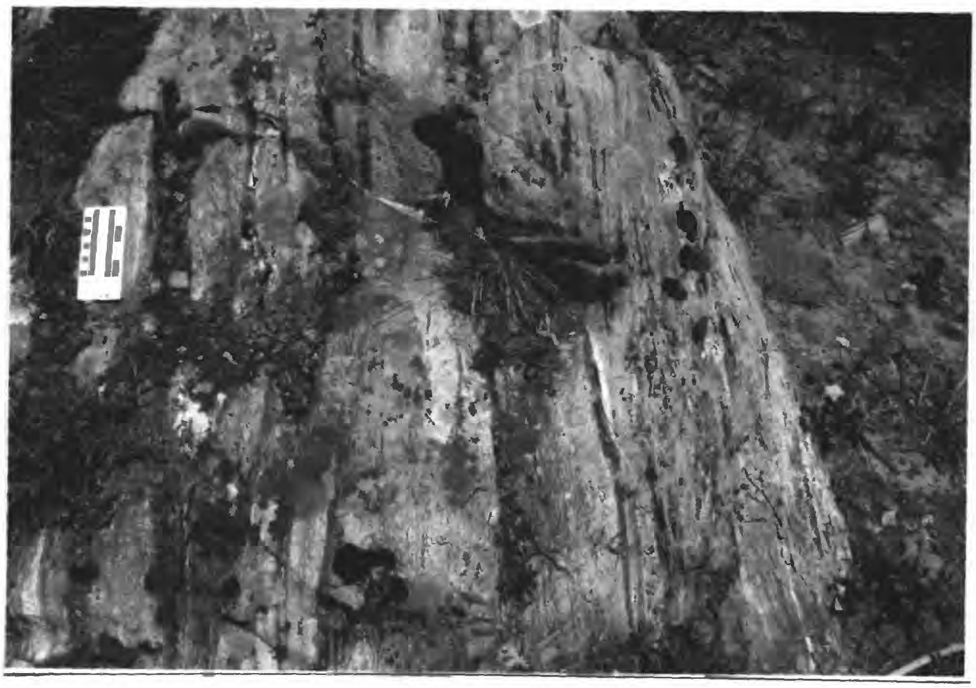


Figure 29. Banded gneiss with alternating quartzo-feldspathic and amphibole-rich layers, Irving Formation, east of Fall Creek.

Table 8

Modal analyses of felsic volcaniclastic rocks of the Irving Formation.

Sample No.	21	22	23	30	31	42	43	64	86	87	88	101	103	104	105
apatite	P	P	P	P	< 1	P	P	P	P	< 1	P	P	P	< 1	< 1
biotite	< 1	20	17	23	P	20	25	20	18	13	39	34	13	13	28
calcite	P	...	...	< 1	2	...	...	...	...	P	P	...	...	...	...
epidote	...	...	P	P	4	P	...	1	P	P	P	1	2	4	1
hornblende	...	...	...	...	24	...	...	...	...	...	...	...	...	...	P
microcline	< 1	...	...	3	8	...	5	8	2	12	...	...	P	P	...
muscovite	42	12	10	6	...	...	2	3	2	2	...	...	P	P	...
myrmekite	...	P	P	P	P	...	< 1	...	P	P	...	...	...	...	...
opaque oxides	2	< 1	P	< 1	2	< 1	1	P	2	2	1	2	3	3	1
perthite	...	...	...	< 1	< 1	...	...	...	...	2	...	...	...	...	...
plagioclase	P	7	14	15	58	32	10	24	32	23	40	18	37	36	33
quartz	55	59	59	52	1	44	56	43	44	44	20	45	45	43	36
sphene	...	...	...	...	< 1	...	...	...	...	...	...	...	...	...	< 1
tourmaline	...	...	P	...	...	...	...	...	...	...	...	...	...	...	...
zircon	...	P	P	P	P	P	P	P	P	P	P	P	P	P	P
Retrograde:															
chlorite	P	1	P	P	P	P	< 1	1	P	2	P	P	P	< 1	P
sericite	P	P	P	P	P	3	P	P	P	P	P	P	P	P	P
Veinlet minerals (not counted):															
chlorite	...	...	...	...	...	...	...	...	...	...	...	...	P	...	...
sericite	...	...	...	...	...	...	...	...	...	...	...	...	P	...	...
Points Counted	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300

P indicates that mineral is present but not encountered; leader indicates that mineral is not present.

mafic rocks in the Irving Formation appear concordant and no evidence was found to support an intrusive origin for Irving felsites. Features indicative of rhyolitic lava flows such as poorly foliated massive layers, recrystallized spherulites, relict flow banding and porphyritic texture, and flow breccia were not found.

The fine, uniform, grain size of felsic schist and gneiss in the Irving Formation leaves tuffs, reworked tuffs, or arkosic sands as the possible protoliths to be considered. It is here proposed that the felsic schists and gneisses in this unit originated as crystal-rich tuffs or reworked tuffs because of their geochemical characteristics (refer to page 76). Features indicative of epiclastic debris such as beds with variable composition and textures, polycrystalline lithic fragments, mineral overgrowths, and rounded grains were not observed. A volcaniclastic origin for these rocks is consistent with their close spatial and temporal association with the volcano-plutonic basement complex in the Needle Mountains.

Locally, black to greenish-black, irregular and discontinuous layers and lenses of amphibolite are exposed in the felsic schist and gneiss belt of the Irving Formation. Outcrops of amphibolite are 2-10 m thick and rarely up to one hundred meters long. They contain abundant, subhedral, 1-4 mm, crystals of amphibole which typically define a crude lineation. No attempt was made to map out these amphibolite exposures their origin is uncertain. They may represent basaltic flows similar to those observed by Barker (1969c) in the Twilight Gneiss, or mafic dikes.

Mafic Intrusive Rocks

Howe (1904), Cross and others (1905), Cross and Larsen (1935), and Larsen and Cross (1956) suggest that diabase, diorite, and gabbro were the protoliths for much of the metamorphosed igneous rocks of the Irving Formation in the southeastern Needle Mountains. "Feldspathic plutonic rocks" were also noted in the Irving Formation in the southeastern Needles by Barker (1969c). Although no extensive exposures of plutonic rocks were encountered in the Irving during this study, small masses of mafic intrusive rock were observed. These rocks typically occur as dikes, 1-3 m wide, and small irregular-shaped bodies up to several hundreds of meters in area. Many of these intrusive masses clearly cross-cut volcanogenic rocks of the Irving Formation, while intrusive origins were inferred for other exposures from their petrology and outcrop distribution.

Two varieties of mafic plutonic rock (Table 9) were most commonly observed in the Irving Formation during this investigation (Plates 1-3). Phaneritic, medium- to coarse-grained metagabbro with subequal proportions of amphibole and plagioclase that typically define a blasto-subophitic texture, is widely exposed in the Hell Canyon area and crops out locally in the Dead Horse Creek area (e.g. samples 74 and 155). Mafic plutonic rocks consisting chiefly of, .5 mm to 1 cm, crystals of hornblende were found throughout the Vallecito Creek-Lake Creek area. This latter group includes rocks containing hornblende pseudomorphs of, subhedral to euhedral, primary pyroxene phenocrysts in a very fine-grained, greenish-gray matrix of Fe-rich epidote, opaque oxides, hornblende, and plagioclase (e.g. samples 39 and 126), and lesser phaneritic, medium- to coarse-grained, amphibole-rich rocks (e.g.

Table 9

Modal analyses of mafic intrusive rocks, Irving Formation.

Rock Type	1	2	3	2	2	1	4	3
Sample No.	39	58	74	78	118b	126	137	155
apatite	...	P	P	...	...	...	...	...
biotite	1	9	2	...	...	6	...	1
calcite	...	P	...	...	2	1	...	...
epidote	21	17	2	21	24	48	...	2
hornblende	62	62	48	70	68	39	...	43
muscovite	...	...	...	...	2	...	...	< 1
opaque oxides	2	P	2	5	2	1	14	3
plagioclase (phenocrysts)*	...	...	44	...	...	...	...	46
plagioclase (matrix)	10	12	P	P	...	1	...	...
polycrystalline quartz	...	...	...	...	...	...	2	...
quartz	...	...	2	...	...	...	P	3
sphene	...	...	P	...	...	...	...	...
Retrograde:								
chlorite	4	P	P	5	1	3	10+	1
sericite	P	P	P	...	...	1	74+	P
Veinlet minerals (not counted):								
calcite	...	...	...	P	...	P	...	...
epidote	...	...	...	...	...	...	...	P
plagioclase	P	...	...	...	...	...	...	...
quartz	P	...	P	...	...	...	...	P
Points Counted	300	200	200	200	200	200	200	500

* unaltered and recrystallized or altered fractions of crystals were included.
+ minerals occur in matrix and as pseudomorphs of amphibole phenocrysts; may be primary and/or retrograde.

Description of Rock Types: 1 = amphibole-rich rocks with amphibole pseudomorphs of primary pyroxene phenocrysts; 2 = medium- to coarse-grained amphibole-rich rocks; 3 = metagabbro; 4 = porphyritic rock with chlorite + sericite + opaque oxide pseudomorphs of primary hornblende megacrysts.

samples 58, 78, and 118b). Porphyritic intrusive rock (sample 137) containing chlorite + sericite + opaque oxide pseudomorphs of, 1-5 cm, euhedral primary amphibole megacrysts in a fine-grained matrix of sericite, opaque oxides, quartz, and polygranular quartz, crops out locally. No attempt is made to differentiate between intrusive lithologies in the study area (mi on Plates 1 and 2).

Outcrops of mafic intrusive rocks in the Irving are black to grayish-black on all surfaces. A faint foliation is visible locally, but generally is absent. All intrusive lithologies included in map unit (mi) contain metamorphic mineral assemblages.

Conglomerate of Fall Creek

The conglomerate of Fall Creek is a massive, polymictic, clast- to matrix-supported conglomerate that contains a spectrum of angular to subrounded, granule to boulder sized fragments that commonly range between 5-14 cm in length (Figure 30). Clast types observed in the conglomerate of Fall Creek include:

1) bluish-gray to grayish-white, medium- to fine-grained quartzite composed chiefly of quartz ± magnetite ± hematite.
2) grayish-white to white vein quartz
3) fine-grained, intermediate to mafic volcanic rock.
4) porphyritic, intermediate to mafic volcanic rock with 1-5 mm anhedral to subhedral crystals of plagioclase ± amphibole
5) medium- to coarse-grained, phaneritic, mafic igneous rock composed of subequal proportions of amphibole and plagioclase
6) massive, medium- to coarse-grained quartzo-feldspathic rock.
7) white to gray, very fine-grained rock with randomly oriented needles of amphibole.
8) mafic gneiss
9) very fine-grained muscovite schist (Figure 31)
10) very fine-grained, mafic rock containing, 1-3 cm, red to reddish-brown, oval to suboval inclusions of unknown origin.

Most clast lithologies in the conglomerate of Fall Creek are similar to rocks in the Irving volcano-plutonic complex. Competent clasts are typically angular to subangular while incompetent varieties are commonly stretched and flattened, their long dimensions aligned subparallel to the foliation in the surrounding matrix.

Clasts in the conglomerate of Fall Creek are set in a fine- to coarse- grained, grayish-black to dark gray matrix, composed largely of detrital quartz, plagioclase, and lithic fragments of quartz ± opaque oxides. The balance of the matrix generally consists of actinolitic hornblende, biotite, and opaque oxides (hematite and magnetite), together with a host of minor minerals which include apatite, calcite, chlorite, epidote, tourmaline, and zircon (Table 10).

A weak to strong, vertical to subvertical, northeast trending foliation is displayed by the matrix in most outcrops of the conglomerate of Fall Creek. A prominent, steep, south-plunging lineation, defined by incompetent clasts is displayed locally..

The poor sorting and fabric of the conglomerate of Fall Creek, together with its lack of internal stratification and other primary sedimentary structures suggests that it probably originated as a series of debris flows. Local, interlayered sandy lenses (discussed on page

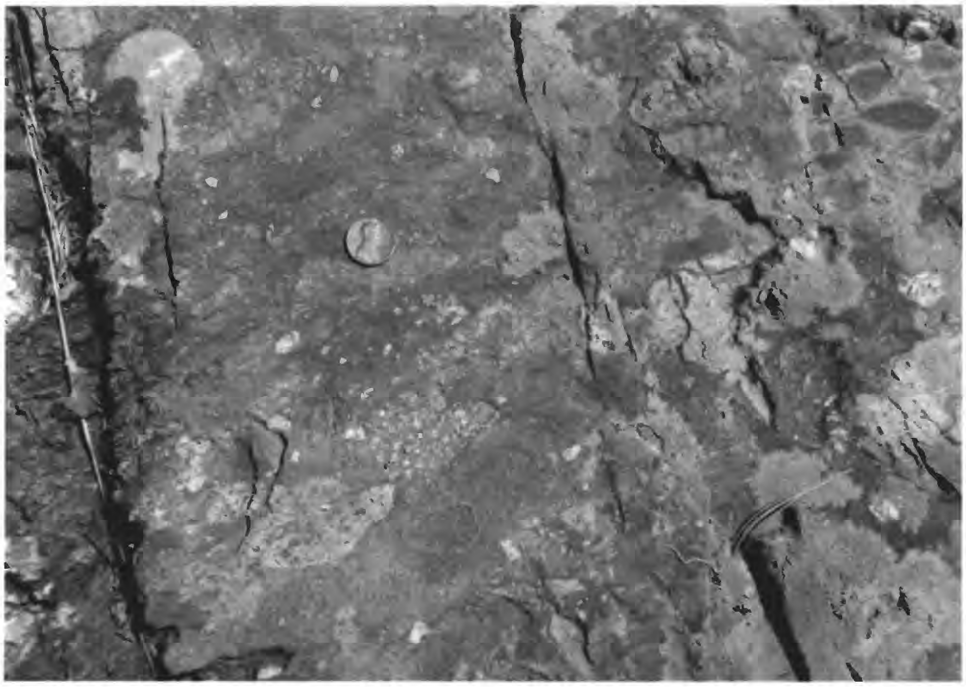


Figure 30. Conglomerate of Fall Creek north of Fall Creek-Weasel Skin Creek confluence. The outcrop exhibits a clast supported fabric and contains pebble- to cobble-sized clasts of quartzite and metabasite.

Figure 31. Felsic schist clast in the conglomerate of Fall Creek , west of Vallecito Creek and north of Fall Creek.

Table 10

Modal analyses of the conglomerate of Fall Creek.

	Matrix						Clasts			
Sample No.	1	3	5	6	19	36	26b+	26f+	109c+	110*
apatite	...	P	P	P	...	...	P	< 1	P	...
biotite	22	P	15	...	...	12	40	< 1	...	...
epidote	3	P	...	5	P	8	P	2	17	3
hornblende	24	24	...	33	31	...	19	52	37	...
opaque oxides	16	30	20	17	18	29	13	6	14	22
plagioclase (phenocrysts)	...	...	...	...	...	...	20	28	...	...
plagioclase (matrix)	2	2	5	7	1	2	3	8	1	...
quartz	31	41	45	24	38	29	3	< 1	3	75
rock fragments	2	3	15	8	11	5	...	...	...	...
tourmaline	...	...	P	...	...	P	...	...	...	...
zircon	...	...	P	...	...	...	...	...	...	...
Retrograde:										
chlorite	P	P	P	5	1	10	2	3	P	...
sericite	...	P	P	< 1	...	...	P	P	28	...
Veinlet minerals (not counted):										
calcite	...	...	...	P	...	...	...	...	...	...
quartz	P	...	...	P	...	...	...	...	...	...
Total Points Counted	200	200	200	200	200	200	200	200	200	200

P indicates mineral is present but not encountered; leader indicates mineral not present.

* quartzite clast; + mafic igneous clast.

26) are interpreted here as small fluvial channels which cut the debris flows.

Vallecito Conglomerate

The Vallecito Conglomerate was named by Cross and others (1905b; page 3) for quartz-rich conglomerate exposed in the canyon of Vallecito Creek. It is a thick succession of interbedded pebble- to cobble-conglomerate, sandstone, and subordinate siltstone that crops out from Vallecito Creek, east-southeast to Lake Creek and the Los Pinos River. Estimates of the aggregate thickness of this unit rocks range from a 800 meters (Barker, 1969c) to over 2,000 meters (Burns and others, 1980).

Conglomerate in the Vallecito varies from clast to matrix supported. Clasts range from less than 2 cm up to 1 m in maximum dimension (commonly 5-15 cm), are subangular to subrounded and include: banded iron formation, chert, jasper, several varieties of massive or thinly laminated to very thin-bedded quartzite, and vein quartz. Clasts of intermediate to mafic metavolcanic rocks, amphibolite, gneiss, greenstone, felsic to intermediate schist, and phyllite have also been noted (Barker, 1969c; Burns and others, 1980; Ethridge and others, 1984; this study). In the Dead Horse Creek area, fine-grained, grayish-black clasts resembling meta-argillite were the most common incompetent clast types observed in the Vallecito Conglomerate during this investigation.

Beds and lenses of sandstone, and sandy matrix of the conglomerate, are fine- to coarse-grained and contain: quartz, muscovite and sericite, epidote, biotite, chlorite, opaque oxides, lithic fragments, tourmaline, potassium feldspar, andalusite, albite, amphibole, apatite, calcite, garnet, leucoxene, monazite, pyrite, rutile , sillimanite, sphene, tourmaline, zircon (Barker, 1969c; Burns and others, 1980).

Bedding in the Vallecito ranges from thin to very thick. Very thin to thin, parallel and contorted lamination is commonly exhibited in silty beds. Planar laminated quartz arenite is also noted by Burns and others (1980). Individual beds may be continuous for hundreds of meters along strike or form lense shaped bodies that extend from several meters up to several hundred meters. Bedding planes are commonly sharp, marked by abrupt textural variations.

Well preserved primary sedimentary structures are ubiquitous in Vallecito rocks and include: trough cross-stratification, planar cross-statification, normal and reverse-grading, scour surfaces, and soft-sediment deformation structures (contorted lamination and small-scale faulting confined to individual beds of siltstone). Burns and others (1980, p. 26 and 63) report ripples, clast imbrication, and possible "burrow stuctures". Foliation and lineation are commonly absent or only weakly developed in most outcrops. Conglomeratic rocks (foliated conglomerate facies of Burns and others, 1980) exposed in the Table Mountain-Dead Horse Creek area, however, commonly exhibit a prominent foliation and pebble lineation. Foliation in this area generally trends west-northwest and dips steeply to the south-southwest while the trend of lineation varies from 30°-60°, south-southwest.

Barker (1969c) suggests that the Vallecito Conglomerate may have been deltaic, with deposition occurring in a tectonically controlled basin. Deposition in an alluvial fan system by high-gradient, short-duration, peak discharge, braided streams and rare debris flows is proposed by Burns and others (1980) and Ethridge and others (1984). They suggest that the source area was located north of the present outcrop belt, with the proposed alluvial fan system prograding southward.

Eolus Granite

The ca. 1.45 Ga (Table 1) Eolus Granite, named after Mount Eolus (Cross and others, 1905), is the most widespread unit of Proterozoic age in the Needle Mountains (Figure 2). Compositionally the Eolus Granite is dominantly quartz monzonite with lesser amounts of granodiorite and granite (Barker, 1969c). Varying proportions of microcline, plagioclase (oligoclase or andesine), microperthite, quartz, biotite, and hornblende are the dominant constituents of these rocks. Accessory and secondary minerals include ilmenite, sphene, epidote, magnetite, zircon, apatite, calcite, muscovite, and chlorite.

The Eolus Granite forms prominent ridges west and east of the study area separating the Irving Formation in the southeastern Needle Mountains from the volcano-plutonic basement complex in the canyon of the Animas River (Figure 2). All contacts between the Eolus Granite and older metamorphosed volcanic and sedimentary rocks in the southeastern Needle Mountains were originally mapped as faults (Cross and others ,1905b; Cross and Larsen, 1935; Larsen and Cross, 1956). Barker (1969c) re-examined the Irving-Eolus contact west of Vallecito Creek in the vicinity of Fall Creek and found zones of intrusive breccia and numerous apophyses extending from the main intrusive body into the older metavolcanic sequence. Based on these and similar observations in other parts of the region Barker re-mapped the Irving/Vallecito-Eolus contacts in the Vallecito Creek-Los Pinos River area as intrusive. Although limited, observations made during this study support an intrusive nature for the contacts between the Eolus Granite and older stratified metamorphic rocks, as suggested by Barker (1969c).

West of Vallecito Creek, from Vallecito campground north to Taylor Creek, the Eolus-Irving contact is marked by zones of breccia in which dark-colored, angular blocks of Irving Formation are dispersed in offshoots of Eolus Granite. Dikes, pods, and lenses of medium- to coarse-grained granitic rock, aplite, pegmatite, and feldspar-quartz porphyry, up to 100 m in length and tens of meters in width, occur in the Irving Formation as far east as Vallecito Creek. Compositionally these apophyses are similar to the main mass of Eolus Granite and a U-Pb age determination (Silver and Barker, 1968) of ca. 1.45 Ga for one dike is identical to that of the main Eolus mass. Numerous offshoots of granitic rock were observed near the Irving-Eolus contact west of Vallecito Creek between the second and fourth footbridges.

A cursory examination of the contact between the Eolus Granite and the older stratified units in the Emerald Lake-Lake Creek area was made during this investigation. Heavy vegetation and Quaternary surface deposits often obscure the contacts in this area. Apophyses of Eolus-type rocks are present in the Irving Formation west of the Irving-Vallecito contact in the vicinity of Hell Canyon and in the Vallecito Conglomerate west of the Lake Creek-Los Pinos River confluence. Barker (1969c) suggests that the linear nature of the contact between the Eolus

Granite and the Vallecito Conglomerate in this area could possibly be due to intrusion along a fault.

Paleozoic Rocks

No attempt was made to subdivide the Paleozoic rocks exposed in the study area. Included in this group of rocks are a variety of marine and nonmarine lithologies including conglomerate, dolomite, limestone, sandstone, siltstone, and shale of the Cambrian Ignacio Quartzite, Devonian Elbert Formation and Ouray Limestone, Mississipian Leadville Limestone, Pennsylvanian Molas and Hermosa Formations, and the Lower Permian Rico Formation (Steven and others, 1974). The thickness of the Paleozoic strata exposed in and around the study area varies from several meters up to one hundred meters or more.

Paleozoic stata, in isolated exposures, lie unconformably upon the Vallecito and Irving Formations at Table Mountain and in Dollar Lake-Hell Canyon area. North and south of Dollar Lake small patches of these rocks are locally faulted against the Irving Formation. Paleozoic rocks form a continous, gently dipping, veneer over the Vallecito Formation on Middle Mountain from just south of Second Creek to the northeast side of Vallecito Reservoir. They are also exposed in the extreme southwestern and western parts of the study area where they unconformably overlie the Vallecito Formation and Eolus Granite and are in fault contact with Eolus rocks on their western exposure (Steven and others, 1974).

Quaternary Deposits

Unconsolidated, Pleistocene through Holocene, surficial deposits derived by glacial, periglacial, erosional, and pedogenic processes occur throughout the study area. Although commonly thin and discontinuous, these deposits locally form extensive blankets over the Precambrian bedrock. Though briefly studied, these deposits are subdivided (Plates 1 and 2) as follows: 1) alluvium and debris flow deposits; 2) bog or pond sediment and soil; 3) ice and/or rock glacier deposits and debris which may have formed through frost action or reworked by processes related to permafrost (patterned ground); 4) rockslides; and 5) talus.

GEOCHEMISTRY

Analytical Methods

Major oxide and selected trace element concentrations were obtained for thirty-two samples of metamorphosed igneous and sedimentary rocks of the Irving Formation. Element abundances and CIPW norms of analyzed samples are presented below.

Major and minor oxides (except FeO, H_2O+, H_2O-, and CO_2) and Cr were analyzed by wavelength-dispersive X-ray fluorescence with total iron reported as Fe_2O_3*. Concentrations of FeO were determined separately by $K_2Cr_2O_7$ titration. Weight percent Fe_2O_3 was calculated from FeO and Fe_2O_3* ($Fe_2O_3 = Fe_2O_3* - FeO \times 1.11$). Energy-dispersive XRF was applied to measure Nb, Rb, Sr, Zr, Y, Ba, Ce, La, Cu, Ni and Zn concentrations in all samples. Abundances of Ba, Co, Ni, Cr, Cs, Hf, Rb, Sb, Ta, Th, U, Zn, Zr, Sc, La, Ce, Nd, Sm, Eu, Gd, Tb, Tm, Yb, and Lu were determined for sixteen samples by instrumental neutron activation analysis (INAA). Details of the analytical methods applied are provided by Baedecker (in press).

Degree of Chemical Alteration

A major concern when dealing with metamorphosed or altered rocks is the degree to which their original chemistry has changed. Metamorphic mineral assemblages and chemical compositions of rocks in the Irving Formation are generally compatible with the hydration of primary mineral phases without extensive element migration. This is supported by the preservation of relict zoning in plagioclase phenocrysts and hornblende pseudomorphs after pyroxene, and the lack of extensive veins and alteration zones. Alteration in these rocks appears to have been minor, and limited primarily to highly mobile elements. For example, some Irving meta-andesites exhibit anomymously low Na_2O concentrations (e.g. < 0.20 weight percent, sample 116) which is attributed to local Na_2O depletion. In addition, some metabasalts (Table 13, sample 56) are nepheline normative, reflecting a low SiO_2/Na_2O ratio (9.4). The alkaline character of the latter is inconsistent with the general subalkaline character of most mafic volcanics in the Irving, and could reflect Na-enrichment or depletion of SiO_2.

In attempting to evaluate the extent of chemical alteration in rocks of the Irving Formation, major and trace elements in mafic and felsic volcanic lithologies were plotted against Zr (Figures 32-35). Zirconium generally exhibits a systematic enrichment in the melt phase during successive stages of igneous differentiation (Hughes, 1982, pages 243 and 267), and is considered to be relatively immobile during post-consolidation alteration and metamorphic processes (Pearce and Cann, 1973; Winchester and Floyd, 1977). Isochemically metamorphosed igneous rocks should therefore exhibit "igneous" variation trends with increasing Zr in more evolved rocks (Wood and others, 1976; Coish, 1977; Kushido and Riccio, 1980).

Mafic lithologies of the Irving exhibit an overall increase in SiO_2, Al_2O_3, Na_2O, K_2O, Rb, Sr, Y, Ba, and a decrease in Fe_2O_3, FeO, MnO, MgO, CaO, Ni, and Cr with increasing Zr. These chemical trends are consistent with igneous fractionation processes. Considerable scatter is apparent for Na_2O, K_2O, Ba, Rb, Sr, Ni, and Cr on these plots. The erratic distribution of Na_2O, K_2O, Ba, Rb, and Sr may be due to local post-magmatic alteration. The wide range in Ni and Cr values at a given concentration of Zr may indicate varying degrees of olivine and pyroxene fractionation or chemical variations in parent magmas.

Major and trace elements in Irving felsites (Figures 34-35) typically exhibit flat trends with increasing Zr, except for a slight overall increase in FeO, minor decrease in Na_2O, and a strong positive correlation of Zr and Y. The latter is consistent with the inferred volcanic origin of these rocks, as concentrations of both elements are generally enriched in more evolved rocks. The high MgO content at high Zr for some felsic samples can not be explained. Variable distribution of K_2O, Ba, Rb, and Sr on these plots may reflect local alteration.

Based on the discussion of alteration in rocks of the Irving Formation presented above and in subsequent sections it is apparent that at least local migration of highly mobile elements occurred during post-consolidation alteration and metamorphic processes. The chemical integrity of protoliths, however, appear to be largely retained.

Volcanic Rocks

Metamorphosed volcanic rocks in the Irving Formation exhibit a bimodal distribution of SiO_2. Silica concentrations range from 46-58 % in mafic lithologies to 70-75 % in felsites (Figure 36). Representive sample suites of mafic and felsic lithologies were collected, indicating that the silica gap exhibited by these rocks is an intrinsic feature rather than a reflection of sampling bias. The bimodality of volcanic rocks in the Irving Formation is analogous to the bimodal distribution of volcanic rocks in other Early Proterozoic "greenstone successions" that occur throughout the southwestern United States (Condie, 1986).

Basaltic to Andesitic Volcanics

Fine- to medium-grained mafic volcanic rocks in the Irving Formation (unit ba, Plates 1 and 2) are broadly classified, based on their SiO_2 concentrations, as basalts (SiO_2 less than 52 %) and basaltic andesites (52-56 % SiO_2) (silica divisions after Peccerillo and Taylor, 1976). Plagioclase phenocryst-rich flow rocks (unit ap) are generally andesitic (56-63 %) in composition, but some contain less than less than 51 % SiO_2.

Irving basalts plot largely within the subalkaline field on the SiO_2-Zr/TiO_2 diagram of Winchester and Floyd (1977) (Figure 37). They generally cluster in the tholeiitic fields on a variety of magma series discriminantion diagrams and their average chemical composition is broadly similar to average tholeiitic basalt (Tables 11-12). These rocks contain contain 47-52 % SiO_2 and 12-18 % Al_2O_3; are characterized by a narrow range of FeO*/MgO (1-2; FeO* = total Fe as FeO), high CaO (7-13 %), and variable Na_2O/K_2O (2-14); and exhibit olivine- or quartz-normative compositions (Table 13). Their wide range of Na_2O/K_2O probably reflects alkali migration before or during metamorphism.

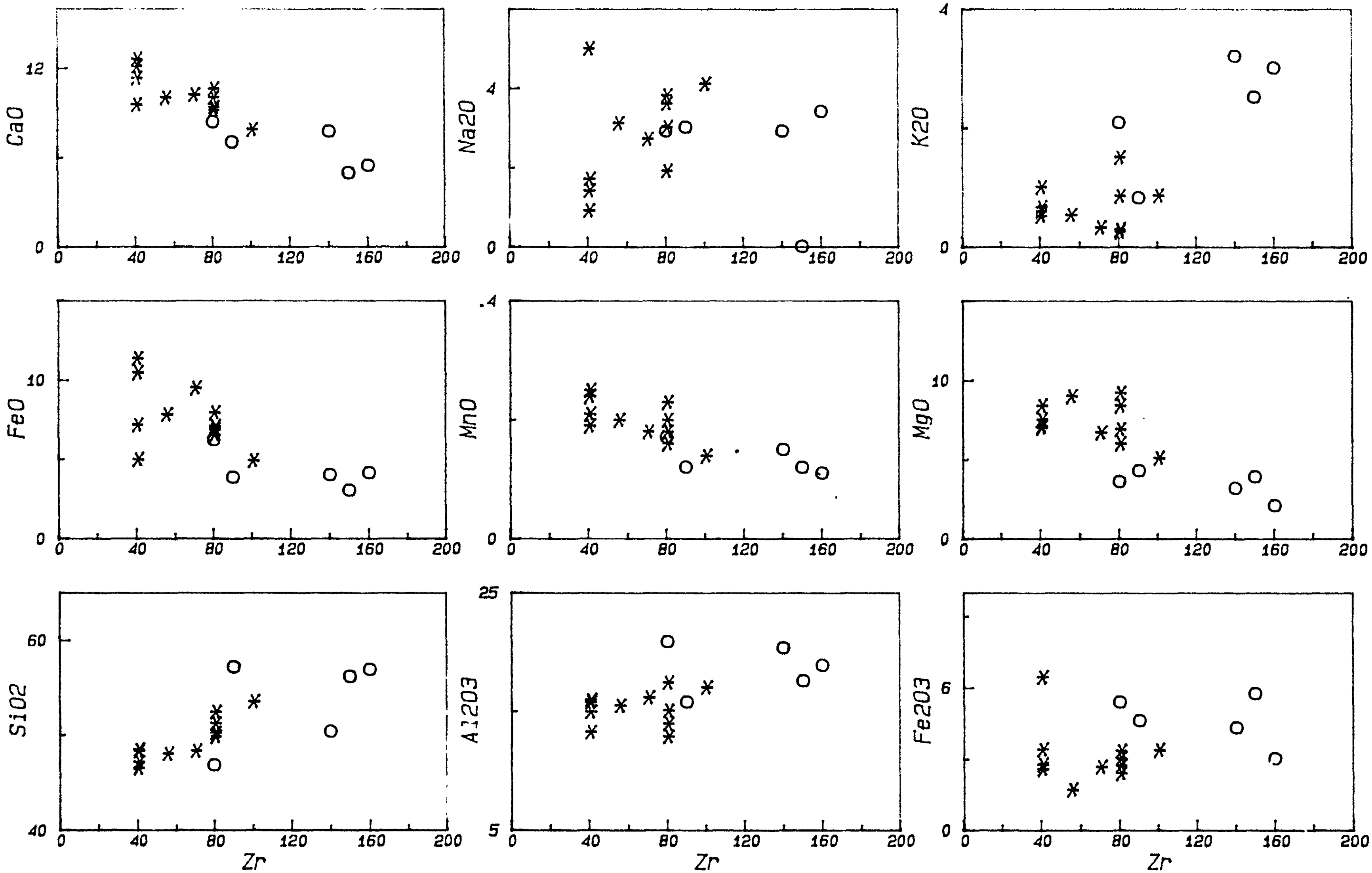


Figure 32. Plots of major elements vs. Zr for mafic volcanic rocks of the Irving Formation. asterisks = rocks of map unit ba; circles = plagioclase phenocryst-rich rocks of map unit ap.

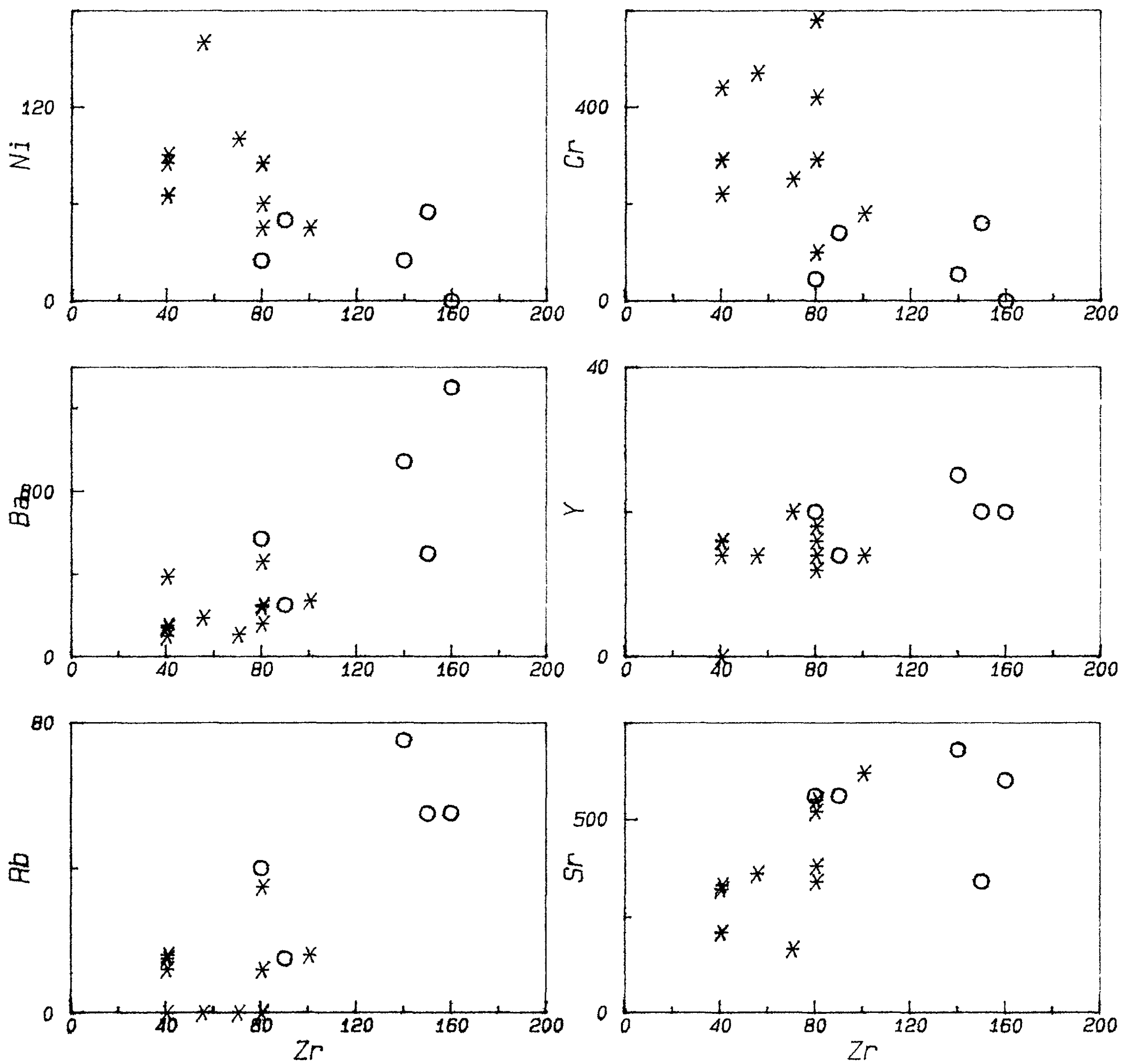


Figure 33. Plots of selected trace elements versus Zr for mafic volcanic rocks of the Irving Formation. Symbols as in Figure 32.

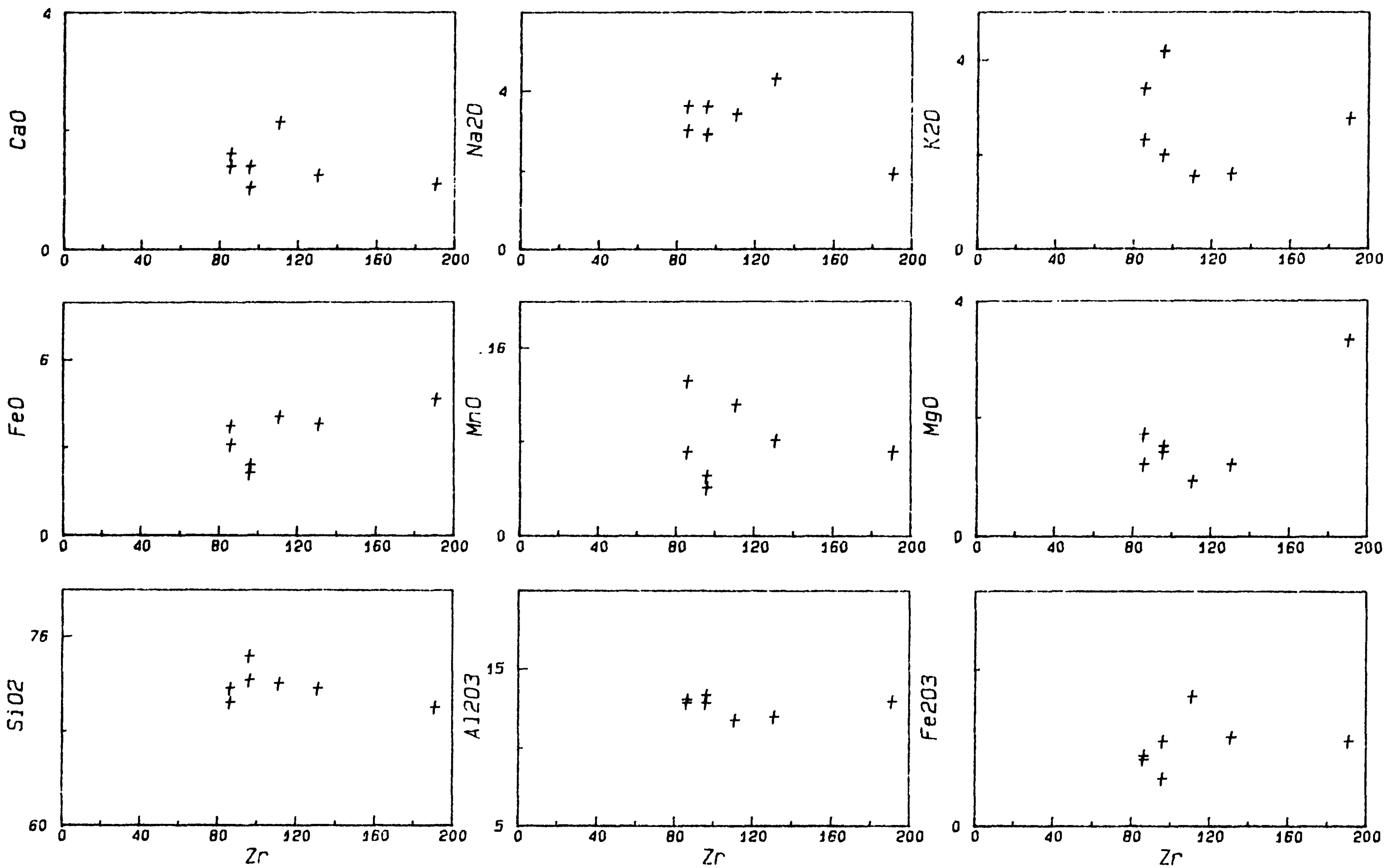


Figure 34. Plots of major elements vs. Zr for Irving felsites. Samples 31 and 88 excluded (see p. 76).

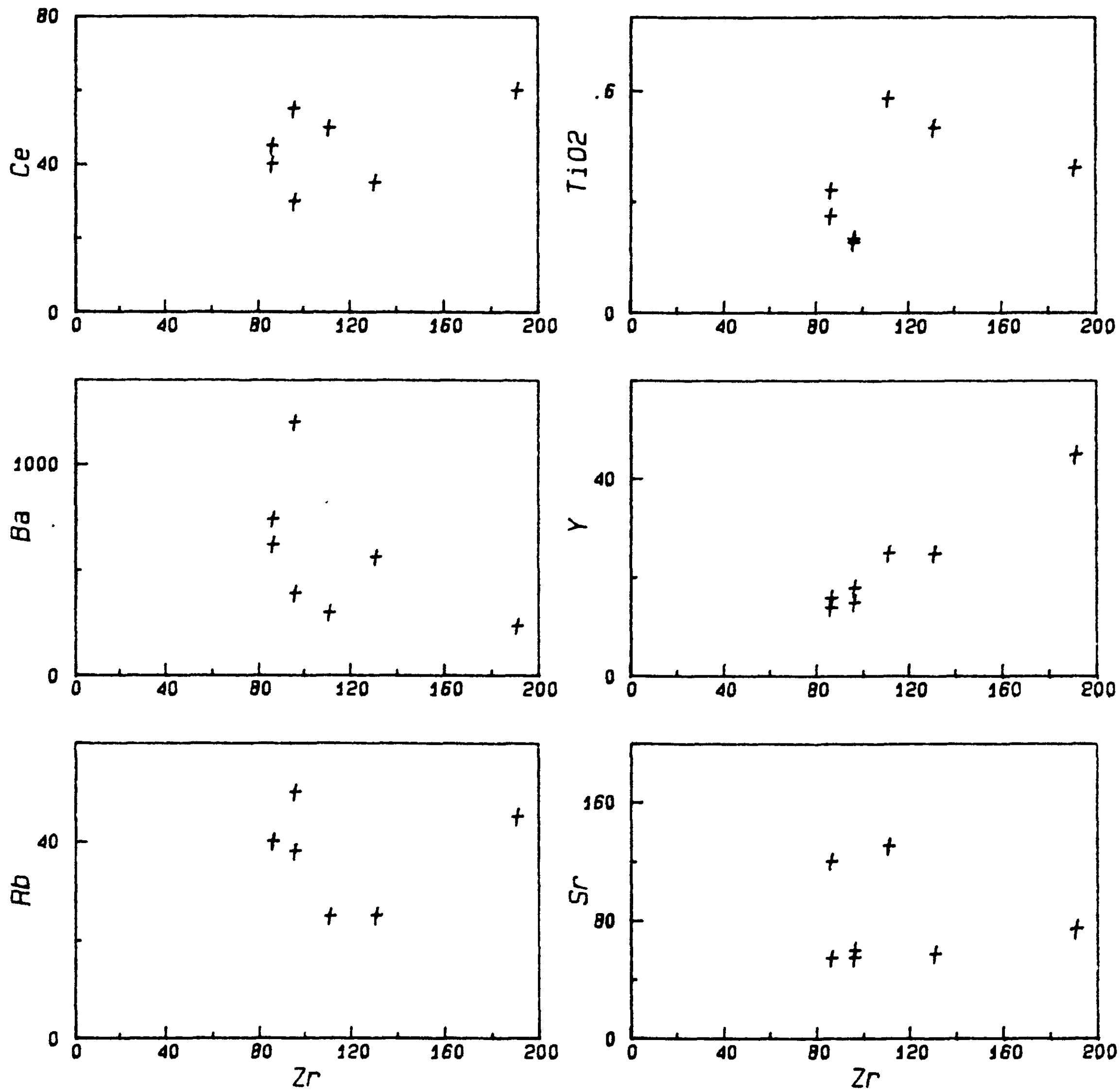


Figure 35. Plot of selected trace elements and TiO_2 versus Zr for felsic rocks of the Irving Formation.

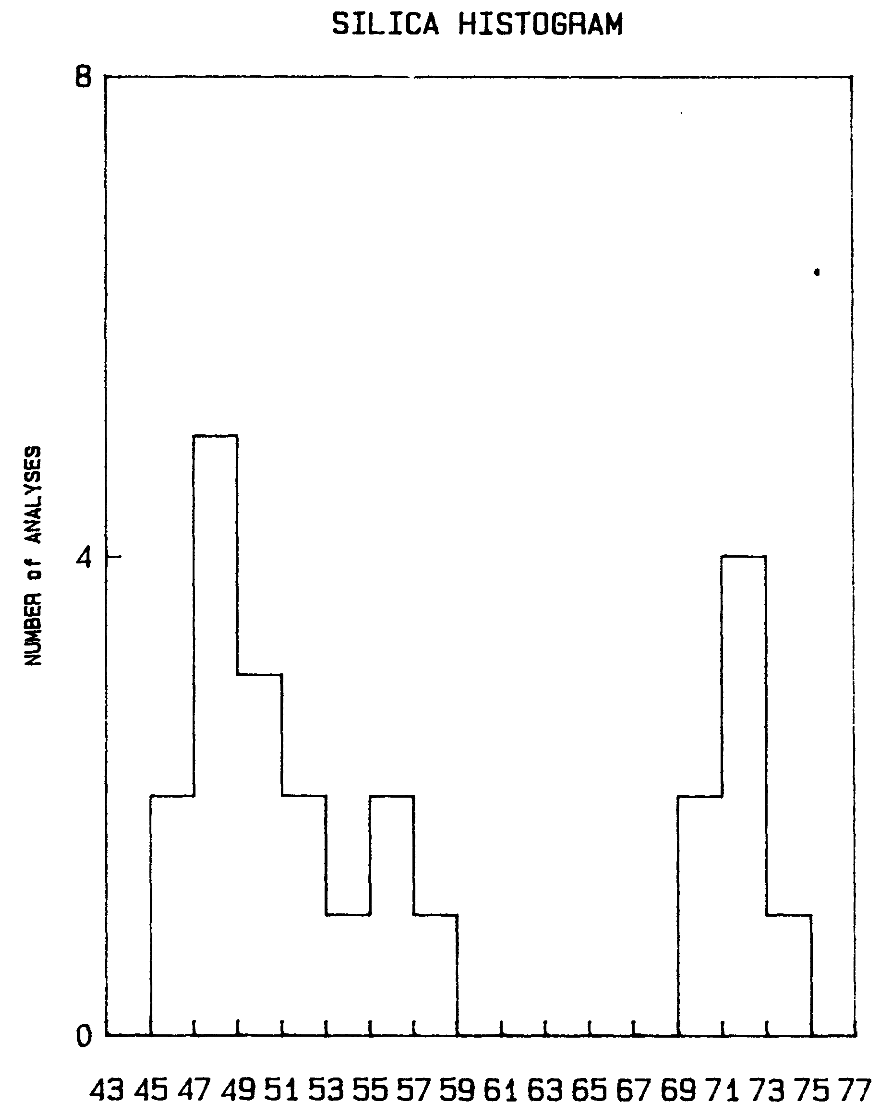


Figure 36. Histogram displaying the bimodal distribution of SiO_2 in metavolcanic rocks of the Irving Formation.

Concentrations of Ni and Cr typically fall between 50-100 ppm and 250-500 ppm, respectively.

Metabasalts in the Irving define two distinct trends on chondrite-normalized REE diagrams (Figure 38). The first group exhibits flat REE distributions with enrichment factors of 9-11 times that of chondrite. These patterns are similar to low-K Archean tholeiite and tholeiites of primitive island arcs (Jakes and Gill, 1970; Condie, 1976; Condie and Moore, 1977). Similar patterns are also exhibited by "transitional-type" MORB (Sun and others, 1979; Condie and Nuter, 1981). The second group are LREE enriched (20-100 times chondrite) and exhibit slightly enriched HREE patterns (6-15 times chondrites). These LREE enriched spectra are similar to those exhibited by "enriched" Archean tholeiite and basalts of the calk-alkaline volcanic arc series (Jakes and Gill, 1970; Condie, 1976).

LREE depleted and enriched patterns in Irving basalts might reflect different magma sources. Similar REE depleted and enriched patterns exhibited by Early Proterozoic mafic volcanic rocks in Gunnison area of west-central Colorado are attributed by Knoper and Condie (1988) to "closed-system fractionation of depleted to variably enriched parental basalts". Modelling of chemical data for basaltic rocks of the Irving Formation, however, is required to fully assess the possible implications of REE patterns in these rocks.

Irving basaltic andesites are distinguished from associated basalts by their higher SiO_2 (52-54 %) and FeO* (7-9 %), lower CaO (7-10 %), and calk-alkaline affinities (Table 11). In addition, Sr (520-620 ppm) and Zr (80-100 ppm) concentrations are typically higher, while Ni (45-60 ppm) contents are lower, than in the basaltic lithologies.

Andesite porphyry in the Irving Formation contains 56-57 % SiO_2, is quartz-normative, and typically exhibits subalkaline and calk-alkaline affinities (Figure 37, Tables 11-12). Compared to associated basalts and basaltic andesites, they generally exhibit higher Al_2O_3 (16-18 %), FeO*/MgO (1.9-3.2), Sr (340-680 ppm), and Zr (90-160 ppm), while CaO (4-7 %), Na_2O/K_2O (.9-1.2), Ni (25-55 ppm), and Cr (45-160 ppm) are commonly lower.

Chondrite-normalized REE spectra (Figure 38) of andesite porphyry are LREE enriched (10-100 times chondrite) with relatively flat HREE patterns (6-15 times chondrite). Overall these patterns are similar to those displayed by "high-alkali" Archean andesite (Condie, 1976) and calk-alkaline andesites (Jakes and Gill, 1970; Condie and Moore, 1977).

Plagioclase phenocryst-rich flow rocks with less than 51 weight percent SiO_2 (Table 13, samples 68 and 127) are characterized by high Al_2O_3 (20-21 %), FeO*/MgO (2.5-3.5), and CaO (7.5-8.5 %); low Na_2O/K_2O (.9-1.4), Ni (25 ppm), and Cr (45-55 ppm); and tholeiitic affinities (Table 11). These rocks exhibit a close spatial association with exposures of andesite porphyry (Plate 3), and display similar modal compositions and overall chemistries to the latter (Tables 6 and 14, Figure 38). This argues that the anomalously low-SiO_2 and high-Al_2O_3 in these rocks could either be a reflection of their higher modal concentrations of relict plagioclase phenocrysts (Table 6, page 39), or that it is a result of post-consolidation alteration and recrystallization. Alternatively, the low SiO_2 and high Al_2O_3 of these rocks might imply that they are high-alumina basalts or plagioclase-enriched tholeiite, to which they exhibit chemical similarities (Table 12).

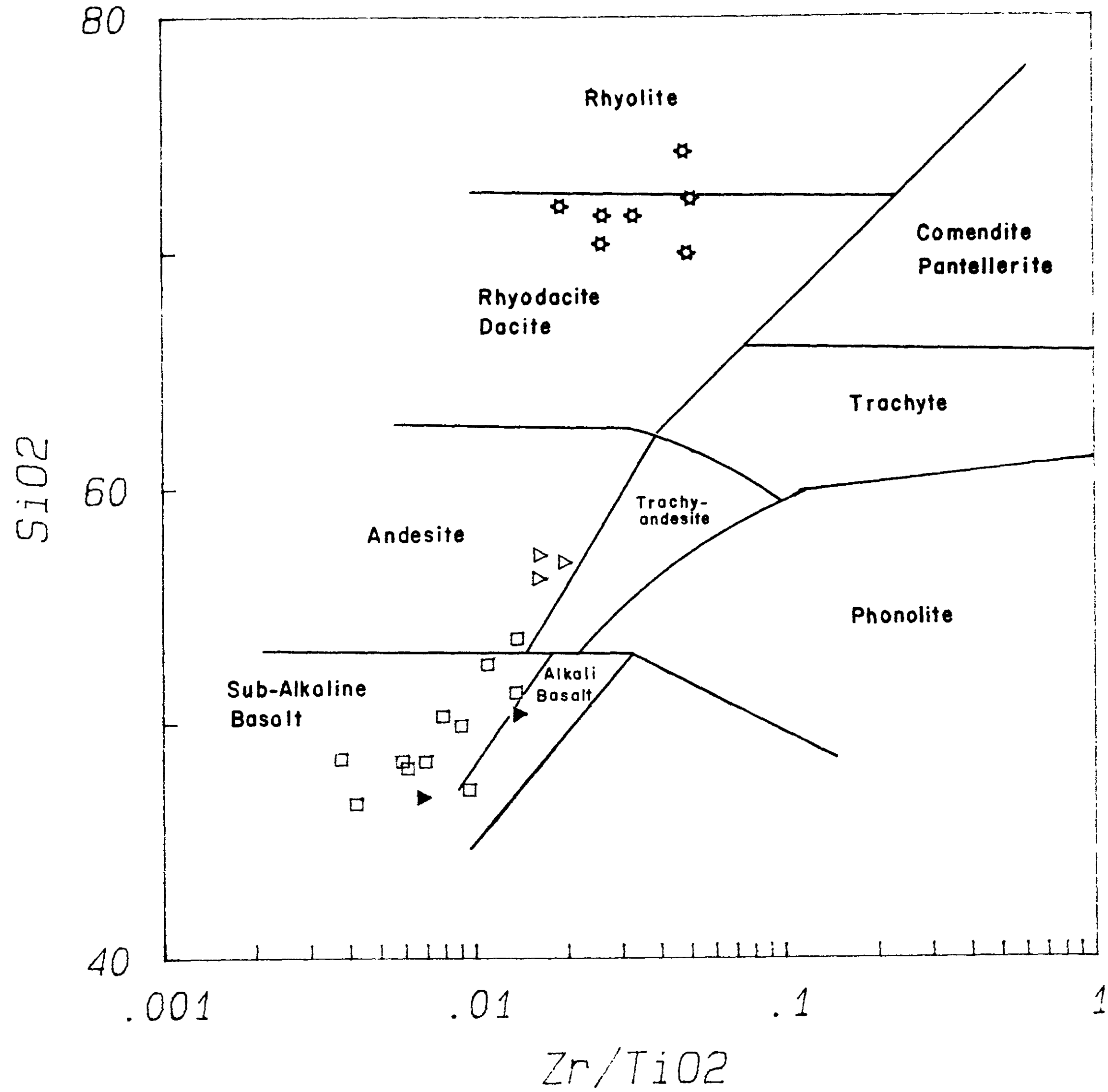


Figure 37. Classification of volcanic rocks of the Irving Formation on the SiO_2-Zr/TiO_2 variation diagram of Winchester and Floyd (1977); squares = basalt and basaltic andesite; open triangles = andesite porphyry; solid triangles = plagioclase phenocryst-rich porphyry with < 52 % SiO_2; stars = felsic volcaniclastic rocks.

Table 11

Summary of the magma series classification schemes applied to Irving metavolcanic rocks.

Plot	Reference	Compositional Limits	Fields Defined	No. of Analyses Mafics	No. of Analyses Felsics	Results (# of samples) Mafics (b,ba,ap,p)	Results (# of samples) Felsics
$Na_2O + K_2O-SiO_2$	Irving & Baragar (1971)	Rhyolitic to Basaltic	ALK,SUBALK	15	7	ALK (1,0,0,2) SUBALK (8,2,2,0)	SUBALK (7)
AFM	Irvine & Baragar (1971)	Rhyolitic to Basaltic	TH, CA	15	7	TH (7,0,0,1) CA (2,2,2,1)	TH (1), CA (6)
FeO^*-FeO^*/MgO	Miyashiro (1975)	Rhyolitic to Basaltic	TH, CA	16	7	TH (9,2,2,2) CA (0,0,1,0)	TH (3), CA (4)
SiO_2-FeO^*/MgO	Miyashiro (1975)	Rhyolitic to Basaltic	Th, Ca	16	7	TH (8,0,1,2) CA (1,2,2,0)	TH (1), CA (6)
SiO_2-Cr	Miyashiro & Shido (1975)	Rhyolitic to Basaltic	TH, CA	15	4	TH (7,0,0,2) CA (2,2,2,0)	CA (4)
Cation Plot	Jensen (1976)	Rhyolitic to Basaltic	TH, CA, K	16	7	TH (8,1,0,1) CA (1,1,3,1)	TH (2), CA (5)
P_2O_5-Zr	Winchester & Floyd (1976)	Basaltic	ALK, TH	16	NA	TH (8,2,3,1) ALK (1,0,0,1)	NA
TiO_2-Zr/P_2O_5	Winchester & Floyd (1976)	Basaltic	ALK, TH	16	NA	TH (16)	NA

Explanation of magma series and rock type abbreviations: ALK (alkaline); SUBALK (subalkaline); TH (tholeiitic); CA (calc-alkaline); K (komatiitic); NA = not applicable.

b = basalt (< 52 % SiO2); ba = basaltic andesite (52-56 % SiO2); ap = andesite porphyry (> 56 % SiO2); p = plagioclase phenocryst-rich porphyry with less than 52 % SiO_2.

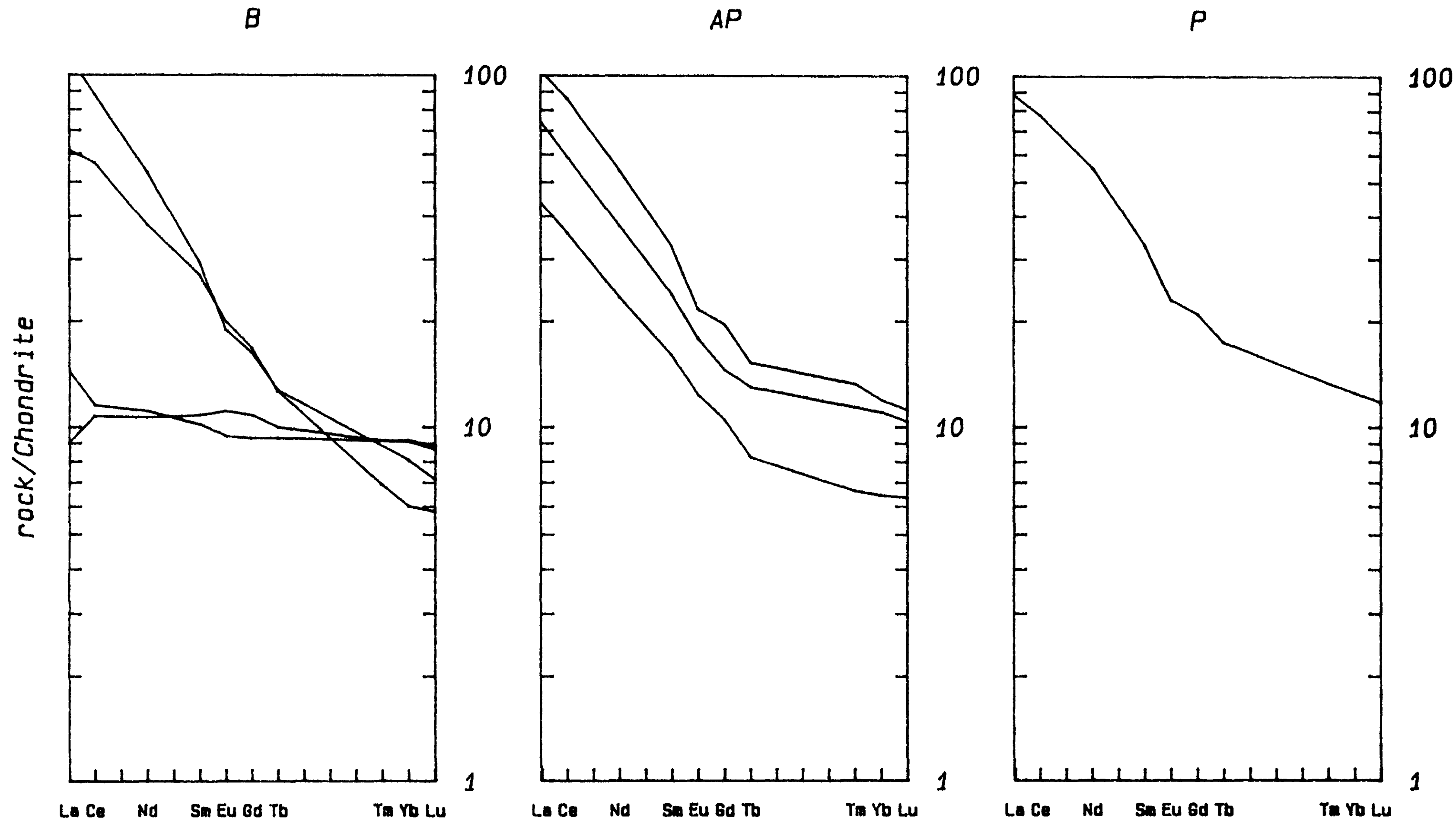


Figure 38. Chondrite-normalized REE spectra for mafic volcanic rocks of the Irving Formation: (B) = basalt; (AP) = andesite porphyry; and (P) = plagioclase phenocryst-rich porphyry of map unit ap with < 52 % SiO_2. Normalizing values are from Boynton (1984).

Table 12

Comparison of the average chemical compositions of basaltic and andesitic volcanic rocks of the Irving Formation with average chemical compositions of some unaltered mafic volcanic rocks.

	1*	2*	3*	4	5	6	7	8*
SiO_2	48.7	54.0	58.6	50.72	52.40	52.04	56.62	60.00
TiO_2	.85	.74	.80	1.96	2.55	1.12	1.08	.69
Al_2O_3	15.1	16.4	18.0	14.98	13.72	18.39	17.54	17.12
Fe_2O_3	3.2	3.0	4.6	3.51	2.20	1.57	1.30	3.91
FeO	8.1	5.8	3.8	8.22	10.99	7.86	6.48	2.58
MnO	0.21	.15	0.12	0.18	0.18	0.15	0.13	0.15
MgO	7.7	6.1	3.5	7.38	4.82	5.24	4.06	3.26
CaO	10.6	8.7	6.0	10.35	8.73	10.08	7.40	7.10
Na_2O	2.6	3.9	3.27	2.44	3.10	2.69	3.94	4.41
K_2O	.63	.88	2.2	0.45	0.92	0.69	1.31	2.0
P_2O_5	.17	.20	.26	0.24	0.39	0.16	0.23	0.28

1. Average of 9 samples of basalt of the Irving Formation.
2. Average of 2 samples of basaltic andesite of the Irving Formation.
3. Average of 3 samples of andesite porphyry of the Irving Formation.
4. Average of 202 samples of tholeiitic basalt (Le Maitre, 1976).
5. Average of 516 samples of tholeiitic andesite.
6. Average of 462 samples of calk-alkaline basalt.
7. Average of 375 samples of calk-alkaline andesite.
8. Calk-alkaline volcanic arc andesite (Jakes and White, 1972).

Examples 4-6 are from Wilkinson (1986).

* Analyses are recalculated to 100 percent volatile-free for comparison.

Table 13

Major and trace element data (XRF), and CIPW norms for basaltic to andesitic volcanics of the Irving Formation.

Rock Type⁺ :	b	b	b	b	ba	ba	b	b	b	p	b	ap	ap	p	ap	b
Sample No.:	8a	13	18a	46	48	53	56	61	66	68	76	116	125	127	131	134
Major Elements (Wt %):																
SiO2	50.3	48.1	46.6	48.5	52.5	53.6	47.2	51.3	49.9	46.9	48.4	56.2	56.9	50.4	57.2	48.4
TiO2	1.02	0.91	0.96	1.07	0.73	0.73	0.42	0.59	0.89	1.19	1.20	0.94	0.83	1.02	0.56	0.58
Al2O3	12.9	15.5	15.0	13.3	15.1	17.1	15.8	14.0	17.5	20.9	16.2	17.6	18.9	20.4	15.8	16.0
Fe2O3	3.36	1.74	2.59	2.79	2.42	3.41	3.42	3.05	2.75	5.41	2.71	5.75	3.03	4.34	4.63	6.46
FeO	7.96	7.84	10.46	11.36	6.54	4.93	7.19	6.89	7.07	6.21	9.54	3.02	4.16	4.02	3.85	4.99
MnO	0.20	0.20	0.21	0.25	0.16	0.14	0.24	0.23	0.18	0.17	0.18	0.12	0.11	0.15	0.12	0.19
MgO	8.4	9.0	7.5	7.1	6.9	5.1	8.4	9.2	6.0	3.6	6.7	3.9	2.1	3.2	4.3	7.0
CaO	10.0	10.0	12.1	11.3	9.15	7.84	9.52	10.6	9.35	8.35	10.2	4.93	5.42	7.70	7.00	12.6
Na2O	3.8	3.1	1.4	1.7	3.6	4.1	5.0	1.9	3.0	2.9	2.7	< 0.20	3.4	2.9	3.0	0.90
K2O	0.28	0.53	1.00	0.51	0.85	0.86	0.66	0.25	1.50	2.08	0.32	2.51	3.00	3.20	0.82	0.59
P2O5	0.32	0.10	0.12	0.13	0.21	0.19	0.14	0.25	0.22	0.23	0.13	0.27	0.33	0.34	0.15	0.12
H2O+	1.23	1.60	1.70	0.76	1.67	1.43	2.08	2.18	1.84	1.65	1.87	3.08	0.71	1.34	0.85	1.68
H2O-	0.06	0.06	0.11	0.06	0.10	0.10	0.08	0.06	0.07	0.06	0.12	0.09	0.08	0.08	0.08	0.08
CO2	0.15	0.15	0.19	0.14	0.23	0.34	0.30	0.17	0.12	0.10	0.18	0.08	0.09	0.08	0.14	0.14
Total	100.86	100.85	100.09	100.22	100.88	100.43	101.24	101.43	101.17	100.43	101.3	< 99.02	99.52	99.61	98.92	100.28
FeO*	10.98	10.44	12.78	13.86	8.71	7.99	10.26	9.63	9.54	11.07	11.97	8.19	6.89	7.92	8.01	10.8
Fe2O3*	12.20	11.60	14.20	15.40	9.68	8.88	11.40	10.70	10.60	12.30	13.30	9.10	7.65	8.80	8.90	12.00
FeO*/MgO	1.3	1.2	1.7	1.9	1.3	1.4	1.2	1.0	1.6	3.1	1.8	2.1	3.2	2.5	1.9	1.5
Na2O/K2O	13.6	5.8	1.4	3.3	4.2	4.8	7.6	7.6	2.0	1.4	8.4	...	1.1	.9	3.7	1.5

Trace Elements (ppm):

Sample No.:	8a	13	18a	46	48	53	56	61	66	68	76	116	125	127	131	134
Nb	12.	< 10.	< 10.	10.	< 10.	< 10.	< 10.	< 10.	< 10.	< 10.	< 10.	12.	12.	14.	< 10.	< 10.
Rb	< 10.	< 10.	16.	< 10.	12.	16.	12.	< 10.	35.	40.	< 10.	55.	55.	75.	15.	15.
Sr	340.	360.	210.	210.	520.	620.	330.	380.	550.	560.	165.	340.	600.	680.	560.	320.
Zr	80.	55.	40.	40.	80.	100.	40.	80.	80.	80.	70.	150.	160.	140.	90.	40.
Y	12.	14.	14.	16.	16.	14.	< 10.	14.	18.	20.	20.	20.	20.	25.	14.	16.
Ba	250.	190.	150.	100.	240.	55.	390.	160.	460.	570.	110.	500.	1300.	940.	250.	140.
Ce	60.	30.	25.	25.	40.	55.	40.	70.	60.	45.	35.	50.	65.	70.	45.	25.
La	25.	< 20.	25.	< 20.	< 20.	< 20.	< 20.	45.	< 20.	< 20.	< 20.	< 20.	< 20.	< 20.	< 20.	< 20.
Cu	130.	120.	60.	100.	75.	20.	80.	20.	25.	70.	180.	30.	70.	230.	50.	65.
Ni	85.	160.	90.	65.	60.	45.	65.	85.	45.	25.	100.	55.	< 20.	25.	50.	85.
Zn	160.	140.	170.	170.	170.	120.	220.	230.	170.	150.	180.	170.	210.	190.	150.	150.
Cr	420.	470.	440.	290.	290.	180.	290.	580.	100.	45.	250.	160.	< 20.	55.	140.	290.

Normative Mineralogy:

Sample No.:	8a	13	18a	46	48	53	56	61	66	68	76	116	125	127	131	134
Q	0.	0.	0.	.4	0.	2.8	0.	4.0	0.	0.	0.	32.5	10.2	.5	16.3	7.7
C	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	6.9	1.0	0.	0.	0.
or	1.7	3.2	6.0	3.1	5.1	5.2	4.0	1.5	9.0	12.5	1.9	15.6	18.5	19.4	5.0	3.6
ab	32.6	26.8	12.1	14.7	31.0	35.4	20.9	16.4	25.8	25.1	23.2	0.	29.3	25.1	26.1	7.8
an	17.6	27.6	32.4	27.7	23.0	26.2	19.1	29.4	30.4	38.7	31.7	23.8	25.2	34.0	27.9	38.7
ne	0.	0.	0.	0.	0.	0.	12.1	0.	0.	0.	0.	0.	0.	0.	0.	0.
di	24.8	18.5	23.2	23.7	17.8	9.8	22.8	18.1	12.5	1.7	15.6	0.	0.	2.3	5.3	19.3
hy	4.4	0.	10.8	23.9	16.3	13.6	0.	24.4	8.5	4.4	14.8	10.2	9.4	9.5	11.1	12.0
ol	11.2	19.1	9.6	0.	1.3	0.	15.0	0.	7.5	6.8	6.1	0.	0.	0.	0.	0.
mt	4.9	2.6	3.8	4.1	3.6	5.0	6.2	4.5	4.1	8.0	4.0	7.8	4.5	6.4	6.9	9.6
il	2.0	1.8	1.9	2.1	1.4	1.4	.8	1.1	1.7	2.3	2.3	1.9	1.6	2.0	1.1	1.2
ap	.8	.2	.3	.3	.5	.5	.3	.6	.5	.6	.3	.7	.8	.8	.4	.3
Total	100.	99.8	100.1	100.	100.	99.9	101.2	100.	100.	100.1	99.9	99.4	100.5	100.	100.1	100.2

Note: Total for major oxides calculated with total Fe as Fe2O3*, as reported in XRF analyses, FeO* = 0.9 x Fe2O3*

⁺ (b = basalt; ba = basaltic andesite; ap = andesite porphyry; p = plagioclase phenocryst-rich porphyry of map unit ap with < 52 % SiO_2).

Table 14

Trace element data (INAA) for volcanogenic and plutonic rocks of the Irving Formation.

Rock Type:	MV								GW	MI			FV			
	b	b	b	ap	ap	p	ap	b								
Sample No.:	8a	13	61	116	125	127	131	134	57a	39	74	126	42	64	86	101
Ba	257.	171.	157.	497.	1290.	973.	248.	127.	1080.	434.	167.	367.	392.	1270.	596.	537.
Co	43.1	52.1	43.6	24.5	16.1	29.5	30.2	51.9	24.5	44.6	42.3	43.9	1.10	1.71	3.81	3.77
Ni	66.3	134.0	78.6	48.4	14.6	24.7	49.1	58.0	40.1	71.7	66.5	67.9	9.8	6.7	< 17.0	10.4
Cr	305.	341.	433.	134.	5.8	48.1	113.	212.	158.	337.	185.	388.	0.961	< 2.0	2.27	1.13
Cs	< 0.39	1.14	0.401	2.53	1.51	1.79	0.844	0.793	4.82	0.677	0.974	1.01	3.84	0.755	2.89	4.39
Hf	1.83	1.38	1.85	3.65	3.87	3.31	2.05	0.791	3.28	1.48	2.11	2.42	2.70	2.60	2.32	3.80
Rb	9.9	9.67	< 1.0	54.7	57.3	75.2	16.	14.3	107.	15.2	14.9	32.	44.4	58.2	44.6	33.5
Sb	1.29	2.25	1.26	1.94	1.07	2.02	0.588	1.53	1.3	1.14	1.16	1.46	0.367	0.092	0.284	0.098
Ta	0.363	0.157	0.229	0.586	0.576	0.642	0.304	0.0656	0.530	0.223	0.224	0.226	0.353	0.244	0.301	0.428
Th	3.66	0.228	7.24	3.83	4.17	3.77	2.30	0.479	3.37	2.28	1.05	8.4	4.35	4.19	3.35	3.90
U	1.49	0.159	3.61	2.24	2.27	1.84	1.04	0.328	1.77	1.17	0.526	3.59	1.88	2.18	2.05	2.15
Zn	68.	< 49.	126.	93.8	116.	107.	84.2	n.d.	94.8	122.	106.	82.	58.4	38.5	107.	91.1
Zr	78.9	53.	76.3	147.	135.	120.	86.4	n.d.	110.	n.d.	76.2	127.	94.2	91.2	82.2	141.
Sc	35.3	44.1	39.0	19.7	14.0	19.9	19.4	49.0	25.1	40.4	39.4	46.5	11.7	12.0	16.1	14.1
La	19.0	2.80	34.8	22.8	31.7	27.2	13.5	4.46	21.5	18.0	6.42	67.3	15.6	20.8	16.5	12.6
Ce	45.5	8.70	70.8	47.5	69.3	62.6	28.8	9.27	45.2	40.4	15.3	153.0	36.6	44.5	34.3	31.0
Nd	22.5	6.37	31.8	22.4	32.3	32.9	14.0	6.63	23.9	20.2	10.1	32.0	17.2	22.1	19.0	15.9
Sm	5.25	2.11	5.71	4.64	6.36	6.44	3.10	1.98	4.66	4.47	3.27	14.1	3.82	4.85	4.46	4.01
Eu	1.46	0.815	1.38	1.30	1.58	1.68	.90	0.690	1.20	1.24	1.06	3.44	0.811	1.15	1.07	1.05
Gd	4.33	2.79	4.19	3.74	5.05	5.41	2.71	2.40	3.87	4.08	3.84	9.10	3.57	4.06	3.82	3.86
Tb	0.596	0.472	0.599	0.612	0.718	0.818	0.389	0.442	0.567	0.582	0.676	0.983	0.520	0.604	0.609	0.702
Tm	0.222	0.296	n.d.	0.367	0.427	0.427	0.214	n.d.	0.297	0.292	n.d.	0.243	0.404	0.302	0.367	0.427
Yb	1.25	1.91	1.68	2.29	2.48	2.59	1.34	1.89	1.82	1.83	2.98	1.15	2.55	1.90	2.31	3.37
Lu	0.186	0.284	0.229	0.332	0.358	0.376	0.204	0.277	0.292	0.265	0.468	0.135	0.369	0.294	0.369	0.475

MV = mafic volcanics (b = basalt; ap = andesite porphyry; p = plagioclase phenocryst-rich porphyry of map unit ap with < 52 % SiO_2; GW = graywacke; MI = mafic intrusives; FV = felsic volcaniclastic rocks.

n.d. = data not obtained.

Felsic Volcaniclastic Rocks

Metamorphosed felsic volcaniclastic rocks (unit fv, Plate 1) of the Irving Formation exhibit strong chemical affinities to rhyolite of the Twilight Gneiss and metamorphosed felsic volcanic and volcaniclastic rocks of central Colorado (Table 15). Except for higher Fe_2O_3 + FeO and MgO, and lower K_2O contents, major element analyses of felsic schists and gneisses of the Irving Formation are analogous to those of unaltered rhyolitic volcanic rocks (Table 16). It is noteworthy that the average major element chemical composition of felsic rocks in the Irving differs considerably from those of most sedimentary rocks, but is similar to the average composition obtained for seven Phanerozoic graywackes with dacitic to rhyolitic SiO_2 concentrations (Table 16, column 6).

Felsic rocks of the Irving Formation are classified as rhyolite or rhyodacite on the SiO_2-Zr/TiO_2 diagram of Winchester and Floyd (1977) (Figure 37). They contain 70-75 % SiO_2, 11-14 % Al_2O_3, .5-3.5 % MgO, and 1-2.4 % CaO (Table 17). FeO*/MgO values are typically lower than 4.0 and Na_2O/K_2O varies from less than 1.0 to 2.7. These rocks are characterized by very low concentrations of Ni (6-25 ppm) and Cr (.9-3.0), and variable Rb (25-45 ppm), Sr (55-130 ppm), and Ba (240-1200 ppm) (Table 17). On different discrimination diagrams, rhyolitic rocks of the Irving generally exhibit calk-alkaline affinities (Table 11).

Irving felsites display enriched LREE (9-70 times chondrite) patterns, and moderate negative and minor negative Tb anomolies, on chondrite normalized plots (Figure 39). Heavy REE patterns are flat with enrichment factors of 9-14 times that of chondrite. Compared to Early Proterozoic felsic volcanics in the Gunnison and Salida areas of central Colorado, felsic lithologies of the Irving Formation display lower overall REE abundances relative to chondrite, and lack the pronounced negative or positive Eu anomolies typically seen in REE specta of the former (Condie and Nuter, 1981; Boardman and Condie, 1986). Chondrite-normalized REE patterns of Irving felsites fall within the range for "modern siliceous volcanics" and are similar to those of "undepleted" Archean "siliceous volcanics" (Condie, 1976).

Two samples (31 and 88) collected within unit (fv) of the Irving Formation contain 50-60 weight percent silica. Sample 31 is a banded gneiss, exposed at the mafic-felsic contact in the Fall Creek area, that contains amphibole- and quartz + plagioclase-rich layers. The mafic character of this rock is attributed to mixing of mafic and felsic debris during deposition. Sample 88 contains lower modal quartz and a higher volume percent of plagioclase and biotite than felsic schist and gneiss samples with rhyolitic SiO_2 contents. It is uncertain wether the mafic character of sample 88 is primary or a result of extensive alteration. The distribution of this more mafic lithology appears to be very local, however, as rhyolitic schists comprise adjacent exposures. Because of their local distribution and anomalous chemical affinities, analyses for samples 31 and 88 are not applied on any of the discriminant diagrams presented and will not be discussed further.

Sedimentary Rocks

The range of major and trace elements in graywacke and siltstone of the Irving Formation is fairly limited, except for variable Rb (45-100),

Table 15

Comparison of average major and selected trace element data for rhyolitic rocks of the Irving Formation with chemical data for the Twilight Gneiss and metamorphosed felsic volcanic rocks of central Colorado.

Major Oxides (Wt %):	1	2	3	4	5	6	7	8	9
SiO2	71.71 (1.4)	73.2 (2.5)	74.32 (2.5)	66.17 (5.6)	72.30 (3.1)	71.00 (5.4)	74.18 (2.7)	71.65 (3.4)	65.95 (3.5)
TiO2	0.35 (0.1)	0.18 (0.6)	0.30 (0.1)	0.76 (0.2)	0.30 (0.1)	0.40 (0.1)	0.21 (0.06)	0.31 (0.1)	0.53 (0.2)
Al2O3	12.63 (0.6)	13.5 (.08)	13.28 (1.1)	15.91 (1.2)	12.10 (.9)	13.90 (2.2)	12.41 (1.1)	12.74 (1.7)	15.23 (1.3)
Fe2O3	1.41 (0.4)	0.73 (0.4)	1.70 (0.6)	1.79 (1.1)	3.40 (1.1)	3.80 (1.3)	2.67 (0.4)	4.05 (1.2)	5.07 (1.5)
FeO	3.37 (0.9)	2.50 (1.1)	1.25 (0.4)	3.36 (1.5)	*	*	*	*	*
MnO	0.08 (0.03)	0.10 (0.07)	n.d.	n.d.	n.d.	n.d.	0.04 (0.01)	0.07 (0.04)	0.18 (0.3)
MgO	1.6 (0.8)	0.70 (0.5)	0.85 (0.6)	1.25 (0.6)	0.5 (0.4)	1.80 (1.0)	0.61 (0.1)	1.33 (0.9)	1.74 (0.8)
CaO	1.42 (0.4)	1.90 (0.9)	1.15 (0.7)	1.60 (1.0)	1.10 (1.6)	1.40 (0.4)	1.22 (0.8)	1.73 (1.1)	2.92 (1.2)
Na2O	3.24 (0.8)	4.00 (0.5)	2.66 (1.0)	3.42 (1.4)	3.60 (1.6)	3.70 (1.9)	4.16 (0.6)	2.94 (1.3)	3.58 (1.3)
K2O	2.53 (1.0)	2.00 (0.8)	4.02 (1.7)	3.64 (1.1)	3.40 (1.5)	2.40 (0.7)	3.24 (1.4)	3.31 (1.8)	3.53 (1.3)
P2O5	0.08 (0.4)	0.06 (0.04)	n.d.	n.d.	n.d.	n.d.	0.05 (0.02)	0.07 (0.03)	0.13 (0.07)
Trace Elements (ppm):									
Rb	38 (9.5)	45 (29)	123 (30)	97 (88)	59 (27)	77 (27)	71 (20)	87 (41)	79 (12)
Sr	79 (32)	175 (46)	64 (44)	n.d.	108 (62)	154 (83)	91 (30)	155 (100)	240 (100)
Zr	113 (37.5)	n.d.	288 (56)	n.d.	350 (128)	321 (137)	340 (100)	408 (185)	253 (76)
Y	23 (11)	n.d.	n.d.	n.d.	89 (51)	55 (21)	58 (21)	60 (23)	44 (13)
Ba	579 (327)	780 (225)	1311 (499)	922 (483)	n.d.	n.d.	n.d.	n.d.	n.d.
Ce	45 (11)	n.d.	109 (21)	102 (18)	n.d.	n.d.	86 (25)	n.d.	n.d.

n.d. = not determined; * = total iron reported as Fe_2O_3; ( ) = standard deviation.

1. Average of 7 samples of felsic schist and gneiss (SiO_2 > 70%) from the Irving Formation (SE Needles).
2. Average of 9 samples of metamorphosed dacite from the Twilight Gneiss (Barker, 1969c; Barker and others, 1976).
3. Average of 10 samples of felsic volcanic rock from the Dubois Greenstone succession, central Colorado (Condie and Nuter, 1981).
4. Average of 6 samples of felsic volcaniclastic rock from the Dubois Greenstone succession, central Colorado (Condie and Nuter, 1981).
5. Average of 18 samples of felsic volcanic rock from the Gunnison area, central Colorado (Bickford and Boardman, 1984).
6. Average of 16 samples of felsic volcanic rock from the Salida area, central Colorado (Bickford and Boardman, 1984).
7. Average of 9 samples of felsic volcanic rock of the Salida area, central Colorado (Boardman and Condie, 1986).
8. Average of 11 samples of lithic clast-rich felsic volcaniclastic rock of the Salida area, central Colorado (Boardman and Condie, 1986).
9. Average of 12 samples of bedded felsic volcaniclastic rock of the Salida area, central Colorado (Boardman and Condie, 1986).

Table 16

Comparison of the average major element composition of rhyolitic volcanic rocks of the Irving Formation with average chemical compositions of selected quartzo-feldspathic volcanic and sedimentary rocks.

	1	2	3	4	5	6	7	8
SiO2	71.74	72.82	74.62	70.35	75.24 (4.2)	71.74 (3.1)	95.40	66.10
TiO2	0.35	0.28	0.24	0.54	0.25 (0.1)	0.51 (0.3)	0.20	0.30
Al2O3	12.63	13.27	12.95	14.90	10.73 (1.9)	12.16 (1.5)	1.10	8.10
Fe2O3	1.41	1.48	1.10	2.10	1.77 (1.4)	1.11 (0.9)	0.40	3.80
FeO	3.37	1.11	2.01	1.95	0.95 (0.3)	3.25 (1.0)	0.20	1.40
MnO	0.08	0.06	0.08	0.11	0.25 (0.3)	0.10 (0.07)	n.d.	0.10
MgO	1.6	0.39	0.19	0.92	0.57 (0.5)	1.77 (0.6)	0.10	2.40
CaO	1.42	1.14	1.87	3.92	1.59 (1.5)	1.29 (0.6)	1.60	6.20
Na2O	3.24	3.55	4.38	3.99	2.55 (1.6)	3.30 (1.0)	0.10	0.90
K2O	2.53	4.30	2.52	1.07	4.39 (1.1)	1.90 (0.4)	0.20	1.30
P2O5	0.08	0.07	0.05	0.15	0.25 (0.1)	0.13 (0.08)	n.d.	0.10

n.d. = not determined; ( ) = standard deviation.

1. Average of 7 samples of felsic schist and gneiss of the Irving Formation.
2. Average of 670 samples of rhyolite (Le Maitre, 1976).
3. Average of 17 samples of calk-alkaline rhyolite from Iceland (Ewart, 1979, page 46).
4) Average of 19 samples of low-K rhyolite from the Japan-Kuriles-Saipan region (Ewart, 1979, page 112).
5. Average of 6 samples of arkose with 70-80 weight percent SiO_2 (data from Pettijohn, 1963).
6. Average of 7 samples of graywacke with 68-76 weight percent SiO_2 (data from Pettijohn, 1963).
7. Average of 26 samples of orthoquartzite (Pettijohn, 1963).
8. Average of 20 samples of lithic arenite (Pettijohn, 1963).

Table 17

Major and trace element data (XRF), and CIPW norms for felsic volcaniclastics of the Irving Formation.

Sample No.:	23	30	31	42	64	86	88	101	105
Major Elements (Wt %):									
SiO_2	70.0	71.6	55.2	74.3	72.3	70.4	57.7	71.6	72.0
TiO_2	0.39	0.26	0.55	0.20	0.19	0.33	0.55	0.50	0.58
Al_2O_3	12.9	12.8	17.0	12.8	13.3	13.0	16.6	11.9	11.7
Fe_2O_3	1.08	0.84	3.51	0.60	1.08	0.89	2.20	1.13	1.65
FeO	4.59	3.06	3.86	2.09	2.37	3.66	6.62	3.76	4.01
MnO	0.07	0.07	0.07	0.05	0.04	0.13	0.17	0.08	0.11
MgO	3.3	1.7	2.1	1.5	1.4	1.2	3.2	1.2	0.92
CaO	1.10	1.61	8.50	1.40	1.05	1.40	2.75	1.25	2.14
Na_2O	1.9	3.0	5.20	3.6	2.9	3.6	3.9	4.3	3.4
K_2O	2.75	3.37	2.30	1.99	4.18	2.30	3.30	1.60	1.55
P_2O_5	0.04	0.07	0.41	0.06	0.05	0.10	0.15	0.10	0.14
H_2O+	1.34	0.75	0.27	0.76	0.83	0.82	1.26	0.58	0.52
H_2O-	0.11	0.07	0.08	0.06	0.06	0.02	0.02	0.02	0.04
CO_2	0.09	0.34	0.74	0.14	0.09	0.18	0.36	0.08	0.08
Total	100.37	99.88	100.22	99.78	100.1	98.44	99.51	98.51	99.28
FeO^*	5.56	3.82	7.02	2.63	3.34	4.49	8.60	4.77	5.49
$Fe_2O_3^*$	6.18	4.24	7.80	2.92	3.71	4.99	9.55	5.30	6.10
FeO^*/MgO	1.7	2.2	3.3	1.7	2.4	3.7	2.7	4.0	6.0
Na_2O/K_2O	.7	.9	2.3	1.8	.7	1.6	1.2	2.7	2.2
Trace Elements (ppm):									
Nb	12.	< 10.	< 10.	< 10.	< 10.	< 10.	< 10.	< 10.	10.
Rb	45.	40.	55.	38.	50.	40.	95.	25.	25.
Sr	75.	55.	480.	55.	60.	120.	270.	58.	130.
Zr	190.	85.	80.	95.	95.	85.	85.	130.	110.
Y	45.	14.	16.	15.	18.	16.	14.	25.	25.
Ba	240.	740.	240.	390.	1200.	620.	720.	560.	300.
Ce	60.	40.	55.	55.	30.	45.	45.	35.	50.
La	< 20.	< 20.	< 20.	< 20.	< 20.	< 20.	< 20.	< 20.	25.
Cu	25.	45.	25.	< 20.	< 20.	< 20.	< 20.	< 20.	25.
Ni	< 20.	< 20.	< 20.	< 20.	< 20.	< 20.	< 20.	< 20.	25.
Zn	230.	170.	120.	90.	55.	180.	170.	150.	150.
Cr	< 20.	< 20.	< 20.	< 20.	< 20.	< 20.	60.	< 20.	< 20.
Normative mineralogy:									
Q	38.8	33.9	0.	39.8	34.2	34.6	7.9	34.8	39.0
C	5.0	1.5	0.	2.4	2.2	2.4	2.0	1.1	.9
or	16.6	20.2	13.8	11.9	25.0	14.0	20.1	9.7	9.3
ab	16.4	25.8	43.3	30.9	24.8	31.4	34.0	37.4	29.3
an	5.3	7.7	16.5	6.6	4.9	6.5	13.0	5.7	9.9
ne	0.	0.	.7	0.	0.	0.	0.	0.	0.
di	0.	0.	18.6	0.	0.	0.	0.	0.	0.
hy	15.5	9.0	0.	6.9	6.8	9.0	18.2	8.5	7.7
ol	0.0	0.	0.	0.	0.	0.	0.	0.	0.
mt	1.6	1.3	5.2	.9	1.6	1.3	3.3	1.7	2.4
il	.8	.5	1.1	.4	.4	.6	1.1	1.0	1.1
ap	.1	.2	1.0	.1	.1	.2	.4	.2	.3
Total	99.3	100.1	100.2	99.9	100.	100.	100.	100.1	99.9

Note: Total for major oxides calculated with total Fe as $Fe_2O_3^*$, as reported in XRF analyses;

$FeO^* = (0.9 \times Fe_2O_3^*)$.

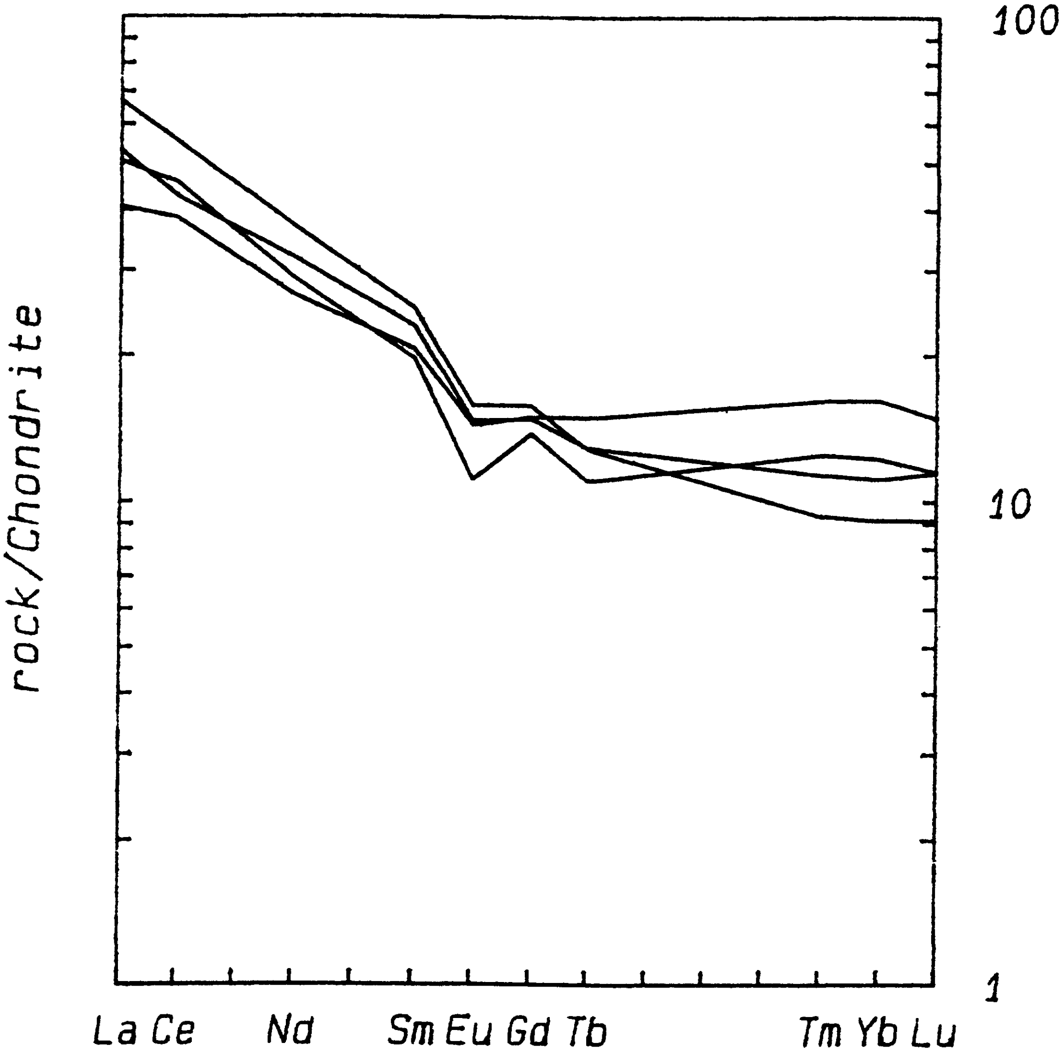


Figure 39. Chondrite-normalized REE spectra for rhyolitic rocks of the Irving Formation.

Ba (530-1000), and Cr (30-190) (Table 18). Major element compositions of these rocks are grossly comparable to volcanogenic quartz-poor graywackes (Taylor and McLennan, 1985, Tables 6.8 and 6.9). Trace element abundances in graywacke of the Irving Formation (sample 57a in Tables 14 and 18) are considerably higher, however, than those in quartz-poor Phanerozoic graywackes, but are similar to trace element abundances in Archean graywackes (Taylor and McLennan, Table 6.13). Irving graywacke exhibits trace element affinities that are transitional between oceanic island arc and continental island arc graywackes (Bhatia and Crook, 1986, Table 5 and Figure 9). Chondrite-normalized REE spectra (Figure 40, sample 57a) are LREE-enriched (15-80 times chondrite) relative to HREE (9-11 times chondrite). This pattern is similar to those of "volcaniclastic sediments" in the Dubois Greenstone belt of central Colorado (Condie and Nuter, 1981), except the latter are generally more enriched in REE. Graywacke and siltstone of the Irving Formation are broadly similar in chemical composition to associated andesitic rocks which suggests that rocks of andesitic composition may have been the primary source of clastic material in these volcanoclastic sediments.

Mafic Intrusives

Mafic intrusive rocks of the Irving Formation (Table 19) are characterized by low SiO_2 (43-50 %); variable Na_2O/K_2O (1.0-3.1) and MgO (6-12 %); high CaO (10-15 %), FeO* (9-12 %), and Cr (340-540 ppm); and olivine- or quartz-normative mineralogies. Na_2O in several samples is anomalously low (< 0.20) which could reflect Na-depletion due to alteration. Relative to average gabbro (Le Maitre, 1976), mafic plutonic rocks of the Irving generally contain lower SiO_2 and Al_2O_3, and higher MgO and CaO. On the R1-R2 variation diagram of De la Roche and others (1980) mafic intrusives from the Irving plot in the olivine gabbro field (samples 39, 58, and 74) or near the field of peridotite (samples 78 and 126). The low Na_2O contents of samples 78 and 126, however, reduces confidence in their ultramafic classification. It is interesting to note though, that the modal (Table 9) compositions of these rocks are consistent with their ultramafic classification on the R1-R2 diagram.

Tectonic Setting

General Discussion

Deciphering the tectonomagmatic setting of Archean and Proterozoic volcanic sequences using geochemical data is fraught by several fundamental problems. Field boundaries on proposed discriminant diagrams are commonly derived by plotting chemical data from unaltered Phanerozoic volcanic suites. Application of such diagrams to pre-Phanerozoic volcanic suites assumes that plate tectonic processes, magma genesis, and chemical signatures of ancient and modern volcanic rocks are generally comparable. This makes no allowance, however, for major chemical changes in potential source regions of magmas due to

Table 18

Major and trace element data (XRF), and CIPW norms for sedimentary rocks of the Irving Formation.

Sample No.	57a	67	81
Major elements (Wt %):			
SiO_2	55.0	63.4	58.8
TiO_2	0.82	0.68	0.65
Al_2O_3	19.2	17.0	16.0
Fe_2O_3	6.98	1.16	3.87
FeO	2.31	4.21	5.61
MnO	0.09	0.05	0.22
MgO	2.9	2.3	2.6
CaO	3.25	2.50	3.85
Na_2O	1.5	5.1	3.4
K_2O	4.77	1.64	2.21
P_2O_5	0.20	0.22	0.22
H_2O+	2.45	1.32	0.90
H_2O-	0.27	0.02	0.04
CO_2	0.10	0.07	0.25
Total	100.09	100.13	100.51
FeO^*	8.59	5.24	9.09
$Fe_2O_3^*$	9.54	5.83	10.10
FeO^*/MgO	3.0	2.3	3.5
Na_2O/K_2O	.3	3.1	1.5
Trace Elements (ppm):			
Nb	16.	12.	12.
Rb	100.	45.	55.
Sr	320.	400.	380.
Zr	130.	160.	110.
Y	20.	25.	18.
Ba	1000.	550.	530.
Ce	35.	80.	55.
La	< 20.	35.	25.
Cu	175.	110.	75.
Ni	50.	< 20.	< 20.
Zn	150.	200.	180.
Cr	190.	30.	40.
Normative Mineralogy:			
Q	17.8	17.0	16.6
C	6.3	2.9	1.6
or	29.1	9.9	13.4
ab	13.1	43.9	29.5
an	15.3	11.2	18.1
hy	7.4	11.7	13.3
mt	5.5	1.7	5.8
hm	3.4	0.	0.
il	1.6	1.3	1.3
ap	.5	.5	.5
Total	100.	100.1	100.1

Note: Total for major oxides calculated with all Fe as $Fe_2O_3^*$, as reported in XRF analyses; $FeO^* = (0.9 \times Fe_2O_3^*)$; 57a = graywacke; 67 & 81 = siltstone.

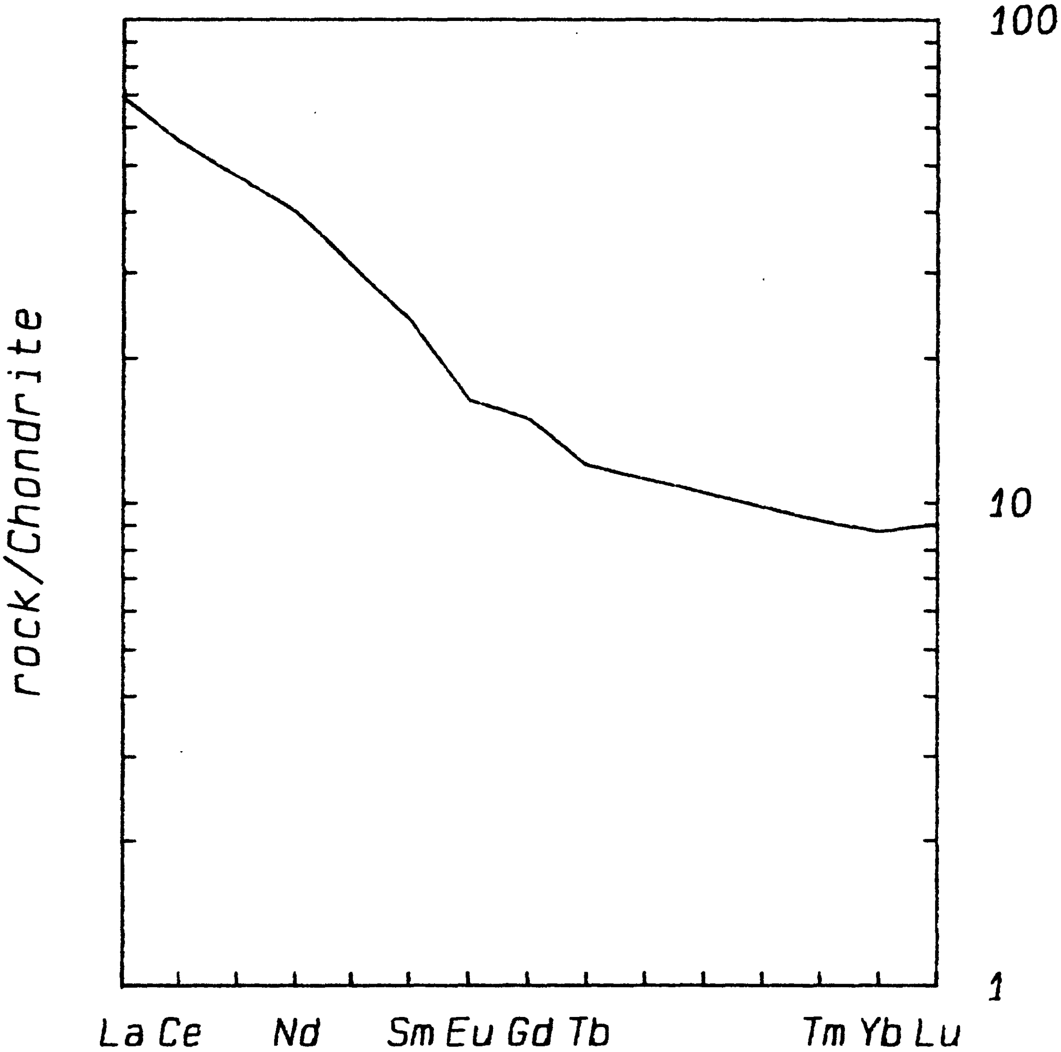


Figure 40. Chondrite-normalized REE distributions for graywacke (sample 57a) of the Irving Formation.

Table 19

Major and trace element data (XRF), and CIPW norms for mafic intrusive rocks of the Irving Formation.

Sample No.:	39	58	74	78	126
Major Oxides (Wt %):					
SiO2	49.2	48.4	49.5	43.2	46.0
TiO2	0.71	0.32	0.88	0.60	0.52
Al2O3	14.0	15.0	17.0	12.8	13.3
Fe2O3	4.23	3.04	2.24	5.66	4.10
FeO	6.55	6.99	7.80	6.61	5.67
MnO	0.18	0.20	0.18	0.18	0.19
MgO	8.9	8.7	6.5	11.8	10.9
CaO	10.2	10.4	10.9	14.6	13.9
Na2O	2.7	2.1	2.4	< 0.20	< 0.20
K2O	0.93	2.15	0.78	0.56	1.40
P2O5	0.25	0.10	0.14	0.12	0.52
H2O+	0.27	2.06	1.92	2.56	2.46
H2O-	0.08	0.12	0.11	0.06	0.04
CO2	0.74	1.03	0.09	1.09	1.06
Total	99.66	101.38	101.30	100.57	100.69
FeO*	10.35	9.72	9.81	11.70	9.36
Fe2O3*	11.50	10.80	10.90	13.00	10.40
FeO*/MgO	1.2	1.1	1.5	.99	.86
Na2O/K2O	2.9	.98	3.1	...	...
Trace Elements (ppm):					
Nb	10.	< 10.	< 10.	< 10.	< 10.
Rb	15.	55.	14.	20.	32.
Sr	450.	370.	230.	790.	670.
Zr	70.	30.	85.	65.	110.
Y	16.	< 10.	25.	14.	18.
Ba	450.	540.	130.	190.	350.
Ce	35.	25.	50.	50.	150.
La	< 20.	< 20.	< 20.	< 20.	85.
Cu	70.	55.	80.	380.	100.
Ni	90.	40.	75.	85.	80.
Zn	170.	175.	150.	140.	150.
Cr	440.	370.	260.	340.	540.
Normative minerals:					
Q	0.	0.	0.	0.	.3
or	5.6	13.0	4.7	3.4	8.6
ab	23.3	18.1	20.7	0.	0.
an	23.8	25.8	33.9	34.6	33.3
di	21.0	21.4	16.5	31.8	27.6
hy	11.5	0.	16.2	14.2	21.8
ol	6.4	16.2	2.7	6.0	0.
mt	6.3	4.5	3.3	8.5	6.2
il	1.4	.6	1.7	1.2	1.0
ap	.6	.2	.3	.3	1.3
Total	99.9	99.8	100.	100.	100.1

Samples 58 & 78 are medium- to coarse-grained amphibole-rich rocks; sample 74 is a medium-metagabbro with subequal proportions of plagioclase and amphibole; samples 39 and 126 are amphibole-rich and exhibit a relict porphyritic texture defined by amphibole pseudomorphs of primary pyroxene phenocrysts.

Note: Total for major oxides calculated with total Fe as Fe_2O_3*, as reported in XRF analyses; FeO* = (0.9 x Fe2O3*).

progressive crustal fractionation and cratonization since the Precambrian (Goodwin, 1981). Furthermore, the affect of the temporal decrease in global heat flow since the Proterozoic, which influenced the depth and degree of partial melting, on the geochemical signatures of ancient and recent volcanic assemblages are generally not accounted for either. In addition, some discriminants, notably K_2O and Na_2O, used to decipher the magma series and tectonic settings of recent volcanic rocks are highly susceptible to mobilization during diagenesis, hydrothermal events, and metamorphic processes, and are therefore generally not applicable to ancient metavolcanic suites (e.g. Smith and Smith, 1976).

Chemical distinction of the tectonic setting of modern and ancient rocks is further complicated by the wide chemical variation that rocks of particular magma series may exhibit, and also the possible occurrence of several different magma series in a given tectonic environment (e.g. eruption of lavas with MORB affinities in a back-arc basin, and low-k tholeiite to alkaline series in a nearby mature island-arc; Hughes, 1982, chapter 11). Furthermore, it has been demonstrated (Holm, 1982; Thompson and others, 1980) that some proposed variation diagrams do not allow clear distinction of magma series and tectonic settings, even for relatively unaltered volcanic suites.

It is evident that although field boundaries defined by modern volcanic rocks serve as a useful reference framework to evaluate Precambrian data, the application of such diagrams could give misleading results, if relied upon exclusively. Prolific application of certain chemical variation diagrams to Archean and Proterozoic rocks has demonstrated their utility as a supplement to field observations in establishing the magmatic and tectonic history of Precambrian rocks.

In evaluating the paleotectonic setting of volcanogenic rocks of the Irving Formation, a variety of chemical variation diagrams were employed in order to obtain the most probable results. The use of diagrams employing large-ion lithophile elements as discriminants is limited in the following discussion due to their apparent local migration in rocks of the Irving Formation.

Irving Formation

The association of mafic flows and tuffs in the Irving Formation with turbidite and debris flow deposits, chert, and pillow lava and pillow breccia is consistent with a submarine environment of deposition. Tectonic environments associated with active oceanic volcanism include intra-plate oceanic islands, mid-oceanic ridges, oceanic and continental margin arcs, and back arcs.

The bimodal metavolcanic assemblage and tuffaceous rocks in the Irving are inconsistent with deposition at a mid-oceanic ridge or strictly within a back-arc basin (Hughes, 1982, page 279; Rogers, 1982). The apparent absence of alkalic rocks in the Irving is atypical of an oceanic-island setting. Furthermore, mafic rocks of the Irving (.56-1.2 % TiO_2) lack the TiO_2-enriched character of oceanic-island tholeiites and alkalic basalts (TiO_2 commonly exceeding 2.0 %; Hughes, 1982, Tables 9.2, 9.4, and 9.6; Basaltic Volcanism Study Project, 1981, chapter 1.2.6). The low TiO_2 concentrations and subalkaline character of Irving mafic volcanics are typical of volcanic arc suites (Jakes and White, 1972; Garcia, 1978; Rogers, 1982). In addition, the Al_2O_3 (15.5-

19.0 %), FeO* (6.8-8.2 %), TiO_2 (.56-1.02 %), Zr (90-160), Y (14-25), Nb (< 10-14), Ta (.304-.642), Ce (45-70), Zr/TiO_2 (.03), and Nb/Y (0.6) of Irving andesites all fall within elemental ranges for modern volcanic arc andesites (Bailey, 1981, p. 140).

The bimodal volcanic suite, interflow chert and volcaniclastic sediments, minor pillow lava and breccia, low volume of mafic tuff, and high basalt to andesite ratio in the Irving Formation are consistent with deposition in a primitive island arc (Jakes and Gill, 1970; Jakes and White, 1971, 1972; Gill and Stork, 1979; Rogers, 1982). The calk-alkaline affinities of felsic to intermediate lithologies in the Irving, high proportion of rhyolitic volcanic rocks, and chondrite-normalized REE spectra of Irving andesites are typical features of evolved island arcs or "Andean type" volcanic arcs (Jakes and White, 1971, 1972; Garcia, 1978; Bailey, 1981).

Chemical data of rhyolitic to basaltic metavolcanic rocks in the Irving were applied to a variety of binary and ternary chemical-tectonic disrimination diagrams (Table 20, Figures 41-42). Collectively, these discriminant plots support a volcanic arc environment of deposition.

On MORB-normalized diagrams (Figure 43) basaltic and andesitic volcanic rocks of the Irving exhibit negative Ta or Ta-Nb anomalies, and a relative enrichment of large-ion lithophile elements (LILE, Sr to Ta), Ce, P, and Sm. Different degrees of enrichment of Sr to Ba on these plots, especially for basaltic lithologies, probably reflects local alteration. MORB-normalized element patterns of Irving basalts and andesites are analogous to those of arc volcanic rocks (Pearce and others, 1981; Pearce, 1982, 1983; Pharoah and Pearce, 1984; Condie, 1986). Similar element patterns are documented, however, for marginal basin lavas or LILE-enriched continental tholeiites erupted during crustal attenuation (Pearce and others, 1981; Pearce, 1982; Pharaoh and Pearce, 1984; Saunders and Tarney, 1984). Some Irving basalts are depleted in Ta to Yb relative to MORB, analogous to island arc tholeiitic basalts. Others, however, are enriched in Ta, Nb, Ce, P, and Sm relative to MORB, similar to volcanic rocks of evolved island arcs or continental arcs (Figures 43-44). Andesitic lithologies are generally enriched in Ta and Sm, and exhibit MORB-normalized patterns that resemble those of average continental island arc or "Andean" arc andesites (Figure 45).

MORB-normalized spectra for rhyolitic lithologies of the Irving Formation are characterized by LILE and LREE enrichment, and pronounced negative Sr, P, Ta, and Ti anomalies (Figure 46). These patterns are analogous to those exhibited by various 1740-1800 Ma rhyolites and dacites in the southwestern United States (Condie, 1986). Condie (1986) notes that similar element distributions are exhibited by rhyolites erupted in continental-margin arcs or evolved oceanic arcs. ORG-normalized variation diagrams (Pearce and others, 1984) for felsic rocks of the Irving Formation are characterized by pronounced enrichment of K_2O, Rb, Ba, and Th relative to all other element plotted and ORG (oceanic ridge granite) (Figure 47). Irving felsites also exhibit positive Ce and Sm anomalies and variable negative Ta-Nb, Hf-Zr, and Y analomalies on the ORG-normalized diagrams. These patterns are similar to those exhibited by volcanic arc granites, especially calk-alkaline oceanic arc granites (e.g. Jamaica pattern in Pearce and others, 1984, Figure 1b) (Figure 48).

Based on field and geochemical criteria, it is here proposed that volcanic and associated sedimentary rocks of the Irving Formation were deposited in an oceanic island arc or continental margin arc. Chemical data suggests this volcanogenic succession resembles an evolved arc assemblage. Deposition of at least some of the volcanic and associated sedimentary rocks in the Irving in an adjacent back-arc basin may also have occurred.

A volcanic arc setting for rocks of the Irving Formation in the southeastern Needle Mountains is consistent with the eugeosynclinal setting proposed by Barker (1969c). "Arc magmatism and cannibalistic sedimentation" at a convergent margin along the Wyoming Province craton has generally been proposed for Early Proterozoic rocks of the "Colorado province" (Bickford and others, 1986; Reed and others, 1987; refer to page 33). Generation of the Irving volcano-plutonic complex through arc magmatism and submarine sedimentation is therefore consistent with proposed regional models.

Table 20

Summary of chemical-tectonic setting classifications applied to metavolcanic rocks of the Irving Formation.

Plot	Source	Compositional Restrictions	Fields Defined	No. of Analyses Applied	Results (No. of samples)
Ti-Zr	Pearce & Cann (1973)	Basaltic (12% < CaO + MgO < 20%)	LKT, CAB, OFB, LCO	11	LKT (3), CAB (5), OFB (1), LCO (2)
Ti/100-Zr-Y*3	Pearce & Cann (1973)	Basaltic (12% < CaO + MgO < 20%)	LKT, CAB, WPB, LCO	11	LKT (1), CAB (2), LCO (2)
TiO_2-FeO*/MgO	Miyashiro (1975)	Rhyolitic to Basaltic	IAV, AT	16 7	Mafics: IAV (13), AT or IAV (3) Felsics: IAV (5)
Ti-Cr	Pearce (1975)	Basaltic to Andesitic	LKT, OFB	15	LKT (9), OFB (6)
F_1-F_2	Pearce (1976)	Basaltic (12% < CaO + MgO < 20%)	CAB/LKT, OFB, WPB, SHO	11	CAB/LKT (5), WPB (5), SHO (1)
F_2-F_3	Pearce (1976)	Basaltic (12% < CaO + MgO < 20%)	LKT, CAB, OFB, SHO	11	LKT (2), CAB (4), SHO (1)
Zr/Y-Ti/Y	Pearce & Gale (1977)	Basaltic	PMB, WPB	15	PMB (14), WPB (1)
Ti/Cr - Ni	Beccaluva & others (1979)	Tholeiitic with 40-56 % SiO_2	IAT, OFT	13	IAT (11), OFT (2)
Th-Ta	Wood & others (1979)	Basaltic	CPM, MORB	8	CPM (7), MORB (1)
Ta-Th-Hf/3	Wood (1980)	Rhyolitic to Basaltic	N-MORB, E-MORB, AWPB, DPMCA, DPMTH	8 4	Mafics: DPMCA (7), N-MORB (1) Felsics: DPMCA (4)
Ti-Zr	Pearce & others (1981)	Rhyolitic to Basaltic	VAL, MORB, WPL	16 7	Mafics: VAL (11), VAL or MORB (5) Felsics: VAL (7)
Cr-Y	Pearce & others (1981)	Basaltic to Andesitic	VAB, WPB, MORB	14	VAB (14)
Th/Yb-Ta/Yb	Pearce & others (1981)	Basaltic	VAB, MORB, WPB	8	VAB (8)
TiO_2-MnO-P_2O_5	Mullen (1983)	Basaltic (45-54 wt. % SiO_2)	IAT, CAB, MORB, OIT, OIA	13	IAT (7), CAB (6)
MORB-spidergram	Pearce (1983)			8 4	Mafics: VA, BA, or LILE-CT Felsics: VA
Ta-Yb	Pearce & others (1984)	Granitic	VAG, ORG, WPG, syn-COLG post-COLG	4	VAG (4)
ORG-spidergram	Pearce & others (1984)	Granitic		4	VAG
La/Yb-Yb	Condie (1986)	Felsic Volcanics	arcs, extensional basins	4	arcs (4)

Explanation of tectonic field abbreviations: LKT (low-K tholeiite); CAB (calc-alkaline basalt); WPB (within plate basalt); OFB (ocean floor basalt); MORB (mid oceanic ridge basalt); VAL (volcanic arc lavas); VAB (volcanic arc basalts); IAT (island arc tholeiite); OFT (ocean floor tholeiite); AT (abyssal tholeiite); LCO (LKT + CAB + OFB) IAV (island-arc volcanics); OIT (ocean island tholeiites); OIA (ocean island alkalic basalts); VAG (volcanic arc granites); ORG (ocean ridge granites); WPG (within plate granites); syn-CORG (syn-collision granites); post-COLG (post-collision granites); N-MORB (N-type MORB); E-MORB/THWPB (E-type MORB and tholeiitic within plate basalts); AWPB (alkaline within plate basalts and differentiates); DPBCA (destructive plate margin, calk-alkaline); DPMTH (destructive plate margin, primitive arc tholeiites); DPMCA (destructive plate margin, calc-alkaline); CPM (convergent plate margin series); LILE-CT (LIL-enriched continental tholeiite); VA (volcanic arc); BA (back-arc basin volcanics).

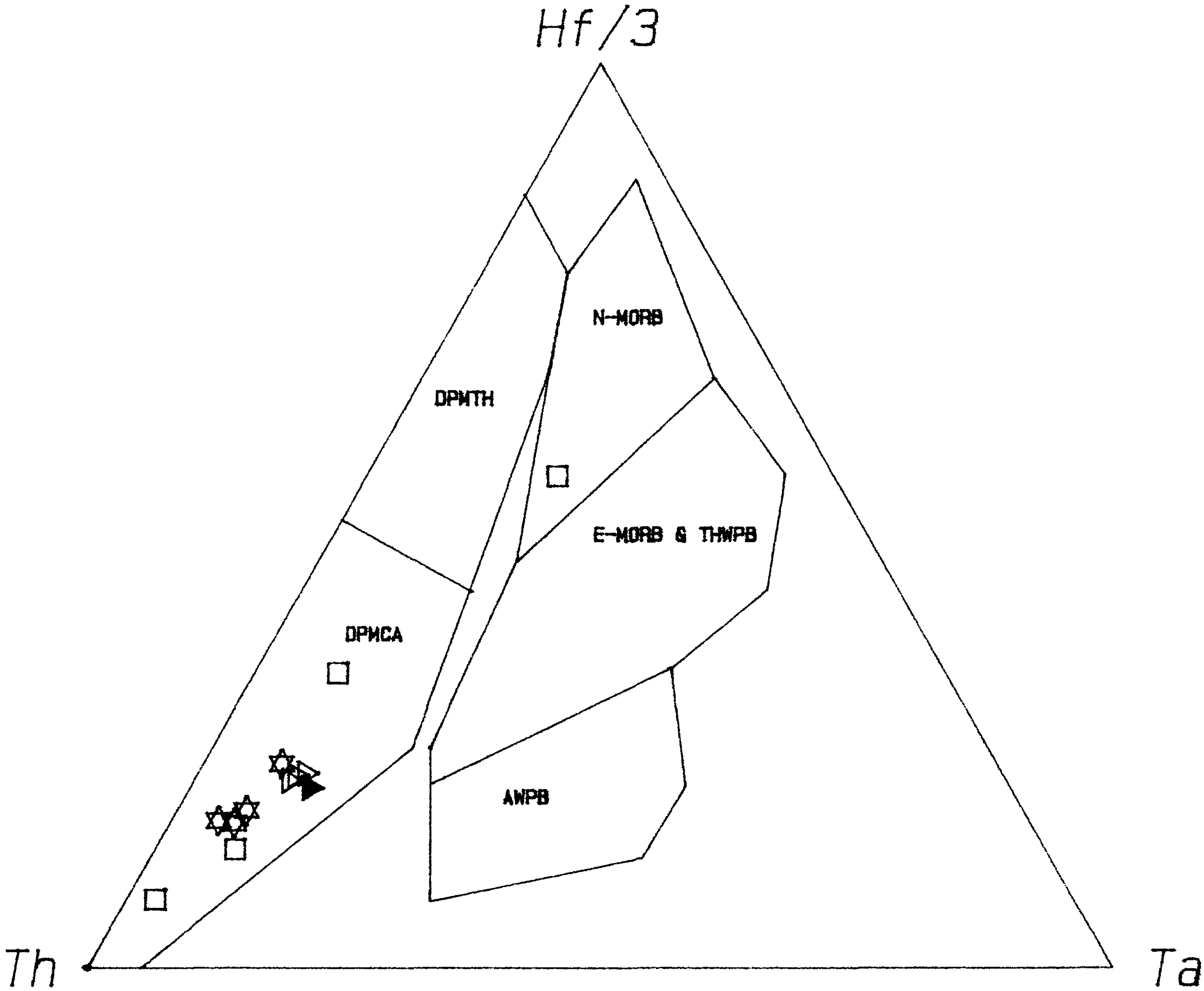


Figure 41. Ternary proportions of Th, Ta, and Hf/3 for volcanic rocks of the Irving Formation. Tectonic fields are from Wood (1980). Symbols as in Figure 37.

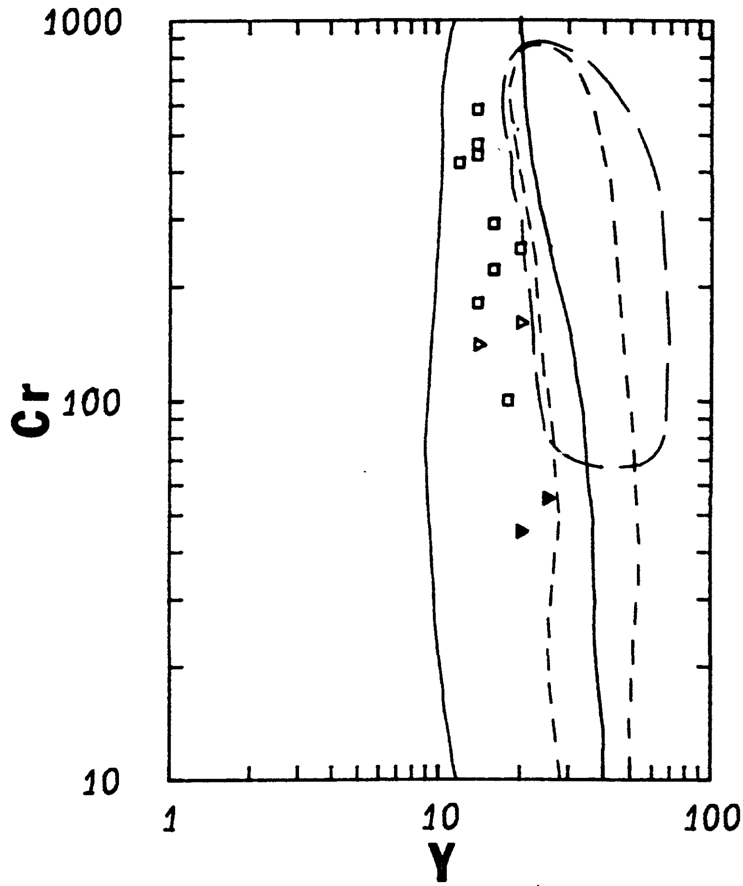


Figure 42. Plot of Irving mafic volcanics on Cr-Y tectonic classification diagram of Pearce and others (1981). Boundaries: solid (volcanic arc basalts); long dashed (MORB); short dashed (WPB). Symbols as in Figure 37.

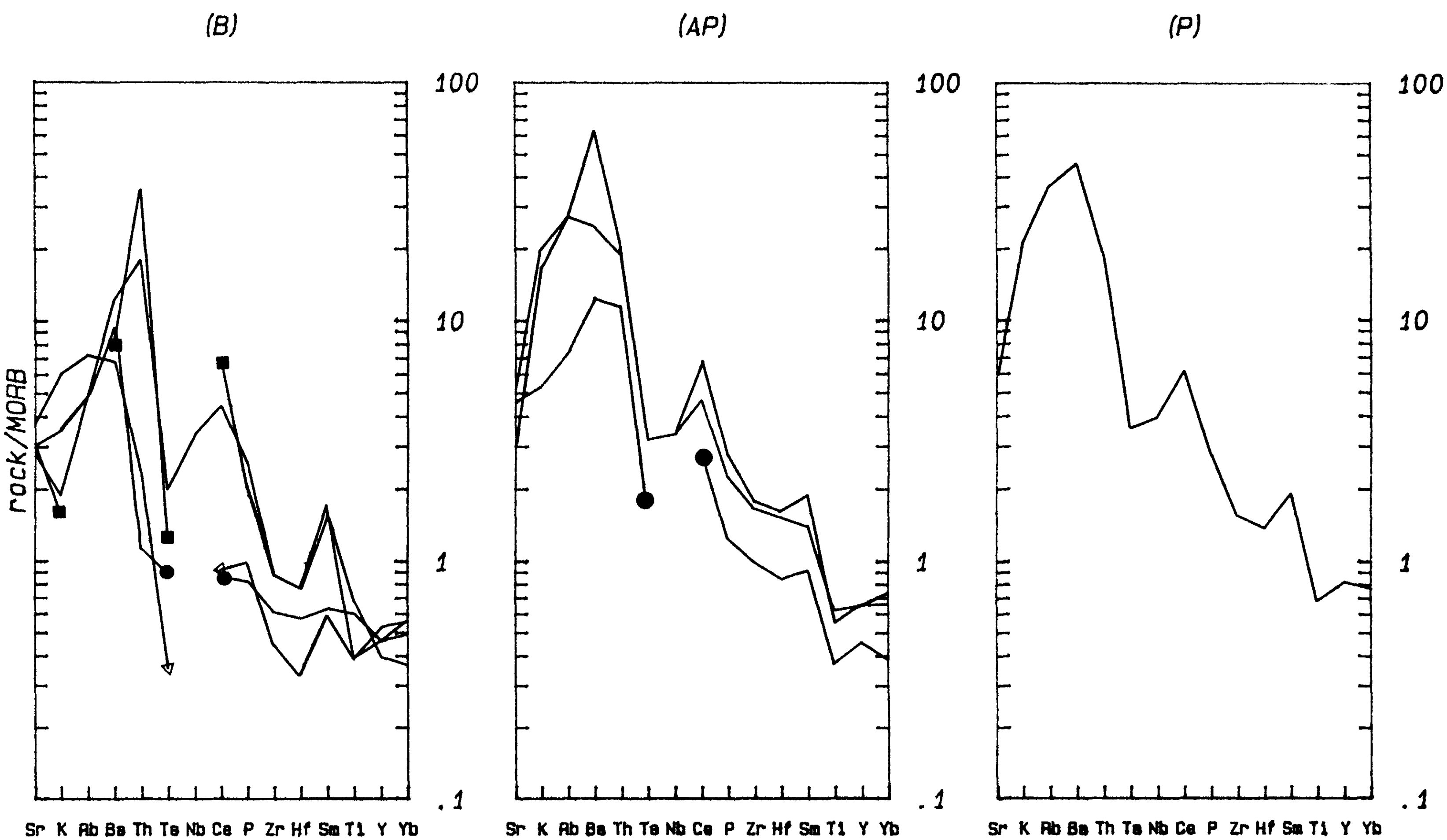


Figure 43. MORB-normalized element patterns for mafic volcanic rocks of the Irving Formation: (B) = basalts; (AP) = andesite porphyry; (P) = plagioclase phenocryst-rich porphyry with less than 52 % SiO_2. Symbols mark gaps in patterns due to lack of data. Normalizing values are from Pearce (1983).

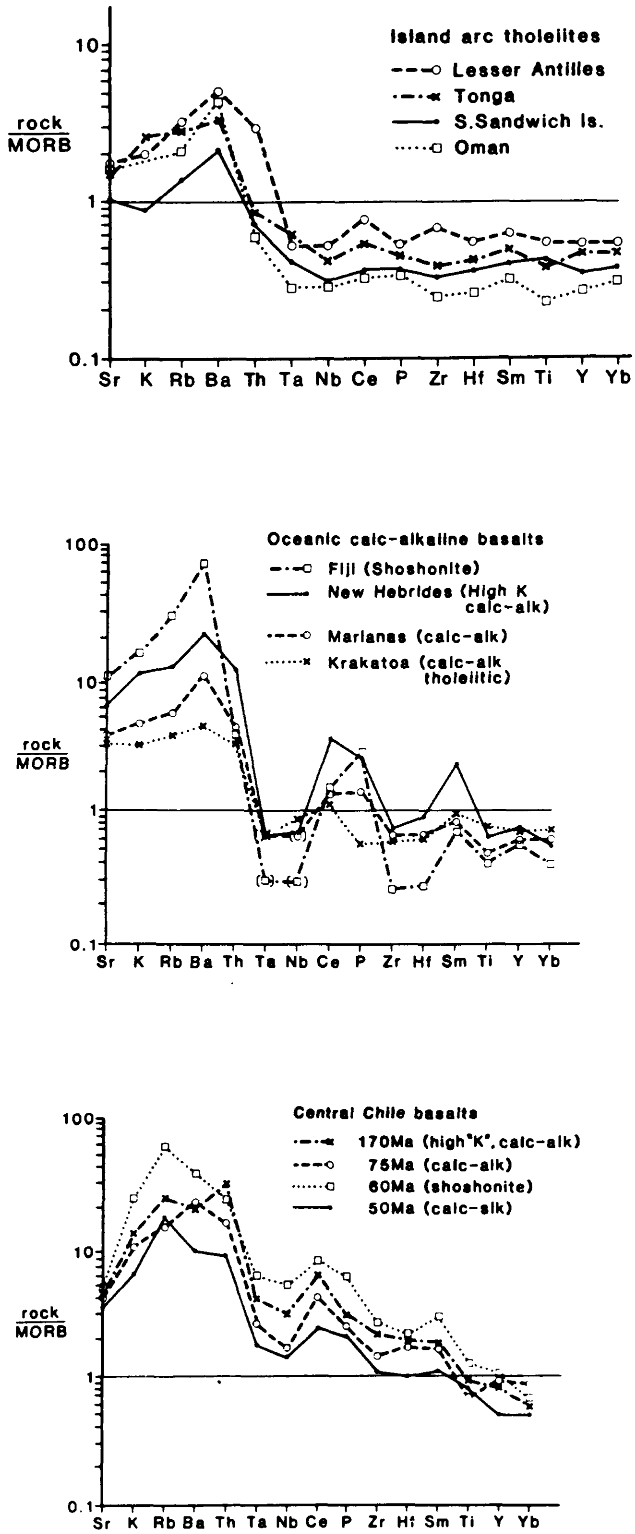


Figure 44. MORB-normalized element distributions for various volcanic arc basalts (from Pearce, 1983).

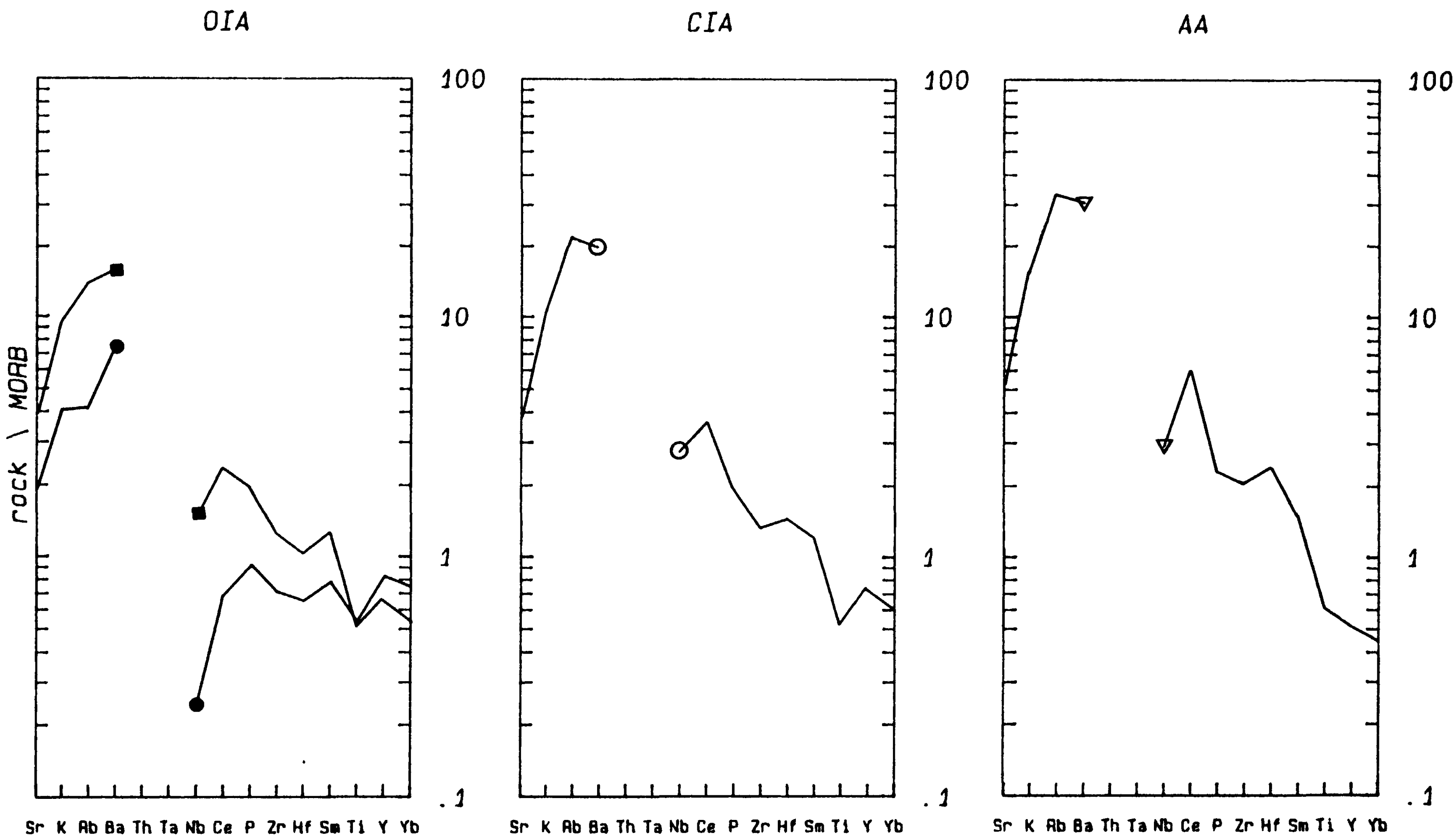


Figure 45. Average MORB-normalized spectra for andesites of oceanic island arcs (OIA), continental island arcs (CIA), and Andean arcs (AA) (data from Bailey, 1981). Symbols mark gaps where data was not available.

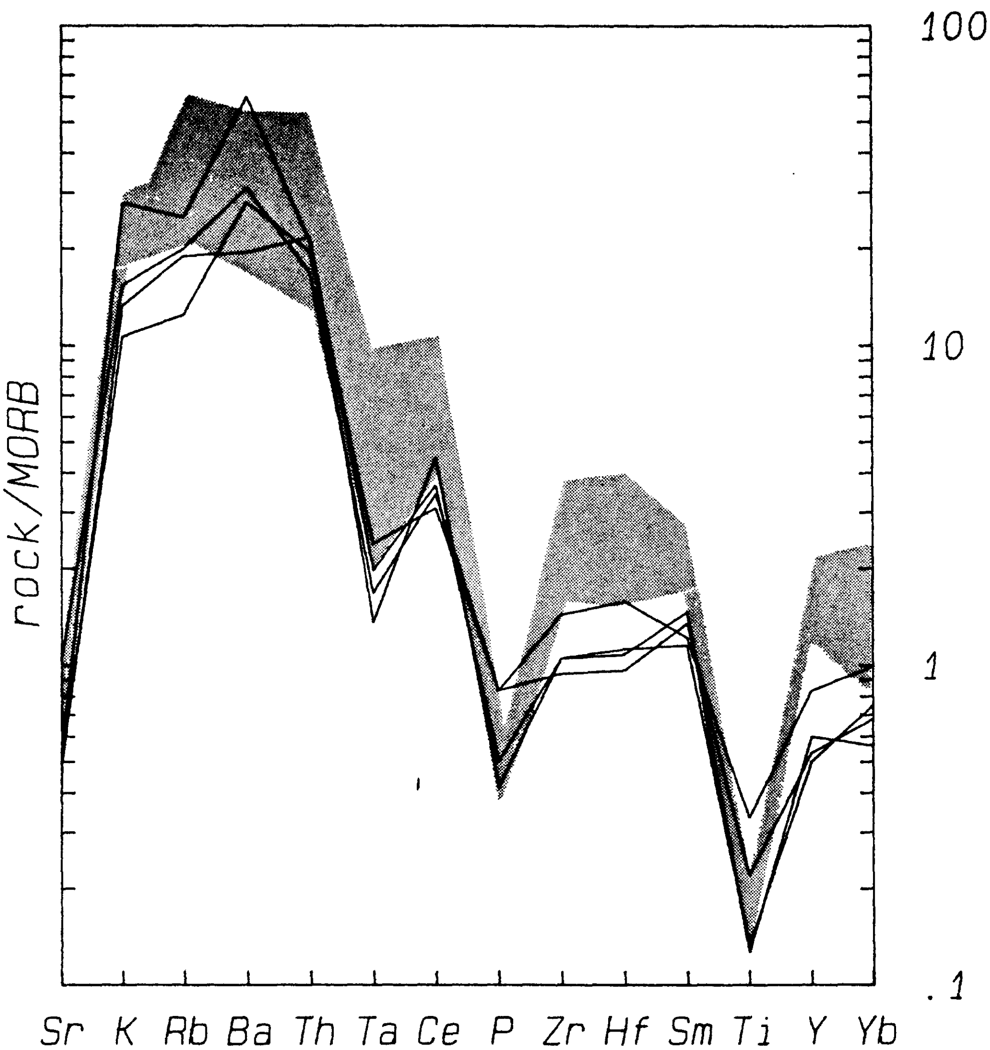


Figure 46. MORB-normalized element distributions of felsic volcaniclastic rocks of the Irving Formation. Shaded area marks the range in MORB-normalized element patterns for average rhyolites from various 1740-1800 Ma terranes in the southwestern United States (from Condie, 1986).

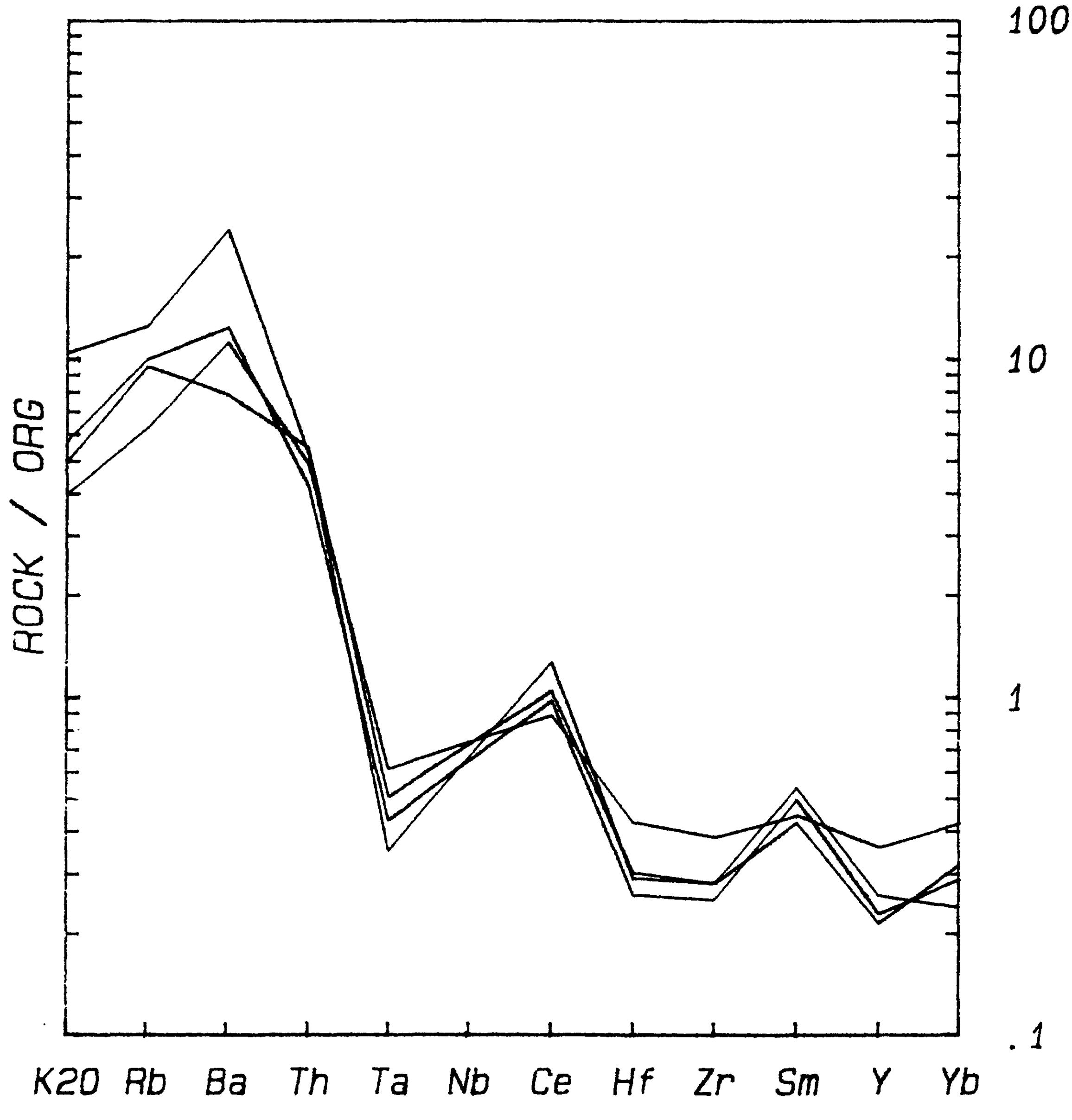
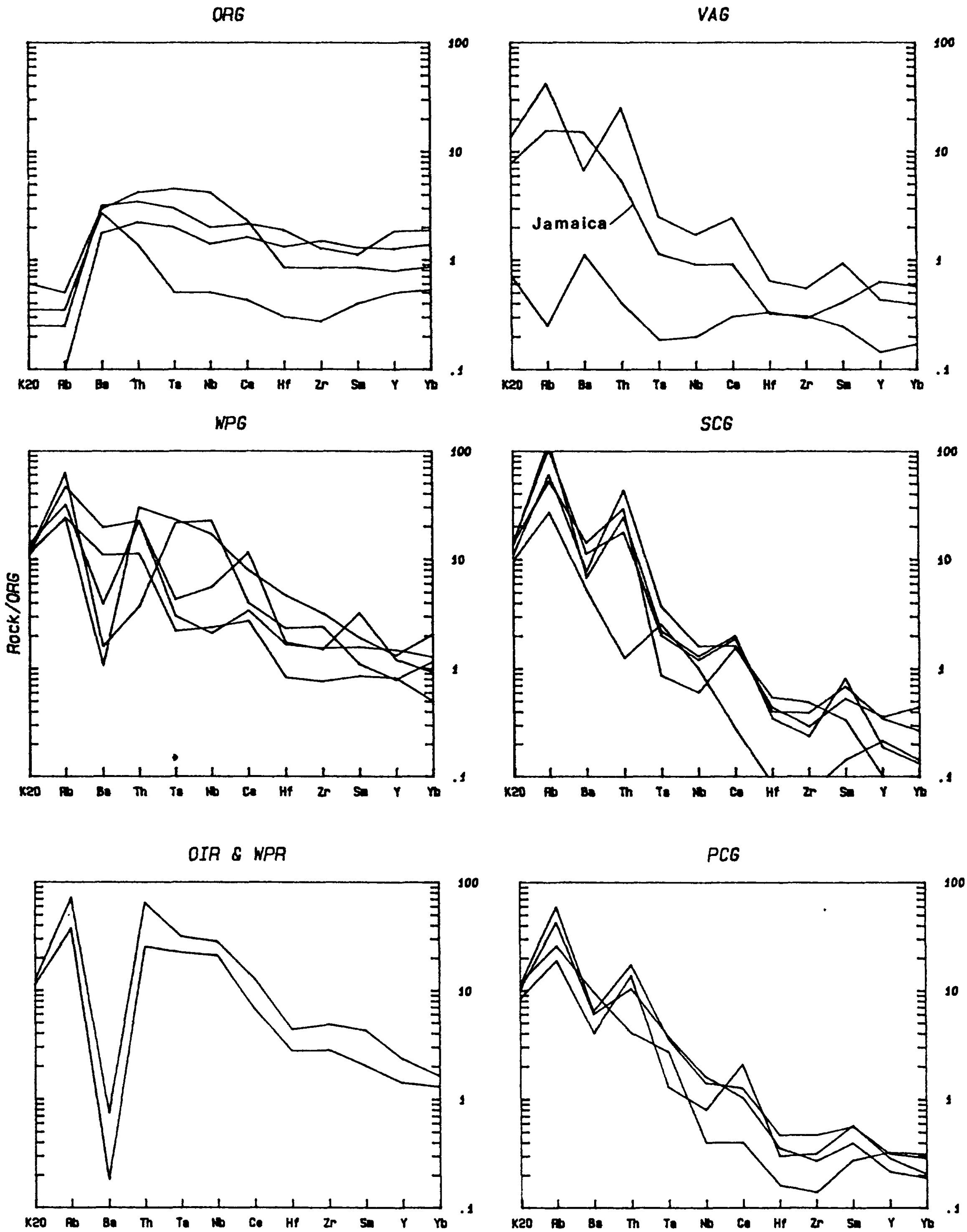


Figure 47. ORG (oceanic ridge granite)-normalized element distributions for rhyolitic volcanic rocks of the Irving Formation. Normalizing values are from Pearce and others (1984). Segments from Ta to Ce are not actual, since data was not obtained for Nb.

Figure 48. ORG-normalized element distributions for granitic and rhyolitic rocks from various known tectonic environments. Data for oceanic ridge granites (ORG), volcanic arc granites (VAG), within plate granites (WPG), syn-collision granites (SCG), and post-collision granites (PCG) are from Pearce and others (1984). Within plate rhyolite (WPR, Deccan Trap) and oceanic island rhyolite (OIR, Ascension Island) chemistries are from Lightfoot and others (1987) and Thompson and others (1984), respectively.


ORG
VAG
Jamaica
WPG
SCG
OIR & WPR
PCG
Rock/ORG
100
10
1
.1
K20
Rb
Ba
Th
Ta
Nb
Ce
Hf
Zr
Sm
Y
Yb

METAMORPHISM

At least three metamorphic events are recorded in rocks of the Irving Formation in the southeastern Needle Mountains. In order of occurrence these are: 1) prograde regional metamorphism; 2) incipient to extensive retrograde recrystallization; and 3) local, contact metamorphism related to intrusion of the Eolus Granite. The prograde and retrograde events may have been closely related.

Regional Metamorphism

Igneous and sedimentary rocks of the Irving Formation have undergone epidote-amphibolite to lower amphibolite facies prograde regional metamorphism. This regional event is reflected by partial to complete recrystallization of protoliths and the development of a weak to strong penetrative foliation.

The common occurrence of hornblende (pleochroism: X = pale brown; Y = dark olive-green; Z = dark bluish-green) with oligoclase-andesine, and Fe-rich epidote (Table 21), together with the absence of prograde actinolite, albite, and chlorite, in mafic volcanic and intrusive rocks of the Irving Formation, reflects a minimum temperature of regional metamorphism of approximately 525-570° C (Liou and others, 1974; Winkler, 1979; Moody and others, 1983; Figure 49). The occurrence of sphene in some samples may indicate that, at least locally, temperatures did not exceed 525-550° C (Liou and others, 1974; Moody and others, 1983). Laird (1982) notes that sphene is common in greenschist and epidote-amphibolite facies rocks, but is less common in amphibolite of both low- and medium-pressure series. Experimental study of the compositional variability of amphibolite over a range of T, P, and f_{O_2} (Spear, 1981), however, suggests that sphene is stable at higher temperatures than suggested by Liou and others (1974) and Moody and others (1983), with increasing oxygen fugacity.

A reliable estimate of absolute minimum and maximum pressures of regional metamorphism can not be determined from mineral assemblages of Irving metabasites. Systematic variations of mineral chemistry have been applied to obtain reliable estimates of pressures associated with regional metamorphism of mafic igneous rocks (Laird, 1980, 1982; Laird and Albee, 1981), however, microprobe analyses are necessary.

Mineral assemblages in graywacke and siltstone in the Irving are similar to those found in samples of mafic volcanic rocks (Table 23) and provide little additional information regarding pressure and temperature conditions of regional metamorphism. Andalusite (?) porphyroblasts were locally observed in metamorphosed tuffaceous sedimentary rocks of the Irving Formation. Barker (1969c; page A5) also reports sericite and chloritoid pseudomorphs of andalusite in "pelitic schist" in the Irving Formation on the northwest side of Irving Peak. The exposure noted by Barker (1969c) crops outside the present study area and was not examined by this author. It is uncertain whether the andalusite in these rocks is a product of prograde regional metamorphism of the Irving, or if it reflects a later thermal event. In either case, the presence of andalusite indicates a metamorphic event in which pressures did not exceed 4-5 kb (Richardson and others, 1968; Holdaway, 1971).

Table 21

Mineral assemblages of metamorphosed igneous and sedimentary rocks of the Irving Formation.

MAFIC VOLCANIC ROCKS (31 samples)

1)	Bt + Ep + Hbl + Op + Pl ± Cal ± Spn ± Qtz	(19 samples)
2)	Bt + Cal + Ep + Op + Pl ± Qtz	(3 samples)
3)	Ep + Hbl + Pl + Op	(2 samples)
4)	Bt + Ep + Hbl + Ms + Op + Pl	(2 samples)*
5)	Cal + Cpx + Ep + Hbl + Pl + Qtz ± Bt	(2 samples)
6)	Cal + Ep + Pl + Op + Tur	(1 sample)
7)	Bt + Ep + Pl + Op + Tur	(1 sample)
8)	Bt + Ms + Pl + Op + Tur	(1 sample)

MAFIC INTRUSIVE ROCKS (4 samples)

1)	Bt + Cal + Ep + Hbl + Op + Pl	(2 samples)
2)	Ep + Hbl + Op + Pl	(1 sample)
3)	Cal + Ep + Hbl + Ms + Op	(1 sample)

GRAYWACKE & SILTSTONE (5 samples)

Bt + Ep + Op + Pl + Qtz ± (Ap, Hbl, Tur) (5 samples)

CHERT (3 samples)

Qtz + Op + Cal ± (Ap, Ep, Ms) (3 samples)

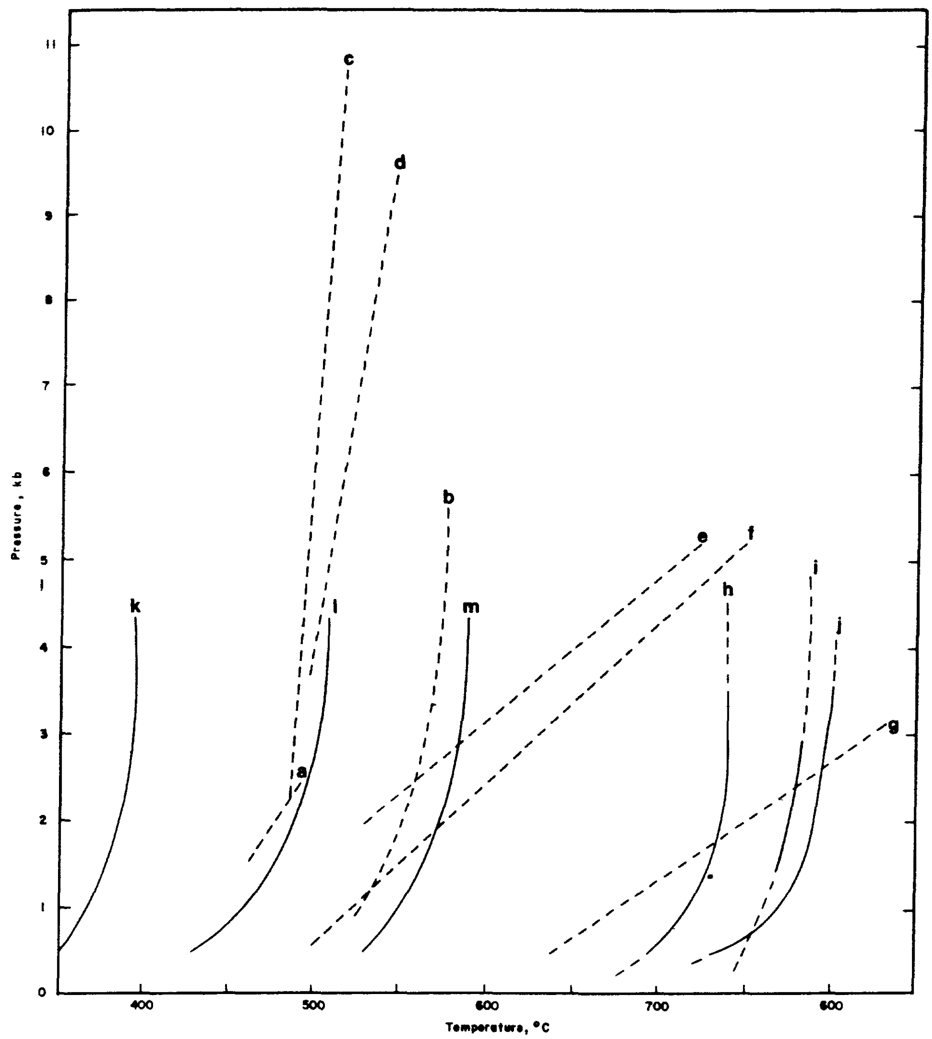
FELSIC VOLCANICLASTIC ROCKS (17 samples)

1)	Bt + Ep + Ms + Mc + Op + Pl + Qtz ± Cal	(6 samples)
2)	Bt + Ms + Op + Pl + Qtz ± Cal	(2 samples)
3)	Bt + Ep + Ms + Op + Pl + Qtz ± Tur	(2 samples)
4)	Bt + Ep + Pl + Op + Qtz ± Cal	(2 samples)
5)	Bt + Ep + Hbl + Op + Pl + Qtz ± Ms ± Spn	(2 samples)
6)	Bt + Ms + Mc + Pl + Op + Qtz	(1 sample)
7)	Cal + Bt + Ep + Hbl + Ms + Mc + Op + Pl + Qtz + Spn	(1 sample)

* contact metamorphic assemblage observed locally in Irving rocks collected near the Irving-Eolus contact in the Fall Creek area.

Mineral abbreviations: Ap = apatite; Bt = biotite; Cal = calcite; Cpx = clinopyroxene; Ep = epidote; Hbl = hornblende; Mc = microcline; Ms = Muscovite; Op = opaques; Pl = plagioclase; Spn = sphene; Tur = tourmaline; Qtz = quartz; Zrn = zircon.

Figure 49. Experimentally determined phase stability curves for metamorphosed mafic rocks. QFM, HM, IM, and NNO refer to quartz-fayalite-magnetite, hematite,-magnetite, ilmenite-magnetite, and nickel sponge-nickel oxide, fo_2 buffers, respectively. Stability curves are as follows: Liou and others (1974) [a) Chl decreasing curve (Ab + Ep + Chl + Qtz = oligoclase + tschermakite + Fe_3O_4 + H_2O); b) Chl-out (Chl + Spn + Qtz = aluminous amphibole + ilm + H_2O)]: Winkler (1979) [c) Hbl-in (Act + Czo + Chl + Qtz = Hbl); d) Pl (An_{17}) + Hbl-in]: Spear (1981) [e-g) Spn-out for WM, QFM, and HM buffers, respectively; h-j) Cpx-in for HM, WM, and QFM buffers, respectively: Moody and others (1983) [k-m) Chl decreasing/amphibole increasing, spn-out, and Chl-out, respectively; n-o) Spn-out for NNO and HM buffers, respectively. Mineral abbreviations listed in Table 23.



Pressure, kb
0
1
2
3
4
5
6
7
8
9
10
11
400
500
600
700
600
Temperature, °C
a
b
c
d
e
f
g
h
i
j
k
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m

Felsic volcaniclastic rocks in the Irving Formation typically contain the assemblage biotite + muscovite + oligoclase-andesine + quartz + epidote ± microcline; bluish-green hornblende occurs in some samples (Table 23). Mineral assemblages of Irving felsites are generally stable through the P-T conditions of greenschist to amphibolite facies metamorphism (e.g. Fyfe and others, 1958; Turner, 1980) and do not provide a reliable estimate of absolute temperatures and pressures of regional metamorphism (e.g. Fyfe and others, 1958; Turner 1980). The common occurrence of oligoclase-andesine and epidote, locally with hornblende, and the rare occurrence of garnet (see page 69) in these rocks, however, supports the interpretation that the grade of regional metamorphism ranged between upper greenschist to lower amphibolite facies.

Retrograde Recrystallization

Retrograde recrystallization, recognized by the partial to complete alteration of biotite and hornblende to chlorite, and plagioclase to sericite, is common in rocks of the Irving Formation. In relation to prograde regional metamorphism, retrograde metamorphism in the Irving Formation reflects a decrease in temperature and/or an increase in water pressure (Spry, 1969, page 301). Neither the duration of this event, nor the time span between prograde and retrograde recrystallization in the Irving are known.

Retrograde recrystallization in these rocks may have been promoted by one or more of the following: 1) lower grade regional metamorphism subsequent to epidote amphibolite-lower amphibolite prograde metamorphism; 2) expulsion of water by continued prograde metamorphism at depth (e.g. Cady, 1969, page 29); or 3) recrystallization associated with intrusion of the Eolus Granite.

Contact Metamorphism

Mafic metavolcanic rocks exposed near the Eolus-Irving contact in the Fall Creek area locally contain hornblende + andesine + pyroxene + epidote + quartz + opaque oxides ± biotite (Table 23); these rocks also display static textures defined by decussate biotite, hornblende, and pyroxene, and poikiloblastic hornblende that envelops crystals of plagioclase and pyroxene. Clinopyroxene in these rocks reflects an increase in grade of metamorphism (middle-upper amphibolite grade) which is attributed to thermal metamorphism associated with intrusion of the Eolus granite.

STRUCTURAL GEOLOGY

Resolution of the structural history of the Irving Formation in the southeastern Needle Mountains is complicated by the massive nature of many of its lithologies and lack of marker units or beds. Features such as folded foliation and obliquely intersecting penetrative fabrics indicate, however, that several episodes of deformation have occurred.

Trends of Penetrative Fabrics

Foliation in rocks of the Irving Formation varies from weak to prominent. Felsic lithologies generally exhibit a strong schistosity or gneissic banding while mafic volcanics and associated sediments are largely massive and weakly foliated. Foliation throughout the Irving typically trends between N 20° W to N 20° E and is generally steep to vertical. Mineral lineations defined by clusters of hornblende and biotite, typically plunge steeply to the south (Plate 1).

Folding and Faulting

Isoclinal to open, mesoscopic folds were observed throughout the Irving Formation. Ptygmatic and intrafolial folds defined by veins and lenses of quartz occur locally. Folding is more commonly displayed by felsites, but numerous small-scale folds are also exhibited in some outcrops of mafic lithologies. Folded foliation is commonly displayed by Irving lithologies, and locally an axial plane cleavage is developed, as well (see Figure 28). Orientations of mesoscopic folds observed are variable, but most plunge steeply to the south.

Stratigraphic complexity is apparent in the Irving between Emerald Lake and the head of Dead Horse Creek (Plates 1 and 2). Volcaniclastic sediments exposed in this area dip and young to the east, southeast, and southwest. At this time a viable structural interpretation to explain these stratigraphic relationships can not be given. They may reflect folding in the Irving both prior to and during deformation of the overlying Vallecito Conglomerate and conglomerate of Fall Creek.

Deformation of the basement-cover sequence in the southeastern Needle Mountains is reflected in a series of upright to steeply inclined, open to close, shallowly south-plunging folds. These folds are cut by a series of east-west or north-northeast trending, steeply dipping to vertical faults (Figure 50; Plates 1, 2, and 4).

Major north-northeast trending faults or fault zones in the study area exhibit both pre- and post-Paleozoic east-side-down, dip-slip movement (faults A and B in Figure 50), and typically postdate the latest movement on east-west trending faults. Offset of depositional contacts between the Irving Formation, Vallecito Conglomerate, and conglomerate of Fall Creek on major east-west trending faults (labeled C, D, and E on Figure 50) suggests from 400 m (fault E) to 0.5 km (faults C and D) of apparent dextral (fault C) or sinistral movement (faults D and E). The widespread occurrence of andesite porphyry in the block between faults C and D, but general lack of this lithology to the south of fault D may indicate that this fault has undergone south-side-down oblique-slip movement.

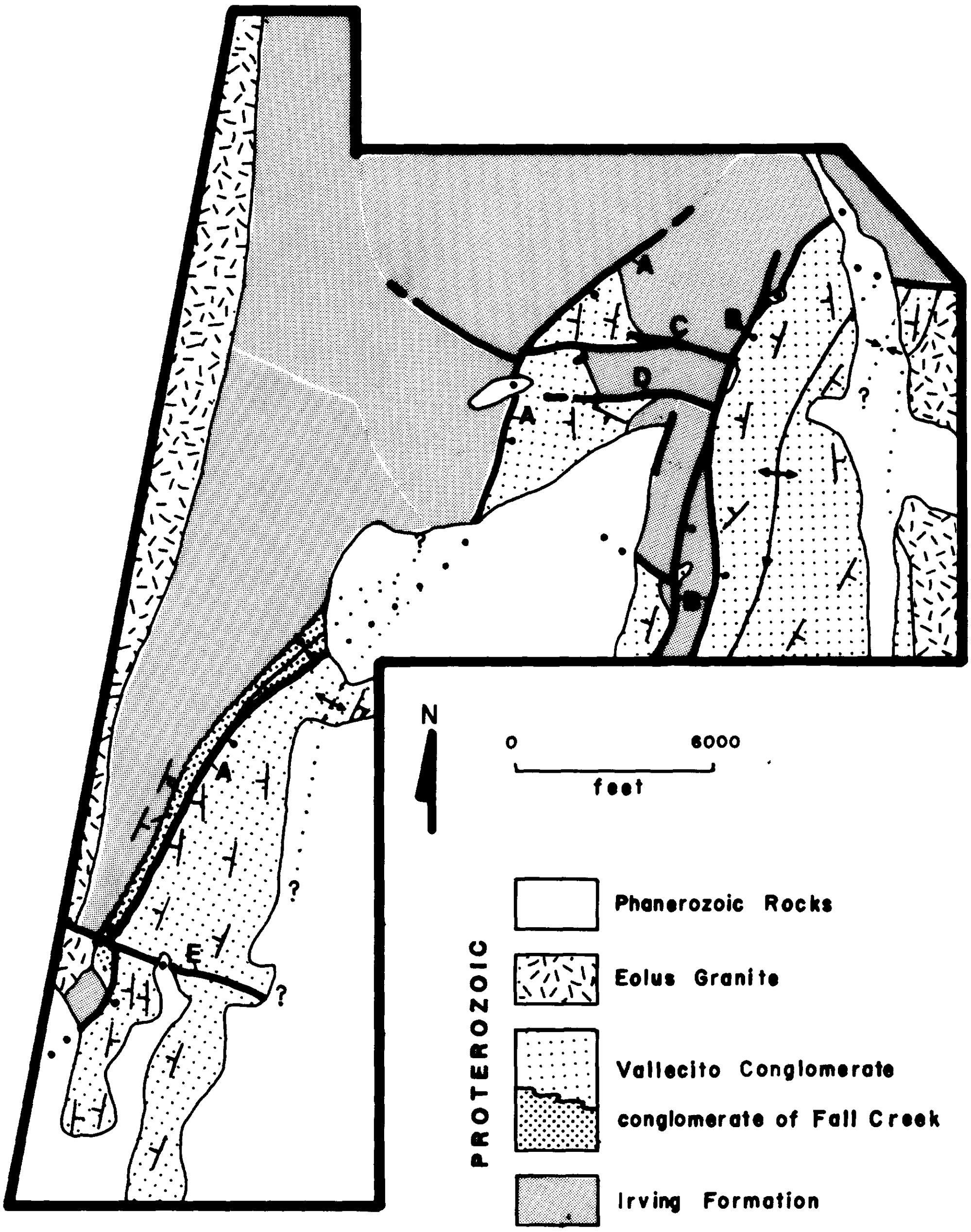

Figure 50. Generalized sketch map of Plate 1. Major faults discussed in text are denoted by alphabetic labels.

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