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WEATHERING AND DEVELOPMENT OF WEATHERING RESIDUALS ON THE BOULDER BATHOLITH, SOUTHWESTERN MONTANA

by

Wayne Allen Wetzel

B.S., Montana State University, 1971

M.S., University of Idaho, 1973

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
in the Department
of
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ABSTRACT

This investigation focuses on geochemical alterations in quartz monzonite and related plutonic rocks of the Boulder batholith in southwestern Montana. In particular, <u>in situ</u> regolith materials taken from beneath Tertiary (early Eocene and early Oligocene) volcanic field detritus were compared with similar materials from regoliths that had not experienced volcanic burial.

An assessment of possible paleoclimatic influences preserved in the sub-volcanic regoliths was done. The results are related to the morphogenetic origins of granitic weathering residuals on the batholith. It is concluded that no climatic bias is detectable in the sub-volcanic materials. However, this conclusion is tempered by the evidence that the volcanic coverings on the plutonic rocks do not halt the weathering process and may even enhance the formation of regolith materials by facilitating vadose zone chemical reactions. The analyses employed X-ray fluorescence of powdered regolith samples and petrologic analyses of thin sections.

Lack of a distinctive difference being recognized between meteoric weathering and hydrothermal alteration has so far complicated the study of weathering residuals. The analyses of X-ray fluorescence powder samples in this study suggest that differences between hydrothermal and meteoric alteration can be distinguished by the relative amounts of elemental constituents

present or absent in weathered samples. This difference is distinguishable despite subsequent exposure of hydrothermally altered rock to supergene weathering.

Geologic relations and evidence from the analysis suggest that many distinct weathering and denudation processes are responsible for the varied weathering residual forms. Also indicated from geologic relations, is that the present landscape is geologically older than the conventionally interpreted Pliocene-Pleistocene age.

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I thank the Montana Department of Natural Resources and Conservation for allowing me to work flexibly at my duties in order to complete this thesis. I also thank the many co-employees who have handled many of my responsibilities in order to facilitate this work.

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CHAPTER 1

PURPOSE AND OBJECTIVES

Perspective:

Many early studies in inselberg landscape development were able to provide insights that have not since been eclipsed. Many of these early enquiries were in the tropics as a result of geomorphic enquiry in colonial acquisitions of several European nations. These include the works of Bornhardt (1900), Falconer (1911,1912), Campbell (1917), Woolnough (1927, 1930), Wayland (1934), Harrison (1934), Jessen (1936), and Willis (1936). The origins of modern concepts regarding deep weathering, laterization, etch-planation, and saprolite stripping stem from the writings of these investigators. Most of this work, however, was too obscure to be noticed or was simply ignored by contemporaries.

David L. Linton's landmark paper 'The Problem of Tors' (1955), owing something to Linton's stature among British geomorphologists, forced the issue of weathering and inselberg landscape development to advance on several fronts. First of all, Linton's interpretation of the origin of the Dartmoor tors as possibly paleo-tropical placed before mid-latitude geomorphologists a view of landscapes that, with further inquiry, progressively required a knowledge of tropical weathering and denudation conditions. Prior to this, the only landscapes widely recognized as being inherited from earlier geologic times were the glacial and periglacial features of the Pleistocene.

Secondly, controversy over which investigator could best explain the origin of tors and other inselberg forms led to a general recognition of the need for scientific methods to support one's views. In a classic authorial clash about some British tors, Linton deduced his conclusions from observations only but had no "field evidence" of sub-soil deep chemical weathering that was "clearly demonstrable" (Linton, 1955, 1964). While Linton never produced such field evidence, his critics (who in retrospect may have been the more logical) had no real evidence to support their claims of the absence of such weathering either (Palmer and Neilson, 1962; Palmer and Radley 1961). With the rapid onset of the quantitive revolution at about this time, researchers began to realize a need to use scientific methods to obtain the data necessary to back or refute "clearly demonstrable" observations.

Finally, the pursuit of an answer to the dilemma caused by conflicting evidence on modes of origins of granitic inselbergs has led to a realization that there are no universal solutions. This has led Cunningham (1969, 1971) to propose the 'principle of convergence' in inselberg landscapes. This basically means that characteristic inselberg forms may come about by a number of geomorphic processes acting independently or in combination. Further, these characteristic forms may appear, decay, and appear again a number of times during the evolution of a landscape.

Purpose:

The purpose of this study is to evaluate some disputed issues of inselberg origins through the use of some laboratory techniques to supplement traditional field observation analyses. Specifically, these techniques are to be used as an aid in interpreting the processes responsible for weathering and the development of weathering residuals on plutonic rocks of the Boulder batholith in southwestern Montana, U.S.A.. Thomas (1978b) provides an excellent review of past and present techniques and problems in the geomorphic inquiry into granitic inselberg landscapes, though many of the controversies addressed in the review are beyond the scope of this inquiry. Nevertheless, Thomas' (1978b) review has provided a landmark for focusing future research. Among the areas foremost in needing additional work, the use of geochemical methods in geomorphic research is recognized as a particularly critical need.

Primary foci in this study are the relative roles of climate, geology, lithology, drainage, and topography in the development and distribution of weathering profiles and related inselberg forms in the study area. Each of these factors has been either demonstrated or asserted to have had a major influence in the development of granitic landscapes on a world-wide basis. Since the existence (and, as often interpreted, persistence) of weathering residuals is documented in nearly every conceivable climate, rock type, and topographic position, the permutations of likely explanations for the origin and distribution of inselberg forms are nearly endless. For this reason, the present study could have added one more case study to the already very large numbers of such studies offering yet another explanation.

For two reasons, however, this thesis adds an extra dimension to earlier work in this area. First, this study has been specifically designed to use geochemical and optical techniques not generally employed by landscape geomorphologists to aid in the interpretation of the landscape evolution. Second, though a great deal of geologic work has been done in the American West, including studies on weathered granitics, there has been no attempt to relate the greater portion of these studies to a framework explaining origin, age, paleoclimatic significance, and distribution of forms. It is hoped that this thesis will, to a degree, provide that dimension to geomorphic research in the chosen area of the Northern Rocky Mountains.

Objectives:

Major objectives of this thesis are:

1. To attempt to distinguish between types of weathering alterations (hydrothermal, meteoric, metasomatic) present in rocks of the Boulder batholith and to analyze how each weathering type may affect the development of inselberg forms.
2. To assess, within unavoidable limitations, whether meteoric weathering observed on the intrusive rocks of the Boulder batholith shows demonstrable mineral-specific alterations

that may be attributable to paleoclimatic influences, as suggested by a number of climatic geomorphologists.

3. To attempt to determine reasons for the persistence of weathering residuals in this particular landscape, as revealed in powder samples and thin sections, in conjunction with conventional geomorphic analysis, from the weathered regolith and from residual forms.
4. To attempt an explanation of landscape development of inselbergs on the Boulder batholith consistent with these findings.
5. To discover limitations of this mode of inquiry and postulate new directions to improve the explanatory value of these relatively new methods in granitic inselberg studies.

Definitions:

As pointed out by Thomas (1965) and Melcon (1975), a good deal of controversy in the study of weathering stems solely from a lack of precision in terminology. This lack of imagination in creating new terms for newly discovered situations, or, conversely, the inappropriate creation of new terms to cover already adequately defined landforms or processes, have also posed problems. It is not the intent of this study to resolve these, but it is hoped that the following definitions adapted from Melcon (1975) will avoid confusion in interpreting references made to weathering residuals in this thesis. As pointed out by Melcon, some of these terms have unfortunately become associated with particular morphogenetic theories for the origin of weathering residuals. Unless otherwise noted in this text, the terms presented here have no innate connotation implied.

bornhardts are dome-shaped hills which stand clearly above the surrounding terrain (often by as much as several hundred metres). An abrupt junction or piedmont angle occurs as one moves from the general surface to the steep sides of the bornhardt.

kopjes or castle-kopjes are jointed, bedrock landforms often displaying a castellated profile, and which may be distinguished from a tor by their greater size and mixture of angular and rounded forms.

clitter are boulders of rounded or angular form not rooted in bedrock or related in any orderly way to a tor. Clitter is normally found at or above the surface, with few or no fines between boulders.

a corestone is an ellipsoidal or spheroid boulder entirely detached from bedrock which is not related in an orderly fashion to a tor. Corestones may occur at the surface or be buried *in situ* within regolith materials as a product of pan-directional subsurface weathering attack.

domical inselbergs are dome-shaped hills which stand clearly above the surrounding surface but which lack the abrupt, marginal transition characteristic of bornhardts.

duricrust has two distinct meanings in common usage. First, duricrust is the generic term for a hardened layer above or within a soil profile. Three characteristic chemical types of duricrust are called 'ferricrete' (iron-rich layer also commonly called laterite), 'silicrete' (silica-rich), or 'calcrete' (lime-rich). Second, duricrust is also used to describe case-hardening of the exposed surface of rock (in this case, granitic rocks) which often exhibits a greater degree of weathering beneath the crust. The term 'indurated crust' is used synonomously with this second meaning in this study.

fins or blades are joint-bounded, bedrock outcrops exhibiting close vertical or nearly vertical jointing and are from a few metres to a few tens of metres in height.

regolith or weathered regolith refers to *in situ* rock material that is altered in such a way that physical disaggregation and/or stripping is easily accomplished by erosion when compared to the same erosive action on unaltered rock. Unaltered rock within the regolith may appear as corestones or incipient tors.

weathering residuals include tors, fins, bornhardts, castle kopjes, corestones and domical inselbergs generally attributed to the development of a regolith by chemical weathering with subsequent erosive stripping (two-stage morphogenesis). The term 'inselberg' will be used synonomously with 'weathering residual'.

CHAPTER 2

STUDY AREA DESCRIPTION

Location:

The study area, covering some 15,000 km^2 in western Montana, comprises the exposed outcrop of the intrusive complex known collectively as the Boulder batholith and the immediately surrounding area. This surrounding area includes portions of basins filled with Tertiary and Quaternary deposits; older, pre-batholithic sedimentary and metamorphic rocks, and both pre- and post-intrusive volcanics. Figure 1 shows this area of Western Montana, comprising parts of Broadwater, Deer Lodge, Jefferson, Lewis and Clark, Madison, Powell, and Silverbow Counties. The main focus of the study is in the area shown by the mapped outcrop of the Butte Quartz Monzonite in Figure 1 (5,700 km^2), although some satellite plutons, especially south and southeast of Butte, were also investigated.

Relief and Physiographic Setting:

Relief ranges from 3070 m. in the Highland Mountains near the southern end of the Boulder batholith, to 1050 m. at the point where the Missouri River leaves the study area northeast of Helena. Relief amplitude on the batholithic rocks is generally much less pronounced than these extremes, averaging about 450 m. between major ridges and valleys in the quartz monzonite. This is shown diagramatically in cross-sectional view in Figure 1A. The geologic units in Figure 1A are the same

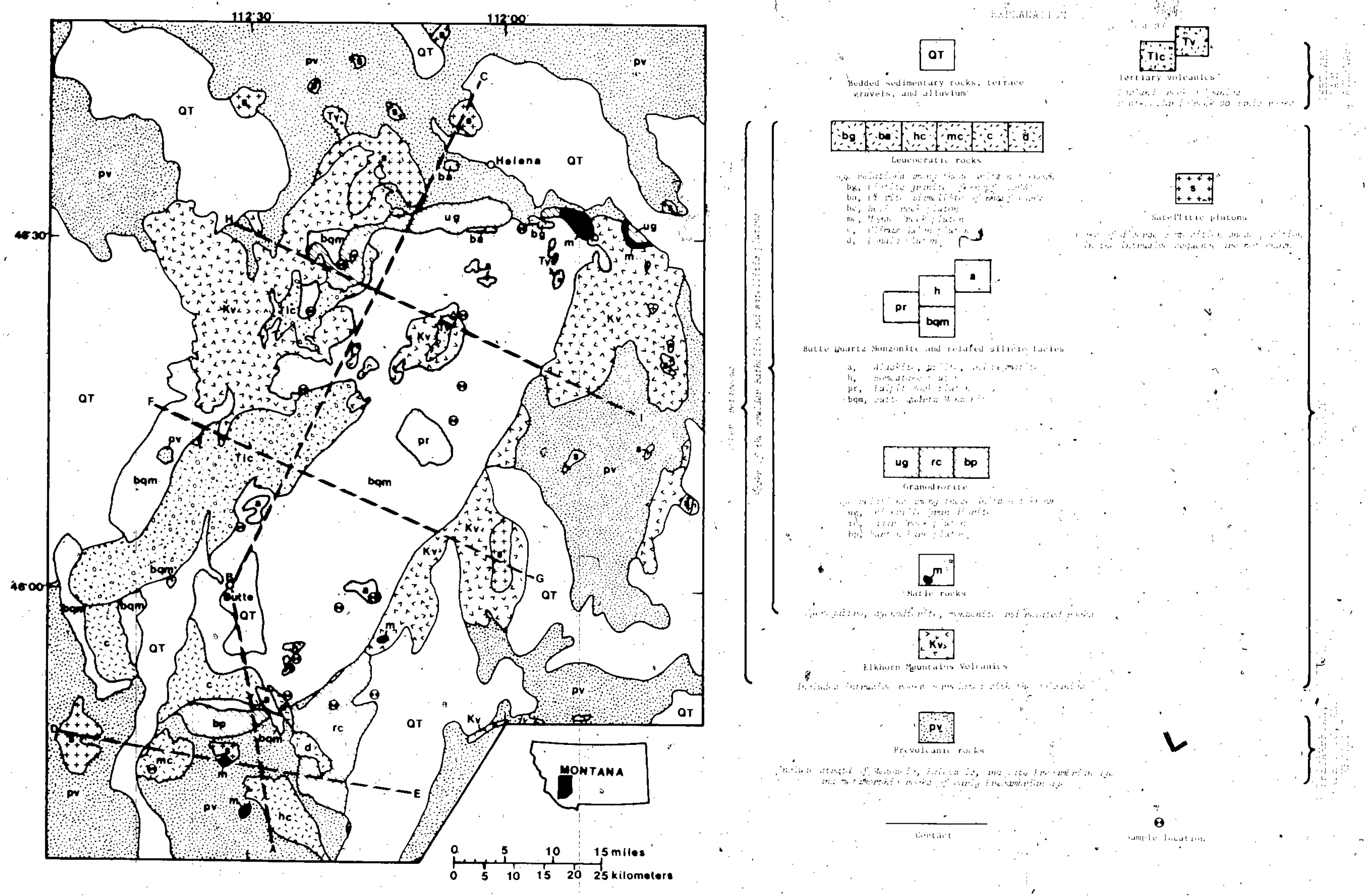


Figure 1. Generalized Geologic Map of Boulder Batholith and Vicinity (Modified from Tilling, et al., 1968)

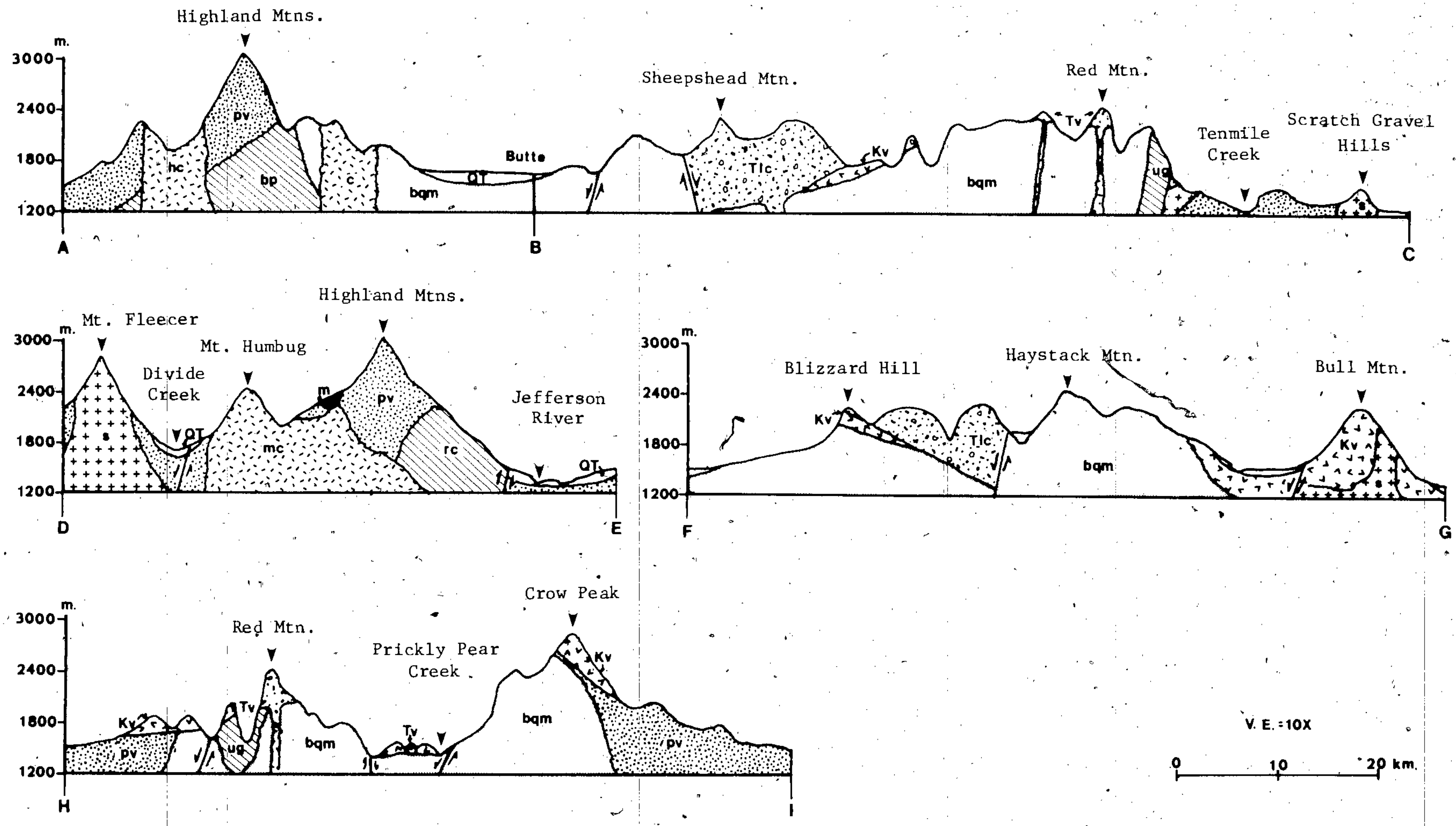


Figure 1A. Generalized Cross-Sectional View of Geology and Topography. (Rock Units are from Figure 1) as in Figure 1. Using LANDSTAT imagery Figure 2 provides a view of most of the study area and shows the location of the sample sites and some landmarks. Maps at a larger scale, showing topography and relief in the vicinity of the sample sites, are included in Chapter 4.

The study area is located in what Fenneman (1931) describes as the Northern Rocky Mountain Province. To a certain degree, the physiography of this province is distinctive for its failure to fit into other well-defined physiographic categories recognized by early geomorphologists in the western United States. Southwestern Montana, a portion of this Province described by Crowley (1972) as the Broad Valley Rockies, is considered the most physiographically diverse region of Montana. The characteristic, broad valleys have led to some speculation that this portion of Montana is a northern extension of the Basin and Range Province. A problem with this interpretation is that the physical separation of most mountains into distinct ranges is indefinite. This is particularly true of the mountainous areas of the Boulder batholith. Many so-called ranges are as wide as they are long. Also, because of complex geologic relationships, the alignment of both valleys and mountainous areas is certainly more varied than the more orderly alignment of these features in the Basin and Range Province.

The mountains of the study area are described by Fenneman (1931) thus:

"The Continental Divide [see Figure 3] traverses almost the

Figure 2. LANDSTAT Image of Approximate Area Shown in Figure 1

EXPLANATION

COUNTIES

LC	Lewis and Clark County
DL	Deer Lodge County
SB	Silver Bow County
B	Broadwater County
J	Jefferson County
M	Madison County
P	Powell County

SAMPLE SITES

1. Border Zone **
2. Tenmile Creek *
3. Old Baldy Mountain *
4. Clancy Gulch **
5. Lockhart Meadows •
6. Wickes-Boulder Road •
7. Boomerang Gulch **
8. Browns Gulch •
9. Spire Rock •
10. Big Pipestone Creek •
11. Homestake Pass •
12. Pipestone Pass •
13. Pipestone Road **
14. Jefferson Basin
15. Moose Creek

* X-ray Analysis Only

LANDMARKS

NB	Northern Boulder Mountains
SB	Southern Boulder Mountains
EH	Elkhorn Mountains
BM	Bull Mountain
BR	Boulder River
JR	Jefferson River
MR	Missouri River
CF	Clarks Fork River (Silver Bow Creek)
BH	Big Hole River
PP	Prickly Pear Creek
LB	Little Blackfoot River
WT	Whitetail Creek

** X-ray and Petrologic Analysis

Scale Approximate to Figure 1.

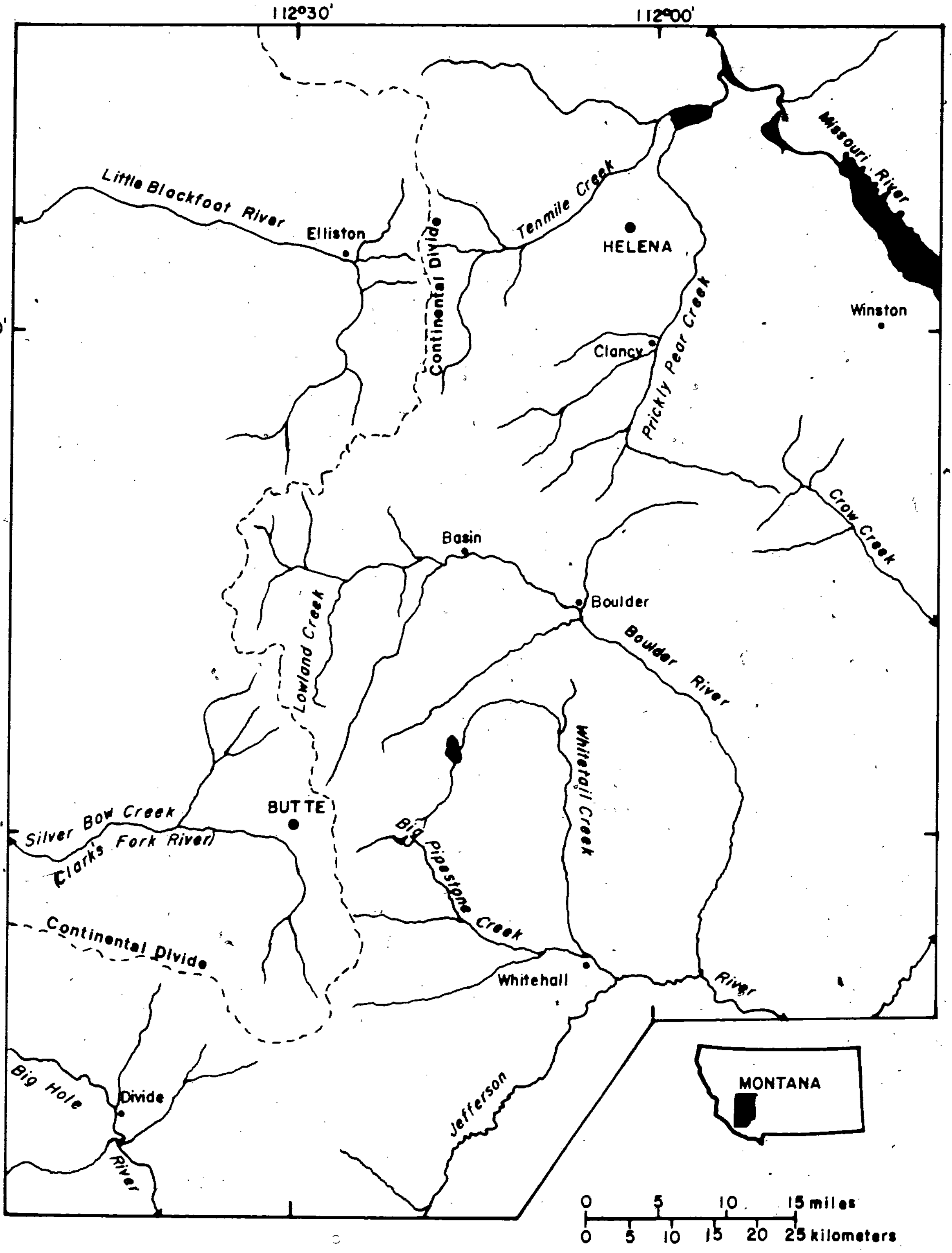


Figure 3. Drainage within the study area.

> entire length of this district, turning back to the northwest from its southern end, yet there is no linear range. The divide west of Helena is on the "deeply dissected plateau country" which is here a "broad, grassy, soil-covered axis" less than 7,000 ft. high [Barrell, 1907]. North and east of Butte it is a mountainous area having no commanding summits, but with a general level 7,000 to 8,000 ft. high. Here on the east slope of the Continental Divide is an old surface of deeply decayed granite remarkably free from rugged peaks...Here and there are exceptions to the general prevalence of flat summits or accordant ridge crests. The most conspicuous is found in the Highland Mountains [see Figure 1A], a small group 16 miles south of Butte. Here are alpine peaks rising to 10,000." (Fenneman, 1931, p. 214-215).

The mountains of the Boulder batholith and adjacent 'ranges' are generally surrounded and separated by broad basins occasionally containing up to 1000 m. of Tertiary and Quaternary deposits. At a number of places, hovever, the 'separation' between mountainous areas is simply a narrow river-cut gorge (like the Boulder River gorge separating the northern and southern Boulder Mountains) or is a band of hills lower in elevation than the other mountainous zones (for example, the Elkhorn Mountains are really contiguous with the northern Boulder Mountains along the divide between the Prickly Pear Creek and Boulder River drainages). The geologic history and its relationship to physiography in the area is discussed in greater detail in Chapter 3.

Access:

Most of the area of the exposed Boulder batholith is public land but is dotted with innumerable private parcels and mining claims. Some of the best vertical exposures of weathering profiles in the predominant rock, the Butte Quartz Monzonite, are in roadcuts along Interstate 90 southeast from Butte to Whitehall (see location of cities in Figure 3). Exposures were also investigated along other highways and roads ranging from paved primary highways to jeep trails. Most of the field investigation and selection of many sample sites involved hours of walking along indistinct, formational contacts in rugged terrain.

Drainage: [See Figure 3]

The Boulder River and numerous tributaries drain the central portion of the Boulder batholith, starting near the west central edge and leaving the eastern edge of the batholith near the town of Boulder. From here the river turns southward and joins the Jefferson River near the southeastern portion of the study area. The Boulder River, Big Hole River, and other minor tributaries such as Whitetail and Big Pipestone Creeks, flow into the Jefferson River which continues easterly out of the study area to where it combines with the Madison and Gallatin Rivers near Three Forks to form the Missouri River. The Missouri River flows north to northwesterly and re-enters the study area east of Helena. Three major impoundments form Canyon Ferry Reservoir east of Winston; Hauser Lake northeast of Helena; and Holter Lake north of Hauser Lake and just outside the study area. Some smaller streams such as Crow Creek, Tenmile Creek, and Prickly Pear Creek flow directly into the Missouri or impoundments of it. All of these rivers are east of the Continental Divide (dashed line in Figure 3) and are eventually tributary to the Mississippi River.

West of the Continental Divide, Silver Bow Creek becomes the mainstem of the Clark Fork River just northwest of where it leaves the study area. The Little Blackfoot River drains part of the northern end of the Boulder batholith and joins the Clark Fork River west of where it exits the study area. The Clark Fork is eventually tributary to the Columbia River.

Climate:

While upwards of seventy years of climatological data are available in the larger cities of Butte and Helena, these records are not easily extrapolated over the entire study area in order to derive an adequate description of prevailing climatic conditions. Differences of elevation and aspect, of orographic and rain-shadow precipitation patterns, and of both natural and manipulated vegetative patterns are so varied that climate is probably most appropriately if evasively described as a 'mountain climate'. This implies that, within wide extremes, almost any circumstance of temperature or precipitation could occur regardless of the time of the year. In this circumstance, mean annual or monthly temperature and precipitation figures can be considered only broadly indicative of climate, and are relatively meaningless in interpretating the climatic influence in geomorphic processes. Nevertheless, for comparative purposes, Table 1 presents such data for Helena and Butte, the stations with the longest periods of record. The variation

TABLE 1

AVERAGE TEMPERATURE AND PRECIPITATION DATA FOR HELENA AND BUTTE

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
TEMP (C)													
HELENA	-7.4	-4.9	-0.3	6.3	11.6	15.3	20.2	19.0	13.3	7.6	-0.2	-4.3	6.3
BUTTE	-9.4	-6.9	-3.2	3.6	8.5	12.4	17.1	13.1	10.7	5.3	-2.4	-6.6	3.7
PRECIP (mm)													
HELENA	14.0	9.7	16.3	23.6	44.7	60.5	24.4	24.9	19.6	15.0	15.5	14.7	289.1
BUTTE	13.7	4.8	16.0	29.0	46.5	68.3	27.2	28.7	30.0	16.5	14.7	8.9	309.1

Source: U.S. Department of Commerce, 1980 between the two stations is mostly attributable to the approximately 500 m. of elevational difference (Helena, 1148 m.; Butte, 1681 m.) and to the relative impact of modified marine influences on opposite sides of the Continental Divide, Helena being on the Atlantic, Butte on the Pacific flank (see Figure 3).

Probably more significant than the figures in Table 1, because of demonstrated effects of frost cycling as a mechanical weathering agent (Melcon, 1975), are the possibilities of freeze-thaw conditions at each station. Within the historical record, Butte has recorded freezing temperatures in every month of the year, and Helena in every month except July. This is coupled with mid-winter 'chinooks' or thaws where temperature extremes may fluctuate from -35° centigrade (C) to 15° C in less than one day along the eastern side of the Continental Divide.

The effect of elevational differences on climate is difficult to ascertain because of the lack of long-term data for higher elevations. One observation from limited temperature readings taken at the communications booster station at the top of East Ridge (2475 m.), about six kilometers northeast from the weather station at Butte (about 800 m. lower), is revealing. On colder winter mornings, when a temperature inversion persists in the basin to the west, the readings on East Ridge can average 4° to 6° C. warmer than Butte. Similar variation will occur on warm, summer days when East Ridge will be cooler than the basin centre (Hood, 1963). Thus, higher elevation has the effect of smoothing temperature extremes. As may be expected, precipitation generally increases with altitude. Estimates of mean annual precipitation at East Ridge (635 mm.; Ross and Hunter, 1976) are about twice that at Butte (309 mm.).

Aspect differences also may have a profound effect, both directly through incident radiation and indirectly through vegetative patterns. This is especially true of ridge-valley systems that trend east and west. North-facing slopes will most often be timbered, while south-facing slopes are either grassy or a mixture of grass and trees that has been described as parkland or parkland savanna. Insulating effects of the coniferous overstory, which is prevalent on north aspects, tend to have a temperature effect similar to that of elevation, that is, on the average, to produce cooler conditions in summer and warmer in winter. By way of contrast, sparse tree and/or grass covered slopes on southern aspects experience greater incident solar radiation at all times of the year, but these slopes also experience greater radiation loss at night, resulting in greater diurnal and seasonal temperature fluctuations. Frost churning and minor solifluction in the Bozeman area has been observed by Griffith (Dept. of Natural Resources and Conservation soils scientist, personal communication, 1981) to occur on south slopes, but not on north slopes. Apparently, temperature buffering effects by vegetative cover and low incident radiation keep north aspects permanently frozen during the colder months, with a limited period of freeze-thaw activity occurring in the spring and fall. South aspects, however, because of large diurnal temperature changes at the soil-air interface, can experience frost cycling in any 24-hour period in the year. Road cuts through quartz monzonite demonstrate the relative effectiveness of south aspect frost cycling in grus formation. While cut slopes of northern aspect may be virtually unchanged over 20 years, many adjacent cut slopes of southern aspect are nearly mantled in a talus of grus.

The increase in moisture with elevation would seem to provide increased opportunity for both chemical and physical weathering. This is offset somewhat by increased exposure to wind which has the effect of redistributing snowfall and creating soil moisture depletion through rapid evapotranspiration. Trees exhibit stunting and wind deformation as a result of moisture stress and exposure at nearly all high elevation sites in the study area.

Vegetation:

Climax vegetation communities based upon soils and climate have been recently mapped at 1:1,000,000 scale for Montana (Ross and Hunter, 1976). Although the technique is not always precise in terms of describing existing vegetation, it does provide information on diversity under conditions of assumed long-term stability in vegetative communities. The actual vegetation present may reflect other factors such as insects, disease, or fire, or human related factors such as grazing or logging. Also, to the degree that natural influences, such as insects and fire, nearly always interrupt the inferred succession and so prevent the climax from occurring, some long terms norms are better described by using a successional, fire dependent ecotype, rather than the climax concept. This is particularly true of lodgepole pine (Pinus contorta latifolia), probably the most abundant contemporary species in the study area.

Ross and Hunter (1976) identify several broad climax vegetation regimes within the present study area that are extensive enough to warrant characterization. These include two closely related forest vegetation associations and two grassland associations. Species, in the general order of dominance in climax communities, are listed in Appendix 1 for the four major associations in the study area.

Forest Vegetation Types. Most of the mountainous area of the Elkhorn Mountains and northern and southern Boulder Mountains is characterized by the most common forest type, the subalpine fir (Abies lasiocarpa) and Douglas fir (Pseudotsuga menziesii) climax forest. This type occurs on deeper soils with cryic temperature regimes and, in this case, igneous (both volcanic and plutonic) soil parent materials. Precipitation ranges from 500 to 1100 mm. per year. As mentioned earlier, slope aspects tend to influence the distribution of trees in this type (and others). This forest type may occur as low as 1650 to 1800 m. on north and east aspects, while it generally begins at 1950 to 2100 m. on south and west facing slopes. The total elevational range is from 1650 to 2700 m., with the subalpine fir (Abies lasiocarpa) climax occurring above the Douglas fir (Pseudotsuga menziesii) zone. Engelmann spruce

(*Picea engelmannii*) also occurs in the wetter zones of this forest type, primarily at the higher altitudes.

The second forest type, the subalpine fir (*Abies lasiocarpa*), Douglas fir (*Pseudotsuga menziesii*) and Ponderosa pine (*Pinus ponderosa*) climax forest resembles the previous type except for its moisture stress resistant Ponderosa pine component. The Ponderosa pine extends the lower elevational limit down to 900 m. on north and east aspects and to 1650 m. on drier south and west slopes. This type occurs primarily in parts of the northern Boulder Mountains in the Little Blackfoot River, Tenmile Creek, and Prickly Pear Creek drainages.

In both climax forest types, loss of the canopy by natural (fire, insects, disease) or manmade (clearcutting) causes has led to invasion by what are generally regarded as successional species. These include limber pine (*Pinus flexilis*) at lower elevations, lodgepole pine (*Pinus contorta latifolia*) throughout most of the elevational range, and whitebark pine (*Pinus albicaulis*) in the higher elevations. Pfister et al., (1977) postulate that, generally, there is insufficient evidence to conclude that species other than lodgepole pine (and its closely related species limber pine and whitebark pine) constitute a potential climax. Lodgepole pine has been documented to maintain itself by cyclic Mountain pine beetle (*Dendroctonus ponderosae Hopkins*) infestations causing a massive fuel buildup which is followed ~~closely~~ by forest fire. This type of high fuel load forest fire, while eliminating virtually every other tree species from competition, triggers the opening of serotinous lodgepole pine cones which reseed the burned area. This will produce a stand of nearly pure lodgepole pine which will again be ripe for infestation in 60 to 200 years (Cole, 1978; Roe and Amman, 1970). Thus Pfister, et al. (1977) conclude that habitat types, recognized as a climax or terminal successional phase, probably do exist for lodgepole and whitebark pine. Figure 4 shows a generalized zonation of forest trees in the general study area.

In terms of the interpreted effects on weathering processes, it probably makes little difference if a lodgepole pine habitat type has maintained itself over time or, conversely, the successional process resulted in climax vegetation types. Fire in the Northern Rocky Mountains is so common that it is rare for any individual sites to remain unburned over a 500 year period. Hence, vegetative renewal is extremely rapid on a geologic time scale. Further, both situations represent a coniferous overstory, with similar humic acids and chelating agents capable of aiding in the weathering processes.

One distinction should be made, however. The weathering rate may significantly differ under different coniferous canopies and this inferred difference may result in strikingly different landscapes over time. First, there is a tendency for climax communities of Douglas fir to provide better canopy shade and moisture retention, making intense fire less likely. Conversely, Ponderosa pine at low elevation dry sites is actually fire resistant with its thick bark, while lodgepole

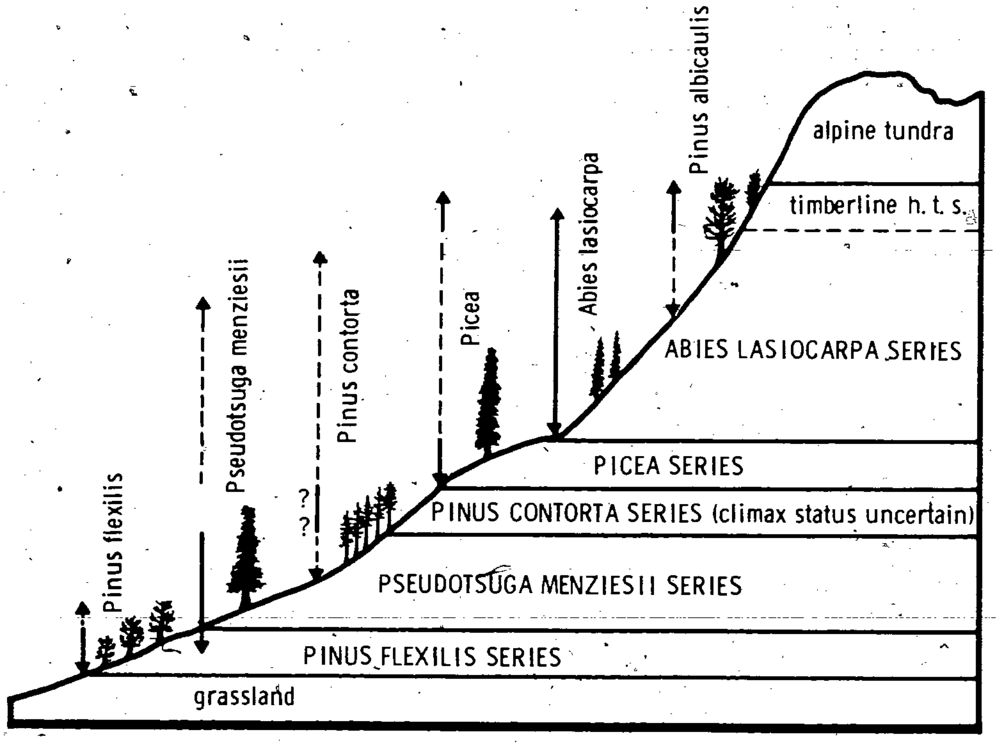


Figure 4. Generalized distribution of forest trees in southwestern and south-central Montana. Arrows show the relative elevational range of each species; solid portion the arrow indicates where a species is the potential climax and dashed portion shows where it is seral. (After Pfister et al., 1977).

pine, as mentioned earlier, is fire dependent for propagation. One consequence of frequent fire is the opportunity for increased stripping of soil and regolith during the two to five years (or more) of primary vegetative recovery. Hence, certain species indicative of frequent fires also tend to be associated with exhumed weathering residuals. This is generally tripping of soil and regolith during the two to five years (or more) of primary vegetative recovery. Hence, certain species indicative of frequent fires also tend to be associated with exhumed weathering residuals. This is generally true in the study area and it is also a common observation to note 'pine parkland-tor landscapes' in both scientific and promotional literature.

The prominence of fossil conifer needles and petrified wood in the early Eocene Lowland Creek Volcanics suggest that, regardless of inferred Tertiary climates from fossils in the basin sediments, coniferous forests probably occupied the mountainous terrain in the study area throughout the Tertiary period (Smedes, 1962; Balstar, 1971). Hence, a certain degree of vegetative type continuity is indicated throughout the time the batholith has been exposed.

Rangeland Vegetation Types. The silty range site complex (Ross and Hunter, 1976) occurs in the study area at lower elevations within the intermontane basins. Examples of this type occur in the Helena basin, North Boulder valley, Deerlodge valley, and the basin surrounding Butte. Primary grass components are Rough fescue (*Festuca scabrella*), Idaho fescue

(Festuca idahoensis) and Bluebunch wheatgrass (Agropyron spicatum) with Big sagebrush (Artemesia tridentata) as the dominant shrub. Soils are generally deep and precipitation varies from 250 to 500 mm. per year.

Ross and Hunter (1976) show the shallow to very shallow range site complex occurring generally at the basin margins and on foothills. This type is indicated in the lower North Boulder valley, Jefferson basin, and around the southern margins of the Boulder batholith. It is dominated by Bluebunch wheatgrass (Agropyron spicatum), with Big sagebrush (Artemesia tridentata) in shallow soil sites and additional Mountain mahogany (Cercocarpus ledifolius), Limber pine (Pinus flexilis), and Rocky Mountain juniper (Juniperus scopuloram) growing in cracks and crevices at very shallow soil sites. This second range complex is transitional between the grassland and forest types and may occur at a variety of elevations, depending on aspect, soil depth, and soil moisture capacity.

Soils:

Due to the focus of this study, discussion of soils will deal only with soils developed on the Boulder batholith and satellitic plutons. Soils on the batholith, where present, are typically entisols, or more specifically cryorthents (USDA, 1975). Soil horizons are generally not recognizable, although an ochric epidedon may be present at some sites. Cryic temperature regimes exist under present climatic conditions. Fossil solifluction lobes as well as lobate protalus mounds and ramparts near rhyolitic outcrops (Ruppel, 1962) indicate that a pergelic soil temperature regime existed for a time during the Pleistocene and may exist at present at some high elevation sites.

Soil parent material in almost all cases is quartz monzonite, though some soils sampled had developed on granodiorite and quartz latite. Partial chemical weathering of individual crystals in combination with cryic conditions has resulted in an *in situ* matrix of coarse, sandy, regolith material commonly referred to as 'grus'. Characteristics of the parent rock and weathering processes are also described in other sections of this thesis.

Monomineerallic grains of the grus tend to range from 2 to 10 mm. in the largest dimension, with 3 mm. being a modal grain size. Some individual quartz and feldspar phenocrysts up to 60 mm. long, exposed in the grus, have been observed by the author, and even longer crystals were seen on relatively unweathered outcrops. As an indicator of horizon changes, color was not appropriate as a differentiating criterion. Ferric oxide staining along crystal faces from weathering of ferromagnesium minerals (primarily biotite and hornblende) are seen in many places to pervade the entire depth of the weathered regolith. In some roadcuts, this was observed to exceed 20 m. Also common were linear stained conduits along joints or occasional hydrothermal veins. An example typical of the coarse-grained texture and lack of vertical zonation is shown in Photograph 1.

Photograph 1. Soils exposed in a roadcut near Clancy. Note the coarse texture of the 'grus' composed of monomineralic grains of decomposed quartz monzonite, and the apparent lack of distinctive soil horizons even at the top of the profile.

The lack of any significant horizon zonation is often taken as an indication of relative recency in pedogenic process. However, at dry sites with good drainage, the limiting factor to zonation is probably the rate at which a surface veneer of crystalline quartz and feldspar grains are chemically altered and reduced to secondary minerals. Buildup of fines appeared to occur only at poorly drained sites. This coupled with minimal illuviation at well-drained sites suggests that a high percentage of the fines in the ochral epidedon are removed by surface runoff. Lack of fines available for illuviation and the coarse texture of the surface and subsurface are not conducive to horizon zonation even over long periods of time; thus the relative age of the 'soil' is not readily obtained by standard pedological observations (USDA, 1975).

Eolian soils of volcanic ash are particularly prevalent in northwestern Montana and some 'ash cap' soils also occur on the Boulder batholith. Both the Glacier Peak and Mazama ashes are locally present (Sirucek, 1978; Nasmith et al., 1967), but are normally so thin where they occur that no special characterization is necessary. Also, localized thin histosols occur in bogs or hollows where organic material has accumulated.

At the Boomerang Gulch sample site (No. 7 in Figure 2) where some zonation was apparent, the soil proved to be a buried paleosol of early Oligocene age. A thin upper horizon of 5 to 10 cm. and a second horizon of 20 cm. were distinguishable. The color of the two horizons was similar, ranging from yellowish brown (10YR 7/6) to pale brown (10 YR 5/4). However, color may not be an important indicator of the original paleosol since burial by the highly porous rhyolitic overburden may have changed many soil characteristics, including color, in roughly 36 million years.

CHAPTER 3

GEOLOGY

Introduction:

Reference should be made to Figure 1, the geologic map, for areal distribution of rock types and identification of major groupings explained in more detail in this section. The Boulder batholith, exposed over 5700 square kilometers in the centre of the study area, intrudes rocks that range from Precambrian gneiss of the Wyoming cratonic shelf block (Rb/Sr radiometric dates of 2938 to 2110 million years; James and Hedge, 1980; Brookins, 1965) up to the late Cretaceous Elkhorn Mountains Volcanics (K/Ar date of 77.6 to 78.8 m.y.; Tilling et al., 1968). The prevolcanic (Elkhorn Mountains) rocks are collectively mapped in Figure 1 and represent a wide variety of rocks characterized in some detail in this section. Generally the volcanic and plutonic rocks associated with the batholith are mapped in more detail than either younger or older rocks in Figure 1. No attempt, however, was made to map at this scale those minor subdivisions of the volcanic and plutonic units which are recognized in the literature. For example, three units are broadly identified in the Elkhorn Mountains Volcanics (Klepper et al., 1957); seven in the Lowland Creek Volcanics (Smedes, 1962); and even the quartz monzonite, generally recognized as originating from a single homogenous melt, has been differentiated into numerous map units by using a color and texture classification (Becraft, et al., 1963). Also consolidated for mapping at this scale are the basin fill sediments, ranging from early Tertiary to Holocene in age.

Figure 5 illustrates Balstar's (1971) stratigraphic correlations for areas that are partially contained within the study area boundary. The vertical spacing assigned to the various periods and epochs does not relate proportionately to either time duration or formation thickness. Table 2 summarizes much of this information for the pre-Elkhorn Mountains Volcanics rocks. This section will concern the rock types and will include significant geological processes and events deemed by other investigators and by this author to be important in the formation of the present landscape.

Prevolcanic Rocks:

Archean. The oldest rocks exposed in the study area (and in all Montana) are Archean metamorphic rocks consisting primarily of flow-banded, coarse-grained gneiss with perthitic K-feldspar, quartz, pink garnet, and rare plagioclase grains (James and Hedge, 1980). These rocks were sufficiently high standing during late Cretaceous (Laramide) mountain building as to pose a barrier to eastward moving eugeosynclinal rocks, such that the extensive thrust faulting characteristic of the Overthrust Belt is not nearly as widespread in the southeastern portion of the study area. This cratonic block extends southeastward from the southern end of the batholith to the Beartooth Mountains north and east of Yellowstone National Park, though it is covered with younger volcanics in the Gallatin Range and Yellowstone Park.

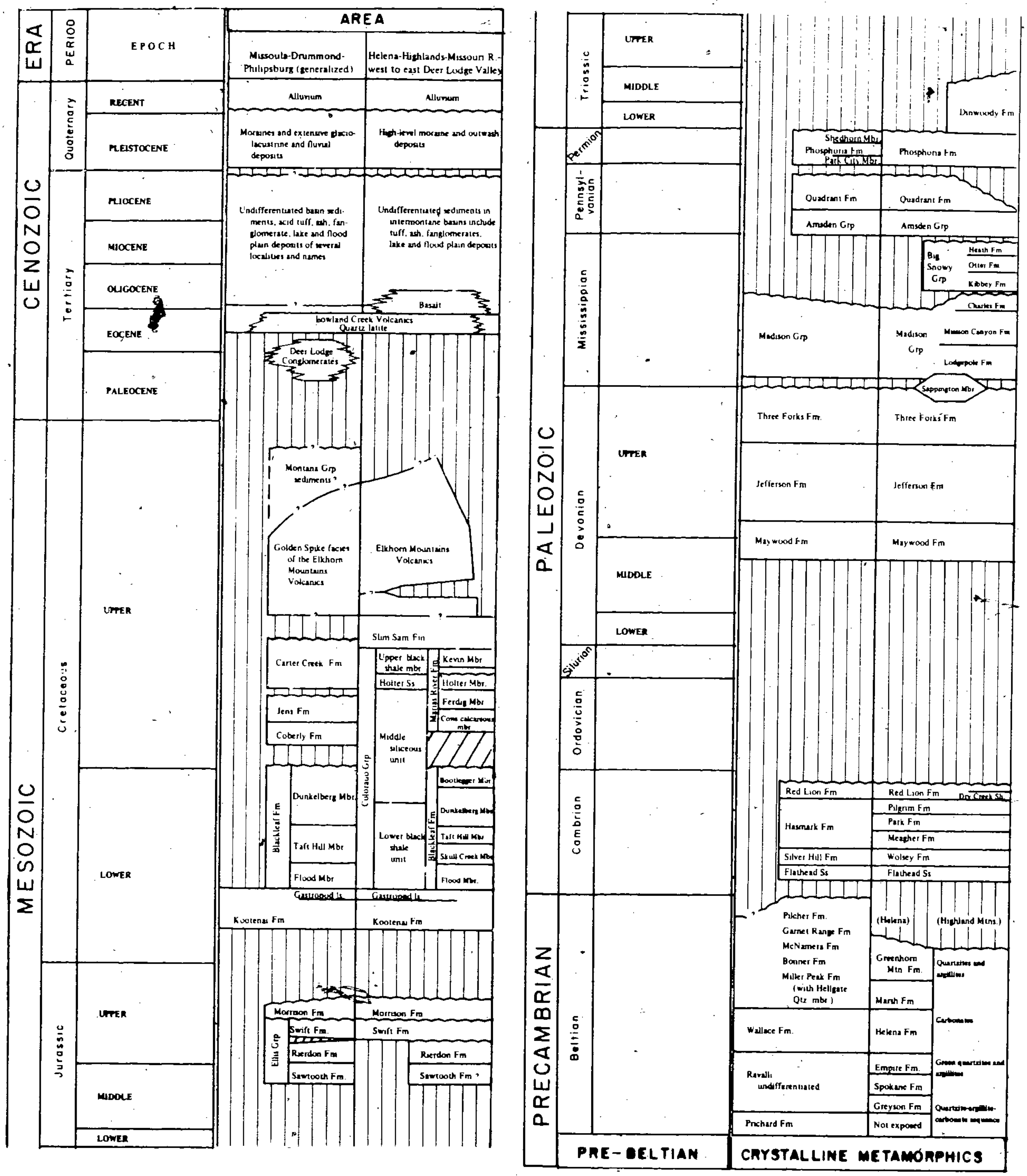


Figure 5. Stratigraphic correlations. Generalized column for portions of the area shown in the geologic map (Figure 1). (Adapted from Balstar, 1971).

TABLE 2
PRE-ELKHORN MOUNTAINS VOLCANICS STRATIGRAPHY

PERIOD/FORMATION	ROCK TYPE	THICKNESS (m)	RADIOMETRIC AGE	DISTRIBUTION	AUTHORS
BELTIAN					
Prichard Fm.	Banded blue/grey to blue/black shale with some sandstone.	2400 m.	1330 m.y.	Not exposed in study area but correlated with Lahood Fm. in SE portion	Ransome;1905 McMannis;1963 Obradovitch and Peterman;1968
Greyson Fm.	Grey siliceous and arenaceous shale; buff, green/grey bands.	900 m.	1325 m.y.	Exposed in Helena area and and southern Elkhorn Mtns.	Walcott;1899 Mueller;1971
Spokane Fm.	Red siliceous and arenaceous shale.	> 2745 m.	?	Spokane Hills between Helena and Missouri River.	Walcott;1899 Fenton and Fenton;1937
Empire Fm.	Green/grey massively bedded siliceous shale.	180 m.	?	Exposed in general vicinity of Helena.	Walcott;1899 Mudge;1966
Helena Fm.	Limestone	720 m.	?	Exposed in general vicinity of Helena.	Walcott;1899
Marsh Fm.	Argillaceous siltstone	900 m.	?	Belt Mtns. and Helena area.	Wolcott;1899 Knopf;1950
Greenhorn Mtn. Fm.	Quartzite	540 m.	1130 m.y.	Northwest of Helena near study area boundary.	Knopf;1950,1963 Obradovitch and Peterman;1968
			Unconformity		
CAMBRIAN					
Flathead Fm.	Reddish-brown persistant sandstone or quartzite.	40 m.	542 m.y.	Exposed above Beltian rocks within study area	Peale;1893 Chandhari and Brookins;1969
Wolsey Fm.	Fine grained sandstone and purple chloritic shale.	25-100 m.	?	Generally present above Flathead sandstone.	Weed;1899 Deiss;1936
Meagher Fm.	Cliff forming limestone and dolomitic limestone.	75-150 m.	?	Associated with other Paleozoic rocks.	Weed;1899 Deiss;1936 Lochman-Balk;1956
Park Fm.	Grey/green micaceous shale.	0-135 m.	?	Associated with other Paleozoic rocks.	Weed;1899 Deiss;1936 Lochman-Balk;1956
Pilgrim Fm.	Dense grey limestone with shaly lenses.	0-180 m.	?	Associated with other Paleozoic rocks.	Weed;1899 Deiss;1936 Lochman-Balk;1956

TABLE 2 (CONTINUED)

Red Lion Fm.	Siliceous limestone with calcareous shale	0-85 m.	?	Associated with other Paleozoic rocks.	Emmons and Calkins;1913
			Disconformity		
DEVONIAN					
Maywood Fm.	Thin bedded dolomitic limestone and calcareous shale.	0-90 m.	?	Associated with other Paleozoic rocks.	Emmons and Calkins;1913
Jefferson Fm.	Brown dolomite.	60-210 m.	?	Associated with other Paleozoic rocks.	Peale;1893
Three Forks Fm.	Shaly dolomite, shale and limestone.	0-80 m.	?	Associated with other Paleozoic rocks.	Peale;1893
			Disconformity		
Sappington Fm.	Carbonaceous shale with argillaceous siltstone.	5-30 m.	?	Occurs locally in SE portion of study area.	Berry;1943
			Disconformity		
MISSISSIPPIAN					
Madison Gp.	Clear to locally argillaceous limestone.	0-660 m.	?	Associated with other Paleozoic rocks.	Peale;1893 Collier and Cathcart;1922
			Unconformity		
Big Snowy Gp.	Sandstone, shale, and limestone.	120-300 m.	?	Present east of study area.	Weed;1899 Scott;1935
			Disconformity		
PENNSYLVANIAN					
Amsden Fm.	Red shale and white limestone.	25-130 m.	?	Associated with Paleozoic rocks in study area.	Darton;1904 Scott;1935
			Disconformity		
Quadrant Fm.	White and yellowish quartzite.	100 m.	?	Associated with Paleozoic rocks in study area.	Peale;1893 Scott;1935
			Disconformity		
PERMIAN					
Phosphoria Fm.	Grey/tan dolomite, chert and phosphatic shale	0-240 m.	?	Associated with Paleozoic rocks in study area.	Richards and Mansfield;1912
			Disconformity		
JURASSIC					
Ellis Gp.	Glauconitic, calcareous sandstone; fossiliferous oolitic limestone; and silty shale.	0-90 m.	?	Occurs above Paleozoic rocks; highly metamorphosed near batholthic contact.	Peale;1893 Cobban; 1953
Morrison Fm.	Basal sandstone;varicolored shale and redbeds; fluvial, paludal, or lacustrine origin.	0-90 m.+	?	Associated with Mesozoic rocks in study area.	Emmons et al.; 1896
			Unconformity		

TABLE 2 (CONTINUED)

CRETACEOUS					
Kootenai Fm.	Three or more sandstone beds with varicolored nonmarine siltstones	90-180 m.	?	Locally present with other Mesozoic rocks in area.	Dawson;1885
			Disconformity 87-95 m.y.		
Colorado Gp.	Grey to black marine shale with some siltstone and limestone beds.	450-660 m.		Erosional remnants near N. and S. ends of batholith.	Hayden;1876 Obradovich and Cobban;1975
Slim Sam Fm.	Greyish nearshore marine sandstone grading upward to tuff.	75-135 m.	?	Type area in southern Elkhorn Mountains.	Klepper, et al.; 1957

Late Precambrian. Rocks deposited in the eugeosynclinal trough that was present in the study area during late Precambrian are collectively referred to as the Belt series or supergroup. In general, surficially exposed Beltian sediments are younger to the north and west of the study area. The LaHood Formation (McMannis, 1963) is exposed in the study area near the confluence of the Boulder and Jefferson Rivers. It consists of a coarse arkose, greywacke conglomerate up to 3000 m. thick, and represents the time stratigraphic equivalent of the Prichard Formation described in Table 2. The LaHood Formation probably represents near-shore, shallow marine and deltaic deposits eroded from the block of crystalline metamorphics previously described. Younger Beltian rocks generally suggest deposition in successively deeper marine environments until thedeposition of the Marsh Formation. This suggests an early Beltian transgressive sea, with regression occurring after deposition of the Helena Formation. This regression continued until uplift resulted in elevation of these deposits above sea level, with erosional removal of some of the younger deposits occurring in the study area.

Cambrian. By middle Cambrian, a transgressive sea returned, successively depositing the Flathead (sandstone), Wolsey (shale), and Meagher (limestone) formations over the Beltian rocks in the study area (Lochman-Balk, 1972). A minor regression led to deposition of the Park (shale) Formation, followed by continued transgression and deposition of the carbonate Pilgrim and Red Lion formations. Post-Cambrian erosion has removed deposits that are inferred by Foster (1947) to have been conformably deposited over late Cambrian marine sediments up until late Ordovician. Although the Silurian sea represented the maximum transgression of any Paleozoic sea in what is presently the western United States, it appears Silurian deposits did not generally occur in Western Montana, but a thick sequence is preserved in the Williston Basin in northeastern Montana. In the study area, an erosional period is suggested from middle Ordovician until middle Devonian.

Devonian. A cordilleran geosyncline developed during middle Devonian, extending northeastward from near the vicinity of the Grand Canyon towards the present Salt Lake basin and then northward into Canada, extending directly through the study area in west central Montana. Deposition in this miogeosynclinal trench is characterized by shallow, marine, carbonate rocks. It appears from unconformities both below and above the Sappington Formation that, at least in southwestern Montana, the Devonian sea retreated completely, readvanced, retreated, and then readvanced again by early Mississippian time.

Mississippian. The last Devonian transgression continued into the early part of the Mississippian period, and was followed by a long period of tectonic quiescence. During this time extensive deposition of carbonates known collectively as the Madison group occurred over nearly the entire Northern Rocky Mountain area. By middle to late Mississippian, uplift occurred and karst topography developed in the Mission Canyon limestone, the uppermost unit of the Madison group (Craig, 1972). This unit is noted in Montana for paleo-karst where younger units have been removed to expose this former landscape. The Mission Canyon limestone is also the host for more than 90 percent of the nearly 100 major caves discovered in Montana (Campbell, 1978). The Lewis and Clark Caverns, near where the Jefferson River exits the study area, is a famous cave complex in the Madison group.

Rocks of the Big Snowy group thin erosionally or depositionally to the west, and are generally much different from early Mississippian carbonates. In Montana, the Big Snowy group is primarily terrigenous, with non-marine, brackish water clastics and evaporites. Big Snowy rocks were deposited along the eastern portion of the study area, although the outcrop is discontinuous due to erosion. To the west, the Madison group unconformity is invariably overlain by Pennsylvanian rocks, suggesting that the Big Snowy group was never deposited there.

<u>Pennsylvanian</u>. Late Mississippian or early Pennsylvanian uplift resulted in erosional removal of the Big Snowy group in much of central Montana, and left topography of considerable relief prior to the return of the sea in early Pennsylvanian times. The axis of the Cordilleran geosyncline in central Idaho roughly paralleled the northwest trend of the Montana-Idaho border. Uplift in north-central Montana found the study area on a transgressive sea shelf on which shales and carbonates of the Amsden Formation were deposited. Regression of the sea resulted in a disconformity between the Amsden and overlying Quadrant Formation. Readvance of the sea led to the deposition of a

nearly uniform, eastward-thinning wedge of the Quadrant quartz sandstone. Erosion removed any overlying Pennsylvanian rocks in south-central Montana, and variations of local thickness in the Quadrant Formation are inferred to be erosional rather than depositional (Maughan and Roberts, 1967).

Permian. Subaerial erosion apparently continued from upper Pennsylvanian to late Permian times in southwestern Montana; however, the disconformity between the Quadrant Formation and the Phosphoria Formation suggests some slight tectonic activity in the region during this time. Elsewhere in Colorado, Wyoming, and the southwestern Rocky Mountain region, deposition of arkosic red beds during upper Pennsylvanian and lower Permian resulted from the initial tectonic activity associated with the 'ancestral Rocky Mountains' developed prior to the Laramide orogeny. Transgression of the late Permian sea into south central Montana resulted in a unique depositional environment. The most specialized aspect was the presence of upwelling currents with low pH, which brought to shallow depths cold oceanic water rich in nitrogen, carbon dioxide, and phosphorus (McKelvey, et al., 1959, p. 23-29). The Phosphoria Formation, where present, is mined extensively for phosphates from just northwest of the study area to northern Utah. To the southeast of the study area in south central Montana, the Triassic Dinwoody Formation conformably overlies the Phosphoria Formation. However, in the study area, middle and upper Jurassic rocks lie above the erosional disconformity developed on the Phosphoria suggesting little orogenic activity during the relatively long erosional period.

Jurassic. Jurassic and younger Cretaceous rocks are present in the study area, but the best exposed locations are within the contact metamorphic aureole of the Boulder batholith (Knopf, 1963). Descriptions offered here and in Table 2 are for the original unmetamorphosed sediments. Ellis group sediments include, from oldest to youngest, the Sawtooth Formation (sandstone-siltstone), Rierdon Formation (oolitic limestone), and the Swift Formation (glauconitic flaggy sandstone), with disconformities between each formation. The Sawtooth and Rierdon formations have not been recognized in the study area, but the Swift Formation is recognizable in its metamorphosed state, suggesting the other formations may also be present. All these units were originally of relatively shallow marine origin.

The Morrison Formation and its origin are somewhat enigmatic, defying early attempts to explain the depositional environment and source of the formation, which is a widespread, relatively consistent unit clearly of continental origin. Stokes (1944, 1950) suggested that the Morrison evolved by deposition from intermittent streams and sheetwash in a relatively dry climate. Much of the fine-grained varicolored mudstone is of volcanic eolian origin, interlayered with non-volcanic wind-blown dust. Internal drainage in Montana is also suggested by the presence of extensive deposits of shaly coal and lacustrine limestones.

Cretaceous. The Cretaceous period brought the first major shift in relative land-sea relationships. Prior to this, the geosynclinal trough to the west running from Arizona through Idaho and Western Montana (though occasionally uplifted and erosionally exposed), represented the seaward portion of the continental margin with the eastern cratonic block supplying the detrital materials. Beginning sometime in early Cretaceous, the geosynclinal area to the west was uplifted and a trough developed from the present Gulf of Mexico to Alaska's North Slope. In Montana the inland Cretaceous sea received its sediments from the west and transgressive sequences were from the east.

The Kootenai Formation, the lowest Cretaceous strata present, is a non-marine, yet fairly uniform deposit like the Morrison Formation which it unconformably overlies in the study area. A disconformity above the Kootenai marks the initial transgressive sequence of the Cretaceous sea and the deposition of the Colorado group marine shales. The Cretaceous sea was relatively stable, and, in addition to the shale, numerous falls of volcanic ash gave rise to thick bentonite beds in the depositional sequence. In middle-to-late Cretaceous, the sea began receding and deposited the Slim Sam Formation (sandstone with ash beds) in the study area. This is the last formation in the stratigraphic sequence prior to uplift and eruption of the Elkhorn Mountains Volcanics. Once the Cretaceous sea retreated the study area was never again in a marine environment.

Mountain building beginning in late Cretaceous has proceeded intermittently until the present.

Boulder Batholith and Associated Rocks:

General Description. The Boulder batholith lies in Western Montana in what Fenneman (1931) has described as the Northern Rocky Mountains physiographic province. As generally interpreted through geologic events, the readily traceable physiographic history of Western Montana begins with the Laramide orogeny. During the main orogeny near the close of the Mesozoic, the supracrustal Beltian sedimentary rocks in a geosyncline to the west of the general study area were translated eastward and thrust upon and against the west edge of the craton to form what is called the Montana Disturbed Belt.

Because the Precambrian basement rocks south of the salient in the Wyoming Shelf block stood so high, the strata were crumpled against it and not thrust as far eastward as were those above the Alberta Shelf which stood at intermediate depth. This, in addition to the detachment of a Belt sedimentary prism, resulted in an eastward surge of strata causing an eastward bulge of the Disturbed Belt in the vicinity east of the Boulder batholith. In association with this bulge, tear zones occurred along the northern and southern borders of the Belt sedimentary wedge (Schmidt, et al., 1977). Geologic events subsequently responsible for the present physiography of Western Montana, as interpreted by the early works of Alden (1953), Atwood (1916), and Pardee (1950), are summarized in Table 3A.

TABLE 3A
INTERPRETATIONS OF LATE CRETACEOUS TO RECENT GEOLOGIC HISTORY

Adapted from Ruppel (1963)	Western Montana				
	Alden (1953)		Atwood (1916)		Pardee (1950)
Pleistocene and Recent	See Text.	Recurrent uplift.	Early glaciation.		Present cycle of renewed uplift and valley cutting.
Pliocene	Erosion of deep canyons. Erosion, cutting of piedmont benches and upland erosion surface.		Drainage changes and dissection of valley fills.		Recurrent uplift and local block faulting and warping; old valley cycle coincides with a halt in the uplift. General reelevation of region; accelerated local crustal movements.
Miocene	Deposition of Bozeman 'lake-beds'. Western Montana a region of considerable relief with hills and mountains in much the same position as now although not as high above adjacent valley floors.		Renewal of mountain growth; tilting of Bozeman beds. Intermediate erosion surface in mountain valleys.	Deposition of Bozeman beds.	Drainage becomes sluggish or ponded because of slow crustal movements that outlined present basins and ranges. Erosion of highlands and development of late Tertiary peneplane. Deposition of lake beds in basins.
Oligocene			Closing of drainage by Snake River lavas. Development of intermontane troughs and a mature topography in mountains.		
Paleocene and Eocene	Erosion; uplands reduced to areas of moderate relief; possibly local Eocene glaciation.		Uplift and deformation of peneplane. Development of Summit peneplane.		Crustal stability and long period of erosion to give surface of moderate to slight relief.
Late Cretaceous			Mountain growth.		Elevation.

The sequence, as generally interpreted, is one of Laramide mountain building followed by a relatively long period of crustal stability such that by late Eocene most vestiges of earlier mountains were eroded to a surface of moderate to slight relief. During this erosion period the major delineations between the mountain blocks and the intermontane basins became established through normal faulting along the basin perimeters. However, many of these mountain block/basin boundaries were initially poorly defined because detrital filling of the basins actually buried the margins of the mountain blocks during periods of stability. Some remnants of these early Tertiary sediments that lap the mountain blocks have been elevated by subsequent orogenic events and are now exposed topographically higher than younger sediments now filling the adjacent basins.

Alden (1953), Atwood (1916) and Pardee (1950) infer that late Eocene, Oligocene, and Miocene mountain building and erosion occurred contemporaneously with periodic volcanic activity and deposition of tuffaceous sediments (widely misnamed as 'lake beds') in the basins. The present landscape was thought to be foreshadowed in the topography and drainage established by Pliocene time, though present relief amplitude is inferred to be greater than at any time since Miocene.

During the Pleistocene, the Cordilleran ice sheet influenced topography in most of northwestern Montana, with local ice sheets developing in the northern Boulder Mountains (Ruppel, 1962) and farther south on the Yellowstone plateau (Montagne, 1972). With some significant exceptions that will be discussed later, mountain glaciers developed in most mountainous areas of the Northern Rocky province.

Focusing more specifically on events within the study area, Table 3B summarizes the interpretations of Freeman, et al., (1958), Klepper, et al., (1957), and Ruppel, (1963). These interpretations, supplemented by views of this author, provide the basis for the following account of the geologic history of the study area.

Effects of the Laramide Orogeny. Overlap of Laramide thrust faulting and emplacement of the Boulder batholith are described in detail by Robinson, et al., (1968), and their relations are indicated by the facts that some thrusts predate, some are contemporaneous, and others are post-batholith in age. Some of the thrusts were clearly deformed by emplacement of the batholith and others are cut by the oldest pluton~~s~~ of the batholith. Some thrusts cut and transported plutonic rocks from satellitic plutons of the batholith. These complex relations are taken to indicate a continuum of folds, thrusts, and generation and emplacement of the magma.

Magma generated during the early stages of this orogeny gave rise to volcanism in a vast area surrounding the Boulder batholith climaxed by the outpouring of vast quantities of ash flows which are now thick sheets of densely-welded tuff of the Elkhorn Mountains Volcanics. Following this eruptive episode, the volcanic pile (according to Smedes, 1967) foundered into hypabyssal magma chambers, leaving remnants of at least two calderas. Much of the collapse structure associated with the

TABLE 3B
INTERPRETATIONS OF LATE CRETACEOUS TO RECENT GEOLOGIC HISTORY

	Townsend Valley, Montana (Freeman. Ruppel and Klepper, 1958)		Elkhorn Mountains, Montana (Klepper, Weeks and Ruppel, 1957)			Basin Quadrangle, Montana (Ruppel, 1963)	
Pleistocene and Recent	Deposition of gravels.	Recurrent block faulting that resulted in uplift of mountains adjacent to the Townsend valley.	See text.	Recurrent block faulting.	Recurrent uplift.	See text.	Recurrent uplift.
Pliocene	Slight tilting or warping. Period of relative stability; pediment formed. Slight tilting or warping.					Erosion; cutting of strath terraces; superposition of Boulder River.	
Miocene	Deposition of Miocene-Pliocene sedimentary tuff. Erosion.		Deposition of late Miocene-early Pliocene tuffaceous sediments and gravel. Erosion.			Volcanism, eruption of rhyolite. Uplift, erosion of sharp valleys. Erosion to a surface of low relief.	
Oligocene	Deposition of Oligocene sedimentary tuff.		Deposition of Oligocene tuffaceous sediments and gravel.			Volcanism, eruption of quartz latite.	
Paleocene and Eocene	Long period of erosion to form a mature mountainous area with broad intermontane basins, probably in part outlined by faults.		Erosion to produce a mature landscape.	?		Erosion to surface of moderate relief; erosion of ancestral stream channels.	?
Late Cretaceous	Intrusion of monzonite stocks. Strong folding culminating in thrust faulting in Hossfeldt Hills. Vulcanism and intrusion of diorite porphyry. Local warping and uplift.	Uplift.	Emplacement of Boulder batholith and associated bodies. Strong folding and faulting. Volcanism and associated intrusion of dioritic-andesitic rocks; local folding and broad arching.			Emplacement of Boulder batholith. Volcanism, accompanied and followed by folding and faulting.	

formation of the calderas was subsequently invaded and obliterated by later intrusion of parental batholithic magma.

Deformation associated with the orogeny began as local episodes shortly before the Elkhorn Mountains Volcanics were extruded in late Cretaceous time and continued episodically, with climax before or at the close of volcanism. Although the volcanics are deformed less intensely than the underlying sedimentary strata, they were involved in regional folding of north-northeast trend, and were displaced along major thrust faults.

The regional extent of these volcanic deposits was generally more widespread than the exposed remnants shown in Figure 1 would suggest. The Livingston Formation (late Cretaceous to Eocene) is comprised of erosional detritus from the Elkhorn Mountains Volcanics pile and extends over 160 kilometers to the southeast of the volcanic type area.

Emplacement of the Boulder Batholith. The presence of isolated outcrops of synorogenic conglomerates and the regionally unconformable contact between the Elkhorn Mountains Volcanics and pre-volcanic rocks suggest regional uplift prior to extrusion and deposition of the volcanics (Schmidt, 1973; Schmidt, et al., 1977). Uplift may have continued during the accumulation of the volcanics as higher units have incorporated erosional debris derived from lower units (Eckerty, 1968; Robinson, et al., 1968; and Smedes, 1967). It is not certain whether this uplift is associated with the incipient stages of the Boulder batholith intrusion. In any case, the conglomerates, which are clearly prevolcanic, are certainly too old to contain eroded debris from the batholith and none of the overlying volcanics contain clastic detritus from what could be considered plutonic sources. This evidence and the inferred assimilation of caldera structures in the volcanics suggest a time separation between the volcanic episode and subsequent intrusion of the Boulder batholith. A time discrepancy in radiometric dates for the two rock types of several million years is also indicated [for example, dates for the Elkhorn Mountains Volcanics average 78 m.y.b.p. ± 2 m.y.; dates for the rocks of the Boulder batholith indicate a range from 71 to 77 m.y.b.p. with an uncertainty of ± 2.5 m.y.; (Daniel and Berg, 1981; Obradovitch and Cobban, 1975; Protska, 1966)].

Notwithstanding a plethora of accumulated geologic and geophysical evidence, at least three conflicting models for emplacement of the Boulder batholith have been proposed, each of which purport to use this evidence to explain the mode of emplacement. At least one of these models theorizes that the batholith emplacement had a role in the regional deformation and two theories place the magma as more or less contemporaneous with the Elkhorn Mountains Volcanics.

Because the Boulder batholith intrudes and is in contact with the Elkhorn Mountains Volcanics of approximately the same age, Hamilton and Myers conclude that:

> "...the batholith magma flowed, in effect a gigantic mantled lava flow, across a broad basin..."[The mantle was]"...a crust of volcanic rocks perhaps 2 km thick [that] floated upon granitic magma over a region of about 7000 square kilometers..."(Hamilton and Myers, 1967, p. C7-C9).

This view was elaborated on later, with its apparent implications on structure:

> "The Boulder batholith formed as a thin and shallow mass (about 5 km thick) that spread over a floor of premagmatic rocks and that was covered for the most part by its own volcanic ejecta..." [and]"...was emplaced during a small part of the period of regional eastward thrust faulting or miogeoclinal and foreland-basin strata over the cratonic crystalline basement." [However,]"...the spreading batholith produced westward reversed overturning in structures to the west, and to the east and south it caused outward spreading in an arcuate bulge broadly concentric to itself." (Hamilton and Myers, 1974, p.365).

A second model proposes influence from the roughly contemporaneous Idaho batholith magma and from crustal deformations related to this batholithic emplacement, resulting in the eastward slippage of the Sapphire mountain block from the doming magma chamber. Loosely summarized, this model proposes:

> "The Boulder batholith is a tabular body somewhere between 5 km and 15 km or more thick"...[which formed from magma injected eastward and southeastward from beneath the Sapphire tectonic block.] "The magma reached the surface in the depression east of the Sapphire block, with the Boulder batholith rising as a giant pool of molten rock beneath its own extrusive blanket." (Hyndman, et al., 1975, p. 401).

The localization of emplacement may have been fault controlled, but the movements of the Sapphire block and the intrusion of the batholith are interpreted to be more restricted in time than the regional, eastward thrust faulting. As generally inferred, faulting west of the batholith is related to the detachment of the Sapphire block and faulting to the east is related to general spreading movements of the overthrust belt; neither was caused or significantly modified by intrusion of the Boulder batholith.

Klepper, et al., (1971a) used gravity studies (Burfeind, 1967; Bonini, 1969) to show that the maximum thickness is more in the range of nine to 15 kilometers and that the Boulder batholith exhibits a classical 'root'. Further, the extent of the Elkhorn Mountains Volcanics field covers nearly three times the area of the batholith and thus cannot be logically considered a floating crustal cap over a tabular molten body as hypothesized by Hamilton and Myer (1967). Klepper, et al., (1971a) propose the batholith was intruded transgressively from below and reached to within a few kilometers of the surface, having filled a complex of former volcanic magma chambers. Also, the two-magma compositional framework of the batholith may complicate interpretations for the other two hypotheses (Tilling, 1973). Intrusion may have been intitially controlled by basement faults, which, in the case of the Boulder batholith, would exist below the thick prism of Beltian and younger rocks of the salient. Thus, while minor structural deformation may have occurred at the margins of the batholith, the emplacement of the batholith is construed to be more a result than a cause of the regional structure and did not play a significant role in the tectonic development of the salient.

The western edge of the Boulder batholith, where a substantial portion of the original cover remains intact over the batholith and where the batholith seems to thin, is where much of the evidence purporting the batholith to be tabular has been gathered. This is also the area where Hyndman, et al., (1975) proposed the lateral extrusion of magma from the northwest. However, this same evidence earlier led Lawson (1914) to question whether the batholith might not be a laccolith. Ruppel (1963) also postulates that a floor may exist under the batholithic rocks in the Basin quadrangle. In addition to evidence based upon Grout and Balk's (1934) interpretation of the orientation and physical characteristics of joints, which suggests lateral emplacement of the magma in the northwestern portion of the batholith, Ruppel states:

> "...the relations of aplite and alaskite to Butte quartz monzonite and the relations of lineaments to batholithic and roof rocks....suggest the presence of a floor beneath the batholithic rocks in the [Basin] map area. The relative paucity of aplite and alaskite in the map area as compared to areas farther east suggests the absence of a deep-seated crystallizing reservoir that could provide abundant late residues rich in silica and potassium, and may indicate that the Butte quartz monzonite and granodiorite may be floored by older rocks in the [Basin] area, but not farther east. Further, the northeast and northwest trends of the prominent lineaments in the roof rocks and batholithic rocks in the map area are strikingly similar to major structural trends in southwestern Montana that are thought to reflect basement structures periodically active from Precambrian time. The similarity and continuity of the lineaments in the Basin quadrangle and elsewhere in southwestern Montana strongly suggest a common origin, and therefore suggest that the part of the batholith that underlies the quadrangle may be floored by older rocks in which structures have been reactivated since intrusion of the batholithic rocks. In adjacent areas, where there is no evidence that suggests a possible floor, the lineaments that cut batholithic rocks typically trend about north or east instead of northeast and northwest. However, it is possible that renewed tectonic forces have formed structures in batholithic rocks in the Basin quadrangle that are similar to earlier structures formed in older rocks by recurrent movements in the basement." (Ruppel, 1963, p. 38-39)

The eastern part of the Boulder batholith was emplaced along a pre-existing fault zone of north to northeast trend. Parts of this fault zone were obliterated by stoping during emplacement; however, the nearly straight contact and steep wall relations between the batholith and older rocks along the eastern border attest to the fault-related influences. Some late plutons of the batholith and innumerable small bodies of aplite-alaskite-pegmatite were emplaced along a north-northeast zone to the east of the axis of the batholith, and in this same area occur abundant post-batholith veins, and dikes and plugs of Eocene quartz latite and Oligocene rhyolite. Taken all together, these features indicate that faults of north-northeast trend have played a prominent role before, during, and after emplacement of the batholith.

During and shortly after the emplacement of the Boulder batholith, simultaneous movement occurred along faults in the Basin area, Elkhorn Mountains, and farther east in the Townsend valley, generally elevating the present mountain blocks (Ruppel, 1963; Klepper, et al., 1957; and Freeman, et al., 1958). These early mountains were eroded and certain areas of the batholith were known to be exposed by early Eocene.

Elkhorn Mountains Volcanics. As indicated earlier, the Elkhorn Mountains Volcanics, although closely associated in time with the emplacement of the Boulder batholith, are somewhat more mafic than the batholithic rocks. The volcanics comprise three members in the type area: a lower member consisting of rhyodacitic and trachyandesitic pyroclastic rocks; a middle member characterized by rhyolitic welded tuffs alternating with andesitic and rhyodacitic tuff and tuff breccia; and an upper member composed mainly of airlaid tuff and waterlaid tuff and conglomerate that are largely debris eroded from the lower members (Klepper, et al., 1971b).

Related intrusives of the Elkhorn Mountains Volcanics are similar in composition to the volcanics and seem to be products of the same magma. The intrusives are generally large, irregular, partly concordant bodies of syenodiorite porphyry or granodiorite porphyry. In areas of poor exposures or structural complexity it is often difficult to distinguish between the intrusive and extrusive phases. Because of similarities in composition and in appearance, the two phases are mapped together in Figure 1.

The rocks are mainly grey and greenish-grey with primary components of plagioclase, augite, hornblende, magnetite, and, rare hypersthene and olivine. The lower member is generally present outside the margins of the Boulder batholith; however, there is a tendency for the limit of emplacement of the batholithic rocks to follow a single stratigraphic horizon in the welded tuff of the middle member (Ruppel, 1963, p. 6). This would tend to indicate that stoping was effective in the lower member, but the massive welded tuffs of the middle member were an effective deterrent to further upward progress by stoping. The xenoliths frequently found in the quartz monzonite are likely to be from the lower member of the Elkhorn Mountains Volcanics.

~~Batholithic Emplacement Series~~: The composite nature of the Boulder batholith has been described by a number of investigators [Knopf (1957), Klepper (1962), Smedes, et al., (1962), Becraft, et al., (1963), Ruppel (1963), Tilling (1964), and Smedes (1966))]. Rocks of the batholith range in composition from syenogabbro to alaskite, but approximately 90 percent of the exposed area is quartz monzonite or granodiorite. More than two thirds of the exposed rock from the batholith is mapped in Figure 1 as the Butte Quartz Monzonite.

Numerous petrographic facies have been mapped within the Butte Quartz Monzonite (Becraft, et al., 1963; Ruppel, 1963). These facies are based primarily upon slight textural and/or compositional changes that generally occur over subtle gradations rather than with sharp contacts within the typically coarse-grained quartz monzonite. In fact, it has been stated:

> "Despite slight but mappable textural and compositional differences, all the rocks that constitute the Butte Quartz Monzonite, except maybe three fine-grained types, are considered part of a single large pluton."(Becraft, et al., 1963, p. 8)

It appears that no large intrusive masses of distinctly younger or older age are included within the Butte Quartz Monzonite.

Field relations indicate small masses of syenogabbro, syenodiorite, and melamonzonite (mafic rocks in Figure 1), are consistently the oldest batholithic rocks. K-Ar radiometric ages confirm this (Tilling, et al., 1968). Next in the intrusive sequence are the plutons of relatively dark-colored granodiorite of the Radar Creek pluton (Tilling, 1964) and Burton Park pluton (Smedes, 1967) near the southern end of the Boulder batholith, and the Unionville Granodiorite (Knopf, 1963) near the northern end. These rocks are cut by the Butte Quartz Monzonite, which tends to be slightly more felsic. The Butte

Quartz Monzonite, its silicic facies, and the abundant alaskite bodies form a continuous, genetically related series, as shown by close petrographic similarity and by both crosscutting and gradational contacts between different rock types. The silicic facies of the Butte Quartz Monzonite (e.g. Pulpit Rock and Homestake plutons) generally grade into, but locally cut the Butte Quartz Monzonite. At any locality, the more felsic of the two rock types is normally considered to be the younger, as would be expected by the reaction series crystallization relationships established by Bowen (1928).

Last in the intrusive sequence are the leucocratic granodiorites and quartz monzonites of the Donald, Hell Canyon, Moose Creek, and Climax Gulch plutons in the southern part of the Boulder batholith and plutons of biotite adamellite and biotite granite (Knopf, 1963) in the northern part. Rocks of the Donald and Climax Gulch plutons cut the Butte Quartz Monzonite, but the Moose Creek and Hell Canyon plutons are not in direct contact with the other batholithic rocks at the surface. Their position in the intrusive sequence is inferred from lithologic similarity and proximity to the Donald pluton.

The Boulder batholith is fringed by many small satellite bodies, ranging in composition from syenogabbro to silicic quartz monzonite. Most of these masses are homogenous, but many are composite (Tilling, 1964). Because these masses are intruded into country rock of many different ages the plutons cannot be fitted into the intrusive sequence on strictly geological evidence. A recent published compendium of radiometric dates of rocks in Montana by Daniel and Berg (1981) offers dates for some of these satellite plutons (this publication post dates the compilation of Figure 1). Radiometric ages show substantial variation between emplacement ages of the satellite plutons. For instance, hornblende from the Scratch Gravel Hills (7 km. northwest of Helena) is dated at 86.1 ± 4.0 million years before present (m.y.b.p.), and a date for muscovite from an unnamed pluton 30 km. southwest of Butte is 59.1 ± 2.1 m.y.b.p.; or an approximately 27 m.y. range in emplacement dates. Nevertheless, limited isotopic age data, field relations, and petrographic similarities support the notion that most satellitic bodies were congruent in time span with the Boulder batholith (approximately 71-77 m.y.b.p.).

Mineralogy: Numerous chemical analyses show that most of the rocks making up the Butte Quartz Monzonite fall within a narrow range in composition (Ruppel, 1963; Klepper, et al., 1957; Becraft, et al., 1963). This narrow range is not so apparent in normative reconstitution and modal analyses of thin sections. Norms attempt to recalculate the original mineral composition of the rock based on idealized back reaction equations using the available elemental constituents from the chemical analysis. This will only coincidentally yield the rock's original mineral constituents, because the idealized reactions do not account for elemental substitutions and alternative reactions that occur. Modal analysis of mineral consitituents by thin section is usually biased by the placement of the slice and the portion of the section analyzed.

Estimation error increases in coarse-grained rocks where important minor and major minerals may be locally absent in the examined section. An extreme case could occur where one mineral such as quartz or plagioclase could be 100 percent represented in an examination of a pegmatite vein or rock with large phenocrysts. In any case, there is generally much less variability in available chemical analyses than in the other conventional methods of reporting results.

Chemical analyses of 'typical' samples of previously discussed batholithic and associated rocks are shown in Table 4. Table 5 shows calculated normal mineralic composition, and Figure 6 shows modal analyses of a wider variety of samples, based on thin section estimates with feldspar and quartz recalculated to 100 percent. Attempts at mapping facies of the quartz monzonite have been successful using variations in grain size, color, and texture in the Jefferson City quadrangle, but again, chemical variation is not sufficient in most cases to discern compositional differences between these color/texture units (Becraft, et al., 1963, p. 15). However, some important characteristics were found using this technique. Most important, was that textural differences are common in batholithic rocks near the margins, but relatively uniform coarse-to-medium textured rocks predominate deeper within the Boulder batholith. This suggests;

> "...that all or most of the rock types making up the Butte quartz monzonite are parts of a single pluton, and that the textural variations resulted from considerable mixing, during emplacement and crystallization, between fractions of the magma that had reached different degrees of crystallinity. (Becraft, et al., 1963, p. 15)"

TABLE 4

CHEMICAL ANALYSES OF SELECTED BATHOLITHIC AND RELATED ROCKS

Chemical Constituents	Samples					
	A	B	C	D	E	F
SiO_2	56.2	58.1	55.2	60.4	70.9	77.8
TiO_2	.66	.57	1.1	.69	.08	.06
Al_2O_3	16.8	17.4	16.4	17.8	14.4	12.9
Fe_2O_3	4.0	3.9	4.1	3.7	1.5	.35
FeO	3.1	2.1	5.0	3.0	.68	.17
MnO	.18	.15	.18	.14	.08	.01
MgO	2.6	2.4	4.1	2.5	.72	.14
CaO	5.4	6.9	7.3	6.3	2.3	.68
Na_2O	2.6	3.4	3.0	3.0	3.4	3.1
K_2O	3.0	2.9	2.3	1.8	4.4	4.8
P_2O_5	.38	.34	3.1	.22	.08	.01
Ignition Loss	5.1	1.8	.66	1.0	.79	.20
Total	100.0	101.0	100.0	101.0	99.5	100.2

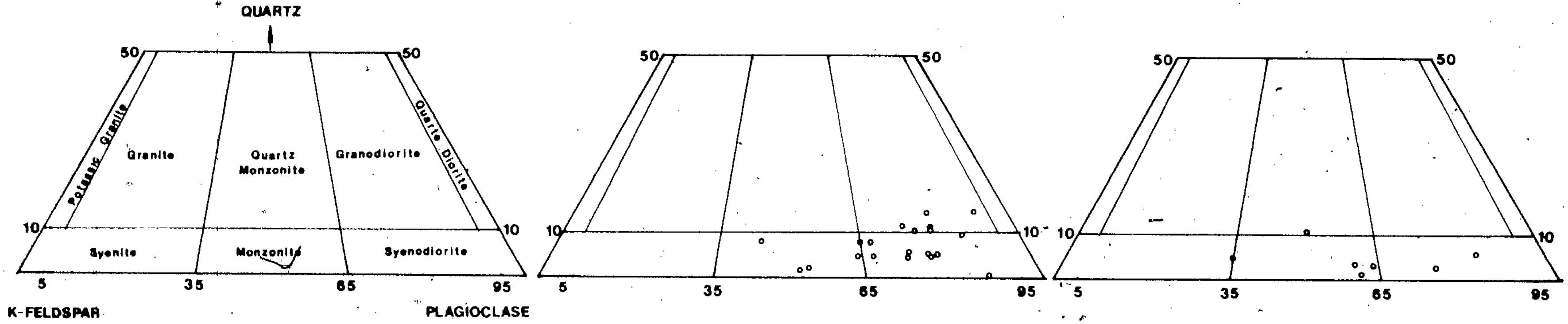
A = Sample 2; Klepper et al. 1971b; Extrusive Elkhorn Mtns Vol.
B = Sample 12; Klepper et al. 1971b; Intrusive Elkhorn Mtns Vol.
C = Sample 15; Klepper et al. 1971b; Mafic intrusive.
D = Sample 49KCL; Klepper et al. 1957; Granodiorite.
E = Sample 3BC7; Becraft et al. 1963; Butte Quartz Monzonite.
F = Sample 3BC5; Becraft et al. 1963; Alaskite.

TABLE 5

CALCULATED NORMS OF SELECTED BATHOLITHIC AND RELATED ROCKS

Mineral	A	B	C	D	E	F
Quartz	15.2	11.6	8.2	12.0	28.6	40.0
Orthoclase	18.9	17.1	13.6	12.0	26.7	28.4
Albite	23.1	28.8	25.4	32.2	29.3	26.2
Anorthite	25.6	23.7	24.5	29.8	10.8	3.6
Wollastonite	-	3.5	4.0	+	-	-
Enstatite	6.8	6.0	10.2	+	-	-
Ferrosilite	1.9	-	4.3	+	-	-
Magnetite	6.8	5.6	5.9	3.0	1.6	.5
Illmenite	1.4	1.1	2.1	+	.5	-
Apatite	1.0	.8	.1	+	-	-
Corundum	.4	-	-	-	-	.9
Hypersthene	-	-	-	+	1.8	.3

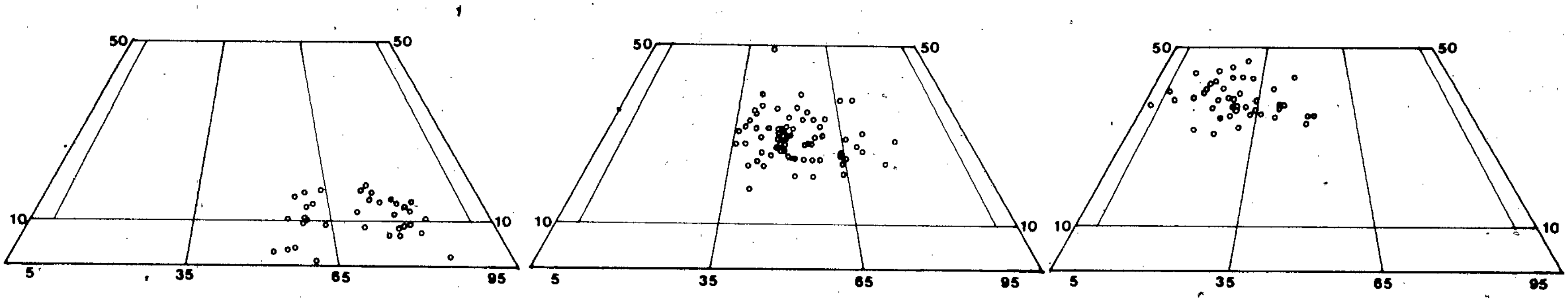
A = Sample 2; Klepper et al. 1971b; Extrusive Elkhorn Mtns Vol.
B = Sample 12; Klepper et al. 1971b; Intrusive Elkhorn Mtns Vol.
C = Sample 15; Klepper et al. 1971b; Mafic intrusive.
D = Sample 49KCL; Klepper et al. 1957; Granodiorite.
E = Sample 3BC7; Becraft et al. 1963; Butte Quartz Monzonite.
F = Sample 3BC5; Becraft et al. 1963; Alaskite.
+ = present; - = absent.



Nomenclature of coarser grained intrusive rocks.
Adapted from A. Johannsen (1939).

Intrusive rocks related to Elkhorn Mountains
Volcanics (from Klepper, et al., 1971)

Mafic intrusive rocks.
(from Klepper, et al.,1971; Protska, 1966)



Granodiorite and related rocks.
(from Klepper et al., 1971)

Butte Quartz Monzonite.
(from Becraft, et al., 1963)

Alaskite and related felsic rocks.
(from Becraft, et al., 1963)

FIGURE 6
MODAL ANALYSES OF REPRESENTATIVE INTRUSIVE ROCKS

This view is contested somewhat by Tilling (1973), who shows the Boulder batholith to constitute two contemporaneous but chemically distinct magmatic series. However, the fact that Becraft, et al. (1963) formed these conclusions from observations completely from within the northern and central portions of the batholith lends to their credibility, since Tilling's "sodic series" occurs only at the southern end of the exposed batholith. Besides mixing, metasomatic influences from exchange reactions with country rock (Cunningham, 1971), marginal chilling and differential stress (Balk, 1937), and marginal variation in pressure exerted by volatiles must also be invoked as possibilities to explain any batholithic margin petrographic variations.

Alaskitic rocks consist primarily of quartz and K-feldspar. The term alaskite was originally proposed by Spurr (1900) for plutonic rocks with a predominance of these two minerals with small (less than 5 percent) quantities of ferromagnesium minerals and where the plagioclase is albite (Johannsen, 1931). Thus, as originally defined, alaskite had a strict compositional connotation. Roberts (1953) was the first to apply the term to the late phase deuteric rocks within the quartz monzonite. In this study, the term alaskite includes alaskite porphyry, aplite, and pegmatite.

Alaskite consists of quartz (about 30 percent); K-feldspar (about 30 to 50 percent); plagioclase, locally altered to dickite or kaolinite; biotite (usually less than 1 percent); and trace amounts of zircon, apatite, hematite, magnetite, and pyrite. Tourmaline is locally abundant and secondary minerals are dickite or kaolinite, rutile, illite, chlorite, limonite, hematite, leucozene, and epidote (Becraft, et al., 1963). The alaskite bodies range in size from small veins to large irregular bodies with .6 km^2 of surface exposure or more. Most dike or sill-like outcrops appear to have intruded along poorly developed joints. Commonly a dike will follow one joint for a short distance and then follow a differently oriented joint. This lack of preferred orientation and the fact that chilled margins on the dike-like bodies are uncommon (Roberts, 1953), suggest that the jointing system was not yet well established and the quartz monzonite, though solidified, was at about the same temperature as the intruding alaskite. This supports the conclusion by Tilling, et al. (1968) that the alaskite, rather than a vestige of a later felsic intrusive sequence, is a successive fractional distillate of the quartz monzonite parental magma.

In the modal analyses presented in Figure 6, granodiorite samples have, as expected, less quartz and K-feldspar but more plagioclase than the quartz monzonite. Klepper et al.(1957, p.50) characterize the granodiorite intrusive bodies in the southern Elkhorn Mountains as having 55 to 65 percent plagioclase, 10 to 20 percent K-feldspar, 15 to 20 percent quartz, and 10 to 15 percent hornblende and biotite in approximately equal amounts. Small amounts of magnetite, apatite, and sphene are common. In the granodiorite, as well as the quartz monzonite, plagioclase and the mafic minerals commonly have one or more crystal faces; K-feldspar seldom exhibits crystal faces; and quartz is almost invariably anhedral and moulded around grains of other minerals. Every specimen examined showed some effects of weathering. This is partly due to deuteric processes (such as plagioclase zoning and kaolin clouding in K-feldspar) and partly due to supergene weathering (biotite expansion and alteration to chlorite; ferric oxide staining from hornblende).

A slightly mafic variety of granodiorite, with up to 30 percent combined biotite, hornblende, augite and iron oxides, occurs in some locations at the margins of the Boulder batholith. It is thought that this variety is a reaction product between andesitic volcanic rocks (Elkhorn Mountains Volcanics) and the quartz monzonite (Klepper, et al., 1957, p. 49). Erosion has apparently stripped this septum of rock from most areas of the batholith so that exposures are not common away from its margins.

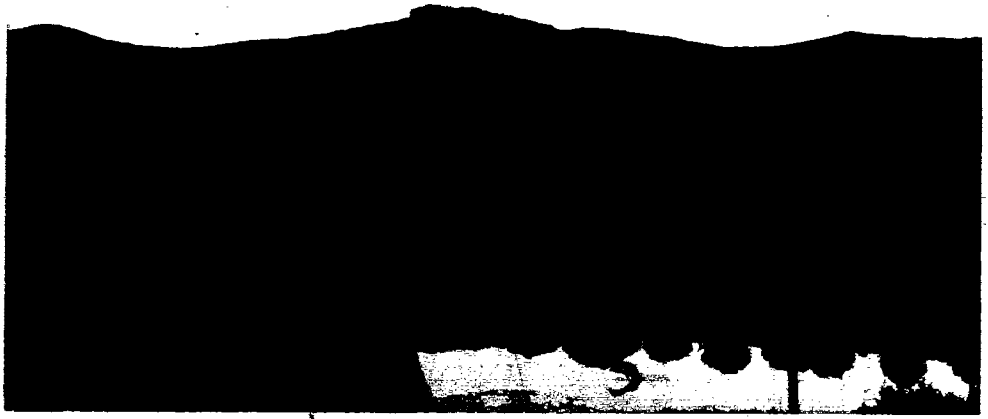
Relative proportions of the plagioclase and K-feldspar do not change appreciably from the granodiorite to the more mafic intrusions. The primary substitution is of diverse ferro-magnesium minerals replacing quartz as major minerals. Volumetrically these rocks do not consititute a major portion of the batholith and were not sampled or analyzed in this study.

<u>Post-Batholithic Events</u>. Within the study area, the oldest rocks which clearly contain detritus derived from unroofing of the Boulder batholith are early Tertiary sediments containing

Oligocene fossils. These units are the Renova Formation (Kuenzi, 1966, 1971) in the Jefferson basin and the equivalent Climbing Arrow Formation (Robinson, 1963) in the Three Forks basin. In the Jefferson basin, between Big and Little Pipestone Creeks, the Renova Formation of early Oligocene age rests nonconformably on batholithic rocks. Although this unit is composed predominantly of volcanic, glass-bearing, montmorillonite mudstone, at least four percent of the deposit is arkose (Kuenzi,1966). The source of this arkosic component is almost certainly the Boulder batholith. Younger sediments observed in the Jefferson basin contain ever increasing proportions of grus from the batholith. However, north and west of Butte, quartz latite tuff and welded tuff of the early Eocene Lowland Creek volcanics unconformably rest upon the eroded and weathered batholithic rocks and contain fragments of plutonic rocks (Smedes, 1962; Smedes and Thomas, 1965).

It would appear from this evidence that the western 'laccolith' portion of the Boulder batholith was unroofed and widely exposed by early Eocene, yet evidence of detritus accumulating in the basins to the east before early Oligocene is not documented. This seems incongruous with conventional concepts of uplift and erosional removal when applied to this setting. Evidence from present relationships in the northeast trending fault zone would suggest the eastern edge of the batholith has been tectonically very active since emplacement. Description of the erosional surface upon which the Lowland Creek volcanics accumulated is described as "...a mature mountainous surface having a maximum relief of perhaps 3000 feet." (Ruppel, 1963, p.83). While this might suggest substantial uplift and erosion along the western edge of the batholith, the volcanics were deposited in a structural trench at least partially bounded on the east by the present Elk Park fault (see Figure 1A). The southwest to northeast lineament bounding the volcanic field on the east margin suggests that the eastern portion of the batholith was upthrown relative to the western portion even as early as in Eocene times. This higher, eastern block apparently contained the eastward spread of volcanic deposition, which means the fault and trench either predate the volcanics or developed contemporaneously, perhaps as a result of crustal adjustments related to internal displacement of magma and external loading by eruptive deposits.

Photograph 2 shows the vicinity of the the present day, fault scarp bounded contact between the Butte Quartz Monzonite and the Lowland Creek volcanics northeast of Butte. An interesting point worth noting is that the top of Sheepshead Mountain (centre horizon) is the same approximate elevation as the 'eastern block' southern Boulder Mountains directly behind the camera. The uppermost lava unit capping Sheepshead Mountain must closely represent the total accumulated height of the volcanic deposits. Therefore, erosion and relief development in the Lowland Creek volcanics may be roughly indicative of regional erosion in the past 48 to 50 million years in the western portion of the Boulder batholith.



Photograph 2. Fault bounded contact between quartz monzonite (foreground) and Lowland Creek volcanics at Elk Park northeast of Butte. The contact is beneath the basin fill at this point and runs roughly parallel to the powerlines, with the forested slopes in the background entirely on volcanics. Nearly the entire stratigraphic column for the seven volcanic units mapped by Smedes (1962) is exposed in Lowland Creek, which is just over the horizon from the uppermost lava unit capping Sheepshead Mountain (centre).

If this same degree of erosional exposure were extrapolated to the eastern portion of the batholith (for instance the southern Boulder Mountains), it is unlikely that, assuming a roof existed there, this degree of erosion would not leave at least some roof pendants.

Based upon the evidence for uplift in the Boulder batholith east of the Lowland Creek volcanic field, both prior to and following the volcanic episode, it seems unlikely the eastern portion of the batholith and particularly the southern Boulder Mountains were not also exposed by early Eocene. Therefore, the relative lack of plutonic detritus in the Oligocene Renova Formation probably has an alternative explanation.

Several explanations seem plausible. First, at the time Kuenzi (1966) studied the Tertiary stratigraphy in the Jefferson basin it was generally thought the logical source of Oligocene tuffaceous sediments in the study area basins would be either the Lowland Creek or the older Elkhorn Mountains Volcanics. Indeed, Smedes (1962) originally assigned the Lowland Creek volcanics to Oligocene. As Table 3B shows, Klepper, et al., (1957), and Freeman, et al. (1958) correlate Oligocene tuffaceous sediments with the quartz latite volcanics which Ruppel (1963) also assigns to the Oligocene. The fact that later radiometric dating reassigns the Lowland Creek volcanics to the Eocene (Smedes and Thomas, 1965) raises the possibility of incorrect dating of the sediments from their fossils.

Even allowing an early Eocene age for the Lowland Creek volcanics and acknowledging the general agreement by early investigators that the next source of tuffaceous sediments was the rhyolite of Miocene to Pliocene age (Table 3B), recent radiometric dating of the rhyolite offers another possiblity. The rhyolite (post-Lowland Creek volcanics in Figure 1) is now dated as 35 to 37 million years before present at two areas south of Helena (Chadwick, 1978; Daniel and Berg, 1981). This means that the rhyolite volcanic field centered in the northern portion of the Boulder batholith may be responsible for tuffaceous sediments of Oligocene age in adjacent basins.

With a logical source area in the northern portion of the Boulder batholith for the Tertiary volcanic components of the Renova Formation, several other related points become significant in any speculation on physiographic history. First, Ruppel (1963, p.83) indicates that the Lowland Creek volcanics episode resulted in a drainage diversion of the ancestral Boulder River from its original course towards the southwest from the vicinity of Basin to basically its present course southeast from Basin. This diversion provided a mechanism for fluvial transport of Eocene and later Oligocene volcanics into the North Boulder and Jefferson basins. Second, Kuenzi and Richard (1969, p.319) found that:

> "A comparison of the topography developed during the early and middle Tertiary episodes of erosion, and the postulated ...origin of the Jefferson River gorge suggest that the North Boulder and Jefferson basins drained to the southwest during the middle Tertiary lacuna, rather than eastward into the Three Forks basin, as Perry (1934) and Atwood (1916) inferred long ago."

This means that, during the Oligocene prior to the cutting of the Jefferson River gorge, fluvial deposits carried by the

Boulder River would have been deposited in the Jefferson basin. This idea is further reinforced by a postulated topographic map of the early Tertiary erosion surface in the Jefferson Island quadrangle which infers a continuous drainage divide between the North Boulder and Jefferson basins to the northwest and the Three Forks basin to the southeast (Richard, 1966, Figure 3).

Third, it is clear from examination of more recent basin deposits in the vicinity of the town of Boulder, that a high proportion of the basin fill deposits along the Boulder River at the margin of the Boulder batholith are of Lowland Creek and post-Lowland Creek volcanic origin (Wetzel, 1981b). Botz (1968) has estimated that the deposits just south of Boulder are 60 percent volcanic and 40 percent granitic. Coupled with this, there is a stream gradient change where the Boulder River leaves an entrenched gorge and enters the broad North Boulder valley. This causes larger diameter alluvial materials to aggrade, causing some stream braiding. By the time the river is well into the basin, silt is a dominant fraction in the deposits. Tertiary volcanic fines might be expected in the Renova Formation in the Jefferson basin if the source area were nearly 50 kilometers away, since either eolian or fluvial transport would tend to preferentially deposit fines over substantial distances.

Finally, although granitic rock fragments as well as monomineralic grains from the Boulder batholith occur throughout exposures of the Renova Formation in the Jefferson basin, this detritus is not nearly so abundant as in the overlying Sixmile Creek Formation (early Miocene to Pliocene) where it is probably the most abundant component (Kuenzi, 1966,1971). Significant in this is that the depositional environment of the Renova Formation and equivalent Climbing Arrow Formation is interpreted to be low-energy floodplain and pond environments of an aggrading stream system. Mineralogy, texture, flora and fauna seem to suggest a warm, humid climate (Kuenzi, 1971; Robinson, 1963). By contrast, the overlying Sixmile Creek Formation suggests a relatively high energy ephemeral and perennial stream channel environment with some overbank deposits and an inferred more arid climate (Kuenzi, 1971). This might suggest several possibilities for the lack of plutonic material in the Renova Formation other than the inference by Smedes and Schmidt (1979, p.34) that "...much of the volcanic [Elkhorn Mountains] roof covering the batholith was still intact in early Oligocene time." For example, the depositional environment contrast between the Renova and Sixmile Creek formations seems to suggest that uplift may have occurred in the latter case. Conversely, there may have not been significant relief differences between the Jefferson basin and the batholith during deposition of the Renova Formation. Another factor may be that the early Tertiary drainage divide to the west of the Jefferson basin may have been near the present margin of the batholith, limiting the availability of batholith rocks in the immediate area. Evidence of stream capture is ubiquitous throughout the study area, making it difficult to infer with any reasonable assurance the size or shape of Tertiary drainage basins from present drainage. Finally, Paleocene uplift and erosion, that would seem necessary to expose the batholith, may have resulted in sediment stripping or non-deposition along the basin margins similar to present conditions. There is presently insufficient evidence from well logs to determine if Eocene (or older) deposits exist near the centre of the Tertiary basins in the study area. In any case, the lack of plutonic detritus in the Oligocene Renova Formation cannot be taken as prima facie evidence that the nearby batholith had not been unroofed.

The best evidence, then, which offers the time of earliest exposure of the batholith is the early Eocene radiometric date for the Lowland Creek volcanics by Smedes and Thomas (1965). Simply knowing that a weathered regolith of Eocene vintage underlies the volcanics does not resolve the problem of determining the characteristics of Eocene weathering in the quartz monzonite. Generally the configuration of the surface on which the Eocene volcanic rocks accumulated is imperfectly known. However, limited exposures of the surface being exhumed near Basin and north of Butte suggest it was a mature mountainous surface having a maximum relief of perhaps 900 metres (Ruppel, 1963, p.83). In the vicinity of Butte and along Interstate 15 west of Butte the quartz latite rocks also overlie the batholithic rocks, but highway road cuts are not strategically located to best observe the relationship between the two rock types and observed contacts away from the road cuts are gradational. The pre-existing surface at this point, though exhibiting some relief, is more subdued than that documented by Ruppel in the northern part of the Boulder batholith.

The drainage pattern that developed before the eruption of the quartz latitic volcanic rocks appears similar to that of the present. The quartz latite locally fills joint or fault controlled northeast and northwest trending stream channels that are being exhumed by present streams. This, and other field evidence of congruent stream exploitation in adjacent stream reaches on quartz latite and quartz monzonite, suggests that lithological differences have not played a major role in the re-establishment of drainage after the eruptive sequence. As mentioned before, however, the volcanics did divert the ancestral Boulder river from a south or southwest trending valley and caused a drainage reversal. As with smaller streams, the Boulder River established a channel that cuts transversely across quartz monzonite and quartz latite dikes with no apparent exploitive preference.

The similarity between stream downcutting of the quartz monzonite and quartz latite is echoed by the obvious compositional similarities (quartz latite is the extrusive equivalent of quartz monzonite) and by an occasional tendency to produce similar appearing weathering residuals. For example, the sample site in Brown's Gulch (No. 8 in Figure 2) was originally investigated because massive, spheroidally weathered blocks viewed from a distance appeared to be a typical quartz monzonite outcrop emerging from the surrounding volcanic cover. On close inspection, the spheroidally weathered blocks were discovered to be part of a weathered unit of the Lowland Creek volcanics.

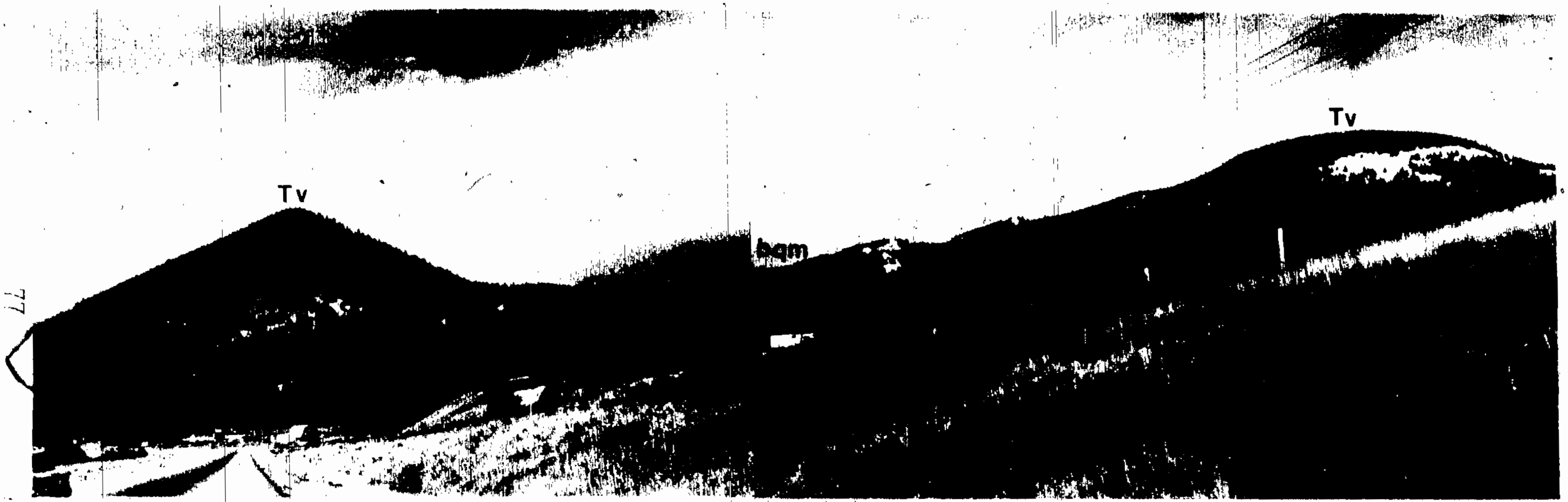
Ruppel (1963) thought that the eruption of the Lowland Creek volcanics was followed by erosion that extended through Oligocene and much of the Miocene (see Table 3B). However, as with other early studies that relied solely on relative dating techniques, the age perspective of the landscape was, without exception, underestimated. For example, the Oligocene-Miocene erosion surface of Ruppel in Table 3B predates the post-Lowland Creek volcanics. Chadwick's (1978) early Oligocene radiometric date for the volcanics means that the pre-rhyolite surface must be middle to late Eocene in age; an age underestimation on Ruppel's part of as much as 40 million years.

Following this long period of erosion, uplift initiated stream channel downcutting along northeast and northwest trending, structurally weak zones in the pre-Tertiary rocks. It appears likely that superposition of the Boulder River across a structurally-controlled, earlier drainage pattern was initiated at this time. Ruppel (1963) interprets the angular unconformity between the Lowland Creek volcanics and the subsequent rhyolitic volcanic episode to be a result of this uplift. Initiation of the incision of the Boulder River upstream from the town of Boulder must, therefore, either predate or be contemporaneous with the eruption of the Oligocene rhyolite, rather than being Pliocene as shown in Table 3B. Continuation of the downcutting, including the cutting of strath terraces, may have occurred throughout the entire ensuing time until the present. The steep-walled canyon between Basin and Boulder still exhibits a relatively steep stream gradient, indicating contemporary downcutting. This gorge of the Boulder River, having some 325 metres of relief, gives one approximation of the probable maximum relief development in this area since late Eocene.

Following the early Oligocene post-Lowland Creek volcanic episode, rhyolite blanketed a large area in the northern Boulder mountains between Basin and Rimini, about 24 kilometers northeast. The actual extent and contiguity of the volcanic field creates some problem in the interpretation of the age of the inselberg forms in the northern portion of the Boulder batholith. The rhyolite generally fractures easily and is talus forming (Whipple, 1973). A typical outcrop is shown in Photograph 3 near a sample site on Boomerang Gulch north of Boulder. The rhyolite also tends to occupy the highest topographic position where it occurs, suggesting its fracturing and permeability makes the rhyolite relatively resistant to fluvial erosion when compared to the underlying batholithic rocks which are subject to granular disintegration. Photograph 4, looking east from near Clancy, shows this relationship. The two hills in this photograph are part of a chain of rhyolite-capped hills extending northwestward into the Helena basin.

If these rhyolite-capped hills represent valley fill remnants of a once more-extensive cover that now (due to topographic inversion) occupy hilltops along a ridge line, then the inselberg landscape at altitudes below the inferred valley floor at the base of the rhyolite must be post-Oligocene in age. However, nearly 18 kilometers distance and 500 metres of

Photograph 3. Outcrop of Post-Lowland Creek rhyolite at the Boomerang Gulch sample site. Frost shattering, platy fractures, and talus typify these volcanics.



Photograph 4. Post-Lowland Creek volcanics (Tv) overlying the Butte Quartz Monzonite (bqm) southeast of Helena near Clancy. Some talus developed on the volcanics is barely visible through openings in the trees on the conical hill to the left. Preexisting surface on the quartz monzonite shows inselberg forms typical of the northern portion of the batholith in the Prickly Pear drainage.

relief lie between the deposits shown in Photograph 4 and the nearest remnants of extensive and mostly contiguous rhyolite cover southeast of Rimini. Erosional removal of all traces of a continuous volcanic cover and entrenchment of Prickly Pear Creek and its tributaries since Oligocene would suggest that Prickly Pear Creek, a considerably smaller stream than the Boulder River, accomplished a greater volumetric excavation in essentially the same geologic time.

Another alternative is that the linearly-orientated volcanic deposits in Photograph 4 are the result of isolated eruptions that are related, but not contiguous to the main volcanic field. In this case, the linear trend to the deposits may be fault related or due to some other linear, structurally weak zone. Evidence for this include what appear to be nearly vertical flow structures (as in Photograph 3) in areas where the volcanics have not degraded entirely into talus. Ruppel (1963, p.84) cites the possibility that isolated occurrences of rhyolite to the west and north of the primary area of exposure may also have been originally noncontiguous. In this case, the inselbergs apparent in the landscape in Photograph 4 and which, due to their proximity to the rhyolite cover, could be inferred to be recently excavated from under the rhyolite and therefore, might have originally developed in the Eocene. This interpretation would be consistent with independent observations of granitic inselbergs achieving great antiquity (Twidale, 1976; King, 1950, 1960; Mabbutt, 1965, 1967; Barton, 1916; Bain, 1923; Griggs, 1936; and Wahrhaftig, 1965; to cite a few). This hypothesis also does not require a massive late Tertiary excavation by Prickly Pear Creek. However, the entire landscape cannot necessarily be classified as Eocene, since an interpretion of a discontinuous Oligocene volcanic cover removes the means by which relative dating away from the margins of the volcanics can be accomplished. Thus, inselbergs away from the granitic/rhyolitic contact may have been exhumed as recently as in the Pleistocene.

A middle Tertiary unconformity mapped in the Townsend, Clarkston, Three Forks, Boulder, and Jefferson basins suggests that erosion between early Oligocene and late Miocene was successful in the excavation of a substantial volume of the early Tertiary basin fill (Robinson, 1960, p. B227-B228; Kuenzi and Richard, 1969, p. 315). Topography within these and probably other Tertiary basins is a product of a similar Quaternary erosion phase which has removed a considerable volume of the upper Tertiary basin fill deposits, and, in places, has exhumed the middle and early Tertiary erosion surfaces.

It is obvious that substantial post-rhyolitic erosion did occur, as evidenced by Pleistocene strath terraces and alluvial deposits along streams and in basins surrounding the Boulder batholith. However, the present landscape appears to have maintained much the same relief amplitude and appearance since perhaps Oligocene or Miocene.

The effects of the Pleistocene epoch in the study area are particularly difficult to interpret. As stated earlier, Ruppel (1962) documents the existence of a Pleistocene ice sheet in the northern Boulder Mountains. Although the mountain blocks both north and south of the Boulder River are presently similar in elevation, there is no clear evidence of glaciation in the southern Boulder Mountains. As described by Ruppel,

> "...the southern part of the Boulder Mountains appears to be a deeply weathered upland erosion surface, underlain mainly by granitic rocks of the Boulder batholith, now dissected by rejuvenated streams. Similarly, no glacial deposits like those in the northern Boulder Mountains or the contemporaneous deposits in the Elkhorn Mountains are known on Bull Mountain, which now reaches to about the same altitude as the Boulder Mountains. Unlike the Boulder Mountains, however, small glacial deposits thought to be contemporaneous with the "Late", perhaps late Wisconsin, stage in the Elkhorn Mountains have been recognized on Bull Mountain...Thus, in the northern part of the Boulder batholith there appears to have been an early Pleistocene (?) glaciation only in the Elkhorn Mountains, an early Wisconsin (?) glaciation only in the Elkhorn Mountains and the northern part of the Boulder Mountains, and a late Wisconsin (?) glaciation only in the Elkhorn Mountains and on Bull Mountain; no ice seems to have accumulated at any time in the southern part of the Boulder Mountains."(Ruppel, 1962, p. G-13)

Ruppel's analysis of the relative age of glaciation depends, in part upon the degree of weathering exhibited by quartz monzonite in the morainal deposits. For example,

> "...quartz monzonite boulders in the till typically are disintegrated to a depth of 3 to 6 inches and most fragments of quartz monzonite that were less than 1 foot in diameter have been completely destroyed by granular disintegration. The weathering rinds on ice-carved outcrops of quartz monzonite similarly are 3 to 6 inches deep." (Ruppel, 1962, p. G-11).

This provides one indication of weathering rates in the area, in terms of quartz monzonite weathering under post-Pleistocene conditions. It also begs the question of intact survival of pre-glacial weathered crusts and weathering residual forms under ice sheet conditions such as have been documented by Fitzpatrick (1963), Cunningham (1965; 1968), Caine (1967), Ford (1967), Feininger (1971), and Melcon (1975). This will be discussed in more depth in a later section.

In any case, the Pleistocene history of these adjacent mountain blocks appears to have been considerably different, even though they are nearly congruent in elevation at present. Ruppel notes that these differences are probably not caused by locally controlled climatic conditions, but rather reflect recurrent differential uplift of the individual mountain masses (Ruppel, personal communication, 1981). This is particularly true of the southern Boulder Mountains and Bull Mountain. Post-Pleistocene uplift in the southern Boulder Mountains may also explain the uncharacteristically deep entrenchment of Big Pipestone Creek and its tributaries relative to stream valleys at other locales within the Boulder batholith.

Early Pleistocene alluvial fan deposits exhibit approximately 200 m. of elevational difference across a fault identified by Stickney and Bingler (1981, p. 9), where the Helena basin abuts the northern Elkhorn Mountains. Although some of this differential must be attributable to the natural slope of the fan deposits, this gives one example of the possible order-of- magnitude for Pleistocene fault offset. No comparable studies of deposits in the southern Boulder batholith region are available for regional contra~~sts~~. Nor is not known how much elevational offset would be required to explain the glaciation inconsistencies proposed by Ruppel (1962).

5

Post-glacial alluvium deposited along major streams and alluvial fans along smaller drainages appears to be the only significant Holocene deposits. It is thought that, although basic elements of the landscape like mountain blocks and basins have been roughly the same since the Laramide mountain building, present landscape features such as drainage, relief, and vegetation types have only been similar to those of the present since after the early Oligocene volcanic episode. This excepts, of course, locally occurring major glacial effects from the Pleistocene.

Of particular importance to this study is the fact that the present exposed surface of the Boulder batholith and related rocks is a composite surface which includes parts exhumed from two earlier surfaces – one developed in Eocene and now being exposed from beneath quartz latitic volcanic rock, and one of late Tertiary age now being exhumed from beneath rhyolitic volcanic rocks. Finally, of course, the major portion of the batholith has been continuously exposed since at least Eocene times and provides a standard of comparison with weathering residues and landforms emergent from the exhumed surfaces.

Landforms:

Within a relatively large study area, almost every combination of agencies producing landforms is present. Nevertheless, some generalizations can be made. Discussion will focus on the landforms developed on the plutonic rocks of the Boulder batholith.

Quartz monzonite is present in every topographic position from valley floor to mountain peak, and the degree of weathered material present reflects both the relative potential for erosive removal and the effectiveness of protective cover. For instance, it appears that intact regoliths of about the same thickness (15-20 m.) occur in the Boulder valley (1500 m. elevation) and approximately 25 kilometers away beneath rhyolitic cover on Old Baldy Mountain (2425 m. elevation). In between these points, however, regolith thickness varies considerably, with clitter (comprised of exhumed corestones), tors, and various weathering residuals representing the effects of erosional stripping.

In mountainous areas, the quartz monzonite tends to form subdued, rounded topography which supports a coniferous tree cover except in the most exposed areas and on bedrock outcrops. Although relief amplitude of 1000 m. is common when comparing an isolated peak with an adjacent basin, 200 to 300 m. or less is common in first and second order drainages. The topography in the northern Boulder Mountains has been additionally subdued by Pleistocene ice sheet effects (Ruppel, 1962). However, the lack of sharp contrasts between nunataks and the surrounding landscape suggests minimal ice movement and consequent glacial scouring in the accumulation zone. Scouring and development of typical U-shaped valleys becomes more apparent along major drainageways (Tenmile Creek, Basin Creek, Little Blackfoot River) away from the central accumulation zone.

Limited pediment zones occur in the quartz monzonite in the vicinity of Boulder and west of Whitehall. The quartz monzonite appears to be the only batholithic rock that maintains well-defined pediment slopes under present circumstances. However, the actual development of the pediments must predate inferred late Pleistocene uplift which has resulted in dissection of the pediments near Whitehall. The restriction of definable pediments on batholithic rocks to quartz monzonite areas coincides with the observations of Warnke (1969, p. 387; personal communication, 1981) in California generally and in the central Mojave Desert in particular. Tertiary sediments, especially those derived from quartz monzonite grus, also maintain pediment slopes, though no observations of adjacent, coextensive pediments were observed.

The existence of small, slightly concave, planar surfaces with intact regoliths are interpreted to be equivalent in description, if not origin, to the 'piedmonttreppen' of Wahrhaftig (1965; after Penck, 1927), or the 'internal pediments' of Warnke (1969). Rather than being dissected remnants of an uplifted pediment surface, these internal pediments are thought to be graded to a local, resistant, bedrock base level. Thus, one surface would not necessarily correlate with another non-contiguous surface. Nevertheless, at least one fairly large pediment surface (Spire Rock Flats) west of Whitehall seems to exhibit elevational correlations on interfluves between presently dissecting streams.

A number of intermediate scale landforms are present on the mountainous portions of the Boulder batholith and are locally present as upstanding 'inselberge' above the pediment surfaces. These landforms range in relief from up to 150 m of relief on weathering residuals exhibiting domical jointing patterns (or domical inselbergs), to tors and elephantine boulders only two to 15 m. in height.

There is a distinct lithologic preference for positive relief in leucocratic batholithic rocks, although some mafic intrusions occasionally exhibit relief positive landforms. Perhaps the most pronounced example of this is the relative weathering resistance of alaskite, when compared to quartz monzonite. Figure 7 shows diagrammatically this relationship and the inferred silicification of quartz monzonite near alaskite intrusions. Photograph 5 shows an alaskite plug exhibiting characteristics similar to Figure 7. Alaskite may occur as a 'plug' defining an individual domical inselberg or may occur as a swarm of dikes defining a ridge line. The relationship shown in Figure 7 occurs consistently whether the landforms involved are large or small.

Leucocratic rocks (see Figure 1) also seemed to be consistent in the formation of domical inselberg forms. Photograph 6 shows a panoramic view of inselbergs typically formed in the leucocratic Moose Creek pluton.

In the quartz monzonite uplands, the largest area of plutonic rocks in the study area, positive relief forms seem to be a result primarily of either the original batholithic roof,

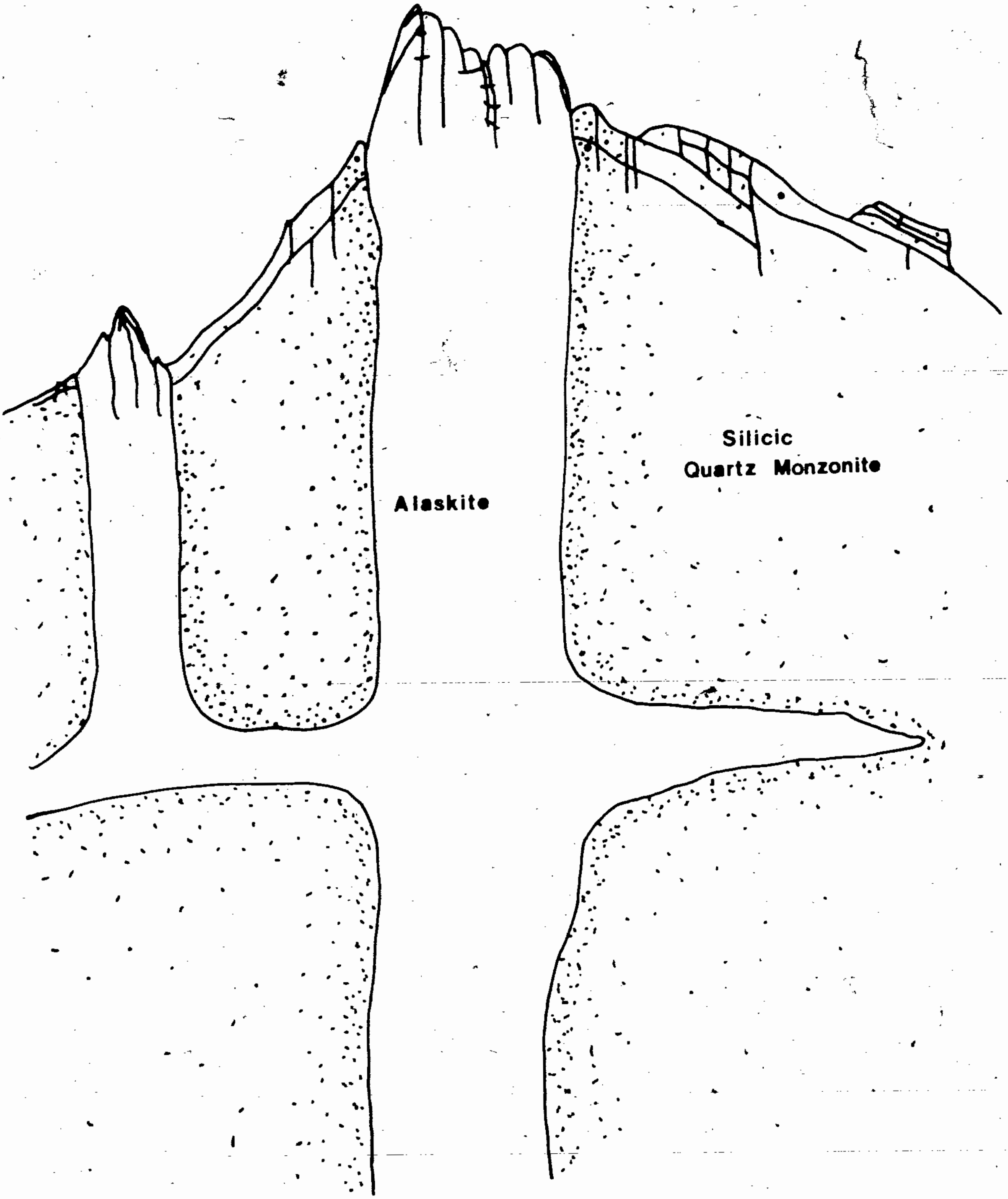
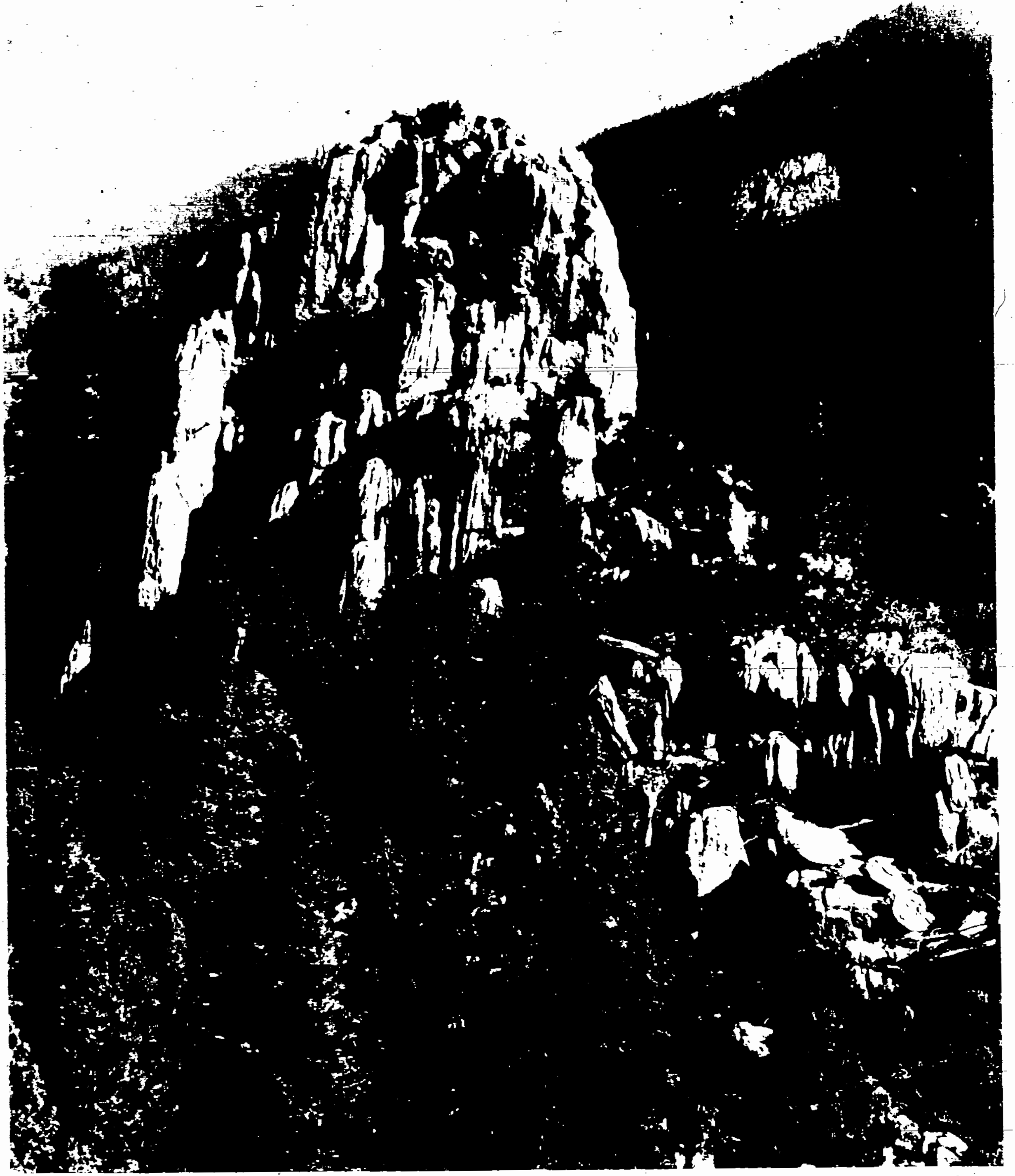
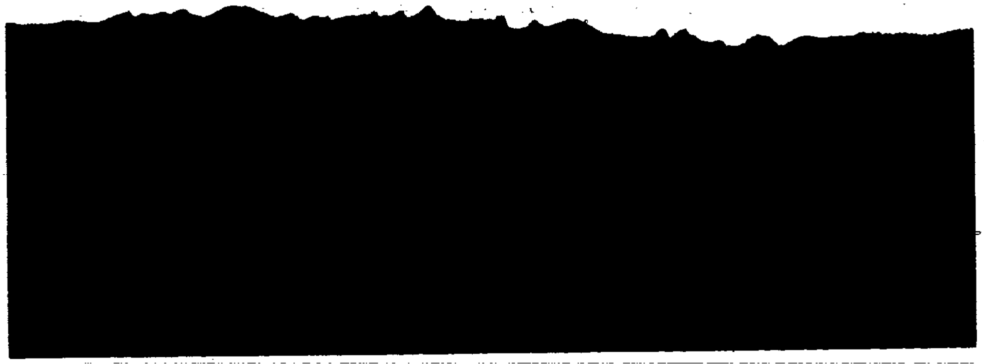


Figure 7. Diagrammatic Sketch of Field Relations Between Alaskite and Butte Quartz Monzonite. (Stipple indicates degree of silicification).



Photograph 5. Alaskite plug. Note the domical inselberg shape and additional plug in the background. View is north from Spire Rock west of Whitehall.

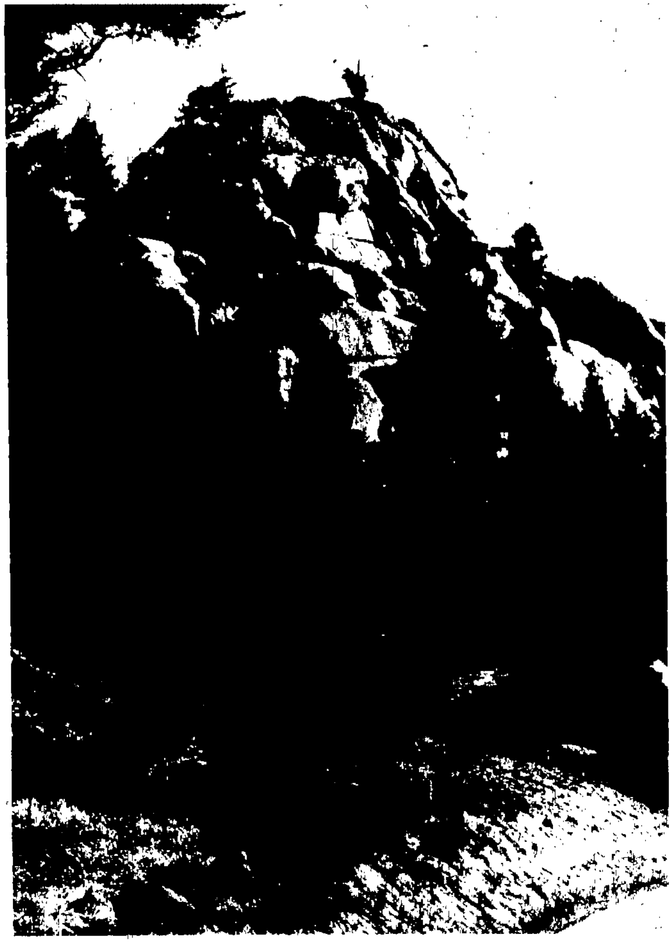


Photograph 6. Weathering residuals developed on leucocratic rocks of the Moose Creek pluton. View is east from the vicinity of Divide. Montana southwest of Butte.

the erosional exposure of an uneven weathering front, or rapid stream incision around (or nearly around) a massive block of quartz monzonite. The ubiquitous presence of vertical joints, some of which are fairly closely spaced, seems anomalous when the quartz monzonite inselbergs are compared to those cited in the literature, since closely spaced joints are most often cited as a reason for not developing upstanding weathering residuals. For example, Photograph 7 shows a typical quartz monzonite landform, the spacing of the wheel tracks (bottom left) providing a relative scale. Similarly, a less common inselberg with well developed horizontal jointing is shown in Photograph 8. Though dissimilar in jointing pattern, the landforms are remarkably similar in overall appearance.

Some positive relief forms occur as prominent inselbergs despite the numerous joints (Photograph 9), while, only a few hundred meters away appears only a boulderized clitter pile (Photograph 10). Tors, not as common in the study area as other inselbergs, are nonetheless present (Photographs 11 and 12). Some theories on the reasons for such diversity and about the origin of the forms will be discussed in more detail in Chapter Three.

The granodiorite (e.g., the Radar Creek pluton) does not seem to maintain either pediments or distinctive inselberg forms. Despite the fact that the surface presently being dissected at Spire Flats encounters some concurrent interfluvial summits across the granodiorite lithologic boundary, the interfluves are not the characteristic broad, planar,

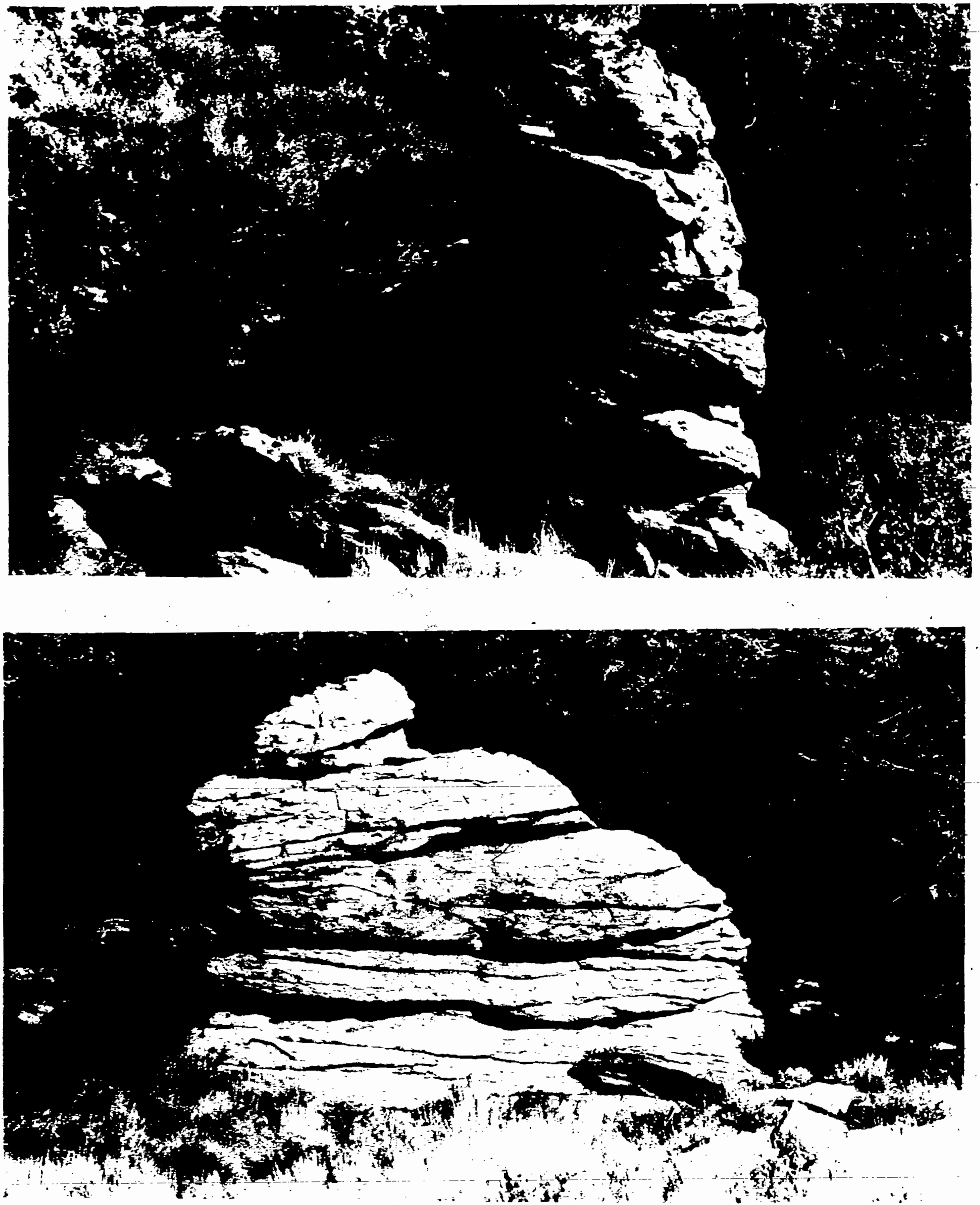


Photograph 7. Jointing patterns. This inselberg shows primarily vertical jointing with some domical unloading joints. (left)

Photograph 8. Jointing patterns. Here horizontal and domical joint patterns are prevalent. (right)

Photograph 9. Jointed residual near Homestake Pass. Some outcrops of the quartz monzonite, though heavily jointed, have relatively little clitter.

Photograph 10. Clitter near Homestake Pass. Many outcrops are a mass of a boulder-strewn hills.

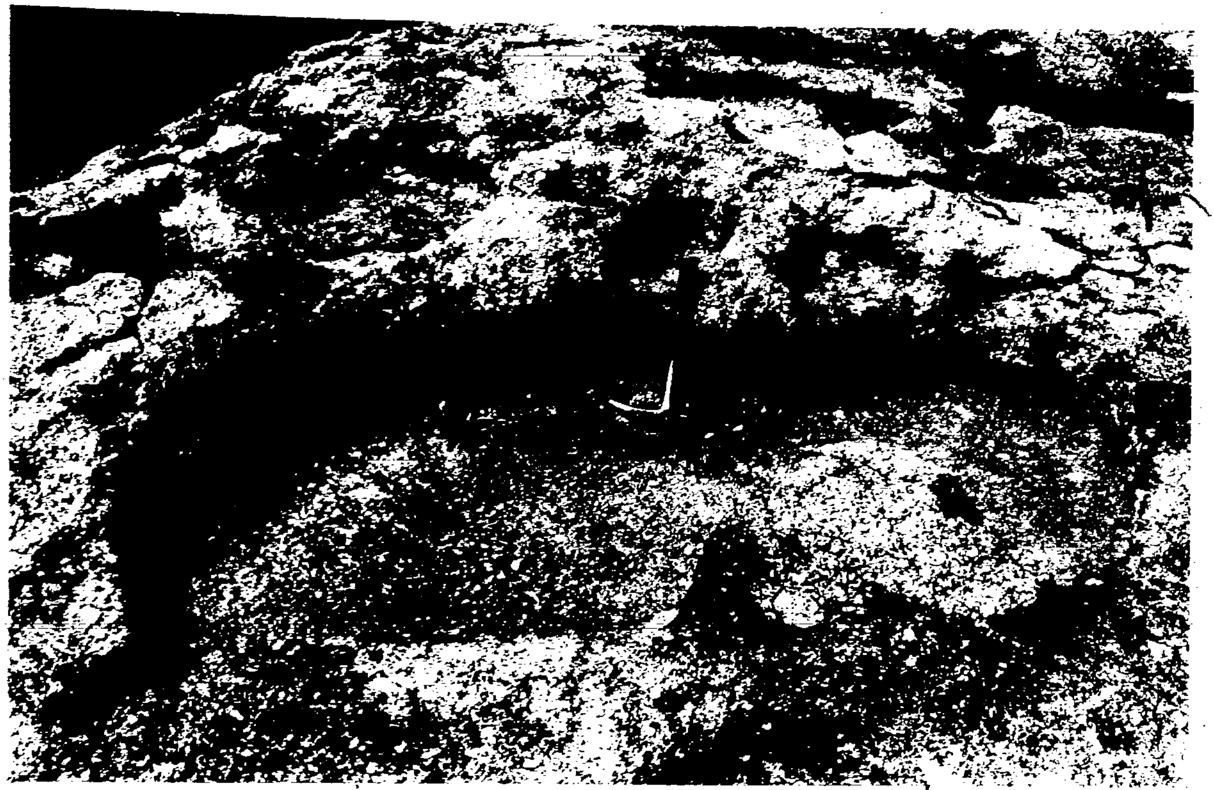


Photographs 11 and 12. Tors on the Spire Rock Flats surface west of Whitehall.

concave surfaces found on the quartz monzonite. While some boulderized clitter is present, the granodiorite does not seem to have the characteristic mesoscale inselbergs found in the felsic rocks.

Mafic rocks occasionally exhibit positive relief when compared to the quartz monzonite, but are generally so limited in extent that features such as pediments could not be accurately discerned, even if present. Generally no distinctive weathering residual forms exist, with the possible exception of the Ringing Rocks, a monzonitic intrusion east of Spire Flats near Whitehall (Protska, 1966). Here, a pile of irregularly shaped, indurated boulders show evidence of chemical weathering. However, only the thinnest of ferric oxide crusts covers what must be considered fresh rock. The boulder pile, suspending many of the rocks by only a few contact points on adjacent boulders, derives its distinctive name from the bell-like tone shich results when a boulder is struck with a hammer. This is apparently a unique, weathering landform, since no parallel has been discovered by this author in the extensive literature on weathering residuals.

A number of 'micro' weathering forms exist on the weathering residuals. These include panholes (gnammas, weathering pits; see Photograph 13), indurated crusts (duricrusts), and occasional 'tafoni' (Photograph 14) and 'lapies' [Cunningham (1971), Twidale and Corbin (1963), Roberts (1968), Dragovitch (1968,1969), and Segerstrom and Henriquez (1964)]. These features are ubiquitous and were not studied in detail except



Photograph 13. Weathering pits and indurated crusts near Spire Rock west of Whitehall.

Photograph 14. Tafoni (solution pit on a vertical face) on an inselberg near Spire Rock.

where it was thought that they offered opportunities to date the landforms on which they occurred. Ruppel (personal communication, 1981) considers that the weathering pits are of either Pleistocene or post-Pleistocene age although they are relatively uncommon in areas of Pleistocene glaciation. This author considers the Pleistocene as a minimum age for most of the microforms, although small panholes do exist on some residuals inferred to have been exhumed in the Pleistocene. This will be discussed in a later section.

CHAPTER 3

LITERATURE REVIEW

Introduction:

Inselberg forms on granitic rocks have been the object of controversy and study for nearly 150 years. The focus of the controversy deals with generating a satisfactory explanation for why inselbergs exist as upstanding outcrops above a low gradient surface comprised of rock presumed to be of the same lithology.

The global distribution of tor-like forms documented from tropical Africa (Handley, 1952) to areas exposed by recently retreated glacial ice in the Canadian arctic (J. Andrews in Cunningham, 1968) has defied any single, adequate explanation of origin. Kessel (1973) has also documented the wide latitudinal distribution of domical inselberg forms. Cunningham (1969) has postulated that granitic landforms exhibit 'convergence', a condition:

> "...whereby disparate processes, or different emphases of the same processes, may produce similar results at a particular stage in their operation. A basic dilemma is thus posed for the geomorphologist that discrete classifications whether by process, by denudation chronology, or by morphogenetic region do not necessarily demarcate discrete classifications of landscape features." (Cunningham, 1969, p. 58)

Despite this dilemma, a number of theories purporting to explain weathering residual origins have been proposed These have been categorized into four basic types by Melcon (1975): two-stage (or multi-stage) morphogenesis forms; subaerial one-stage morphogenesis forms; erosional residuals; and structurally-induced landforms.

Theories of Inselberg Origins:

Two-Stage Morphogenesis. Those who advocate two-stage morphogenesis suggest that the conditions under which the area concerned is weathered differs from the conditions under which the area was earlier eroded and residuals exhumed. In fact advocates usually postulate that neither the conditions of regolith preparation nor those of exhumation are similar to conditions presently experienced at the site and thus (unacknowledged) envisage three stages. Distinctions between conditions before, during, or following exhumation are attributed to changes induced by climate (for example, Tertiary-warm to Pleistocene-cold), by local or regional base level adjustment, or by changes in vegetative cover. It is supposed that each of these changes, either singly or in combination, may create conditions wherein regolith stripping exceeds weathering penetration. Linton's (1955) work, the classical two-stage interpretation, is illustrated by Figure 8. In this Figure, differentially-jointed bedrock (a) is acted upon by (supposed) warm temperate to subtropical climates for sufficient time to create a differentiated subsurface landscape (b) consisting of in situ weathered regolith (with corestones) and zones of less weathered rock ('incipient tors'). A change in climate during Pleistocene times accelerated removal rates of the regolith, exposing the differentially-jointed and weathered subsurface landscape as tors (c) standing above surface BB, the 'basal platform' or weathering front. Linton postulated that active glacial ice would destroy tors and thus regarded tors in

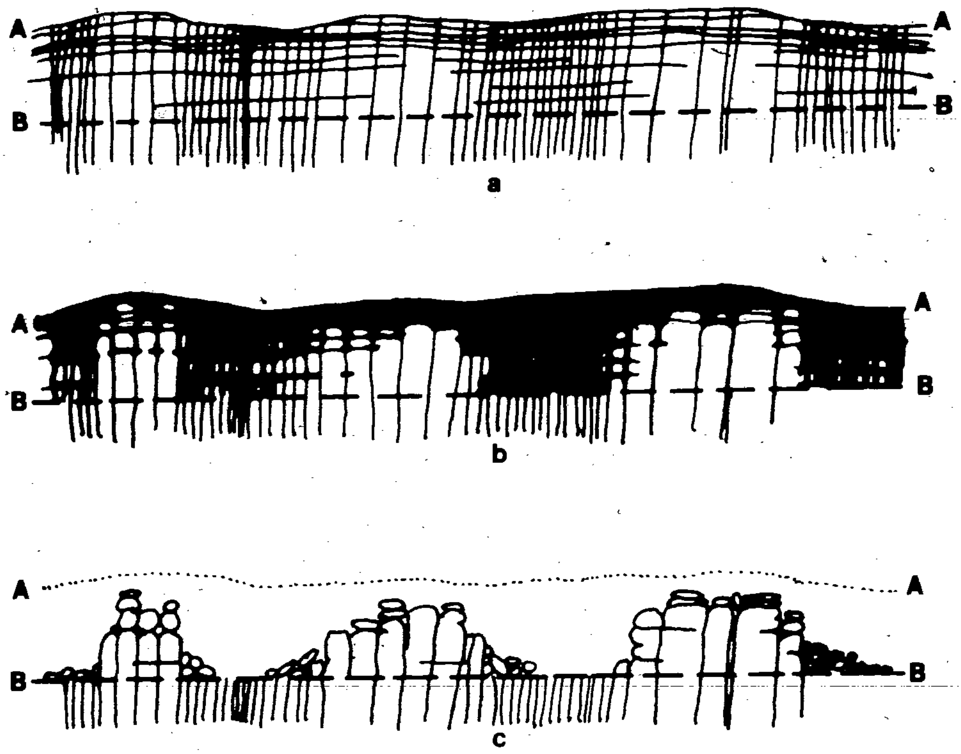


Figure 8. Tor Evolution. Stages in the evolution of a group of tors, illustrating the importance of joint spacing (after Linton, 1955, p. 475). In a, the original land surface (AA) with joint spacing is shown; differential weathering occurs because of more intense weathering along closely spaced joints in b; stripping of regolith in c exhumes tors from the weathered mantle. Line BB, which represented the water table in Linton's diagram, was considered to limit the depth of weathering. This has been widely disputed by other investigators, as discussed subsequently in this Chapter.

the British Isles as indicating areas never glaciated (including nunataks). Cunningham (1965, 1968) has cited evidence that tors have survived glaciation in both Britain and northern Canada. Further, Linton's claim that warm, wet climatic conditions were necessary to initially prepare a regolith for exhumation of tors does not explain the occurrence of tors and other residuals in areas where neither the present, Pleistocene, nor pre-Pleistocene climates fit these characteristics (Stoddart, 1969; Cunningham, 1978).

Ollier (1959, 1960), Mabbutt (1961), Thomas (1965), and many others ascribe weathering residual morphogenesis to the two or multi-stage theory, but under many contrasting climatic conditions. Bornhardts generally attain greater height than can be accomplished in one cycle of weathering and stripping without uplift, so these are interpreted by some (Thomas, 1966; Meyer, 1967) to require multiple cycles in which successively more of the bornhardt is exhumed. Once initially exposed, tors and bornhardts may survive a very long time (Twidale, 1976) because of the much faster rate of weathering attack in the vadose zone in the surrounding regolith. Rather than the number of cycles, the ultimate limiting factor in the height of a domed inselberg (or bornhardt) is thought by some investigators to be related to internal rock strength (King 1975), to latent vertical jointing (Thomas, 1965; Pugh, 1956) or to basal sapping in the hillfoot zone (Bakker and Levelt, 1964; Budel, 1957; King, 1948, 1953, 1962). Above a critical height the structure will begin to collapse.

One-Stage Morphogenesis. Advocates of this contrary theory imply that no climatic or tectonic change need be invoked to explain tor origins. The most popular variation of this theory associates tor formation with cold environment removal systems (solifluction, altiplanation, etc.) and was advocated first by Albers (1930) and Peltier (1950). This theory is exemplified in the works of Palmer and Neilson (1961) and Palmer and Radley (1962) in Great Britain, Wood (1969) in New Zealand, Demek and Czudek (1971) in Czechoslovakia, Dahl (1966) in Norway, and Caine (1967) in Tasmania.

A common theme in these studies is the presumption that cold (Pleistocene-?) climatic conditions which induced permafrost on lower slopes (where water is most likely to exist) also promoted solifluction on upper slopes, removing any previous regolith and subsequent frost-shattered material. Following this, it is suggested, differential frost shattering created an initial scarp which underwent lateral retreat (Czudek, 1964) and created 'altiplanation terraces' (Demek and Czudek, 1971). Tors and kopjes are supposedly left as unconsumed stacks in the altiplanation process.

Adherents of this theory generally describe the resultant landforms as 'angular', since the selective action of frost shattering under subaerial conditions offers no good explanation for rounding of an initial joint-bounded cuboid block (Melcon, 1975). In some cases, the apparent 'angularity' or 'rounding' may be in the eye of the beholder. For example, Palmer and Radley (1962), propose the angular Millstone Grit tors in the

English Pennines are a result of isolation along a frost-shattered retreating scarp face, initially created by glacial meltwater overflow (See Palmer and Radley, 1962, Figures 12 and 13, p. 47). Linton (1964) viewed the same tors as forms rounded along joint faces by pre-Pleistocene subsurface weathering, but did not oppose the removal of the weathered fines by solifluction since this is consistent with his earlier theory (Linton, 1955) of tor origins at Dartmoor, England (See Linton, 1964, Figure 1, p. 21). A sharp contrast between descriptions of angular periglacial forms and rounded residuals exhibiting initial subsurface differentiation is common in the literature. An exact distinction between these two supposed modes of origin is perhaps not warranted in all cases. Cunningham (1965) points out that the Pennine tors are basically rounded forms (supporting Linton's contention), but that the tors have been sharply modified by frost shattering in many cases, such that the initial subsurface rounding is not always readily apparent. Melcon (1975) regards the primary distinctions establishing that tors are of periglacial origin include the absence of significant chemical alteration on joint surfaces, angular rather than rounded form, and close association with other periglacial phenomena, but even this does not preclude totally masked effects of earlier subsurface differentiation.

One-stage morphogenesis advocates do not necessarily deny the existence of a pre-existing (Tertiary?) weathered regolith. However, their emphasis is placed on residuals produced by frost shattering of coherent material that is exposed after solifluction has removed previously weathered material (Eden and Green, 1971). Viewed in this sense, differences between 'so-called' one-stage and two-stage morphogenetic forms are not distinct. It is also uncertain whether Pleistocene conditions need necessarily be invoked to explain frost-molded forms in higher latitudes and altitudes where seasonal and diurnal temperature changes are such that freeze-thaw cycling may occur under present climatic conditions. Like Linton (1955), Palmer and Neilson (1961) also erroneously thought that the tors they studied could not have survived glaciation. The fact that many tors occurring in the tropics, where periglacial conditions cannot be construed to have occurred in either the Mesozoic or Cenozoic eras and are demonstrably pre-glacial (Browne, 1964; Melcon, 1975), prevents any universal application of this theory.

<u>Theories involving Erosional Residuals</u>. Tors and bornhardts may also be formed in temperate or tropical climates through processes of hillslope development, involving initial dissection by streams followed by pedimentation and parallel scarp retreat, as proposed by King (1948) for bornhardts. King's theory is an extension of Penck's (1927) 'piedmontreppen' concept which further suggests that valley slopes undergo parallel retreat following stream dissection, leaving resistant stacks as residuals above a pediplane. However, Penck considered his 'primarrumpf' or initial surface at the beginning of uplift could include residuals from an earlier cycle of uplift. This would explain such features as 'summit tors' or residuals

capping undissected upland surfaces. Despite supposed differences between Penck's and Davis' theories concerning uplift and erosional cycles, it is difficult to see how the 'primarrumpf' of Penck differs from the 'old-from-birth peneplain' described by Davis (1922).

A model for both scarp retreat and dip slope free-face (or 'Auchtenstuffen') retreat is inferred by Cunningham (1964) where scarp retreat gives rise to 'stacks' or valley-side tors and dip slope retreat gives rise to 'summit tors' in tilted sedimentary structures. Other variations wherein tors are assumed to be tropical or paleotropical forms that evolve subaerially throughout their existence are critiqued briefly by Cunningham (1969). Oberlander (1972) proposes strictly a fluvial origin for some 'boulder domes' in the Mojave Desert through stripping of a Tertiary regolith by lateral stream migration and sheetwash processes.

Structural Theories. Structural influences in the evolution of weathering residuals may fit into a sub-class of the previously discussed stage-oriented theories, as in the case of theories emphasizing jointing. Linton's (1955) own work emphasizes joint control in tor evolution. The joint systems which are important factors in most granitic landforms can result from processes of emplacement and crystallization (Exley, 1958; Balk, 1937); diastrophism (Twidale, 1967); or from subsequent relief development causing 'unloading' or 'dilation' joints characteristic of domed inselbergs (Chapman and Rioux, 1958; White, 1945; Twidale, 1964).

Structural influence may also be entirely endogenic. Examples include bornhardts derived from 'cupola forms' in the batholith roof and thus related to the nature of the emplacement (Cunningham, 1971). Metosomatic and hydrothermal pre-conditioning (which may strengthen or weaken granite and wall rock near the pluton roof) may determine to a degree the nature of the erosional landscape. Exogenic alteration must also be considered, especially if the conditions at the time of erosional exposure of a pluton are conducive to intensive or prolonged meteoric weathering. As a pluton roof thins, the upper volumes of the pluton are penetrated by the weathering front, so that the upper part of plutons may already exhibit weathering differentiation before exposure. This is postulated by Cunningham (1971) in southern Idaho, and by Volborth (1962) in Nevada.

Lithology also deserves considerable attention. Biotite weathering (both meteoric and endogenic) has been widely adduced to explain landscape features [McKeen Ridge tors (Melcon, 1975); 'stepped topography' of the Sierra Nevada (Wahrhaftig, 1965); Sherman Surface correspondence to one phase of the Sherman granite in Wyoming (Eggler, et al., 1969); and 'rapakivi-type', incoherent granite in Nevada (Volborth, 1962)]. Warnke (1969) observes that Mojave Desert pediment slopes develop only on quartz monzonite and that the only positive relief on pediments is related to leucocratic (pegmatite and aplite) intrusions which resist 'pediplanation' more than the country rock. An important point brought out by Jeje (1974) and demonstrated by

Eggler, et al., (1969) is that petrological differences too small to justify further classificatory and/or mapping units may be responsible for very significant landscape differentiation. These factors leading to weathering differentiations are covered in more detail in Chapter 7.

Sedimentary and metamorphic rocks may give rise to weathering residuals, although attention to these landforms is not nearly as frequent in the literature as to similar forms in igneous intrusives. Where non-granitic residuals are reported, bedding and foliation planes are important in the expression of the resultant landforms. Horizontal bedding planes in coarse sandstones may result in tor forms similar to those cited by Demek (1964, Plate 6, p. 15) in Czechoslovakia. Tilting of bedding planes of the Millstone Grit in the English Pennines (Palmer and Radley, 1962) has had the effect of creating tors of slightly different form but demonstrates that bedding planes in sedimentary rocks tend to concentrate weathering in much the same fashion as do horizontal joints in granites.

Foliation planes in metamorphic rocks can also influence subsurface weathering attack and the eventual expression of residuals. McGraw (1965) reports 'fretted tors' and an irregular weathering front where the dip of foliation in the Otago Schist was moderate to steep, whereas blocky tors and a nearly horizontal weathering front [similar to Linton's (1955) 'basal platform'] occurs where schistosity parallels the surface. This is one reason why the contention that the 'basal platform' is the expression of a former water table (Figure 8) should not be uncritically accepted It also suggests that the influence of structure, especially extension joints, should be studied further.

Theory Application Problems. These popular theories of inselberg origins provide convenient explanations useful in justification of the existence of weathering residuals to the uninitiated. Beyond this, these theories should be used as standard explanations in scientific investigations with caution. There are several reasons for this.

First, in the nearly 30 years since Linton (1955) first popularized the study of weathering residuals, it has become clear that there are no absolute, universal explanations for them. For example, the Dartmoor area used by Linton as the prototype area to demonstrate two-stage morphogenesis of tors was also used as the type area for explaining their origin by periglacial weathering (Eden and Green, 1971). There is still no consensus whether the disintegrated material necessary to Linton's explanation is due to past meteoric effects, recent meteoric effects, or is a result of pneumatolytic alteration (Palmer and Neilson, 1961).

A second problem is demonstrated by the considerable heat but little light generated by subsequent studies on Dartmoor. The strong advocacy of proponents such as Linton and Palmer has resulted in a tendency for their theories to circumscribe later research rather than stimulating new thoughts and directions. This has occurred in much the same way that American geomorphologists still tend to look at the world through

'Davisian'-coloured glasses. Many contemporary investigators use, and accept without criticism, the postulates of these theories.

It has to be conceded that, while weathering residuals such as tors and domical inselbergs exhibit characteristic shapes that are recognized in a wide range of different climates and latitudes, no one theory suits all circumstances of inselberg origin. The great numbers of tors and bornhardts reported from areas which are not now experiencing tropical conditions, nor have done so for at least several million years, would suggest that the most popular (two-stage) theory may explain far fewer weathering residuals than is commonly thought (Cunningham, 1968).

Weathering:

Many problems arise concerning weathering in the study of inselbergs. Because some investigators dispute the popular two-stage (weathering-exhumation) morphogenesis theory, then weathering and its relationship to the genesis of inselberg forms is a major problem. Even among those who ascribe to the two-stage morphogenesis theory, there is no common acceptance of weathering causes and processes in the subsurface differentiation of a regolith or in the resultant emergent landscape.

In studying the weathering of plutonic rocks, such as those which constitute the inselbergs of the study area, investigators have typically addressed studies which give partial solutions to unique cases, limited in scope by polarized controversies which have so far defied resolution. From the number of these unresolved controversies such as constant volume vs. expansion/contraction weathering; pan-directional subsurface vs. bias-directional atmospheric weathering; hydrothermal vs. meteoric weathering; granular disintegration vs. joint breakage; zonal climatic morphogenesis vs. azonal time dependent forms; subaerial vs. subsurface; or subtropical vs. periglacial genesis; to mention a few, it is clear that the weathering problem has acquired permutations of complexity. To add to that complexity, most recent studies have centered on areas in the temperate regions where many factors (notably climate) can be demonstrated to have been highly variable over geological time. Further, because additional supportive studies providing absolute measures of such variables as date of emplacement (in the case of plutons), of date of erosional exposure, of time exposed to meteroric weathering, and date of exhumation may be needed to make valid conclusions about emergent inselberg landscapes, the situation in any study invariably exceeds in complexity the expertise of any individual investigator.

Failure to completely resolve complex situations in weathering studies is common, the more so since increasing specialization in academic pursuits often isolates the researcher from a particularly relevant body of knowledge necessary to the solution of a particular problem. The well equipped researcher studying granitic landforms, such as those in the study area, would need both broad and specific knowledge in the fields of geomorphology, structural geology, petrology, chemistry, ground water hydrology, soil chemistry, paleontology, biology, and botany, and be capable in field and experimental methods appropriate to all of them.

Physical Weathering:

Physical weathering of granitic rocks theoretically involves only a change in outward form of the original rock with no alteration of its chemical makeup. Disaggregation of individual crystals in granitic rocks by repeated freezing and thawing is an often cited example of physical weathering (Kessler, et al., 1940; Dunn and Hudec, 1966) although there is some doubt as to whether chemical or mechanical weathering are ever acting alone. Physical weathering has been invoked as the primary causative force in several studies invoking single-stage morphogenesis of inselberg forms.

This theory is best demonstrated in the work of Demek (1964) and Czudek (1964) which describes tors formed, it is supposed, in their entirety by Pleistocene frost attack. These writers postulate angular tors as a product of a general scheme of periglacial slope development including altiplanation terraces, felsenmeer, solifluction, and escarpment retreat. Palmer and Radley (1961) and Palmer and Neilson (1962) used this periglacial hypothesis, perhaps incorrectly, in the dispute with Linton (1955) over the origin of the Dartmoor tors. Dahl (1966) in Norway and Derbyshire (1972) in Antarctica have postulated limited chemical weathering combines with periglacial conditions to produce tor-like forms without forming an initial regolith.

The angularity of subaerially sculpted, periglacial forms contrasts with the rounded appearance produced by subsurface chemical weathering. The difference is usually attributed to the markedly different behavior and nature of the attack, particulary the selectivity of frost action when compared with subsurface weathering. A general association of rounded form and subsurface genesis occurs in the literature, but the association is complicated by the periglacial resculpting of two stage tors (as in Dartmoor) and the structurally-determined angularity of two stage schist tors (Raeside 1949). A further complication arises from an incomplete understanding of subsurface periglacial processes and their effects.

King (1948, 1959, 1966) initially regarded stream incision and parallel slope retreat as mechanisms explaining inselberg landscapes in Africa. This theory involves a joint-controlled drainage pattern followed by uplift that results in deep stream incision. This is followed by parallel slope retreat and pediment formation that eventually result in isolated interfluvial remnants which achieve a characteristic domical shape by release or unloading jointing. Kings's theory does not satisfactorily explain the significance of chemically weathered regoliths surrounding the base of inselbergs, the existence of tors apparently exhumed from a regolith on the summits of some domical inselbergs and bornhardts, or the lack of surrounding pediments in association with domical inselbergs (Eden, 1971).

Thomas (1966) has offered an alternative hypothesis that suggests a two stage morphogenesis with initial chemical weathering of a regolith to produce domed inselbergs and bornhardts. King (1975) later invoked lithologic differences which result in selective survival of bornhardts, including lithologic changes caused by chemical induration during emplacement. Though King has not retreated from proposing fluvial processes and slope retreat as the mechanism for exposure of the basic inselberg form, his newer theory emphasizes that the exhumation as well as ultimate survival of bornhardts is conditioned by weathering resistance acquired prior to exhumation.

Formation of inselberg forms by primarily physical weathering processes is a theme emphasised in a number of other studies, some of which are mentioned in the previous section on subaerial one-stage morphogenesis. Melcon (1975) provides an excellent review of these studies, but since the form of residuals in the study area suggests limited applicability of these studies the matter is not pursued here. Aspects of mechanical weathering are mentioned, however, wherever appropriate to discussion throughout the thesis.

Chemical Weathering:

Chemical weathering in rocks is essentially an irreversible process wherein environmental changes create disequilibrium in chemical bonds of the crystal lattice of minerals. For granitic rocks, the temperature and pressure conditions, as well as available reactants, are markedly different when the rather extreme conditions of heat and pressure during formation are compared to the conditions of near-surface or subaerial exposure. Changes lead to spontaneous reactions seeking to recreate an equilibrium between the minerals and their environment. These reactions create different and more stable mineral assemblages by addition, removal, and/or substitution of molecules in the crystal lattices of the original minerals. These more stable minerals are themselves subjected to environmental disequilibrium through time, promoting further weathering. Water is of almost universal importance in chemical weathering, being a reactant itself, a medium in which various substituting agents can be carried and which, through circulation in the hydrologic cycle, maintains a disequilibrium at the mineral surface. Chorley (1969) and Ollier (1969) each provide a summary of the role of water in rock weathering.

The complexity of combinations of chemical reactions in the environment are not completely understood and are variable from place to place as well as vertically in the regolith. Melcon states:

> "Chemical weathering proceeds by exothermic reactions subject to the laws of chemical equilibria, and plausible reaction formulas can be developed which depict idealized reactions and reaction sequences. Although useful for purposes of exposition they reflect poorly the complexity and variability of field weathering conditions. Chemical weathering may completely decompose a rock unit, or, by selective and limited alteration, cause its mechanical disaggregation." (Melcon, 1975 p. 69)

Another factor sometimes overlooked is the <u>rate</u> of weathering. Ollier points out:

> "Equilibrium relations determine the maximum amount of a mineral that can be dissolved in any system. However, the actual amount that really is dissolved depends on rate factors. Rate factors have often been overlooked in weathering studies,...(and) it is important to realize that simple chemical equations illustrate possible courses of chemical reactions but they do not tell the rate of reaction, which really determines whether the reaction is important in weathering or not." (Ollier, 1969, p.27)

A number of variable factors (e.g., jointing, grain size, soil moisture availability, petrology, temperature, precipitation, relief, vegetation and drainage) work together to create differential chemical weathering in a regolith. While a specific combination of a number of these factors may result in ideal inselberg possibilities (e.g. coarse grained quartz monzonite with open, widely spaced joints in a humid environment), inselbergs do not necessarily occur in the 'ideal' situation and, contrariwise, do occur where nearly all conditions seem opposed to their formation. Because these variable factors can influence both the rate and type of reactions, resultant weathering exhibits considerable variability. As pointed out by Ollier:

> "The greater the number of variables in a system, the harder it is to predict the course of a reaction, and the number of variables in weathering is often great. In the simple solution of calcite, $CaCO3$, for example, there are seven variables, even at constant temperature and pressure. Furthermore, even a simple reaction may occur in a number of different stages; the solution of calcite, for instance, takes place in four distinct stages, and even more stages are involved in the alteration of complex silicate minerals to clay." (Ollier, 1969, p. 27).

The Role of Ground Water:

One of the controversies in weathering originated with the claim by Linton (1955) that alteration by weathering virtually ceased below the water table. A misconception held by Linton was that chemical weathering takes place only in the acid, aerobic, vadose zone and that equilibrium is reached and maintained in the slightly alkaline, anerobic environment below the water table. Reiche (1950) also considered that effective weathering extends approximately to the water table, although he recognized that ground water circulation permits some alteration to greater depths in formations or rock zones of high permeability. This is the reasoning followed by Linton (1955) in his study of tors. Linton described the 'basal platform' upon which the Dartmoor tors stood, as probable evidence for a former level of the water table (see Figure 8). More recently, evidence suggests that the basal platforms cited by Linton and by others may represent broadly curvilinear, stress-induced joint planes which developed in parallel with the pre-existing land surface.

Dixey (1931) had earlier suggested an absolute limit on the depth of weathering when he pointed out that with increasing depth in the ground, confining pressures exclude further ground water penetration. This proposal would allow that weathering could take place below the water table. Campbell (1917) claimed that weathering could continue to 30 meters below the water table.

De Lapparent (1941) distinguished two zones of sub-water table weathering. He recognized a 'zone d'alteration inferieure' within which slow water penetration via 'microfissures' and cleavage planes in the rock leads to alteration of plagioclase and other silicate minerals to sericite, and of ferromagnesian minerals to chlorite. This he distinguished clearly from the 'zone superieure d'alteration', where more rapid circulation of ground water intensifies the process of hydrolysis, resulting in the formation of kaolin group clay minerals.

Nye (1955), working in Nigeria, concluded that rock below the water table could be altered considerably, mainly in the alteration of feldspars. He also noted a dramatic pH change associated with the water table, with an acidic reaction (pH of 5.5 - 6.7) above and an alkaline reaction (pH of 8.0) below. He implied that with slightly alkaline ground water, iron can be oxidized without being aerated. Baglord, et al., (1963), abraded minerals into distilled and carbon dioxide charged water and found that equilibrium was reached for many common minerals at between pH 8.0 and 11.0. Since abrasion presumably only speeds the reaction by increasing the surface area, this study demonstrates that the equilibrium pH for most minerals is not reached even below the water table. Further, though ground water circulation is relatively slow in terms of the total hydrologic cycle, it is relatively rapid on a geologic time scale necessary to deeply weather rocks. Unless complete stagnation occurs, it has to be concluded that ground water must be considered as supplying constant disequilibrium conditions on mineral surfaces below the water table.

This concept implies that meteoric weathering can penetrate as deeply as ground water percolation, but the profile of weathering with depth will not necessarily be the same (Nossin and Levelt, 1967). Seismic profiles over weathered granitic regoliths have consistently shown the weathering front to be highly variable. This has also been shown by Mabbutt (1961), who claims the weathering front exhibits more relief than the initiating surface. Because chemical reactions are guided by environmental conditions which vary with depth, even where petrology is constant, both the weathering products formed and the weathering front would logically show some variability and would not merely parallel the surface.

Dennen and Anderson (1962), in a spectro-chemical study of weathering products, considered local environmental conditions to be more significant in determining chemical changes in rocks with weathering than are either climate or mineralogy. In any case, this differentiation of weathering products with depth has long been evident in soil profile studies, but has been generally lacking in studies of deep weathering profiles. Nossin and Levelt (1967) are notable exceptions to this rule. They point out that environmental changes with depth are represented by the type of secondary minerals present, with initial secondary minerals being altered as they come closer to the the surface. The logical collorary to this is that the chemistry of weathering, the type of secondary minerals formed, and rate of weathering at the weathering front cannot be accurately assessed by measurement of near surface parameters.

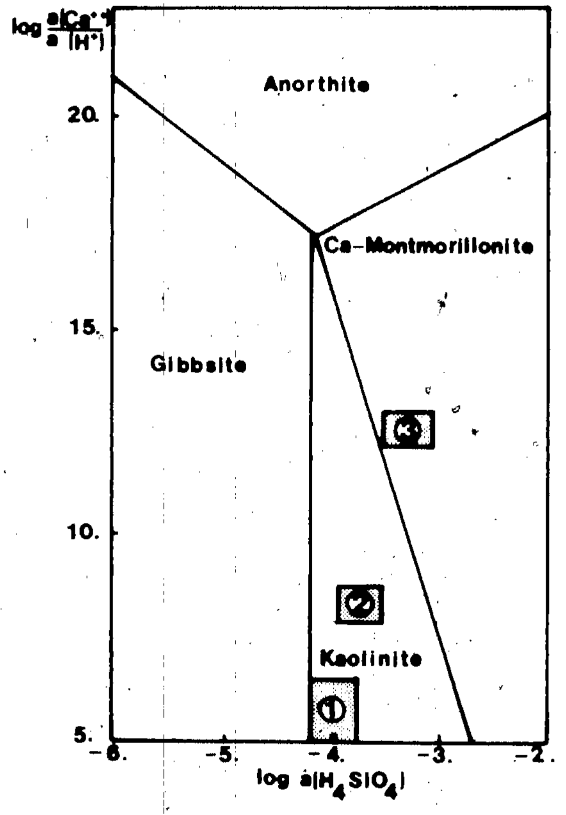
Hydration and reduction with base exchange are considered to be the most common reactions below the water table. Hydration, the incorporation of molecular water into the mineral structure, necessitates changes to the structure which are almost always thought to be accompanied by a volume increase. However, Ollier contends:

> "As mineral alterations result in the formation of new minerals of lower density than the originals, it is usually assumed that the mineral expands on weathering. Rocks, being composed of minerals, are assumed to expand likewise when weathered. Commonly when a rock weathers at the earth's surface it does expand, the change in volume causing distinctive weathering features. However, a great deal of weathering occurs without volume change. Constant volume weathering takes place at some depth below the earth's surface.
>
> In many areas where there is extensive deep weathering it is found that structures of the original rock are perfectly preserved despite extensive chemical and mineral alteration. Small quartz veins are often the best indicators, but joints, small faults, original bedding or gneissic banding, xenoliths, and many other sedimentary, igneous or structural features may be preserved as ghost structures in the weathered material.
>
> The outline of original joint blocks can be seen, and the joints remain straight. It seems very unlikely that joint blocks could expand without deforming or destroying the joint pattern, yet joints between thoroughly weathered blocks remain straight, and furthermore in attitudes that match the jointing in associated unweathered rock." (Ollier, 1969, p. 174)

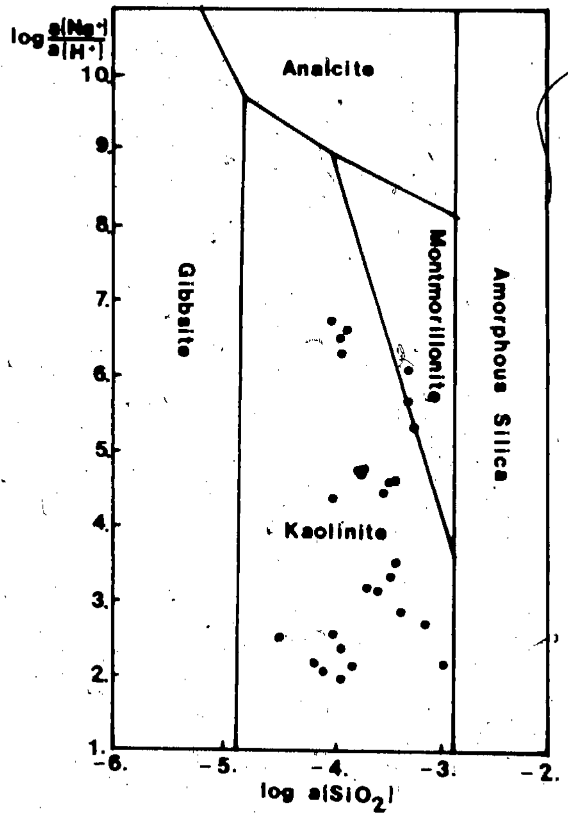
Ollier also contends that constant volume weathering may occur as close as 1 m. from the surface. This claim creates problems for theoretical hydration occurring well below the water table, because, of all reactions, hydration seems least likely to yield the same volume. If correct, this adds another complex dimension into environmental variability, where confining pressure at the weathering front affects chemical equilibrium such that idealized descriptions of weathering reactions may not apply.

Solution, in association with hydration, has been used as a possible explanation for constant volume alteration. Brickner (1968) recognized that the remarkable constancy of dissolved silica in natural waters, well below the saturation level for amorphous silica, suggests a mineralogical control of dissolved products by silicate rocks. Further, by back-reacting the silica and soluble cations in natural waters, the mineral(s) responsible for the dissolved cations could be derived by comparison of fresh rock chemical analysis with that of the residual material, with additions of the dissolved cations in the natural waters. Thus, Brickner calculated that oligoclase and biotite weathering account for nearly all the dissolved load from streams and ground water in a small mid-latitude drainage basin located entirely on granite. Brickner also noted that the reaction between rain and feldspars is rapid (experimental study showed only a few hours to a few days are needed to reach the equilibrium silica concentration). In the reaction, SiO_2 is released until the concentration approaches 4 micrograms/liter, after which any further silica released combines with aluminum hydroxide to form kaolinite. This will continue until either aluminum hydroxide or silica are no longer available to sustain the reaction. Figure 9 exhibits equilibrium diagrams of natural

Figure 9. Equilibrium diagrams for natural waters.



Equilibrium diagram for the system $CaO-SiO_2-Al_2O_3-H_2O$ at 25°C., and 1 atmosphere. Position of natural waters are shown at (1) Ivory Coast, (2) France, and (3) Chad. (after Tardy, et al., 1973, page 278).



Equilibrium diagram for the system $Na_2O-Al_2O_3-SiO_2-H_2O$ at 25°C. and 1 atmosphere. Showing positions of waters from granite and rhyolite drainages. (after Hess, 1966, as adapted by Brickner, 1968, page 111).

waters showing a tendency for alteration to kaolinite in more humid climates.

The Role of Climate:

Another controversy in the evolution of inselberg forms is the question of 'klimamorphologie'. Climatic morphogenesis implies that the effects of the persistence of a given climate type (assuming this concept is valid) over significant geological time produces a regional suite of landforms indicative of weathering and removal agents in that climate. The widespread association of tors and other inselberg forms in granitics with moderate to deep weathering profiles has, for some, come to imply that climates known to have produced such regoliths in the tropics must at one time have prevailed outside the tropics where similar associations occur. Because of relatively rapid climatic fluctuations in Quaternary times, climatic geomorphologists studying weathered regoliths have commonly sought their origins in pre-Quaternary times. Inselberg forms are thus favoured topics for some paleoclimatic investigations.

Although two-stage morphogenesis is not universally accepted, most investigators concede that inselbergs can result from stripping of a differentially-weathered regolith. A number of authors, particularly those who have lived or studied in the tropics (Budel, 1958; Cotton, 1961, 1962; Tricart, 1972; Dury, 1971; and many others), adhere to the concept of climatic morphogenetic regions, and especially emphasize the role of tropical climates in the formation of a weathered regolith. This has prompted the supposition (Linton, 1955; Thorpe, 1969; Oberlander, 1972) that warmer, wetter climatic conditions than presently occur are needed to explain the occurence of regoliths in mid-latitudes. Conceptually appealing theories, such as that the savanna climate is the most likely to produce inselbergs through wet season weathering and dry season stripping, have firmly embedded 'klimamorphologie' into the fabric of the study of weathering residuals. Since weathered regoliths and inselberg landscapes have been widely studied in the tropics, a popular theme among climatic geomorphologists is that inselberg landscapes in other latitudes are prima facie evidence of former tropical climates there.

The problem in this interpretation is not whether tors, bornhardts, and other inselberg forms are tropical forms, but whether essentially the same types of weathering residuals can be produced outside the tropics without necessarily invoking a bias towards tropical climate morphogenesis. A number of investigators examined weathering by using only precipitation as an indicator. Because of the importance of water in chemical and physical weathering, it is not surprising that a correlaton between precipitation and weathering exists. For example, Barshad (1966) found a relationship between characteristic secondary minerals formed and mean annual precipitation. Weinert (1965) combined temperature with precipitation to describe characteristic weathering suites in South Africa that varied with potential evapotranspiration.

Other approaches to the notion of climatic morphogenetic regions have used not only climatic but also biotic indicators for delineation. Perhaps most well known is that of Peltier (1950), whose inductive approach uses mean temperature and precipitation figures to define hypothetical zones of climatic influence and attendant weathering and removal processes. Budel (1963) used a synthetic approach by looking at dominant landforms and processes in zones defined by broad vegetation, soil, and climatic regions based on the present climate. Tricart and Callieaux (1962) echo to a degree the work of Budel, but their own work and that of Strakov (1967) center more on processes involved in the development of landforms than on the landforms themselves. Strakov (1967) proposed a zonal model for tectonically inactive areas (shown in Figure 10). Factors included in his model are precipitation, vegetation, evaporation, and mean annual temperature. These factors are presumed to produce conditions conducive to the formation of deep weathering mantles in certain latitudinal zones. In Figure 10 Strakov shows the humid tropics and wetter mid-latitude zones as providing the best opportunity for deep weathering. It should be noted, however, that this model does not necessarily imply, as others have contended, that weathering products will differ between zones. Nikofferoff (1959) and Strakov (1967) view the situation of soil formation and weathering as a continuous 'universal' process, operating in the same way over the earth, but at different rates. This theory, though it incorporates important climatic and biotic factors, tends to

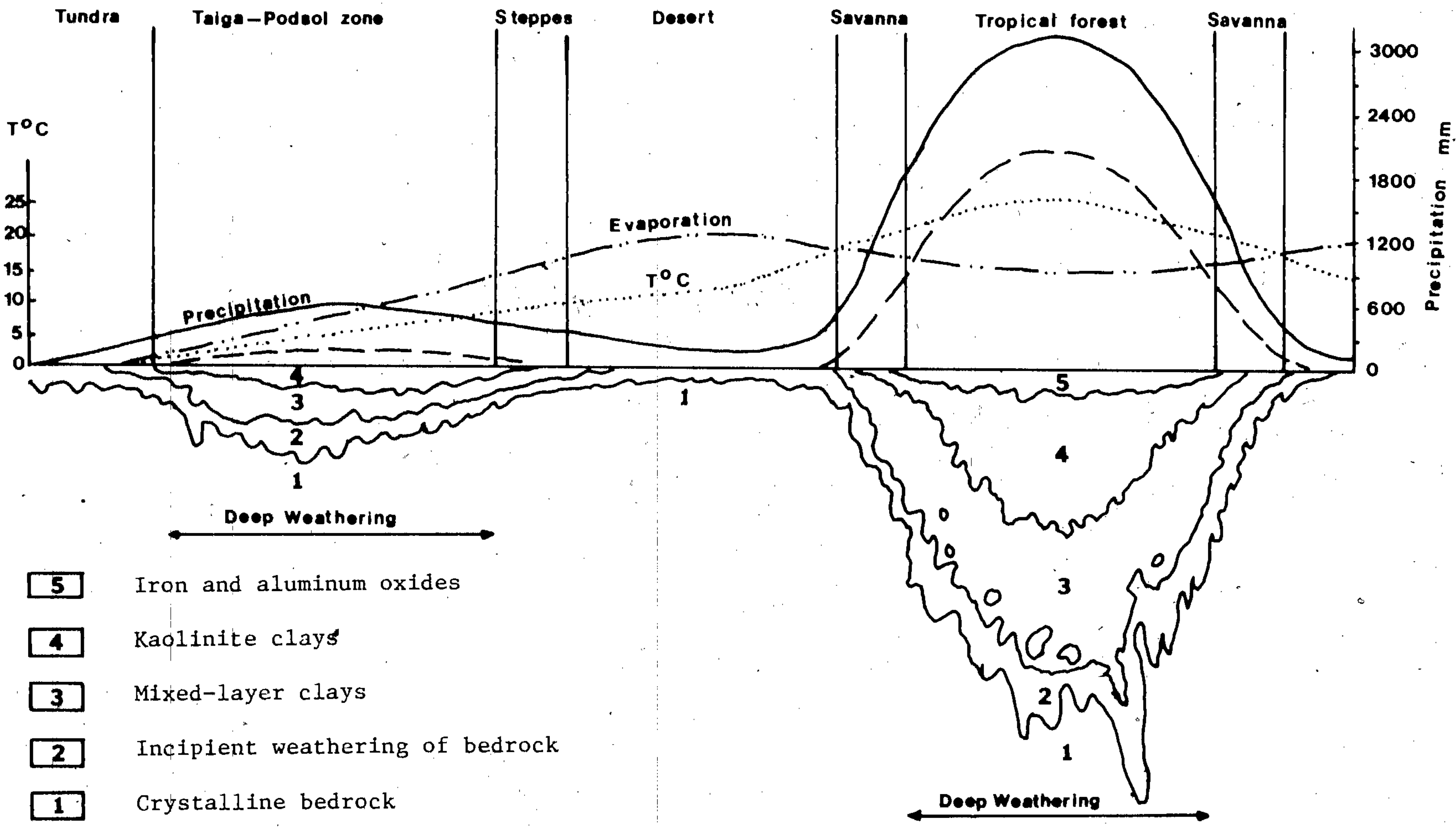


Figure 10. Schematic of the formation of weathering mantles in tectonically inactive areas (adapted from Strakov, 1967, p. 9).

substitute time for location as the controlling variable. Thus while climate affects rate of weathering, enough time and tectonic stability (and essential climatic and biotic factors) could, according to Strakov and Nikofferoff, eventually yield the same weathering forms and residues in the higher latitudes as in the tropics.

Regardless of the perspective taken by advocates of 'klimamorphologie', the validity of the 'climatic morphogenetic region' is threatened by two persistent problems (Stoddart, 1968). The first is that of interference, such as where distinctive climatic zones existing during and since Quaternary times overlap in a broad boundary zone and anomalous landforms may occur which are indicative of more than one morphogenetic region. This is especially thought to occur in tectonically active areas, and where Quaternary climatic fluctuations were extreme. The second is that of succession, where an assemblage of climatically-induced landforms are not completely or immediately formed or erased before the advent of a different climate. These landforms may exhibit a longevity in the subsequent climate not characteristic of them in the climate of their origin.

Other studies have come to the conclusion that climate _per se_ is not an important factor in guiding the direction of weathering reactions. Dennen and Anderson state:

> "Climatic factors (mean temperature, mean rainfall) apparently have no direct influence on the weathering reactions in kind, but are probably effective in degree." (Dennen and Anderson, 1962, p. 383)

This conclusion is reiterated by Pickering, whose experimental results:

> "...indicate that the dissolution reactions in silicate rocks are essentially the same regardless of temperature, and should dispel any idea that chemical weathering processes are different in the tropics than in cooler climates. The chief beneficial effect that high temperatures have on chemical weathering is to speed up dissolution reactions which can take place in aqueous solutions at any temperature. Chemical weathering should thus be more rapid in tropical climates than in cooler climates, if other weathering factors are equal, but no different in its manner of progress." (Pickering, (1962, p. 1197)

Tardy, et al., (1973), in a study of weathering differences in tropical and temperate climates, also found that changes from primary to secondary minerals followed the same sequence in all climatic areas. This does not mean, however, that differences induced by climate are negligible. Since all climates will weather separate primary minerals at a distinct rate and to a different degree, the dominant secondary mineral assemblage produced tends to reflect the weathering sequence and environment of the primary mineral most susceptible in each climate. This could be offered as at least one explanation for the apparently divergent claims that first, different climates produce different weathering residues and second, minerals tend to undergo the same sequence of chemical breakdown regardless of climate. The mineral specific weathering sequence demonstrated by Tardy, et al. (1973) is shown in Table 6.

The associations most commonly found by Tardy et al. (1973) in sandy saprolites (grus) are listed in Table 7.

TABLE 6
SECONDARY MINERALS FORMED BY WEATHERING OF SPECIFIC MINERALS

K-feldspar————————> Kaolinite ————————>Gibbsite

Biotite —> (Chlorite) ————>Montmorillonite
\
\-> Vermiculite —> Al-Vermiculite —>Kaolinite

Plagioclase—>Vermiculite—>Montmorillonite—>Kaolinite—>Gibbsite

———— PROGRESSIVE WEATHERING ————>

TABLE 7
SANDY SAPROLITE WEATHERING ASSOCIATIONS

Temperate Climates:	Biotite————>Vermiculite Plagioclase—>Montmorillonite and Kaolinite
Arid Climates:	Biotite————>Montmorillonite Plagioclase———>Kaolinite
Humid Tropical Climates:	Biotite————>Kaolinite Plagioclase———>Kaolinite K-feldspar———>kaolinite
Very Humid Tropical Climates:	Biotite————>Kaolinite K-feldspar———>Kaolinite and Gibbsite Plagioclase———>Gibbsite

Acceptance of these progressions would imply that over a long period of time at constant climatic conditions, all weathering would lead to the same end (i.e., gibbsite followed by complete dissolution). However, mechanical erosion is likely to intervene before this end is reached, so that in most cases this circumstance can be regarded as hypothetical even in the humid tropics.

The fact that deep weathering profiles are more common in the tropics than in the higher latitudes, is no surprise, since weathering rates are greatly influenced by temperature. Also, few tropical areas have experienced glaciation capable of removing a regolith in the way that Pleistocene glaciations did in higher latitudes. Lukashev (1958) postulates that a 10° C. rise in temperature will result in a 2 to 2.5 X increase in weathering through the greater dissassociation of water into component ions at higher temperatures.

Intense leaching and chemical activity are promoted by the high precipitation and warm temperatures in the tropics, and result in rapid decomposition of bedrock. Moreover, stable cratonic areas in the tropics have been subjected to similar weathering processes over periods which are very long term in the geologic time scale.

However, absence of climatic bias in weathering reactions suggests that deep weathering cannot be regarded as a tropical phenomena. While marked differences in the rates of weathering will exist because of climate, relief, and other factors, the development of a regolith cannot be relegated to a particular climatic zone. Evidence supports the concept that the only condition necessary for the formation of a weathered regolith is that chemical weathering decomposes rock faster than erosional processes remove regolith material. Production of a deep weathering regolith is favored by the combination of moderate to heavy precipitation with a tectonically stable, low relief area in which erosion is minimized.

Thus, deep weathering profiles will develop more slowly in mid-latitiudes than the tropics because of the lesser rate of chemical weathering and slower production of decomposed rock. The mid-latitude regolith will result in less gain in regolith depth over a given period as compared with the tropics. Also more time will be needed to re-establish a regolith in the mid-latitides following tectonically or climatically induced disturbance (e.g., glaciation) and removal. Therefore, the absence of extensive intact regoliths in the mid-latitudes is no indication that they never existed, nor that regoliths could not form under present conditions. The documentation of Pleistocene glacial removals of regolith from the Canadian Shield (Feininger, 1971), of Tertiary regoliths and tors which have survived active glaciation in the Cairngorm Mountains and the Isle of Arran, Scotland (Cunningham, 1968), and of climatic changes to aridity which resulted in the stripping of weathered mantles (Oberlander 1972), provide evidence that many mid-latitude regoliths have been removed, diminished, or simply disguised by climatic aberrations of the Pleistocene.

With reference to landforms emergent from these regoliths, Kessel (1973, p. 101) reviewed available studies on inselbergs and concluded that "...inselbergs including bornhardts [domed inselbergs] are found in practically all climates". His review cites studies from humid tropical, savanna, subtropical and semi-arid Mediterranean, humid continental, and sub-arctic climatic zones and gives a relative percentage of weathering residual studies in each zone.

For a number of reasons, the proportion of investigations in each zone is not particularly indicative of the actual distribution of inselbergs. First of all, there tends to be a naturally occurring disparity in the amount and focus of geomorphic research between climatic regions. That is, a lack of studies of inselberg forms does not necessarily reflect the absence of inselbergs, but rather may reflect a regional lack of interest in studying the forms that are present. Secondly, Thomas (1978b) suggests that the terminology used and conceptual framework of the investigator may vary widely. For instance, though western Montana offers perhaps a dozen or more distinct areas affording opportunities for study of weathering residuals developed on igneous bodies, very few have been studied from this perspective and only very recently have any studies (USDA, 1977; Simons, et al., 1979) referred to residual forms with the terminology (tors, domical inselbergs, etc.) commonly used by non-American geomorphologists. Distribution of geomorphologists and their areas fo interest must be an important factor.

The Role of Lithology and Structure:

Although their occurrence in coarse-grained granitic rocks is a pervasive theme in the literature (Thomas 1978b), weathering residuals are reported on a wide variety of rock types. The prevalent association of granitic rock types with weathering residuals has led to a situation (which is not justifiable) where the weathering landforms developed on granitics are commonly regarded as the standard of comparison for virtually every weathering form on other rock types. This review will focus solely on weathering in coarse-grained granitic rocks similar to those found in the Boulder batholith.

Petrology. Weathering susceptibility in silicate rocks has been shown by Goldich (1938) to approximate the reverse of the reaction series postulated by Bowen (1928). This generally means the higher the silica content the less susceptible a mineral is to alteration. Strunz (1941, in Keller, 1957) paralleled this classification of susceptibility by speculating that weathering was related to how closely each mineral structure imitated the three dimensional tetrahedral array of quartz, where Si:O bonds are satisfied without extraneous ions. A tidy, reverse relationship between Goldich's and Bowen's series is not necessarily to be expected because of the great disparity in pressure and temperature between the environments of formation and of weathering. Also, the micas and feldspars are generally found to be exceptions to this susceptibility of weathering order. For example, field studies of weathering susceptibility tend to find the same sequence (see Dennen and Anderson 1962, Harris and Adams 1966, Nossen and Levelt 1967, Ollier et al. 1963), with anomalous weathering in feldspars, especially plagioclase (Todd, 1968; Dumanowski, 1968), and in biotite (Blank, 1951; Dumanowski, 1964; Melcon, 1975; Eggler et al., 1969; and Oberlander, 1972).

Granitic rocks, then, are composed of minerals with a varying degree of weathering susceptibility, and the degree to which the mineralogy differs will in large measure determine the nature of weathering attack. For example, weathering residuals are commonly reported in coarse-grained granitics (Linton, 1955; Ollier, 1960; Demek, 1964a, 1964b; Melcon, 1975). In some cases, the distribution of residuals has been attributed to a change from coarse-grained to a less resistant, fine-grained granitic variety (Radwanski and Ollier, 1959; Eden and Green, 1971). This has theoretically been attributed to smaller crystals having a greater surface area per unit vol~~ume than~~ larger crystals (Melcon 1975), though Ruxton and Berry (1957) have reported the reverse of this relationship in Hong Kong landforms.

Probably more important than crystal size is the interlocking nature or natural cohesiveness of the crystals in the granitic rock. Volborth (1962) has shown that many characteristics of crystalline interlocks are dependent upon the crystallization environment and whether the pluton roof can withstand the increasing vapour pressure during the final stages of crystallization. If vapour pressure is maintained, the final minerals to form tend to show more euhedral crystalline structures, resulting in 'rapikivi-type' or 'moro' granite which disaggregates readily because of the many parting planes along crystal faces. Conversely, if through volcanism, rapid loss of vapour pressure occurs then "...many centers of crystallization will form..." and the residual fluids will result in "...second generation feldspars and quartz." (Volborth, 1962, p. 817). This second generation quartz and feldspar will crystallize in the miarolitic cavities that make 'rapakivi' granites so porous, without attaining characteristic crystalline faces. Thus, the late deuteric phase can influence porosity, mineral size, cohesion, and jointing from latent stress set up in crystallization centres (Balk, 1937).

The sharply contrasting weathering susceptibility of individual minerals in granitic rocks seems to have some bearing on the distribution of weathering residuals. However, it is rare that this influence can be separated from other factors. In some cases, plutonic rocks richer in ferromagnesian minerals have been shown to result in subdued topography, with less relief than adjacent granitic rock types (Nossin, 1964; Schroder, 1973). Again, this generalization is not strictly true in all situations, since Warnke (1969) postulates that, while quartz monzonite is the rock type invariably associated with pediments, rocks either more felsic or mafic give rise to positive relief. The smooth, granitic Red Hills adjacent to the rugged, gabbro peaks of the Coolins on the Isle of Skye, Scotland illustrate this same qualification (Cunningham, 1982, personal communication). The resistant minerals in granitic rocks tend to slow the chemical weathering attack affecting the more susceptible minerals. However, the degree to which coarse-grained granitics result in differential weathering attack and weathering residuals is related to the ability of susceptible minerals to induce stress and even fracturing in surrounding, less susceptible minerals. Bakker (1967) has described the wide occurrence of sandy regoliths in the mid-latitudes developed by the process of 'arenisation'; the disruption of crystalline bonds by expansion of susceptible minerals resulting in *in situ* grus which may retain the original structure of joints and veins. Ollier (1966, 1971), as discussed earlier, has disputed the concept that expansion of selectively weathered minerals results in a volume change capable of crystal disaggregation in granites. Rather, Ollier postulates, the confining pressures at the weathering front cause 'constant volume alteration', except in near surface environments. The argument is largely academic, since fracturing of surrounding crystals by expansion of biotite can be readily demonstrated in thin sections. Even if constant volume alteration does occur, analytical proof of this concept is difficult given the near impossibility of analyzing an altered sample without releasing latent stress once confining pressures are removed.

Jointing. Both Handley (1952) and Linton (1955) deduced that structural controls, related to the orthogonal spacing of joints in granites, were primarily responsible for directing the subsurface weathering attack. Also, bi-directional attack at joint plane intersections was thought to result in rounding or 'spheroidal weathering' of original blocky structures. In this view, wherein horizontal structures are commonly deemed subordinate to vertical discontinuities in guiding agents of denudation, the spacing of vertical joints has typically been credited with creating differential subsurface alteration. Linton's original diagram illustrating the importance of joint spacing is shown in Figure 8. Although the original explanation was to explain the morphogenesis of tors on Dartmoor, the theory was readily and perhaps hastily extended to other areas and landforms (Ollier, 1960, Mabbutt, 1961; Thomas, 1965).

Reasons for jointing are numerous and will not be fully reviewed here. Price (1966) provides a review of the theory of brittle fracture in isotropic, homogenous solids and relates this theory to common rocks, including granites. Balk (1937) has described structural behavior, including jointing, in igneous rocks and derived a great deal of insight about jointing from observations taken from the Boulder batholith in Montana (Grout and Balk, 1934).

Vertical joints are commonly attributed to lateral extension during uplift, creating stress which may exceed the tensile strength of the rock. Since the stress is not preferential on the horizontal plane, granitics tend to develop orthogonal to sub-perpendicular vertical joint sets. Horizontal joints are commonly attributed to tensile fracture related to pressure release through erosional unloading, changing the vertical pressure gradient from earlier equilibrium conditions and expanding the rock in a direction normal to the plane of unloading. These are called extension fractures (Billings, 1972) and can often result in curvilinear joint patterns where jointing develops in parallel with either differential landscape denudation or the original pluton roof configuration. [see Blank (1951), Thomas (1965, 1966b, 1974b), Twidale (1964), Kranck (1957), Jahns (1943), Hack (1966)].

The fact that jointing commonly follows the surface configuration of domes and domical inselbergs has generated considerable speculation as to the sequence of cause and effect. That is, it is not known if extension (exfoliation, sheeting, domical, etc.) joints are a cause or a consequence of the domical form of many inselbergs. Generally, there is evidence on both sides of the question to suggest that either case may happen. Some domical forms seem to be inherited from 'cupolas' in the batholith roof (Cunningham, 1971), but other predestined domes may result from crystallization centres theorized by Volborth (1962) or from marginal cooling in the peripheral zone of a pluton (Balk, 1937). Others regard the formation of domical structures as induced by near-surface response to topography developed on an exhumed pluton. Chapman (1958) points out that an infinite number of potential joint planes exist and extension joints that do appear are necessarily of surface origin. This view is supported by Gilbert (1904), Matthes (1930), White, (1945), Twidale (1964), and in particular by King (1948, 1966), in his pedimentation and parallel slope retreat theory of bornhardt development. It is apparent that many factors and processes can result in a domical landform in granitic rocks, thus making domical inselbergs and bornhardts excellent examples of the 'principle of convergence' (White, 1945; Cunningham, 1969, 1971).

Vertical joints, however, have been ascribed the most importance in development of smaller scale landforms such as tors and fins or blades. In addition to Linton's (1955) theoretical explanation for tors, others actually measuring joint density have used this parameter to explain landscape differentiation (Kaitanen, 1969; Thomas, 1974b). Twidale (1964) describes similar variations in joint density, but stresses that joint openness and orientation are just as significant as frequency. In most cases, however, measurement of joint density is problematic due to incomplete exposure of bedrock and:

> "...in the field only those fractures which have dilated sufficiently to be detected can be recorded. Tightly closed and incipient joints are passed over unknowingly." (Chapman, 1958, p. 532.)

The role of joint density in both incipient weathering and ultimate differentiation at the weathering front as originally proposed by Linton (1955) has generally been uncritically accepted as plausible, possible, and indeed, probable. However, no study has yet established any conclusive evidence that verifies this concept in a field situation, nor have specific causes of variable joint density been adequately demonstrated. Indeed, many other factors may be responsible for variation of the weathering front, including mineralogy (Volborth, 1962), micro-cracks (Bisdom, 1967), and potential jointing (Chapman, 1958), all of which may influence porosity and weatherability of the rock.

Perhaps the one significant feature that seems to be attributable to jointing is the paucity of tor landforms where jointing is irregular. Oberlander (1972) reports from the Mojave Desert only irregular blocks, walls, and pinnacles in areas where non-orthogonal jointing occurs, instead of characteristic boulder-mantled domes and tors. This same observation is applicable to the Boulder batholith, where in some areas secondary jointing related to the varied tectonic history largely precludes the tor landforms that occasionally occur on other areas of the batholith.

The Role of Biotic Agents:

Geomorphologists have, for the most part, ignored investigation of the role of vegetation in either the development or stripping of regoliths. Vegetation is usually considered a portion of the climatic milieu (Thomas, 1978b). This neglect of vegetation is perhaps understandable, since, given the azonal distribution of weathering residuals, vegetation may not have been viewed as necessary to the weathering process. This is especially true in arid areas where vegetation is sparse. The one theme that has pervaded the literature is the concept that a savanna climate (and implied vegetation type) would be most advantageous for the formation of weathering residuals (Cotton, 1961,1962; Cunningham, 1978). The optimal 'savanna' conditions would provide both high temperatures and seasonally abundant rainfall conducive to rapid weathering, while the relatively sparse vegetation abets stripping. Strakov (1967) includes vegetation in the complex of factors affecting weathering. The problem currently seems to be one of lack of investigation, not lack of recognition of the importance of effects attributable to vegetation.

Vegetation affects the weathering process in several important ways. These are direct biogeochemical interaction; indirect biogeochemical interaction; and mechanical breakage. The biogeochemical processes are probably the most important in terms of weathering in granites, since chemical alteration of primary minerals by biotic compounds is as effective as, for example, tree roots, at causing disaggregation and formation of grus. In fact, the development of micro-cracks by chemical alteration of susceptible minerals through biotic agents like lichens may be a necessary step to provide an initially suitable rooting medium.

Biogeochemical interactions that are directly induced by vegetation include the discharge of acids from root hairs and the removal of free cations for photosynthetic processes. Lichens accomplish the same end a little more directly without the benefit of roots. Acid discharges from the root hairs of plants are closely related to organic acids in soils. As the result of the life processes of micro-organisms and the discharges from plant roots, low-molecular organic acids are formed in soils (acetic, formic, isocitric, lactic, oxalic, tartaric, malic, succinic, gluconic, butyric, fumaric, etc., Kononova, 1951; Peyve, 1961). These compounds greatly affect the general acidity of the soil and the dynamics of mobile cations and anions in a regolith. Acids, formed indirectly through decay of vegetation and by rainfall through a vegetative canopy, have a similar effect on soil pH.

In many cases, soil bacteria (the 'silicate bacteria' of Aleksandrov, 1953; Aleksandrov and Zak, 1950) can directly affect the breakdown of silicate minerals. The effect of silicate bacteria on aluminosilicates (for example, on biotite or muscovite) is to free interlayer potassium and make it mobile and available for use by plants. In a regolith the most favourable conditions for life processes of silicate bacteria occur around the roots of plants, making these organisms to some degree rhizospheric. Thus, symbiosis may exist where silicate bacteria, mobilizing chemical elements from aluminosilicates, make these elements available in a form useable by plants which absorb the freed cations.

The importance of these silicate bacteria to the study of weathering residuals also lies in the fact that this group of micro-organisms is azonal, occurring in virtually all elevational and climatic zones on the earth's surface (Drzal and Smyk, 1968). This is not to claim that silicate bacteria are responsible for the azonal distribution of weathering residuals, but the correlation certainly suggests that further investigation is warranted.

Most studies of weathering focus on the primary importance of water as a weathering agent [see Chorley (1969) for a review of the role of water]. The relative importance of biotic factors in emphasized by the following quote:

> "The presence of water as the most efficient solvent and its physiochemical properties and biochemical activity are responsible for separation and enrichment processes in the

> [fresh water] cycle. Even more effective in mobilization and transportation processes during weathering is the biosynthesis of chelating and sequestering agents." (Pauli, 1968, p. 45)

It is evident that the presence of vegetation materially increases the rate of weathering (Cawley, et al., 1969; Strakov, 1967).

In an east-west transect studying soil clay distribution from the Sierra Nevada to the Great Basin of the western United States, halloysite was found in soils under pine forests (in a humid, leaching environment), whereas at sites under desert shrub vegetation (semi-arid, non-leaching) montmorillonite was more common (Birkeland, 1969). The purpose of Birkeland's study was to focus on paleoclimatic implications of soil clay distribution over an area showing persistent climatic differences over time and where climatic change would affect all parts of the transect roughly equally. The same association of secondary minerals was found under coniferous and sagebrush-grassland vegetation types, on the Boulder and Idaho batholiths respectively (Tolar, 1959; Hood, 1963; Clayton, 1974). Under these circumstances, however, both vegetative types are found in close association and the same broad climatic conditions must be inferred to have operated over time. One possible conclusion that can be drawn, is that the clay minerals developed are related to the vegetative cover (as is concluded by Hood, 1963). To the extent that the vegetative patterns on the Boulder batholith exhibit microclimatic variations related to factors such as slope aspect, the arguement becomes circular and it becomes difficult to determine whether vegetation is causative or merely correlative with clay mineralogy. Power (1969) adopts the approach that climate is but one of many influences affecting soil and clay mineral forming processes, and postulates that studies interpreting paleoclimates from clay mineralogy generally ignore important influences like vegetation. Thomas (1978b) and others have also recognized the inadequacy of studying weathering landforms from a single perspective.

The final influence of vegetation mentioned here is related to the influence it has on the stripping process. As noted earlier, the relatively sparse vegetation of the tropical savanna is thought by some to present conditions ideal for erosional stripping of regoliths. Work by Hack and Goodlett (1960, p. 58) suggests the "...elegance of the adjustment of vegetation, landforms, and soils..." results in a situation where different denudation rates can be inferred by existing patterns of vegetation. This is particulary evident on 'asymmetrical valleys' (Hack and Goodlett, 1960, p. 41; Thornbury, 1954, p. 112; Judson and Andrews, 1955, p. 333). Soil moisture availability, controlled primarily by aspect, appears to be the critical factor in vegetative control in the development of valley asymmetry. Even more important from Hack and Goodlett (1960), is the concept that regardless of the nature of the vegetative cover, the only time erosional stripping will overtake weathering is when continuous adjustments in the 'steady-state open system' (Strahler, 1952, p. 934) are interrupted by an abrupt change. Such change must be of a magnitude that the system cannot compensate, and a new dynamic equilibrium, requiring substantial geologic time to become established, is initiated. These changes can be brought about by uplift, climatic change, or vegetative disruptions like fire or agricultural clearing. This concept is echoed by Douglas (1969), who concludes that without similar influences brought on by abrupt change, the processes operating in the tropics are no more effective at denudation than the processes operating in the mid-latitudes. Neither this author nor Douglas would necessarily advocate a 'catastrophist' view of geomorphology, but some account must be taken of wildfire, volcanoes, torrential floods, and other catastrophic occurrences capable of altering the influence of vegetation. Such influences are not only significant geomorphic factors in their own right (e.g., Mt. St. Helens), but are also significant as initiators of change in the geomorphic landscape. Godard (1966) has also argued for the 'element of crisis' as the initiating step leading to exhumation of weathering residuals. Despite these works reviewed here, one must admit that the role of vegetation in geomorphic processes, and in particular, in weathering and exhumation processes as they relate to granitic landforms, is neither well studied nor understood.

CHAPTER 4

STUDY DESIGN AND ANALYTICAL METHODS

Study Design:

Simply stated, the intent of this study has been to gather and compare rock samples from weathering profiles beneath Tertiary volcanic or sedimentary covers, which have preserved intact saprolites formed on the Boulder batholith during earlier periods of exposure. The nature of these profiles is such that nearly all sample sites exhibited some weathering, and this was assumed to increase toward the top of the profile where this could not be visually ascertained due to limited exposures. Usually rock ranged from nearly fresh (requiring a hammer to chip a sample) to rock that crumbled easily in hand specimen to grus. A prerequisite for most of the samples collected was that of being obtained from a regolith that had been buried by volcanic or sedimentary deposits. This prerequisite was necessary to attempt to answer two questions. First, do volcanic and sedimentary covers protect regoliths from being influenced by weathering from contemporary climatic conditions? This, of course, depends to a certain degree on the thickness and porosity of the volcanic cover which will affect weathering penetration through the cover. All samples of this type were of necessity taken near the erosionally or depositionally thinned edge of the volcanic cover. Second, can relict weathering influences be differentiated from contemporary effects? To answer this question obviously required comparison with batholithic rocks not overlapped by volcanics. Collected rock samples were prepared and analyzed both in X-ray fluorescence powdered samples and in thin sections for the purpose of determining cation gains and losses and mineral specific alterations during weathering. This information is used subsequently to form hypotheses concerning possible climatic (both contemporary and paleoclimatic) and hydrothermal influences exhibited in the weathering samples and to supplement field observations concerning the origin and development of weathering residuals on the Boulder batholith. The value of these analytical techniques as an aid in geomorphic research on weathering residuals is briefly assessed.

Sample Collection:

Ideally, a sample collection scheme of this sort would require drill core samples. An attempt was made to obtain samples from mining claims in those areas where post-batholithic volcanism had led to mining and prospecting activity in association with volcanic cover deposits. For a variety of reasons this met with limited success. First, there was natural suspicion by claim operators of anyone doing investigative work for whatever reason. Second, there was a certain reluctance by operators to part with even a small portion of a drill core sample without extracting an exorbitant remuneration. Third, state and federal laws governing mining activities provide a blanket of anonymity that makes both owners and claim locations difficult to find without _a priori_ knowledge. Finally, the sample collection phase was done prior to recent price increases of precious metals, at a time when mining and prospecting activity was at a lull. Under these circumstances, most operators had not done any core drilling, and any samples taken from a mine site generally required entry into underground mine workings that had not been used since the early 1940's. Obtaining core samples thus met with limited success. Only one site in upper Clancy Gulch (No. 4 in Figure 2) provided such samples. These cores had been discarded and the only sampling control provided is that the three samples from this site came from the same core extracted from a mine adit penetrating a hillslope littered with Lowland Creek volcanic debris of Eocene age.

In association with attempts to locate mines, most of the contacts between batholithic rocks and younger volcanic rocks were walked to look for appropriate sample sites. Unfortunately, in most cases, the frost-fractured, talus forming volcanic rocks do not produce abrupt, clearly defined contacts with the underlying batholithic rocks.

In consequence, most of the samples used were taken either in road cuts or in prospect pits, ubiquitous phenomena on the Boulder batholith consisting of elongated trenches, bulldozer wide, and perhaps 3 to 10 m. deep at the deepest point. The road cuts offering exposures of batholithic rocks under volcanic cover were almost always on narrow, mining or Forest Service access roads, the cuts rarely exceeding 3 m. in height. With such a thin cover that a shallow road cut provided exposure of the underlying granitics, the degree of protection offered from current climatic conditions might be questioned. Nevertheless, under the circumstances, these were often the best samples obtainable.

A few samples were obtained from more recent and generally deeper road cuts along primary highways and the two interstate highway systems traversing the Boulder batholith. Some samples were also obtained from batholithic rocks from areas that appear to have been continuously exposed since the breaching of the batholith roof during the Eocene. For the most part, these rocks had been earlier analyzed (Wetzel, 1976) and provide a control for contrasting with samples that were exposed and then reburied by volcanic and sedimentary deposits. Four additional samples, two each from two sample locations, were collected and analyzed from exposed portions of the batholith to provide additional contrasts. One site introduces weathering influences from a different rock type (granodiorite) to the analysis. The sample sites are generally located with respect to the geological units shown in Figure 1. More precise locations are shown on the LANDSTAT imagery of Figure 2 and in subsequent maps in Chapter 5 showing the sample sites on portions of U.S. Geological Survey quadrangle sheets. Figure 11 indexes the Geological Survey quadrangles within the study area, with shaded areas showing the location of map portions presented in Chapters 5 and 7.

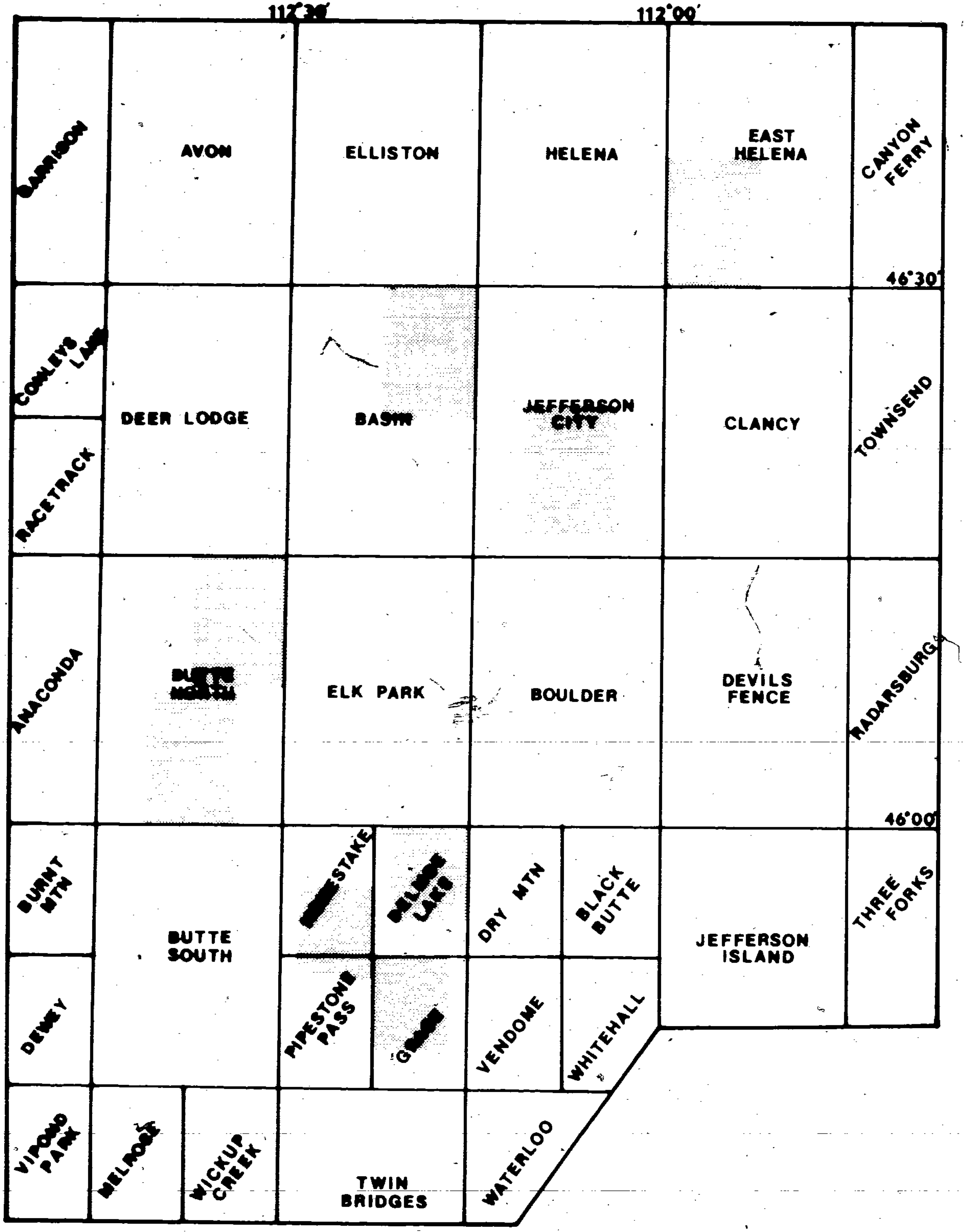


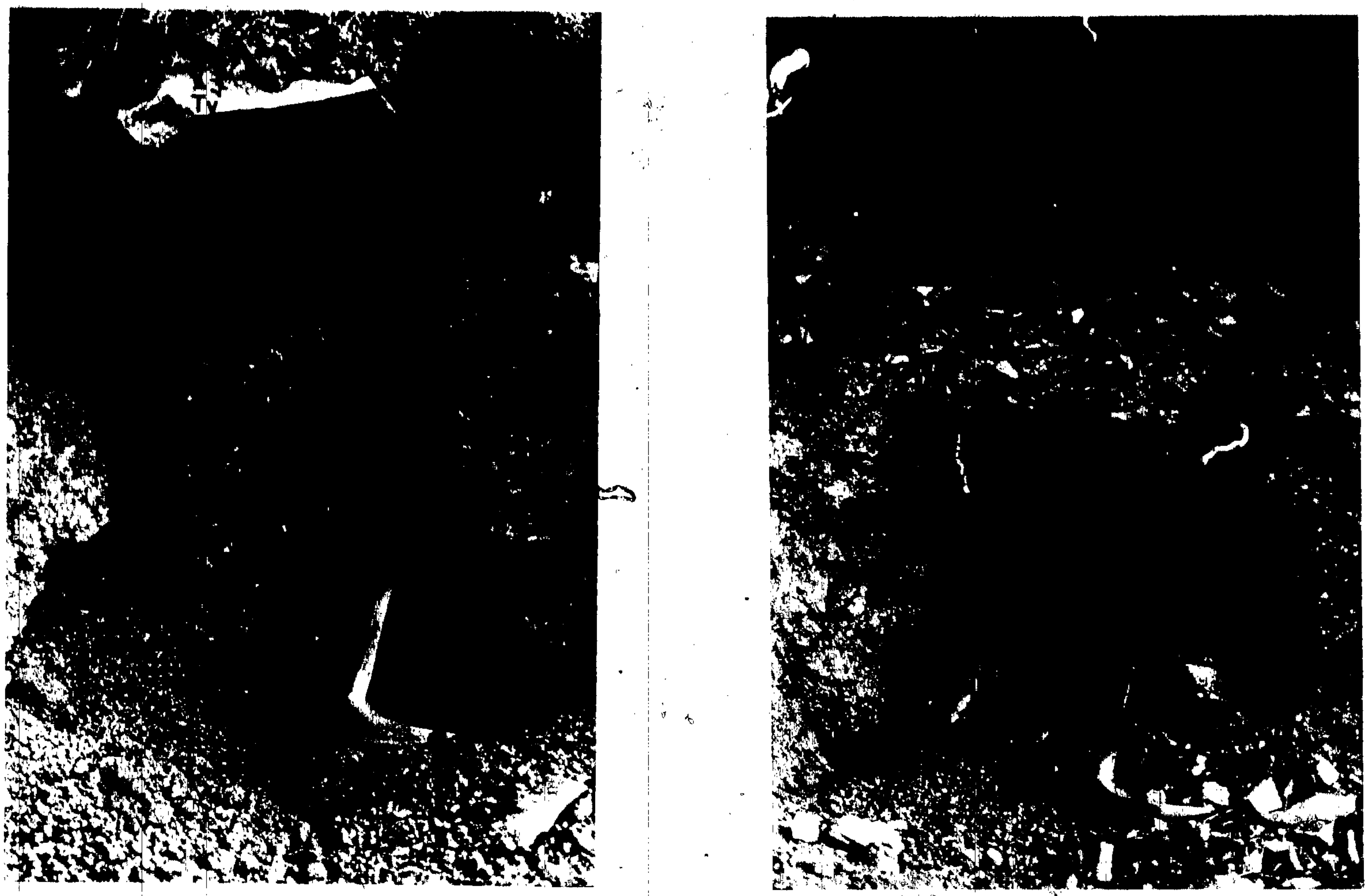
Figure 11. Index to U.S. Geological Survey Quadrangle Maps. Shaded areas indicate areas covered by sample site location maps in Chapter 5 and Figure 24 in Chapter 7.

Samples are labeled with an alphabetic (one or two letters) prefix and a numerical suffix. The alphabetic prefix denotes the initial categorization for the type of cover over the regolith. For example, R means a sample from under the rhyolitic Tertiary volcanics (Oligocene) near the northern end of the Boulder batholith; LC denotes Lowland Creek volcanics; U denotes uncovered or continously exposed sample sites; and BZ means the samples came from the border zone between the Boulder batholith and the host rock. The numbering system is sequential for each sample taken within an alphabetic group. For subgroups, representing a single collection site, the first or lowest number in that subgroup corresponds to the least weathered sample collected in the field; the highest number in each subgroup represents the most altered sample. Table 8, presented with the results in Chapter 5, lists the samples analyzed and relates them to sample locations shown in Figure 2 (and on larger scale location maps also in Chapter 5). Gaps in the numbering sequence represent samples not subjected to any laboratory related analysis, usually due to disaggregation during transit which made obtaining representative powdered samples or thin sections impossible.

Some problems, subsequent to the collection of the samples, arose through alternative interpretations of the geologic setting made by different investigators. One instance is particularly important in the interpretation of the results. Photograph 3 in the geology chapter shows an outcrop of volcanic rock at the Boomerang Gulch sample site (No. 7 in Figure 2).

Photographs 15 and 16 show sample pits at the Boomerang Gulch site, and are characteristic of pits dug at other locations to expose the underlying quartz monzonite. In outcrop appearance and in hand specimen examination, this volcanic outcrop is typical of literally hundreds of other outcrops of the post-Lowland Creek rhyolite covering batholithic rocks in the northern portion of the Boulder batholith. On this basis, the four samples collected at this location were assigned an R prefix, meaning they were collected from beneath the post-Lowland Creek rhyolite overburden and thus might reflect early Oligocene climatic influence in mineral specific alterations. However, Becraft, et al., (1963) have mapped this unit as part of the Lowland Creek volcanics to which Smedes and Thomas (1965) assigned an Eocene age by radiometric methods. Knowing whether the regolith preserved here is Eocene or Oligocene is fundamental to the proposed comparative analysis, but no radiometric dating has been done on specimens from this particular outcrop by either Becraft, et al.,(1963) or this author. Also, this outcrop is physically separated from other rocks of the Lowland Creek group. Thus, on the basis of frequent recognition of this unit in the field while searching for sample sites, a tentative R prefix remains in the sample description.

Similar problems occur at the sample site on Clancy Gulch (No. 4 in Figure 2). There is some question whether the sample site is from below the cover of the basal breccia unit of the Lowland Creek volcanics described by Smedes (1962), or whether it is from below the roof pendant of Elkhorn Mountains Volcanics



Photographs 15 and 16. Sample pits at Boomerang Gulch exposing weathered regolith beneath Oligocene rhyolitic overburden.

which outcrops on either side of the breccia unit at the sample site. Clarification of this point would require entry into an abandoned, partially-collapsed mining adit.

Another sample gathering problem stems from the inability to gather samples showing contrasting vertical profile weathering in close proximity to each other (in order to minimize effects from areal compositional variance inherent in plutonic rocks). For example, samples R-3 through R-6 gathered at Old Baldy Mountain (No. 3 in Figure 2) were gathered in separate exploration pits over approximately 400 m. linear distance. Though the samples were arranged according to intensity of iron staining (and presumably weathering), the X-ray analysis of these samples showed no trends that were apparent where better sampling control could be exercised.

X-ray Fluorescence Analytical Procedures:

Introduction. Energy dispersive X-ray fluorescence (EDXF) is a relatively recent analytical method for distinguishing elements in rock samples. Initial application of the technique was for the determination of trace elements as these tend to have middle to high atomic numbers (Z) and are thus more easily detected with conventional high energy or 'hard' X-rays (see for example, Chamberlain and Leech, 1966; Blount, et al., 1972; or Goulding and Jaklevic, 1973). Progress in the development of the silicon-lithium or Si(Li) detector X-ray spectrometer for detection of energy dispersive (fluorescence) and wavelength dispersive (diffraction) X-rays has enhanced detection capabilities down to and including carbon (Z=6) (Porter and Woldseth, 1973). Other applications involve 'fingerprinting' of obsidian artifacts as a means of reconstructing trade patterns from archeological evidence (Bennett and D'Auria, 1974), and extension of the detection limit in silicate rocks to oxygen (Z=8) by the use of low energy 'soft' X-rays and 'open window' detection systems (Gregory and Ereiser, 1974). More recently, Thomas (1978a) has initiated the use of this technique in the study of granite weathering.

Apparatus. The EDXF system consists of an X-ray tube with a gold anode primary target, High speed electrons bombarding the primary target 'knock' inner K or L shell electrons from their orbital paths, causing an outer shell electron to move closer to the nucleus to act as a replacement. This movement releases energy in the form of bremsstrahlung radiation or X-ray photons. These photons irradiate a secondary target, again producing X-rays at the K shell energy level of the secondary target. Choice of a secondary target depends on the range of Z values the investigator wants. Spectral intensity decreases as the range of atomic numbers below the secondary target increases. Hence, silicon (Z=14) is barely detectable with molybdenum (Z=42), but is readily detectable with titanium (Z=22) as a secondary target.

Sample Preparation. Samples were ground to a fine powder by first grinding, then passing the sample through an .088 mm. sieve. Residue left in the sieve was then reground and sieved, and this process repeated until the entire sample passed through the mesh, creating a grain size distribution less than or equal to .088 mm. This procedure was necessary to ensure that large individual mineral crystals are not overrepresented in the X-ray spectra. Presumably, the ground mixture represents the proportionate composition of the original sample, no matter where the X-rays strike the sample.

The samples analyzed were a variety of igneous intrusive rocks, which by their nature were comprised of medium to large individual crystals with occasional larger phenocrysts. Strict compositional control of the samples was not possible, but rock fragments to be powdered were selected to avoid large phenocrysts which could bias the sample. Also the volume of the original ground sample was two to three times the volume of the subsample weighed out to be used in the X-ray analysis. Because of mixing during the grinding process, the subsample selected for analysis from a larger population of individual crystal components should better represent the average composition of the rock.

Other sample preparation techniques range from simple washing (in order to non-destructively analyze an artifact; Bennett and D'Auria, 1973), to a more difficult lithium borate fusion, dispersing the sample in a glass bead (Gregory and Ereiser, 1974). In this analysis, the powder sample method was used because it avoids unwanted background matrix effects from the fusion methods and provides an acceptable dispersion of individual crystal constituents in the powdered sample. Samples consisted of six grams of powdered rock spread evenly over the sample holder surface. This amount of powder constitutes a 'thick' sample and ensured the incident radiation is either absorbed in the sample or backscattered from it. There are three major considerations attributable to the thickness of the sample: specimen absorption of the characteristic X-rays ('thick' sample consideration); scatter mass of the specimen which is directly proportional to its thickness ('thin' sample consideration); and susceptibility to system fluorescence that may occur when the excitation energy passes through the specimen and fluoresces material in the specimen chamber. This, in turn, can come back through the sample and be registered along with the characteristic X-rays ('thin' sample consideration). A thick sample eliminates problems encountered with thin samples, but creates a 'matrix' effect wherein radiation emitted from the specimen is reabsorbed by the mass of the specimen, thus lowering the count of characteristic X-rays and increasing the background effects of scattered radiation (Porter and Woldseth, 1973; Goulding and Jaklevic, 1973). One common matrix correction technique to account for small variations in specimen thickness is to use the Compton (incoherent) scatter peak as an internal correction standard, since the ratio of peak counts to Compton backscatter counts tends to remain constant (Gregory and Ereiser, 1974). This technique of matrix correction was used in this analysis.

Analytical Methods. In this analysis, a molybdenum (Z=42) secondary target was used, irradiating each powdered sample and causing characteristic K_α and K_β X-rays for elements with $Z<42$, and L_α and L_β X-rays for elements with $Z>42$ which were present in the samples. These X-rays were collected by the Si(Li) detection system and converted to electronic signals and were then summed by one of two systems.

During the initial analysis, spectral data for each specimen were collected for 15 minutes on a mini-computer connected to the EDXF unit. The mini-computer collected spectra over 512 channels with a detection range from approximately 1.100 keV to 18.000 keV, allowing detection of K_α radiation from sodium ($Z=11$) to molybdenum ($Z=42$). In the samples analyzed, however, the first significant peak detected was the potassium K_α peak ($Z=19$; keV = 3.312); elements below potassium were not particularly sensitive to radiation from the molybdenum secondary target.

Using the mini-computer, six elemental peaks were identified for computation of peak intensity. These peaks were selected on the basis of their significance to weathering processes in silicate rocks, as determined in earlier work by the author (Wetzel, 1976). Peak intensity is the integral of counts/channel minus background scattering, or the net peak area. Potassium K_α, calcium K_α plus potassium K_β, calcium K_β, iron K_α, rubidium K_α, and strontium K_α net peaks were calculated. Through successive additions of known quantities of a particular element to develop a calibration curve, EDXF can be used for quantitative determination of major and trace elements in silicate rocks. Internal standards for qualitative work can be generated by standardization of peak intensity to either a non-varying elemental peak common to all samples or to the internally consistent Compton backscatter peak of 16.9 keV with a molybdenum target, as explained previously. The Compton peak was used to standardize the data for qualitative comparison in this case, and the corrected peak intensities are listed in the section on results (see Table 8).

This data, when analyzed, indicated that several of the spectra generated would graphically demonstrate trends apparent in the data. Therefore, 11 samples were selected for reanalysis for 15 minutes with the EDXF apparatus connected to a Skipp multi-channel analyzer, with each spectrum occupying a 400 channel segment. Detection limits were approximately the same, but fewer channels were available for display of the spectrum. Spectral data is in machine readible form in the analyzer and was transferred to magnetic tape and taken to the computing centre. Here in matrix form, the data was graphically represented on a semi-log plot and subjected to SAMPØ, an energy peak analysis program developed by Routti and Prussin (1969). SAMPØ fits a polynomial gaussian distribution with exponential tails to the energy peaks. The gaussian distribution was originally developed from magnetic data, but is also useful for X-ray emission energy peaks because of the tendency for both to be slightly skewed towards the low energy side of the distribution. The gaussian polynomial fit applies to the peak centre and is extrapolated continously with calculated exponential tails. Again, the background signals caused by incoherent (Compton) scatter of photons deflected by nuclei in the powdered sample matrix is subtracted from the peak intensity (area).

Following an initial calibration period to provide the best fit of the data, SAMPO performs Chi-square goodness-of-fit (for unacceptable data variation) and Sigma (for distribution shape) tests to reject statistically insignificant peaks in the spectrum. Graphical displays of spectra from some of the analyzed samples are also presented in the section describing results of the analysis (See Figures 14, 15, 20, and 22).

It was realized from earlier work (Wetzel, 1976) that variance, particularly from the output of the X-ray generator, was to be expected unless all of the samples were analyzed consecutively without interruption by other users requiring different voltage settings. Minimization of variance was accomplished by analyzing the initial full sample, and the subsequent samples selected for spectral display overnight, on two different occasions when no other users would interrupt the continuity of the analyses.

Sample Preparation for Petrologic Analyses:

Since only a portion of each original sample was powdered for the X-ray analysis, there was usually enough of the original rock sample to obtain a chip large enough for preparation of thin sections. Disaggregation of weathered samples presented some problems, both while samples were being obtained and during transportation between the field site and the laboratory. Not all of the samples were prepared as thin sections. This is partly because of pervasive disaggregation and loss of original structure, and partly due to lack of definitive weathering trends exhibited during the X-ray fluorescence examination. Except for fresh rock samples, all samples exhibiting weathering were immobilized in a polymeric resin to preserve original structure during the slicing and grinding process. Of 14 samples processed, 11 were suitable for comparative examination with the samples analyzed by X-ray fluorescence. No special preparation other than the resin encasement was performed. Feldspars and alteration products were sufficiently identifiable for purposes of this examination to preclude the need for staining preparations. The purpose of the examination was to observe if presumed weathering patterns suggested by the X-ray fluorescence were confirmed by optical examination. While these procedures are commonly practiced in the preparation of thin sections, very little work along this line has been done by geomorphologists intent upon describing weathering processes and changes in granitic regoliths.

CHAPTER 5

RESULTS

Results of the X-ray Fluorescence Analysis:

The X-ray analysis was a useful and fast technique for quickly determining relative amounts of elemental constituents in the samples. On the basis of knowledge as to which cations were being lost from an increasingly weathered profile, the X-ray analysis provided a good method of screening initial samples for further, more time-consuming examination. For this reason, most of the samples were subjected to X-ray fluorescence, while only those with clearly demonstrable weathering trends were examined in thin section under a petrographic microscope.

Selected samples were analyzed more than once, both during the initial analyses of all the powdered samples and in the subsequent analyses, to produce graphical displays of X-ray fluorescence spectra. Replication of selected samples during the initial analyses allowed a determination of the inherent variability of this technique. The second analyses also provided an opportunity for checking reproducibility of the initial results.

Samples replicated within the initial analyses showed less than 1 percent variation for all elemental peaks that were studied. Because all experimental conditions (sample thickness, machine settings, etc.) were not exactly duplicated in the subsequent analyses when compared to the same samples in the first analyses, variation was considerably more than 1 percent. For example, in the raw data (peak intensity before standardization to the Compton backscatter peak) the $K_{k\alpha}$ peak between paired samples varied between 8 and 10 percent; $Ca_{k\alpha}$ varied 5 to 9 percent; $Fe_{k\alpha}$ varied 2 to 8 percent; and the Compton peak varied between 5 to 7 percent. Standardization of peak data tended to decrease the upper limit of variance by about 1 percent or more (e.g. $K_{k\alpha}$ was 8 to 9 percent; $Ca_{k\alpha}$ was 5 to 6 percent; $Fe_{k\alpha}$ was 2 to 6 percent).

Though this comparison showed considerable variation, the results varied consistently in the same direction between analyses. For example, when ratio of peak intensity between two samples in the intitial analyses is compared to the ratio for the same samples in the replication, the variance between ratios is less than 1 percent for all elemental peaks studied except for Fe, which varies as much as 4 percent in some comparisons.

For purposes of this study, the peak intensity data used to generate Table 8 (and Table 9) were all from the initial, complete sample analyses showing variations of less than 1 percent in replicated samples. The spectra generated for visual purposes from several selected sample locations were all taken from the second analysis. Thus, while peak intensities in the spectra may not reflect the exact numerical values in Table 8, they nevertheless express the correct spectral relationships between different specimens in Table 8.

As mentioned earlier, the thickness of the sample can affect spectral counts. Though the samples were the same weight,

TABLE 8

SELECTED PEAK INTENSITIES
(Standardized to the Compton Backscatter Peak x 1000))

SAMPLE*	$K_{k\alpha}$	$Ca_{k\alpha}$	$Fe_{k\alpha}$	$Rb_{k\alpha}$	$Sr_{k\alpha}$
Tenmile Creek					
R1	65	98	2575	369	3137
R2	56	62	2229	395	2337
Old Baldy Mtn.					
R3	110	100	4332	677	1667
R4	88	94	3702	565	1997
R5	99	68	7726	481	1643
R6	95	99	9076	386	1872
Boomerang Gulch					
R7	63	98	4070	460	1947
R8	75	86	3764	475	1702
R9	100	59	3196	535	1682
R10	106	41	1890	553	1679
Clancy Gulch					
LC1	96	159	4784	549	2097
LC2	110	90	3749	689	1299
LC3	127	82	4633	777	1132
Lockhart Meadows					
LC6	97	128	4413	486	2819
LC7	82	93	5338	430	2272
Browns Gulch					
LC9	55	99	4019	286	3194
LC10	61	114	4344	280	2518
LC11	66	110	4888	300	2319
Wickes-Boulder Rd.					
LC12	109	76	3480	625	2005
LC13	106	47	5642	575	1522
LC14	141	34	8426	626	1656
Pipestone Pass					
U1	47	13	3801	261	1479
U2	51	48	1902	347	2086
Pipestone Road					
U3	72	156	4408	275	3173
U4	64	156	4122	267	2908
Border Zone					
BZ1	106	102	5783	501	2692
BZ2	78	143	8798	336	1891

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* Sample identification sites are explained on page 140 and are shown in Figures 2, 12, 13, 16, 17, 18, 19, and 21.

weathered samples tended to produce more volume for the same weight when powdered, thus making slightly thicker samples. This thickness variation causes some variation in the Compton backscatter peak. However, as shown by Gregory and Ereiser (1974), Compton variation due to sample thickness also proportionally affects the spectral peaks of the elements in the powdered sample. Therefore, the matrix correction values (peak intensity:Compton peak ratio) in Table 8 represent a more correct qualitative comparison than the unadjusted peak intensities.

The range in variation of the Compton backscatter peaks in the raw data is about 12.5 percent if the highest and lowest counts are compared. However, the Compton peak variation between samples collected at individual sites is much less (1 to 4 percent). Considering the variation in unstandardized peak intensity between samples at any single collection site is normally more than five times the relative magnitude of the Compton variation, changes in spectral intensity between samples are attributed to weathering alterations rather than aberrations in Compton peak intensity.

Some common characteristics among samples, where sampling control was best, included a tendency for potassium (K) to increase proportionally with increased weathering while calcium (Ca) decreased. For example, relative peak intensities actually showed reverse trends for these two constituents at many sample sites with increased weathering (see Table 8).

Another general trend that can be drawn from Table 8 is a tendency for iron (Fe) to decrease relative to other elemental constituents with increased weathering under the rhyolitic volcanics (R-prefix) and at uncovered (U-prefix) sites. Lowland Creek volcanics (LC-prefix) and border zone (BZ-prefix) sites tend to show increases in Fe. The exact causes of these differences are not known, but some possibilities will be examined in the discussion of individual sites.

Rubidium (Rb) does not seem to show any consistent trend that is related to weathering. However, with few exceptions, strontium (Sr) tends to decrease relative to other constituents with increased weathering. Probably more important than individual peak intensities is the ratio of Rb/Sr shown in Table 9 (along with other selected ratios). Here, except where hydrothermal or possible metasomatic influences are probable (Pipestone Pass and border zone), the samples show an increase in the Rb/Sr ratio with increased weathering.

Table 9 also shows (with some exceptions that will be discussed in association with individual collection sites) more clearly the increase in K, relative to Ca, with increased weathering. The K/Fe and Ca/Fe ratios do not seem to show any discernibly consistent trends, but this is partly due to the large discrepancy in K and Ca peak intensities compared to Fe. When compared in ratio form, the intense Fe peak tends to minimize the numerical difference between the smaller peaks.

Individual Sample Site Analysis. As mentioned earlier, inability to obtain samples showing distinct contrasting degrees of weathering at some sites led to sampling over considerable

TABLE 9

RATIOS OF SELECTED PEAK INTENSITIES

SAMPLE*	K/Ca	K/Fe	Ca/Fe	Rb/Sr
Tenmile Creek				
R1	.675	.025	.038	.118
R2	.894	.025	.028	.169
Old Baldy Mtn.				
R3	1.096	.025	.023	.406
R4	.931	.024	.026	.028
R5	1.461	.013	.009	.293
R6	.950	.010	.011	.206
Boomerang Gulch				
R7	.642	.016	.024	.233
R8	.875	.020	.023	.279
R9	1.689	.031	.019	.318
R10	2.386	.052	.022	.329
Clancy Gulch				
LC1	.606	.020	.033	.262
LC2	1.228	.029	.024	.530
LC3	1.542	.027	.018	.687
Lockhart Meadows				
LC6	.756	.022	.029	.172
LC7	.884	.015	.017	.189
Browns Gulch				
LC9	.553	.014	.025	.089
LC10	.536	.014	.026	.111
LC11	.599	.013	.022	.128
Wickes-Boulder Rd.				
LC12	1.434	.031	.022	.312
LC13	2.219	.019	.008	.378
LC14	4.139	.017	.004	.378
Pipestone Pass				
U1	3.505	.012	.004	.176
U2	1.503	.027	.025	.166
Pipestone Road				
U3	.464	.016	.035	.087
U4	.413	.016	.038	.092
Border Zone				
BZ1	.741	.018	.025	.188
BZ2	.766	.009	.012	.178

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* Sample identification sites are explained on page 140 and are shown in Figures 2, 12, 13, 16, 17, 18, 19, and 21.

linear distances. This resulted in the introduction of sampling error through subjective inference of the degree of weathering and through compositional variance. Where this occurred, variations in peak intensity were such that no discernible trends could be established. This is most apparent in the data for Old Baldy Mountain (R-3 to R-6). To a certain extent, natural compositional variation is present in any sampling scheme of silicate rocks. This variation is thought to be minimized at the other sample sites through sample collections no more than a few metres apart. Thus, trends toward enrichment or depletion of elemental constituents within any one collection of samples are thought to reflect the weathering environment rather than compositional or site variations. Comparisons between sample sites are deemed to be valid only when the trends already mentioned are compared. Comparison of actual data values would introduce compositional and site variance which cannot be totally reconciled for comparative purposes even with the use of quantitative chemical analyses. The following chapter presents a discussion of how the results presented here are interpreted. However, points of discussion that specifically relate to individual sample sites are included, for the sake of continuity, with the results pertaining to each site.

Tenmile Creek.

The two samples from upper Tenmile Creek (R-1 and R-2) were taken from a road cut in the northeast 1/4 of Section 8, Township 8 North, Range 5 West, Montana Principle Meridian

(NE1/4, S8, T8N, R5W at the location shown in Figure 12). The site can be reached from the Gould Reservoir road above the old mining town of Rimini. The road mentioned is more recent than the map compilation and therefore does not show on the map at the sample site location. The site is about 20 to 25 m. below the gradational contact with Oligocene rhyolite on the southeast side of Tenmile Creek. The contact can be traced at approximately the same elevation across the narrow valley (400 m.) on the northwest side of Tenmile Creek, but is not exposed in any road cuts across the valley.

The exposure consists of a weathered regolith on a pre-Pleistocene valley side slope that has been modified by glaciation associated with the northern Boulder Mountains Pleistocene ice sheet (Ruppel, 1962). Recent excavation at this site is afforded by a Forest Service road about 15 years old. The weathered regolith material has been eroding from the exposed cut slope and on to the road bed. This material is periodically removed by the Forest Service so that near the bottom of the exposure a relatively fresh cut is maintained.

The samples taken include one of relatively fresh rock from a large corestone (R-1), which was hard enough to require a hammer to obtain a sample. The other sample (R-2) was from regolith material adjacent to the corestone about 1 m. away. Here the material was friable and hand specimens crumbled easily. With the exception of the one large corestone, only 'ghost' structures of joints remain as evidence of <u>in situ</u> weathering. As at most sample sites, the lack of a reference

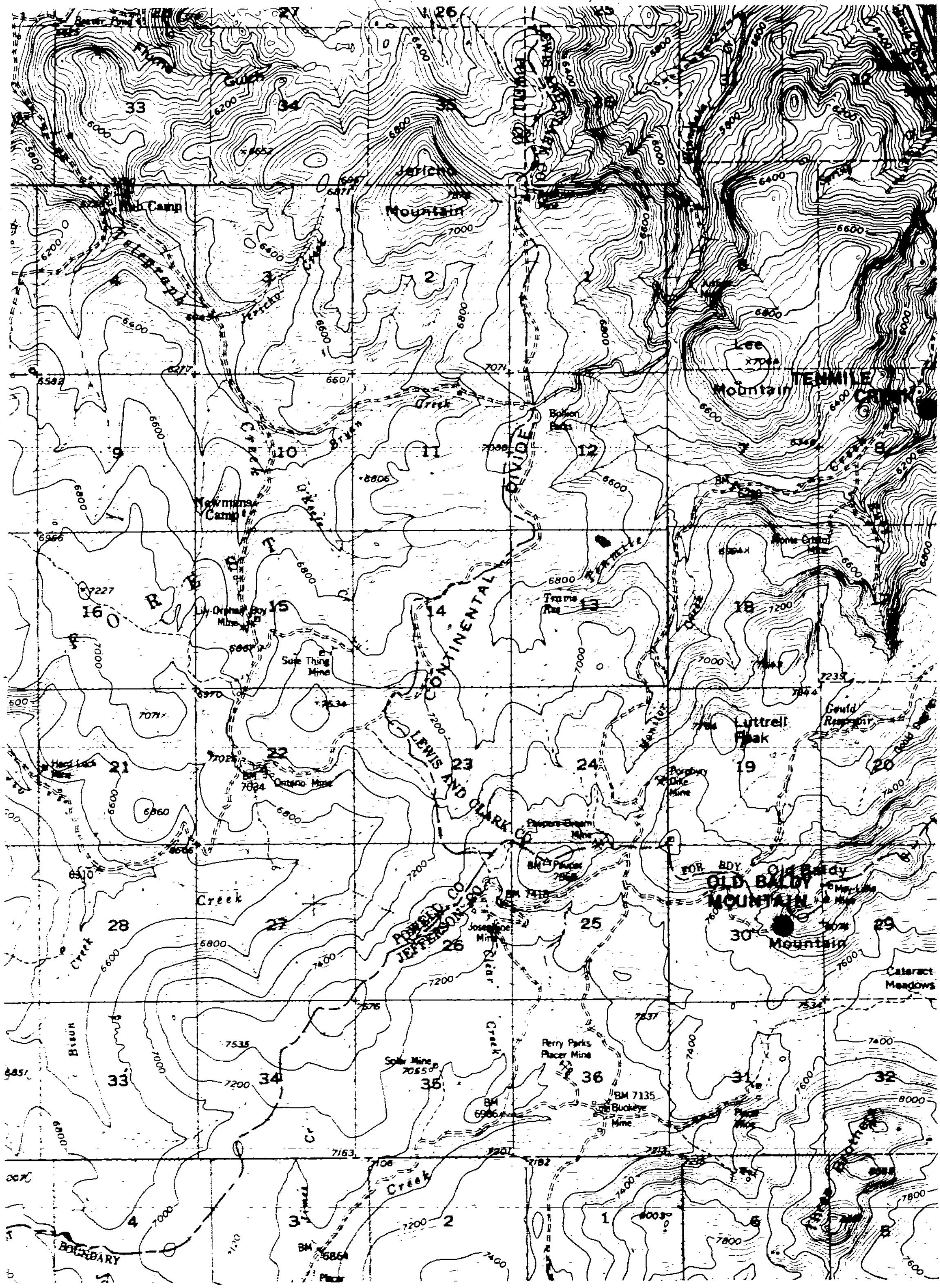


Figure 12. Northeast portion of the Basin 15' quadrangle (1;62,500) showing location of the Tenmile Creek and Old Baldy Mountain sample sites.

soil 'horizon' near the contact with the rhyolite led to abandonment of any attempt to characterize the vertical profile. Also, since no apparent differentiation occurred in the entire profile, the weathered sample was taken at the same level as the corestone sample to reflect weathering environments at equivalent depth.

In the X-ray fluorescence analysis, K and Ca peak intensity both decline in the weathered sample, but since the Ca peak declines considerably the more, the K/Ca ratio shows an increase with weathering. The Fe peak intensity registers a decline in the weathered sample, even though the presence of iron oxides is more apparent in the weathered zone. This would indicate that iron staining is not necessarily a good indicator of the total Fe present in the sample. It also indicated that weathering conditions at some point in time were favourable to the mobilization of Fe, and resulted in the loss of some Fe from the regolith. A slight enrichment of Rb with a depletion of Sr resulted in a characteristic increase in the Rb/Sr ratio.

Old Baldy Mountain.

The samples at Old Baldy Mountain were collected at various locations in the E1/2, S30, T8N, R5W (also Figure 12) and as mentioned earlier, exhibit no clearly discernible weathering trends for any of the monitored elements. The likely causes of variance are attributed to both compositional and weathering environment changes over relatively short distances. However, an additional possibility is hydrothermal alteration of deuteric origin, or later hydrothermal effects related to the Oligocene volcanism. The entire area is dotted with mining properties exploiting vein deposits related to enrichment during the volcanic episode. No meaningful characterization of the X-ray analysis is possible due to variation in the sample results.

Boomerang Gulch.

The four samples gathered at this site were collected progressively deeper in a paleosol which was in contact with overlying rhyolitic overburden. The sample site is near the centre of the SW1/4, S7, T6N, R4W, (Figure 13) along a mining road of undetermined age. The samples ranged from pervasively weathered quartz monzonite (with substantial secondary mineral formation) to coherent, but still weathered, quartz monzonite in a corestone. All samples showed evidence of subaerial weathering with expansion of biotite, breakage of the original crystalline matrix, and mobilization of iron oxides.

X-ray analyses exhibited clear trends for all five elements initially monitored. While K and Rb increased, Ca, Fe, and Sr all decreased with weathering. The K/Ca ratio in the most weathered zone at the top of the profile is nearly four times the ratio in the corestone, indicating a considerable loss of Ca from the regolith. Because K and Rb had trends opposite to those of Fe and Sr, the K/Fe and Rb/Sr ratios both show distinct increases with weathering. However, Ca and Fe, exhibiting parallel tendencies of decline, give the Ca/Fe ratio no clear trend. Figure 14 shows the X-ray fluorescence spectra generated for these four samples. Clearly visible are the relative reversals of the K and Ca peaks and the growth of the Rb peak

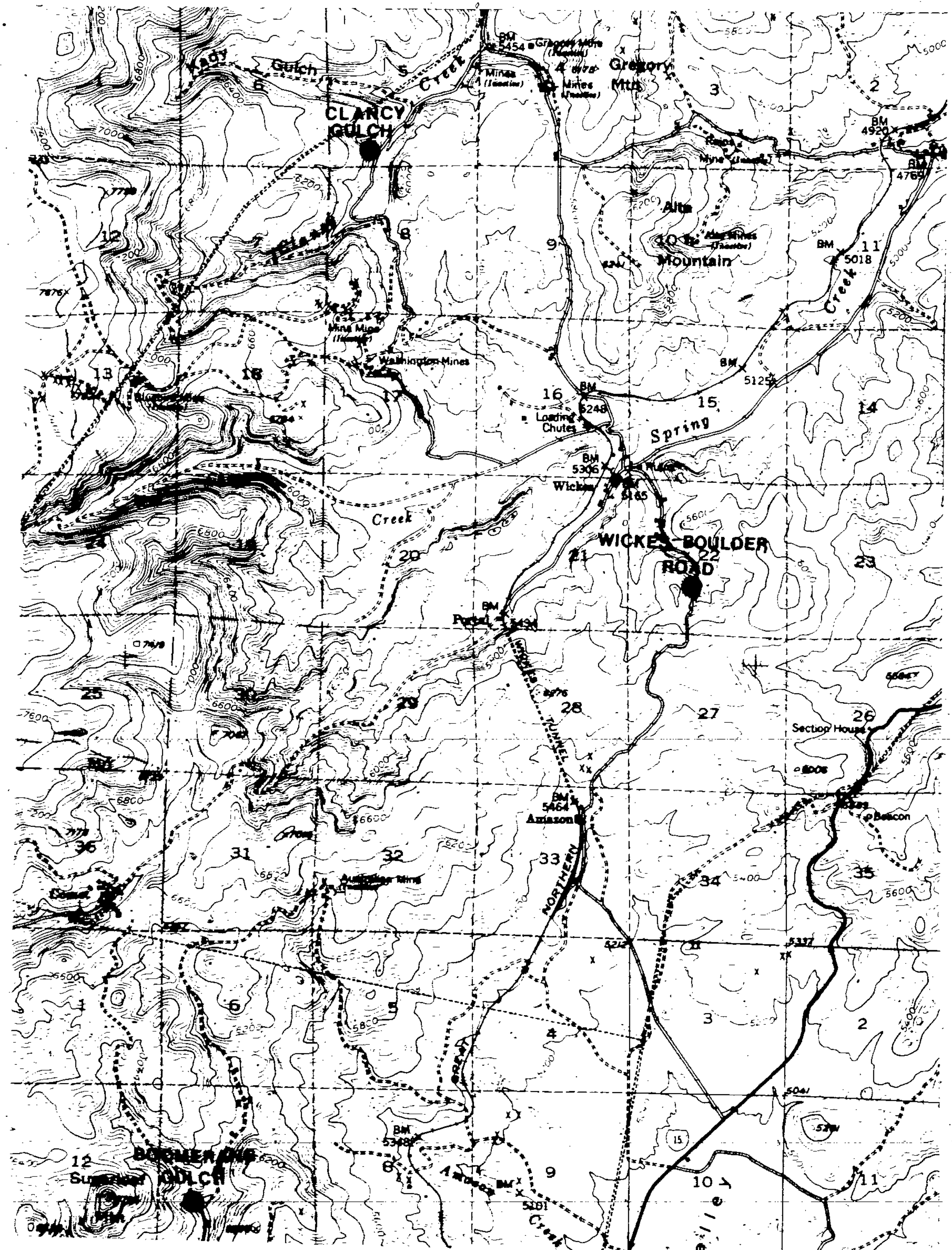
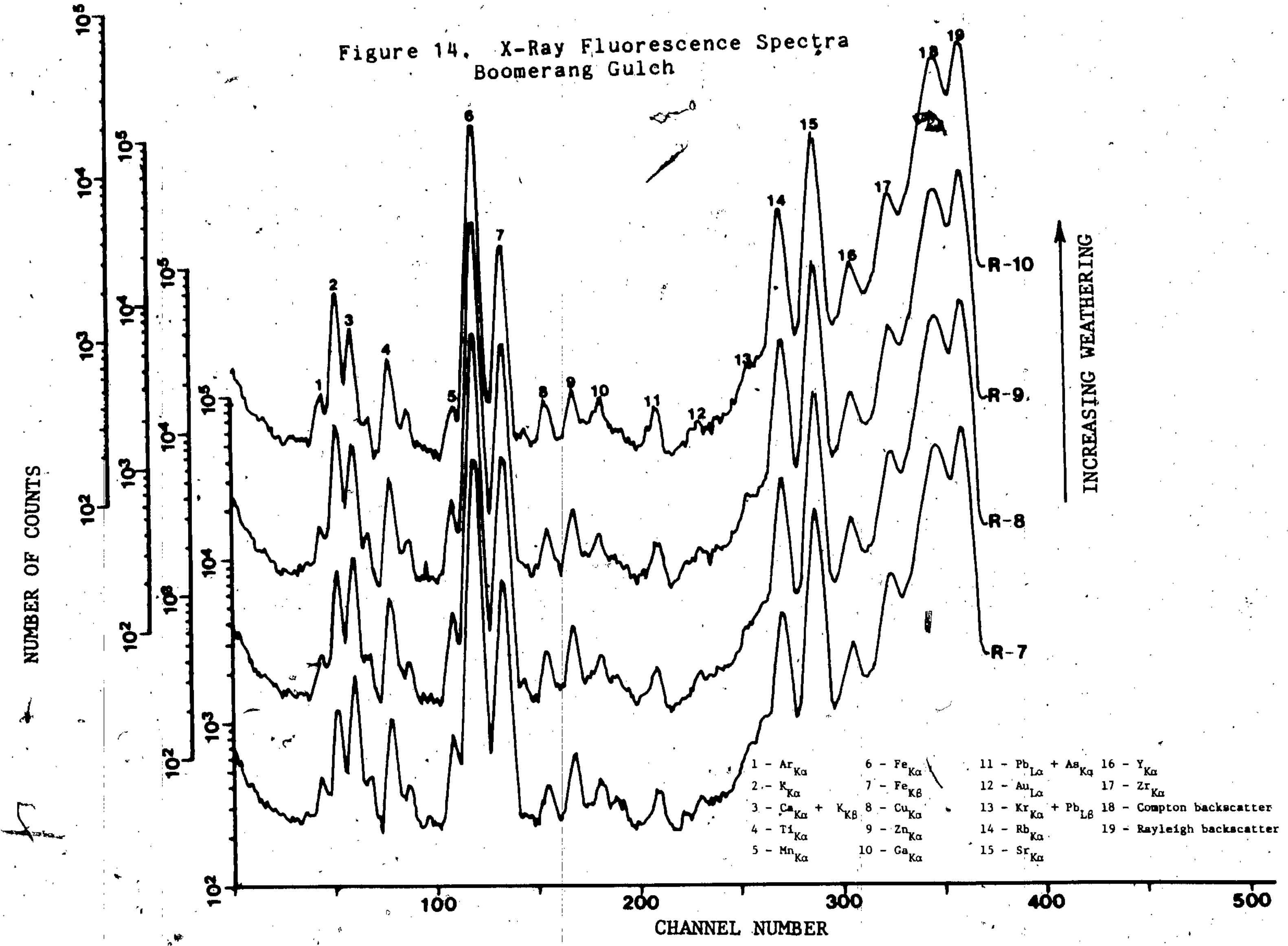


Figure 13. South-central portion of the Jefferson City 15' quadrangle (1:62,500) showing locations of the Boomerang Gulch, Clancy Gulch, and Wickes-Boulder Road sample sites.

Figure 14. X-Ray Fluorescence Spectra
Boomerang Gulch

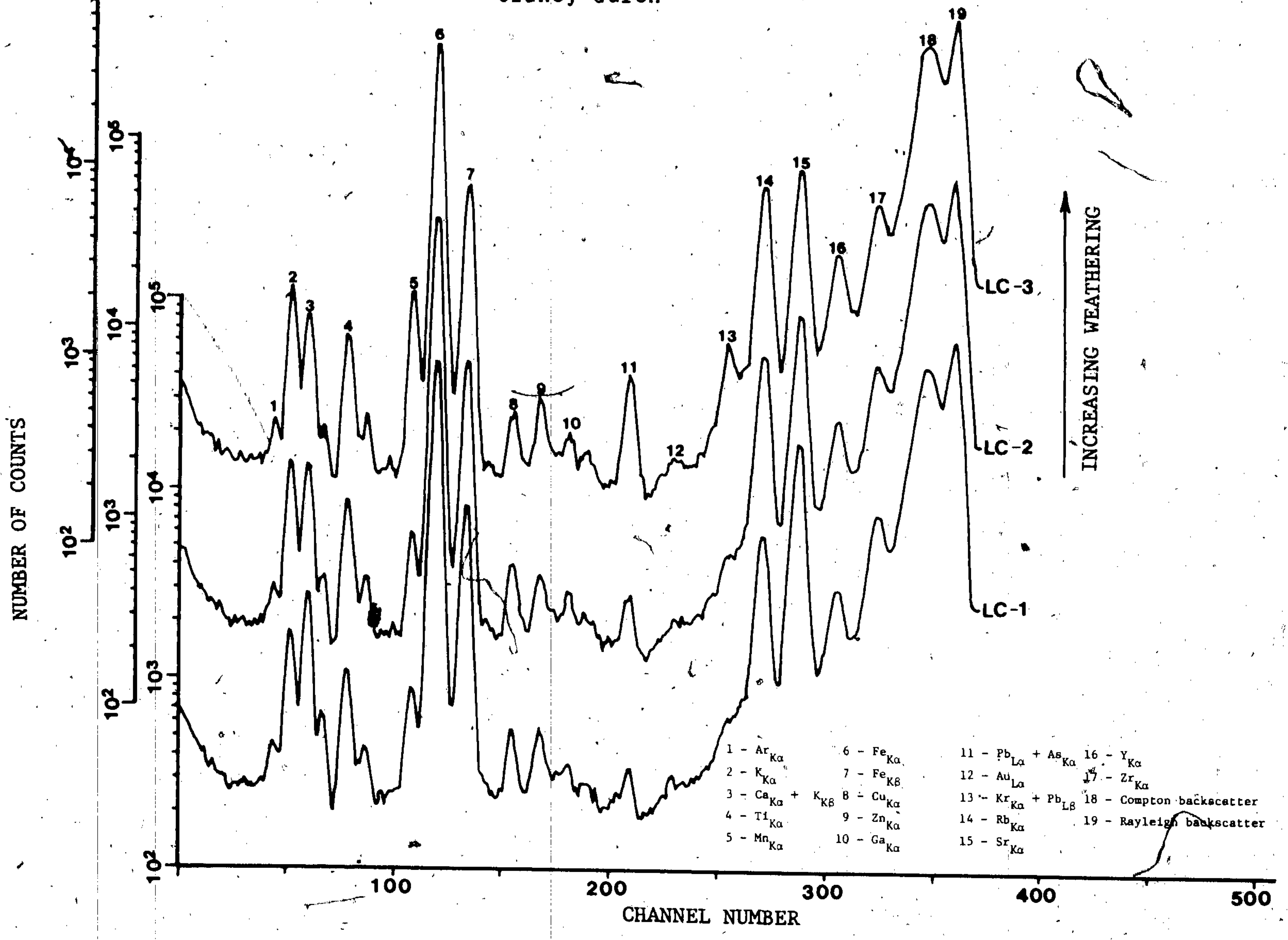


while the Sr peak declines. Significant from Figure 14 is the fact that the successive spectral signatures, represented by increasingly weathered samples, show trends exactly parallel to spectra developed from a weathering profile in the Spire Rock Flats area (west of Whitehall) which has never been covered by post-batholithic volcanic or sedimentary rocks (Wetzel, 1976).

Clancy Gulch.

These samples, as mentioned earlier, are from discarded drill cores taken from an adit in upper Clancy Gulch in SW1/4, S5, T7N, R4W (Figure 13). Classified as samples from beneath the Eocene Lowland Creek volcanics, the possibility remains that the plutonic rocks may be first in contact with a roof pendant of the Elkhorn Mountains Volcanics rather than ~~with~~ the Tertiary volcanics. Failure to resolve the nature of the cap rock obscures any interpretation of the results, but the analysis is nevertheless interesting in that it suggests the weathering is similar to that encountered in Boomerang Gulch. As seen in Figure 15, the K and Ca peaks exhibit an intensity reversal and the Rb peak again increases while Sr decreases. The one difference is the lack of a definite weathering trend with respect to the Fe peak intensity (as shown in Table 8). Because of the numerous mining properties in the vicinity and the obvious origin of the samples, deuteric alteration is a possibility also at this site. The trends displayed, however, are generally opposite to those displayed by hydrothermal vein alteration examined near Homestake Pass (where K was depleted relative to Ca, Fe increased, and Rb and Sr showed little

Figure 15. X-Ray Fluorescence Spectra
Clancy Gulch



change; Wetzel, 1976). This suggests the samples are probably demonstrating supergene alterations like those at Boomerang Gulch.

Wickes-Boulder Road.

These samples were from a road cut about 1.2 km. from the early Montana mining and smelting town of Wickes. As the road travels over the hill from Wickes to Boulder, it encounters the contact between the quartz monzonite and the overlying Lowland Creek volcanics in the NE1/4, SW1/4, S22, T7N, R4W (Figure 13). All the samples were acquired in vertical profile and were altered to some degree so that no 'fresh' rock comparison was possible. Also, all samples had pervasive ~~iron~~ staining which was in part attributable to mobilization and downward leaching of Fe from overlying quartz latite. As indicated in Table 8, the weathering trends are similar to most other quartz monzonite sites with respect to K and Ca. The increase in Fe with weathering is problematic. While some downward leaching of Fe was inferred by streaking patterns on fresh quartz latite in the road cut, the degree of contribution to the quartz monzonite regolith is not known. Also, as pointed out by the variation in the Old Baldy Mountain samples, the degree of 'rust' color is not necessarily an accurate measure of the relative amounts of Fe present in the sample. Iron increases toward the top of the weathering profile, but no discernible 'mottled' or 'pallid' (in the sense used by Dury, 1969; see also p. 172) zones were present to indicate whether Fe depletion had necessarily occurred at depth, or whether the Fe enrichment in the top of the profile was simply a result of proximity to the quartz latite.

The most significant point to be drawn is that these samples indicate a strong possibility that buried regolith materials may acquire extraneous characteristics from subsequent supergene weathering on the overburden. This also indirectly complicates the contention of Cunningham (1971, p.425-426) that, as the country rock thins during initial exhumation of a pluton, preweathering or preconditioning of plutonic rocks undoubtedly occurs via meteoric waters which reach and penetrate joint systems in the intrusive. In this instance, cations in the penetrating waters contributed by the cap rock may well affect equilibrium relations, and thus preferentially influence weathering reactions in the underlying plutonic rocks.

In Table 9, a particularly marked increase in the K/Ca ratio, along with a discernible decrease in the K/Fe and Ca/Fe ratios underscores the relative increase of Fe. Other studies on the mobilization and precipitation of metals in syenite mine spoils in the Little Belt Mountains of central Montana indicate that Fe crosses an abrupt solution/precipitation interface at about pH 3.2 to 3.5, below which solubility of Fe increases exponentially under field conditions (Wetzel, 1982). The fact that Fe is mobilized under current conditions suggests a fairly acidic vadose zone at this location (possibly from metallic sulfide ore veins in the rhyolite reacting with water). Given the solubility of Ca under acidic conditions, this may explain the high K/Ca ratio. Also, as soil water pH is buffered through reactions occurring with downward penetration, an Fe precipitation zone would be expected. It may be coincidence or a lithologic influence that accounts for the Fe-enriched zone near the top of the buried regolith.

Lockhart Meadows.

Two samples taken here came from a road cut along the county road between Basin and Deer Lodge, near the upper end of the Boulder River. The sample site is located in the SE1/4, S25, T6N, R8W (Figure 16), and consists of an inlier of quartz monzonite surrounded by Eocene Lowland Creek volcanics. Because of blasting to excavate the quartz monzonite, the unweathered interior of a large monolith was exposed and the unaltered sample was taken from this source. The weathered sample was taken at the same horizontal level from an adjacent intensely weathered joint (hydrothermal vein ?).

From Table 8 it is apparent that the Lockhart Meadows samples do not represent the postulated normal weathering trend with loss of both K and Rb with increased weathering. Instead, the ratios of K to Ca and Rb to Sr in Table 9 increase, indicating that Ca and Sr are leaving the system faster than are K and Rb. It is unwise to suggest a 'trend' with only two samples, so it is uncertain whether the weathered/unweathered variations are due to hydrothermal alteration, distinctive Eocene weathering, overburden influences, or simply chance selection of samples. However, no definite 'seriticized zone' or 'argillized zone', which Sales and Meyer (1948, p. 5) have

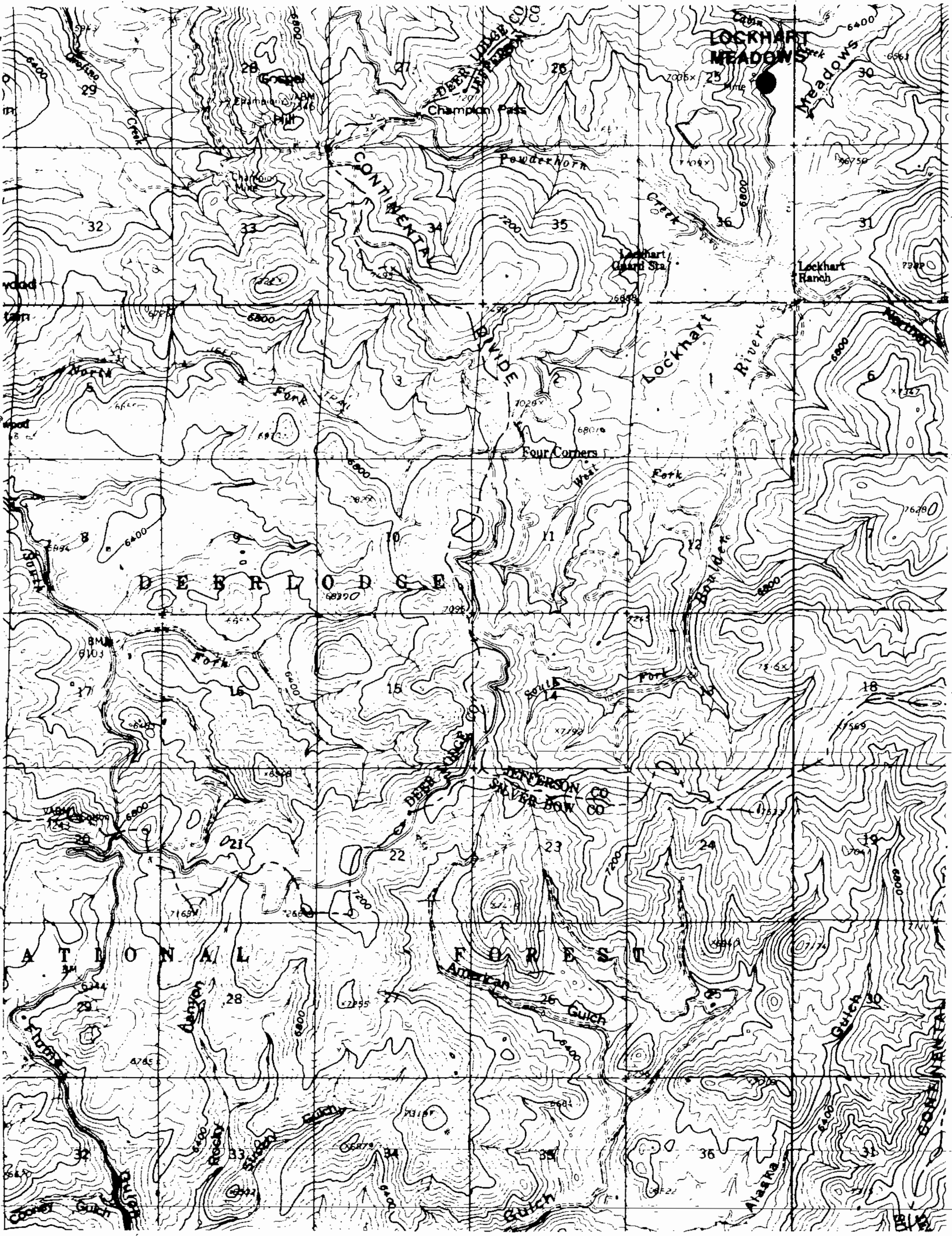


Figure 16. Northeast portion of the Butte North 15' quadrangle (1:62,500) showing location of the Lockhart Meadows sample site.

associated with hydrothermal alteration in the Butte area, was detected at the site.

Browns Gulch.

Browns Gulch samples were taken from a weathered unit of the Lowland Creek volcanics that exhibited spheroidal weathering and, from a distance, looked very much like the quartz monzonite inlier at Lockhart Meadows. From the location of the sample ~~site~~ (SW1/4, NW1/4, S28, T4N, R8W, in Figure 17) and the description of the volcanic stratigraphy, one would tentatively assign these samples to the lower lava unit of the Lowland Creek volcanics (Smedes, 1962, p. 262). The rocks are porphyritic with an aphanitic groundmass of devitrified glass, studded with phenocrysts of plagioclase, pyroxene, hornblende, quartz and biotite. Even on close inspection, the number and size of the phenocrysts gives the rock a resemblance to the coarse-grained plutonic rocks. It was obvious from the location of the sample site and from similar, rounded forms incipient in the saprolite that supergene weathering, followed by stripping, had occurred. Further, within the zone of subsurface weathering and regolith development, the rock exhibits granular disintegration upon exposure. This is in sharp contrast to weathering in the same lava unit where subsurface weathering does not appear to have occurred. Here the unit weathers to blocky, angular, talus coated with ferric oxides. In fact, this contrast can be experienced at the sample site by simply examining the volcanic rocks on the valley side immediately above the regolith, which

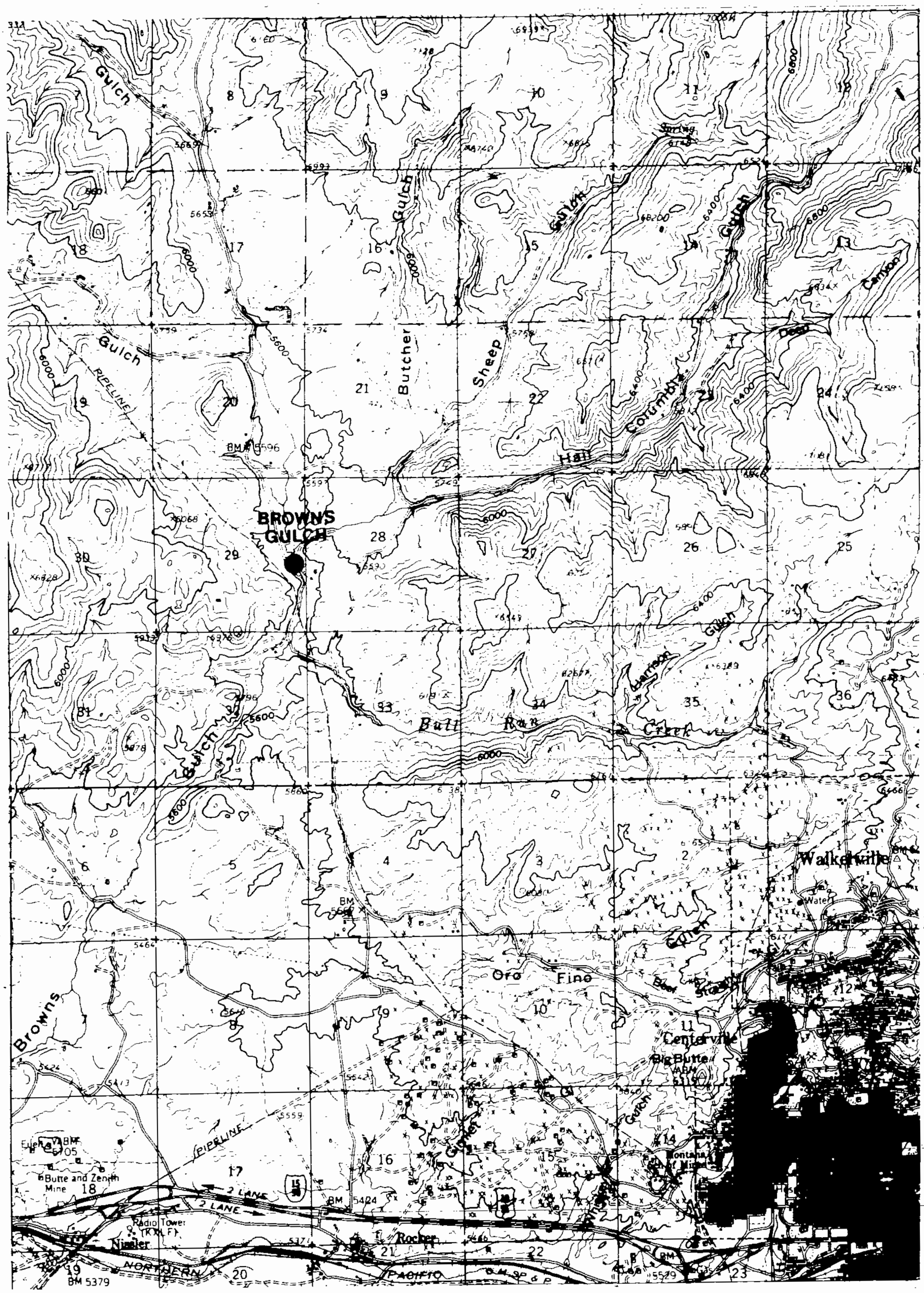


Figure 17. South-central portion of the Butte North 15' quadrangle showing location of the Browns Gulch sample site.

is exposed only in the first 20-30 m. above the bottom of Browns Gulch.

The regolith showed vague zonations resembling descriptions of 'mottled' and 'pallid' zones, terms more widely used in international literature (Whitehouse, 1940; Dury, 1969). A sample was taken from each such zone. No apparent 'duricrust' (in the sense used by Dury, 1969) occurred, so the third sample, inferred to be the most weathered, was taken from near the top of the regolith in what would be considered part of the 'mottled' zone. The ferric oxide staining on most of the lava unit would not qualify as 'duricrust' since it occurs as a veneer on unaltered rocks and on rocks that are not even closely associated with the weathered regolith. This veneer also does not result in the case hardening associated with indurated crusts. Natural color variations in the lava unit result in shades of grey, brown, purple, red, and greenish black (Smedes, 1962, p. 262), so that inferred weathering zonations based upon color are somewhat tenuous.

The pattern of weathering in the quartz latite lava unit, though similar in outward appearance, does not appear to be typical of the weathering in the quartz monzonite, its intrusive equivalent. The biggest difference seems to be that both Ca and Fe tend to increase relative to other constituents with increased weathering (see Table 8). The increase in Fe in more weathered surface horizons would be consistent with the concentration of sesquioxides thought to occur in the upper horizons of deep weathering profiles. Thus, the concept of mottled and pallid zones at this site may have some validity, but does not explain why a similar phenomenon does not occur on the quartz monzonite. The increase in Ca is probably due to the apparent resistance of the plagioclase phenocrysts to weathering. Not only does the plagioclase resist weathering at this site, but individual crystals were virtually indestructable in the preparation of powdered samples for the X-ray analysis. All peak intensity ratios except Rb/Sr, show no definite trend with weathering and, in fact, show very little change at all. The Rb/Sr ratio shows a 'normal' increase with weathering.

Pipestone Pass.

The samples from Pipestone Pass (U-1 and U-2) show alterations that appear to be hydrothermally induced. Earlier investigations into X-ray fluorescence spectral signatures for hydrothermally-altered quartz monzonite indicate nearly opposite trends for supergene and hypogene weathering (Wetzel, 1976). That is, elements which normally decrease with supergene weathering (like Ca, Ti, Mn, Fe, Zn, and Sr) have a tendency to increase in hydrothermally-altered rocks relative to other constituents. Perhaps this difference is taken into account by the fact that hydrothermal alterations during late phase crystallization are not strictly analogous to the leaching process that accompanies meteoric weathering. Thus, the relative abundance of cations that are normally leached by meteoric influences appears to be a good indicator of hydrothermal alteration on the Boulder batholith.

The two samples were taken from a road cut on Highway 10 on the north side of the road in the NE1/4, NW1/4, S11, T1N, R7W (Figure 18). Both samples are weathered, but the vein sample is altered to the degree that it disaggregates in hand specimen, whereas the relatively unaltered rock required a hammer blow to chip a sample.

The trend in Table 8 does not correlate perfectly with four samples analyzed in 1976 near Homestake Pass (Wetzel, 1976; site shown in Figure 18), but it does show an uncharacteristic increase in Ca and Sr which does not normally occur at supergene weathering sites in the quartz monzonite. The slight increase in K is the smallest in any group of samples used in this study, and may not be significant. The decrease in Fe with weathering is more characteristic of meteoric effects than hydrothermal influences. However, the presence of 'Liesegang' or 'diffusion' rings may be partly responsible (Carl and Amstutz, 1958; Augustithis and Ottemann, 1966; Ollier, 1967). The presence of the rings in the intensely weathered zone suggests that sample placement may have a strong effect on the relative intensity of the Fe peak. No notation of the exact placement of the sample relative to an 'iron enriched' ring was made in the field, and it was not possible to add this notation during the analysis in a completely objective manner.

Taken as a whole, and in the light of earlier work by the author to specifically differentiate between hydrothermal and meteoric weathering, it appears that hydrothermal alteration is present at the site but some meteoric influences may be present

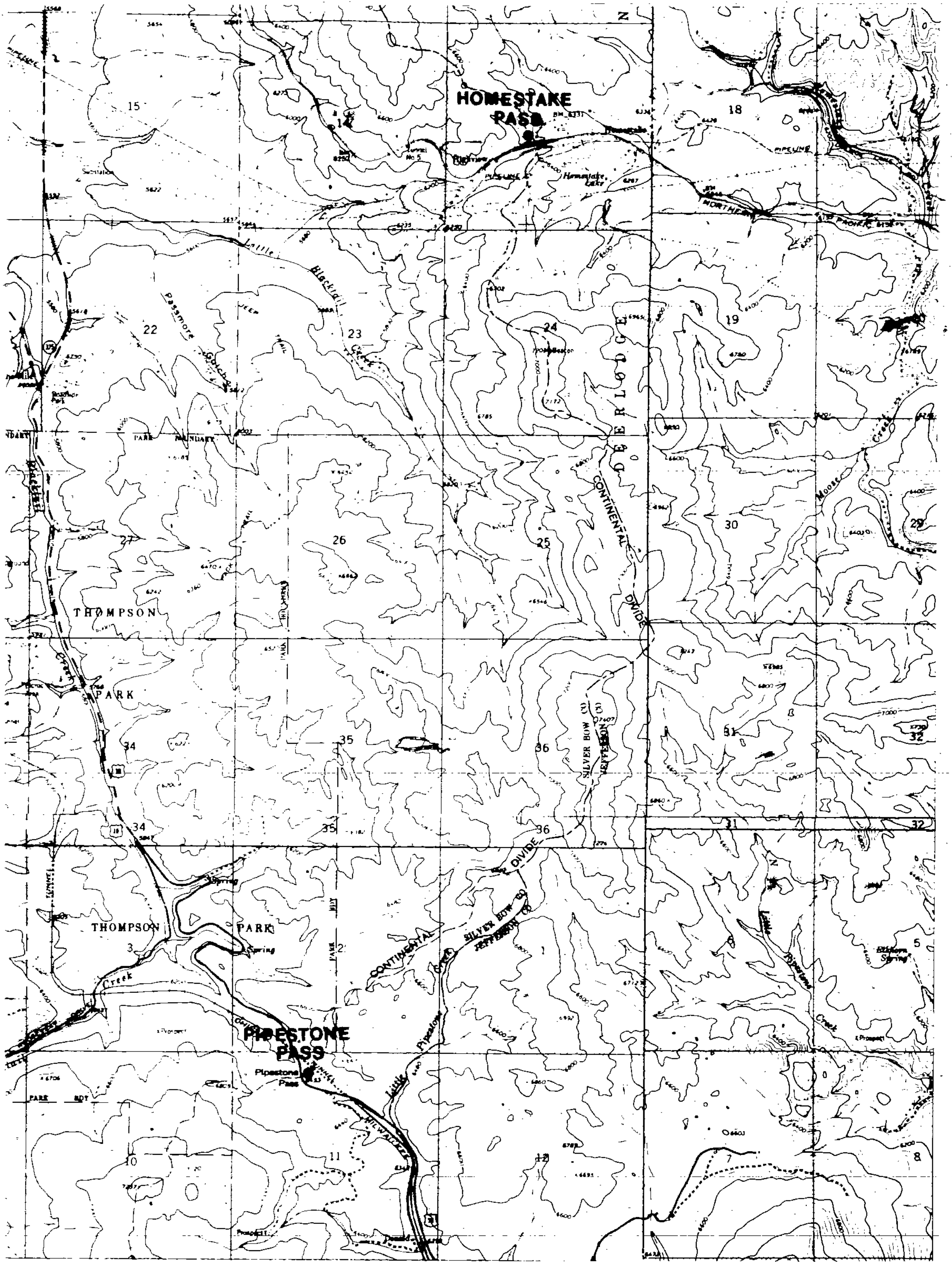


Figure 18. Portions of the Homestake and Pipestone Pass 71/2' quadrangles (reduced from 1:24,00 to 1:45,000) showing the location of the Pipestone Pass sample site and the Homestake Pass site analyzed in 1976 by the author.

also. It is not certain whether the 'Liesegang rings' are deuteric or meteoric in origin. Melcon (1975) describes the same phenomenon occurring in a tor landscape in southern British Columbia, where there is no evidence for hydrothermal origin. He found that corestones presently being exhumed from the Tertiary Princeton sediment do not have diffusion rings while tors that have been subaerially exposed have often developed several, concentric, diffusion ring zones. In contrast, the same concentric zoning that occurs at Pipestone Pass (and numerous other locations in the study area) has been described by Weed (1912) as occurring at considerable depth in the mines at Butte in obvious association with hydrothermally-enriched ore deposits.

Pipestone Road.

These samples (U-3 and U-4) were collected in a road cut located at SE1/4, NW1/4, SE1/4, S16, T1N, R5W (Figure 19) along Highway 10 between Pipestone Pass and Whitehall. Both samples are specimens of the Radar Creek granodiorite, one of the intrusions slightly more mafic than the quartz monzonite of the Boulder batholith intrusive complex.

The site is characterized by none of the distinctive weathering residuals usually associated with weathering in the quartz monzonite and alaskite. The weathering at this site appears to be caused entirely by meteoric agents without significant influence from joint spacing, so that the regolith is developing generally parallel with the land surface and ranges between 5 and 10 m. in depth. The transition along the

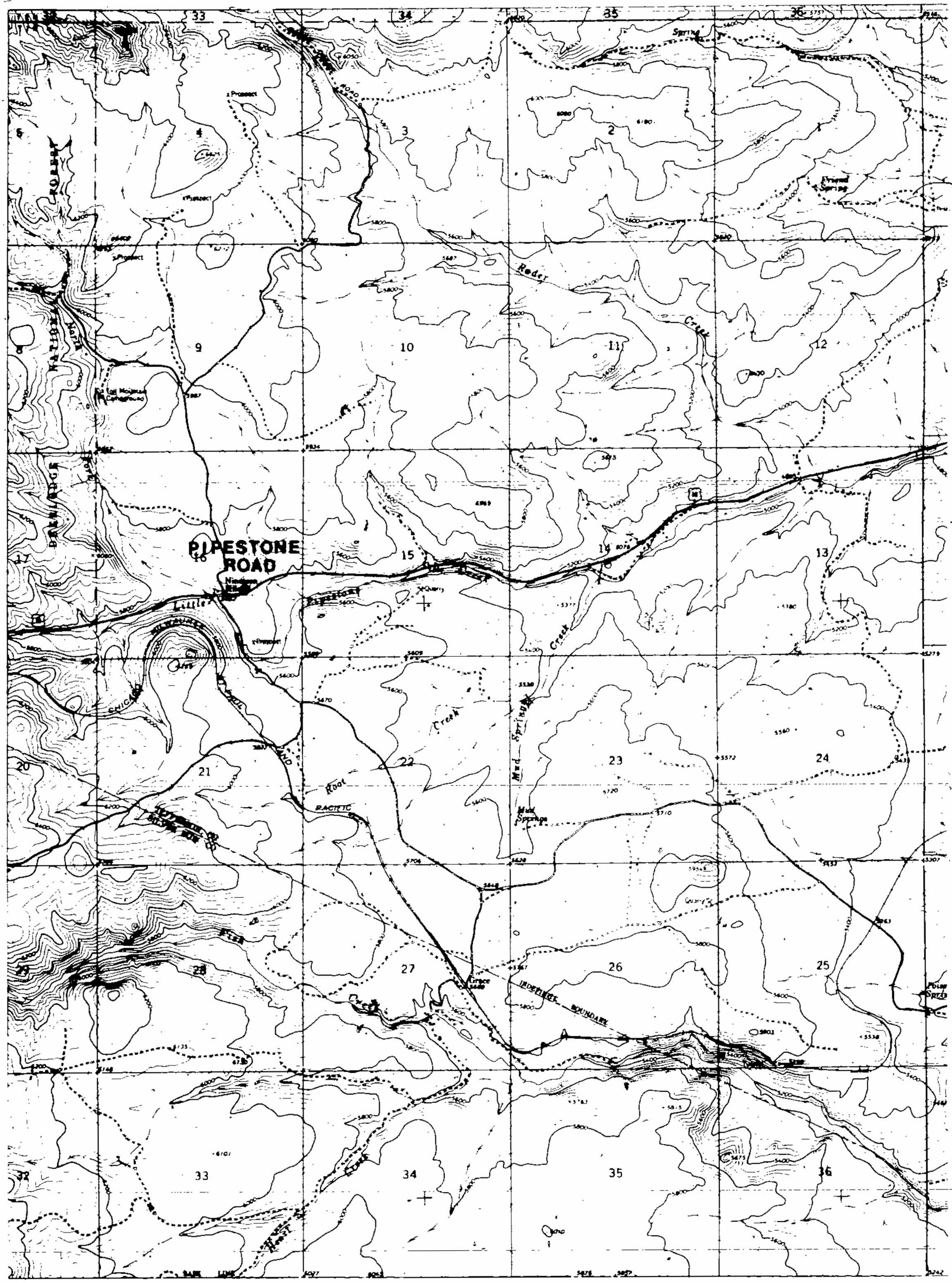


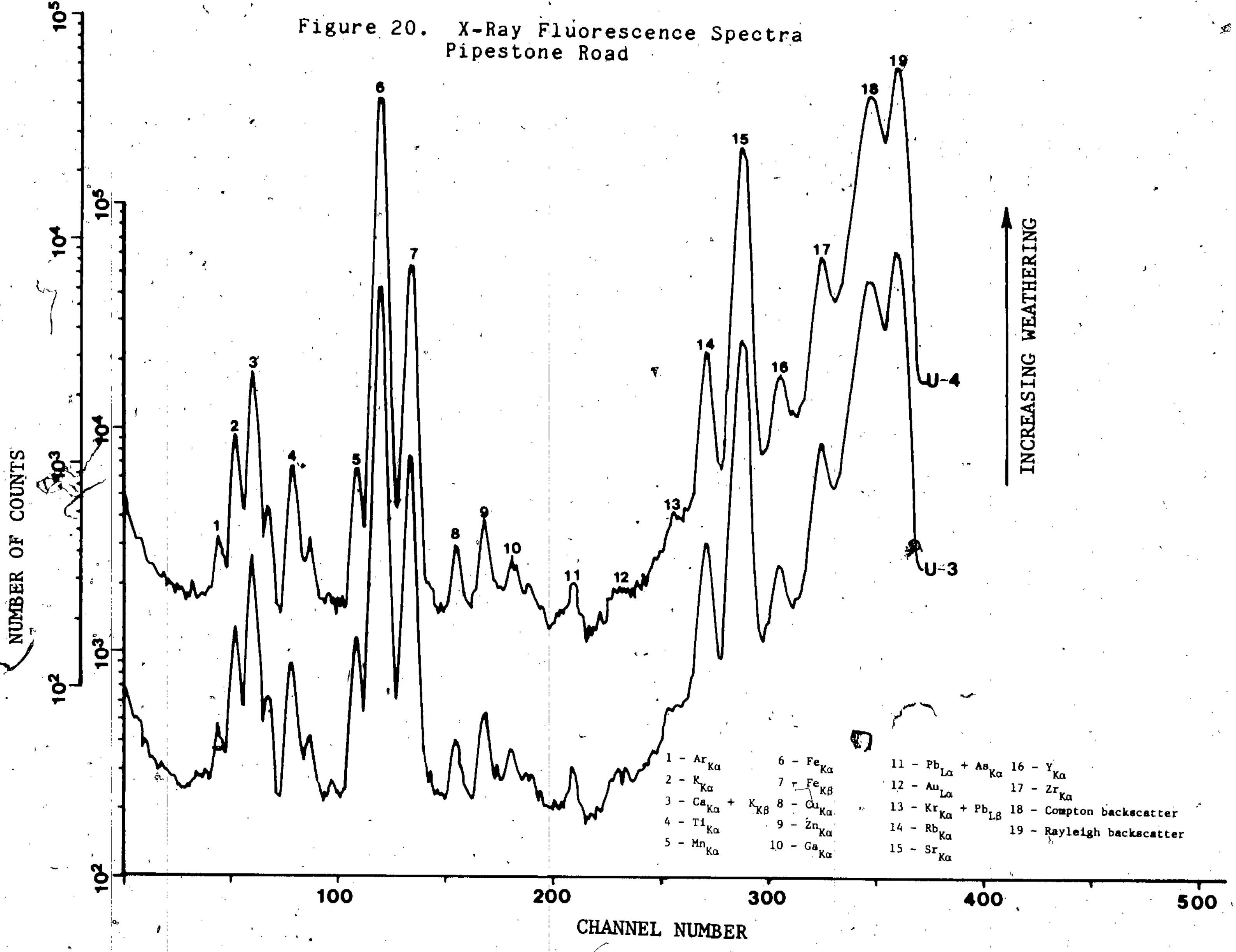
Figure 19. Northwest portion of the Grace 71/2' quadrangle (reduced to 1:45,000) showing the location of the Pipestone Road sample site.

weathering front is very abrupt, ~~ranging, in a vertical distance~~ of no more than 30-40 mm, from rock that is friable in the hand to rock that is difficult to chip with a hammer. Photograph 17 shows this transition where it occurs along a joint-bounded face, but the transition is apparently not joint-controlled everywhere in the exposed roadcut. Corestones are conspicuous by their absence in the regolith. The site shows no evidence of burial by either volcanic debris or sediments wasting off of the Boulder batholith, and may have been continously exposed to meteoric weathering since erosion exposed the batholith during the Eocene.

The particular enigma posed by these specimens is that marked differences in specimen strength and bearing capacity are not accompanied by any large differences in the relative abundance of elemental constituents. Figure 20 shows the similarity of spectra for the two samples, and Table 8 indicates that only small differences occur in the peaks monitored for this analysis. The selected peak intensity ratios also show very little difference (See Table 9). This result, of near chemical equivalency is contrary to similar circumstances encountered with quartz monzonite and alaskite where obvious disaggregative weathering is accompanied by easily perceptible spectral differences from spectra of fresh rock. These samples seem to fit entirely within early descriptions of weathering in the batholithic rocks, where weathering was attributed almost entirely to physical weathering agents. For example, Weed states:

Photograph 17. Abrupt weathering front transition at the Pipestone Road sample site.

Figure 20. X-Ray Fluorescence Spectra
Pipestone Road



> "The changes in character of the rock are largely physical, and its disintegration is due to the rapid expansion and contraction to which it is subjected by the extremes of temperature characteristic of the climate...The analysis shows remarkably small chemical alteration." (Weed, 1912, p. 86-87)

One point that should be emphasized, however, is that this is the only site examined where the weathering is obviously meteoric and where K decreases rather than Ca. Though the loss of K is slight, the logical source of K is either K-feldspar or biotite. Biotite releases K in the chloritization process, which is usually accompanied by a slight expansion. In almost all batholithic rocks the K-feldspar crystallized late in the reaction series, and thus occurs in subhedral to anhedral (and often interstitial) forms. Minor alteration of K-feldspar could thus also lead to disruption of crystalline bonds. Disaggregation causes are examined in more detail in the following section on petrological analyses of thin sections made from these samples.

Border Zone.

The border zone samples (BZ-1 and BZ-2) were collected in order to discern what effects might result from close contact with country rock at the Boulder batholith margins. The samples were collected in a road cut along Highway 91 in the NE1/4, SW1/4, S23, T9N, R3W, (Figure 21) where muscovite-biotite granite of Knopf (1963) is in contact with Madison Group limestones along the northern margin of the Boulder batholith. Examination of Table 8 shows that nearly every trend normally found in supergene weathering at other sample sites is reversed

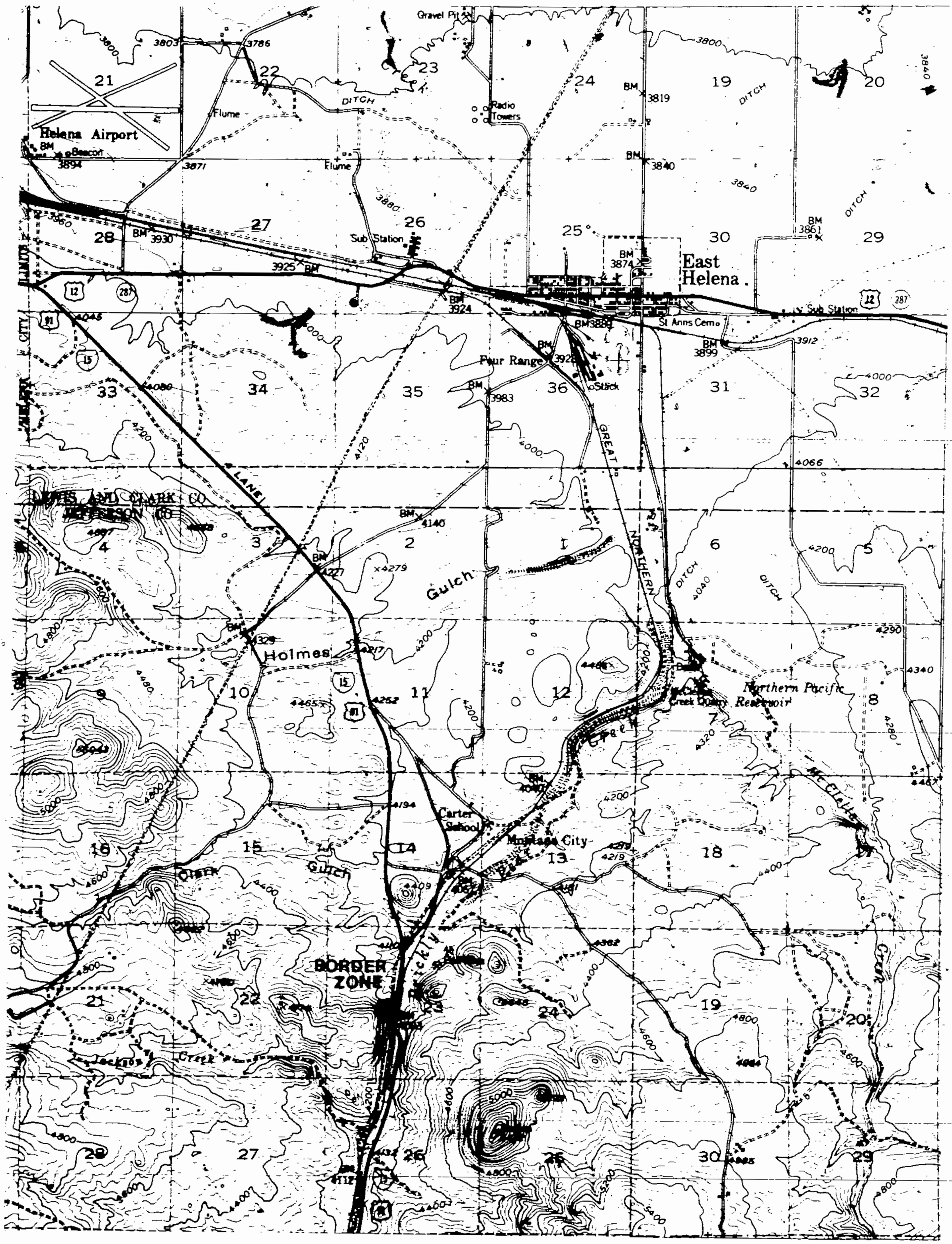


Figure 21. Southwest portion of the East Helena 15' quadrangle (1:62,500) showing the location of the Border Zone sample site.

here. That is, K and Rb decline relative to other constituents, while Fe and Sr increase. Only Ca declines in a fashion similar to effects of meteoric weathering. Figure 22 shows the spectra generated for these two samples.

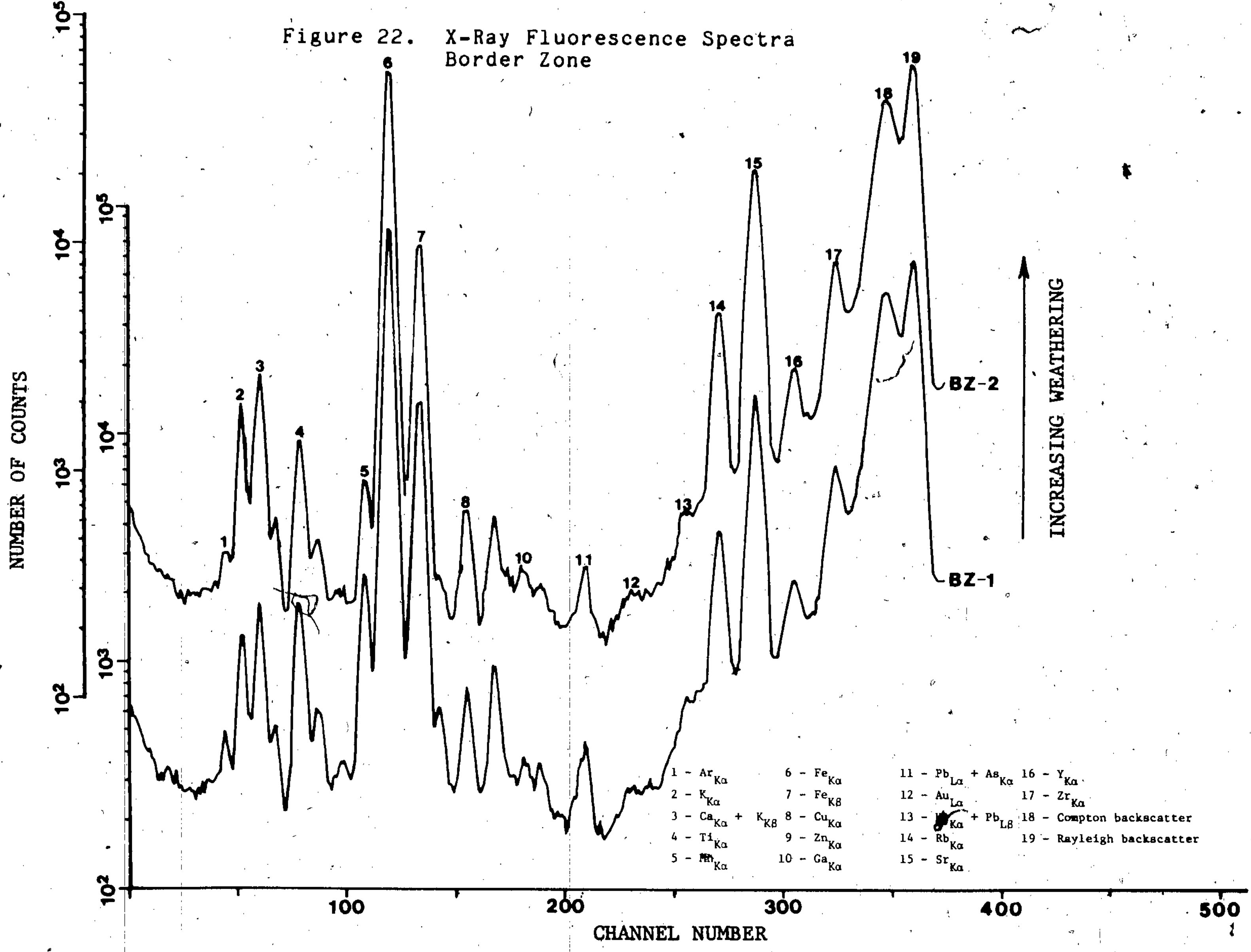
One complicating factor in the analysis here is the fact that alaskitic dikes were present in the fresh rock. In fact, the fresh rock somewhat resembles a dike cutting through saprolite. The presence of alaskite may have influenced the high K peak intensity in the fresh rock sample.

In Table 9, with the exception of samples at Old Baldy Mountain, where no trend could be established, the ratio most consistent with presumed weathering type (meteoric or hydrothermal) based on field examination, is the Rb/Sr ratio. At this site and at Pipestone Pass, a decrease in the Rb/Sr ratio suggests hydrothermal (and possible metasomatic ?) alteration. At all other analyzed sites, the Rb/Sr ratio increased with increased weathering, suggesting meteoric alteration.

Petrologic Analysis Results:

Mineralogical changes occurring during weathering are first described generally in primary mineral constituents. This is followed by specific examination of sample groups subjected to the petrologic analysis. Only major minerals will be discussed, except where minor minerals appear to have some importance in the weathering process.

Figure 22. X-Ray Fluorescence Spectra
Border Zone



Quartz. Being composed primarily of SiO_2, quartz was not sensitive to the X-ray analysis using Mo as a secondary target. Thus trends in the weathering of quartz were not established by the X-ray analysis. However, earlier studies using a Ti secondary target showed, within the limits of the method of analysis, only small decreases in the peak intensity of Si with increased weathering of either meteoric or hydrothermal origin (Wetzel, 1976). This is confirmed in the optical examination of thin sections, which showed virtually no change in quartz with weathering, except for secondary fracturing caused by biotite expansion in occasional samples. This result also echoes earlier work by Hood (1963) in the Butte Quartz Monzonite using X-ray diffraction. Tolar (1959, p.10) found quartz enrichment in the A-horizon soils in quartz monzonite of the Idaho batholith, which he attributed to eluviation of clays into the B-horizon. As explained in an earlier section, conventional pedogenic processes do not appear to have similarly influenced the *in situ* regolith of the Boulder batholith. In sieve analyses used by Hood (1963, p.13) to differentiate horizons in the regolith, the results are largely artificial. That is, suggested modal phi size changes in the different horizons are not supported by Hood's original data. This tends to support the conclusion that quartz, as a major component, does not significantly vary in abundance with depth in the weathering profile, nor does it appear to show any substantial effect from chemical alteration through the profile.

Feldspar. One of the hypotheses generated during the X-ray fluorescence analysis was of possibly faster weathering of plagioclase as compared to K-feldspar, as evidenced by the loss of Ca relative to K with increased weathering. This hypothesis does not seem to be directly confirmed by the limited number of sample sections examined. Table 10 shows relative degree and type of alteration in specific samples that were examined. Appendix 2 includes the full petrologic analyses for the samples listed in Table 10.

TABLE 10
MINERAL SPECIFIC ALTERATIONS FOR MAJOR MINERALS

Sample	Plagioclase	K-feldspar	Biotite
R-7	K-	K,Z-	C+,O+
R-8	Z+	K	C-,O+
R-9	K-	K-	C+,O+
R-10	K-	K	O+
LC-1	K	K	C+,O-
LC-2	K+	K	C-,O-
LC-3	K+	K	O
BZ-1		K-	
BZ-2	K+(?)	K+(?)	O+
U-3	Z-	Z-	C-
U-4	Z	Z	C-,O-

K = kaolinization
Z = crystal zoning
C = chloritization
O = oxidation

\+ = extensive
\- = minor

The earliest alteration occurring in the Butte quartz monzonite is identified by zonation or concentric compositional changes within individual feldspar crystals. This is caused by the changes in composition of the melt during the crystallization process, as described by Bowen's (1928) continuous reaction series.

Zonal differences on a broader scale also exist along the contact margins of the Boulder batholith where a calcic facies of plagioclase grades inward from the margin. This is generally assumed to result from metasomatic exchange with the country rock. Again, no studies have specifically linked this phenomenon to regolith formation, or ultimately, to weathering residuals.

Plagioclase, being part of the continuous reactions series, as described by Bowen (1928), varies a great deal in terms of deuteric zoning effects as the composition of the melt changed with cooling. However, not all plagioclase crystals examined in this study exhibited zoning and in no case did zoning appear to precondition plagioclase to subsequent meteoric attack. Only in the case of the granodiorite along Pipestone Road (U-3 and U-4) did the weathered sample appear to have more extensive zoning effects. The degree to which individual crystals show zoning while others a short distance away do not, is exhibited by the extensive zoning found in plagioclase in sample R-8. At the same location, samples, showing less (R-7) and more (R-9 and R-10) weathering, exhibited little or no evidence of zoning in plagioclase. Thus, the difference in plagioclase zoning exhibited between U-3 and U-4 is probably not a logical explanation for differential weathering between the two samples.

The facts that plagioclase in the quartz monzonite tends towards the calcic end of the series and that Ca is apparently removed in solution from meteoric weathering profiles suggest that kaolinization of plagioclase is largely supergene. At those sites where Ca decreased with weathering [at Boomerang Gulch and Clancy Gulch (R-7 to R-10 and LC-1 to LC-3)] a degree of kaolinization was apparent, as shown in Table 10. However, the degree of difference in plagioclase kaolinization between thin sections proved to be small. At present, no practical method exists of exactly equating the degree of kaolinization in the thin sections to the X-ray results. Further, the state of preservation of plagioclase and K-feldspar is such that the rapidity of the reaction postulated by Brickner (1968) must be questioned. This point is discussed further in Chapter 6.

An interesting case occurs at the border zone (BZ-1 and BZ-2) site where no alteration of plagioclase was apparent in the fresh rock (BZ-1), but alteration in the weathered sample was so intense that secondary minerals had completely masked the feldspar and quartz crystals in the thin section. Indeed masking was such that no estimate of primary mineral abundance could be made. The K-feldspar was kaolinized in the fresh rock sample but no other primary mineral was altered, suggesting the kaolinization in the K-feldspar at this site is of deuteric origin. This is generally congruent with the findings of Becraft et al. (1963), Hood (1963), and Robson (1972). The fact that this degree of K-feldspar alteration is present in the meteoric weathering sites, but does not change appreciably with increased weathering, suggests a relative immunity of K-feldspar to meteoric weathering, even though crystals may be previously altered deuterically. At the border zone site, where hydrothermal alteration is invoked, the K-feldspar is just as extensively weathered as plagioclase.

The granodiorite at the road cut along the Pipestone Road (U-3 and U-4) shows no significant difference in either plagioclase or K-feldspar with weathering. Examination of the thin sections indicates that the only difference in K-feldspar between samples is occasional fracturing in the weathered sample due to biotite expansion. The loss of K, then, is attributed to chloritization of the biotite with resultant release of K cations.

Biotite. Biotite in the Butte Quartz Monzonite is altered in a similar fashion to biotites in other areas referred to in the literature. Hood (1963) described only the appearance and colour changes accompanying the weathering of biotite in the quartz monzonite, and assumes alteration is meteoric and is produced by present environmental conditions.

At the Boomerang Gulch site the alteration of biotite by transformation of external surfaces to chlorite followed by oxidation does not seem to have a logical trend. The degree of alteration to chlorite was extensive in samples R-7 and R-9, less extensive in R-8, and minor in R-10 (the most altered sample). In sample R-10, the biotite appeared to be mechanically fractured. The source of the fracturing is not known, but it may have been related to disturbance in the process of making thin sections, since biotite tended to disaggregate even while encased in resin. The oxidation of iron was pervasive in the biotite, and is interpreted to follow the alteration to chlorite, since chlorite, where present, also exhibited oxidation.

The Clancy Gulch samples, however, do show some trends that are interesting. First of all, chloritization is most extensive in the freshest rock sample (LC-1); decreases in the intermediate weathering sample (LC-2); and is virtually non-existent in the most extensively altered sample (LC-3). One possible explanation for the decrease in chlorite with weathering is that chlorite is unstable and undergoes further alteration to a secondary mineral suite.

Interestingly, the Border Zone samples exhibit no chloritization, which suggests the alteration of biotite to chlorite is not an effect of either hydrothermal or 'reverse aureole' effects. If anything, the biotite at this site is being replaced by hematite, and is heavily oxidized in the alteration process. Oxidation also tends to increase with weathering at the Clancy Gulch site, though no hydrothermal influence has necessarily been invoked here. In a meteorically weathered site, the effect of oxidation would logically increase toward the top of the weathering profile where free oxygen, or oxygen dissolved in ground water, becomes more abundant. This is especially noticeable on ferromagnesian minerals.

The chloritization of biotite (and hornblende), at Pipestone Road in the Radar Creek granodiorite, is not very different in the two samples. However, the samples were taken only a few centimeters apart across the abrupt weathering front boundary in a road cut. Additional work would be necessary to establish the degree of chloritization further below or above the weathering front. It is apparent from the thin sections that biotite and (occasionally) hornblende are the minerals which induce 'grussification' above the weathering front. At the Pipestone Road sample site, the degree of grussification is essentially the same throughout the weathered zone from the top of the profile to the weathering front. Samples taken well below the weathering front would be needed to establish if chloritization only just precedes the weathering front (as U-3, taken from fresh rock immediately below the transition to grus, suggests), or whether it occurs as frequently at greater depths and may be of deuteric origin in the Radar Creek pluton.

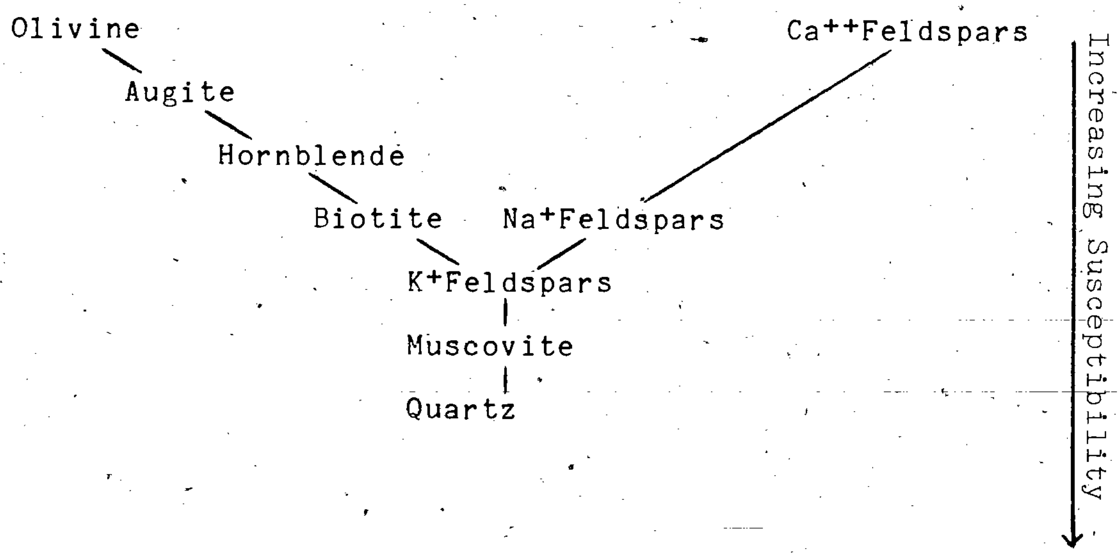
CHAPTER 6

DISCUSSION OF RESULTS

Weathering Trends:

The decreases in Ca relative to K in Tables 8 and 9 most probably reflect a relatively faster weathering rate of plagioclase (when compared to K-feldspar), with removal of Ca in solution. This is in accordance with other work dealing with weathering susceptibility in silicate minerals. It has been already remarked that Goldich (1938) postulated that the weathering susceptibility of minerals in igneous rocks is exactly the reverse order of the mineral crystallization reaction series developed by Bowen (1928) for igneous melts. This reaction series and the inferred susceptibility to weathering is shown in Figure 23.

Figure 23
BOWEN'S REACTION SERIES



Melcon (1975) points out that the series displayed is not strictly sequential, with biotite and plagioclase reported in the literature as the most readily weathered minerals in granitic rocks. Although weathering susceptibility of the series may be intuitively reasonable on the basis of the degree to which the minerals are removed from their environment of crystallization, efforts at a theoretical justification of the weathering sequence have been unsuccessful. As noted earlier, the large difference in temperature and pressure between the crystallization and weathering environments may preclude a close correspondence. Also, the freeze sequence in a cooling melt would remove virtually an entire suite of certain compounds from the melt simultaneously. This phenomenon has no parallel in weathering. Another missing factor in the explanation of anomalies in the weathering sequence (particularly biotite and muscovite) appears to be the nature of the weathering attack on the differing mineral structures. Recent work by Berner et al., (1980) with a scanning electron microscope indicated that small aberrant 'dislocation outcrops' are the location of primary weathering attack on specific silicate minerals, especially pyroxene and amphibole. Further, the lens-shaped 'etch pits' in each instance seem to controlled by the crystallography of the individual mineral, and can be replicated on fresh crystals using a hydrofluoric-hydrochloric acid treatment which simulates the long term effects of weaker humic acids in the soil.

An interesting trend is the Rb/Sr ratio increase that occurs at presumed meteoric weathering sites. This is consistent with the findings of Bottino and Fullagar (1968), who found Rb/Sr ratio increases of up to 70 percent in the weathered zone of granites in Massachusetts and Virginia. This is not a significant point in terms of weathering in the principal minerals, but may affect the interpretation of radiometric dates using the Rb/Sr ratio. Whole rock radiometric dates tend to be underestimated in weathered samples by as much as 10 percent. The Rb/Sr ratio also seems to be one of the best differentiation criteria between meteoric and hydrothermal alterations, with a tendency to decrease where evidence of hydrothermal alteration is present.

Differentiation of Weathering Types:

The chemical alteration of specific minerals in quartz monzonite and other plutonic rocks can theoretically be attributed to a number of possible environmental conditions. While meteoric weathering is normally invoked as the most likely and prevalent cause of silicate mineral alteration, it is clear that supposed meteoric weathering effects may, in some samples, be due to other causes. The nature and composition of the cooling magma, residual hydrothermal solutions acting both during and after crystallization, and 'reverse aureole' (Cunningham, 1971) or metasomatic exhange with host rocks have all been invoked as causing alterations which may not be distinguishable from meteoric effects.

Silicate magmas experience a change in compositional characteristics during the crystallization process. Normally, the residual melt will become enriched in compounds with lower crystallization temperatures and become depleted in compounds or elemental constituents already incorporated into the structure of minerals that crystallized at higher temperatures. Commonly occurring in the continuous reaction series of feldspars is 'zoning' or changes in composition of individual crystals as elemental depletions result in substitutions at the crystal-magma interface. For example, in a plagioclase crystal, anorthite ($CaAl_2Si_2O_8$), with the highest crystallization temperature, could be (theoretically) zoned concentrically outward with bytownite, labradorite, andesine, oligoclase, and finally albite ($NaAlSi_3O_8$) as substitutions occur. This type of zonation usually causes some irregularities in the crystal structure which could make the crystal less stable in a meteoric weathering environment. Occasionally, clouding in outer zones represent alteration products that are encased in the crystalline structure. These alteration products are considered 'orthomagmatic' (Wahlstrom, 1964) or 'second magmatic' (Shand, 1944), as opposed to hydrothermal alterations which would tend to affect the crystal surface and would occur after crystallization was complete. Because crystals are typically zoned with purer feldspars near the center (grading to a slightly sericitized form on the margin) Weed (1912), Hood (1963), and others have also hypothesized that this type of alteration is late deuteric. Zoning is considered normal in feldspars, and with the exception of one Colorado study (Isherwood and Street, 1976) in which reverse zoning was noted, no attempt has been made to link zonal alterations to differential weathering. Despite extensive study (Haase, et al., 1980), the complexities of compositional flux, material transport, and crystal growth in magmatic melts are still incompletely understood. There was no indication in this study that zoning has any effects which predispose feldspars to meteoric alteration.

Kaolinization in the feldspars of the Boulder batholith shows evidence of both supergene and endogenetic alteration. The kaolinization process in plagioclase is more difficult to attribute to strictly endogenetic processes. It is certain that where hydrothermal alteration can be demonstrated independently of weathering (e.g., mineralization), kaolinite and/or montmorillonite are common weathering products produced from plagioclase. However, laboratory experiments simulating field conditions show that the same feldspar-to-kaolinite reactions can occur with plagioclase (Brickner, 1968) or with K-feldspar (Wallast, 1967). For example, albite (Na-feldspar) reacts rapidly with water under conditions of pressure and temperature present in regolith materials. This produces a solution enriched in cations and silica and an aluminum hydroxide residue. Brickner, (1968) speculated that when silica concentration attains a critical level, in this case about 4 ppm, reaction with the residual aluminum hydroxide occurs and kaolinite is formed. This prevents further increase in silica concentration as long as any aluminum hydroxide remains in the system. Idealized reactions for albite to kaolinite are presented in the two equations below.

(1) $NaAlSi_3O_8 + 7H_2O + H^+ = Na^+ + Al(OH)_3 + 3H_4SiO_4$

(2) $Al(OH)_3 + H_4SiO_4 = 1/2Al_2Si_2O_5(OH)_4 + 5/2H_2O$

With minor substitutions, the two equations given above would also represent the transformation occurring with other cations that substitute for Na in plagioclase.

Most silicate minerals are anhydrous, so that as crystallization proceeds, the water content of the residual magma increases. This produces late phase, hydrothermal solutions which may react with the portions of the melt that have already solidified in the late stages of crystallization. The reaction products of water and crystalline silicates have been thought to produce similar, if not identical, results in both hydrothermal and meteoric weathering. Thus, merely examining the secondary minerals formed is often not enough to distinguish the two types of weathering. For example, a number of weathering residual investigations have suggested hydrothermal origins for at least some of the weathering products without drawing a clearly satisfactory distinction between weathering of hydrothermal and that of meteoric origin [see Exley, 1958; Palmer and Neilson, 1962; Jacobs and Kerr, 1965; Ford, 1967; Caine, 1967; Cunningham 1969, 1971; Eden and Green, 1971; Green and Eden, 1972; and Thomas 1974].

Most studies of hydrothermal alteration have focused upon metalliferous enrichment commonly associated with hydrothermal veins, and in this the Boulder batholith is no exception (see Stone, 1910; Pardee and Schrader, 1933; Sales and Meyer, 1948; Roberts and Gude, 1953; Wright et al., 1956; Wright and Emerson, 1957; Emerson and Wright, 1957; Bieler and Wright, 1960; and Wright and Bieler, 1960). Generally, metalliferous veins, quartz veins, and the like are assumed to be hydrothermal in origin and so the alterations in adjacent rocks are justifiably assumed to be hydrothermal also. The problem occurs when the usual enrichment products are not apparent, a circumstance probably more common than is the occurrence of recognizably 'enriched' hydrothermal sites. In this case, recognition of hydrothermal weathering is particularly difficult. Assessing methods of distinguishing between supergene and hypogene alteration, Konta states:

> "...no method, in particular no laboratory one, has yet been established to clarify the genesis of kaolin sand and to permit a valid comparison of corresponding results obtained for different field occurrences." (Konta, 1969, p.289)

Loughnan (1969) suggests the presence of nacrite or dickite (kaolin group clays having compositions identical to each other and to kaolinite, but which are structurally distinct) would demonstrate non-meteoric weathering, since neither has been recorded as a meteoric weathering product.

The identical composition and visual similarities in appearance of kaolinite and halloysite (meteoric weathering products) to nacrite and dickite (of implied hydrothermal origin) means that observation of these minerals in the field, or in thin section, or in compositional analysis using X-ray fluorescence is not satisfactory for distinguishing between these kaolin-group clays. Since these kaolin clays are structurally distinct, however, a number of laboratory techniques are available to identify these alteration products. Initially in this study X-ray diffraction was used to attempt to distinguish unique weathering products in regoliths. However, technical problems in the alignment of the Debye-Scherrer camera and lack of pure samples to produce necessary reference patterns led to an abandonment of this effort. Nevertheless, this method offers a great deal of promise for weathering studies. In particular, spectral signatures using X-ray wavelength dispersive (diffraction) techniques may be even more effective than X-ray fluorescence in making weathering origin distinctions, particularly where structural rather than compositional differences occur in the alteration products. Other techniques, such as differential thermal analysis (DTA) and electron microscopy, can often be used to verify results of diffraction analysis.

Cunningham (1971) has suggested the presence of altered rock beneath sound rock as an indication of hydrothermal origin. This claim is limited somewhat by the difficulty of finding such an occurrence. Substantiating evidence would also be required to rule out the possibility of alteration by ground water moving laterally through a joint or fracture system.

The X-ray fluorescence method used in this study to distinguish weathering trends and the implied origin of weathering products is, as described earlier, a relatively simple process. On the basis of enrichment and depletion patterns of elemental constituents, the 'fingerprint' of each sample can be compared with others. The interpretation is influenced by compositional variation in the rock, site differences, differing length of exposure to meteoric agents, and other factors which may lead to invalid comparisons. However, by collecting a series of samples at each site (minimizing compositional, site, and exposure differences) in such a way as to determine if a trend in the retention or loss of cations occurs with increasing alteration, considerable information can be obtained from relatively few samples. As the results of the X-ray fluorescence analyses indicate, hydrothermal alteration tends to result in the relative enrichment of a few common (e.g., Ca, Fe, Mn) and less common (e.g., Ti, Cu, Zn, Y, Zr) constituents. As determined in this and earlier studies (Wetzel, 1976), these same constituents tend to decrease relative to other constituents in meteorically weathered sites. These differences, more than any other, seem to 'fingerprint' the types of weathering present in the study area.

In addition to this, the X-ray analysis at the Border Zone site indicates that both Ca and K are diminished, but the K/Ca ratio remains fairly constant (it increases slightly). It is not clear from the appropriate thin section that kaolinitic alteration products are the only secondary minerals present. Sales and Meyer (1948) and Hood (1963) associate montmorillonite or 'yellow clay zones' with hydrothermal alteration on the Boulder batholith. Montmorillonite-group clays as a hydrothermal alteration product would tend to explain the relative retention of Ca at hydrothermal sites, since, after Na, Ca is the most common substitution cation in montmorillonite. Hood (1963) also associates montmorillonite with meteoric weathering, but this in not indicated by the samples in this study. The conclusion that montmorillonite is not a common meteoric weathering product at the sites in this study is reinforced by the loss of Ca in the X-ray analyses. Retention of Ca, being relatively soluble, would probably indicate Ca cation substitution in montmorillonite. Montmorillonite, then, could not generally be interpreted as an indicator of either present or paleo-climatic weathering sequences on rocks of the Boulder batholith (e.g. see Tardy, et al., 1973).

It should be admitted that the basis for concluding that hydrothermal/meteoric differences can be established by using the X-ray fluorescence technique rests on a limited sample. Certainly, substantial additional work should be done to validate any conclusions drawn from this study. It would be important to replicate this work in the study area as well as on other batholiths (and in other climates) to determine adequately whether the results presented here represent a unique or general case.

Paleoclimatic Differences in Weathered Regoliths:

With the small number of useable samples, no attempt at determining any statistical differences between characteristics of the weathering at the various sample sites was made. On the basis of the analytical results, two points did seem clear, however. First, there did seem to be a discernible difference between hydrothermal and meteoric weathering; and, second, there did not seem to be a discernible trend that would distinguish between regoliths of different ages (and presumably different climates). Regarding the possibility that paleoclimates have differentially influenced the mineral specific weathering process (resulting in differing regolith characteristics, alteration products, and ultimately landforms) no definite conclusion is drawn.

A combination of factors make it difficult to determine if, or to what degree, past climates in the study area have differed from the present climate. Certainly, the Pleistocene glacial maximums are separable on the basis of glacial evidence, particularly in the northern Boulder Mountains. However, little is known about the exact nature of Tertiary climates in the mid to high latitudes. This is particularly true for areas that have been tectonically active since late Cretaceous where broad zonal patterns inferred for other areas may not apply. Fossil evidence in the Tertiary basins of the study area tend to suggest warmer, wetter conditions in the early Tertiary, with gradually cooler and drier climates developed prior to the

Pleistocene. However, the correlation of fossil evidence with a particular Tertiary climate is tenuous at best.

For example, the original assignment of the Lowland Creek volcanics to upper Oligocene was made primarily on the basis of fossil leaves in the basal breccia unit (Smedes, 1962, p.264). Subsequent radiometric dating changed that assignment by roughly 20-25 million years to early Eocene. As mentioned earlier, Ruppel's (1963) assessment of the age of rhyolite in the northern portion of the Boulder batholith on strictly geological evidence, may have erred by as much as 35-40 million years. Since age assignments in the adjacent basins (Klepper et al., 1957; Robinson, 1963; Kuenzi, 1966) are based on similar fossil correlations and on assumed connections between tuffaceous sediments and the two Tertiary volcanics, any correlation of climate with a specific Tertiary period must await a general re-evaluation of age relationships. On the basis of recent radiometric dates (Chadwick, 1978; Daniel and Berg, 1981), one would expect interpretations of geologic age and attendant climatic inferences to be shifted backward in time.

Despite global and local evidence of climatic change, caution must be used in extrapolating these interpretations to a specific area. The brevity of facts available for extrapolation of paleoclimates has led Barron et al., (1981), to suggest that a re-examination of earlier interpretations may be in order. This is particularly true of maritime and mountainous zones where steep climatic gradients may have existed.

Coniferous needles in the Lowland Creek volcanics [_Sequoia affinis_ _Lesquereux_ (= _S_. _haydenii_ _Lesquereux_), Cockerell in Jennings (1920), pl. 27, Fig. 3] would suggest the early Eocene climate favoured coniferous vegetation on portions of the Boulder batholith inferred earlier to have experienced uplift and relief development similar to the present mountainous terrain (Smedes, 1962). As mentioned earlier, the species suggests a wetter, warmer climate. This, coupled with the intact regolith beneath the Lowland Creek volcanics suggests the climate prior to that time was conducive to development of deep weathering on the granitic rocks. Any degree of difference between the residues in the regolith induced by the early Tertiary climate and similar regoliths not covered by the Lowland Creek volcanics is not apparent from the analysis used in this study.

A number of explanations are possible. First, the effect of different climates over time may not result in different weathering products. This is essentially the conclusion of Tardy et al. (1973), who, as discussed in the literature review, found that the order of appearance of secondary minerals in granitics remains the same regardless of the nature of climates or the topographic position. This supposes that the major factor which would differentiate regoliths is the rate of weathering, which is to a certain degree controlled by climatic factors [as described by Strakov (1967)]. Re-examination of the samples using quantitative comparisons would be necessary to determine if differences in absolute amounts of elemental constituents reflected paleoclimatic changes. This type of analysis is complicated by the fact that truly 'fresh' rock samples are often not available at sample sites. Given natural compositional variations between sites, rock unaltered by climatic influences would be needed to provide a standard for comparison.

As a second explanation one might assume, for example, that at least in the mountainous portions of the study area, climate in the Tertiary was not significantly different from that at present. However, while elevation has a tendency to smooth effects of temperature extremes, a supposedly wetter Tertiary climate would presumably increase significantly the amount of moisture available for chemical reactions in the regolith of mountainous areas and accelerate erosion. This, coupled with fossil evidence suggesting substantial floral and faunal changes in this locale during the Tertiary (Robinson, 1960; Smedes, 1962; Kuenzi, 1966), does not make this alternative very plausible.

A third alternative that might explain why the regoliths appear similar is related to the nature of the protective cover offered by the volcanic deposits. The volcanics might prevent or delay erosional stripping of a regolith, but, because of the highly permeable nature of the volcanics, would not prevent post-volcanic climatic conditions from influencing the regolith, even though buried. This would place all regoliths, whether buried or subaerial, on essentially the same plane of development with regard to paleoclimatic influences (with some possible modifications resulting from the thickness and permeability of the overburden). Further, burial by volcanic debris might actually be conducive to regolith formation if there was none present at the time of burial. In particular, chloritization of biotite, which appears to occur at depth and seems to be responsible for <u>in situ</u> grus formation in the regolith, might be induced by burial. If this phenomenon did occur it would call for re-examination of the common technique of establishing the minimum age of a regolith by the age of the overlying materials (see Dury et al., 1969, Ford, 1967; Melcon, 1975). Fortunately, in at least the Boomerang Gulch case, a paleosol present immediately beneath the Oligocene rhyolite suggests that the regolith was developed prior to the volcanic episode.

Even with evidence of a paleosol establishing the correct relative age of a regolith, other evidence suggests that meteoric weathering does not stop with burial. In fact, nearly all lines of evidence in the study area indicate that regolith is best formed in a vadose zone environment. Alluvial boulders of quartz monzonite up to 1 m. diameter sandwiched between the welded tuff and lower lava units of the Lowland Creek volcanics are now easily disaggregated (Smedes, 1962, p.261). If one assumes the boulders were competent when deposited by alluvial means (likely) and were not weathered prior to burial (also likely, given the relatively short duration of the volcanic sequence), then the logical conclusion is that the boulders were weathered after burial. It is apparent that very specific, possibly rare, circumstances would probably have to exist to preserve a weathered landscape, so that its weathering was arrested from time of burial.

Cunningham states:

> "...the upper part of a pluton will be considerably preconditioned, and differentially so, in advance of its eventual exhumation; pre-conditioned by early, intense and widespread emplacement exchanges with the country rock; pre-conditioned by late "weathering" penetrations which would be largely one way effects from the thinning overburden to the country rock...While the detailed characteristics of such late penetrations will vary with the nature of the pluton below it, it should be emphasized that disintegration of the uppermost parts will precede the exposure of all plutons. It has been widely assumed in landscapes where rock-rot is marked, but where tropical climatic conditions are not now operating, that such rotting is fossil proof of former tropical conditions there. At least in landscapes involving the upper volumes of plutons this may be erroneous. Former tropical weathering would need to be proven across a variety of rocks, and "evidence" from plutonic material should be regarded as the least reliable." (Cunningham, 1971, p. 425).

This logic, with the exception of reactive transfers that might occur during the high temperature/pressure conditions of emplacement, is completely transferable to situations of burial by volcanic or sedimentary covers. It has been generally ignored in investigations of weathering residuals. With the exception of the regolith developed at the Browns Gulch site, there was no evidence observed within the thesis area of pervasive 'tropical weathering' on rocks other than plutonic rocks. There are some 'red beds' in the sediments below Tertiary pediments in the Boulder and Jefferson basins. However, Power (1969) has pointed out that red color does not necessarily imply 'laterization' in soils and has no exclusive climatic significance.

If one supposes that weathering 'types' specific to particular climates exist, the further question arises as to whether their characteristics might not be now masked by later climatic conditions. There does not seem to be any strong evidence from the analyses in this study indicating that a 'tropical climate' (or any warmer, wetter climate) produced weathering during Eocene or Oligocene times which has been changed by more recent climate. This is basically the same conclusion reached by Furtado (1968) in comparing granites in the intertropical region under different climates. The analysis here did show that if there are any different 'types' of weathering present, they are meteoric and hydrothermal.

Given these two weathering suites, the evidence against proposing a masking effect during the present climate is indirect but nevertheless persuasive. In this study and in earlier work (Wetzel, 1976) using the X-ray fluorescence technique, hydrothermal alterations were readily distinguishable from meteoric weathering. This distinction was clear even though the hydrothermal alteration present at both Homestake Pass (in 1976) and at Pipestone Pass (this study) have probably been subaerially worked on since Eocene. This leads one to doubt the ability of recent climatic conditions to mask supposedly quite different effects of early Tertiary climates. It leads one, instead, to support the concept that any climatic differences over the past 50 million years (in the study area at least) are more likely to be reflected in the rate of penetration of the weathering front than in any distinctive differences in weathering products.

Mineralic Influences in Regolith Development:

Examination of the thin sections points out the importance of biotite in the formation of weathering mantles in the plutonic rocks of the Boulder batholith. In studies elsewhere by Wahrhaftig (1965), Clark (1968), Nettleton et al.(1970), Basham (1974) and Isherwood and Street (1976), partial alteration and expansion of biotite was generally considered to precondition the process of grus formation. Eggler et al. (1969) showed that the tendency for biotite granite in Wyoming to form grus is enhanced by high temperature deuteric or hydrothermal oxidation of biotite. This alteration was used to distinguish between oxidized and non-oxidized emplacement sequences as an explanation of tor distribution on the weathered surface. Cunningham's (1969) morphogenetic model of tors and domical inselbergs in the same area of Wyoming has shown that the lithologic considerations proposed by Eggler et al. (1969) do not account for the distribution of all weathering residuals. Thus, despite a major role played by biotite, with its susceptibility to weathering in granitics, geomorphic considerations external to lithology are required to complete any picture of granitic landscape evolution.

In the petrologic analyses, the transformation of biotite to chlorite is indicated beyond a doubt as the process by which most fresh rock is altered to a state where disaggregation of crystalline bonds is readily accomplished by physical weathering. This transformation also appears to initiate the development of micro-crack systems which facilitate circulation of water (see Bisdom, 1967). It is possible that substantial meteoric alteration of feldspars is not effective until this micro-crack system appears.

The decrease in chlorite in the upper portions of weathering profiles, as suggested earlier, may indicate chlorite is unstable and undergoes additional transformation to a more stable secondary mineral suite. In fact, a number of investigators have recognized that individual minerals in crystalline silicate rocks weather to preferred secondary minerals in well-established sequences (Jackson, et al., 1948; Sherman, 1952; Fields and Swindale, 1954; Craig and Loughnan, 1964; Loughnan, 1969; Tardy, 1969). With biotite, the sequence is commonly forked, and the sequence followed is dependent on the weathering environment. The sequence is as follows:

```
Biotite -> (Chlorite) -> Montmorillonite
              \
               ---> Vermiculite -> Al-vermiculite -> Kaolinite
                         progressive weathering  >
```

Lelong and Millot (1966) contend that chlorite does not form under usual, near-surface, weathering conditions but does form readily in deeper zones characterized by "retrodiagenesis" of granites. This suggests that the penetration of the weathering front may be primarily attributed to chloritization of biotite. A corollary of this concept is that under certain conditions, the differentiation of two-stage weathering residuals may be as much attributable to a localized paucity of biotite as to the penetration of meteoric waters along unequally distributed joints and fissures.

The nearly fresh appearance of both plagioclase and K-feldspar in thin sections of meteoric weathering residues does not seem consistent with the loss of Ca relative to K in the X-ray spectra. This is additionally puzzling because the chloritization of biotite should also result in the loss of K. One possible explanation for the (normally) increasing K/Ca ratio with weathering, is that K is retained by biotite as it is released in the limited weathering of K-feldspar. The biotite-chlorite transformation is reversible under soil environment conditions and can, in fact, be simply done in a laboratory by treating chloritized biotite with a K-enriched solution (Hood, 1963). The presumption that chloritization of biotite at the weathering front results in a micro-crack system which enables weathering reactions to begin in other minerals, could possibly lead to a situation where the absolute amount of K was relatively constant throughout a weathering profile. That is, transfers of K in solution between K-feldspar and biotite may account for the fact that chloritization decreases near the top of the weathering profile. In such circumstances K-feldspar would theoretically become increasingly altered near the soil surface.

The above hypothesis does not, however, account for the formation of kaolin group clays which are inhibited by the presence of free cations. Nor is this idea completely congruent with studies measuring cation concentrations from small watersheds in granitic rocks on a portion of the Idaho batholith in western Montana. Foggin and Forcier (1974, 1977) found that Ca and K cations from these drainages were released in roughly equivalent amounts and that vegetative removal, causing extra leaching, increased the release of both cations. However, the use of total solute concentrations as an integration of reactions within a drainage basin has poor explanatory value for response to reactions at any individual site.

Given the coniferous vegetation at nearly every site sampled in this study, an alternative explanation may lie in the effect of organic acids on biotite. Organic acids effect the weathering of mica minerals by the following processes:

> "First, H^+ ions of the acids replace the interlayer K^+ ions in a manner similar to the replacing actions of other cations and render the layers expansible. Second, H^+ ions migrate into the octahedral and tetrahedral positions, extracting the multivalent cations therein and rendering the weathered edge fragile. Extraction of multivalent cations is further facilitated by the chelating properties of organic acids. Consequently, in agitated systems the weathered edge disintegrates and dissolves in the acid solution. Such a pattern would gradually expose new surfaces for ion entry, allowing continued action of weathering agents and repetition of the weathering process." (Boyle, et al., 1974, p. 42)

But, this does not explain the relative retention of K apparent in the X-ray analyses, nor is it clear why the 'weathered edge' chlorite would dissolve in the weakly acid environment without any further alteration of the remaining biotite, as is indicated by the lack of chloritization of the weathered edge of biotite grains in thin sections of the most heavily weathered rock samples (see samples LC1 to LC3 in Table 10).

Quantitative chemical analyses (Freeman, et al., 1958; Becraft et al., 1963) of the Butte Quartz Monzonite indicate that K and Ca are of roughly equal percentage in type specimens, but K becomes dominant as the rocks tend toward alaskite whereas Ca is more prevalent as the composition moves toward granodiorite. At most sites it appears that, regardless of the original proportion of the two elements, the K/Ca ratio increases with meteoric weathering. Taken alone, quantitative chemical analyses of the weathered samples would not reveal significantly more about increases in the K/Ca ratio with weathering than the present qualitative approach. However, with solute concentration data, this analysis would provide absolute elemental quantities that could be used in back-reaction formulae [as proposed by Brickner (1968)] to derive mineral specific alterations from the minerals in fresh rock. Brickner's (1968) method does not, however, account for imponderables in the regolith, such as cation exchange between K-feldspar and biotite, and is limited to sites where representative fresh rock samples are obtainable.

The remarkably fresh appearance of plagioclase, K-feldspar, and quartz in the thin sections of the present analyses would, using conventional optical techniques, lead to the often-repeated conclusion that little or no chemical alteration is occurring in the regolith. Virtually every early investigator working with the Butte Quartz Monzonite has reached this conclusion, and many have attributed formation of grus solely to physical weathering agents except where hydrothermal alteration is present. Hood (1963) provided the first comprehensive look at the nature of the chemical alterations in quartz monzonite in the vicinity of Butte, but also found no extensive alteration of quartz or feldspar crystals to be visible in thin sections. Techniques using a scanning electron microscope (SEM) indicate that dissolution features are visible on 'fresh'-appearing silicate minerals that are not detectable under a petrographic microscope (Berner et al., 1980). During the petrologic analyses performed in the present study, no obvious rounding or etching of quartz grains was visible in areas where meteoric weathering is inferred. However, no opportunity was afforded in this study to look for solution etching features demonstrated by Doornkamp (1974) on Dartmoor granites using a SEM.

As an aside, Doornkamp (1974) contended that these features were supportive of Linton's (1955) conclusion that weathering features at the Two Bridges quarry on Dartmoor were due to a warmer, wetter Tertiary climate [and also supportive of Eden and Green's (1971) conclusion that most vestiges of this climatic influence are now removed]. But this contention is not necessarily supported either from Dartmoor or Boulder batholith evidence. The tendency to find chemical alteration of quartz only in obvious hydrothermal situations on the Boulder batholith suggests that Palmer and Neilson's (1962) hypothesis of pneumatolytic alteration at the Two Bridges quarry may be feasible. Certainly the effects of hydrothermal alteration must be identified and taken into account prior to invoking pervasive climatic effects. This is especially critical in the mid-latitudes, but cannot be ignored even for conclusions drawn from studies in the tropics (for example, Doornkamp and Krinsley, 1971).

The evidence from these studies using SEM's shows that a fresh, unweathered appearance for most of the major minerals in the plutonic rocks of the Boulder batholith is not conclusive evidence that chemical alteration is lacking. Certainly, some of the chemical changes suggested by the X-ray fluorescence analyses in this study and the standard chemical analyses used by Hood (1963) have to be attributed to feldspar alterations.

Rate of Feldspar Alteration:

The appearance of relatively-fresh feldspar crystals showing effects of alteration to kaolinite only along crystal surface boundaries at the Boomerang Gulch site may give some insight into the relative rate of transformation of feldspars to secondary minerals. As already established, the paleosol preserved at this site suggests that regolith formation occurred as early as 36 to 38 million years before present (m.y.b.p.), prior to burial by rhyolite. This is as much as two to three times longer than conventional wisdom would suggest any site would survive subaerially in an area that had experienced tectonic uplift (see Ahnert, 1970). The fact that the regolith survived beneath the rhyolite is probably not as significant as the fact that the alteration of the feldspars in the regolith is essentially no different from weathering exhibited at any other of the meteorically-altered sites sampled. Conjecture that the regolith was protected from weathering by the rhyolite, in effect suspending alteration of the feldspars, controverts an earlier suggestion and evidence that the volcanic cover may even be conducive to regolith formation. There is a definite implication here that 'sandy saprolites', once created, can exist virtually unchanged for long periods of geologic time. If the volcanics at the Boomerang Gulch site are correctly mapped by Becraft et al., (1963) as early Eocene, making the regolith 48 to 50 m.y.b.p., then the time the regolith has remained relatively unchanged is extended even farther.

The formation of saprolite, containing a large proportion of partly altered primary minerals and a small proportion of secondary minerals, is an almost universal phenomenon in exposed granitic rocks in temperate climates. On the other hand, regoliths that exhibit complete dissolution of primary minerals are rare outside the tropics. This may imply that two thresholds of weathering exist. This is reinforced by the occurrence of sandy saprolites in the tropics. Also implied is that the conditions and/or rate of development of sandy saprolite may be decidedly different from that of lateritic profiles predominating in secondary minerals derived from _in situ_ dissolution of silicates. Certainly the grussification process is sufficiently rapid to create weathering profiles in excess of 20 m. even in areas that are tectonically active and where the probability of erosional removal is great.

Tardy, et al., (1973) have stated:

> "Over a very long period under the influence of constant climatic conditions in an open environment, all weathering can lead to the same end (for example, to gibbsite and then complete dissolution). However, in most cases, mechanical erosion intervenes before the end is reached. This is particularly true in climates which are neither very humid nor very warm." (Tardy, et al., 1973, p. 276)

If it can be inferred that climate changed appreciably over most of the Tertiary in the study area, it would appear that this is equally true in the case of variable climatic conditions. Given the long time apparently necessary for dissolution of primary minerals at the Boomerang Gulch site, it is reasonable to assume that only in the rarest of circumstances would weathering, more advanced than that presently occurring, develop prior to erosional intervention. The paucity of secondary minerals there would also tend to explain the general lack of soil development on the granitics in the study area.

The cumulative effect of climate has been the production of a regolith which has exhibited very little evidence of change over a relatively long geologic time. To the extent that the pervasive weathering of primary minerals occurs only at hydrothermally altered sites in the study area, it does not appear that even presumed warmer, wetter Tertiary climates (Linton, 1955; Doornkamp, 1974) have produced a regolith directly comparable to those in the tropics which are characterized by dissolution of one or more primary minerals. A determination of whether the regolith present on the Boulder batholith is unique in this respect is not possible at this time. However, a preponderance of studies in the American West suggests that grus (Nettleton, et al. 1968; Blair, 1975; Eggler, et al., 1969; Wahrhaftig, 1965; Melcon, 1975) or rapakivi-type granite (Volborth, 1962) is the norm rather than the exception in weathered regoliths on granitic rocks. Significantly, expansion of biotite is credited with formation of the grus in each of these studies. From this it would again seem that past, mineral specific weathering is not different in kind (for example, 'tropical' weathering) and may not even be readily distinguishable from the degree of alteration present. That is, once biotite has initially expanded and disrupted the crystalline matrix, further change may not be readily detectable even over long periods of geological time.

One possibile explanation of this is the theory that quartz monzonite (and perhaps any alkaline granitic) has two, mineral specific, weathering thresholds. One threshold seems to be reached relatively quickly over a wide range of climates, and requires only prolonged contact between biotite (muscovite), moisture, and, perhaps, biotic weathering agents in a subsurface environment (Reiche, 1950; Pauli, 1968; Jackson and Keller, 1970; Ivashov, 1974). The other threshold, leading to dissolution of one or more primary minerals, requires higher temperatures, precipitation, and possibly concentrations of bio-chemical chelating and sequestering agents (Strakov, 1967; Pauli, 1968). Without these, the process of dissolution is inordinately long.

Water, as discussed earlier, is a major transporting agent and reactant in silicate mineral weathering. The dissociation of water into the component ions increases with a rise in temperature, resulting in a rise in the inherent reactivity of the water. This relationship is shown in Table 11. Generally,

TABLE 11
RELATIVE DISSOCIATION OF WATER WITH TEMPERATURE

Temperature °C.	0	10	18	34	50
Relative Dissociation	1	1.7	2.4	4.5	8.0

(from Lukashev, 1958, p. 65)

the greater availability of hydrogen ions in warmer ground water and vadose zone moisture would be significant factors in increasing the weathering rate. Also, in light of the evidence reviewed by Ivashov (1974), one must agree with the early conclusion of Reiche (1950) that biosphere influences may be perhaps the most important of all in weathering. The speed and intensity of reactions can thus be expected to rise with both an increase of temperature and biotic activity in an area. There seems to be little evidence that the postulated second threshold of weathering (extensive dissolution of primary minerals), requiring as it does sufficient temperature, precipitation, biotic activity, and time, was ever reached in the study area during the Tertiary.

Clay Minerals in the Regolith:

Keller (1957) has presented a summary of conditions thought to influence the formation of kaolin and montmorillonite clay groups. For formation of kaolin type minerals there must be an excess of hydrogen ions, coupled with removal of calcium, magnesium, sodium, potassium, and iron. The removal of these elements is important because they do not enter the structure of kaolin-type minerals, so their presence would tend to inhibit formation of such minerals. The ratio of aluminum to silicon in kaolin type minerals is 1:1. Most rocks of the Boulder batholith contain more silica than alumina, therefore removal of silica in solution is also necessary. The excess of hydrogen ions is necessary to maintain electrical neutrality by replacing the positively charged cations. Hydrogen is also incorporated into the mineral structure of kaolin minerals.

The formation of montmorillonite type clays is favored by the retention of magnesium, calcium, and iron, with no excess of hydrogen. An excess of hydrogen would tend to displace the divalent metal cations which are common constituents of the montmorillonite structure. The ratio of aluminum to silicon in montmorillonite is about 1:3, so retention of silica is necessary.

At least three micro-environmental factors are considered important in determining secondary mineral alteration; the leaching conditions, the pH of the ground water, and the aluminum:silicon ratio. To a certain degree, these factors interact. In the study area for example, higher precipitation zones, conducive to leaching, also tend to support coniferous vegetation, which, as shown in rain water collected beneath coniferous canopies at several sample sites in this study, can significantly lower the pH of summer precipitation (pH values of 3.8 to 5.2 were common; rainfall tended to be slightly acid to neutral, 5.8 to 7.0). Lowering of pH will, in turn, cause more silica to be mobilized. The fact that all the sample sites were from areas with a forest canopy or mixed forest-grassland vegetation, and tended toward kaolin type clays, is more a reflection of available subvolcanic sample sites than deliberate design. Hood (1963) attempted structured sampling from both coniferous and sagebrush/grassland sites, and found that montmorillonite type clays predominated at the sagebrush/grassland sites. In general, the fact that a site does not support trees suggests less precipitation, less leaching, higher pH, and greater retention of silica. All of these conditions would be conducive to montmorillonite formation. In both the forest or grassland/sagebrush case, the primary source of the clay minerals in the regolith seems to be biotite, which was shown earlier (see Tardy et al. 1973) to form either montmorillonite or kaolinite after initial alteration to chlorite. Regardless of the secondary mineral predominating, the clay fraction is still very small when compared to the primary minerals present.

Some kaolin-group minerals, in particular halloysite, seem to be related to feldspar alteration. These clay minerals are almost always found in cracks and along grain edges, but the bulk of the individual feldspar grains appear fresh. This would seem to indicate the clays are forming at the surface of the altering crystals. Experimental work (Garrels and Howard, 1959) has led to the postulation that a thin layer of aluminum silicate material (from which the alkali metals have been replaced by hydrogen ions) is formed around feldspar crystals by hydrolysis. The diffusion of hydrogen ions inward subsequently acts as a barrier to further reactions with the crystal. It is this surface layer which is converted to halloysite. Halloysite is stable under a wide range of environmental conditions, thus, unless it is leached away or becomes unstable through a change in weathering environments, it acts as a deterrent to further reactions at the crystal surface. The longevity of feldspars in the regolith at the Boomerang Gulch site and generally over the Boulder batholith is probably attributable to this crystal surface barrier.

CHAPTER 7

WEATHERING RESIDUAL ANALYSIS

The tors, castle kopjes, domical inselbergs, and other residual landforms in the study area all appear to exhibit characteristics of classical 'two-stage morphogenesis'. There are, however, a number of characteristics of the analyzed regolith samples and of the landforms exhumed from the regolith that seem significant in light of other studies on weathering residuals. The three most important implications of the study focus on:

1. The interpretation of the age of the inselberg landscape.
2. The role and influence of lithology and structure in subsurface differentiation and subaerial survival of weathering residuals.
3. The multiple nature of implied inselberg morphogenesis.

Age of the Landscape:

Assigning the age of an inselberg landscape has proved a persistent problem. Only relative age dating techniques have proven useful, as no isotopic decay functions relevant to incipient weathering in granitics have ever been recognized. The frequent association of radiometrically datable, post-batholithic volcanics resting upon exhumed plutonic rocks is perhaps the most common method of assignment of a minimum age for weathering in the plutonic rocks. Dury, et al. (1969) have used this technique to date a lateritic profile in Australia as occurring prior to middle Miocene. Browne (1964) was actually able to date tor landscapes in Australia by Eocene basalts that flowed around the tors. Others have inferred relative dates of weathering from superjacent or receding sedimentary covers which are younger than the granitics (Falconer, 1911; Savigear, 1960; Jeje, 1972; Melcon, 1975). In most cases, however, direct evidence of either preburial development of weathering or landforms is complicated by the possibilities of weathering occurring beneath the protective cover, by reversed aureole influences existing in portions of plutons near the contact with the roof (Cunningham, 1971), or by pre-weathering edge effects as the cover erosionally thins (see Thomas, 1978b, p. 32, Fig. 3). Only the conviction that the paleosol apparent at the Boomerang Gulch site exhibits characteristics indicative of subaerial origin, offers any reasonable assurance of the inferred, early Oligocene age. To the extent that no other site exhibits a clearly defined paleosol suggestive of subaerial origin or burial of a prevolcanic weathering residual, no conclusive date for the age of weathering on the prevolcanic surfaces can be generally applied.

However, a number of observations about the age of regoliths and inselberg forms are warranted. The evidence presented by Ruppel (1963, p. G-11), citing 3 to 6 inches of weathering rind penetration on quartz monzonite boulders in glacial till and ice-carved outcrops is roughly congruent with his estimate that weathering profiles and landforms on the Boulder batholith are of Pliocene to Holocene age (personal communication, 1981). If the weathering rinds have formed since an early Wisconsin (?)

glaciation (Lemke, et al., 1965), then extrapolation of a continuous rate over time suggests that 5 to 10 million years are required to produce 20 m. of regolith materials. The fallacies of using such an estimated rate are readily apparent. First, even if the weathering process proceeded by the same reactions throughout the profile, the weathering rate would not be constant over time. Climatic change would, at least, affect the rate at which weathering proceeds (see Table 11). Again, changes in physio-chemcial environments with depth in the regolith (Nossin and Levelt, 1967) result in changing equilibria between minerals both in the regolith and penetrating waters. This generally results in a lowered potential for weathering reactions at depth because of solute saturation and the weathering rate would be further diminished if the thickness of regolith material above the weathering front increased. This situation is made even more unpredictable by the influence of variable erosional stripping rates. Finally, as pointed out earlier, survival of weathering crusts and residuals under glacial ice is fairly commonplace. Bashenina (1965) even postulates that chemical weathering may actually have progressed beneath a cover of glacial ice on Novaya Zemlya. Thus inferred post-glacial weathering may not be entirely post-glacial in all cases, further confusing this issue.

Thomas, in a discussion of sequential development of inselberg landscapes, states:

> "The preformation of 30-50 m of weathering in crystalline rocks may occupy 10^5-10^6 years; perhaps even 10^7

> years, while the removal of saprolite to these depths can probably be accomplished in 10^3-10^4 years. Tors and small domes of little more than 10-20 m relief could therefore have been excavated in Holocene time. Large bornhardts of 100-500 m height would require proportionately much longer, because simple excavation cannot account for such hills." (Thomas, 1978b, p. 33)

This supposed standard would suggest that many of the inselberg forms of low relief in the study area are Pliocene to Holocene in age, and are being exhumed from a regolith that is older, perhaps much older, than the inselbergs.

From the field evidence, however, it appears that the opposite circumstance is also true in some situations. That is, some weathering residuals appear to be much older than the surrounding regolith. For example, in several successive road cuts of Interstate 15 in the vicinity of Clancy [see Photographs 18 and 19; which are similar to an analogous situation detected by Thomas (1974b, Figure 10)], low relief tors and boulder piles (2-10 m.) capping small, ephemeral interfluves, are completely disconnected from sound bedrock by as much as 20 m. of saprolite. There is usually no evidence that the saprolite stops at the bottom of these road cuts and there are no corestones that might indicate proximity to the weathering front. The interpretation to be attached to these appearances seems clear. The detached tors and boulders must be older than the regolith formed beneath them and must have been exhumed from an even older regolith. Further, sound bedrock probably existed in close contact with the base of the tors and boulders on the interfluves at the time they were initially exhumed, since it is not common to find incipient tors and large corestones separated

Photograph 18. Weathered regolith beneath an ephemeral drainage. Note the small tor on the interfluve and more competent rock along the side of the drainageway at the base of the largest Ponderosa pine near the center of the photograph. This site is at the Clancy exit from Interstate 15.

Photograph 19. Weathered regolith exposed in a roadcut. The weathering extends well below the exposed boulders surviving from an earlier erosional phase, suggesting the surface boulders may be older than weathering in the subjacent regolith. This site is along a county road south of Helena.

vertically in a weathering profile by substantial amounts of weathered material. Without the benefit of evidence in these several large road cuts, conventional wisdom would dictate that the tor-boulder landscape is a result of geologically recent, incomplete excavation of the regolith. Under the circumstances, however, if the regolith were considered to be Pliocene in age, the depth of weathering would suggest that the tors and boulders (and an inferred previous regolith) would undoubtedly be older.

Farther up the Prickly Pear drainage system (see Figure 3) this situation is repeated many times. However, with elevational gain approaching the divide (elevation 1706 m.) between Prickly Pear Creek and Muskrat Creek (tributary to the Boulder River), the regolith gets thinner and connections between bedrock and surface boulders occur. This would indicate either a decreased weathering rate with elevation or an increased stripping rate, or both.

Even higher in the Prickly Pear drainage (elevation 2288 m), near the edge of the Boulder batholith in upper Dutchman Creek draining westward from the Elkhorn Mountains, it is apparent that stripping processes have exceeded regolith formation at least since the last Pleistocene glacial advance. Here an older regolith (possibly equivalent with the missing regolith that formed the tor-boulder landscape lower in the drainage) has been stripped, leaving several km^2 of the land surface littered with exhumed corestones ranging in size from small boulders to rounded blocks up to 20 m. long in their longest dimension.

There is additional evidence that some landforms have endured through several successive sequences of regolith formation and stripping. Several bornhardts in the vicinity of (and including) Spire Rock rise approximately 130 m. above the Spire Rock Flats pediment surface, west of Whitehall (see Figure 24]. The longevity of these forms and others, both near Spire Rock and in the Prickly Pear Creek drainage, must be primarily attributed to a relatively resistant lithology. Virtually every large inselberg standing above a planar surface is alaskite. Alaskite, rich in quartz and K-feldspar and low in biotite and plagioclase, would, given the analytical results of this study, logically be resistant. However, there are two significant features about the alaskite bornhardts relevant to their relative age and their possible denudation chronology.

First, the height of the bornhardts is at least twice the depth of any surviving regolith, suggesting sequential (or perhaps continuous) uplift and regolith formation. To the extent that an average of 20 m. of regolith may account for weathering and inselberg forms dating to pre-Pliocene, the height of the bornhardts suggests a much greater age for these forms.

A large kopje, just south of Spire Rock, rises about 60 m. above the Spire Rock Flats surface (Photograph 20). On top of the kopje are several alaskite boulders that are considerably more weathered than the upper surface of the kopje. Photograph 21 shows the scale and weathering contrast between the top of the kopje and the large boulder which can be seen to the right of center in Photograph 20. The generally rounded form of the

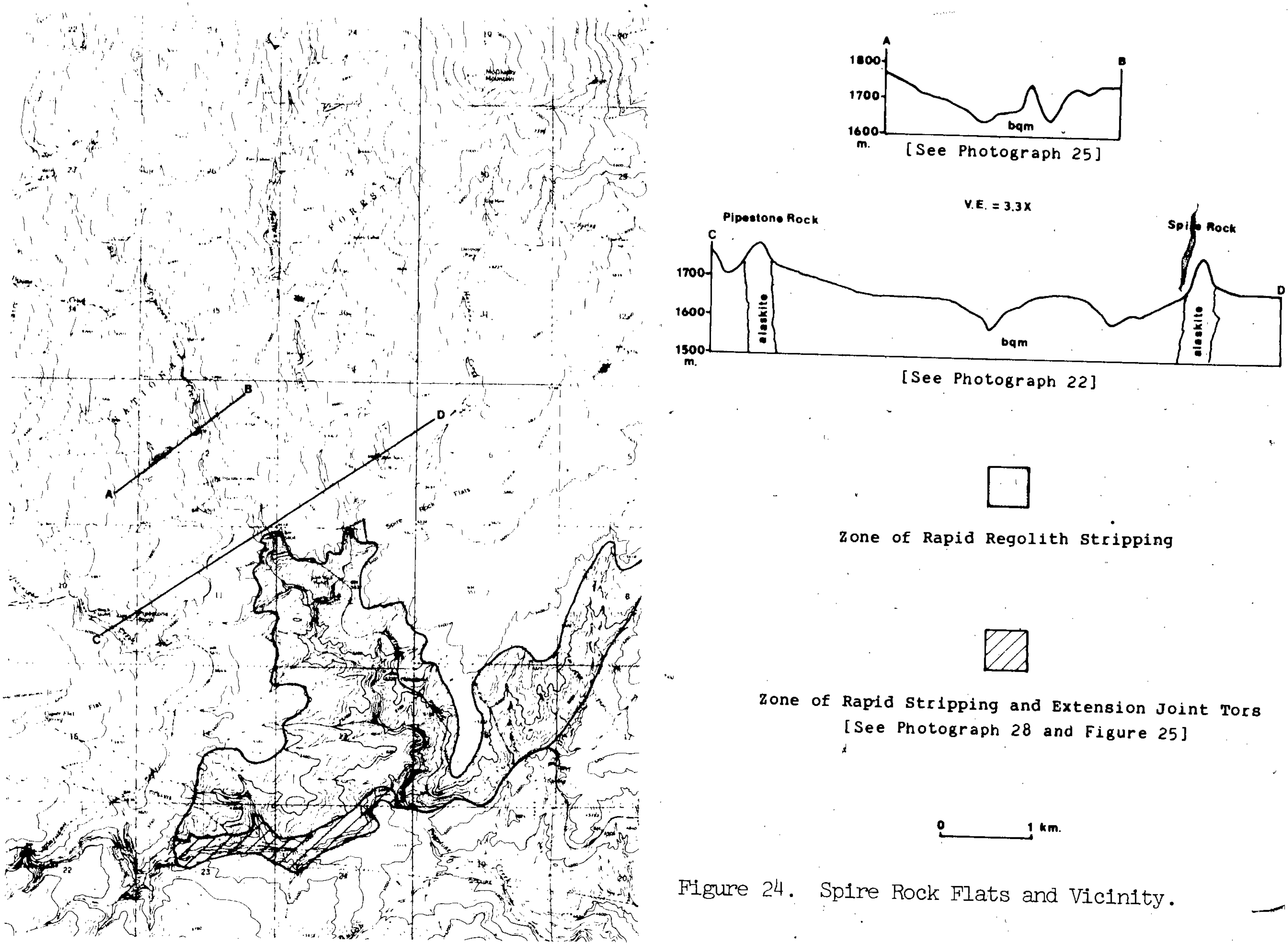
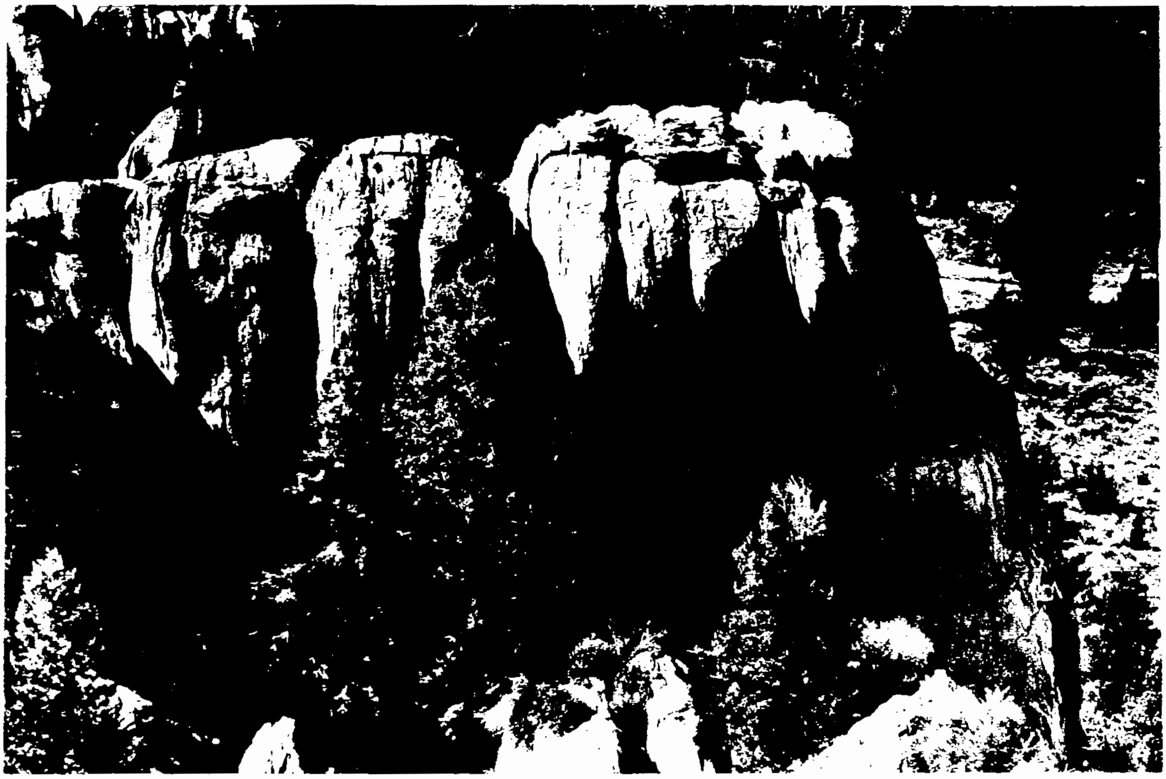


Figure 24. Spire Rock Flats and Vicinity.

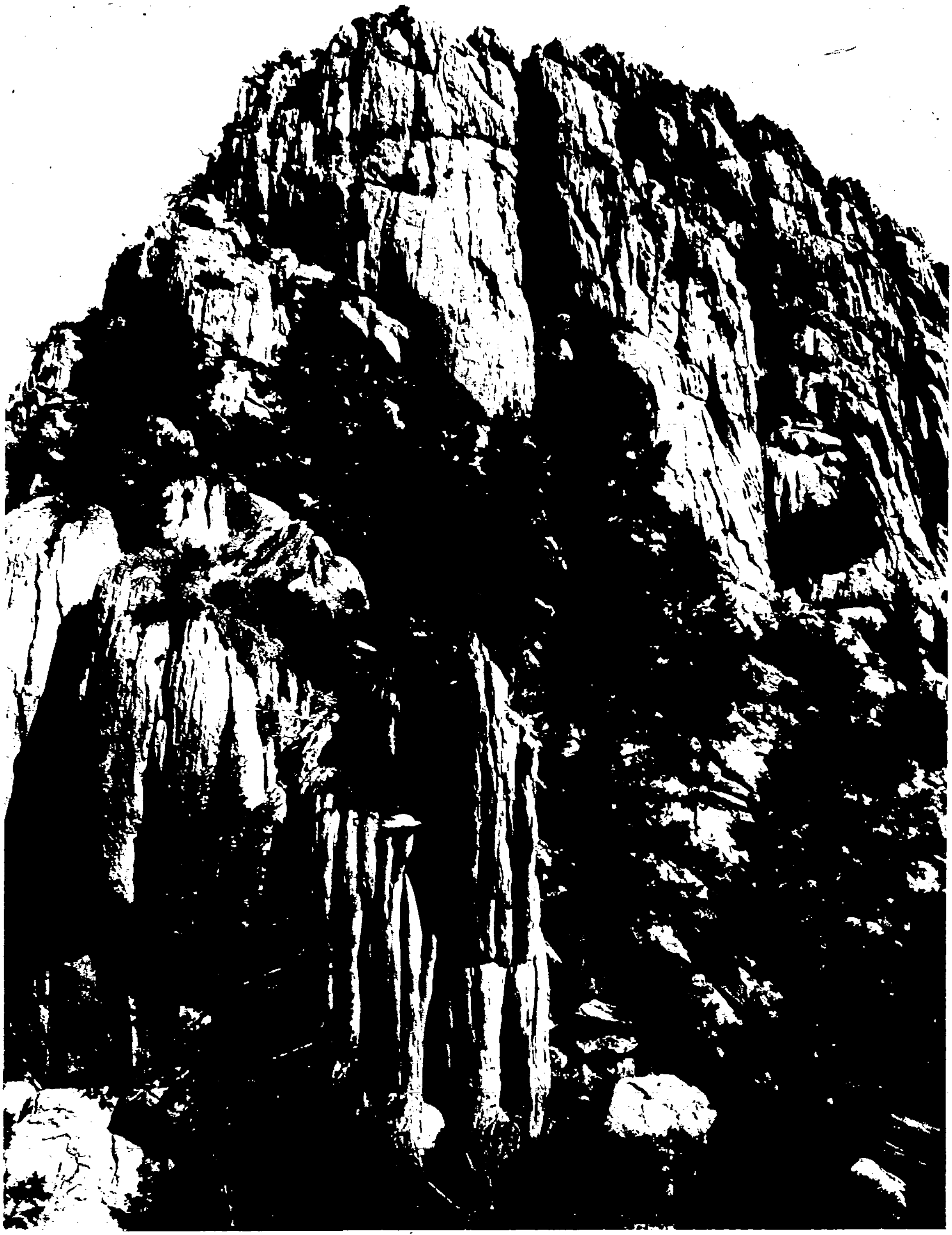


Photograph 20. Large kopje south of Spire Rock.

Photograph 21. Weathered alaskite boulder on top of the kopje shown above in Photograph 20.

joint-bounded blocks of the kopje suggest subsurface differentiation, and, indeed, the boulders resting on the kopje may also have originally been the result of similar subsurface weathering. This suggests that at least 60 m. (or possibly more) of regolith has been stripped from the Spire Rock Flats surface. To the degree that the boulders on the kopje exhibit coalescing panholes, residual indurated crust 'gargoyles', and angular features that seem the result of longer subaerial exposure than the underlying kopje, at least one generation of residuals older than the kopje is inferred at this site.

The micro-weathering features suggest a second relative dating possibility, where the upper surfaces of the bornhardts appear to have undergone greater subaerial exposure than the lower surfaces of the same landforms. It is not clear from the evidence of microforms whether the exhumation process was cyclic or continuous, but the tectonic history clearly suggests sequential regolith formation followed by stripping. The upper surfaces of the alaskite bornhardts are typified by 'gargoyles' (see Photograph 13, p. 88) resulting from coalescence of panholes or 'gnammas'. At Spire Rock (see Photograph 22, taken from the top of the kopje in Photograph 20), a horizontal joint plane, approximately 40 m. below the top of the inselberg, exhibited coalescing panholes with overflow channels developing as described by Cunningham (1964). This would suggest less subaerial exposure to the extent that one can deduce from the evidence and relevant literature that panholes are subaerially induced (see Twidale and Corbin, 1963; Cunningham, 1971). Small



Photograph 22. Spire Rock viewed from the south. Vertical and domical joints dominate in the alaskite bornhardts.

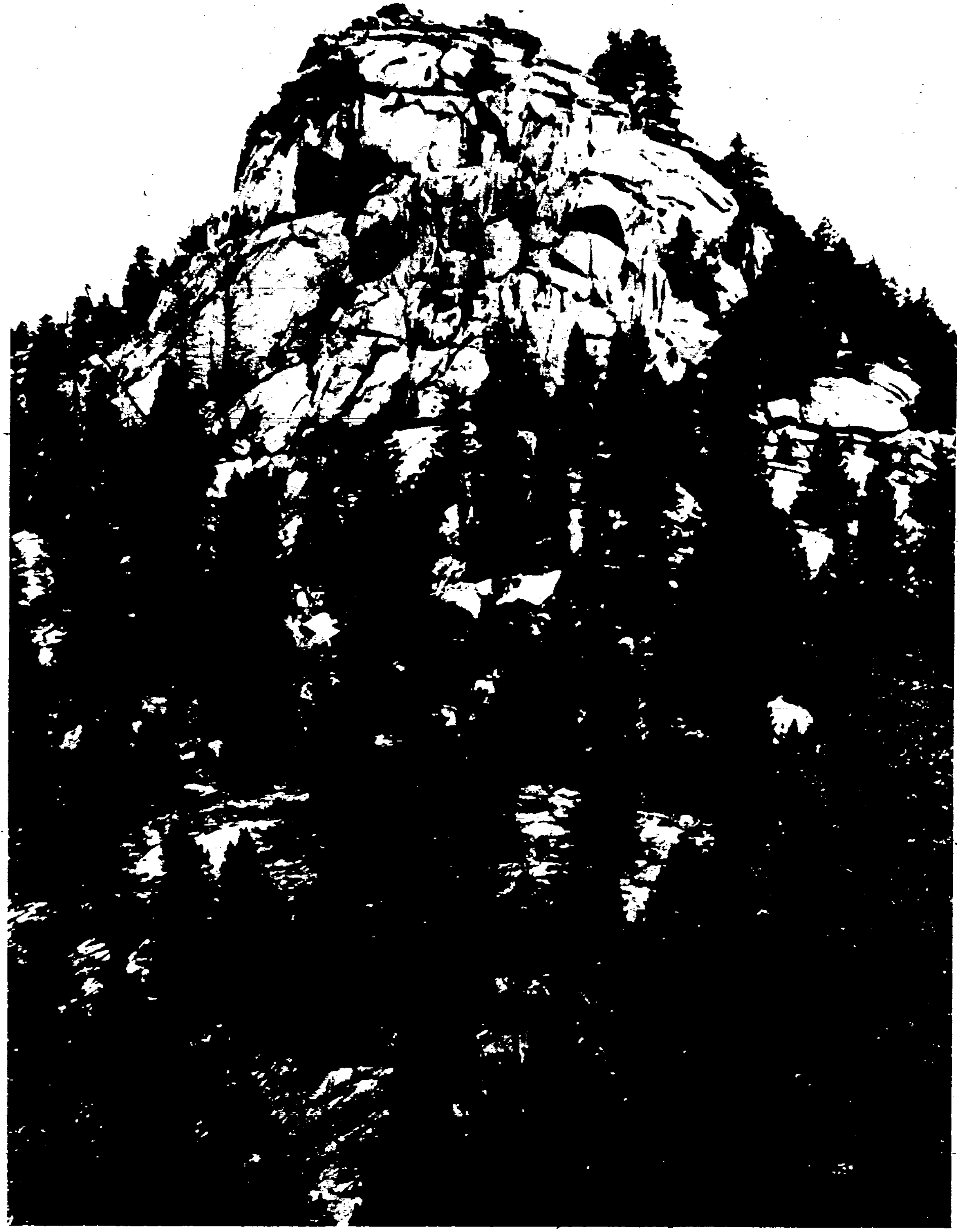
tors and boulders at the level of the Spire Rock Flats surface also have panholes, but they are generally small and not coalescing. Small panholes often occur on whalebacks or 'ruwares' of bedrock exposed on the thinly-mantled Spire Rock Flats surface. The youngest subaerial forms appear, then, to be on the lowest relief landforms. This conclusion is also indicated by cavities developed on the underside of exfoliation sheets (Photograph 23). These cavities appear to occur only under sheets that exhibit well-developed panholes on the upper surface. These cavities seem to be a result of rock flaking, caused by crystallization of salts dissolved in water that has percolated through the exfoliation sheet from panholes developed on the upper surface. The cavities were only observed near the tops of domical inselbergs and bornhardts, where both exfoliation and panholes were well developed. Also, where exfoliation sheets near the tops of the observed domical inselbergs have moved downslope under the influence of gravity, the surface underneath exhibits almost no evidence of subaerial weathering. This contrasts sharply with the upper surface of the exfoliation sheets which have undergone longer subaerial exposure (see Photograph 24).

Since the Spire Rock Flats surface is presently undergoing dissection by rejuvenated streams, there was also an opportunity to see if panholes were developing on more recently exposed quartz monzonite. Here, the evidence becomes somewhat confusing. A large domical inselberg about 2 km. west of Spire Rock also has 'gargoyle' forms at the summit, which lies at or

Photograph 23. Salt weathering cavities beneath an exfoliation sheet on the inselberg in Photograph 25.

Photograph 24. Contrasting weathering above and below an exfoliation sheet (also on the inselberg in Photograph 25).

slightly above grade with the Spire Flats surface (see section AB in Figure 24 and Photograph 25). Again, solution pits decrease in size and frequency as the level of Big Pipestone Creek, the dissecting stream, is approached. Near the level of the stream, they are virtually non-existent. It seems that three possible explanations exist. First, the quartz monzonite domical inselberg and the alaskite bornhardts could be approximately the same age, suggesting that the dissection and evolution of the Spire Flats surface are roughly contemporaneous. However, this does not seem supported by the field evidence, since the pediment is graded to a different level than are the dissecting streams. Second, the similarity of micro-weathering forms on the two inselbergs of different ages could be accounted for by the differing lithology. This idea is supported by the fact that, in close detail, the micro-forms are generally dissimilar in appearance, with the alaskite exhibiting weathering attack focused in a micro-joint system. This tends to create joint-elongated panholes, which result in overflow channels along the joint system before the panholes can get very large. This is perhaps best exhibited at Pipestone Rock, an alaskite plug about 4 km. southwest of Spire Rock (see section CD in Figure 24). The panholes on the quartz monzonite inselberg, on the other hand, did not exhibit this tendency (see, for example, Photograph 13, p. 88). Third, is the possibility that panholes are simply poor indicators of relative age of the landforms on which they occur, at least in comparing landforms at different locations. Cunningham (1965)



Photograph 25. Domical inselberg developed by stream incision and exfoliation on the Butte Quartz Monzonite, as depicted by cross-section AB in Figure 24..

found it difficult to use panholes as a consistent measure of relative age of tors in the South Pennines, England. Significantly, in that area tor bases decapitated by Pleistocene continental ice sheets did not exhibit panholes, while the ice-rafted tor tops did, suggesting that the panholes are probably pre-Wisconsin and possibly pre-Pleistocene in age. Not enough work has been done in glaciated areas of the study area to draw a general conclusion.

Lithologic and Structural Control in Weathering Residuals:

Lithologic controls in the differentiation of the landscape appear to be most directly affected by the presence of biotite in the rock matrix. Significant amounts of biotite in the coarse-grained batholithic rocks seems to be essential in the grussification process producing a sandy saprolite. This is indicated by this study and by others examining similar plutonic rocks (Isherwood and Street, 1976; Melcon, 1975; Eggler, et al., 1969; Nettleton, et al., 1968; Wahrhaftig, 1965). This process, by which sandy saprolite is developed through chemical attack and alteration of biotite (Tardy, et al., 1973), is the primary mode of regolith formation by meteoric agents on the Boulder batholith.

Not enough information is available in either this study, or others similar to it, to determine whether absolute mica content can be used as an effective guage of weathering susceptibility. Practical problems exist in linking biotite and muscovite content to observed weathering. In many cases it is not possible to separate other influences such as microclimate, joint openness and density, relief, and drainage, that may also lead to preferential weathering independent of mica content. Also, most studies focus on the remaining weathering residue, with little or no investigation of the weathered material that has been deposited elsewhere. Indeed, to be effective, such investigation would have to focus on weathering differences in a regolith exhibiting incipient residuals.

A number of authors have claimed no changes in rock composition occurring across the piedmont angle, the abrupt change in slope between the stripped surface and an inselberg (King, 1948,1962; Kessel, 1973,1974). This would necessarily infer that subsurface differentiation [or in the case of King (1948), subaerial differentiation] is independent of lithology. Later work by King (1975) inferring 'metasomatic hardening' of bornhardts as a primary influence in the differentiation and survival of these landforms, raises questions about the methods by which he earlier determined that no change in compositon was involved. Jeje (1974) suggests that small differences in mineral composition, insufficient to warrant a separately mappable unit, may nevertheless be significant in the differentiation of weathering residuals. This same line of reasoning is followed by Eggler, et al., (1969), but strict application of the lithologic control concept in this instance fails to account for other influences (Cunningham, 1969).

The work of Volborth (1962) may have some significance in explaining the mineral variation of the Boulder batholith and resultant evolution of inselbergs. As mentioned earlier, rapid pressure release, through venting of residual fluids during later phases of the crystallization process, results in crystallization of second generation quartz and feldspar in miarolitic cavities. This concept is also supported by the work of Tuttle and Bowen (1938). Several lines of evidence point towards a reasonable liklihood that this type of pressure release occurred within the pluton. First, even early investigators (Billingsley, 1916; Grout and Balk, 1934) recognized that only a relatively-thin mantle of rock formed the roof of the Boulder batholith. Thus, the increasing vapor pressure with continued crystallization would be liableto release along any structural irregularity in the roof capping the batholith. Second, the common occurrence of an anhedral quartz and K-feldspar matrix 'cementing' other euhedral crystals together is characteristic of granites where roof rock has been breached but atypical of 'rapakivi' or 'moro' granites where most crystals are euhedral (Volborth, 1953, 1962; Eskola, 1948). The latter case indicates longer maintenance of system pressure during the crystallization process. The third factor is the predominance of alaskite (including aplite and pegmatite) in veins, dikes, sills, and irregular bodies. These felsic rocks represent the quartz and feldspar enriched products of forced crystallization that occurs with a pressure release (Volborth, 1962).

The exact expression of a pressure loss in a volume of cooling magma as large as the Boulder batholith cannot be accurately assessed. Volborth (1962, p. 817) postulates that "many centers of crystallization will form". It is unclear if this hypothetical result would result from a single breach in the pluton roof, or whether each center would be related to a pressure loss zone. Analogies with a flowing well penetrating an artesian aquifer or a 'gusher' oil well, would suggest that the radial spread of pressure loss (and growth of a crystallization zone) would be a function of the vent discharge rate, duration of discharge, and the existence of conduits such as joints, which would spread pressure loss faster than through the rest of the medium (Jenkins and Prentice, 1982). Any analysis would be complicated by the variable viscosity of the melt and self-sealing nature of the vents. However, to the extent that the crystallization centers and alaskitic rocks would coincide, these centers, once exposed, would tend to exhibit relative resistance to weathering compared to zones where pressure was at least partially maintained. This resistance would result from the high content of quartz and K-feldspar in the alaskite and also the filling of the miarolitic cavities of the partially solidified, adjacent, quartz monzonite melt. This is generally consistent with observed field relations between alaskite and quartz monzonite (as expressed in Figure 7). It is also consistent with a phenomenon not reported elsewhere in the literature. That is, the occurrence of a 10 mm. thick indurated layer which lines interior joint-planes in the large, silicic, quartz monzonite kopje immediately south of the alaskitic Spire Rock (see Photograph 26).

Ruppel (1963) indicated that the relative paucity of alaskite and aplite in the Basin quadrangle in the north west portion of the Boulder batholith was most likely to result from laccolith tendencies along the western edge of the batholith. This would limit the amount of subjacent magma and necessarily restrict the availability of residual fluid necessary for formation of alaskitic bodies. Another factor may be the resistant, welded tuff comprising the middle member of the Elkhorn Mountains Volcanics, which consistently forms the pluton roof in this area. That is, the resistant, welded tuff unit may have maintained internal pressure in this zone longer than occurred in the eastern portion of the batholith where alaskite is common. No analysis of thin sections from this portion of the Boulder batholith was performed to ascertain the nature of quartz and feldspar crystals within the quartz monzonitic rocks.

The relative resistance of the alaskitic rocks is shown by the fact that alaskite is always expressed as positive relief when compared to the quartz monzonite. An unaltered alaskite dike will often be seen cutting diagonally across a weathered regolith of quartz monzonite in road cuts, indicating relative resistance under similar, subsurface weathering conditions. Strong joint control over some smaller streams is apparent in aerial photographs of the study area, but many streams also seem to be located where there is an absence of alaskite. Large scale field maps, indicating alaskite veins and bodies too small

Photograph 26. Induration along an interior joint plane. This has not been previously reported by others studying granitic weathering residuals.

to map individually on smaller scale, published, geologic maps, show an overwhelming correspondence between alaskite and ridge lines or drainage divides (Becraft and Pinckney, 1961; Pinckney and Becraft, 1961; Becraft, et al., 1963). This agrees with the earlier observations of Roberts (1953). Further, in areas where alaskite is rare (such as the western edge of the batholith), characteristic weathering residuals consist primarily of small piles of exhumed corestones, indicating that resistance to weathering may exhibit substantially different tendencies in the quartz monzonite and result in different weathering residuals. Important exceptions to this are the frequent domical inselbergs along the western and southern edges of the Boulder batholith where leucocratic satellite plutons (like the Moose Creek pluton) are present. Here, each pluton appears to be compositionally more like the silicic facies of the Butte Quartz Monzonite, yet forms similar to the alaskite bornhardts are quite common.

Twidale (1964, 1971, 1976) also postulates that crystallization centers exist in granitic rocks, but focuses on the stress differential and resultant jointing patterns that such centers would cause, rather than on the origin of these centers as 'compressional foci'. In his view, the centers of crystallization would result in resistant kernels in the pluton. During the erosional exposure of the landscape, these resistant kernels would be exposed and would generally result in upstanding residuals (Twidale, 1971; Twidale and Bourne, 1975). The location of these residuals would be independent of local or regional base levels (Thomas, 1974b), or of planation related to stream incision and parallel slope retreat as advocated by King (1948, 1953, 1962).

The lithologic differences between the quartz monzonite and alaskite makes it difficult to discern and separate those influences due to lithologic resistance from those due to compressional stress as theorized by Twidale (1964). The fact that bornhardts and domical inselbergs on the Boulder batholith are not as tall or as perfectly formed as many described in the literature suggests that regular jointing patterns have probably been supplemented by tectonically-induced stress joints [for a contrast, see the accounts of bornhardts developed on stable cratonic blocks in the tropics in King (1966) and Thomas (1966a, 1966b, 1967)].

There seems to be no convincing field evidence that the domical joints on alaskite bornhardts and domical inselbergs need stress induced by 'compressional foci' to explain their existence. While the concept of sheeting or extension joints, related to compressional stress release, has intuitive appeal as an explanation for the dome form, extension jointing can also be seen parallel to the land surface along recent stream incisions of Big Pipestone and Halfway Creeks. Thus, although there is no theoretical objection to the domical shape being attributed to stress at the time of emplacement, there is no empirical evidence that this concept need be invoked to explain the domical inselbergs in the study area. Simple unloading (Chapman and Rioux, 1958) during the stripping process seems to adequately explain the imperfect domical jointing and appears to have a general application to other situations in the study area. One exception to this is briefly discussed in the section on morphogenesis of forms.

The development of many irregular vertical joints seems to be best explained by the highly variable tectonic history of the area (Ruppel, 1962). This irregular joint system may also explain the general lack of tors; whereas fins, blades, and boulder piles are common as meso-scale weathering residuals on the quartz monzonite. This is essentially the conclusion of Oberlander (1972), from a study of similar forms in the Mojave Desert in California.

Most joint planes and dike planes intruding along joints strike about N. 40° W. in the southern portion of the Boulder batholith and about due north in the northern portion. These joints are nearly vertical or dip steeply to the west. The facts that hornblende crystals show alignment and dikes have most commonly intruded along these joint planes, suggest that this joint system may have been established prior to complete cooling and crystallization (Grout and Balk, 1934). The complementary orthogonal to sub-orthogonal joint planes do not often show hornblende crystal alignment, but there are exceptions to this rule. Joint planes differing from this supposed initial joint system are suggested to be tectonically induced by later uplift. The numerous tectonic, stress-induced joints may be the limiting factor in the height of domical inselberg and bornhardt forms. A number of the irregular joint systems may also be related to marginal, stress-induced joints (Grout and Balk, 1934). Inferred nearness of the existing land surface to the pre-existing pluton roof (Billingsley, 1916), is supported by "local gently dipping schlieren in the roof zone" described by Schmidt et al. (1979, p.13). The schlieren generally represent drag structures within the crystallizing magma resulting from movement near the contact zone. This drag, creating stress perpendicular to the contact, is responsible for marginal joints that would theoretically diminish toward the pluton center. Normally, near the pluton roof the movement of magma would be nearly vertical, but an uneven roof (cupolas, downward projections, etc.) might induce some jointing patterns analagous to marginal joints. The interpretation of jointing patterns as influences on weathering residuals in the near roof zone is somewhat problematic. In granitic rocks, the upper parts of intrusions may be inherently more jointed than deeper masses (Balk, 1937; Cunningham, 1971; Twidale, 1971; Thomas 1974a), so that continued erosional removal may lead to decidedly different weathering residual forms with depth. This may help explain why a quartz monzonite, domical inselberg (Photograph 25) exists below the Spire Rock Flats surface, while above this surface, quartz monzonite is generally expressed as individual boulderized hills or single boulders. Only rarely does quartz monzonite form domical inselberg or bornhardt forms above the Spire Rock Flats surface, and even these inselbergs are heavily jointed. It should be noted that other factors, such as relative age, could also account for the observed differences.

Morphogenesis of Inselbergs:

Although the Boulder batholith may not be unique in this respect, it is an ideal area to demonstrate the principle of 'convergence' in the development of granitic landforms. Varied modes of origin attributed to inselberg landscapes can be readily demonstrated. This is significant to the degree that some of the same characteristic forms can be shown to be formed by different processes. Because of the variety of forms in the Spire Rock Flats area, much of the analysis is focused on the area shown in Figure 24.

Endogenetic Forms. A number of forms may be inherited from the contact with country rock at the top and margins of the pluton. On the Boulder batholith the evidence for this is mostly indirect. Admittedly, the batholith contact with roof rocks has been reported as uneven in accounts by other investigators (Billingsley, 1916; Pardee and Schrader, 1933; Grout and Balk, 1934; Ruppel, 1963; Knopf, 1963), and this has been verified by direct observation. Clear contacts can be seen along Prickly Pear Creek near the border zone sample site (see Figure 2); in the abandoned Spring Hill Mine about 6 km. south of Helena; near the southern end of the batholith by Lime Kiln Springs (25 km. southeast of Butte); and on the western slope of Elkhorn Peak (a twin peak to Crow Peak shown in Figure 1A). None of these areas, however, show contacts irregular enough to account for cupola forms in the inferred roof zone comparable with those reported by Cunningham (1971) in southeastern Idaho or by Volborth (1962) in Nevada. Nevertheless, a number of these cupola-shaped weathering residuals (50-70 m. in height) in the southern Boulder Mountains show evidence of schlieren roughly parallel to the present surface configuration, and this suggests that some of these forms may be inherited from the pluton roof. The lack of recognizable, roof pendants in this area does raise questions about the degree of inference that can be drawn from the schlieren, although xenoliths are common in the quartz monzonite. Perhaps an equally likely explanation for these forms is that proposed by Cunningham (1971). That is, the mostly-conical, boulderized hills and occasional domical inselbergs in the study area may result from differentiation imposed during the thinning and eventual stripping of the pluton roof. The differential attack of the pluton may have been guided not only by variable roof thickness and by joint systems prevalent in the roof contact zone, but also by the trends of the schlieren. The boulderized form of these hills is probably due to the numerous irregular joints from various causes (e.g., marginal cooling, compressional foci, and tectonically induced joints).

Fluvial Process Forms. The alaskite bornhardt and domical inselberg forms at Spire Rock and vicinity, are the only large inselberg forms that rise *above* a surface which can be inferred to be a pediment. There seems to be no implication that these inselberg forms are necessarily the end products of either parallel slope retreat (King, 1966) or laterally migrating streams during a wetter Pleistocene (?) epoch (Oberlander, 1972). Rather, the relative resistance of alaskite, as well as its tendency to preferentially direct fluvial erosional agents to more easily eroded quartz monzonite, seem sufficient to explain the bornhardts.

Thus, these monoliths would probably exist regardless of the inferred mode of stripping. The thin mantle and graded profile that are present where the surface is not presently being dissected certainly are in conformity with descriptions of other pediments in the region (Montagne, et al. 1968; Montagne, personal communication, 1982). The Spire Rock Flats surface has no clearly defined 'piedmont angle', but at about the point of slope change, a zone of exhumed, elephantine, quartz monzonite boulders is common. This suggests that the surface was extending into the mountainous fringe.

One explanation, tied to Ruppel's (1962) suggestion of post-Pleistocene tectonism in the southern Boulder Mountains, seems to fit the observed circumstances. This scenario requires relative stability in the southern Boulder Mountains and Spire Rock Flats area during, and probably for some time prior, to the Pleistocene. During this time, the Spire Rock Flats pediment was probably graded to a local base level in the Jefferson Basin, and, although some uplift occurred, erosional efficiency on the pediment was such that the pediment surface remained mostly intact and at grade. This would, at least partially, explain the stripping that exhumed the alaskite bornhardts, and would also account for the erosional remnants of pediments developed on late Tertiary deposits in the Jefferson basin. These pedimented sediments of the Sixmile Formation and younger deposits (Kuenzi, 1966, 1971) are now physically separated from the Spire Rock Flats surface because of uplift along the basin margin and extensive, erosional removal presently occurring within the basin (Kuenzi and Richard, 1969). However, the arkosic nature of the late Tertiary sediments and graded surfaces on top of erosional remnants suggest a possible pre-uplift relationship between the surface developed on the Boulder batholith and nearby similar surfaces in ~~the~~ Jefferson basin. Ruppel's (1962) contention that the major uplift occurred in either late Pleistocene or Holocene may account for the lack of glacial ice in the southern Boulder Mountains during the Pleistocene. Also, the stripping of any residual regolith on the Spire Rock Flats seems best explained by sheetwash during the Pleistocene, prior to dissection by streams following the late Pleistocene uplift. No direct evidence was found to suggest that solifluction was a major agent removing weathered material from the Spire Rock Flats surface during the Pleistocene (as has been suggested for stripped surfaces elsewhere in the mid-latitudes—see Demek, 1964b; Waters, 1964; Montagne, et al. 1968; Czudek and Demek, 1971). There is evidence in road cuts through regoliths of the upland surface that frost churning or "geliturbation" (Waters, 1964) occurred at higher elevations during the Pleistocene, and may be presently active.

Most of the landforms developed on the quartz monzonite above the Spire Rock Flats are boulder-mantled hills, though, as indicated earlier, some domical inselbergs exhibiting schlieren also occur. In many places, regoliths are still quite deep and along some interfluves, small patches of regolith are essentially intact. This is especially true in portions of drainage basins above marked nick points on Homestake and Big Pipestone Creeks near the Continental Divide. From this, it appears that many of the differences in landscape appearance between Spire Rock Flats on the eastern margin of the Boulder batholith and the uplands of the southern Boulder Mountains may result from different stripping processes in the two areas.

The difference seems related to dissection by definite channelized flow in both perennial and ephemeral streams on the upland surface, while there is considerable evidence for sheetwash and anastomatic streams being the primary excavation processes on the Spire Rock Flats. In this, the mode of denudation does not seem to be solely directed by lithologic control, as suggested by Warnke (1969). Rather, the relationship seems significantly related to local relief and base levels, aspect, and vegetation.

Stream dissection on the upland surface shows definite structural control. On aerial photographs, small streams and intermittent drainage channels are incised in rectilinear fashion, exploiting the sub-orthogonal N. 40° W. primary joint set that predominates in the southern portion of the Boulder batholith. Significantly, although the residual forms on the upland surface are clearly being exhumed and compartmentalized by channelized flow, there is generally little evidence of pediments or characteristic 'piedmont angles' between the incising streams and weathering residuals. This raises serious questions about the applicability of pedimentation and/or parallel slope retreat theories that have been associated with exhumation by stream entrenchment (King, 1948, 1953, 1957; Pugh, 1956; Kessel 1973, 1974). Of course, others have also disputed the necessity of pediments as a defining feature associated with domical inselbergs (Handley, 1952; Thomas, 1965; Eden, 1971). The significant point, brought out by the facts that domical inselbergs occur both with and without surrounding pediments, is that pedimentation is not necessarily an integral process in the exhumation of domical inselbergs and bornhardts. Pediments are graded slope, equilibrium forms (Hack, 1960), and only under fortuitous circumstances of tectonic quiescence do they appear to be associated with weathering residuals of the Boulder batholith. Pediments planed smoothly across tilted Paleozoic rocks of varied erosional resistance in the Yellowstone River Valley near Livingston, Montana (Montagne et al., 1968) suggest that weathering residuals should, in fact, be readily consumed by pedimentation processes. The relative resistance of the alaskite bornhardts, and the open system feedback (Strahler, 1952) that seems to result in exploitation by fluvial processes where alaskite is not abundant, probably account for the survival of the alaskite forms on the Spire Rock Flats surface, even assuming late Tertiary pedimentation. Conversely, the survival of ubiquitous inselberg forms on the uplands above the Spire Rock Flats surface would seem to be related to the fact that pedimentation (or Pleistocene cyroplanation, or altiplanation of Czudek and Demek, 1971) did not occur here.

Structural Forms. In association with tectonically-induced stream dissection, many weathering residuals have developed curvilinear extension joints, resulting in characteristic domical shapes (see Photographs 7 and 8). This joint related, domical form is generally best preserved on the flanks of inselbergs that are close to a presently incising stream at lower elevations (see Photograph 27). This is illustrated in Photograph 25, showing the quartz monzonite domical inselberg lying generally below the Spire Rock Flats surface (location is shown in cross section AB of Figure 24). Again, it is not known if this better state of preservation is caused by more massive joints in the rock with increasing depth of incision; is related to relative youth of the recently exhumed landforms; or is due to drag on steep valley sides removing weathered sheets. Probably all three influences are significant. One large blade (50-60 m. high x 10 m. at the base) near the nick point of Homestake Creek shows joint density increase towards the top of the blade, and this jointing pattern is characteristic of many other similar forms on the Boulder batholith. The blade is somewhat unique, showing virtually no evidence of horizontal joints, the antithesis of a tor form.

Nearby, also on Homestake Creek, is the most common occurrence of landforms most resembling the classical tors in

Photograph 27. Domical jointing on the flanks of the incised channel of Big Pipestone Creek near the domical inselberg shown in Photograph 25.

form. This area is outlined in Figure 24. These tors are clearly structural forms, related to extension jointing sheets in the massive quartz monzonite exposed by the incision of Homestake Creek. Similar forms occur in the vicinity of Welch's quarry near Pipestone Rock. This relationship is illustrated in Photograph 28 and is shown diagramatically in Figure 25. The fact that these tors occasionally extend partially down the joint- bounded plane of the convex hillslope attests to the influence of extension joints in the development of these forms. Projection of the pre-incision surface together with exhumed boulders suggest a regolith was present prior to the stream incision. It is not clear how the weathered mantle relates to the tors.

Particularly confusing in this respect is the rounded appearance of the exposed surfaces of the tors. If the extension joints developed parallel with the stream incision, the inferred origin of the tors is subaerial. That is, they are remnants of joint bounded sheets which, due to their proximity to the top of the convex slope, have resisted downslope movement and removal by Homestake Creek. Since the joint planes are later than the actual incision and stripping, the remnants of these sheets must also be post-stripping in origin. This concept, advocated by Chapman (1958), does not explain the subsurface weathering inferred from the spheroidal rounding of joint planes. If either the 'compressional foci' (Twidale, 1976) or crystallization center theory (Balk, 1937; Volborth, 1962) is applied, then the curvilinear joint pattern may have

Photograph 28. Extension joint tors along Homestake Creek. View is north from Interstate 90 between Butte and Whitehall.

Figure 25. Sketch of Extension Joint Tors along Homestake Creek.

existed prior to incision by Homestake Creek, and subsurface weathering could have occurred prior to subaerial exposure of the tors. These tors may give some credence to the concept of resistant kernels of rock awaiting exhumation to become bornhardts or other inselberg forms. There is also a further possibility that the existing bare rock, joint-bounded surface upon which the tors rest may have supported a thin, waste mantle (Hurault, 1967; Scott and Street, 1976; Thomas 1978b). In this case, spheroidal weathering may have occurred prior to stripping of the thin mantle. However, if the uplift inferred by Ruppel (1962) is late Pleistocene to Holocene, the stream incision must also be geologically recent. This would make the survival of a thin waste mantle on the steep slope unlikely.

Reinforcement Mechanisms. Once the initial differentiation of a granitic landscape is accomplished, whether by random process or initial structural, lithological, or other influences, the pattern tends to persist because of reinforcing or feedback mechanisms. This is succinctly explained for landforms in general by Twidale (1976), and there are many observations of granitic landforms that seem appropriately explained by this process.

One instance, mentioned earlier, is that one can almost predict that alaskite will outcrop along ridges but be relatively rare in valley floors. In this, it is apparent that initial lithological contrasts have been accentuated by weathering and erosion of weaker zones. Over time, the more resistant alaskitic rocks tend to occupy those portions of the landscape least susceptible to fluvial erosion (interfluves), resulting in a pattern that tends to perpetuate itself even through disruptive influences from uplift. In instances where initial lithological distinctions are subtle, but nevertheless significant (Jeje, 1974), the interpretation of origin and distribution of weathering residuals is greatly complicated by such reinforcement mechanisms. Feedback linkages that are easily recognizable on the Boulder batholith also seem to be related to the 'element of crisis' suggested by Godard (1966) and Douglas (1969). Particularly noticable are the effects of large scale vegetation disruption caused by wildfire or logging, and the equilibrium disruptions caused by geologically-recent uplift.

One reinforcement mechanism observed is commonly noted in weathering residual literature. Its application on the Boulder batholith, simply stated, is that as soon as rapid stripping exhumes relatively-fresh quartz monzonite, the subaerially exposed surface resists weathering. This is perhaps best exemplified in the Interstate 15 road cuts in the Prickly Pear Creek drainage near Clancy (see Photograph 18). Here, not only do tors and boulders cap the summits of interfluves that have completely weathered to grus, but road cuts below the base of small, ephemeral drainagelines show that relatively sound rock exposed along the banks of these drainageways also has weathered rock beneath it lower in the profile. This suggests that the subaerial survival of exhumed residuals may be related to rapid exhumation, regardess of topographic position. Once subaerially exposed, residuals resist the granular disintegration process that is so effective in the subsurface environment (Isherwood and Street, 1976). Sound, or even partially-weathered, quartz monzonite has a low hydraulic conductivity, and thus absorbs moisture slowly and sheds it rapidly through runoff and evaporation. Without a relatively- permeable regolith surrounding the residual to maintain soil moisture more or less constantly at the contact surface of the fresh rock, the rock becomes nearly inert to the effects of water. What moisture is absorbed during precipitation or from melting snow tends to reinforce the durability of the outer shell of the residual. This induration has been called various things (e.g., the 'cuirasse' of Godard, 1966), but most studies of granitic residuals make reference to an indurated shell or crust which subaerially armors exposed residuals. Water entering the exposed rock will react with susceptible minerals and take cations into solution. Because of the slow rate of movement of water through the intercrystalline space, this absorbed water almost never discharges as a liquid. Instead, the water evaporates as it nears the rock/air interface, precipitating the solute load in the external crust of the rock. Earlier X-ray studies by this author, of elemental differences between rock interiors and the indurated crust for both quartz monzonite and alaskite, revealed silica enrichment in the crust (using a titanium secondary target; Wetzel, 1976). A molybdenum secondary target additionally showed enrichment of iron, which may account for the reddish tint of exposed surfaces of many residuals. Others have also recorded this phenomenon (Carl and Amstutz, 1956; Augustithis and Otteman, 1966). These elemental constituents precipitate in micro-cracks, and tend to cement the outer indurated layer of an exposed inselberg even though the interior of the residual may be partially weathered and friable.

Melcon (1975) found similar induration with interior 'rot' in an environment above timberline in south central British Columbia, but no induration occurred on corestones only partially exposed. This lack of significant induration in slightly exposed bedrock is parallel to situations on the Boulder batholith where stripping has been arrested prior to complete loss of the regolith. Where only the rounded tops of corestones are exposed, no weathering crust develops and granular disintegration still continues on the exposed surface. Where exhumation is complete, an indurated crust forms and granular disintegration is largely arrested.

The other reinforcement mechanism suggested by the exposed weathering residuals involves the interactions of vegetation, natural fire, aspect, and uplift, to produce conditions conducive to rapid stripping. Besides the frequent association in the study area of granitic weathering residuals with ponderosa pine (and other dry-site conifers) parkland vegetation mentioned earlier, at least two locations suggest that reinforcing feedback can create a situation where the rate of stripping is rapidly increased. One such area is on the southern exposure of hillslopes along streams dissecting the Spire Rock Flats surface (see Figure 24). The presumed sequence starts with a moderately deep regolith containing numerous large corestones. Uplift triggers the incision of streams, but, because the regolith is relatively stable with intact vegetation, the mantle is stripped only in the immediate vicinity of the dissecting streams. Fire, a frequent natural occurrence, is even more frequent here because of the general southern exposure of the Spire Rocks Flats surface, resulting in excessive drying of vegetation during summer months. Following a fire, lack of protective cover results in some stripping of the regolith prior to re-establishment of grasses and shrubs (which can take one to five years). Loss of a surface layer from the regolith diminishes its depth, and more bare rock surface is exposed. Stress on plants is increased because of reduced soil moisture storage and canopy coverage over a period of many years following a fire. Further, pioneering vegetation (grasses and shrubs) after a fire contains a high proportion of fine fuels, and most of these fuels are close to the ground surface where fire can be sustained even when fuels are somewhat discontinuous. These factors increase the probability of subsequent fires.

Bare rock surfaces, being generally convex (emergent corestones and inselbergs), tend to channelize overland flow into areas away from them to areas occupied by relatively unresistant regolith materials. With cyclic fires and stripping, there is eventually so much bare rock surface exposed that establishment of vegetation becomes difficult. At this point the process becomes self-limiting because the lack of regolith materials for a rooting medium hinders the establishment of a semi-continuous vegetative cover. The area outlined in Figure 24 (see also Photograph 28) seems to have reached this point, with the landscape virtually littered with exhumed corestones and weathering residuals, but with a very sparse vegetative cover. This is an extreme case of the shallow range site association described in the section on vegetation.

The Sweeney Creek Natural Area, a 10 square km. area about 20 km. west of Helena on a tributary of Tenmile Creek, exhibits similar features. Here, however, two fires documented in historic times have devastated the vegetation of the south slope and qualitative descriptions of erosional stripping from the burned area have been recorded (USDA, 1977). In both areas, erosional stripping is most pronounced on steep, southern exposures, presumably because of the efficiency of fire and the difficulty in re-establishment of vegetation on such areas of severe moisture stress.

CHAPTER 8

CONCLUSIONS

This study has attempted to focus primarily on the nature of the weathering environment in regoliths, rather than provide yet another examination of weathering residuals, steeped, as many of these have been, in speculation about the nature of a preparatory material that no longer exists intact around the inselbergs. Particularly significant in this study is the emphasis on examination of regolith materials beneath early Eocene and early Oligocene volcanic covers.

Major objectives at the outset of the study which relate to this emphasis were to differentiate between meteoric and hydrothermal alterations in the plutonic rocks, and to determine if paleoclimatic influences in weathering could be detected in regoliths preserved beneath Tertiary volcanic coverings. Tentative conclusions regarding these objectives that can be drawn from the study are as follows:

1. Hydrothermal and meteoric alterations of the Butte Quartz Monzonite appear to be separable on the basis of trends established for the relative abundance of elemental constituents, as shown by X-ray fluorescence spectra for increasingly weathered specimens. While absolute amounts of nearly every element may decrease with weathering, supergene alterations are characterized by an increase in K relative to Ca and in Rb relative to Sr. Additionally, Ti, Mn, Fe,

and Zn tend to show a marked absolute decrease with increased meteoric weathering (this study and Wetzel, 1976). These trends are reversed when hypogene alteration is involved. This can be demonstrated by the X-ray fluorescence spectral information even where corroborative field evidence (such as from metalliferous veins) is not present. Evidence of mineral alterations, as shown by the petrologic analyses, suggests that K-feldspar shows significant weathering to secondary mineral products only when hydrothermal alteration is indicated by the X-ray fluorescence spectra. Thus, the presence of highly altered K-feldspar and alteration products like nacrite and dickite (Loughnan, 1969) also suggest hydrothermal alteration. Conversely, biotite is usually the only mineral showing significant alteration when spectral patterns indicate that supergene alteration is likely.

The lack of a reliable technique to establish definitively whether hydrothermal or meteoric influences are the cause of weathering in a regolith (and therefore influential in the emergence of subsequent weathering residuals) is a fundamental lacking in previous studies purporting to explain inselberg origins. Perhaps the best example of this is the conflict between Linton (1955) and Palmer and Neilson (1961) over the origin of the Dartmoor tors in southwestern England. Linton believed the tors emerged from a meteorically weathered regolith created by a warmer, wetter climate during the Tertiary. Palmer and Neilson were convinced that the weathered material present was the result of pneumatolytic (hydrothermal) alteration and was not as significant as Pleistocene frost-shattering and solifluction in the origin of the tors. As in most situations involving plutonic rocks, both types of weathering are normally present. The alleged universal explanations of advocates like Linton and Palmer are (and have been) at a stasis awaiting demonstration that hydrothermal and meteoric weathering can be clearly separated. The contention that inselbergs are 'convergent' forms which may arise from circumstances involving either type of weathering is likewise lacking in clear evidence. This study does make this distinction in the Butte Quartz Monzonite, and thus, provides a useful starting point for re-examination and refinement of previous works and a direction for future research.

2. The adjective "protective" used in conjunction with volcanic covers overlying weathered profiles is, at least partially, a misnomer. It is true that a resistant covering will long protect a regolith from being removed by erosion. However, this study suggests that weathering reactions will not simply cease because of burial by younger volcanics or sediments. Indeed, alteration of plutonic rocks beneath a younger covering would likely follow a similar pattern of

pre-weathering to that suggested by Cunningham (1971) for the initial exhumation of a pluton beneath a cap rock being thinned by erosion.

3. Significant in this study is the indication from both the X-ray and petrologic analyses that weathering trends and products in the granitic rocks of the Boulder batholith beneath the volcanic coverings do not seem significantly different from those in areas without the benefit of such protection. The samples best suggesting this (R7 through R10 at Boomerang Gulch) were of necessity collected at the point of contact between the overlying Oligocene volcanics and the Butte Quartz Monzonite. The limited sample size, lack of evidence that the volcanics ever extended substantially farther over the granitics than presently occurs, and inability to obtain drill core samples from under the volcanics, tempers this observation somewhat until further analysis can be undertaken. However, the lack of regolith differentiation at sites in this study, whether sub-volcanic or continuously exposed to meteoric alteration, suggests a fourth conclusion.

4. The study suggests that climatic differences, which may have prevailed prior to the volcanic episodes providing coverings, do not result in distinctive weathering products or trends. Nor are masking effects encountered which might

be expected to reflect Holocene conditions penetrating through the volcanic covering, since subtle effects of hydrothermal alteration are still clearly distinguishable even in areas that are inferred to have been continuously exposed to subaerial influences since the Eocene. Thus, this study supports the concept that weathering reactions in silicate rocks under different climates differ primarily in only the rate of the reactions. It seems axiomatic therefore, despite the widely-held notion to the contrary, that warmer, wetter Tertiary climatic conditions did <u>not</u> produce a regolith substantially different from that being produced under present conditions. It appears that stripping has always intervened before the regolith has progressed beyond the point of being a 'sandy saprolite'.

5. Formation of a sandy saprolite on the Boulder batholith seems initially contingent upon chloritization of biotite which expands upon weathering, disrupting crystalline bonds and creating a regolith of relatively unaltered feldspar, quartz, and accessory mineral crystals. Feldspar crystals appear to armor exposed surfaces with a thin coating of metastable kaolinitic alteration products, and the strong bonding energy of the silica tetrahedrons in quartz also renders it relatively immune to chemical attack in the near surface environment. This has led to a situation where the regolith may persist relatively unchanged for long periods

of geologic time. Though elevation, climate, aspect, topography, vegetation, and regional tectonics may affect the amount of regolith present at any one site by causing variation in the rates of formation or of stripping, the chemical and mineralogical attributes of regolith materials are remarkably similar regardless of wide range of site conditions. This suggests that a certain threshhold of weathering, where partial or complete dissolution of major minerals may occur, has not been reached at present nor during the roughly 50 million years the Boulder batholith has been subaerially exposed. Thus, the weathering within the study area cannot be considered the result of 'tropical weathering'.

Another important focus in the objectives of this thesis is the relationship between the results of the analyses and the development and persistence of weathering residuals in the landscape of the study area. The following two conclusions relate to this aspect:

6. Given the earlier conclusion that volcanic covers do not protect underlying materials from the influences of weathering, it seems inappropriate to contend that much of the etched landscape presently exposed is older than either the Oligocene or Eocene volcanic coverings. Certainly there are intact regoliths as old as Oligocene and probably as old

as Eocene. But since there is not necessarily a correlation between the age of a regolith and the time a weathering residual will be exhumed from it, no definite conclusion about landscape age is appropriate. Certain weathering residuals may range from Eocene to Holocene in age. It has been said that "The essence of geomorphology is the discrimination of the ancient from the modern" (Bryan, 1950, p. 198). It may be that Bryan did not appreciate how ancient are some facets of the modern landscape. From early investigations by others (Freeman, et al., 1958; Ruppel, 1963; etc.), some features of the present landscape have been inferred to be no older than the Pliocene. A tentative conclusion, from relative age relationships in the study area between weathering residuals and regoliths, which, in some cases extend beneath them, is that the Pliocene is probably a minimum age for a majority of the weathering residuals.

7. Lithology and, to a certain degree, structure are major determinants in the differentiation of incipient inselbergs in the regolith, and are dominant both in the development of the initial shape and in influencing the eventual survival of inselbergs once subaerially exposed. There was ample field evidence of induration on the exposed surfaces of residuals, and increases of Fe and Si in the indurated crust were detected during laboratory analyses (Wetzel, 1976).

This induration appears to be of subaerial origin, and is also a major factor in the survival of weathering residuals once they are exhumed from a regolith. A localized paucity of biotite in the rock matrix may also be influential in development of weathering residuals. Certainly rocks with high quartz and K-feldspar but low biotite and plagioclase content tend to form positive relief features. This is most clearly demonstrated by the alaskite end phase of the fractional crystallization of the Butte Quartz Monzonite, though similar tendencies occur in leucocratic satellite plutons.

However, a great number of microenvironmental factors can be demonstrated to also strongly influence weathering and denudation processes. This makes it impossible to single out a preferred mode of inselberg origin that fits neatly into any theoretical framework aimed at providing a universal explanation. Virtually every process and mode of inselberg origin which involves a weathered regolith can be found somewhere within the study area. These facts provide a reminder that factors unique to the study area must be properly taken into account in any conclusion purporting to have general application.

A final focus of the thesis objectives was to assess the value of the techniques used in this study for resolving problems in the study of inselberg landscapes, and to anticipate the next step to be taken in furthering research in this field. The following conclusions relate to this aspect of the study:

8. In retrospect, it is clear that there is considerable room for refinement in sampling procedures, analytical techniques, and study focus. Sampling should have ideally been from drill cores, well away from the erosionally-retreating edge of the volcanic covering, and should have included drill hole samples from a transect across the zone of contact between the volcanic and the granitic rocks. Many other valuable analytical methods (X-ray diffraction, differential thermal analysis for secondary minerals, scanning electron microscopy, analysis of solute loads in natural waters, etc.) are frequently used to examine weathering products and these would have been complementary to the techniques used in this study.

9. Too often, the investigations using these techniques are not taken to the next critical step important to the landscape geomorphologist. Thus, the analysis of weathering products is commonly not related to the landscape in which the products were formed. Frequently the landscape geomorphologist attempting to make this association must rely on information developed by a soil scientist or geologist, with a less than satisfactory transfer and interpretation of this knowledge. Geomorphologists need to

develop their own capabilities and acquire first-hand the information necessary to draw relationships between regoliths and weathering residuals. This has been attempted in this study.

10. Sampling opportunities presented a number of problems. It was apparent during the field investigations that at the existing surface of the Boulder batholith regoliths occur completely intact at some locations and completely stripped at others. This has probably been a common state of affairs throughout the time the batholith has been subaerially exposed, so it is initially impossible to determine exactly what segment of a vertical profile is being sampled, at least in terms of what may have been removed during the Holocene or prior to covering by the Tertiary volcanics. Future work could well be directed at developing baseline information on the characterization of the full vertical profile at a large number of locations. This would form a sound basis for comparison between samples that, due to poor site exposure, may be gathered at an undetermined depth within a profile lacking any meaningful reference horizon. Such wide-ranging information may have added significantly to the present work, but such an ambitious undertaking was never within the intent of this study.

11. Clearly, the work represented by this thesis is intended to be a significant first step towards resolving the impasse caused by the previous lack of a clear distinction between the types of weathering (meteoric or hydrothermal) involved in the formation of regoliths. While the techniques used in this study need both refinement and wider test applications in other areas, they are nevertheless a pointer for the re-evaluation of previous enquiries which simply left this dilemma unresolved. In addition, the contention that climate may influence rate of weathering, but does not fundamentally alter the order of appearance of secondary minerals in a regolith (which has been postulated by a number of other investigators) has been given firm support by the findings of this study.

12. This study has also raised some questons which provide avenues for further research. For example, it casts doubt on the conventionally-accepted relative dating chronology in southwestern Montana, pointing out the liklihood of errors of as much as 40 million years in the interpretation of geologic events in the Tertiary. This has led to a presently ongoing project by the author and others (with the cooperation of the U.S. Geological Survey), to attempt to use X-ray fluorescence to try to correlate Tertiary volcanics of known radiometric age with tuffaceous sediments in southwestern Montana Tertiary basin deposits. If

successful, this study would identify definite time-stratigraphic horizons in the sedimentary deposits and could potentially revise the conventional dating derived from Tertiary fossils in this locale and elsewhere.

APPENDIX 1

DOMINANT SPECIES FOR CLIMAX VEGETATIVE ASSOCIATIONS

I. Subalpine Fir and Douglas Fir Climax Forests.

Dominants	
Subalpine fir	*Abies lasiocarpa*
Douglas fir	*Pseudotsuga menziesii*
Engelman spruce	*Picea engelmannii*
Pinegrass	*Calamagrostis rubescens*
Grouse whortleberry	*Vaccinium scoparium*
Heartleaf arnica	*Arnica cordifolia*
Blue huckleberry	*Vaccinium globulare*
Common beargrass	*Xerophyllum tenax*
Elk sedge	*Carex geyeri*
Dwarf huckleberry	*Vaccinium caespitosum*
Bearded wheatgrass	*Agropyron spicatum*
Mallow ninebark	*Physocarpus malvaceus*
Oregongrape	*Berberis repens*
Saskatoon serviceberry	*Amelanchier alnifolia*
Richardson needlegrass	*Stipa richardsoni*
Columbia needlegrass	*Stipa columbiana*
Spike trisetum	*Trisetum spicatum*
Blue wildrye	*Elymus glaucus*
Idaho fescue	*Festuca idahoensis*

II. Subalpine Fir, Douglas Fir, and Ponderosa Pine Climax Forests

Dominants:	
Subalpine fir	*Abies lasiocarpa*
Douglas fir	*Pseudotsuga menziesii*
Ponderosa pine	*Pinus ponderosa*
Engelman spruce	*Picea engelmannii*
Pinegrass	*Calamagrostis rubescens*
Grouse whortleberry	*Vaccinium scoparium*
Dwarf huckleberry	*Vaccinium caespitosum*
Bluebunch wheatgrass	*Agropyron spicatum*
Mountain brome	*Bromus anomalus*
Columbia needlegrass	*Stipa columbiana*
Elk sedge	*Carex geyeri*
Heartleaf arnica	*Arnica cordifolia*
Snowberry	*Symphoricarpos species*
Mallow ninebark	*Physocarpus malvaceus*
Blue wildrye	*Elymus glaucus*
Richardson needlegrass	*Stipa richardsoni*
Bearded wheatgrass	*Agropyron spicatum*
Idaho fescue	*Festuca idahoensis*
Common beargrass	*Xerophyllum tenax*
Rough fescue	*Festuca scabrella*
Oregongrape	*Berberis repens*
Twinflower	*Linnaea borealis*

III. Silty Range Site Association

Dominants:

Rough fescue	*Festuca scabrella*
Idaho fescue	*Festuca idahoensis*
Bluebunch wheatgrass	*Agropyron spicatum*
Columbia needlegrass	*Stipa columbiana*
Basin wildrye	*Elymus cinereus*
Spikefescue	*Hesperochola kingii*
Parry danthonia	*Danthonia parryi*
Slender wheatgrass	*Agropyron trachycaulum*
Lupine	*Lupinus species*
Sticky geranium	*Geranium viscosissimum*
Arrowleaf balsamroot	*Balsamorhiza sagittata*
Prairiesmoke	*Geum triflorum*
Big sagebrush	*Artemesia tridentata*
Tall larkspur	*Delphinium occidentale*
Prairie junegrass	*Calamouilfa longifolia*
Timber danthonia	*Danthonia intermedia*
Big bluegrass	*Poa ampla*

IV Shallow and Very Shallow Range Site Complex

Dominants (Shallow):

Bluebunch wheatgrass	*Agropyron spicatum*
Rough fescue	*Festuca scabrella*
Needleandthread	*Stipa comata*
Big sagebrush	*Artemesia tridentata*
Prairie junegrass	*Calamouilfa longifolia*
Western wheatgrass	*Agropyron smithii*
Sandberg bluegrass	*Poa secunda*
Grey horsebrush	*Tetradymia canesceus*
Phlox	*Phlox species*

Dominants (Very Shallow):

Bluebunch wheatgrass	*Agropyron spicatum*
Prairie junegrass	*Calamouilfa longifolia*
Western wheatgrass	*Agropyron smithii*
Threadleaf sedge	*Carex filifolia*
Phlox	*Phlox species*
Needleandthread	*Stipa comata*
Sandberg bluegrass	*Poa secunda*

(With the following species in cracks and crevices)

Mountain mahogany	*Cercocarpus ledifolius*
Limber pine	*Pinus flexilis*
Big sagebrush	*Artemesia tridentata*
Rocky Mountain juniper	*Juniperus scopuloram*

APPENDIX 2
PETROLOGIC ANALYSES

Specimen: R-7 Section No: 4 Locality: Boomerang Gulch

Megascopic Description: Field Name: Quartz Monzonite

Plagioclase	10%
Orthoclase	60%
Quartz	15%
Biotite	10%
Magnetite	2%
Hematite	2%
Chlorite	3%

Detailed Description of Individual Minerals:

Plagioclase: (Labradorite-Bytownite)-euhedral; some kaolinization; no zoning; small crystals imbedded in orthoclase.

Orthoclase: Subhedral to anhedral, very large crystals; moderate kaolinization; no oxidation stain; minor zoning; carlsbad twinning.

Quartz: Interstitial, undulatory extinction.

Biotite: Euhedral; extensively chloritized and oxidized; mechanically broken.

Chlorite: Replacing biotite, has minor oxidation on exposed surfaces; altering to hematite.

Weathering: Biotite is heavily weathered by oxidation and chloritization; fractures are coated with oxidation stain; orthoclase showing moderate kaolinization, weathering on crystal surfaces only.

Microtextures and Structures:

Paragenetic Relationships and Origin: Plag = 1st; Mag = 2nd; Bio = 3rd; Ortho = 4th; Qtz = 5th; Chlorite = 6th; Oxidation = 7th; Hematite = 8th.

PETROLOGIC ANALYSES

Specimen: R-8 Section No: 5 Locality: Boomerang Gulch

Megascopic Description: Field Name: Quartz Monzonite

Plagioclase	30%
Orthoclase	35%
Quartz	30%
Biotite	5%
Magnetite	trace
Hematite	trace
Chlorite	trace
Hornblende	trace

Detailed Description of Individual Minerals:

Plagioclase: (Labradorite)-euhedral; extensively zoned; small grains; polysynthetic and carlsbad twinning.

Orthoclase: Anhedral to interstitial (?); minor to moderate kaolinization; large grains; minor carlsbad twinning.

Quartz: Interstitial, undulatory extinction.

Biotite: Euhedral; extensively oxidized on exposed surfaces; moderate to weak oxidation at depth; weakly chloritized.

Chlorite: Some replacement of biotite;

Weathering: Biotite is heavily weathered by oxidation and weakly chloritized; fractures are coated with oxidation stain; orthoclase showing moderate to minor kaolinization;

Microtextures and Structures:

Paragenetic Relationships and Origin: Plag = 1st; Mag = 2nd; Hblde and Bio = 3rd; Ortho = 4th; Qtz = 5th; Chlorite = 6th; Oxidation = 7th; Hematite = 8th.

PETROLOGIC ANALYSES

Specimen: R-9 Section No: 6 Locality: Boomerang Gulch

Megascopic Description: Field Name: Quartz Monzonite

Plagioclase	5%
Orthoclase	70%
Quartz	14%
Biotite	5%
Magnetite	3%
Hematite	trace
Chlorite	3%

Detailed Description of Individual Minerals:

Plagioclase: (Labradorite)-euhedral; masked extinction; small grains; minor kaoliniztion.

Orthoclase: Anhedral; minor graphic texture; minor kaolinization; large crystals.

Quartz: Interstitial.

Biotite: Euhedral; oxidized on exposed surfaces; weathered to chlorite; broken by mechanical weathering.

Chlorite: Replacing biotite; extensively weathered to hematite

Weathering: Minor kaolinization of feldspar, extensive oxidation of biotite and chlorite; biotite weathered to chlorite, chlorite to hematite; fractures are extensively oxidized with coatings on exposed surfaces; biotite more deeply weathered than R-7.

Microtextures and Structures:

Paragenetic Relationships and Origin: Plag = 1st; Mag = 2nd; Bio = 3rd; Ortho = 4th; Ortho and Qtz graphic texture = 5th; Qtz = 6th; Chlorite = 7th; Oxidation = 8th; Hematite = 9th.

PETROLOGIC ANALYSES

Specimen: R-10 Section No: 7 Locality: Boomerang Gulch

Megascopic Description: Field Name: Quartz Monzonite

Plagioclase	10%
Orthoclase	70%
Quartz	15%
Biotite	5%
Magnetite	trace

Detailed Description of Individual Minerals:

Plagioclase:	(Labradorite)-euhedral; polysynthetic and carlsbad twinning; surrounded by large orthoclase crystals.
Orthoclase:	very large euhedral-subhedral crystals; often rimmed by a rust coating; common kaolinization
Quartz:	Interstitial; undulatory extinction.
Biotite:	Euhedral; crystals within rock are unweathered; exposed crystals are extensively oxidized and mechanically weathered.

Weathering: Coated with oxidation stain, primarily from oxidized biotite; biotite extensively broken; orthoclase weathering to kaolinite; most weathering is at crystal surfaces.

Microtextures and Structures:

Paragenetic Relationships and Origin: Plag = 1st; Mag = 2nd; Bio = 3rd; Ortho = 4th; Qtz = 5th; Oxidation = 6th.

PETROLOGIC ANALYSES

Specimen: LC-1 Section No: 10 Locality: Clancy Gulch

Megascopic Description: Field Name: Quartz Monzonite

Plagioclase	15%
Orthoclase	30%
Quartz	25%
Biotite	10%
Magnetite	trace
Hematite	5%
Chlorite	10%
Pyrite	5%

Detailed Description of Individual Minerals:

Plagioclase: Euhedral; moderate to strong kaolinization; polysynthetic twinning.

Orthoclase: Anhedral; minor graphic texture; moderate kaolinization.

Quartz: Interstitial; minor graphic texture.

Biotite: Euhedral; extensivly chloritized, minor evidence of oxidation.

Pyrite: Not oxidized.

Chlorite: Extensively replacing biotite; minor oxidation.

Weathering: Moderate kaolinization of feldspar, extensive chloritization of biotite; minor oxidation of biotite and chlorite.

Microtextures and Structures: Minor graphic texture.

Paragenetic Relationships and Origin: Plag = 1st; Mag = 2nd; Pyrite = 3rd; Bio = 4th; Ortho = 5th; Qtz = 6th; Chlorite = 7th; Oxidation = 8th; Hematite = 9th.

PETROLOGIC ANALYSES

Specimen: LC-2 Section No: 11 Locality: Clancy Gulch

Megascopic Description: Field Name: Quartz Monzonite

Plagioclase	20%
Orthoclase	30%
Quartz	25%
Biotite	10%
Magnetite	trace
Hornblende	10%
Chlorite	trace
Pyrite	5%

Detailed Description of Individual Minerals:

Plagioclase:	Euhedral; moderate to strong kaolinization; weathering masks twinning.
Orthoclase:	Anhedral; common graphic texture; moderate kaolinization.
Quartz:	Interstitial; common graphic texture.
Biotite:	Euhedral; extensivly chloritized, minor evidence of oxidation.
Hornblende:	Anhedral; minor oxidation.
Weathering:	Moderate kaolinization of feldspar, very minor oxidation of biotite and chlorite.

Microtextures and Structures: Common graphic texture.

Paragenetic Relationships and Origin: Plag = 1st; Mag = 2nd; Pyrite = 3rd; Bio = 4th; Hblde = 5th; Ortho = 6th; Graphic texture = 7th; Qtz = 8th; Chlorite = 9th.

PETROLOGIC ANALYSES

Specimen: LC-3   Section No: 12   Locality: Clancy Gulch

Megascopic Description: Field Name: Quartz Monzonite

Plagioclase	25%
Orthoclase	30%
Quartz	25%
Biotite	10%
Magnetite	trace
Hornblende	10%
Chlorite	trace
Pyrite	trace

Detailed Description of Individual Minerals:

Plagioclase: Extensive kaolinization; no crystal form made out.

Orthoclase: Moderate graphic texture; moderate kaolinization.

Quartz: Interstitial; graphic texture; minor void filling in weathered biotite and hornblende.

Biotite: Euhedral; near complete weathering, quartz has filled pore spaces.

Hornblende: Anhedral; as above with biotite.

Weathering: Extensive kaolinization of plagioclase, moderate kaolinization of orthoclase, extensive weathering with moderate oxidation of biotite and hornblende.

Microtextures and Structures: Moderate graphic texture.

Paragenetic Relationships and Origin: Plag = 1st; Mag = 2nd; Pyrite = 3rd; Bio = 4th; Hblde = 5th; Ortho = 6th; Graphic texture = 7th; Qtz = 8th; Chlorite = 9th.

PETROLOGIC ANALYSES

Specimen: BZ-1 Section No: 9 Locality: Montana City

Megascopic Description: Field Name: Quartz Monzonite

Plagioclase	20%
Orthoclase	40%
Quartz	27%
Biotite	10%
Magnetite	trace
Hornblende	3%

Detailed Description of Individual Minerals:

Plagioclase: (Labradorite), euhedral, no zoning, polysynthetic twinning.

Orthoclase: Anhedral, to interstitial, moderately zoned, minor kaolinization, common graphic texture with quartz, minor carlsbad twinning.

Quartz: Interstitial and graphic texture.

Biotite: Euhedral, unweathered.

Hornblende: Unweathered.

Weathering: Sample shows little or no evidence of weathering, one occurance of oxidation and minor kaolinization was observed.

Microtextures and Structures: Common graphic texture.

Paragenetic Relationships and Origin: Plag = 1st; Mag = 2nd; Hblde = 3rd; Bio = 4th; Ortho = 5th; Ortho and Qtz graphic texture =6th; Qtz = 7th.

PETROLOGIC ANALYSES

Specimen: BZ-2   Section No: 8   Locality: Montana City

Megascopic Description: Field Name: Quartz Monzonite

Plagioclase	?
Orthoclase	?
Quartz	?
Biotite	20%
Magnetite	5%
Hematite	15%

Detailed Description of Individual Minerals:

Biotite: Euhedral, extensively replaced by hematite.

Hematite: Pseudomorph of biotite.

Magnetite: Not easily recognizable due to heavy oxidation.

Weathering: Rock is extensively weathered, very heavily kaolinized and oxidized, no observable chlorite.

Microtextures and Structures:

Paragenetic Relationships and Origin: Cannot be discerned with extensive alteration present.

PETROLOGIC ANALYSES

Specimen: U-3 Section No: 1 Locality: Pipestone Road

Megascopic Description: Field Name: Quartz Monzonite

Plagioclase	40%
Orthoclase	18%
Quartz	30%
Biotite	5%
Magnetite	trace
Hornblende	2%
Chlorite	5%

Detailed Description of Individual Minerals:

Plagioclase:	(Labradorite-Bytownite)-commonly euhedral with minor subhedral, polysynthetic and carlsbad twinning; prismatic crystal shape; and some zoning of individual crystal.
Orthoclase:	Subhedral to anhedral, commonly interstitial; occasional zoning, carlsbad twinning.
Quartz:	Anhedral, interstitial, undulatory extinction.
Biotite:	Subhedral; weathering to chlorite.
Hornblende:	Subhedral to anhedral, weathering to chlorite.
Chlorite:	Anhedral, appears to be replacing hornblende and biotite; polysynthetic twinning.

Weathering: Hornblende altering to chlorite; weathering otherwise appears to be minor.

Microtextures and Structures:

Paragenetic Relationships and Origin: Plag = 1st; Mag = 2nd; Bio = 3rd; Hblde = 4th; Ortho = 5th; Qtz =6th; Chlorite = 7th; Oxidation = 8th.

PETROLOGIC ANALYSES

Specimen: U-4 Section No: 2 Locality: Pipestone Road

Megascopic Description: Field Name: Quartz Monzonite

Plagioclase	30%
Orthoclase	35%
Quartz	15%
Biotite	2%
Magnetite	3%
Hornblende	10%
Chlorite	5%

Detailed Description of Individual Minerals:

Plagioclase:	(Labradorite)-euhedral to subhedral, polysynthetic and carlsbad twinning; some zoning of individual crystals.
Orthoclase:	Subhedral to anhedral, minor zoning.
Quartz:	Interstitial.
Biotite:	Euhedral; some oxidation and chloritization.
Hornblende:	Euhedral; some oxidation and chloritization.
Chlorite:	Anhedral, appears to be replacing hornblende and biotite.

Weathering: Oxidation of biotite, hornblende, and magnitite; chloritization of biotite and hornblende; weathering seems relatively minor, but some fracturing of feldspars and quartz near biotite.

Microtextures and Structures:

Paragenetic Relationships and Origin: Plag □ 1st; Mag □ 2nd; Bio = 3rd; Hblde = 4th; Ortho = 5th; Qtz =6th; Chlorite = 7th; Oxidation = 8th.

APPENDIX 3

GEOCHEMICAL WEATHERING AND GRANITIC LANDSCAPES ON THE BOULDER BATHOLITH, WESTERN MONTANA[1]

by Wayne A. Wetzel
(Ph.D. Seminar; Geography Dept., Simon Fraser University)
April, 1976

Introduction:

Tors and other inselberg forms have been the object of controversy and study for nearly 150 years. The controversy deals with generating a satisfactory explanation for why tors exist as upstanding outcrops above a surface of presumably the same lithologic material. Research has been devoted to explaining why tors are not consumed by weathering either during a subsurface evolution stage or during their subaerial exposure. Conjecture has been raised about the nature of the surfaces from which tors protrude. These surfaces have been attributed to former water table positions delimiting the weathering front, to Davisian peneplanation, and to pediplanation advocated by King (1948) and others. The general lack of concensus about these points has provided grounds for many alternative approaches to provide enlightenment, among them geochemical investigation. This seminar deals with a brief

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[1] The text of this seminar is presented as an appendix because results of this earlier investigation, undertaken in 1975 and 1976, are referred to in the body of the thesis and are germane to the conclusions drawn in the present study. To a large extent, the introductory material presented here is a repetition of subjects previously covered in Chapters 1 and 3. Where the discussion is nearly verbatim with the material covered in the thesis, the reader will be referred to the appropriate section of the thesis. Also, since it was not practical to reproduce every slide shown during the seminar, the reader will be directed to appropriate photographs or figures in the body of the thesis.

literature review and preliminary geochemical investigation into a tor-parkland landscape in southwestern Montana.

Early weathering studies centered on the tropics, where processes thought to create tors could be demonstrated without necessarily changing present climatic conditions. David Linton (1955) recognized that tors in the temperate latitudes presented an interpretive problem. Linton's suggestion that the Dartmoor (England) tors were landforms exhumed during the Pleistocene from a previously weathered regolith correlated well with a surmised warmer, wetter Tertiary climate on Dartmoor which would be capable of producing this regolith. This interpretation gave tors considerable prestige as paleoclimatic indicators and sparked a seemingly endless body of literature within this sidelight of geomorphology, both from those who agreed, and, those who disagreed with Linton.

[Major tor-origin theories are discussed at greater length in Chapter 3.]

Some theories have been proposed in an attempt to synthesize these often disparate views. Bertaffalney (1951) proposed that tors and domed inselbergs are examples of the principal of equifinality, implying that the nature of granitic rocks is such that different processes acting at varying rates tend to produce the same final distinctive tor or bornhardt shape. Cunningham (1969) uses a variation of this principle, actually first proposed by White (1945), in his concept of 'convergent landforms'. A major difference between 'equifinality' and 'convergence' is that convergence makes no implication of finality in tor forms (i.e., the distinctive tor form may evolve and decay many times in the evolution of the landscape).

Ollier (1969), Ruxton and Berry (1957), and others have questioned the validity of theoretical frameworks for tor evolution aimed at universal explanations and solutions. Universal explanations are seen as analagous to a small-scale map—all encompassing in a general sense, but lacking explanatory details. Meyer (1967) and Ollier (1969) maintain that the best explanation is the one that fits the circumstances of each situation, hence, each tor landscape is best evaluated on the merits of the information available at each particular site.

A further problem with tors is one of unfilled and overfilled research gaps. This is both a regional and a topical problem. Dartmoor has had every stone turned and every crystal examined in comparison to the paucity of weathering residual literature in North America. Morphological studies relating tors to erosion surfaces, drainage incision and hillslope retreat, cryogenic processes, petrology, jointing, and crystal structure glut the literature, but relatively little work has been done on chemical weathering processes explaining what happens in a weathered regolith and why tors are characteristic products of exhumation.

Soil science investigators have made significant progress in studies of processes involved in residual soil formation and aging through analyses of the the chemical breakdown of the parent rocks. Examples include the dating of till sheets in the American mid-west (Bhattacharya, 1963; Frye, et al., 1968) and assessment of paleoclimates through secondary minerals present in the soil (Birkeland, 1969). Other research thrusts involve control of dissolved solids in natural waters by reactions with silicate minerals (Brickner, 1968).

These approaches rely heavily on chemical and mineralogical analyses of the soil residues and the results testify to the usefulness of geochemical techniques in approaching the problems of tor landscapes. Geomorphologists interested in tors have for years been in a stasis waiting for the initiation of similar geochemical techniques to attempt to pose solutions to the problems focusing upon these several issues:

1. Determining the nature of the processes at work in differing weathering environments containing 'incipient' tors.
2. Positive discernment of differences in weathering products imposed by different modes of alteration (e.g., hydrothermal, metasomatic, meteoric).
3. The role of climate in affecting rate of specific mineral alterations and the possibility of climatic selection of different minerals creating dissimilar weathering environments and regolith characteristics in different climates.
4. The significance of small changes in lithology and structure influencing emergent tor landscapes.
5. The mechanism(s) for producing indurated crusts and other weathering microforms associated with weathering residuals.

With these problems outlined, a brief examination of chemical weathering and the role of climate in weathering is appropriate.

Chemical Weathering:

Chemical weathering occurs when the environment surrounding a rock changes from a system at or near chemical equilibrium to a situation where disequilibrium prevails. Disequilibrium causes a spontaneous reaction between a rock and the surrounding environment to re-establish an equilibrium by the creation of more stable chemical compounds. Plutonic rocks at or near the surface of the earth are nearly always in different surroundings from the environment in which they are formed, thus, they are subject to chemical weathering. Because temperature and abundance of water are perhaps the most important factors in determining the rate of chemical weathering, regoliths on granitic rocks eventually producing tors have been linked to the concept of 'climatic morphogenesis'.

Climatic Geomorphology:

'Climatic morphogenesis' implies that the effects of persistence of a climate over significant geological time produces a regional suite of landforms characteristic of weathering and removal agents in that climate. The widespread association of tors with moderate to deep weathering profiles has, over time, come to imply that climates thought to have produced such regoliths in the tropics must be responsible for the temperate climate regoliths at some time in the geologic past. Because of wide-ranging Quaternary glacial episodes, climatic geomorphology has tended to have a distinctly pre-glacial historical outlook. Tors, often thought to reflect

Tertiary climatic influences, have thus become favoured landforms in paleoclimatic investigations.

Many studies have dealt with the notion of morphogenetic regions, to which several approaches have been tried. Perhaps most well known is that of Peltier (1950), whose inductive approach uses mean temperature and precipitation data to define hypothetical zones of climatic influence and attendent weathering and removal processes. Budel (1957) uses a synthetic approach by looking at dominant landforms and processes in zones defined by broad vegetation, soil, and climatic regions reflected by the present climate. Tricart and Cailleux (1962) reflect to a degree the work of Budel, but their own work and that of Strakov (1967) center more on processes developing landforms than the landforms themselves. Stoddart (1969), in a review of the present state of climatic geomorphology, feels that it is premature to set up world-wide schemes for either present or paleo-morphogenetic regions before a sound factual base exists for the many assumptions involved. Also, Stoddart indicates that climatic geomorphologists have notoriously disregarded the role of structure and lithology in landforms.

Tropical-Temperate Differences:

A continuum of opinion exists regarding weathering processes and their relation to climate. One one end, weathering of rocks (in this case, granitics) is seen as a continuous linear process operating in all climatic zones similarly, but at different rates according to major climatic factors such as temperature and water availability. This is best exemplified by the work of Strakov (1967), who shows development of weathering profiles and secondary mineral assemblages according to variation in precipitation, evaporation, temperature, and vegetation (See Figure 10, p. 123). Moderate deep weathering regolith development occurs in temperate climatic conditions, creating the possibility of contemporary two-stage tors. Others supporting the concept of rate rather than type weathering are Ollier (1967) and Reiche (1950).

On the other end on the continuum are those authors who maintain that climate directly dictates a limited set of weathering possibilities. Hence different weathering products are seen as evidence of distinctive and different climatic genesis.

Most investigators fall between the two extremes and recognize that weathering and secondary mineral suites are characteristic not only of climate, but also of other macro-environmental factors. These factors, such as biological activity, parent rock, relief, topographic position, and drainage can influence the micro-environmental factors more directly diagnostic of weathering reactions.

Tardy, et al., (1973), in a study of weathering differences in tropical and temperate climates, found that primary to secondary mineral changes followed the same sequence in all climatic areas. This doesn't mean, however, that differences induced by climate are negligible. Because all climates affect separate primary minerals to a different degree, the dominant secondary mineral assemblage tends to reflect the weathering sequence of the most susceptible primary mineral in each climatic regime. [The primary-secondary weathering sequence and the associations most commonly found in sandy saprolites (grus) are found in Tables 6 and 7 on page 126 of the thesis.] Tardy, et. al., suggest that, over a long period of time at constant climatic conditions, all weathering would lead to the same end (i.e., gibbsite followed by complete dissolution). However, mechanical erosion normally intervenes before this end is reached.

Mineral specific stability diagrams reflecting equilibrium relations of primary-secondary mineral phases have been used to demonstrate which secondary mineral(s) will form in a regolith from data on silica and cations in solution in natural waters. [Examples are shown in Figure 9 (p. 119) for analcite and anorthite at 1 atm. pressure and 25° C.]

Non-Meteoric Weathering:

The problem of non-meteoric weathering must be examined in granitic terrain, as the nature of batholithic emplacement makes granitics predisposed to hydrothermal and metasomatic alteration through endogenetic reactions. Recognition of the type of alteration (i.e., hydrothermal vs. meteoric) is complicated by accounts in the literature indicating that the weathering products from both types of alteration are the same. Recognition of hydrothermal weathering has been based on interpretive evidence such as widening of a presumed hydrothermal vein with depth or altered rock beneath fresh rock. Other interpretations involve detection of exotic primary or secondary minerals in the alteration products such as tourmaline or zircon and the clay minerals nacrite or dickite.

The possibility exists (and occurs frequently) where indicators such as these are not present and the interpretation of the origin of the alteration products becomes problematic. Eggler, et al., (1969) and Volborth (1962) have cited evidence in Wyoming and Nevada, respectively, where oxidation of femic minerals in certain granitic rocks has affected entire emplacement sequences (e.g., all biotites and hornblende mineral grains are altered). This is presumably due to a relatively high, free oxygen content being present in the melt. During later stages of crystallization, the partial pressure of oxygen in the presence of juvenile water was sufficient to cause spontaneous oxidation of the femic minerals. This resulted in a granite that became incoherent and disaggregated readily upon exposure to limited meteoric weathering. Eggler, et al., have attempted to use this explanation to demonstrate why a pre-oxidation emplacement phase generates tors, while the oxidized phase does not.

In the deuteric, or final, phase of crystallization, metasomatic exchanges between the batholith roof and the host rock may take place causing alterations that may predispose the portion of the pluton near the batholith roof to exhibit uncharacteristic weathering upon exposure. This alteration may not have the same alteration diagnostics that result from hydrothermal or meteoric waters, yet the resultant weathering products may be visually indistinguishable from the products from these other modes of alteration. The resulting complications introduced to tor studies by these unresolved issues concerning non-meteoric weathering are obvious.

Major problems exist in unraveling explanations for tors that are based primarily on interpretive morphological evidence. More and more, investigations into chemical weathering (particularly in relation to granites) provide a framework for those interested in weathering residuals to verify the results of morphological conjecture.

The remainder of this seminar will deal with a brief characterization of the study area; take a look at the results of the initial geochemical analyses; and briefly investigate the possibilities for more traditional geomorphic approaches in the study area.

Study Area Description:

The study area[2] extends from semi-arid steppe in the Jefferson basin to a montane forest zone in the southern Boulder mountains. Higher elevations are dominated by lodgepole pine, an ecological response to frequent natural fire. Rainfall ranges from about 14 inches in the Jefferson Basin to nearly 35 inches along the Continental Divide.

[2] The study area in the initial study consisted of the drainage areas of Homestake and Big Pipestone Creeks. Most of this area actually studied is within the boundaries of the map portion of Figure 24 on page 240. Reference to the study area in the text of the seminar should not be confused with the larger study area of the thesis.

Geology in the northern Rocky Mountains physiographic province (Fenneman, 1932) is extremely complex. The Boulder batholith is in a zone that has undergone a complex sequence of episodic uplift, thrust faulting, folding, normal faulting, and erosional removal and deposition. Country rock around the batholith primarily consists of Precambrian gneiss (prevalent around the southern margins of the batholith) and Belt Supergroup sedimentary rocks (along the northern margins). The batholith intrudes these Precambrian rocks and scattered Paleozoic and Mesozoic sedimentary rocks, but the Cretaceous Elkhorn Mountains Volcanics are the youngest rocks intruded.

The batholithic emplacement progressed along the following series:

1. Ultra-mafic diorite
2. Granodiorite (Radar Creek and Pulpit Rock plutons)
3. Quartz monzonite (Butte Quartz Monzonite)
4. Silicic quartz monzonite and alaskite.

Quartz latite (Lowland Creek Volcanics) and rhyolite (post-Lowland Creek Volcanics) intrude and lie upon the erosional surface of the exposed batholith and are not considered part of the emplacement series [see Figure 1, p. 9].

Average chemical analyses [see Table 4, p. 59] for the plutonic rocks show the expected silica enrichment with progressive crystallization of the melt. It should be noted that the alaskite and silicic Butte Quartz Monzonite are relatively low in iron and are high in potassium, indicating a near absence of femic minerals and an abundance of K-feldspar. This situation is indicative of a higher relative resistance of these rock types to meteoric weathering attack in almost every climate.

Analytical Procedures:

A wide range of analytical methods exist in classical chemistry for the determination of elemental constituents in silicate rocks. Several of these methods, including X-ray fluorescence and volumetric determination of silica content, were used on a test basis to assess the value of each method in the study of weathering residues in silicate rocks. Methods investigated but not actually used include flame photometry and atomic absorption. An attempt to use X-ray diffraction to analyze minerals present in powdered samples was abandoned due to technical difficulties with the mechanical apparatus necessary to do the analysis.

X-Ray Fluorescence. [Procedures for the X-ray fluorescence analyses are discussed in the main body of the thesis on pages 143 through 157 and are not substantially different from the procedures used in this study.]

Volumetric Analysis. Because this method is relatively simple for silica (SiO_2) and silica is one of the least sensitive major constituents to energy dispersive X-ray fluorescence (EDXF), the procedure followed is briefly outlined.

1. Samples are weighed, dried, and then reweighed (1 g. of powdered sample material is used).

2. A sample is fused with sodium hydroxide, then carefully washed and dissolved into a 1 liter volumetric flask using distilled water.

3. Two ml. of the liter of water containing the dissolved sample is complexed with ammomium molybdate reagent (producing a weak yellow colour), then reduced with metol-sulfate (producing a blue colour that deepens with increasing silica content in the dissolved sample).

4. Absorbance spectra for standard solutions containing known amounts of silica are recorded on a spectrophotometer along with spectra from samples with unknown amounts of silica.

5. A calibration curve is determined from the standard solution samples. The percentages of silica in the unknown samples, after correction for any weight/volume differences in the original samples, is determined from the calibration curve.

While useful analytical insights were developed in successfully completing quantitative determination of absolute amounts of silica in a large number of samples, it is concluded that, without 'stock' reagent solutions available for batch analysis, this method is generally more time consuming than other practical methods.

<u>Atomic Absorption.</u> The principle of atomic absorption is relatively simple and not unlike the spectrophotometric technique for silica determination. Normal procedure would involve direct digestion of a sample in hot nitric acid (or

other acids or acid mixtures for analysis of certain elements), rather than the hydroxal fusion used in the silica analysis. The digested sample is then dispersed (atomized in a flame) in a beam of energy, usually from a hollow cathode-ray lamp. Different atoms in the sample absorb the incident energy of certain discrete frequencies (called resonant frequencies), causing a decrease in emerging energy. Wtih suitable instrumentation, the decrease can be measured relative to the incident beam (or other reference) and can be related to the concentration of each given element dispersed in the beam. Ultimately, this is related to the absolute amount of a given element in the sample. Facilities were not available to use this technique in this study.

<u>Flame Photometry.</u> This technique is akin to atomic absorption, as it uses light energy and calibration with a spectrophotometer. The main difference is that instead of a hollow cathode lamp energy to create 'reasonant frequencies', flame photometry uses the principle that an element atomized into an oxygen-propane flame creates visible light spectra characteristic of the elements in the sample (e.g. sodium = yellow). The source of the light energy is the flame itself, with spectra recorded through a filtering system designed to allow only the spectrum of one element to be analyzed at a time. As with silica analysis, unknowns are determined from calibration with known elemental concentrations. Flame photometry has been used in sophisticated labs to determine concentrations of up to 52 elements with detection reliable to

about 10 parts per million. However, this method is most accurate and useful in determining the more common alkaline elements of Na, K, Ca, and Li. It is a complement to the other techniques because it can determine these elements from natural waters, fused/dissolved, or digested sample solutions.

Results of the EDXF Analyses:[3]

Figure A-1 shows several fresh rock samples plotted together with silicic acid as a background standard. The vertical scale is logrithmic, so a small variation in peak size can mean a large variation in the quantity of the element present. The horizontal scale represents different energy levels in kilovolts, though the plot in Figure A-1 (and others) shows the energy channel and not the energy level itself. The spectra in Figure A-1 were generated using a Mo secondary target.

Significant in the patterns shown is a trend towards a reversal of the K and Ca peaks, Ru and Sr peaks, and increases in the Fe peak with samples containing increasingly more femic minerals. Most notable in this regard are the K and Ca peak reversals, which probably reflects changing feldspar compositions in the reaction series.

A secondary target of Ti was used to increase the sensitivity of Si and Al to the X-ray photons. Figure A-2 shows the same samples in Figure A-1, only using the Ti secondary target. Note that while Al remains fairly constant, Si

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[3] Original diagrams for the 1976 seminar are no longer available. The illustrations of EDXF spectra are prints from slides used to illustrate the seminar.

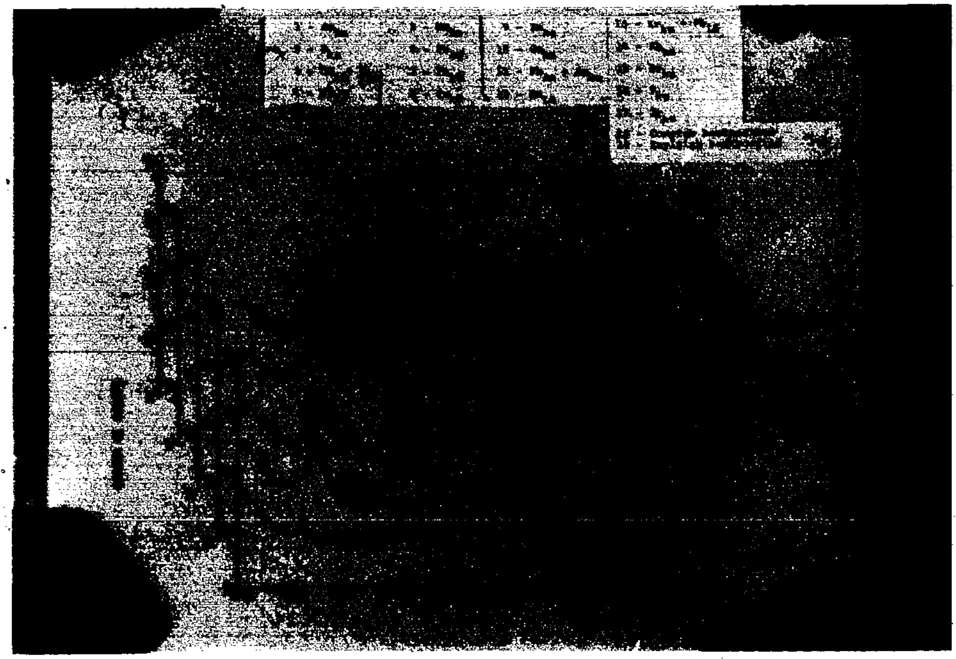


Figure A-1. X-ray fluorescence spectra for fresh rock samples representing emplacement series differences (Mo target).

Figure A-2. X-ray fluorescence spectra for fresh rock samples representing emplacement series differences (Ti target).

decreases in the more mafic rocks. It should also be noted that the silica standard has no Al peak.

Grus samples from the Butte Quartz Monzonite, collected from a variety of locations (weathered joints in road cuts and weathering residuals), show remarkably similar spectral patterns (Figures A-3 and A-4). This may indicate a plateau of weathering in the present climate, may reflect the lithologic homogeneity of the quartz monzonite (even when weathered), or may simply be a coincidence.

Some samples were analyzed at various distances away from a presumed hydrothermal vein near Homestake Pass [location of the site is shown in Figure 18, p. 183]. Spectra were generated from samples taken along a horizontal transect away from the most altered portion of the vein. These samples came from the altered vein, from altered rock adjacent to the vein, from a less altered corestone within the altered rock, and from fresh rock exposed in a roadcut farthest from the vein. Figures A-5 and A-6 show the spectra generated from these samples.

While there is little change apparent in the more exotic trace elements, the decrease in K and the increase in Fe with increased weathering would seem to indicate that K-feldspar is weathering the fastest, an unusual circumstance in the present climate. This observation of weathering in K-feldspar can be verified by looking at individual crystals with a hand lens in samples of the most altered rock.

A final comparison was made between samples of indurated crusts from two alaskite bornhardts [Pipestone Rock and Spire

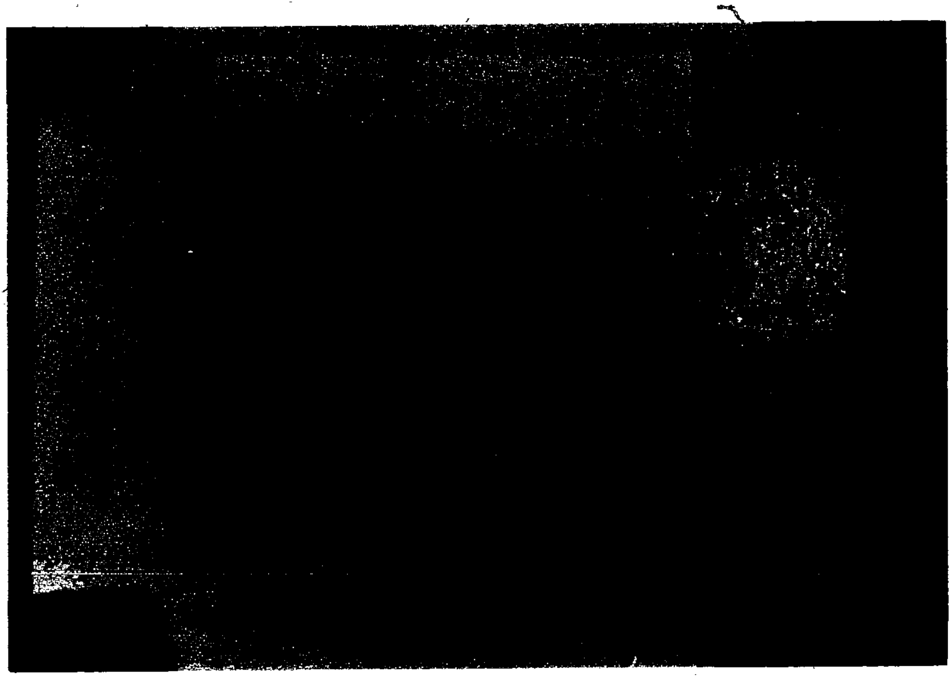


Figure A-3. X-ray fluorescence spectra for grus samples from the Butte Quartz Monzonite (Mo target).

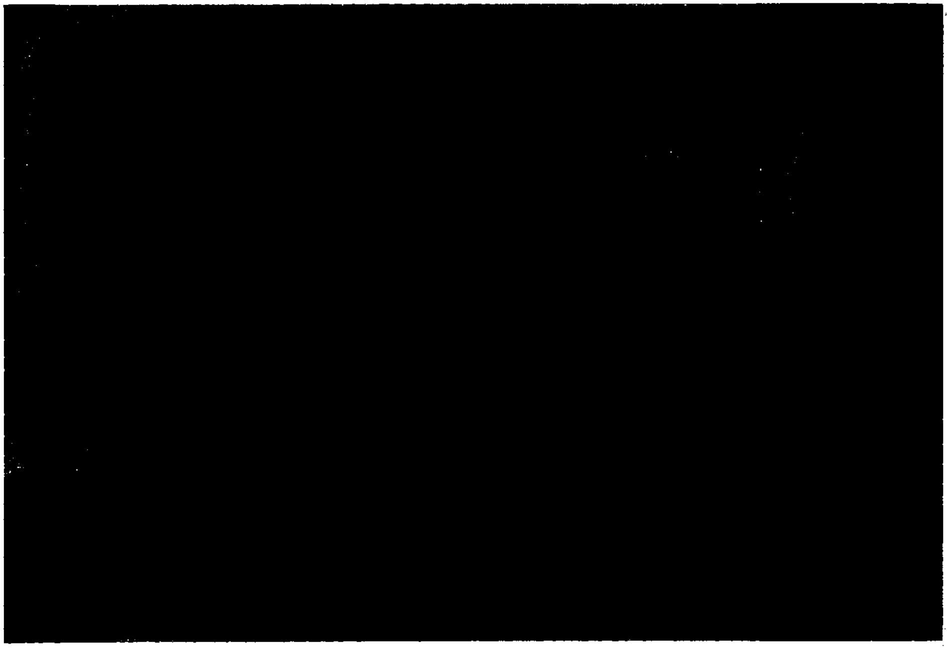


Figure A-4. X-ray fluorescence spectra for grus samples from the Butte Quartz Monzonite (Ti target).

Figure A-5. X-ray fluorescence spectra for hydrothermal vein samples (Mo target).

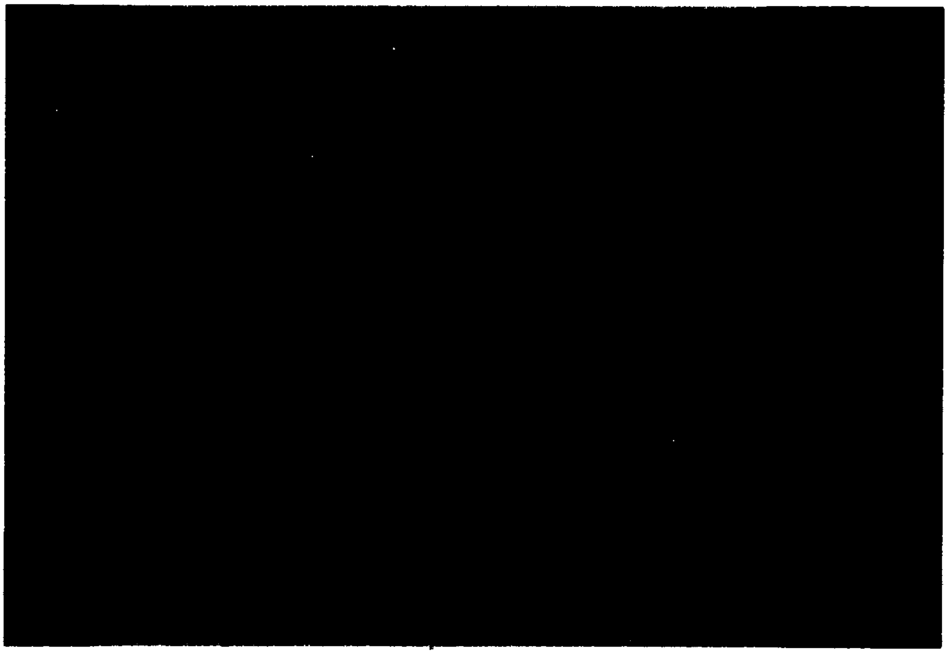


Figure A-6. X-ray fluorescence spectra for hydrothermal vein samples (Ti target).

Rock shown in Figure 24, p. 240], which are, in turn, contrasted with a sample taken from beneath the indurated crust at Spire Rock (Figures A-7 and A-8). In the two samples of crust, the K peak appears noticeably more pronounced than the Ca peak. However, the sub-crust sample indicates a lessening of the K peak and an increase in the Ca peak. One interesting point is that the Fe peak is greater relative to other peaks in the Spire Rock sub-crust sample, even though the sub-crust rock sample appears almost white when compared to the rubric indurated crusts.

By standardizing peak intensities in the samples to the reasonably invariate Compton backscatter peak (less than 2 percent variance), the peak intensity data values for the various samples can be directly compared. Figure A-9 shows the differentially altered samples compared to the fresh rock at the hydrothermally altered vein (F.R. in Figure A-9 = fresh rock or 100 percent values for the various constituents before alteration). Significant in the pattern is the relative enrichment of some more common elements like Ca, Ti, Fe, Cu, and Zn with attendant depletion of Si and K. Care must be taken in interpreting the block diagrams, since percentage relationships, not actual amounts of the various elements are shown. Thus, a seemingly large relative enrichment of a trace element may not be quantitatively as significant as a relatively small change in elements like Si or K, which are major constituents in the samples.

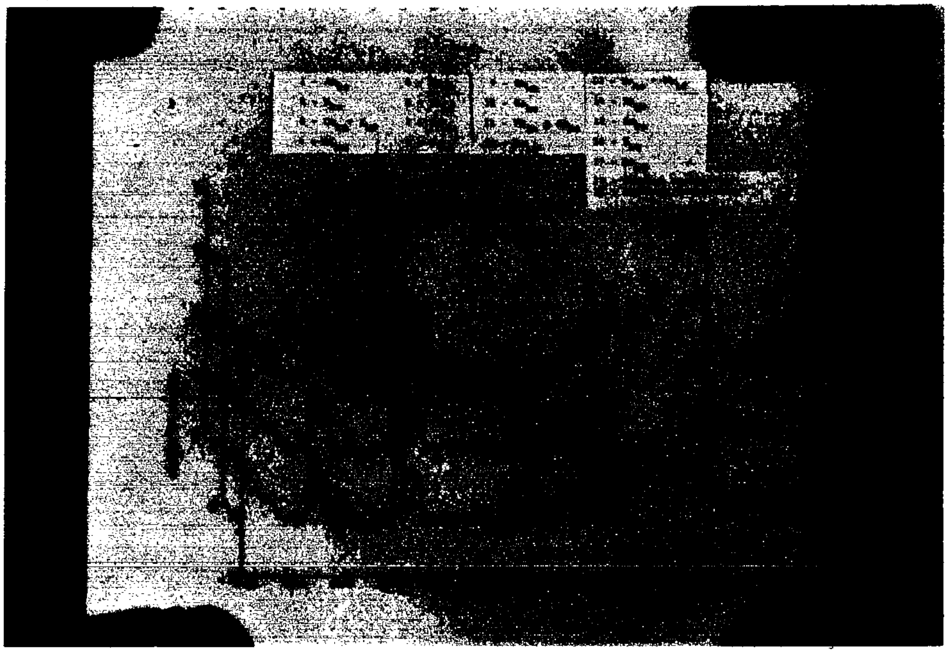


Figure A-7. X-ray fluorescence spectra for indurated crust and sub-crust samples (Mo target).

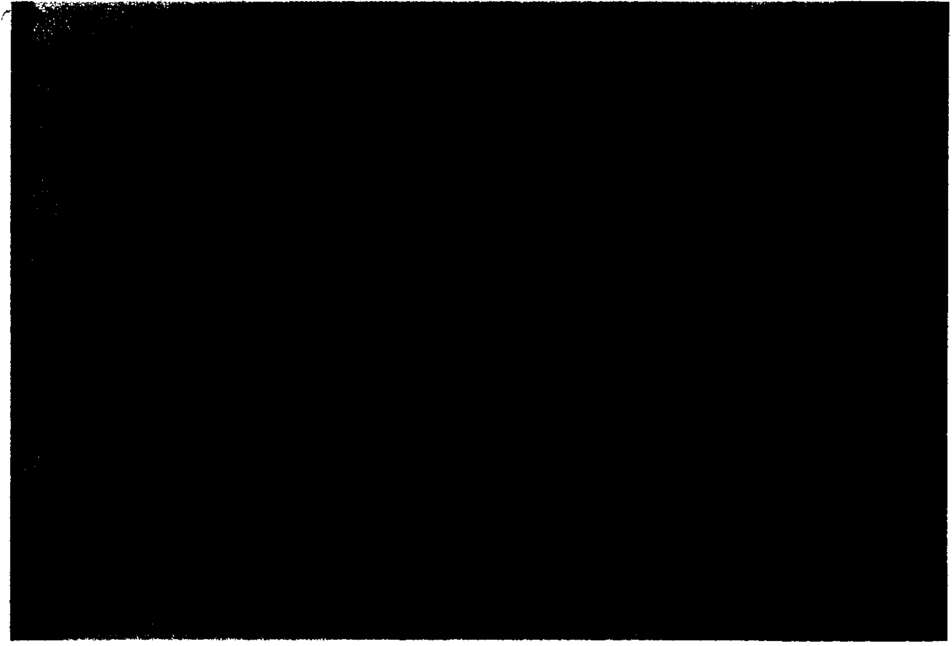


Figure A-8. X-ray fluorescence spectra for indurated crust and sub-crust samples (Ti target).

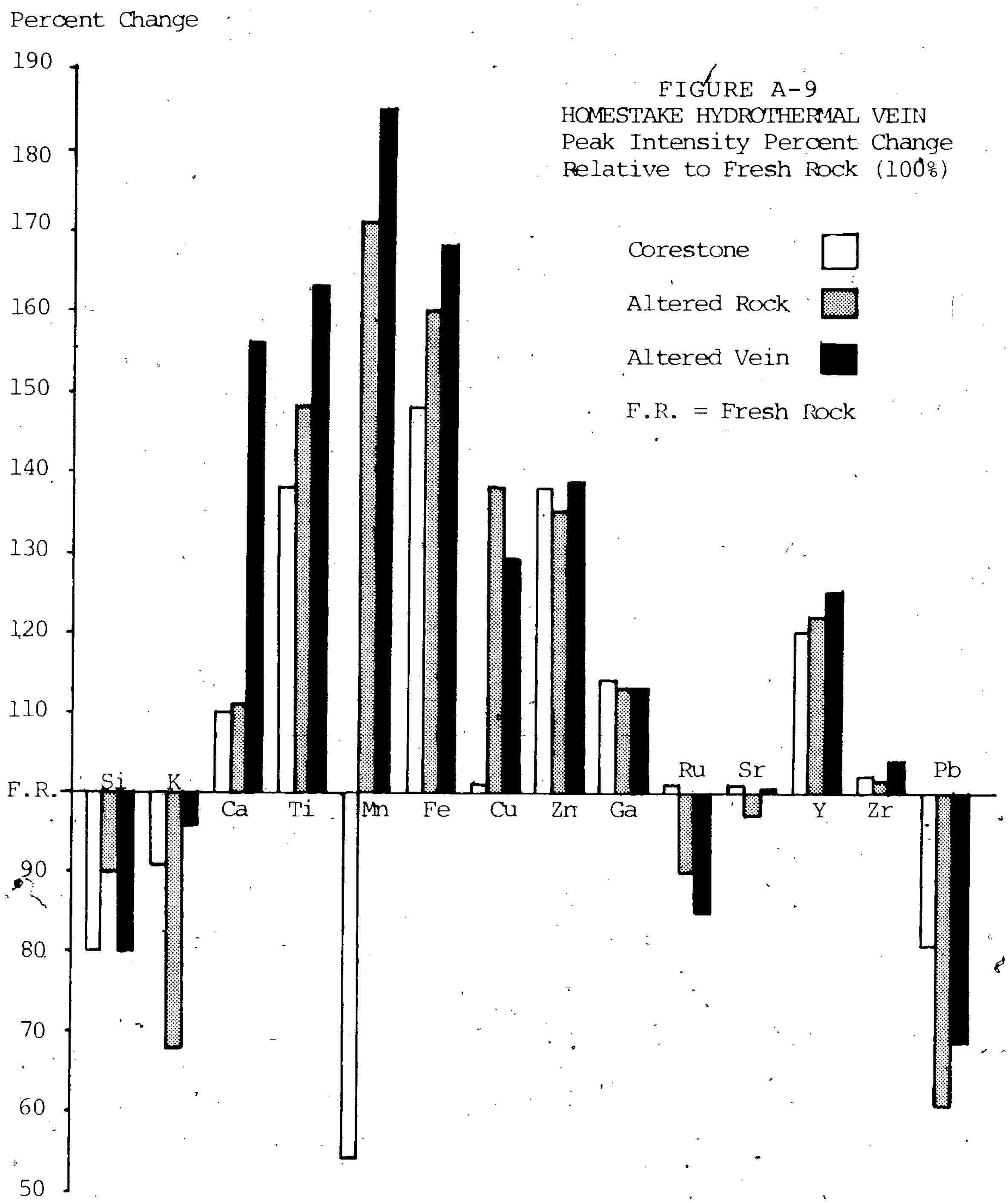


FIGURE A-9
HOMESTAKE HYDROTHERMAL VEIN
Peak Intensity Percent Change
Relative to Fresh Rock (100%)

When grus samples from meteoric weathering sites are compared to peak intensities from fresh rock samples gathered at the same sites, a different pattern from the hydrothermal site is apparent (Figure A-10). Nearly every element that showed enrichment at the hydrothermal vein shows depletion relative to fresh rock at meteoric weathering sites. Use of this technique to establish these contrasting weathering patterns, with some refinement, may offer a relatively easy way to discern between hydrothermal and meteoric alteration in the Butte Quartz Monzonite.

Comparison of the Spire Rock indurated crust (I.C. = indurated crust or 100 Percent in Figure A-11) with the sub-crust sample also adds some insight into the armoring of weathering residuals in the study area. Significant in Figure A-11 is the Si decrease in the sub-crust relative to the indurated crust. This may be due to silicic induration of hypogene origin (related to alaskite intrusion) or may be due to migration of silica in solution from the interior of the rock to the exterior, where evaporation precipitates amorphous silica in the micro-pores of the indurated crust.

In order to use EDXF to examine changes quantitatively, spectra from all elements must be properly calibrated. This can be done by comparing duplicate sample results from two different analytical methods or can be done by the known additions method. Constituent percentage values for EDXF and another method for several duplicate samples can also be compared to derive an EDXF calibration showing enhancement and depression

FIGURE A-10
GRUS SAMPLES

Peak Intensity Percent Change
Relative to Fresh Rock

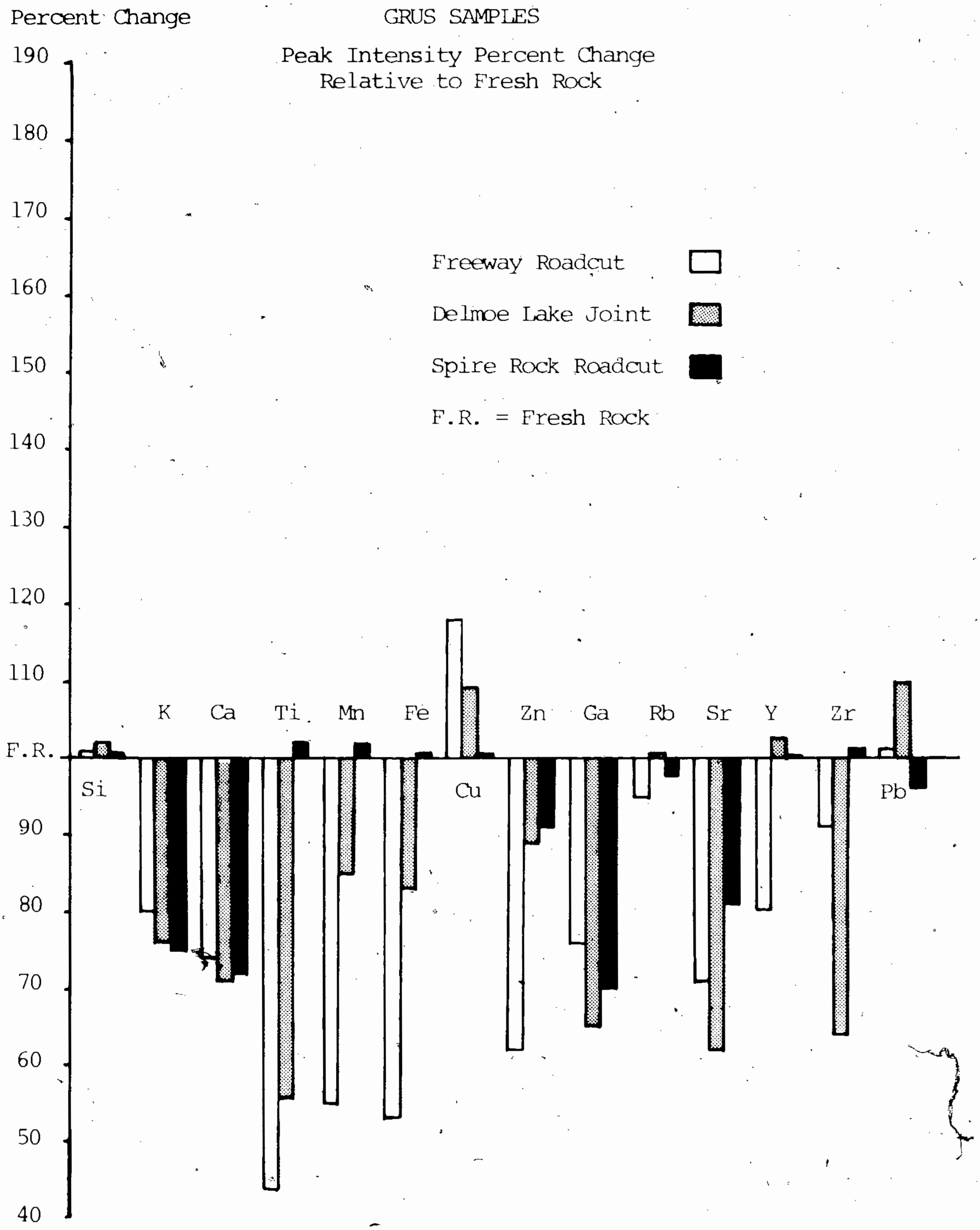
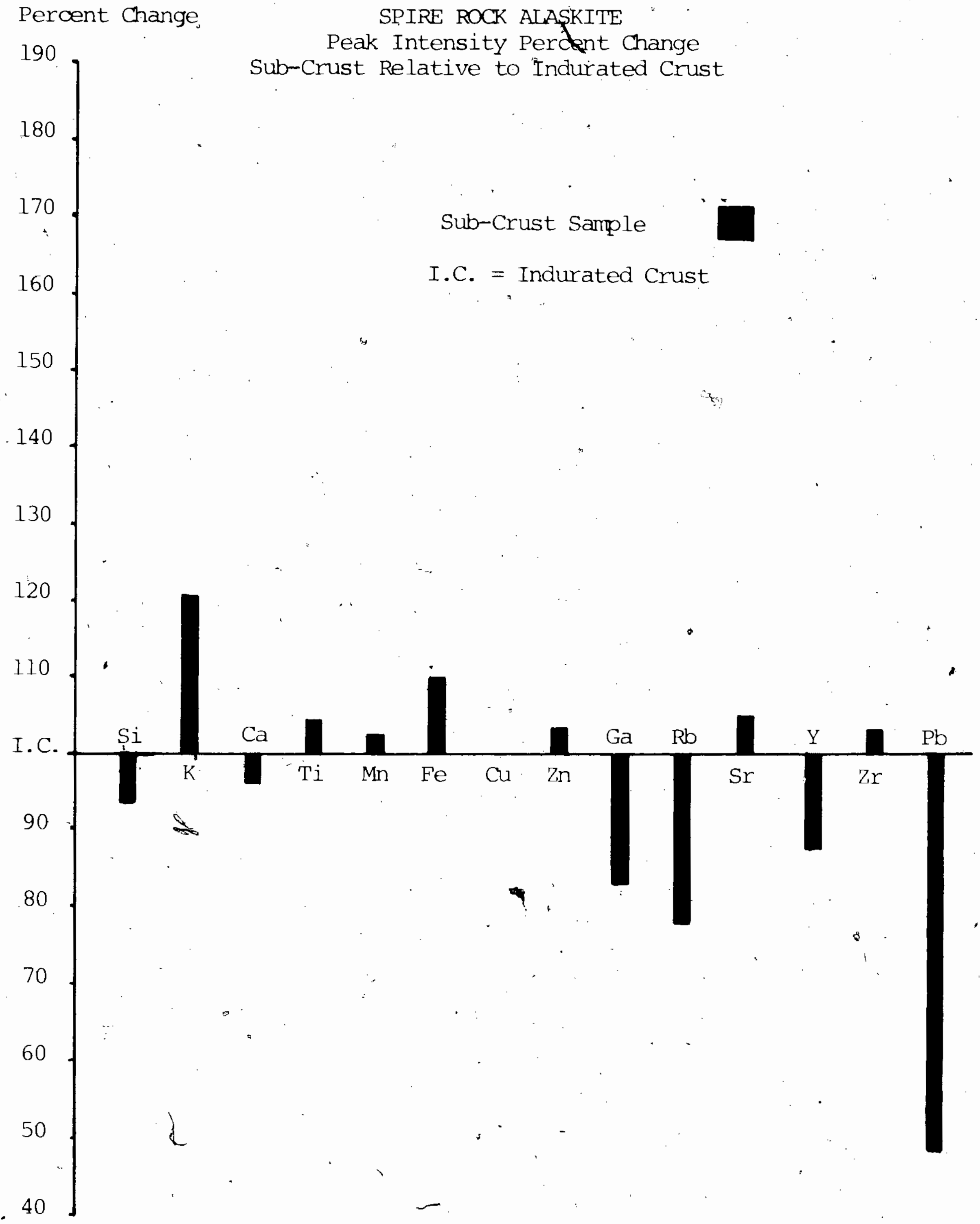


FIGURE A-11

SPIRE ROCK ALASKITE
Peak Intensity Percent Change
Sub-Crust Relative to Indurated Crust



effects. For example, enhancement occurs when elements slightly above the atomic number of Si induce additional fluourescence in the silica fraction. However, because Si is relatively insensitive to fluorescence in a matrix substantially rich in other elements, as Si content decreases, more and more of its low-energy X-rays are reabsorbed by the matrix, leading to a depression effect.

Morphometric Analysis:

It seems almost certain that alaskite and silicified quartz monzonite are responsible for the many major bornhardt features in the area. [This is diagrammatically shown in Figure 7, p. 86]. Minor dikes and dike swarms may be responsible for some smaller alaskite forms as well as influencing trends in relief development by maintaining resistance of ridges and guiding drainage.

Pediments. An almost classical pediment profile for Spire Rock Flats and its parallelism with other nearby pediments mentioned in the local geological literature lends some credence to the theory of pediment retreat as the mode of origin for some weathering residuals in the study area. It would seem that the Jefferson valley is the logical base level control for the formation of the Spire Rock Flats pediment, though the surface is no longer graded to the basin and is being actively dissected by Big Pipestone and Homestake Creeks and their tributaries, all of which are presently graded to the Jefferson River.

An alternative approach to explanation of pediment surfaces on the batholith is that proposed by Wharhaftig (1965). He concludes that stepped surfaces ~~on batho~~liths may occur without successive rejuvenation often proposed by others. This happens by natural expression of weathering differences, leading to zones of exposed, but unweathered, bedrock which act as local base levels for a series of graded 'steps'. The similarity of profiles between the model proposed by Wharhaftig and the stepped profile of Homestake Creek may add validity to this idea, but the natural extension of the stepped-surface model is a series of discordant planar surfaces, each one graded to a different base level. The Spire Flats Surface, at least, seems to have accordant summits between the presently dissecting drainage channels. Valley-side tors and extension jointing features occur along the margins of the incising streams but, for the most part, occur below the level of the pediment surface with mainly larger bornhardt forms existing above the well-defined portion of the pediment surface.

Summary and Conclusions:

The geochemical techniques used in this study would seem to have a wide application in the study of tors. The uses range from general fingerprinting of nearly similar rock types for geological mapping to discernment of subtle changes in elemental and mineralogical composition with progressive weathering. This has appliction to pinpointing differences caused by weathering between tors and the surrounding materials, discerning lithological expression in tors and bornhardts, differentiating between hydrothermal and meteroric alteration products, and determining changes in rock composition expressed by micro-relief (panholes, tafoni, etc.) on the weathering residuals.

The Boulder batholith, providing a variety of both expected and anomalous granitic landforms, is an excellent choice as a study area for investigations concerning weathering residuals. The study area offers opportunity to study anomalous static density curvilinear jointing patterns, as well as regular orthogonal and dilation jointing. Opportunity exists for studying tors in different altitudinal zones and topographic positions. A large number of domical inselbergs and bornhardts are available for study. Numerous micro-forms, such as indurated crusts, panholes and tafoni, exist in the area and may provide suitable subjects for tests of salt weathering, biological action, or frost action in their origin. In sum, the batholith area provides a place to examine the usefulness of a number of geochemical techniques and to add refinements to the study of tors.

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