Ash Flows of the Valley Springs Formation, Calaveras County, California

By

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THESIS

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ABSTRACT

The value of volcanic ash stratigraphy has been realized through recent studies of ash chronology and correlation. In the Sierra Nevada province, where tectonic and geomorphic events have modified the topography, ash chronology has proven to be invaluable in determining the regional stratigraphy and geologic history.

The Valley Springs Formation, exposed to the west of the Sierra Nevada batholith, is composed of rhyolitic ash flow tuffs interbedded with volcanic and fluviatile sediments. During emplacement, the ash flow units commonly were confined to drainage channels incised into the pre-existing topography. These strata represent a time of rhyolitic volcanism during the Miocene epoch, and provide a basis for establishing a Miocene ash chronology for the region.

The writer recognizes three distinct ash flow units within the Valley Springs Formation. Each unit is differentiated on the basis of petrographic character and chemical composition. Further distinctions are based on data obtained from X-ray diffraction analysis of crystallization patterns and radiometric dating. Both qualitative and quantitative analyses were utilized to correlate the ash flow tuff exposures in the study area. The characterization of the ash flows presented in this study will also be useful in extend-

ing ash correlation beyond the study area, in establishing a regional Miocene ash chronology.

Stratigraphic field relationships provide some insight into the relative chronology of the three ash flow units. In field outcrops, the Castle Rock unit clearly underlies both the Chili Gulch unit and the Central Hill unit. Speculation based on outcrop geometry and stratigraphic distribution suggests that the Central Hill tuff is the youngest of the three ash flow units. Potassium-argon radiometric dates from the present study indicate ages of 22.4 $\pm$ 0.1 m.y. (KA 3619) and 23.0 $\pm$ 0.2 m.y. (KA 3622) for the Castle Rock unit and the Central Hill unit respectively. These and previous dates suggest that the time interval represented by the ash flow units could be as little as one to three million years.

The Chili Gulch tuff unit is a densely welded, devitrified ash flow. The flow unit is characterized by zonal variations in crystallization and devitrification, determined by X-ray diffraction analysis. Phenocrysts and pumice fragments make up only a minor part of the total rock. Petrographic study shows axiolitic devitrification of glass shards and pumice fragments. Original shard shapes have been distorted by the compression associated with dense welding.

The Castle Rock tuff unit is a moderately welded, vitric ash flow. The flow unit is essentially vertically homogeneous at various field exposures. Some lateral variation in crystal and pumice content is apparent and may be due to a slight degree of lateral sorting upon emplacement, or non-uniform incorporation of detrital materials. An increase in phenocryst and pumice content distinguishes this unit from the Chili Gulch tuff. Petrographic analysis shows unaltered glass shards, with incipient devitrification in a few pumice fragments. Generally, shards retain their original shapes and uncompressed pumice fragments show well-preserved original vesicularity.

The Central Hill tuff unit is a poorly welded, crystal, vitric tuff-breccia. The flow unit is essentially homogeneous, with locally brecciated zones. This unit is characterized by an abundance of biotite phenocrysts and white pumice fragments. The original vitroclastic texture of the ash flow is well-preserved by distinct shard outlines. Many pumice fragments show compression and elongation, associated with emplacement by a flow mechanism and subsequent welding.

Results of X-ray fluoresence analysis of the chemical composition of the ash flow units are presented by means of single-element, Zr-Sr and Rb:Sr:Zr ternary diagrams. A synthesis of the data, and field and petrographic observations, provided a basis for correlation of exposures within the study area. The most diagnostic elements in differentiating the ash flow units within the Valley Springs

Formation were Zn, Na, Mg, Sr, Zr and Nb.

The writer suggests that the ash units were emplaced by a flow mechanism. Evidence cited includes flow of shards around phenocrysts and pumice fragments, preferred alignment of glass shards, pumice fragments and crystal components, inclusion of surface debris in basal sections of flow, and confinement of deposits to pre-existing drainage channels.

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INTRODUCTION

General Statement

Volcanic ash chronology is an invaluable tool in understanding the stratigraphy and Cenozoic history of the Sierra Nevada and adjacent geologic provinces (Dalrymple, 1963). Tectonic, geomorphic and depositional activity makes it difficult, if not impossible, to associate discontinuous outcrops of correlative rocks. The Miocene Valley Springs Formation, composed of interbedded rhyolitic ash units and sediments, is preserved as erosional remnants of what once was a more extensive valley-fill assemblage. The essentially instantaneously deposited ash units provide a sequence of stratigraphic marker beds, useful in dating and correlating events, both within the immediate area and beyond. Volcanic marker beds are used to solve chronological problems in the fields of paleontology, archaeology and geology (Everndern et al., 1964; Leakey, 1976; Sarna-Wojcicki, 1976). The value of a stratigraphic marker and potential for correlation is increased when the unit is differentiated with respect to lithologic character, petrography, and chemical composition. These data, considered with absolute radiometric ages, provide a basis for reliable correlation.

Previous Work

Preliminary geologic studies of the Valley Springs Formation and associated strata west of the Sierra Nevada were summed up by Gale, Piper et al. (1939) in United States Geological Survey Water Supply Paper 780. The publication describes the type section of the Valley Springs Formation on Valley Springs Peak, near the town of Valley Springs (sec. 11,T.4N.,R.10E.). Even though the description of this section is a sound basis for study of the Valley Springs Formation, the lithologic aspect in other outcrops may vary significantly from that found at the type locality.

Brief mention of the Valley Springs Formation is also found in publications by Lindgren (1911) and Storms (1894). Focus in these studies is on Tertiary sedimentary channel deposits in the Calaveras County area. Many publications, too numerous to mention, discuss topics of interest to the general region of the Sierra Nevada and adjacent provinces, of which the Valley Springs Formation and associated rhyolitic ash units are a part.

An unpublished M.S. thesis (Goldman, 1964) included the Valley Springs Formation in a study of Tertiary fluviatile deposits in the vicinity of Mokelumne Hill. Reconnaissance mapping of portions of the Valley Springs Formation was a part of this work.

Most recent studies of the Valley Springs Formation and associated formations are also found in unpublished geologic maps by Woodward-Clyde Consultants, San Francisco, made in conjunction with a seismicity study for Pacific Gas and Electric Company. These maps provide a substantial amount of information regarding the regional distribution of ash flow units within the Valley Springs Formation.

Previous potassium-argon dates were obtained from some ash units of the Valley Springs Formation, in a Ph.D. dissertation on Cenozoic Chronology of the Sierra Nevada by Dalrymple (1963). Personal communication with Woodward-Clyde Consultants also provided insight into absolute ages of ash flow units within the Valley Springs Formation.

PRESENT INVESTIGATION

Purpose

This study focuses on rhyolitic ash flow units of the Valley Springs Formation, Calaveras County, California. This investigation attempts to differentiate the distinct ash flows within the Valley Springs Formation. Characterization and correlation of distinct flow units includes lithologic character, petrography and morphology of the clastic components of each unit, relative and stratigraphic field relationships, relative and absolute element concentrations, and radiometric ages.

Observational and analytical data were utilized to make geological interpretations and speculations regarding the mode and mechanisms of emplacement of the ash flows and origin of pyroclastic materials.

Procedures

Field work was initiated with a reconnaissance survey of the Valley Springs Formation outcrop localities in the vicinity of the towns of Valley Springs, Mokelumne Hill, San Andreas, Buena Vista and Ione (Figure 1). Particular attention was given to the volcanic tuffs, as distinguished from the sedimentary constituents of the stratigraphic assemblage. Representative samples of the

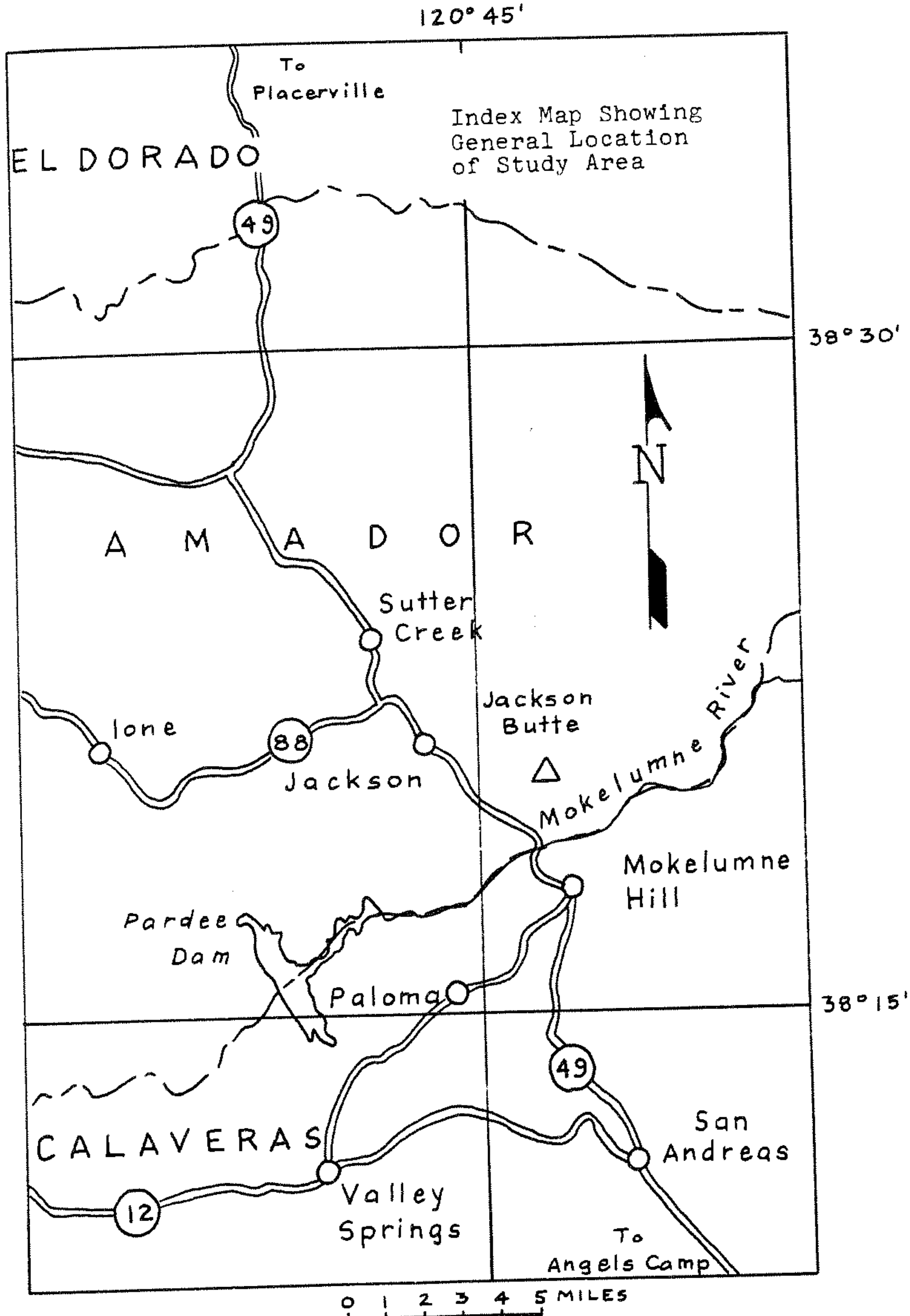

120° 45'
To
Placerville
Index Map Showing
General Location
of Study Area
EL DORADO
49
38° 30'
N
A M A D O R
Sutter
Creek
Ione
88
Jackson
Jackson
Butte
Mokelumne River
Mokelumne
Hill
Pardee
Dam
Paloma
38° 15'
49
CALAVERAS
San
Andreas
12
Valley
Springs
To
Angels Camp
0 1 2 3 4 5 MILES

Figure 1.

volcanic units were collected and described. Samples were collected mainly in the vicinity of Mokelumne Hill. Wherever possible, samples were collected both laterally and vertically at numerous outcrop locations of each unit. At each sample locality, observations were made with respect to the lithologic character of the flow units and their stratigraphic relationships. Laboratory work included 1) petrographic examination and description of tuffs, 2) X-ray diffraction analysis of crystallization products, 3) X-ray fluorescence spectographic analysis of relative and absolute element concentration and 4) radiometric age-dating.

Samples of the rhyolitic ash flow units were examined in thin-section under a petrographic microscope for the purpose of describing textural characteristics and phenocryst content. Shard morphology was noted. Visual estimates were made of relative abundances of ash, crystals, pumice fragments and lithic fragments. Attention was given to welding characteristics and varying degrees of devitrification.

Powdered bulk samples were used for X-ray diffraction studies. Instrumental conditions were identical for all scans so that peak intensities could be compared for different samples. Analysis of the diffraction spectra provided information on mineralogic products of devitrification and other forms of crystallization.

Relative and absolute element concentrations of the ash flow samples were obtained by X-ray fluorescence, using a Spectrace 440 Analyzer (energy-dispersive system using Ag-transmission target tube). The analytical data are presented by graphic techniques which include single-element plots, a Zr-Sr diagram and a Rb:Sr:Zr ternary diagram. A computer program analysis provided determination of similarity between the samples, with respect to chemical composition. The synthesized data are presented in a dendrogram, showing clustering of like samples.

Several potassium-argon dates were determined on samples from the ash flow units. The argon extractions were performed in the K-Ar laboratory in the Department of Geology and Geophysics at the University of California, Berkeley. Quantitative analysis of the argon was done with a Reynolds-type mass spectrometer. Potassium analyses were obtained by flame photometry.

Geologic Setting

The stratigraphic units exposed in the Mokelumne Hill-Valley Springs area are chiefly Tertiary and Quaternary volcanic rocks and sedimentary strata, overlying a basement of metamorphosed, folded, and faulted pre-Tertiary sedimentary and volcanic rocks, intruded by a quartz diorite stock. Focus in this study is on the Miocene rhyolitic volcanics and sediments, identified as the Valley Springs

Formation. The sedimentary portion of the Valley Springs Formation consists of tuffaceous, gray silt and clay, vitric quartzose sand, and local lenses of conglomerate, commonly well-bedded (Gale, Piper et al., 1939). The volcanic component of the Valley Springs Formation includes rhyolitic ash flow tuffs, ranging from densely welded units with zonal variations in texture and composition to relatively uniform, less consolidated ash units.

The Miocene Valley Springs Formation unconformably overlies the Eocene Ione Formation, including white or light-colored clay and clayey quartz sandstone, shale and some lignite beds (Gale, Piper et al.,1939). The non-volcanic origin of the sediments of the Ione Formation distinguishes them from the sediments of the Valley Springs Formation. The Valley Springs Formation is unconformably overlain by the upper Miocene (lower Pliocene?) Mehrten Formation, which includes fluviatile, commonly well-stratified, siltstone, sandstone, and conglomerate beds composed of andesitic detritus. The absence of fresh andesitic detritus in the strata of the Valley Springs Formation distinguishes it from the younger Mehrten Formation.

Distribution and Geometry of the Ash Flow Deposits

Outcrops of the Valley Springs Formation are found in a strip approximately 7-8 miles wide, between the towns of Valley Springs and Wallace, to the west (Gale, Piper et al., 1939). This north-south trending strip extends south to include the town of Jenny Lind and north to the Consumnes River. The zone thins considerably to the north of Wallace, becoming less than two miles wide in many locations. To the east of this strip, towards the foothills of the Sierra Nevada, there remain only intermittent remnants of the Valley Springs rhyolitic strata. Maximum preserved stratigraphic thicknesses of the Valley Springs Formation are exposed at the type section on Valley Springs Peak (420 feet) and on Buena Vista Peak (450 feet), south of the town of Ione (Gale, Piper et al., 1939).

The focus of this study is on rhyolitic ash flow tuffs, which are part of the Valley Springs Formation. The outcrops of the rhyolitic tuffs are few in number. The tuffs are generally found in lenticular deposits, sparsely scattered throughout the areas where the Valley Springs Formation is exposed. The lenticular geometry of the tuff units suggests that the deposits were confined to drainage channels, previously incised into the depositional surface. The remnants that have withstood subsequent erosion are often located along ridges, higher in elevation than the present-day drainage system. The original distribution of deposits, the variability of degree of induration laterally within the tuff units, and the nature of subsequent erosion are all contributing factors to the sparse occurrence of the rhyolitic tuffs on the present topography.

GENERAL STRATIGRAPHY AND RADIOMETRIC DATES

The Valley Springs Formation consists of rhyolitic ash flow tuffs and, commonly, well-bedded sedimentary strata. The sediments include tuffaceous, gray siltstone and claystone, vitric quartzose sandstone, and conglomerates (Figure 7). This series of strata represents a period of fluviatile deposition, accompanied by contemporaneous rhyolitic volcanism (Gale, Piper et al., 1939). The lenticular geometry of the outcrops in the Mokelumne Hill-Valley Springs area suggests that the surface of deposition was highly irregular, characterized by cut-and-fill channel topography. At all localities observed, the rhyolitic ash materials appear to have filled pre-existing drainage channels incised into the depositional surface. The ash flow tuffs, which define drainage channels, are located at higher elevations than the present drainage system. This orientation provides exposures of the contact, defining the channel bed, between the rhyolitic ash fill material and the underlying sediments (Figures 4, 5 and 6).

Based on field and laboratory data from this study, the writer recognizes three chemically and lithologically unique ash flow units in the Valley Springs Formation. All other strata are classified as tuffaceous sediments of a predominantly fluviatile origin. The three ash flow

Figure 2. Extensive Castle Rock ash flow outcrop in foreground. Remnant of Chili Gulch unit visible near top of hill, at left.

Figure 3. Type location of Castle Rock ash flow near Valley Springs.

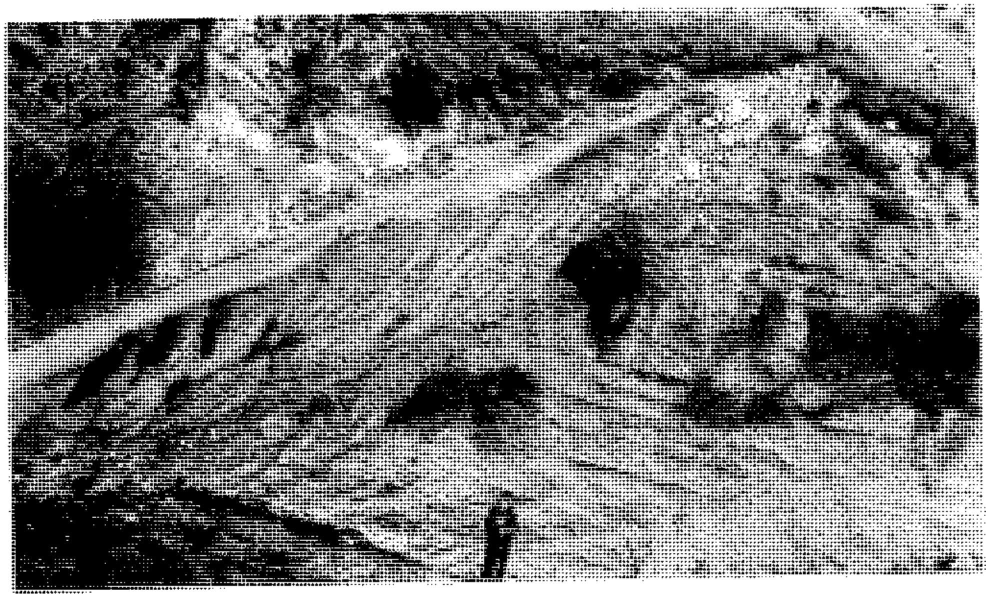


Figure 4. Chili Gulch ash flow partly filling channel in stratified tuffaceous sediments of Valley Springs Formation; roadcut on Highway 49, near Highway 12.

Figure 5. Closer view of Chili Gulch ash flow at same location. Note jointing.

Figure 6. Contact, defining channel bed, between zone of brecciated Central Hill ash flow and underlying sediments. Note baked zone.

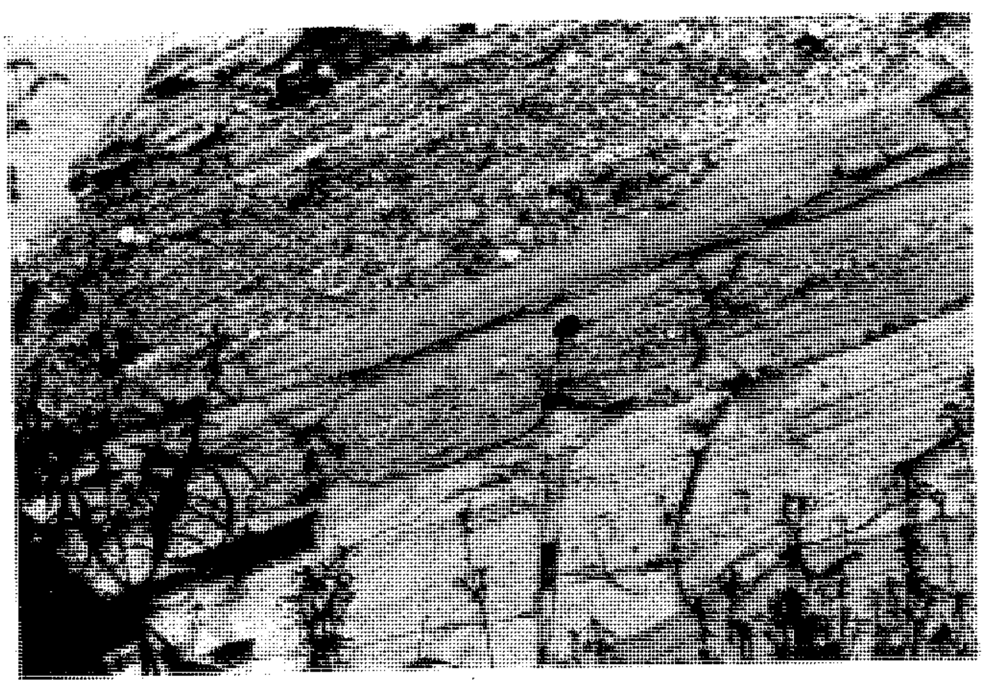


Figure 7. Stratified conglomerates and tuffaceous sediments of the Valley Springs Formation.

units are named after particular localities where prominent exposures of each unit occur: Chili Gulch tuff unit, Castle Rock tuff unit and Central Hill tuff unit. The lithologic character of each unit is discussed in a subsequent section.

Stratigraphic field relationships provide some insight into the relative chronology of the three ash flow deposits. No outcrops were observed which show unequivocal stratigraphic relationships among all three ash flow units. Numerous exposures include two of the three tuff units in juxtaposition, providing an understanding of their stratigraphic relationships. The most frequent field association occurs between the Chili Gulch unit and the Castle Rock unit (Figures 2 and 3). In all cases observed, stratigraphic evidence indicates that the Castle Rock unit underlies the Chili Gulch unit. Some outcrops show the Chili Gulch unit filling a younger channel, incised into an older channel, partly filled by the Castle Rock ash flow. Other outcrops do not show the Chili Gulch unit and Castle Rock unit in direct contact, but do present them in stratigraphic sequence, showing that the Castle Rock unit clearly underlies the Chili Gulch unit. A potassium-argon radiometric date from the present study indicates an age of 22.4 ± 0.1 m.y. (KA 3619) for the Castle Rock unit. Previous dates from the same unit indicate ages of 22.8 ± 0.5 m.y. and 23.1 ± 0.5 m.y. (Dalrymple, 1963). Woodward-

Clyde Consultants, San Francisco (personal communication, 1978) provided an age of 23.0 ± 1.2 m.y. for the Chili Gulch unit.

Stratigraphic relationships suggest that the Castle Rock unit also underlies the Central Hill unit. No outcrops were observed where the two units occur in direct contact with each other. A potassium-argon date from this study indicates an age of 23.0 ± 0.2 m.y. (KA 3622) for the Central Hill unit. Previous dates from the same unit indicate ages of 19.9 ± 0.4 m.y., 21.1 ± 0.4 m.y. and 21.9 ± 0.4 m.y. (Dalrymple, 1963).

Field observations provided no conclusive evidence regarding the stratigraphic relationship between the Chili Gulch unit and Central Hill unit. No outcrops were observed where these two units appeared in unambiguous stratigraphic sequence or in direct contact from cut-and-fill channel association. Speculation, based on outcrop geometry and stratigraphic distribution, suggests that the Central Hill tuff is the youngest of the three ash flow units.

The sedimentary and volcanic strata of the Valley Springs Formation appear to represent a continuous series of depositional and eruptive events. Both gradational and non-gradational contacts were observed among the volcanic and sedimentary strata. No evidence was seen to suggest major unconformities within the strata of the

Valley Springs Formation.

The absolute radiometric dates were not particularly conclusive. The short time interval encompassed by the volcanic events represented in the Valley Springs Formation, and the analytical error in the age calculations, presents ambiguities regarding the absolute chronology of the ash flow units. The time period represented by the tuff units could be as little as one to three million years. During the mineral separation procedures, in preparation for the radiometric dating technique, complications resulted from possible contamination of some of the ash flow samples by older granitic material from the Sierra Nevada complex. The dates presented in this discussion are regarded to be reliable, based on careful preparation and monitoring of techniques. Two other dating attempts were unsuccessful due to probable error introduced in the potassium determination procedures. A reevaluation of the potassium-analysis techniques is in order, to insure greater reliability of radiometric dates in future studies.

LITHOLOGIC CHARACTER

Chili Gulch Unit: Valley Springs Formation

The Chili Gulch tuff unit, named for its exposures around Chili Gulch, south of the Mokelumne Hill townsite, may be classified as a densely welded, devitrified ash flow tuff. Zones within the unit indicate variations in degree of welding and devitrification and crystallization (Figures 8 through 11). The major part of most Chili Gulch tuff outcrops is massive and indurated with local well-defined jointing patterns. Towards the basal section, the unit becomes less welded, with some outcrops being characterized by a basal unwelded zone. The color of the unit varies from buff and pink to gray in the densely welded zones, and is predominantly gray in the unwelded portion. Pumice fragments range from 2-4% of the total rock, increasing in abundance stratigraphically downward. Individual pumice fragments are characterized by both tubular and spherical vesicularity. Compression of the pumices and degree of devitrification varies vertically within the unit (Figures 12 and 13). The original vitroclastic texture of this unit is preserved in varying degrees throughout the section. The trends of preservation of vitroclastic texture generally seem to correspond to the zonal variations in the degree of welding. The compression of the original shard

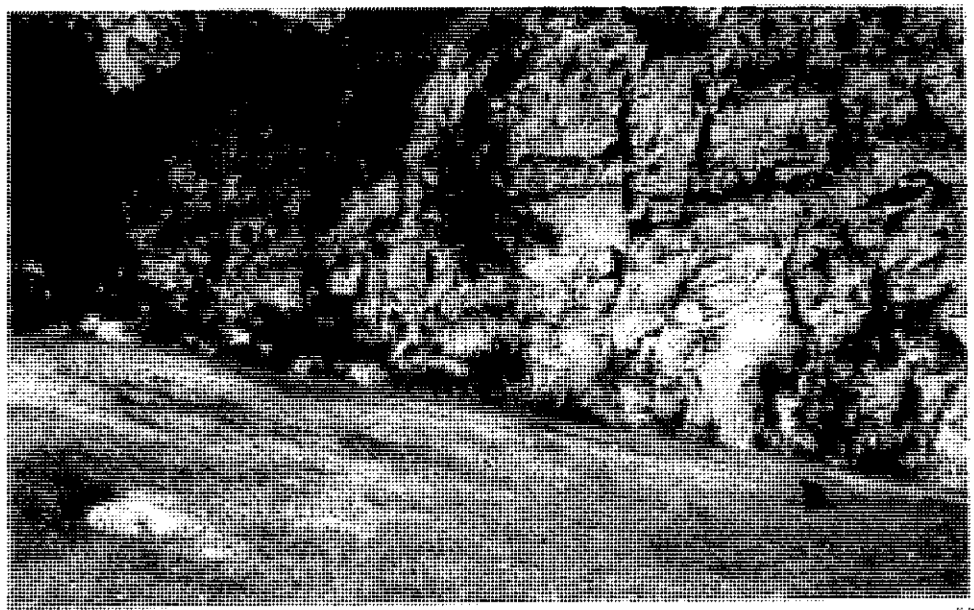


Figure 8. Massive Chili Gulch ash flow outcrop. Mined face shows welded devitrified zone. Welded, non-devitrified zone in foreground (daypack for scale).

Figure 9. Uppermost, devitrified, densely welded zone of Chili Gulch ash flow unit, same location as above.

Figure 10. Chili Gulch tuff unit. Indurated, densely welded zone grading into less welded, pumice-rich basal zone (at hammer).

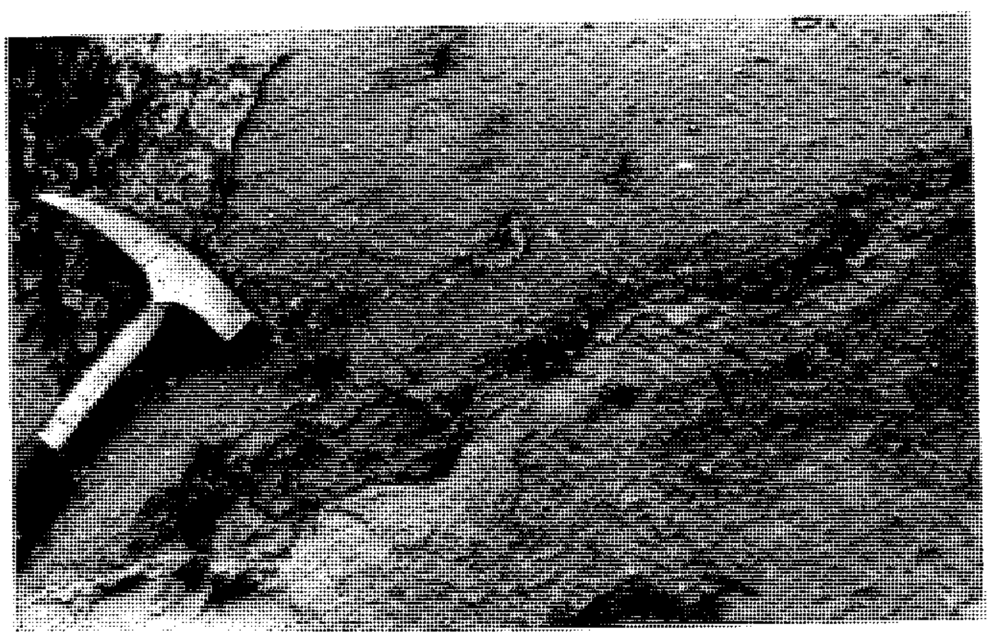


Figure 11. Basal, unwelded, non-devitrified zone of Chili Gulch ash flow. Note abundance of pumice fragments.

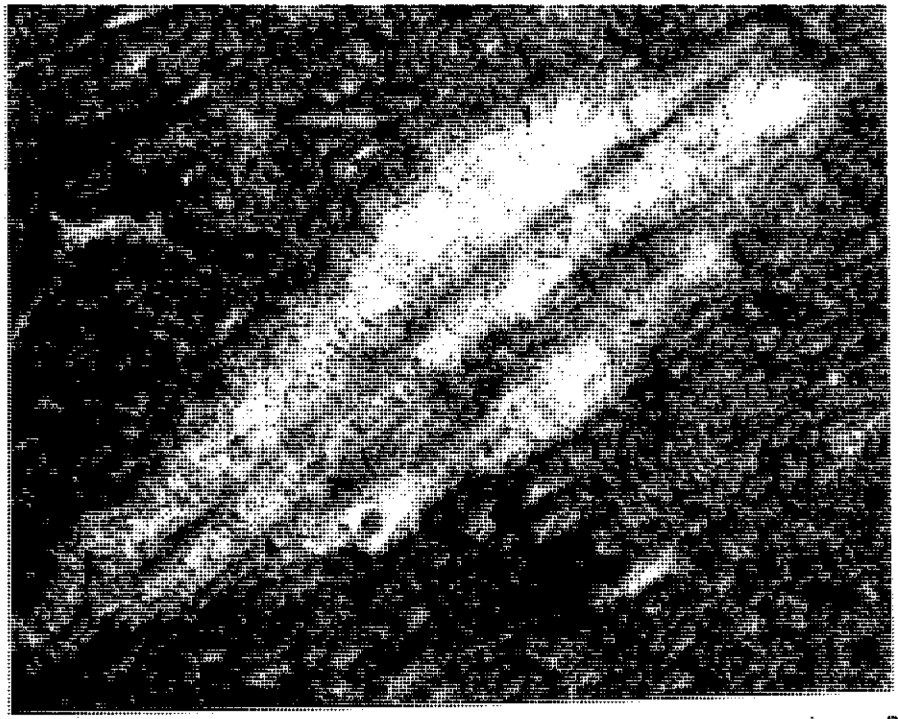


Figure 12. (80X) Elongated, compressed pumice fragment. Dense welding causes shards to become indistinct in groundmass. Chili Gulch unit.

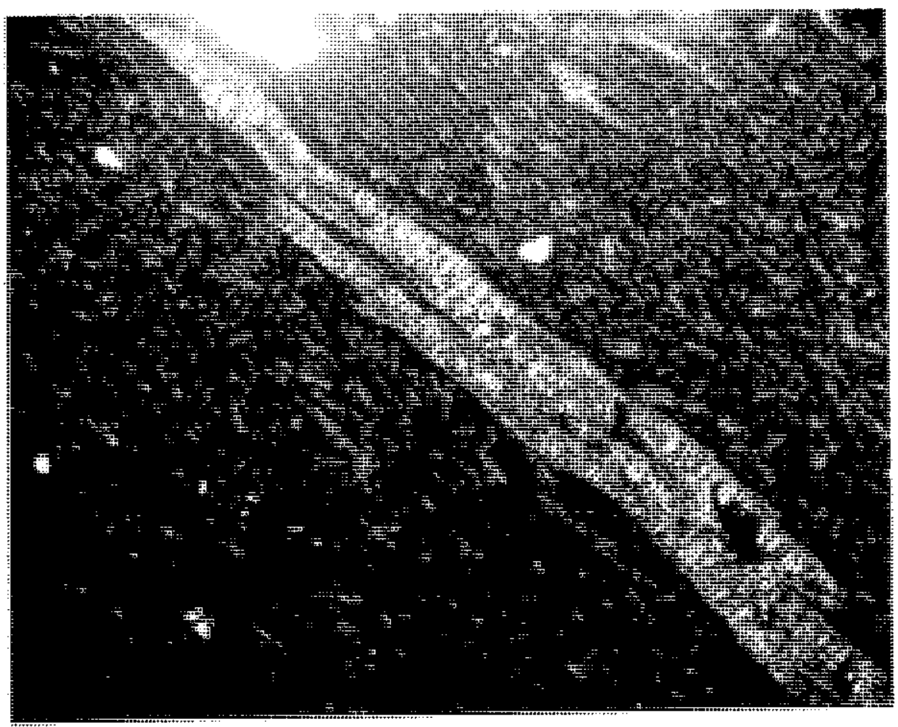


Figure 13. (30X-crossed nichols) Stretched pumice fragment. Axiolitic devitrification of pumice fragment and glass shards. Chili Gulch unit.

shapes also varies vertically within the unit. The glass shards do not preserve much of the original vesicularity of the pumice fragments from which they were formed (Figures 14 and 15). Phenocrysts make up approximately two percent of the total rock throughout the welded section. The percentage of phenocrysts increases to approximately five percent in the basal unwelded zone. However, a portion of the crystals in the basal zone may be a detrital component from the underlying tuffaceous sediments, which was incorporated in the tuff unit upon emplacement. The composition of the phenocrysts is predominantly sanidine, quartz and plagioclase, with minor amounts of biotite. The biotite and quartz appear to be concentrated towards the bottom of the unit. Petrographic and field observations suggest that the quartz content may be supplemented by detrital grains from the underlying sediments. The biotite concentration may be a result of gravity settling of crystals before solidification of the ash flow.

The Chili Gulch unit provides an opportunity for a detailed petrographic study of welding and devitrification. Zonal variations in devitrification and welding are most prominent in the thicker exposures. Some, relatively thin exposures, show no apparent vertical contrasts whatsoever. Even though devitrification and welding occur in superimposed zones, they may be differentiated as two

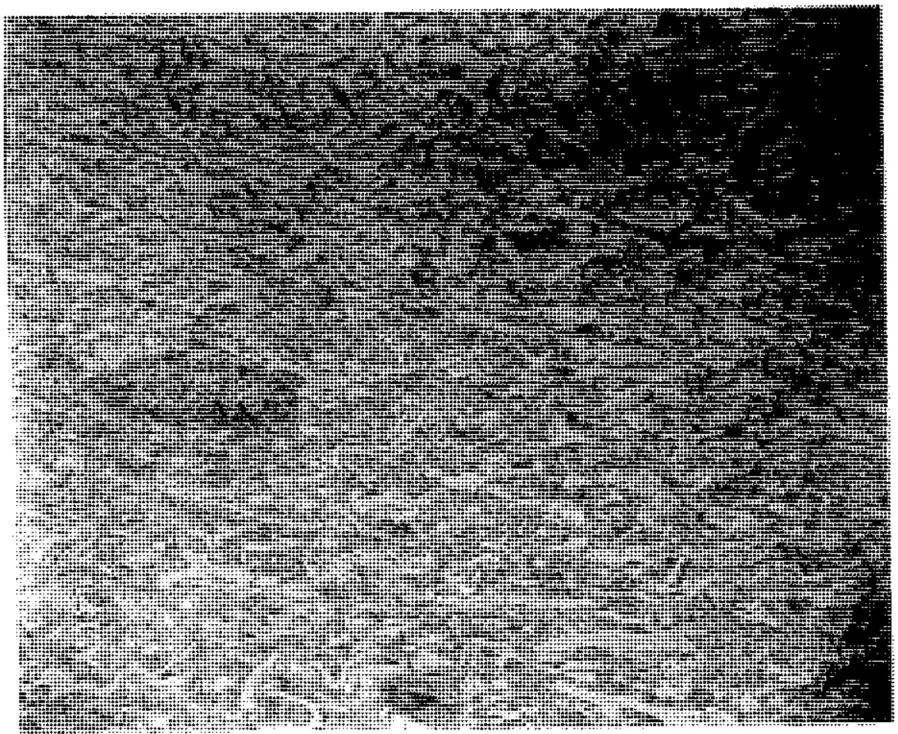


Figure 14. (30X) Chili Gulch ash flow unit. Vitroclastic texture in welded, non-devitrified zone.

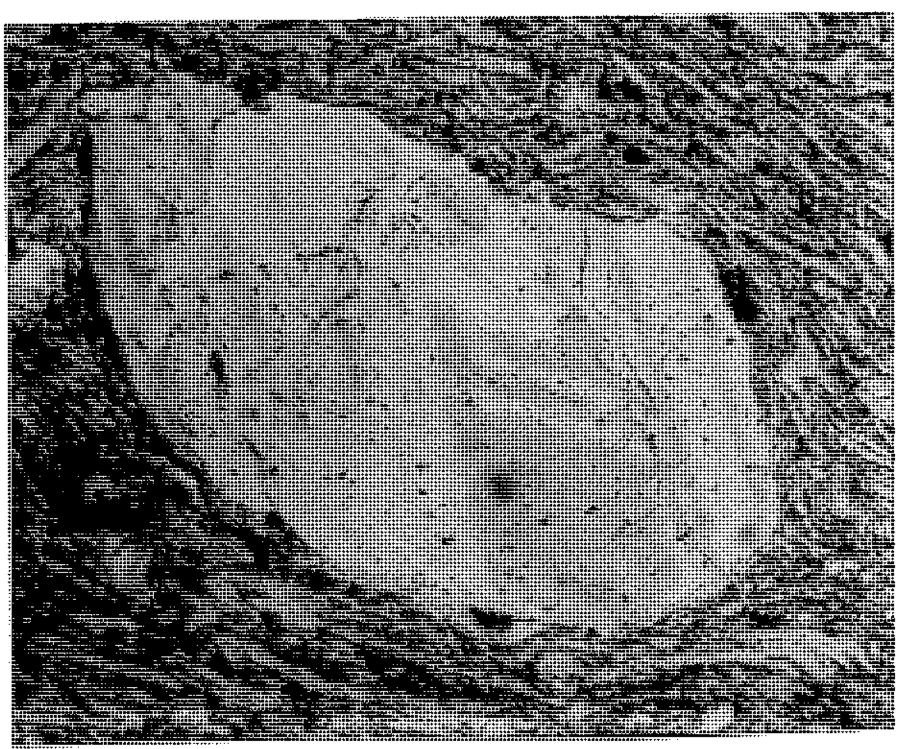


Figure 15. (80X) Glass shards flow around feldspar phenocryst. Chili Gulch unit.

independent processes, thus they are treated separately. The subject of devitrification will be discussed in conjunction with X-ray diffraction analyses since that technique was most successful in obtaining valuable data regarding the devitrification process. The topic of welding is discussed below.

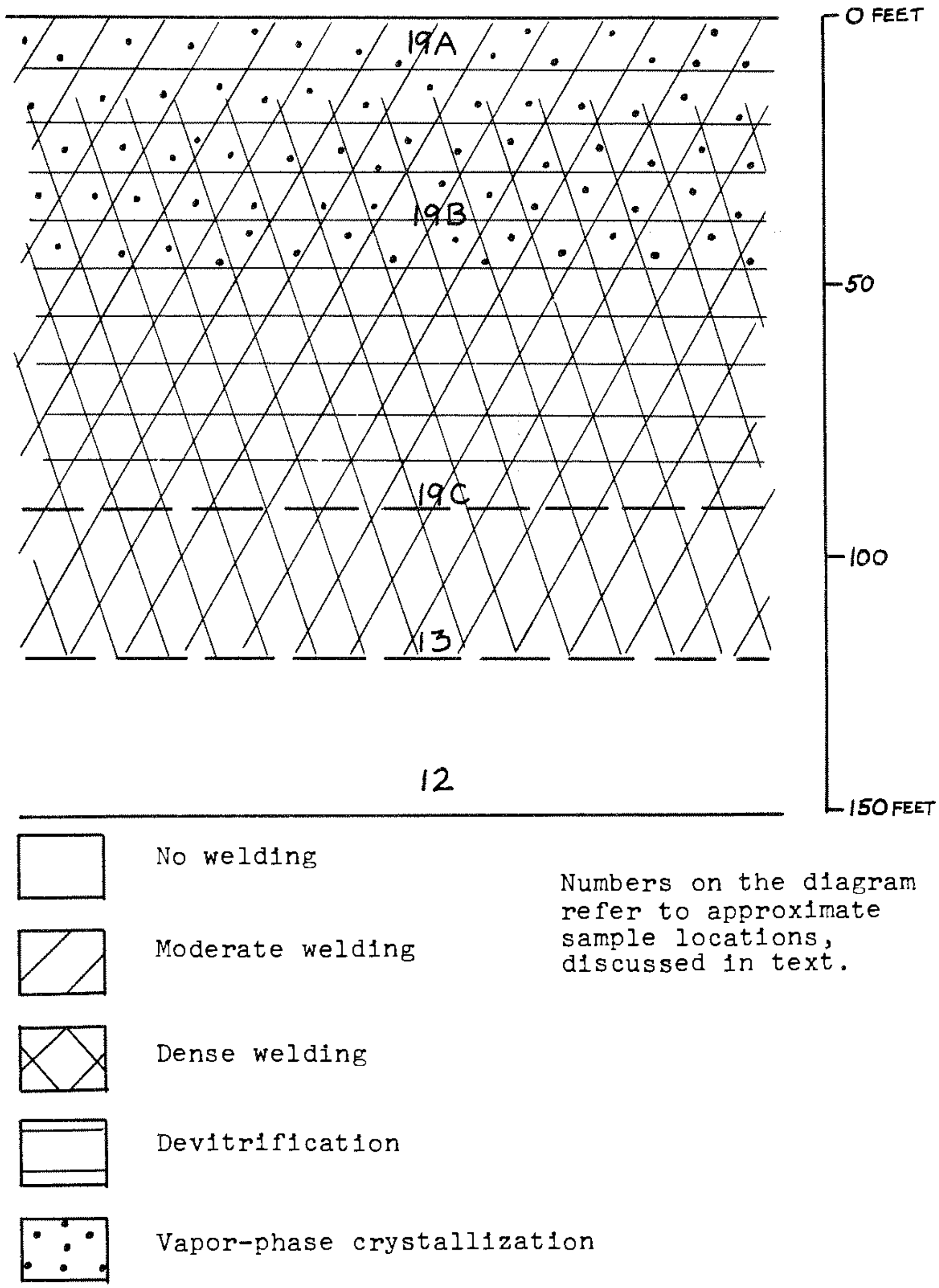
The most complete sequence illustrating degrees of welding and devitrification was observed in an outcrop of the Chili Gulch tuff located approximately 1 1/2 miles south of the town of Mokelumne Hill (Sect.19,T.5N.,R.12E.). The outcrop is approximately 150 feet thick, at its center. The unit decreases in thickness laterally to form a lenticular outcrop which probably defines a drainage channel filled by the ash flow materials. In the discussion that follows, references are made to specific samples within this outcrop, used to illustrate zonal transitions. Gross zonations are apparent even from brief field observation. However, a closer petrographic and chemical analysis indicates that the zonal boundaries are often indistinct, the transitions being gradational in most instances. Attention must be given to the fact that the outcrops are isolated remnants of the original, once more extensive, ash flow. This provides difficulties with regard to regional interpretation of textural variations. The samples noted below serve to represent typical lithologic characteristics which may be expected to occur in the respective zones.

The zones, commonly defined on the basis of degree of welding and devitrification, are essentially in a horizontal orientation within a single outcrop. Figure 16 presents a schematic interpretation of the zonal variations. The diagram is based mainly on field observations and petrographic studies in the laboratory.

Approximately the upper 100 feet of the Chili Gulch outcrop (Sec.19,T.5N.,R.12E.) are moderately to densely welded, massive and locally jointed. Within this 100 foot section, the degree of welding increases downward in the unit. The uppermost 70-80 feet are pink in color, massive, and they are characterized by columnar-like jointing. The lower part of this welded zone is gray in color, massive, and lacks a distinguishable jointing pattern. Sample 19A, from the highest point on the outcrop, is moderately welded. The original vitroclastic texture is relatively well-preserved. Individual glass shards are only slightly compressed. Many of the pumice fragments appear uncompressed, showing preserved original vesicularity. Other pumice fragments show initial signs of compression and stretching, resulting in elongated vesicles.

Sample 19B, taken from a point approximately 40 feet below the top of the outcrop, is densely welded. Even though the original vitroclastic texture is still recognizable, many glass shards have been fused and are almost indistinguishable from the finer-grained groundmass.

Figure 16. Zonal variations in ash flow units.
A generalized section based on observations of the Chili Gulch ash flow unit outcrop (Sec.19,T.5N.,R.12E.). (After Smith, 1969b)



The more clearly defined shards show a preferred orientation, with their longest dimension aligned perpendicular to the vertical direction of compaction. Pumice fragments are compressed and stretched, as is reflected by the tubular nature of elongate, adjoining vesicles. This deformation of the vesicular texture results in a banded appearance of the pumice. The elongation may have been enhanced by the flow process, if compaction occurred, at least in part, before the solidification of the unit.

In sample 19C, collected from a point approximately 100 feet below the top of the outcrop, the degree of welding is even greater than in the zone containing 19B. The original vitroclastic texture is almost totally obscured by fusion of the individual glass shards. Existing shard outlines are indistinct and most of the rock is made up of a uniform fine-ash groundmass. Pumice fragments are stretched and compressed.

The zone below that of 19C is characterized by an abrupt color change, from pink to gray, and a disappearance of the distinct jointing. Sample 13 is densely welded, but not devitrified. The degree of welding seems slightly lower than that in the overlying zone. Original vesicularity has been preserved in many pumice fragments. Also, many pumice fragments do not show signs of compaction. The original vitroclastic texture is extremely well-preserved, due to the unaltered glass shards and preservation of shard outlines. This lower non-devitrified zone of dense welding is sometimes referred to as the basal vitrophyre. Extremely well-compressed, welded pumice fragments and shards appear as black glassy fragments, with parallel orientation. From field observations, even though there exists a dramatic color and lithologic change with the transition into this vitrophyre zone, not much could be learned about the nature of the contact between adjacent zones. Petrographic studies suggest that the transition is relatively abrupt, in comparison to the gradational transitions between zones in the uppermost section of the outcrop.

The vitrophyre zone grades into the underlying unwelded zone, which is also gray in color. The shards show slight preferred orientation, perpendicular to the direction of compaction. The individual shards are generally uncompacted. The original vitroclastic texture tends to be replaced by indistinct shard outlines, representing shards which have been assimilated into a uniform groundmass.

In most other Chili Gulch outcrops, only a portion of the zonal sequence described above is detectable. Most localities show only those zones corresponding to the uppermost welded section, represented by samples 19A, 19B and 19C. The absence of zones may be due to the fact that they never formed, as a result of inadequate thickness and improper cooling conditions at the time of emplacement. Other possible explanations for absent zones may be post-emplacement erosion of portions of the unit or overlap and obstruction from view by overlying strata.

Castle Rock Unit: Valley Springs Formation

The Castle Rock unit, named for its exposures at Castle Rock near the town of Valley Springs, may be classified as a moderately welded, vitric tuff. This unit is generally uniform in mineralogy and texture, vertically in the section. The color within the unit varies from buff to light gray. Field outcrops commonly appear indurated and massive with local patterns of columnar jointing.

Pumice fragments make up to approximately five percent of the total rock, in samples collected. The pumice fragments are uncompressed, but some show slight devitrification (Figure 18). Tubular and spherical vesicularity is typical in pumice fragments. This vesicularity is sometimes also preserved in intricate shard shapes. In some outcrops, pumice fragments appear to be concentrated in the basal zone of the unit. Well-defined shard outlines preserve the original vitroclastic texture of the Castle Rock ash flow (Figure 17). Many shards appear as equant, platy fragments. The average size of the shard component is greater than that in the Chili Gulch unit.

Phenocrysts account for up to ten percent of the

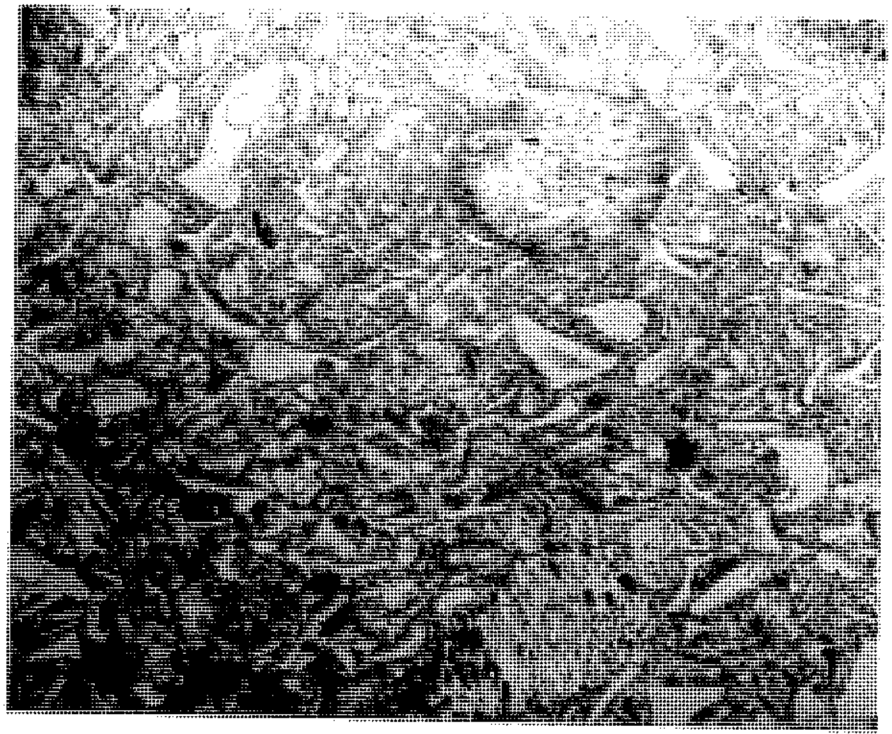


Figure 17. (30X) Castle Rock ash flow unit. Non-devitrified, vitroclastic texture.

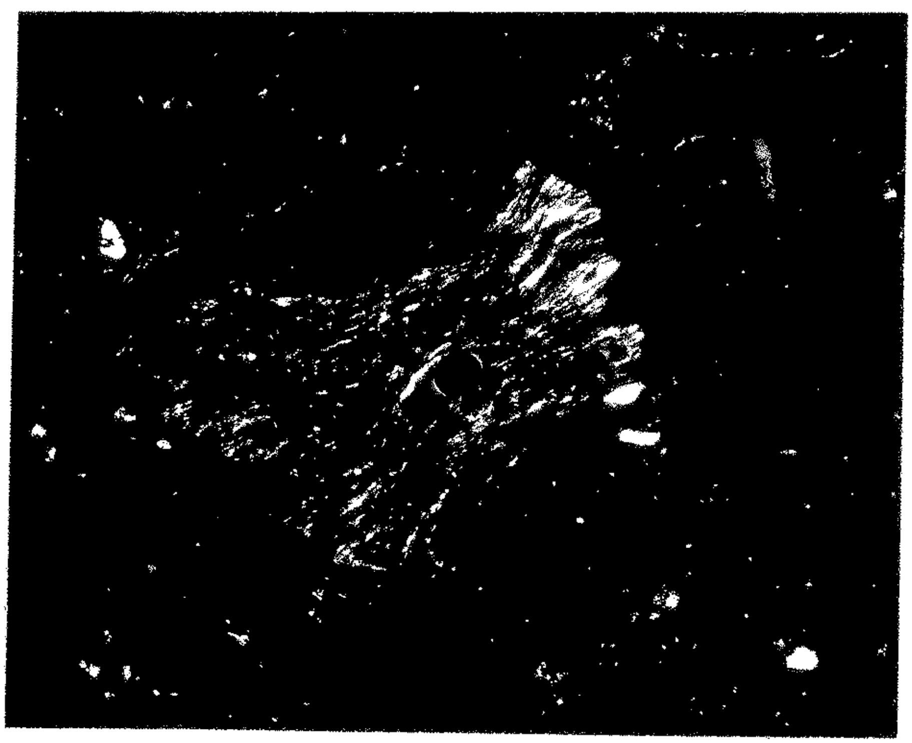


Figure 18. (80X-crossed nichols) Slightly devitrified pumice fragment in groundmass of non-devitrified shards. Castle Rock unit.

total rock. The composition of the phenocrysts is sanidine, albite, quartz and minor, fine-grained biotite. Detrital volcanic rock fragments make up one to two percent of the total rock.

There is no apparent preferred orientation of the glass shards or pumice fragments. Shards, as well as pumice fragments, do not show signs of compression associated with dense welding. In some outcrops there appears to be a concentration of pumice and lithic fragments towards the base of the unit. However, such observations at various localities were not conclusive in this regard.

Central Hill Unit: Valley Springs Formation

The Central Hill unit, named for its exposures on Central Hill south of the Mokelumne Hill townsite, may be classified as a poorly welded, crystal, vitric tuff-breccia. This unit shows no obvious zonal patterns in mineralogy or texture. The Central Hill outcrops are generally massive, with various degrees of induration. The relatively more indurated portions sometimes show blocky jointing (Figure 19). The most unique characteristic of the Central Hill unit is the existence of local discontinuous brecciated lenses (Figure 20). The fragments of the breccia are of the same composition as the rest of the unit. Blocks were seen which measured up to 10-12 inches in diameter. No patterns of distribution of the brecciated

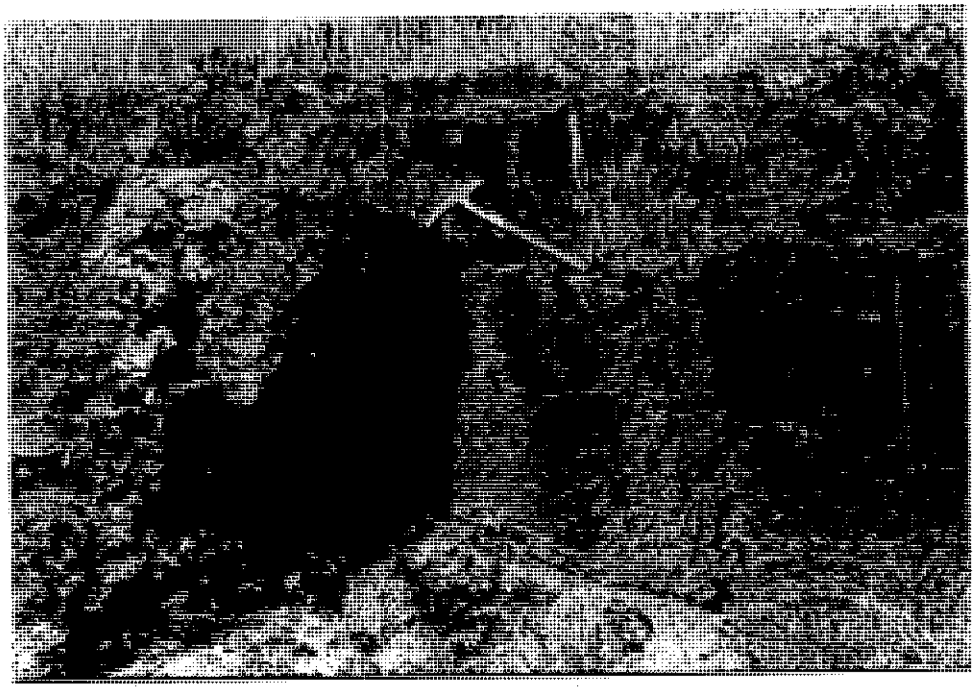


Figure 19. Indurated zone of Central Hill flow. Note massive jointing.

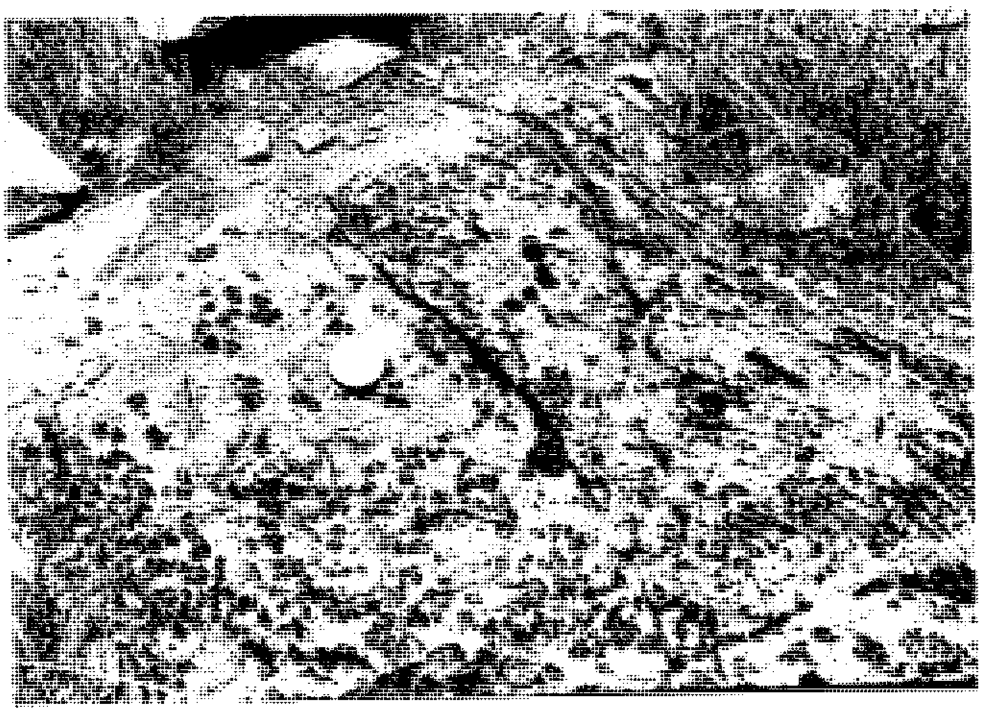


Figure 20. Breccia zone of Central Hill ash flow unit, top of Valley Springs Peak.

portions were apparent. The origin of the breccia may be auto-brecciation during the process of emplacement.

Distinguishing hand-sample characteristics include white pumice fragments and an abundance of biotite phenocrysts. Absolute amounts of pumice fragments and biotite crystals vary from outcrop to outcrop. No distinct vertical variations were recognized.

The original vitroclastic texture of the Central Hill ash flow is well-preserved by distinct shard outlines (Figure 21). The shard shapes resemble the platy, angular shards of the Castle Rock unit, but are generally finer grained and include a component of more delicate shapes. Shards exhibit some degree of preferred orientation.

Phenocrysts make up three to ten percent of the total rock, depending on the sample locality. Phenocryst composition includes biotite, sanidine, albite, and quartz, in decreasing abundances. Large, and often euhedral, biotite crystals account for approximately 50% of the total phenocrysts. In some samples, the biotite shows a preferred alignment (Figure 22). Volcanic rock fragments account for one to two percent of the total rock. Some basal sections are contaminated by a detrital clay component, occurring in minor amounts. The clay was probably incorporated in the process of emplacement.

Many pumice fragments show compression and elonga-

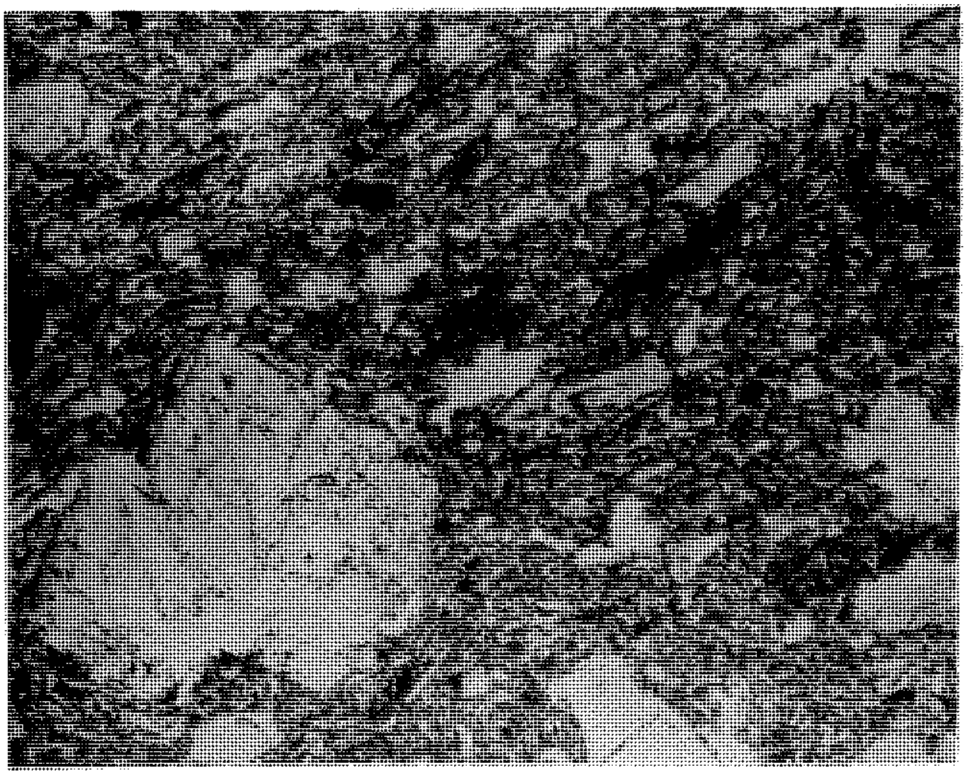


Figure 21. (30X) Central Hill ash flow unit. Poorly welded, crystal, vitric, tuff-breccia. Note flow of shards around feldspar phenocryst.

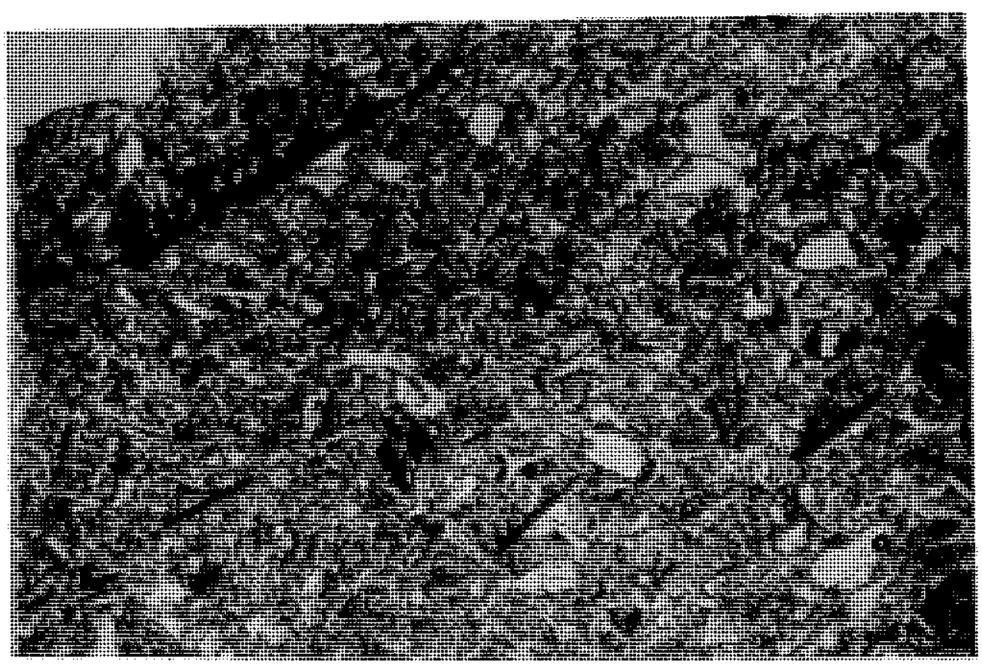


Figure 22. (30X) Preferred orientation of biotite phenocrysts. Central Hill unit.

tion. The original tubular and spherical vesicularity is relatively well-preserved. Rarely do pumice fragments show any evidence of incipient devitrification.

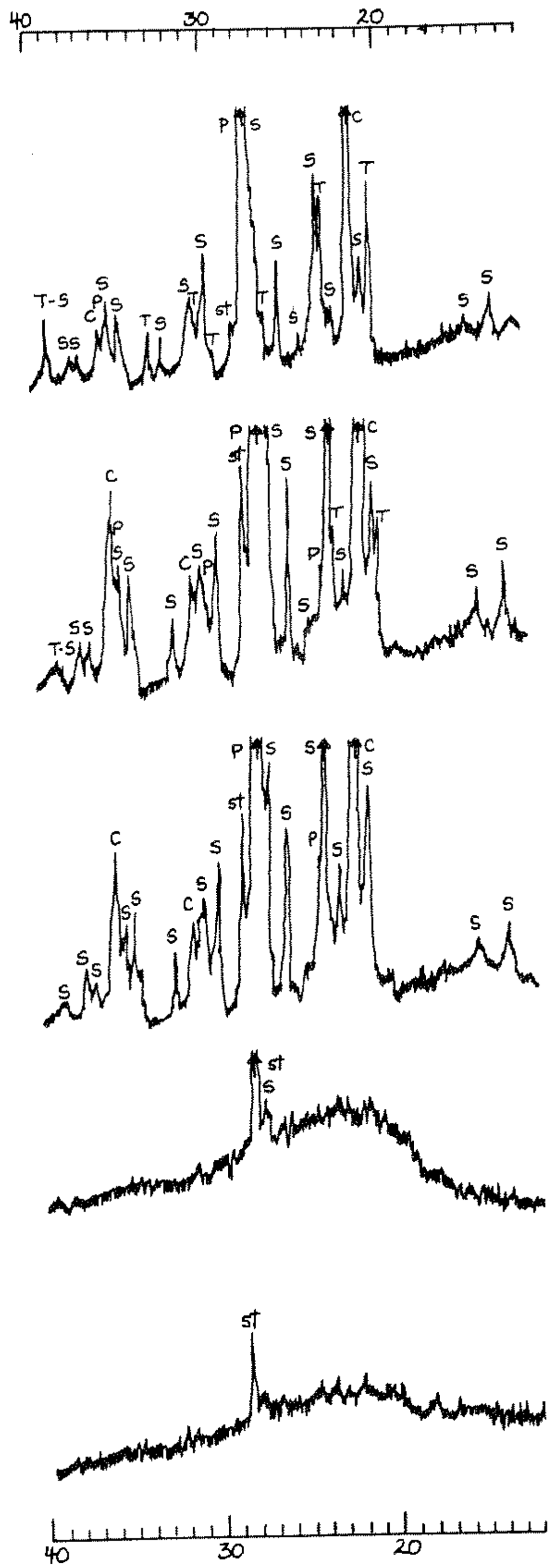
X-RAY DIFFRACTION ANALYSIS: CRYSTALLIZATION

Crystallization in volcanic rocks is common in the form of phenocrysts, devitrification products, or vapor-phase crystals. X-ray diffraction studies were especially helpful in determining products of devitrification and vapor-phase crystallization within the ash flow units. An arbitrary amount of each sample was crushed to obtain a whole-rock powder. Balsam was used to adhere the powder to a glass disc, utilized in the X-ray technique. Analyzing conditions were identical for each sample. Of the three recognized units, the Chili Gulch tuff shows the most complete sequence of zonal variations with respect to welding and devitrification (Figure 16).

The following discussion of the results of X-ray diffraction analysis of the Chili Gulch tuff unit is facilitated by a reproduction of the X-ray diffraction spectra for samples 19A, 19B, 19C, 13 and 12 (Figure 23).

X-ray diffraction spectra show the occurrence of tridymite in samples 19A and 19B, from the uppermost welded zones of the Chili Gulch outcrop, described previously (Sec. 19,T.5N.,R.12E.). A quantitative comparison was made between the ratio of the intensity of the tridymite peaks to the intensity of other mineral peaks in sample

Figure 23. X-ray diffraction spectra. Samples are from the Chili Hill tuff unit (Sec.19,T.5N.,R.12E.).



C = Cristobalite
T = Tridymite
S = Sanidine
P = Plagioclase Feldspar
st= Silicon-standard

Sample 19A: Moderate welding; devitrification; vapor-phase crystallization

Sample 19B: Dense welding; devitrification; vapor-phase crystallization

Sample 19C: Dense welding; devitrification

Sample 13: Dense welding; no devitrification

Sample 12: No welding; no devitrification

19B. The larger ratio of intensities in sample 19A suggests that tridymite is relatively more abundant in sample 19A than in sample 19B. X-ray analyses of the other samples, stratigraphically lower in the Chili Gulch tuff outcrop, show no evidence for the occurrence of tridymite. It is particularly noteworthy that tridymite does not occur in sample 19C, which has been devitrified, as have samples 19A and 19B. This suggests that tridymite is not the common product of devitrification. This observation is in agreement with previous studies of crystallization in ash flows (Smith, 1960b). The fact that tridymite occurs only in the uppermost zones of the section, may indicate that vapor-phase crystallization products dominate in that part of the unit. Vapor-phase crystallization is expected to occur in uppermost sections of a flow unit, where the degree of welding allows for sufficient porosity.

Cristobalite peaks are identified in samples 19A, 19B and 19C, of the uppermost devitrified zones of the Chili Gulch tuff unit. A quantitative comparison of the ratios of the intensity of cristobalite peaks to the intensity of other mineral peaks suggests that cristobalite is more abundant in samples 19B and 19C than in sample 19A. Cristobalite is absent in the non-devitrified samples of the same flow unit. If the suggestions in the preceding paragraph are correct, and thus indicate lack of vapor-phase crystallization in the zone represented by sample

19C, this would suggest that cristobalite is a product of devitrification, rather than of vapor-phase crystallization. Furthermore, the data indicates a greater degree of devitrification in samples 19B and 19C than in 19A. Petrographic studies of these samples support this observation. In the case of samples 19A and 19B, where both devitrification and vapor-phase products occur simultaneously, there still exists some ambiguity with regard to the source of the cristobalite crystals.

Other peaks in the X-ray spectrograms are identified as sanidine. Sanidine abundance varies vertically throughout the Chili Gulch tuff unit, but appears to some degree in every sample. Samples 19A, 19B and 19C all show sanidine peaks of significant intensity. The sanidine peaks of samples 12 and 13 were almost unrecognizable due to their low relative intensities. Data from the X-ray diffraction analyses, considered with results of petrographic studies, present the probability that sanidine is a product of a combination of several crystallization processes. Alkali feldspars are a common devitrification product, as is cristobalite. Also, sanidine occurs as phenocrysts and possible vapor-phase crystals.

Other X-ray peaks are identified as those corresponding to plagioclase feldspars. The overlap of the peaks causes some ambiguity in identification. The plagioclase feldspar peaks match most closely those of albite, but may represent a range of plagioclase compositions. Petrographic studies, comparing indices of refraction, support the existence of albite as phenocrysts in the glass groundmass of the tuff.

A characteristic glass peak (2θ = 18-35°) was very apparent in the non-devitrified samples, 12 and 13. In samples 19A, 19B and 19C, the glass peak was replaced by peaks representing various minerals, as described above.

X-ray diffraction analyses of samples from the Castle Rock unit and the Central Hill unit were not nearly as instructive as for the Chili Gulch ash flow. The X-ray spectra of samples from the Castle Rock tuff unit support the findings of petrographic studies. There essentially is no visible pattern of vertical variability within the unit. Low intensity peaks for sanidine and cristobalite show up in the analysis for sample 42 (Castle Rock unit, Buena Vista Peak). An increase in phenocrysts and beginning stages of devitrification in pumice fragments differentiated this sample from other samples of the Castle Rock group, in petrographic studies. This distinction may be the result of some lateral sorting and differentiation upon emplacement of the unit, and local development of devitrification texture. The occurrence of devitrification in this portion of the Castle Rock unit may indicate non-uniform emplacement and cooling conditions within the unit. Smith (1960b) reported that zonal variations in devitrification and welding commonly are more pronounced in thicker sections of the ash flow unit. This and other aspects of the cooling environment must be considered when interpreting the presence or absence of crystallization zones within an ash flow unit. The glass peak is prominent in all analyses of the Castle Rock unit samples. The relative intensity of the glass peak was slightly less in sample 42, showing some devitrification of pumice fragments, than in other non-devitrified samples of the Castle Rock unit.

The overall lithologic uniformity within the Central Hill tuff unit is also supported by results of X-ray diffraction analysis. No zonal variations within a single flow unit were detected. All samples show the characteristic glass peak, identifying a non-devitrified glass composition. A series of peaks, only remotely recognizable, may be identified as those corresponding to sanidine. However, this identification could not be accomplished with much certainty.

In summary, X-ray diffraction studies were most useful in providing insight with regard to products of devitrification in ash flow units. Vertical changes in mineralogy were successfully detected within a single flow unit. Also, in some cases, analyses were helpful in recognizing lateral differentiation within a unit. In agreement with previous studies of crystallization within ash flows (Smith, 1960b), the present investigation seems to indicate that common devitrification products are cristobalite and alkali feldspars, while tridymite and alkali feldspars typically characterize zones of vapor-phase crystallization. As seen in Figure 16, the zones of devitrification and vapor-phase crystallization are somewhat controlled by zones of welding. However, the zones of crystallization are controlled by other variables as well, thus the zones of crystallization are superimposed upon the zones of welding. This overlap causes some ambiguities in defining the zonal boundaries.

X-RAY FLUORESCENCE ANALYSIS: ELEMENT CONCENTRATIONS

Relative and absolute values of element concentrations in the tuff samples were determined by means of X-ray fluorescence, using a Spectrace 440 Analyzer (energy dispersive system using Ag-transmission target tube). Analyses were carried out on untreated, powdered whole-rock samples, collected laterally and vertically within the ash flow units. The standard used for all elements was G-2.

All samples were analyzed for Na, Mg, Al, Si, P, K, Ca, Ti, Mn, Fe, Co, Ni, Cu, Zn, Ga, W, Pb, Th, Rb, Sr, Y, Zr and Nb. Only relative values were obtained for the elements Na, Mg, Al,Si, P, K, Ca, Ti, and Mn. Even though the absolute concentrations for these elements were not available, the data may be used to determine similarities between samples and to execute the computer-aided cluster analysis. Concentrations of Ni, W and Co in the tuff samples were commonly below the zero level with respect to the calibrated scale for the detection mechanism. The absolute concentration data which were obtained are summarized in Table 1. The values for iron (total Fe^{2+} and Fe^{3+}) denote percentage content of the whole rock. All other element values are parts per million.

The data are presented both analytically and

TABLE 1. ELEMENT CONCENTRATION DATA

Sample	Fe %	Co ppm	Cu ppm	Zn ppm	Ga ppm	W ppm	Pb ppm	Th ppm	Rb ppm	Sr ppm	Y ppm	Zr ppm	Nb ppm
1B	2.2	8	7	61	19	0	34	28	216	17	33	362	32
4	1.4	-	12	80	20	0	30	23	210	23	54	369	32
6	1.7	-	20	33	15	0	22	16	161	81	25	141	16
9	1.3	0	13	53	26	0	35	33	215	25	34	381	33
12	2.2	1	17	144	16	0	38	30	221	25	49	359	33
13	1.8	22	15	145	22	0	40	22	242	35	52	372	29
16	1.8	0	16	142	22	0	39	26	199	34	52	405	33
18	1.5	3	16	69	19	0	30	28	187	33	38	329	28
19A	2.2	19	23	74	25	0	37	26	218	18	54	381	33
19B	1.2	-	16	35	20	0	32	30	208	23	33	360	33
19C	1.9	2	5	89	23	0	34	29	212	34	52	356	31
21	2.5	-	18	28	18	0	25	25	176	136	32	163	15
22	2.8	-	19	34	16	0	24	21	176	128	29	174	11
24A	2.3	-	15	21	18	0	32	24	175	109	18	169	13
24B	2.6	-	12	21	14	0	28	23	163	134	17	158	13
24C	2.4	-	25	24	15	0	36	33	169	147	25	174	14
25	2.3	-	17	31	19	0	32	27	189	150	25	162	14
28A	1.6	21	4	59	18	0	34	21	202	29	47	358	26
28B	2.2	7	5	81	21	0	31	27	207	37	34	351	31
28C	1.4	-	22	64	20	0	29	29	214	32	29	355	30
29A	1.5	-	11	36	16	0	37	16	168	91	28	144	14
29B	1.5	-	12	40	14	0	26	18	161	83	16	138	14
29C	1.4	0	0	35	14	0	27	17	156	81	17	148	12

Table 1. Element Concentration Data (Continued)

Sample	Fe %	Co ppm	Cu ppm	Zn ppm	Ga ppm	W ppm	Pb ppm	Th ppm	Rb ppm	Sr ppm	Y ppm	Zr ppm	Nb ppm
31A	2.7	16	0	118	19	0	35	23	213	36	38	343	27
$31B_1$	2.4	10	0	87	22	0	34	26	188	35	29	356	38
$31B_2$	2.5	-	0	71	22	0	25	29	195	24	27	356	34
32	2.3	7	5	97	24	0	28	25	210	24	39	353	30
33	2.1	-	0	38	25	0	25	27	223	24	46	369	32
34	1.8	-	6	41	15	0	19	18	210	172	27	154	18
35	1.9	-	12	34	17	0	29	21	187	173	21	166	18
36	1.5	-	12	36	15	0	22	24	224	116	27	137	17
40	1.6	-	17	25	18	0	31	23	210	139	24	156	12
42	1.4	18	5	40	16	0	21	22	223	33	28	135	19
43	1.8	-	12	102	24	0	44	28	222	23	45	380	33
44A	1.8	2	0	68	13	0	34	30	193	29	32	323	25
44C	1.5	-	20	66	23	0	26	29	200	32	40	356	29
45A	3.2	6	11	148	24	0	32	29	204	26	30	362	31
45B	1.9	-	0	95	24	0	33	27	207	24	32	382	29
46A	2.6	8	5	94	19	0	43	28	183	38	25	366	30
48	1.5	0	15	53	16	0	28	27	215	30	31	139	18

graphically. Graphic displays include single-element plots (Figures 24 - 30), a Zr-Sr diagram (Figure 31), and a Rb:Sr:Zr ternary diagram (Figure 32). A computer-aided cluster analysis was used to compare chemical similarity between samples.

The most diagnostic elements, Zn, Na, Mg, Sr, Zr, and Nb, were used as variables in the cluster analysis. The choice of elements used was based on potential correlative groups observed in the single-element plots, as well as field and petrographic observations. The elements that are most useful in differentiating units are those which are internally consistent within a flow unit but vary significantly from one flow unit to another.

Figures 24 through 30 summarize single-element concentration data for all samples analyzed. The concentrations of Mn are similar among all samples, making differentiation between groups unsuccessful. The plots for Zn, Na, Mg, Sr, Zr, and Nb show distinct groupings of one or more of the sample groups thought to represent distinct units, based on field and petrographic observations. The remaining single-element plots show a wide range of concentrations within distinct units, with no apparent clustering of chemically unique groups. The single-element concentration data shows that of the three ash flow units, the Chili Gulch unit and the Castle Rock unit are most similar. The only exception is seen in the Mg plot. In

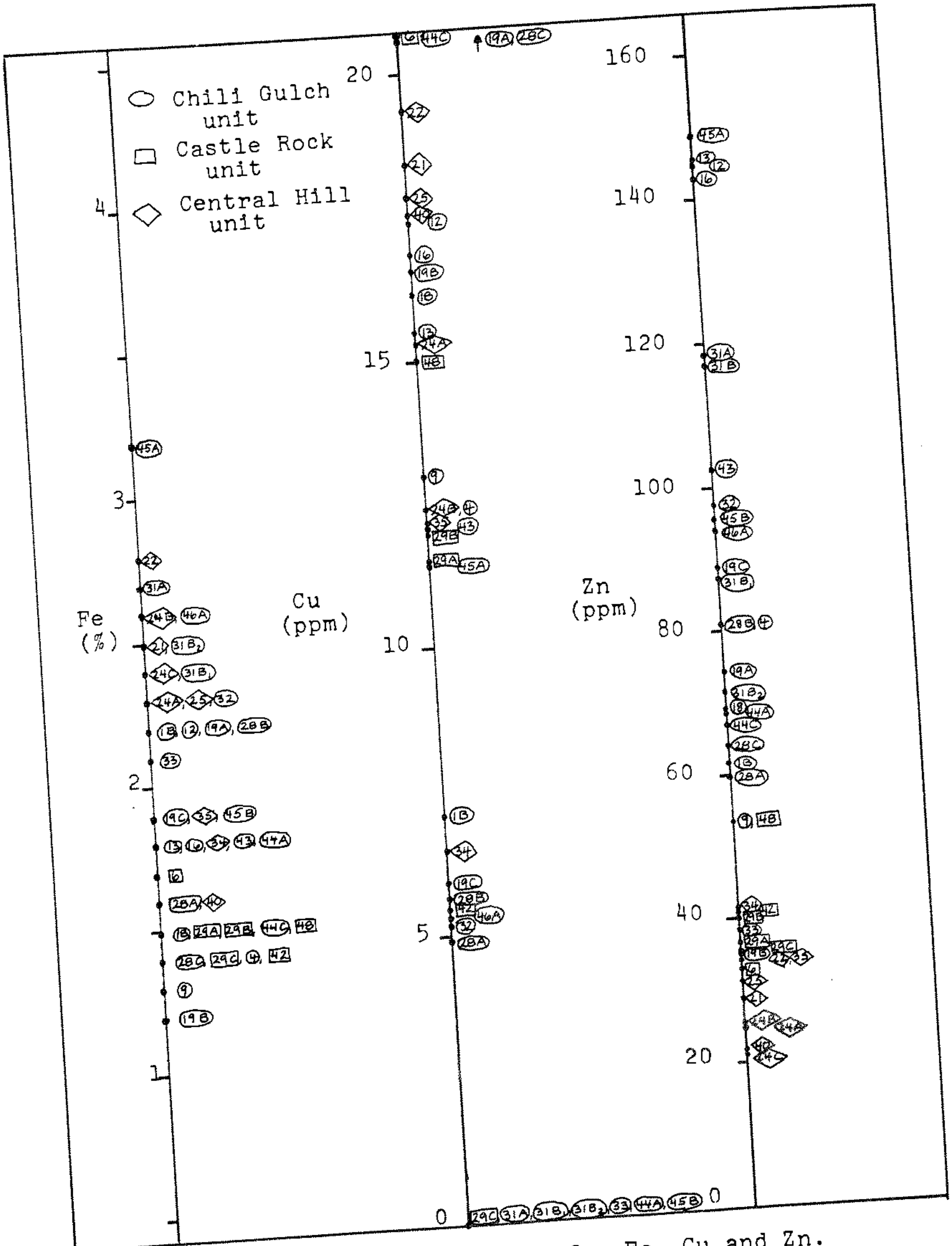


Figure 24. Single-element plots for Fe, Cu and Zn. Numbers refer to sample locations.

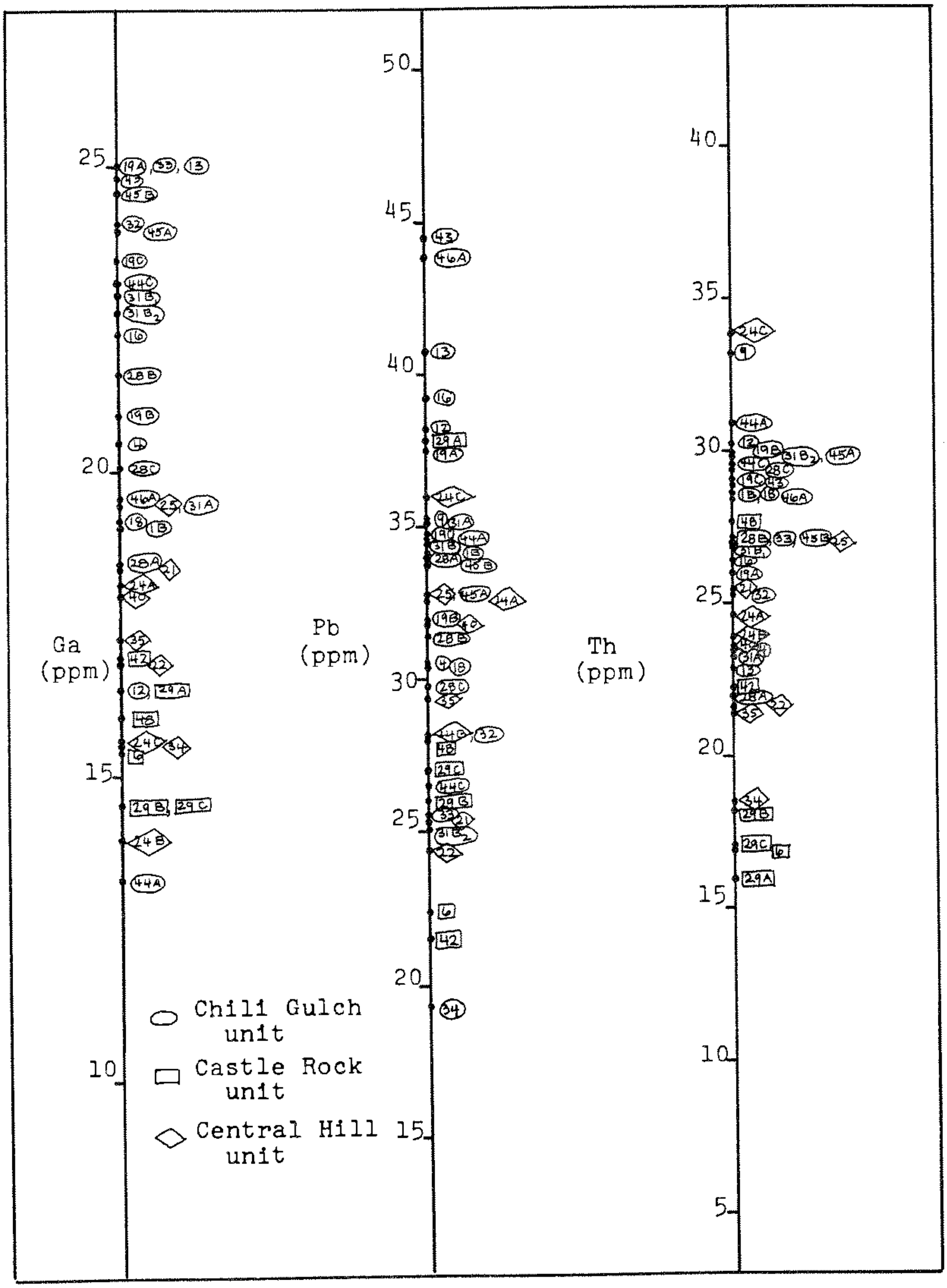


Figure 25. Single-element plots for Ga, Pb and Th. Numbers refer to sample locations.

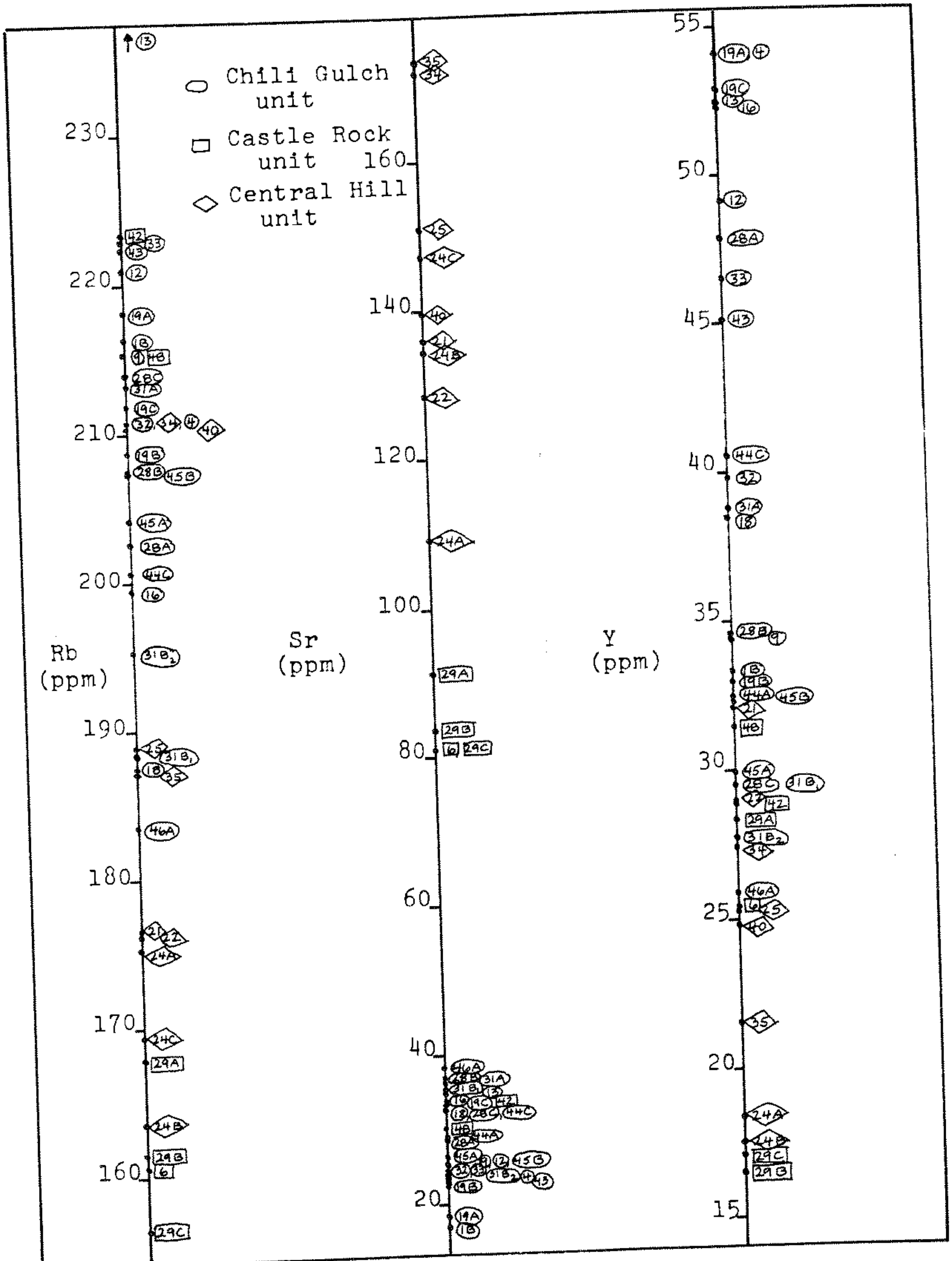


Figure 26. Single-element plots for Rb, Sr and Y. Numbers refer to sample locations.

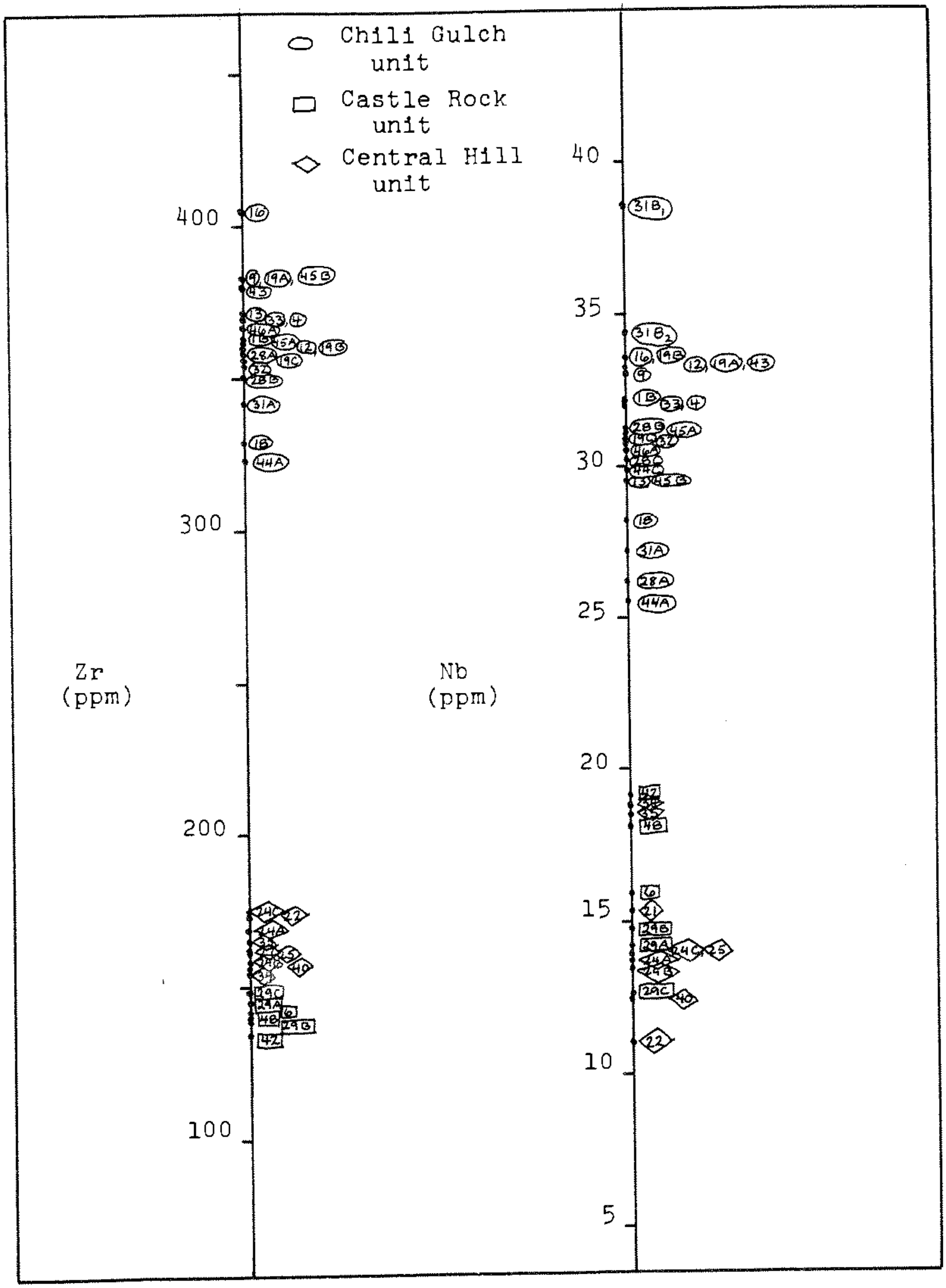


Figure 27. Single-element plots for Zr and Nb. Numbers refer to sample locations.

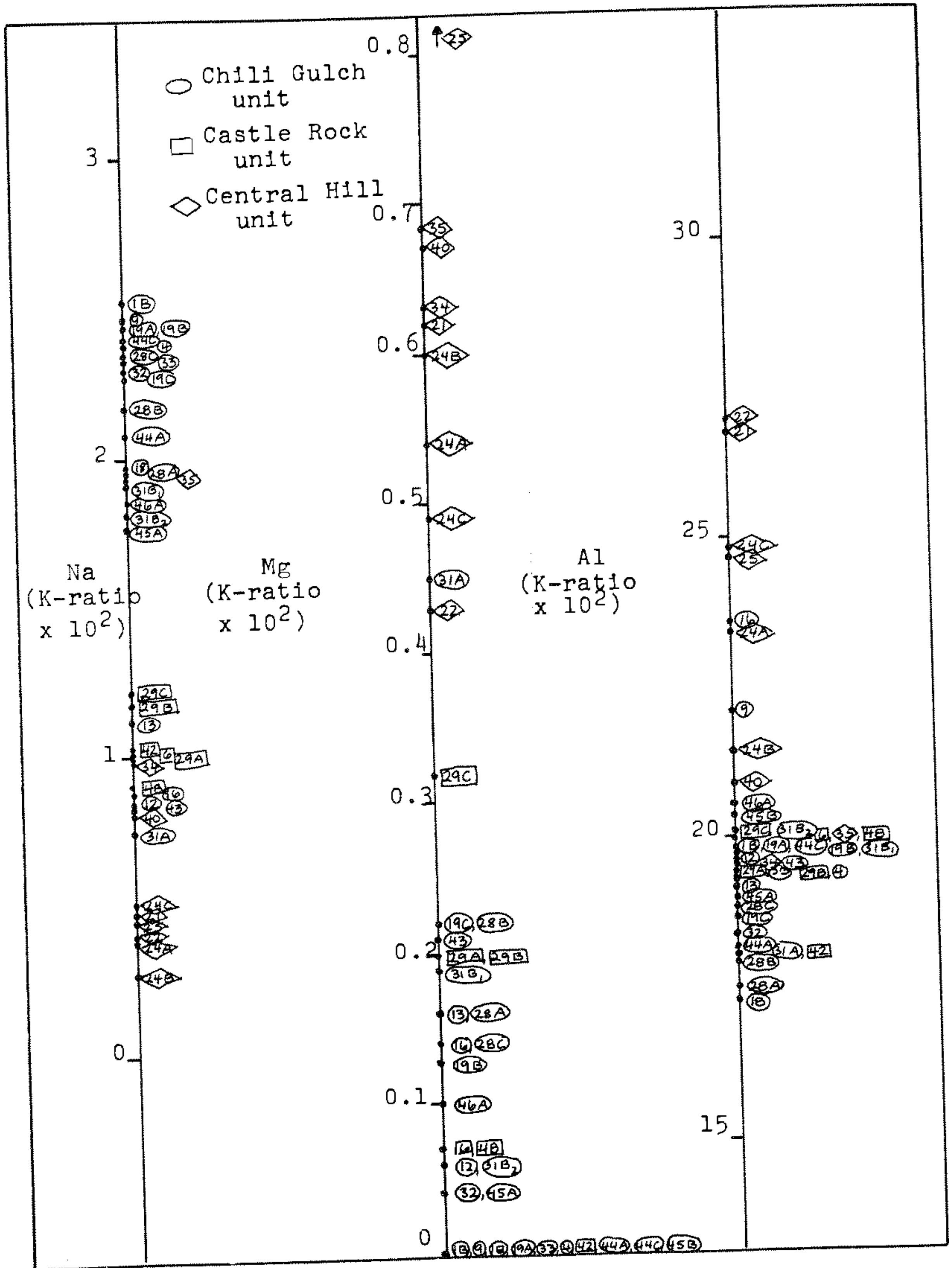


Figure 28. Single-element plots for Na, Mg and Al. Relative abundances only. Numbers refer to sample locations.

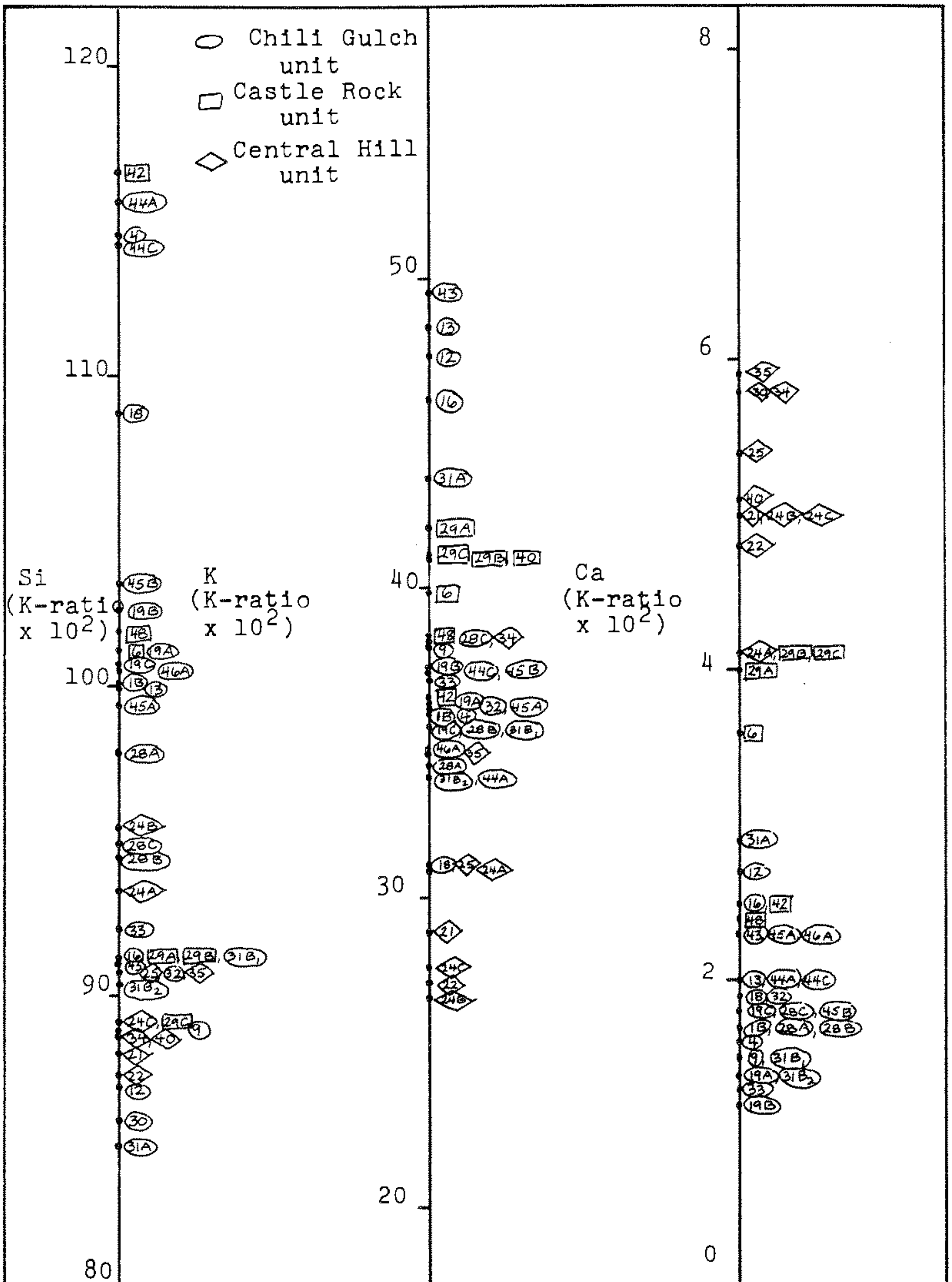


Figure 29. Single-element plots for Si, K and Ca. Relative abundances only. Numbers refer to sample locations.

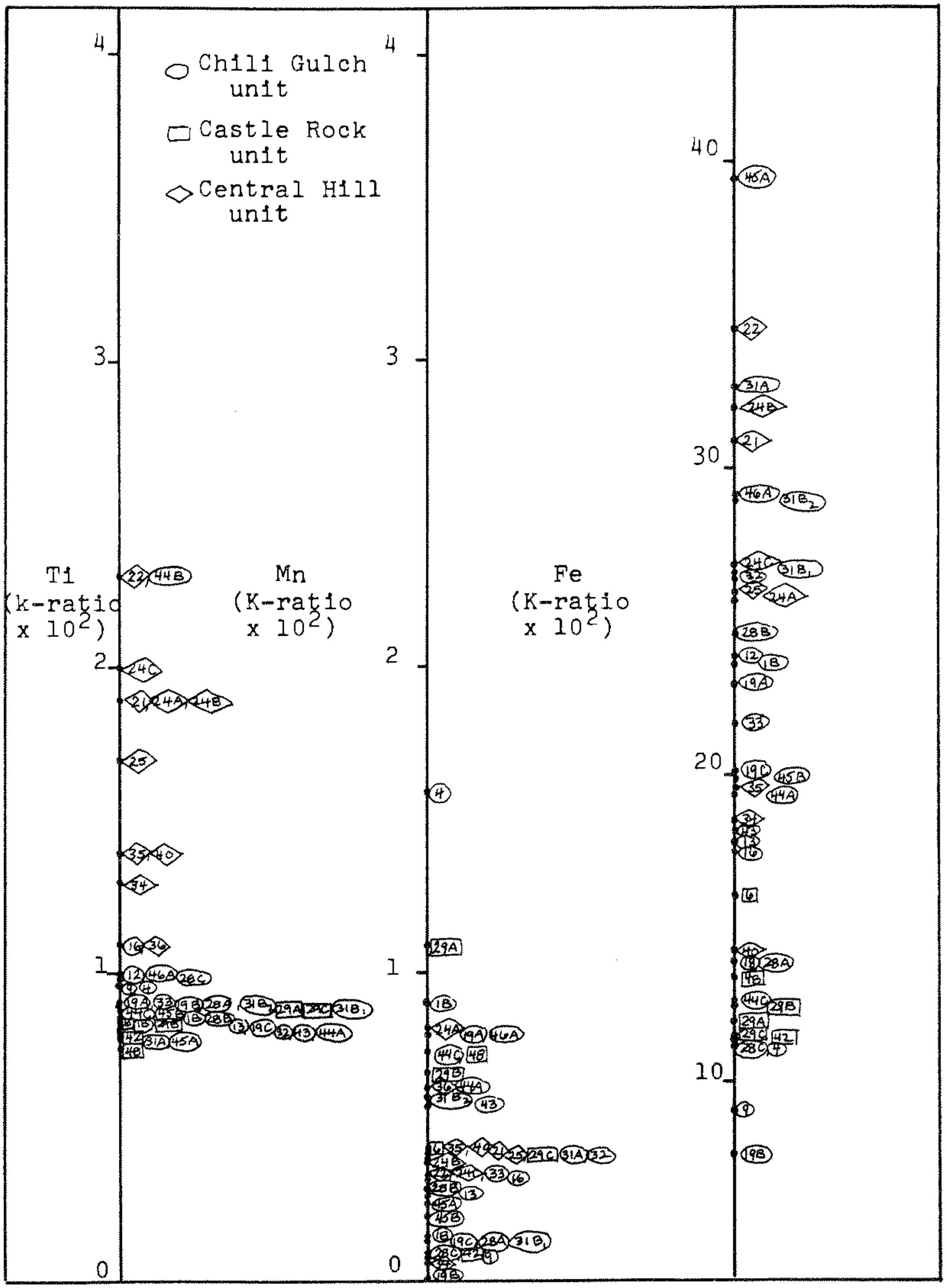


Figure 30. Single-element plots for Ti, Mn and Fe. Relative abundances only. Numbers refer to sample locations.

this example, the Chili Gulch unit is most closely associated with the Central Hill unit.

Some of the single-element plots give important insights into chemical variation within a single flow unit, even though they might not be important in differentiating between two units. Element concentrations for samples 42 and 48 are often extreme values within the characteristic range for the Castle Rock tuff unit. The location of these two samples is on Buena Vista Peak, about ten miles west of the general vicinity of the other samples in the Castle Rock sample group. It may be that the element concentration distinctions of these two samples are due to lateral differentiation or sorting of crystal or other components, in the process of eruption and emplacement of this flow unit. Scatter within distinct units may also be induced by external means of contamination, such as by detrital components.

The diagram (Figure 31) in which Zr was plotted against Sr is very useful in differentiating tuff units within the Valley Springs Formation. This plot of data is more definitive than the ternary diagram of Rb:Sr:Zr (Figure 32). Since the ternary diagram deals with proportions of the elements in the samples, there is a greater chance of overlap of unassociated units. However, the absolute concentrations used in the Zr-Sr diagram result in a more defined grouping of the distinct ash flow

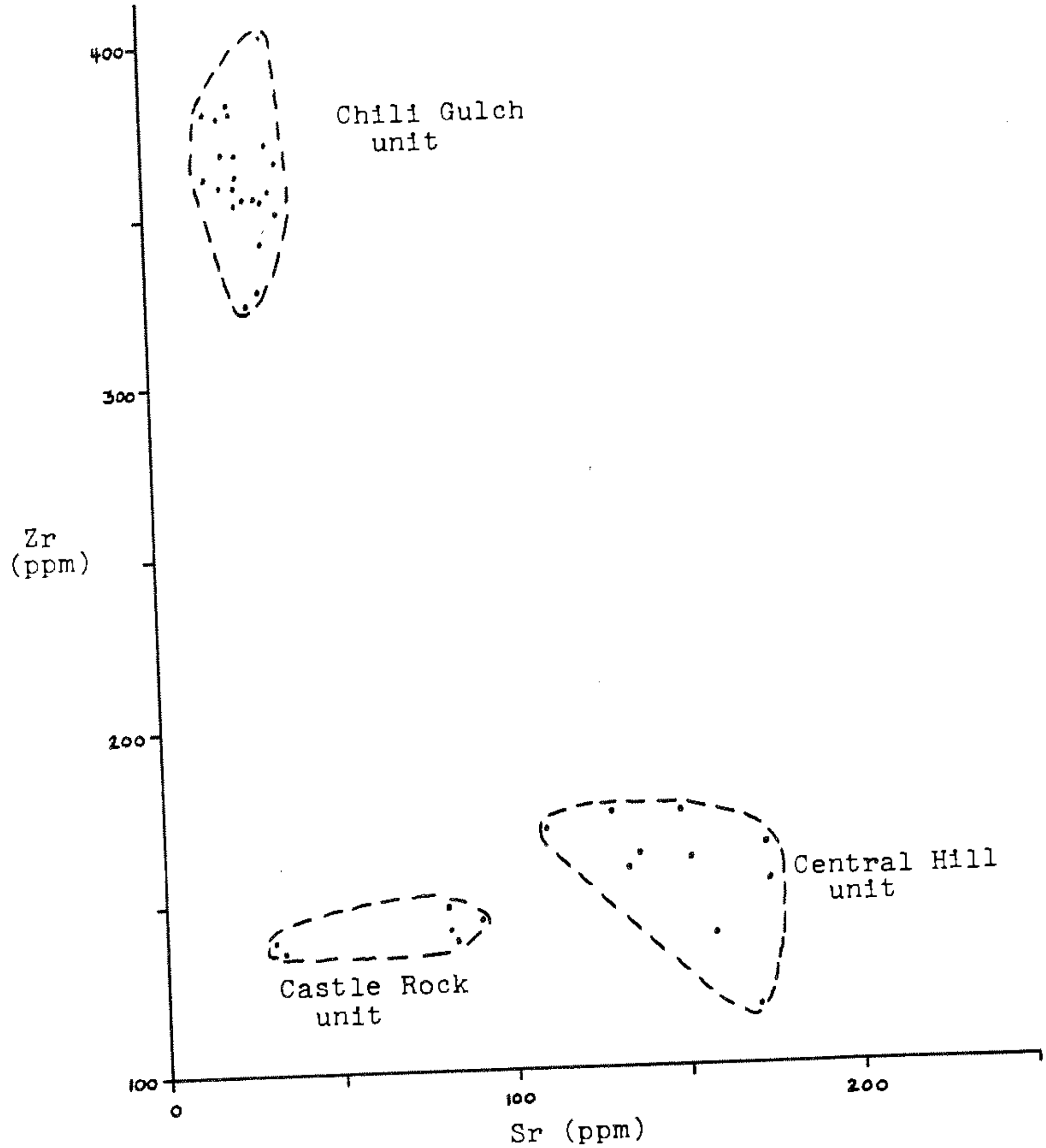


Figure 31. Zr-Sr Diagram.

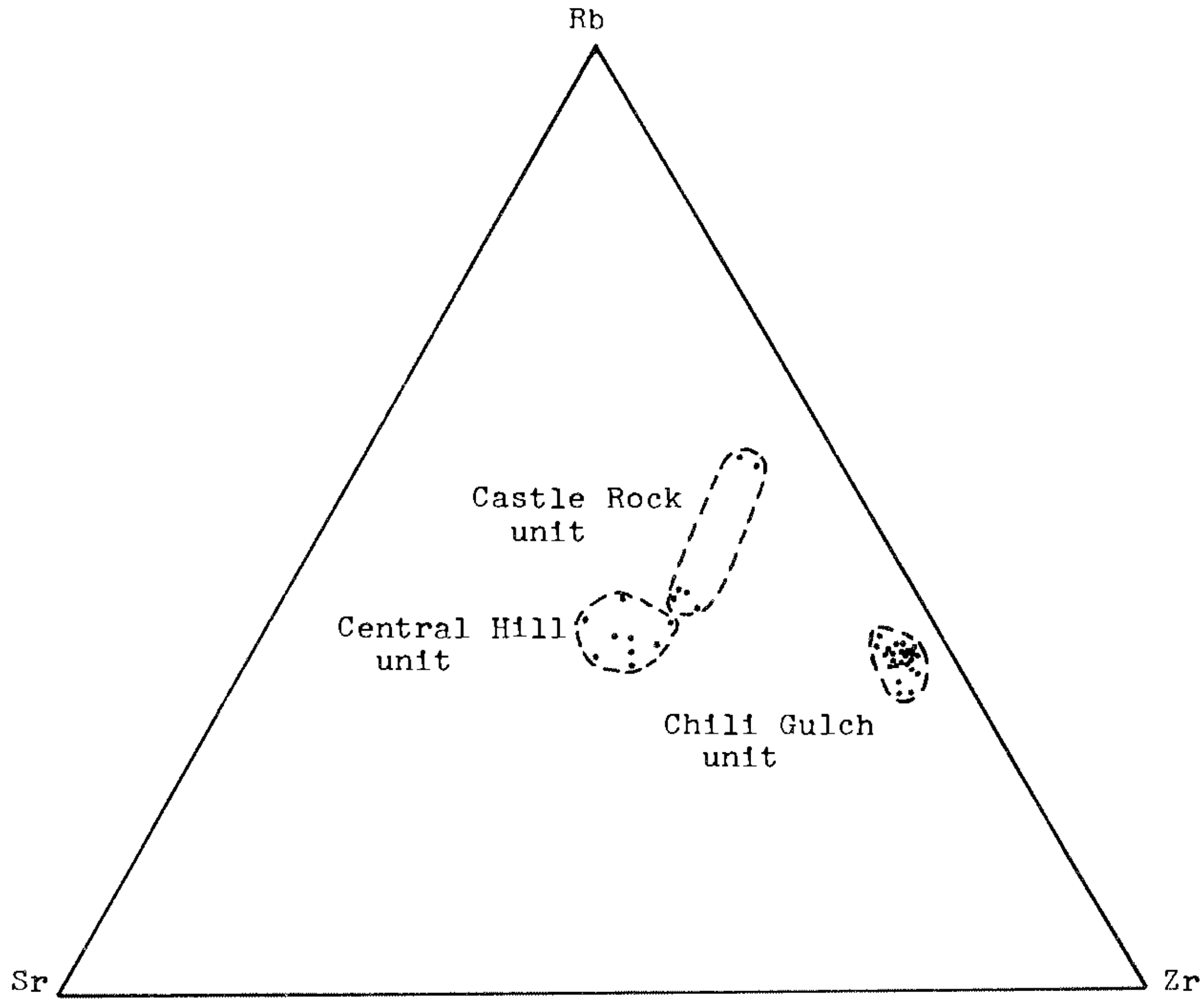


Figure 32. Rb:Sr:Zr Diagram.

units. In both Figures 31 and 32, the samples belonging to the Chili Gulch tuff unit are clearly differentiated from the other samples. The Zr-Sr diagram and Rb:Sr:Zr ternary diagram show the closest similarity between samples of the Chili Gulch unit and those of the Central Hill unit.

CLUSTER ANALYSIS AND CORRELATION

The concentration data representing selected diagnostic elements for all tuff samples were analyzed by means of analytical methods, as well as through graphic methods described earlier. The elements Zn, Na, Mg, Sr, Zr, and Nb were chosen for this purpose since they are elements that distinguish one or more of the proposed correlative tuff groups, in preliminary analyses of petrographic and field data. A computer program was used to calculate similarity coefficients from the chemical data and to compare the data by means of an unweighted-pair average cluster analysis (Sarna-Wojcicki, 1976). In this procedure, successive samples are quantitatively compared and grouped according to degree of chemical similarity. In the dendrogram illustrating the results of this cluster analysis technique, samples that are most similar are linked together at the highest values of the distance function (Figure 33).

The advantage of this method of data analysis is that many samples and variables can be compared simultaneously and presented in a two-dimensional diagram. The choice of the elements to be used in the cluster analysis is somewhat subjective, and affects the results of the clustering process. The variability between the samples

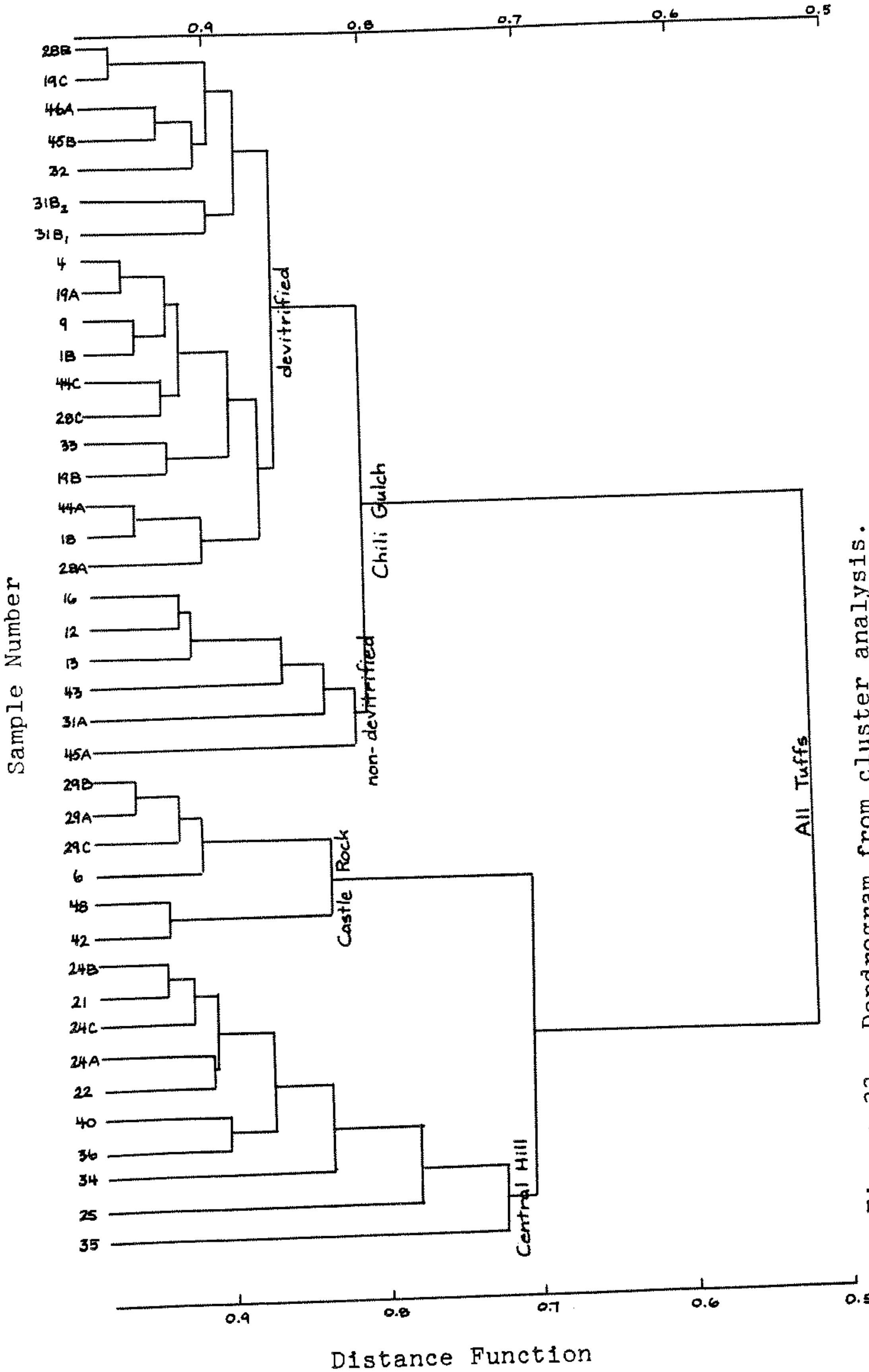


Figure 33. Dendrogram from cluster analysis.

included in a cluster analysis will also have an effect on the outcome of the grouping, since it is affected by the chemical composition of each sample included in the analysis.

In Figure 33, the most similar samples are joined together at the highest values of the distance function. In this representation, samples from the Chili Gulch tuff unit are clearly differentiated from the other samples. Within the Chili Gulch group there exists a sub-group which includes all the samples of this unit which did not show any evidence of devitrification, both in petrographic studies and X-ray diffraction analyses. Samples from the Castle Rock tuff unit are seen to be most similar to samples from the Central Hill tuff unit. However, a distinction can be seen on the dendrogram and is supported by petrographic and chemical data.

By means of the differentiation, chemical and age correlation procedures, three distinct ash flow units were recognized within the volcanic and sedimentary strata. This interpretation is based on a synthesis of all field and laboratory data discussed in this study. Lithologic character, petrography, element content, and the computer-run cluster analysis of chemical similarity among samples were all instrumental in differentiating the ash flow units. One method alone would not provide sufficient evidence to arrive at an interpretation of any reliability.

GEOLOGICAL OBSERVATIONS

The "ash-flow problem" has been summarized by Smith (1960a) and discussed by others in the recent surge of interest regarding pyroclastic deposits. Facets of this problem include recognition and definition of units, as well as interpretation of the mode of emplacement of the deposits. Nomenclature alone has often presented more issues than it has resolved. The writer's use of the term "ash flow" follows the definition by Smith (1960a), in which the term reflects the mode of origin of the deposits. An ash flow deposit is one which results from the passage of a nuee ardente. The deposit contains at least 50 weight percent of ash or fine ash-sized glass shards and crystals, with pumice fragment inclusions. According to the Wentworth and Williams scale, ash is 1-1/4 mm, and fine ash is less than 1/4 mm in diameter. Ignimbrite is a term synonymous with this definition.

Based on data resulting from this study, the writer has chosen to define the three distinct units, seen in the field and differentiated on the basis of chemical and petrographic analyses, as ash flows. Furthermore, the Chili Gulch unit and the Castle Rock unit may be referred to as ash flow tuffs, denoting rocks of compacted volcanic fragments, commonly smaller than ash-sized. The descriptions may be enhanced by referring to the Chili Gulch unit as a densely welded ash flow tuff and the Castle Rock unit as a moderately welded ash flow tuff. The adjective "welded" is used to describe the cohesion or agglutination of fragments within tuffaceous rocks, resulting from having been hot and viscous at the time of emplacement (Smith, 1960a). The writer recognizes some ambiguity in describing the Central Hill unit. Since the unit contains zones of coarse angular components (clasts of similar composition as other parts of the ash flow unit), perhaps the most accurate way to define the Central Hill unit would be to describe it as a partly welded ash flow tuff-breccia. The coarse, clastic texture found locally within the unit may be the result of auto-brecciation of the flow upon emplacement, perhaps aided by minor reworking of the deposits.

The following features are cited by the writer as evidence for emplacement of the pyroclastic units by a flow mechanism:

1. flow of glass shards around phenocrysts and pumice fragments
2. general lack of sorting within a single flow unit
3. inclusion of surface debris in basal sections of a flow unit
4. preferred alignment of glass shards, pumice fragments and crystal components
5. stretched pumice fragments with elongated vesicles

6. concentrations of pumice fragments (and biotite crystals in Central Hill unit)

7. essentially level upper surfaces of units

8. confinement of deposits to topographic lows (drainage channels) of depositional surface.

Not all the lines of evidence are apparent in each of the three ash flows. The Chili Gulch ash flow unit has the most extensive list of features supporting emplacement by flow.

Other features of the ash flow units indicate that heat was retained for long periods of time in the process of emplacement. The existence of welding, as well as devitrification and vapor-phase crystallization, suggest this. Welding and crystallization seem improbable in air-fall deposits, because entrapped heat is relatively low (Smith, 1960a). Prominent jointing in parts of the three ash flow exposures, especially the columnar jointing exhibited in the Castle Rock and Chili Gulch units, also suggests that the deposits cooled in place.

Gale, Piper et al. (1939) stated that very little of the pyroclastic deposits of the Valley Springs Formation are composed of original material. Based on this study, the writer suggests that this is not the case. The three ash flow units recognized, appear to be composed of original pyroclastic flow materials emplaced when extremely hot, and in the most part, they have not been affected by significant post-depositional reworking. Less consolidated basal zones of the flows may show some effects of interaction with the depositional surface. Also, the upper surfaces may have been modified by subsequent channeling and post-depositional erosion. These events do not appear to have been significant in the main emplacement process. The auto-brecciation mechanism suggested to be the probable mode of emplacement for portions of the Central Hill unit, may allow for some degree of "reworking." This process is not distinct from the main depositional event. There appears to be no convincing evidence that water was a significant transport medium in the emplacement of the three major ash flow units within the Valley Springs Formation.

The ash flows of the Valley Springs Formation represent rhyolitic volcanism occurring within the time period of accumulation of the sedimentary cut-and-fill channel assemblage. Little can be said about the source of the pyroclastic materials making up the Valley Springs ash flow sequence. Correlation of units outside of the study area and determination of source vents was beyond the scope of this study. Proposed correlations have included deposits as far away as the basin and range province to the east of the Sierra Nevada. A survey of rhyolitic vents in the Sierra Nevada complex may suggest potential sources of the pyroclastic materials in the Valley Springs Formation and correlative deposits. The occurrence of tuffaceous sediments in other strata of the Valley Springs Formation indicates incorporation of pyroclastic components of similar composition to the ash flows of this study. These secondary deposits probably are derived both locally from erosion of the ash flows within the Valley Springs Formation, and also from other rhyolitic source areas further to the east, in the Sierra Nevada.

CONCLUDING REMARKS

The value of ash flow studies has been realized during the past two decades, with increasing attention being given to these rocks. Ash flow chronology has proven invaluable in approaching problems in the fields of geology, paleontology and archaeology (Sarna-Wojcicki, 1976; Everndern et al., 1964; Leakey, 1976).

Three ash flow units in the Miocene Valley Springs Formation, exposed to the west of the Sierra Nevada batholith, have been identified in this study. Procedures used in this study include field observations and sampling, petrographic study, X-ray diffraction analysis, radiometric dating, X-ray fluorescence element concentration analysis, and computer data reduction. All methods were instrumental in providing a reliable differentiation of the ash flow units. A statistical analysis of both qualitative and quantitative data provided the basis for the interpretations presented in this study.

The unaltered state of the ash flows is an asset in differentiating them with respect to their original state. This characteristic will also be helpful in correlations outside the study area. There seem to exist no obstacles, in this regard, to establishing a more extensive ash chronology based on the ash flows of the Valley

Springs Formation and correlative strata.

The results of this study suggest some insight into the ash flow problem. Several lines of evidence were cited to support a flow mechanism of emplacement for the three major pyroclastic units of the Valley Springs Formation.

Even though it was beyond the scope of this study, detailed inspection of the lateral variations and distribution of the ash flow units could provide information regarding the source area of the rhyolitic pyroclastic deposits. Further analysis of the available element concentration data may also lead to speculations regarding the origin of the rhyolitic magmas and provide a better understanding of the differentiation processes involved in the eruption of the ash flow assemblage.

APPENDIX A

K-Ar Dates and Analytical Data, Valley Springs Formation

KA#	Sample #	Material dated	Sample wt. (gms.)	%K	^{40}Ar rad. $X10^{-11}$ (moles/gm.)	% ^{40}Ar atmos.	Age x 10^6 (years)
3619	1030-48 (Castle Rock unit)	Sanidine	1.643	8.65	33.8	7.1	22.4 ± 0.1
3622	1030-35 (Central Hill unit)	Biotite	0.867	6.71	26.9	40.6	23.0 ± 0.2

APPENDIX B

Sample Localities and Brief Description of Sampled Units

1030-1B. Rhyolite tuff: Chili Gulch unit, Valley Springs Fm.; Mokelumne Hill quadrangle, Sec. 1, T.5N.,R.12E; top of outcrop in roadcut, nw corner of Highway 49 and Highway 26. Welded, devitrified; sanidine, quartz, plagioclase, minor biotite, minor compressed pumice fragments.

1034-4. Rhyolite tuff: Chili Gulch unit, Valley Springs Fm.; Mokelumne Hill quadrangle, Sec. 26, T.5N.,R.11E.; ne corner of Sec. 26 in gravel quarry. Welded, devitrified; sanidine, quartz, plagioclase, minor biotite, minor compressed pumice fragments.

1030-6. Rhyolite tuff: Castle Rock unit, Valley Springs Fm.; San Andreas quadrangle, Sec. 2, T.4N.,R.11E.; near top of Chili Hill. Moderately welded, non-devitrified; sanidine, albite, quartz, minor fine-grained biotite, pumice fragments, minor detrital volcanic rock fragments.

1030-9. Rhyolite tuff: Chili Gulch unit, Valley Springs Fm.; Valley Springs quadrangle, Sec. 8, T.4N.,R.11E., 2,000 ft. west of Youngs Creek, central part of Sec. 8. Welded, devitrified; sanidine, quartz, plagioclase, biotite, minor pumice fragments.

1030-12. Rhyolite tuff: Chili Gulch unit, Valley Springs Fm.; Mokelumne Hill quadrangle, Sec. 19, T.5N.,R.12E., in creek bed, west of mined face. Non-welded, non-devitrified; sanidine, quartz, plagioclase, biotite, abundant pumice fragments.

1030-13. Rhyolite tuff: Chili Gulch unit, Valley Springs Fm.; Mokelumne Hill quadrangle, Sec. 19, T.5N.,R12E., at base of mined face. Densely welded, non-devitrified, sanidine, quartz, plagioclase, minor biotite, pumice fragments, black glassy fragments.

1030-16. Rhyolite tuff: Chili Gulch unit, Valley Springs Fm.; Mokelumne Hill quadrangle, Sec. 19, T.5N.,R12E., south of mined space, near spring. Welded, non-devitrified; sanidine, quartz, plagioclase, biotite, pumice fragments.

1030-18. Rhyolite tuff: Chili Gulch unit, Valley Springs Fm.; Mokelumne Hill quadrangle, Sec. 19, T.5N,R.12E., just south of mined face. Welded, devitrified; sanidine, quartz, plagioclase, biotite, pumice fragments.

1030-19A. Rhyolite tuff: Chili Gulch unit, Valley Springs Fm.; Mokelumne Hill quadrangle, Sec. 19, T.5N.,R.12E., top of mined face. Moderately welded, devitrified; vapor-phase crystallization; sanidine, quartz, plagioclase, minor biotite, compressed pumice fragments.

1030-19B. Rhyolite tuff: Chili Gulch unit, Valley Springs Fm.; Mokelumne Hill quadrangle, Sec. 19, T.5N., R.12E., approximately 40 feet below top of mined face. Densely welded, devitrified; vapor-phase crystallization; sanidine, quartz, plagioclase, minor biotite, compressed pumice fragments.

1030-19C. Rhyolite tuff: Chili Gulch unit, Valley Springs Fm.; Mokelumne Hill quadrangle, Sec. 19, T.5N.,R.12E., approximately 100 feet below top of mined face. Densely welded, devitrified; sanidine, quartz, plagioclase, minor biotite, compressed pumice fragments.

1030-21. Rhyolite tuff-breccia: Central Hill unit, Valley Springs Fm.; Mokelumne Hill quadrangle, Sec. 24, T.5N.,R11E., approximately 1,000 feet south of McSorley Ranch. Poorly welded, non-devitrified; brecciated; abundant biotite, sanidine, albite, quartz, abundant pumice fragments.

1030-22. Rhyolite tuff-breccia: Central Hill unit, Valley Springs Fm.; Mokelumne Hill quadrangle, Sec. 24, T.5N., R.11E., approximately 1,000 feet south of McSorley Ranch. Poorly welded, non-devitrified; brecciated; abundant biotite, sanidine, albite, quartz, abundant pumice fragments.

1030-24A. Rhyolite tuff-breccia: Central Hill unit, Valley Springs Fm.; Mokelumne Hill quadrangle, Sec. 24, T.5N.,R.11E., approximately 1,250 feet south of McSorley Ranch, top of outcrop. Poorly welded, non-devitrified; blocky jointing; abundant biotite, sanidine, albite, quartz, pumice fragments.

1030-24B. Rhyolite tuff-breccia: Central Hill unit, Valley Springs Fm.; Mokelumne Hill quadrangle, Sec. 24, T.5N.,R.11E., approximately 1,250 south of McSorley Ranch, approximately five feet below top of outcrop. Poorly welded, non-devitrified, blocky jointing, abundant biotite, sanidine, albite, quartz, pumice fragments.

1030-24C. Rhyolite tuff-breccia: Central Hill unit, Valley Springs Fm.; Mokelumne Hill quadrangle, Sec. 24, T.5N.,R.11E., approximately 1,250 south of McSorley Ranch, approximately 11 feet below top of outcrop, at base of outcrop. Poorly welded, non-devitrified; abundant biotite, sanidine, albite, quartz, pumice fragments.

1030-25. Rhyolite tuff-breccia: Central Hill unit, Valley Springs Fm.; Mokelumne Hill quadrangle, Sec. 24, T.5N.,R.11E., approximately 1,250 feet south of McSorley Ranch. Poorly welded, non-devitrified; abundant biotite, sanidine, albite, quartz, pumice fragments.

1030-28A. Rhyolite tuff: Chili Gulch unit, Valley Springs Fm.; Mokelumne Hill quadrangle, Sec. 24, T.5N.,R.11E., approximately 3,500 feet west of McSorley Ranch, at top of outcrop. Densely welded, devitrified; sanidine, quartz, plagioclase, minor biotite, compressed pumice fragments.

1030-28B. Rhyolite tuff: Chili Gulch unit, Valley Springs Fm.; Mokelumne Hill quadrangle, Sec. 24, T.5N.,R.11E., approximately 3,500 feet west of McSorley Ranch, approximately eight feet below top of outcrops. Densely welded, devitrified; sanidine, quartz, plagioclase, minor biotite, compressed pumice fragments.

1030-28C. Rhyolite tuff: Chili Gulch unit, Valley Springs Fm.; Mokelumne Hill quadrangle, Sec. 24, T.5N.,R.11E., approximately 3,500 feet west of McSorley Ranch, approximately ten feet below top of outcrop, at base of outcrop. Densely welded, devitrified; sanidine, quartz, plagioclase, minor biotite, compressed pumice fragments.

1030-29A. Rhyolite tuff. Castle Rock unit, Valley Springs Fm., Sec. 24, T.5N.,R.11E., approximately 3,250 feet west of McSorley Ranch, at top of outcrop. Welded, non-devitrified; sanidine, albite, quartz, minor biotite, pumice fragments.

1030-29B. Rhyolite tuff: Castle Rock unit, Valley Springs Fm., Sec. 24, T.5N.,R.11E., approximately 3,250 feet west of McSorley Ranch, approximately 20 feet below top of outcrop. Welded, non-devitrified; sanidine, albite, quartz, minor biotite, pumice fragments.

1030-29C. Rhyolite tuff: Castle Rock unit, Valley Springs Fm., Sec. 24, T.5N.,R.11E., appprox-imately 3,250 feet west of McSorley Ranch, approximately 30 feet below top of outcrop. Welded, non-devitrified; sanidine, albite, quartz, minor biotite, pumice fragments.

1030-31A. Rhyolite tuff: Chili Gulch unit, Valley Springs Fm.; Sec. 18, T.5N.,R.12E., at northwest end of Lombardi Gulch. Moderately welded, non-devitrified; sanidine, quartz, plagioclase, biotite, pumice fragments.

1030-31B. Rhyolite tuff: Chili Gulch unit, Valley Springs Fm.; Sec. 18, T.5N.,R.12E., at northwest end of Lombardi Gulch. Densely welded, devitrified; sanidine, quartz, plagioclase, biotite, pumice fragments.

1030-32. Rhyolite tuff: Chili Gulch unit, Valley Springs Fm., Sec. 18, T.5N.,R.12E., at northwest end of Lombardi Gulch. Densely welded, devitrified; sanidine, quartz, plagioclase, biotite, pumice fragments.

1030-33. Rhyolite tuff: Chili Gulch unit, Valley Springs Fm., Sec. 18, T.5N.,R.12E., at northwest end of Lombardi Gulch. Welded, devitrified; sanidine, quartz, plagioclase, biotite, pumice fragments.

1030-34. Rhyolite tuff-breccia: Central Hill unit, Valley Springs Fm., Sec. 14, T.4N.,R.10E., top of Valley Springs Peak. Poorly welded, non-devitrified; brecciated; abundant biotite, sanidine, albite, quartz, pumice fragments.

1030-35. (KA 3622) Rhyolite tuff-breccia: Central Hill unit, Valley Springs Fm., Sec. 14, T.4N.,R.10E., top of Valley Springs Peak, approximately 1,180 feet elevation. Poorly welded, non-devitrified; brecciated; abundant biotite, sanidine, albite, quartz, pumice fragments. 23.0 $\pm$ 0.2 m.y.

1030-36. Rhyolite tuff-breccia: Central Hill unit, Valley Springs Fm., Sec. 14, T.4N.,R.10E., top of Valley Springs Peak. Poorly welded, non-devitrified; brecciated; abundant biotite, sanidine, albite, quartz, pumice fragments.

1030-40. Rhyolite tuff-breccia: Central Hill unit, Valley Springs Fm., Sec. 2, T.4N.,R.11E., approximately 1,000 feet east of Chili Hill. Poorly welded, non-devitrified; abundant biotite, sanidine, albite, quartz, pumice fragments, detrital rock fragments.

1030-42. Rhyolite tuff: Castle Rock unit, Valley Springs Fm.; Ione quadrangle, Sec. 19, T.5N.,R.10E.; top of south Buena Vista Peak. Moderately welded, incipient devitrification in some pumice fragments; sanidine, albite, quartz, biotite, pumice fragments.

1030-43. Rhyolite tuff: Chili Gulch unit, Valley Springs Fm.; San Andreas quadrangle, Sec. 2, T.4N.,R.11E.; top of Chili Hill. Densely welded, non-devitrified; sanidine, quartz, plagioclase, minor biotite, minor compressed pumice fragments.

1030-45A. Rhyolite tuff: Chili Gulch unit, Valley Springs Fm.; San Andreas quadrangle, Sec. 2, T.4N.,R.11E.; top of Chili Hill, top of outcrop. Densely welded, non-devitrified; sanidine, quartz, plagioclase, minor biotite, minor compressed pumice fragments.

1030-45B. Rhyolite tuff: Chili Gulch unit, Valley Springs Fm.; San Andreas quadrangle, Sec. 2, T.4N.,R.11E.; top of Chili Hill, approximately five feet below top of outcrop. Densely welded, devitrified; sanidine, quartz, plagioclase, minor biotite, minor compressed pumice fragments.

1030-46A. Rhyolite tuff: Chili Gulch unit, Valley Springs Fm.; Mokelumne Hill quadrangle, Sec. 13, T.5N.,R.11E.; southwest flank of Stockton Hill. Densely welded, devitrified; sanidine, quartz, plagioclase, minor biotite, compressed pumice fragments.

1030-48. (KA 3619) Rhyolite tuff: Castle Rock unit, Valley Springs Fm.; Ione quadrangle, Sec. 19, T.5N.,R.10E.; north flank of south Buena Vista Peak, approximately 710 feet elevation. Moderately welded, incipient devitrification in some pumice fragments; sanidine, albite, quartz, biotite, pumice fragments. 22.4 $\pm$ 0.1 m.y.

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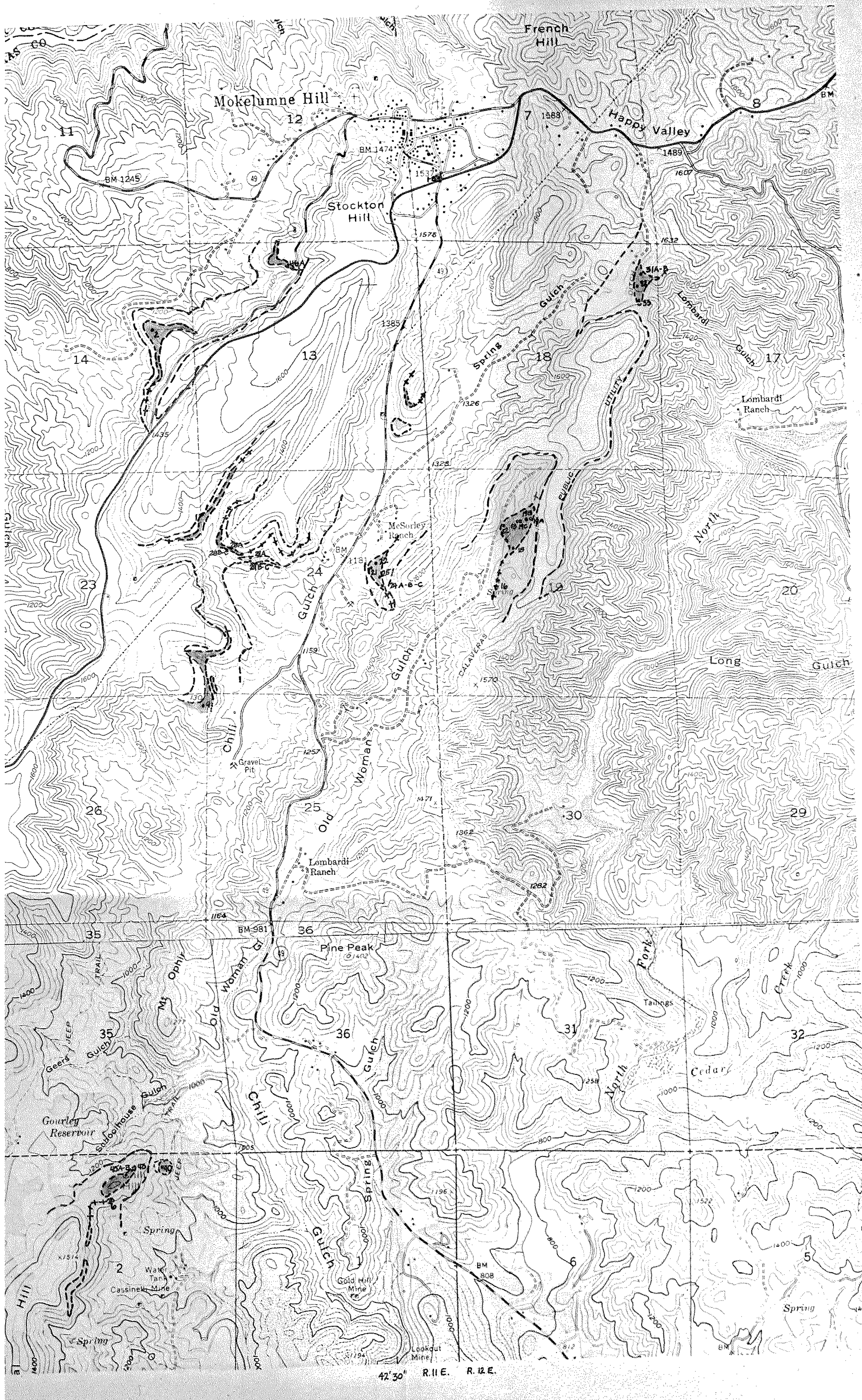


French Hill
Mokelumne Hill
Happy Valley
Stockton Hill
Spring Gulch
Lombardi Gulch
Lombardi Ranch
Public Utility
Calaveras
McSorley Ranch
North Long Gulch
Chili Gulch
Gravel Pit
Old Woman Gulch
Lombardi Ranch
Pine Peak
Mt Ophir
Old Woman Gl
Geers Gulch
Schoolhouse Gulch
Gourley Reservoir
North Fork Cedar Creek
Tailings
Spring Gulch
Spring
Water Tank
Cassinelli Mine
Gold Hill Mine
Lookout Mine
Hill
42'30"
R. 11 E.
R. 12 E.

PLATE I

SAMPLE LOCATION MAP

VALLEY SPRINGS FORMATION:

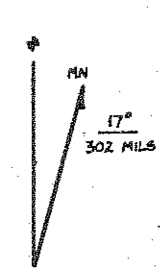
CHILI GULCH TUFF UNIT

CASTLE ROCK TUFF UNIT

CENTRAL HILL TUFF UNIT

TUFFACEOUS SEDIMENTS

NUMBERS ON MAP REFER TO SAMPLE LOCATIONS



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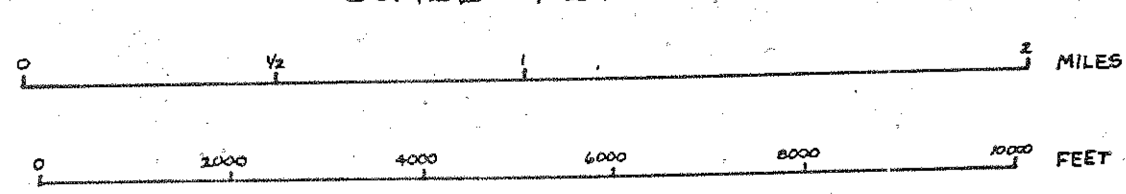

CONTOUR INTERVAL 40 FEET

DATUM IS MEAN SEA LEVEL