STRATIGRAPHY OF TERTIARY VOLCANIC ROCKS IN EASTERN NEVADA

By Earl F. Cook[1]

ABSTRACT

Most of the volcanic rocks of eastern Nevada are ignimbrites: nonsorted sheet-like pyroclastic deposits of probable nuée ardente origin. Overlapping ignimbrites, studied in an area of about 20,000 square miles, include individual units traceable more than 100 miles linearly; some of these units had an original extent of 5,000 to 10,000 square miles or more. Several measured sections exceed 2,000 feet in thickness and include more than a dozen ignimbrites. At least one unit attains 1,000 feet in thickness, but the average thickness is about 200 feet.

Lateral lithologic variation in many of the Nevada ignimbrites is small, whereas the variety among units is great; hence individual ignimbrites may be recognized in widely separated sections. Correlation criteria used include: the ratio between lithic, crystal, and vitric components; identifiable minerals and their proportions; vertical variations in, and overall degree of welding within, units; and the presence and nature of planar and discoidal structures.

Field relations indicate that the upper surface of each ignimbrite was horizontal when deposited, and that the evenness of such surfaces has been modified only by differential compaction over irregular terrain, by subsequent erosion, or by deformation. The extent of each ignimbrite depended largely if not entirely on the basin or depression in which it formed.

The more extensive, consequently the more stratigraphically useful, of the eastern Nevada ignimbrites, are named and described herein. They probably appeared within the middle third of the Tertiary period; thus they represent a relatively brief segment of geologic time. But they document, by their stratigraphic and structural relations, some of the major events in the tectonic history of the region.

The Tertiary volcanic sequence rests on sedimentary rocks ranging in age from Cambrian to Eocene. In many of the eastern Nevada sections the volcanic units are essentially parallel to the underlying sedimentary rocks, although the hiatus represented by the contact in some cases spans most of the Paleozoic and all of the Mesozoic.

The Tertiary volcanic rocks generally decrease in age toward the south and southeast; the stratigraphic relations suggest progressive subsidence from central toward southern Nevada. Although isopach maps of these rock units seem to reflect some contemporaneous linear fracturing, the trends do not parallel present basins and ranges: modern basin-range topography originated after the extrusion of the widespread ignimbrites.

INTRODUCTION

In mapping the Iron Springs district of southwest Utah, J. H. Mackin (Mackin and Nelson, 1950; Mackin, 1952) discovered that the volcanic rocks of the district are mainly ignimbrites, and that these extensive and distinctive rock units lend themselves to stratigraphic interpretation in the manner of sedimentary strata.

---

[1] Executive Secretary, Division of Earth Sciences, National Academy of Sciences -- National Research Council, Washington, D. C.

The Iron Springs district thus became the logical area from which to try to extend the known volcanic stratigraphy westward into Nevada where similar rocks were known, or northward toward the Marysvale district, Utah, where the volcanic sequence had been worked out by Callaghan (1939). However, except for relatively minor projections of the volcanic stratigraphy of the Iron Springs district, northward by Threet and southward by me (Mackin, Cook, and Threet, 1954; Cook, 1957a, 1957b), the regional possibilities of such work went untested until the Gulf Refining Company in 1955 decided to sponsor a study of the volcanic rocks of the eastern Great Basin. Following an initial reconnaissance of the region by Mackin, during which he demonstrated the regional extent of several ignimbrites by field correlation criteria, I began to work out the stratigraphy of the Tertiary volcanic rocks in eastern Nevada.

Since the start of the project, I have examined 84 volcanic sections (see pl. 1) and measured 68 of them, and have collected approximately 1,300 specimens, from which about 800 ground slabs for binocular study and 100 thin sections have been made. The measured sections represent an area of about 25,000 square miles in eastern Nevada and southwest Utah. This area is only the central portion of an arcuate ignimbrite province (see fig. 1) of 60,000 square miles which reaches from the west margin of the Colorado Plateau to western Nevada (Cook, 1960a).

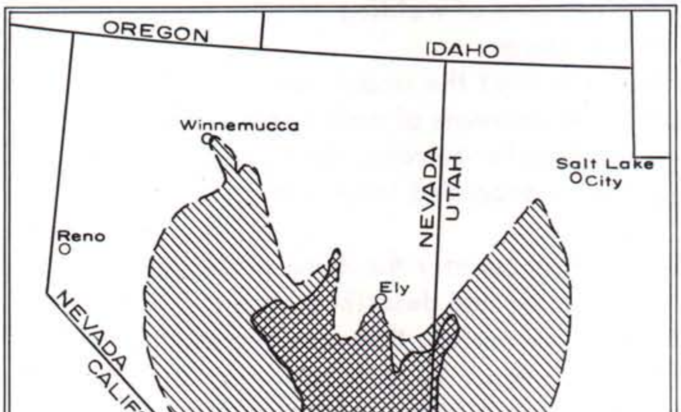


FIGURE 1. Sketch map showing relation of area covered in this report to other known areas of Tertiary ignimbrites.

In eastern Nevada outside the area studied, the Tertiary volcanic rocks are either flow rocks unsuitable for stratigraphic study, or ignimbrites (in extreme northeastern Nevada and in extreme southern Nevada) that seem to belong to different provinces. The same ignimbrites, or some of them, extend westward from the area considered in this report, as determined by Ralph Roberts and others in the Battle Mountain and Antler Peak, Nevada, areas (Toiyabe quartz latite); by Charles Vitaliano in the Gabbs, Austin, and Tonopah areas; and by others in the vicinity of Virginia City, Silver Peak, Beatty, and the A. E. C. Nevada Test Site.

Gulf sponsored the field work during the summers of 1955 and 1956. A grant from the Geological Society of America allowed one month of field work in 1957. Gulf, the Geological Society, and the University of Idaho financed the laboratory work, which was carried out at the University of Washington and the University of Idaho.

Progress on this project was materially aided by fruitful suggestions and the clarification of concepts that came out of discussions and correspondence with Paul Williams and Roger Martin (both of whom worked with me in the field), as well as Felix Chayes, R. L. Christiansen, J. H. Mackin, R. L. Smith, C. M. Tschanz, and C. J. Vitaliano. Paul Williams, Stuart Hill, and William Page made the petrographic analyses on which the histograms are based. The paper profited greatly from the constructive criticism of Mackin and Martin.

ROCK AND ROCK UNIT NAMES USED IN THIS REPORT

Most of the volcanic rock units of eastern Nevada are ignimbrites, that is, sheetlike deposits of relatively nonsorted and nonstratified pyroclastic material. Used in this way, ignimbrite is a rock-unit term, and is not equivalent to welded tuff. An ignimbrite is a mappable rock unit, more or less equivalent to the "ash-flow cooling unit" of Smith (1960b, p. 157), except that an ignimbrite may be made up of material that is not tuff, and was only in part ash during emplacement. Most of the eastern Nevada ignimbrites are largely welded tuff, but some of them are made up chiefly or entirely of nonwelded tuff, and at least one consists of tuffbreccia.

As Marwick (1946) pointed out, Marshall's (1932, p. 200) original definition of ignimbrite refers neither to the degree of welding nor to the size of ejecta. Perhaps unfortunately, Marshall's additional definitions (1935, p. 323, p. 360) appear to require such rocks to be acid, tuffaceous, and welded.[2] These statements led logically to the conclusion that ignimbrite equals welded tuff (Cotton, 1952, p. 204; American Geological Institute, 1957, p. 146).

Marshall made no distinction between rock unit and rock type: he used ignimbrite for both, as have many later authors. In the United States, most authors have preferred welded tuff for the same dual purpose, possibly because it is a less genetic term. Belated recognition that welded tuff is an inappropriate name for a rock unit that is partially or even wholly nonwelded has led to a proposal (Cook, 1955, p. 1544; 1957b, p. 197-198; 1960a, p. 134; Mackin, 1960, p. 84-86) that ignimbrite be defined as a rock-unit term, freed of the welding, size-range, and composition restrictions that some have read into Marshall's definitions of 1935. Solving the same problem in a different way, Ross and Smith (1961, p. 3) used ash-flow tuff as "...an inclusive, general term for consolidated ash-flow beds and rocks that may or may not be either completely or partly welded."

Welded tuff and sillar are here used as rock-type terms. Sillar is nonwelded tuff or tuffbreccia of nuée ardente or ash-flow origin (Fenner, 1940, 1948) commonly poorly sorted; the name is used to distinguish such material from waterlaid or airfall tuff, characteristically more or less well sorted.

[2] It should be pointed out that Marshall did describe many nonwelded structures in his ignimbrites and that some of his type ignimbrites are nonwelded.

Fisher's classification (1960, p. 1864-65) of size terms, slightly modified, is used in this paper:

Clast Size	Clast Name	Rock Name (if majority of clasts are in the size range)
over 256 mm	coarse blocks	pyroclastic breccia
64 - 256 mm	fine blocks	
2 - 64 mm	lapilli	lapillistone
1/16 - 2 mm	coarse ash	tuff
less than 1/16mm	dust (or fine ash)	

Tuffbreccia denotes those rocks in which abundant blocks and lapilli lie in a tuffaceous matrix that comprises at least 25 percent of the rock.

Although the Wentworth and Williams (1932) classification of tuffs as vitric, crystal, or lithic - according as most of the particles are glass, crystals, or rock fragments - may

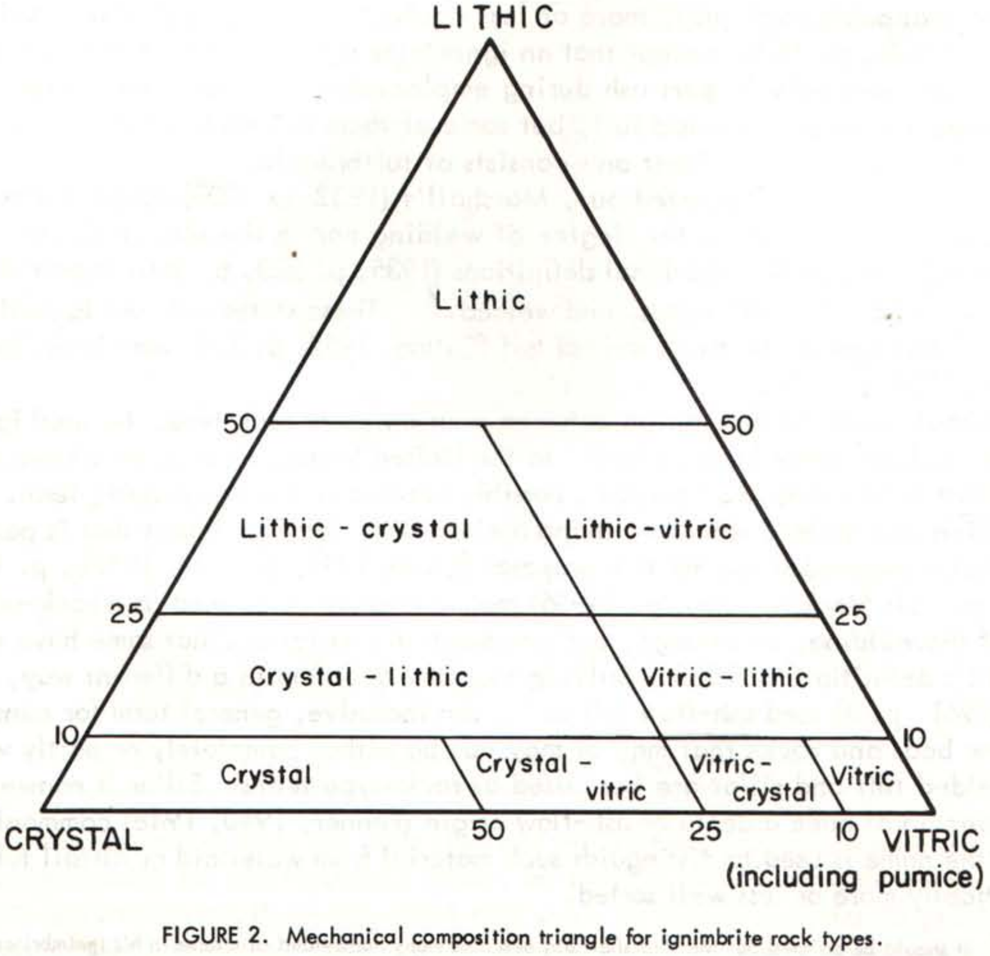


FIGURE 2. Mechanical composition triangle for ignimbrite rock types.

be applied to ignimbrite rocks, a modification of their classification has been found useful. All three elements are important in the constitution of ignimbrites, and it might seem that a classification should give equal weight to each, as the Wentworth and Williams definitions do. In field recognition of ignimbrites, however, accessory and accidental lithic fragments commonly play a greater role than their actual percentage would indicate; for example, there are ignimbrites containing 10 to 15 percent of lithic fragments in which those fragments are a striking and characteristic element. Consequently it is suggested that the lithic component be given greater emphasis than the other two, and that lithic enter the name whenever rock fragments make up more than 10 percent of the rock. Incidentally, it is only possible to apply the "lithic" adjective accurately if the pumice fragments, which may undergo a great change in volume vertically within an ignimbrite, are regarded as vitric rather than lithic.

In addition, because the crystal content of ignimbrites rarely exceeds 50 percent, it is proposed that crystal enter the name at 10 percent and that a rock containing more than 50 percent crystals be called crystal. A triangle illustrating these arbitrary limits is shown in figure 2. This triangle is based upon the composition of Great Basin ignimbrites; a study of published descriptions of ignimbrites from other localities; and a concern for the utility of nomenclature. Probably 90 percent of all ignimbrites will fall below the 10 percent lithic line and to the right of the 50 percent crystal line and will thus be represented by less than 10 percent of the triangle.

CRITERIA FOR IGNIMBRITE CORRELATION

Megascopic Criteria

In many of the Nevada ignimbrites lateral variation in composition and appearance is small, whereas the variety of units is great; hence individual ignimbrites may be recognized in widely separated sections. Correlation criteria include: the ratio between lithic, crystal, and vitric components; identifiable minerals and their proportions; vertical variations in welding as well as overall degree of welding within units; the presence and nature of planar and discoidal structures; color, hardness, and weathering characteristics; and position in the stratigraphic sequence.

Microscopic Criteria

During the winter of 1955-56, Paul Williams (1960) developed a correlation method that quickly proved its usefulness. It consists of identifying on a ground, etched, and cobaltinitrite-stained surface the crystals visible under low power with a binocular microscope, and then plotting in histogram form the relative areas occupied by quartz, sanidine, plagioclase, biotite, and hornblende.

The relative proportions of these crystals tend to remain fairly constant throughout a single ignimbrite, far more constant than degree of welding, color, or pumice content. Variations in phenocryst composition within individual ignimbrites is reflected in the histograms shown in numerical form on the sections in figures 5, 6, and 7. No statistical analysis has been made of the limits of variability within any single ignimbrite, but in most cases it is obvious that the differences in histograms between adjacent ignimbrites

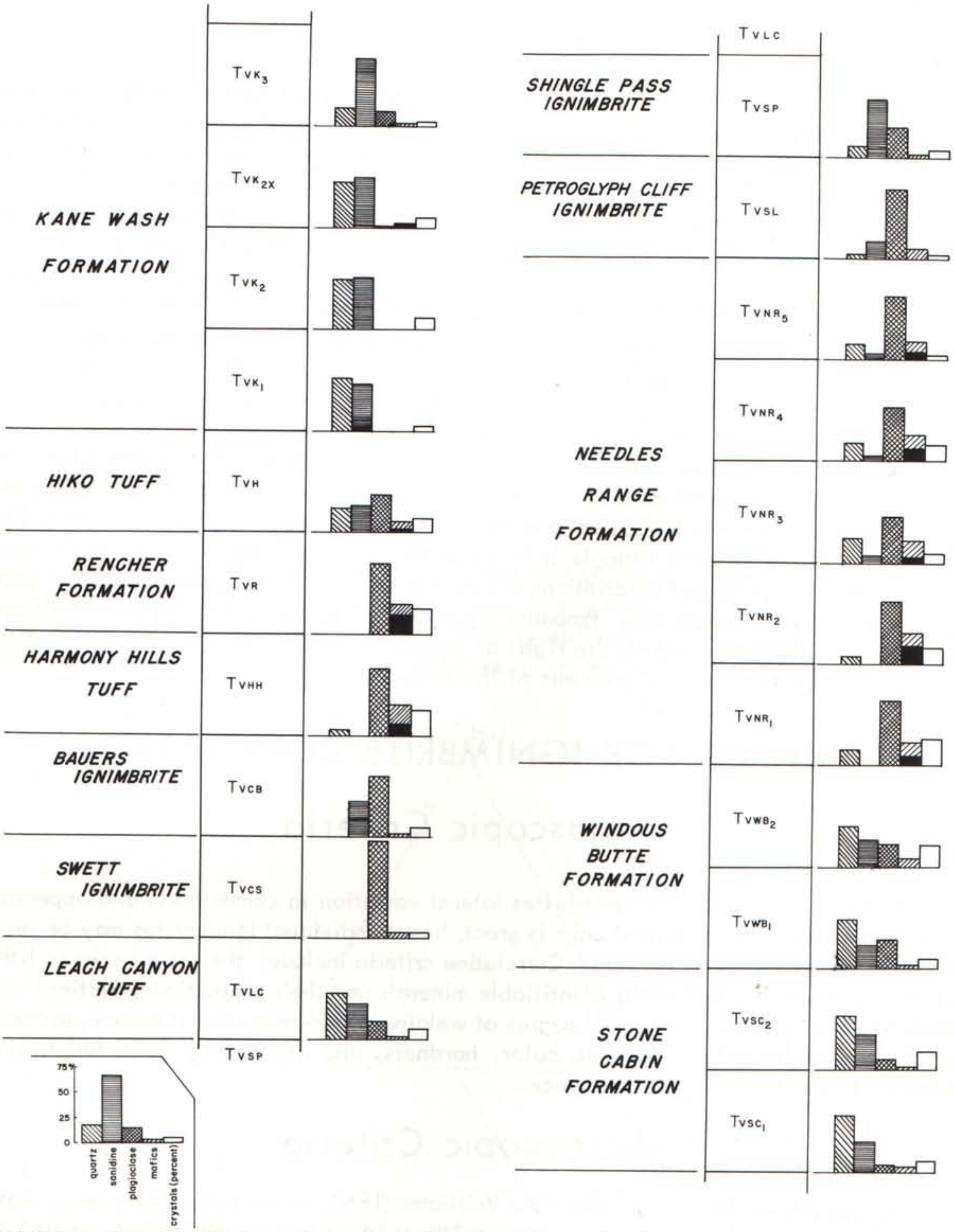


FIGURE 3. Histograms showing mineral composition of named ignimbrite units. The composite thickness of the units represented is about 5,300 feet. All are not present at any one place. Sedimentary and volcanic rock units of local extent are not shown.

Five crystal components of each unit were measured, as shown in the first four columns from the left. The mafic minerals in the fourth column include biotite (cross-hatched), and hornblende (solid black). In each case, the first four columns total 100 percent. Column five indicates the percentage of the rock composed of these crystals, taken collectively. Histograms of Tvwb$_2$ (40/28/23/9//21) and Tvk$_1$ (53/47/0/0//6), expressed in numbers, may be used to gain an idea of the histogram scale.

The percentages of crystals shown in the histograms include only grains large enough for identification by binocular study of stained slices. This percentage may be considerably lower than percentage based on study of thin sections with a petrographic microscope (Williams, 1960, p. 150). Classification of these rocks as crystal, crystal-vitric, and so on (see fig. 2) is not based on the percentages shown in the histograms, but on percentages as determined in thin section, under the petrographic microscope. It should also be emphasized that the phenocryst composition may have little significance in regard to the "chemical" name of the rock (rhyolite, dacite).

is far greater than the range of variability within either ignimbrite. It should be emphasized that the correlations made in this paper were made on lithologic criteria and on similarity in sequence from section to section. The histograms served as independent confirmation of established field correlations. In some areas, however, they provided the key to unraveling stratigraphic and structural relations.

Two specimens with similar histograms may or may not represent the same ignimbrite, but two specimens with widely different mineral proportions may confidently be regarded as representing different ignimbrites. Histograms showing average phenocryst content of all named units, and of some unnamed members of the Needles Range and Kane Wash Formations are given in figure 3.

DESCRIPTION OF NAMED VOLCANIC FORMATIONS

General Remarks

As may be quickly seen from the correlation chart (fig. 4) or any of the three lines of section (figs. 5, 6, 7), only the more extensive of the volcanic units are named and described in this paper.

No regionwide unconformity has been found within the ignimbrite sequence. However, at certain levels unconformities of considerable extent may represent shifts in centers of eruption; pauses in the eruptive activity that allowed local structural adjustments; or deformation that affected part but not all of the region.

Southwest Utah sections used in the correlation chart, in one of the lines of section (fig. 6), and in construction of the distribution and isopach maps, give a more complete picture and a link with the work of Mackin (1960) in that area.

In all the sections in southwest Utah and in several in eastern Nevada, the volcanic sequence rests upon nonvolcanic early Tertiary sedimentary rocks — largely freshwater limestone, siltstone, and conglomerate. Although some of these prevolcanism Tertiary sedimentary rocks have been called Miocene (Tschanz, 1960, p. 204), it now seems clear - if the stratigraphic relations of the volcanic units have been correctly interpreted, and if the few absolute age determinations available (see fig. 4) are correct - that none of them can be younger than Oligocene.

In southwestern Utah, the fluvial and lacustrine beds of the Claron Formation concordantly underlie the ignimbrite sequence, the lowest member of which is a Needles Range ignimbrite (Mackin, 1960, p. 101). In some places, Needles Range tuff is interbedded in the upper part of the Claron. The basal conglomerate of the Claron Formation, which unconformably overlies folded and erosionally truncated Jurassic and Cretaceous formations, spreads eastward as a thinning detrital sheet from Laramide thrust ranges. In most places the Claron consists of a sequence of fresh-water limestones with subordinate calcareous sandstone, limestone pebble conglomerate, and shale above a basal unit of sandstone lenses and quartzite cobble conglomerate. The formation ranges in thickness from 475 to 1,500 feet. Although the lower part of the Claron Formation may be as old as very Late Cretaceous, the upper part in which the tuff of the Needles Range Formation is interbedded is Oligocene, based on an age of 28-29 million years for the Needles Range Formation (Armstrong, 1963, p. 71).

ABSOLUTE AGE*	"GROUP"	UNIT NAMES USED IN THIS REPORT	GRANT, EGAN RANGES	SEAMAN, PAHROCK RANGES; PANACA AREA	HIKO, MEADOW VALLEY RANGES	SOUTHWESTERN UTAH		
						Mackin, 1960	BULL VALLEY *Blank, 1959*	PINE VALLEY MTS *Cook, 1957a*
MIOCENE	D	*KANE WASH FORMATION*			KANE WASH FORMATION		OX VALLEY TUFF	
							COVE MTN. FM.: CEDAR SPGS. M.	
							PILOT CK. BAS.	
		PAGE RANCH FM.: *HIKO TUFF*		PAGE RANCH FM.: HIKO TUFF	PAGE RANCH FM.: HIKO TUFF	PAGE RANCH FM.: KANE POINT TUFF	RACER CANYON TUFF	PAGE RANCH FORMATION
				sillar, sandstone, flows	sillar, sandstone	IRONTOWN MEMBER	WILLOW SPG. M.	
							MAPLE RIDGE POR.	PINE VALLEY LATITE
							SHOAL CK. BRECCIA	
		RENCHER FORMATION		▨	▨	RENCHER FM.	RENCHER FM.	RENCHER FM.
25 MY*	C	*HARMONY HILLS TUFF*		HARMONY HILLS TUFF	HARMONY HILLS TUFF	QUICHAPA FORMATION: HARMONY HILLS TUFF	QUICHAPA FORMATION: HARMONY HILLS TUFF	QUICHAPA GROUP: TV-3
				basalt	▨	▨	LITTLE CREEK BRECCIA	ATCHINSON FORMATION
				sillar				
		CONDOR CANYON FM.: *BAUERS IGNIMBRITE*		CONDOR CANYON FM.: BAUERS IGNIMBRITE	CONDOR CANYON FM.: BAUERS IGNIMBRITE	BAUERS TUFF	BAUERS TUFF	TV-2
				▨	1-3 highly welded ignims.	▨	▨	▨
		SWETT IGNIMBRITE		SWETT IGNIMBRITE	SWETT IGNIMBRITE	SWETT TUFF		
		LEACH CANYON TUFF		LEACH CANYON TUFF	LEACH CANYON TUFF	LEACH CANYON TUFF	LEACH CANYON TUFF	TV-1
OLIGOCENE	B	*PAHROCK Sequence*:	ignimbrites	ignimbrites, flows	PAHROCK sequence (thin ignims., ls., cg.)	ISOM FM.: HOLE-IN-THE-WALL MEMBER BALDHILLS M.	ISOM FM.: HOLE-IN-THE-WALL TUFF BALDHILLS TUFF	CLARON
		SHINGLE PASS IGN.	SHINGLE PASS IGN.	SHINGLE PASS IGN.				
			▨	ignimbrites, flows				
		PETR. CLIFF IGNIM.		PETR. CLIFF IGN.				
				ignims., flows, ls.				
		NEEDLES RANGE FM.:	NEEDLES RANGE FM.: $Tvnr_5$	NEEDLES RANGE FORMATION	▨	NEEDLES RANGE FM.:	CLARON	
			$Tvnr_4$					
			$Tvnr_3$					
28 MY			$Tvnr_2$			MINERSVILLE T.	NEEDLES TUFF	biotite tuff
			$Tvnr_1$			WAH WAH SPGS.T.		
	A	*WINDOUS BUTTE FM.*: *Upper ignimbrite*	WINDOUS BUTTE FM.: Upper ignimbrite	▨		CLARON FORMATION	FORMATION	FORMATION
32 MY		*Lower ignimbrite*	Lower ignimbrite					
			sediments, andes.					
		STONE CABIN FM.: *Upper ignimbrite*	STONE CABIN FM.: Upper ignimbrite					
			seds., flows					
		Lower ignimbrite	Lower ignimbrite					
			sandstone; dacite flows, breccia					
36 MY								
EOCENE		nonvolcanic sedimentary rocks	SHEEP PASS FORMATION	▨	▨			

*Absolute ages from Armstrong, 1963.

FIGURE 4. Correlation chart for the Tertiary volcanic rock units of eastern Nevada and southwestern Utah.

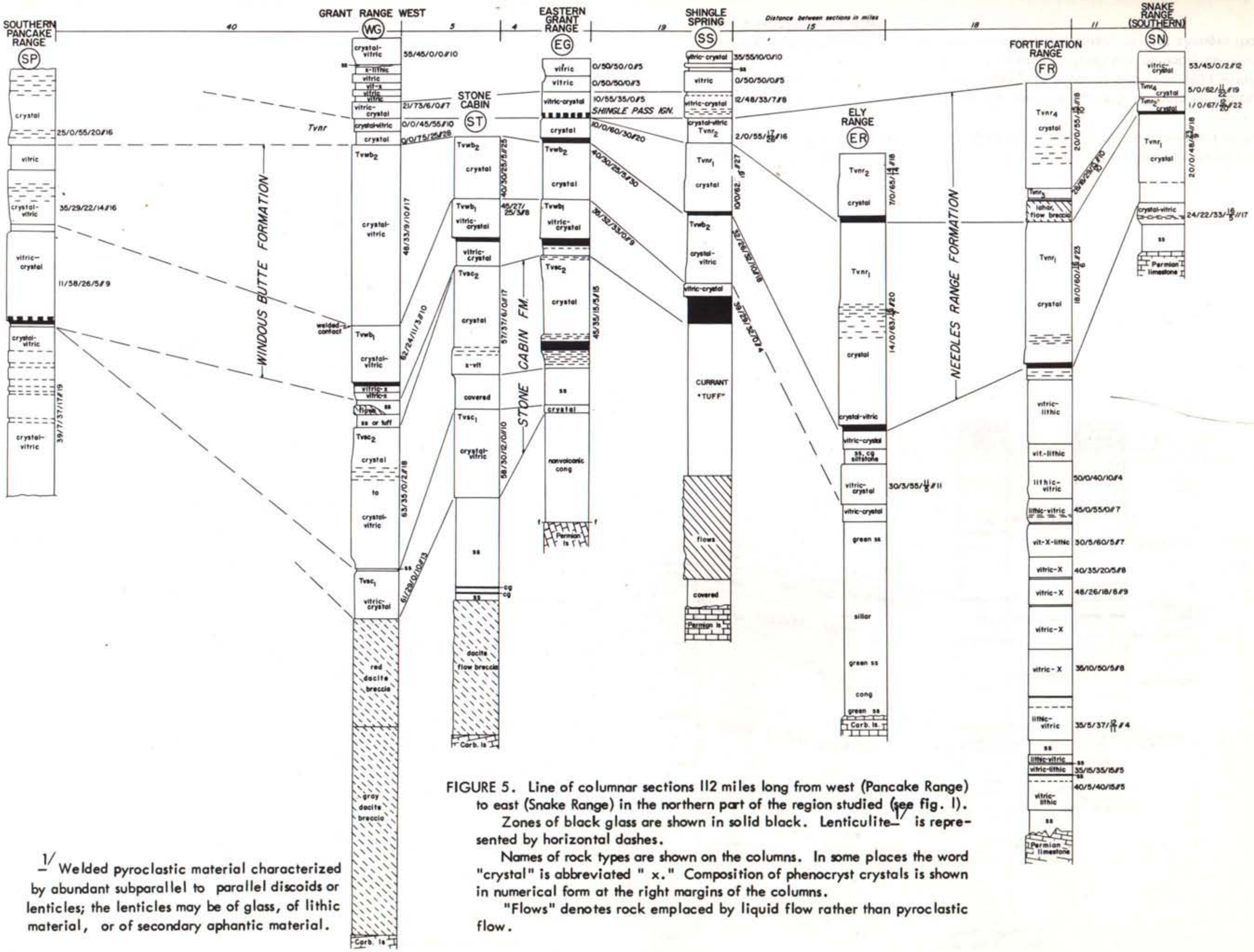


FIGURE 5. Line of columnar sections 112 miles long from west (Pancake Range) to east (Snake Range) in the northern part of the region studied (see fig. 1).

Zones of black glass are shown in solid black. Lenticulite[1] is represented by horizontal dashes.

Names of rock types are shown on the columns. In some places the word "crystal" is abbreviated " x." Composition of phenocryst crystals is shown in numerical form at the right margins of the columns.

"Flows" denotes rock emplaced by liquid flow rather than pyroclastic flow.

[1] Welded pyroclastic material characterized by abundant subparallel to parallel discoids or lenticles; the lenticles may be of glass, of lithic material, or of secondary aphantic material.

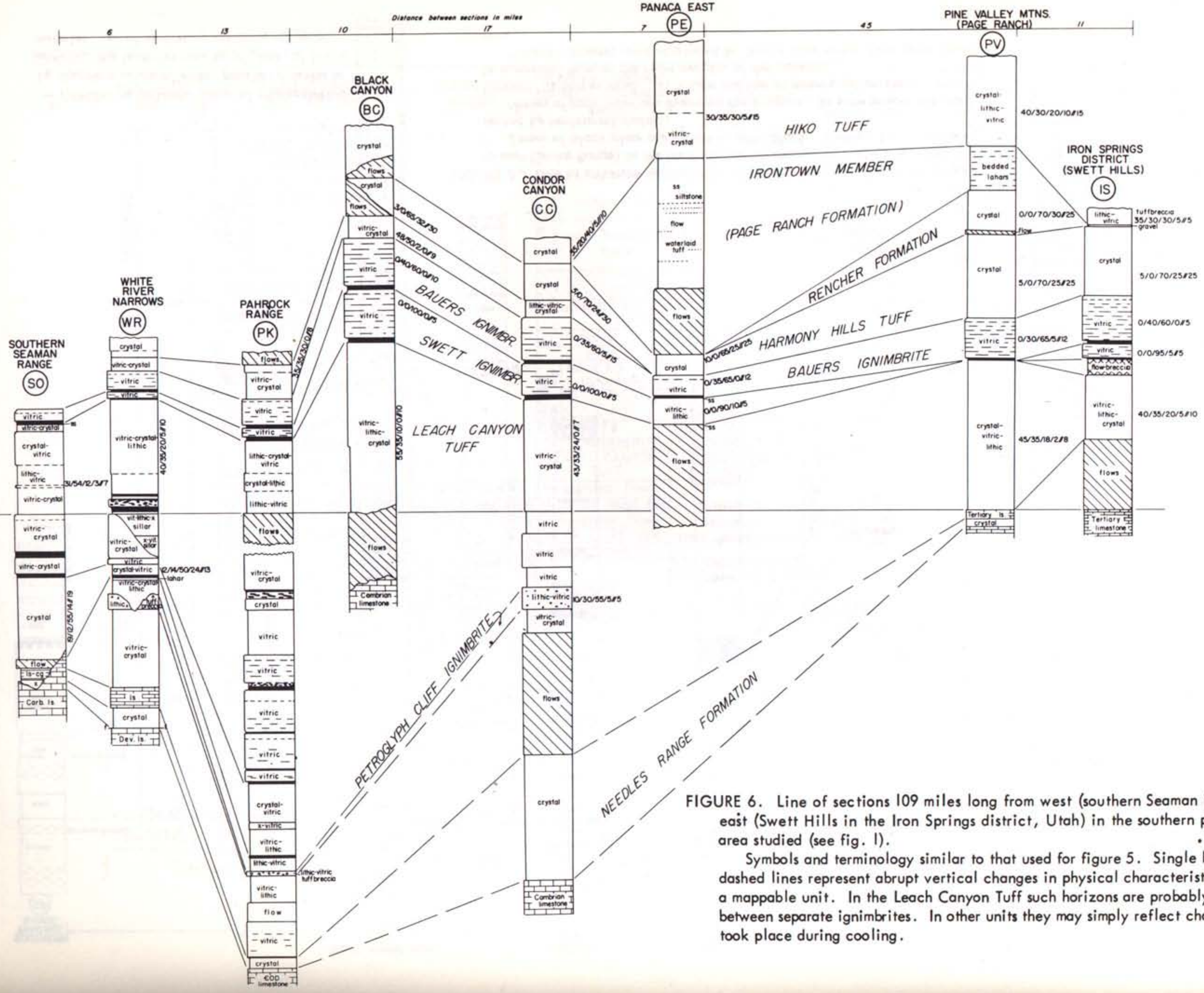


FIGURE 6. Line of sections 109 miles long from west (southern Seaman Range) to east (Swett Hills in the Iron Springs district, Utah) in the southern part of the area studied (see fig. 1).

Symbols and terminology similar to that used for figure 5. Single horizontal dashed lines represent abrupt vertical changes in physical characteristics within a mappable unit. In the Leach Canyon Tuff such horizons are probably contacts between separate ignimbrites. In other units they may simply reflect changes that took place during cooling.

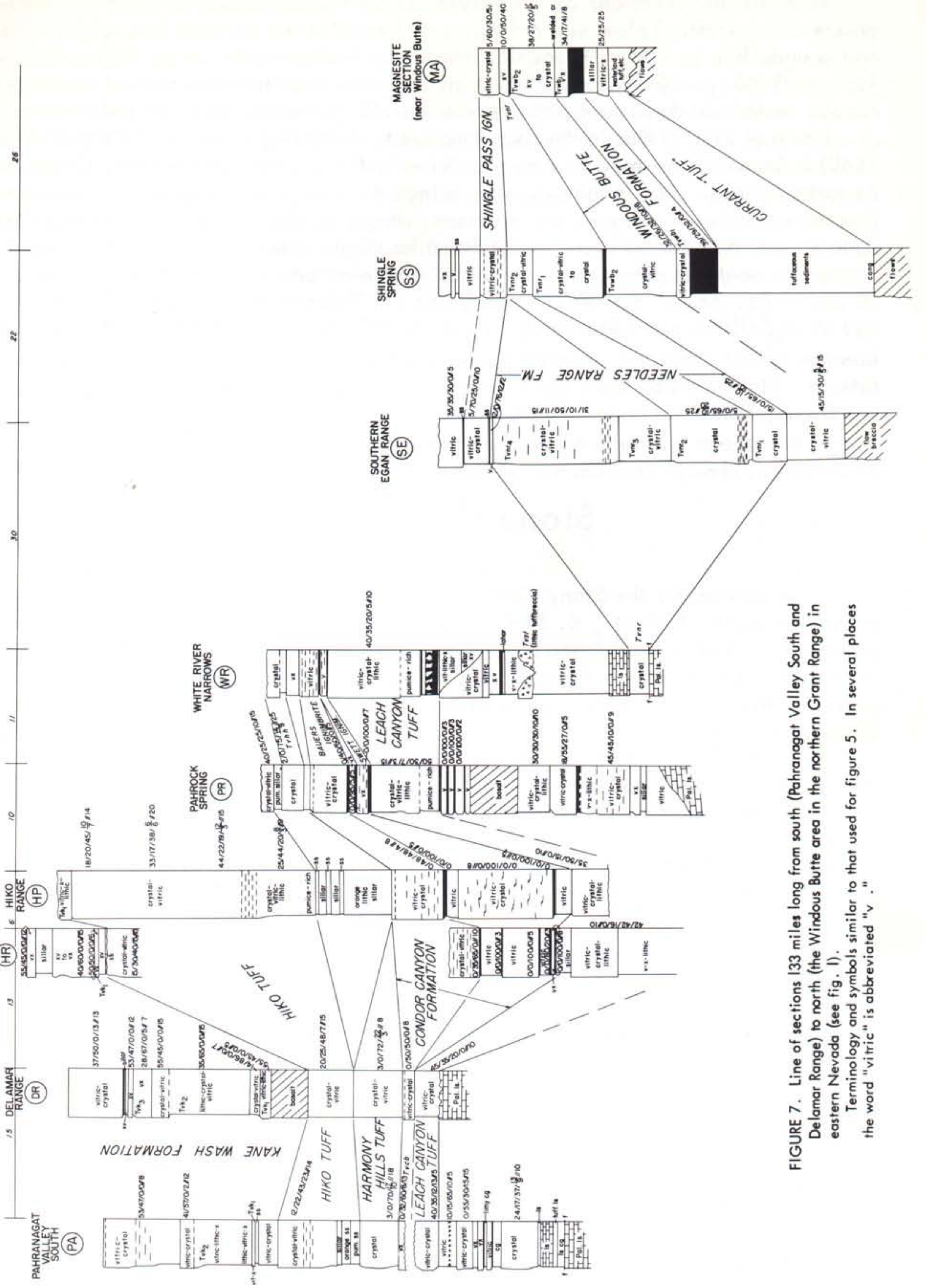


FIGURE 7. Line of sections 133 miles long from south (Pahranagat Valley South and Delamar Range) to north (the Windous Butte area in the northern Grant Range) in eastern Nevada (see fig. 1).

Terminology and symbols similar to that used for figure 5. In several places the word "vitric" is abbreviated "v."

Nonvolcanic limestone conglomerate, as well as tuffaceous lacustrine limestone, occurs concordantly below the ignimbrite sequence in the southern Pahranagat Range, and is underlain by Upper Paleozoic limestone. Farther north, in the Pahrock Range, Tschanz (1960, p. 204) reported lacustrine limestone and well-rounded cobble conglomerate, tentatively dated as of probable Miocene age on the basis of a few pollen species.

North of Shingle Pass in the Egan Range, the Sheep Pass Formation (Winfrey, 1958, 1960) is found at the base of a number of volcanic sections in the Egan, Grant, and Pancake Ranges. The formation, which includes conglomerate-breccia, fresh-water limestone, shale, sandstone, and siltstone, ranges in thickness from 4,000 feet in the Egan Range to about 300 feet in the Pancake Range east of Currant. The Sheep Pass Formation contains nonmarine ostracods, mollusks, and primitive frogs that establish its age as Eocene. A dacite flow overlying the Sheep Pass in the Grant Range has an age of 36^{+3}_{-1} million years (Armstrong, 1963, p. 70). Cretaceous or Early Tertiary sedimentary rocks beneath the volcanic sequence are reported from the White Pine Mountains (Misch, 1960, p. 28); from the Connors Pass area of the Schell Creek Range (Misch and Easton, 1954); and from the northern Schell Creek Range (Young, 1960, p. 163-164).

In the Atlanta district in northeastern Lincoln County, and also in the Monitor Range, flow-banded, chalky, pink-and-white rhyolite appears at the base of the volcanic section.

Stone Cabin Formation

Type section for the Stone Cabin Formation is 8.2 miles southeast of Currant, in sections 5 and 6, T. 9 N., R. 59 E., Nye County, within an east-dipping ignimbrite sequence south of an abandoned cabin constructed of stone blocks (section ST, fig. 5). A dirt road that leads from Currant through the Grant Range to the White River Valley passes by the cabin. Another good exposure of this formation is seen at Grant Range West (section WG, fig. 5).

Known extent of the formation is about 2,500 square miles (fig. 8). The average thickness measured in five sections is 730 feet; the estimated volume is 350 cubic miles.

At the type section two ignimbrites make up the formation, the upper one somewhat less than 690 feet thick, the lower one 430 feet thick. The mineral composition of the two members is remarkably similar; their average histograms are (reduced to numerals):

	Type section	Overall
Upper ignimbrite	57/37/6/0//17[3]	53/35/9/3//18
Lower ignimbrite	58/30/12/0//10	56/30/8/6//11

The lower ignimbrite (Tvsc_1) consists of lightly welded, crystal-vitric, pale gray[4] tuff containing, in its lower portion, sparse dacite fragments to 5 mm in maximum dimension. The quartz is in prominent angular grains with a glassy luster; many of the grains are slightly smoky; although some are as large as 5 mm, most are under 2 mm. Small biotite flakes are scattered through the rock. Small lapilli of pumice, altered and chalky, are numerous. The lower ignimbrite rests on a thick pile of dacitic explosion breccia in the Grant Range West (WG) section, and on volcanic sandstone at the type section.

[3] 57 percent quartz, 37 percent sanidine, 6 percent plagioclase, no mafics, 17 percent of areas measured contained "countable" crystals (more than 1/4 mm long).

[4] Color names according to the rock color chart distributed by the Geological Society of America.

At the type section the upper part of the upper ignimbrite ($Tvsc_2$) is moderately welded, moderate pink crystal tuff, which grades down into a zone of highly welded, pale red pink crystal-vitric tuff with many vague powdery lenticles. A similar gradation in the Grant Range West section involves moderately welded, pale red pink crystal tuff above and pinkish gray crystal-vitric tuff with many orange lenticles below. In the East Grant (section EG, fig. 5) section this ignimbrite has a thick black glass layer in its lower half, overlain by lenticulite and underlain gradationally by gray nonwelded tuff.

Much of the quartz is in prominent angular to subangular grains, slightly smoky; all of it has a pronounced vitreous luster. Maximum size of the quartz grains is 4 mm; most are under 2 mm. Biotite is sparse, in small (under 2 mm, most under 1 mm) shiny flakes. In some portions of the unit, flattened pumice fragments that appear as shreds, wisps, and lenticles to 25 mm in length, define a rude eutaxitic structure (see fig. 9). Some of the rock has a mottled appearance. Locally, in lithoidal portions of the ignimbrite, small earthy spherules are enclosed in gray alteration haloes. Shards are visible in thin section, but in places rather thorough crystallization of the groundmass obscures the shard structure (see fig. 10).

Except in the Grant Range West section, where thin andesite flows and layers of volcanic sandstone intervene, the Stone Cabin Formation is overlain directly by the Windous Butte Formation.

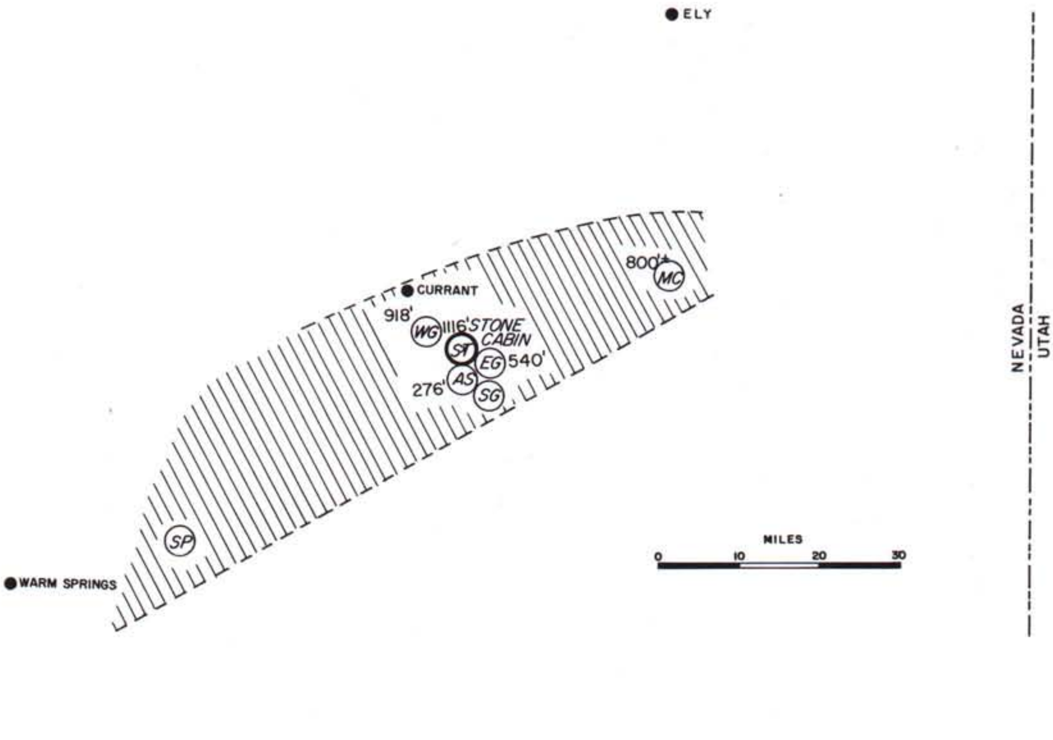


FIGURE 8. Distribution map of the Stone Cabin Formation. Thickness of the formation in sections where it has been identified and measured is shown.

FIGURE 9. Flattened pumice fragments in crystal welded tuff of the Stone Cabin Formation. Plane light.

FIGURE 10. Crystallized groundmass in welded tuff from Stone Cabin Formation. Plane light.

Windous Butte Formation

Type section for the Windous Butte Formation is about one mile south of Windous Butte, in section 12, T. 12 N., R. 60 E., and section 7, T. 12 N., R. 61 E., White Pine County (section MA, fig. 7); because of a low eastward dip the section spreads across the township boundary. Other good sections for this formation are Shingle Springs (section SS, fig. 5, 7) and Stone Cabin (section ST, fig. 5).

The formation as known extends about 5,000 square miles (fig. 11). Average thickness in 11 sections measured is 490 feet. The estimated volume represented in the area studied is 450 cubic miles.

The formation consists of two ignimbrites, lithologically distinct but locally welded together and almost gradational. Petrographically similar, they may represent separate phases of one main eruption.

Although the two ignimbrites are closely similar in composition, they are considerably different in appearance. The upper ignimbrite has more and larger crystals than the lower; the lower ignimbrite is darker and in most sections has a thick, prominent, black-glass zone near its base. Average composition of the intratelluric crystals is as follows:

	Type section	Overall
Upper ignimbrite	38/27/20/15//20	40/28/23/9//21
Lower ignimbrite	34/17/41/8//11	47/23/28/2//8

Histograms for the lower member are probably more inconsistent or erratic than those of any other ignimbrite studied; especially inconsistent is the quartz content.

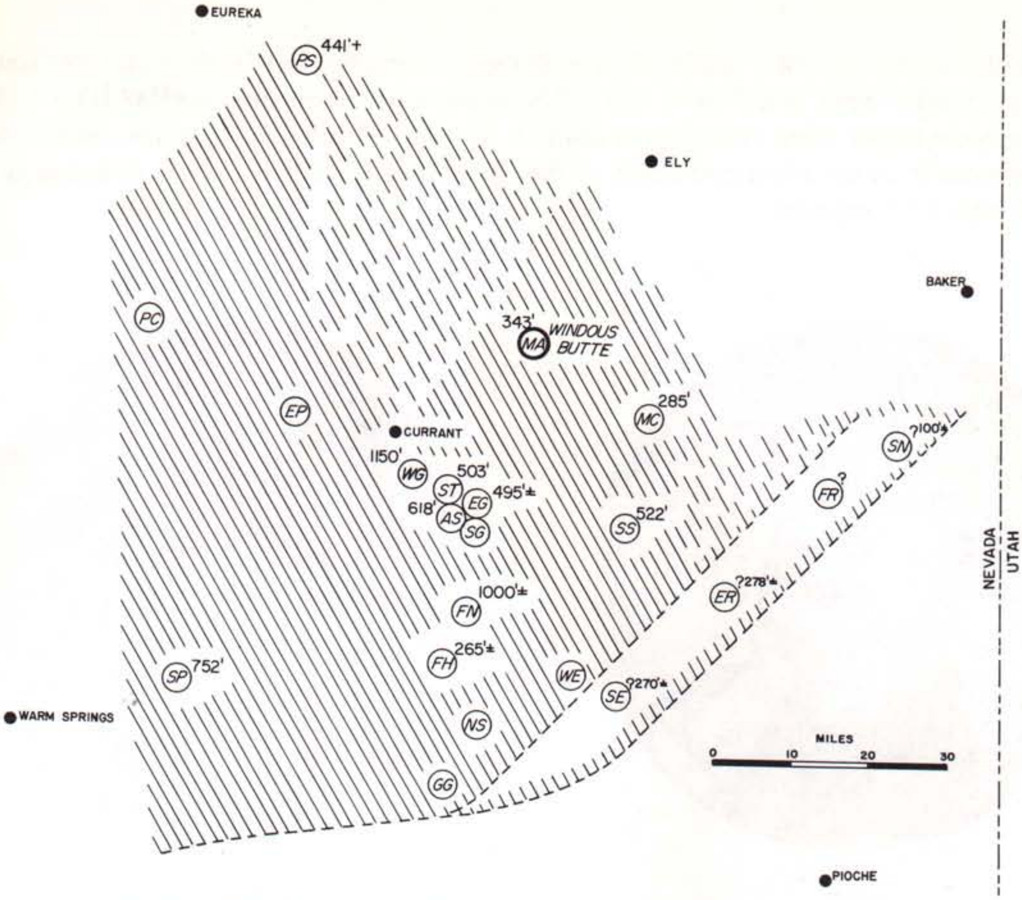


FIGURE 11. Distribution map of the Windous Butte Formation. The hachures are dashed in areas where the formation probably was deposited but where outcrops are not known. The upper ignimbrite (Tvwb$_2$) may be present in the four southeastern sections; the lower ignimbrite is not.

In the sections measured the lower ignimbrite (Tvwb$_1$) ranges in thickness from 138 to 490 feet. It is thinnest in the type section; the upper half there consists of highly welded, pale red purple, crystal-vitric tuff; the lower half, of black porphyritic glass. In thicker sections the rock is pale red to pale reddish brown and highly welded, with 10 to 40 feet of shiny black glass at the base. The Shingle Springs (SS) section shows an exceptional thickness of black glass: 150 feet, of a total unit thickness of 192 feet. In all thin sections of the lower ignimbrite, shard structure is clearly visible, as shown in figure 12.

Crystals comprise about 40 percent of the rock. The glass zone, and even the nonwelded tuff occasionally exposed at the base of the ignimbrite, contain fewer crystals than does the upper part. Crystals visible in hand specimen are quartz, feldspar, and shiny black biotite, none above 2 mm, most below 1 mm.

In the sections measured, the upper ignimbrite (Tvwb$_2$) ranges in thickness from 102 to approximately 1,000 feet. At the type section it is 205 feet of lightly to moderately welded, pale red purple crystal tuff. Much of the rock has a mottled appearance, formed by cream-yellow patches on a grayish pink to grayish red background; it resembles the upper ignimbrite of the Stone Cabin Formation. In the Grant Range West (WG) section the unit is grayish orange to pale greenish yellow. In all but the thinnest section measured (MC, 102 feet), this ignimbrite is at least moderately welded.

Angular smoky quartz, much of it embayed, is prominent in all outcrops; some is as large as 5 mm, most is below 3 mm. The biotite is black and smaller than 1.5 mm. Under the microscope shard structure is seen in portions of all thin sections, even though the groundmass is in an advanced stage of devitrification (see fig. 13). Average crystal content is about 55 percent.

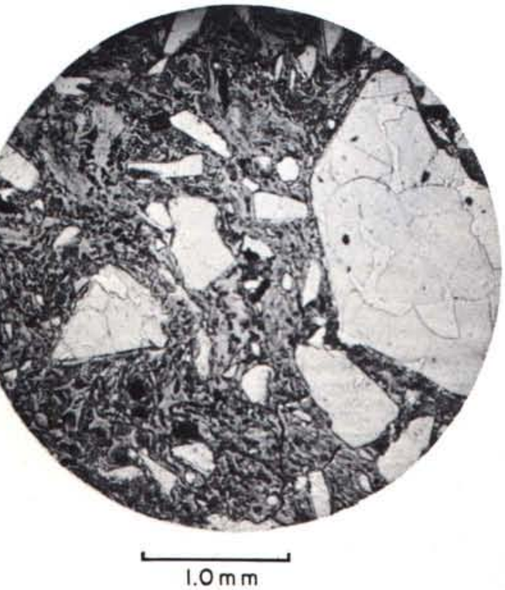


FIGURE 12. Broken crystals, shards, and small pumice fragments in crystal-vitric welded tuff of the Windous Butte Formation (lower ignimbrite). Plane light.

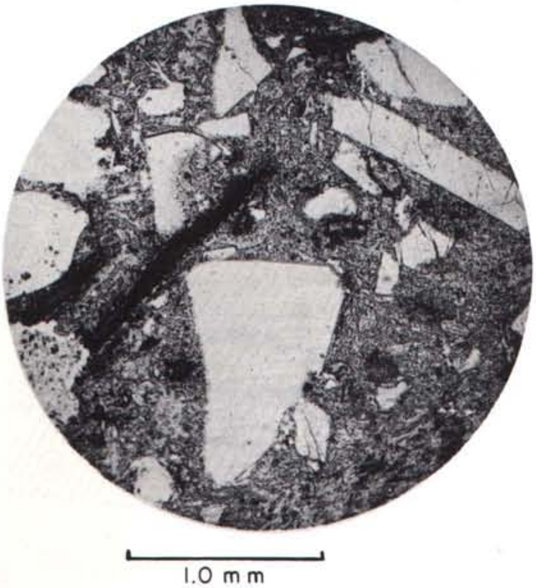


FIGURE 13. Partly devitrified (crystallized) groundmass in crystal welded tuff of the Windous Butte Formation (upper ignimbrite). Plane light.

The two units were erupted in such rapid succession that, in the Grant Range outcrops, they appear welded together. In some exposures the contact is a wavy surface; this irregularity may have been caused by some plastic flowage after deposition of the upper member. In the South Pancake (see section SP, fig. 5) section the two members, although not welded together, have an unusual contact: the nonwelded upper portion of the lower member, apparently in its full thickness, is overlain by the nonwelded basal portion of the upper member.

Evernden and others (1964) have dated the Windous Butte Formation at Sheep in the Egan Range (32.6 million years) and in the Grant Range (32.0 million years).

The Windous Butte Formation is overlain by the Needles Range Formation.

Needles Range Formation

The Needles Range Formation, named by Mackin (1960, p. 99) for exposures in the Needles Range of western Utah, extends from the Paunsaugunt Plateau in Utah westward through eastern Nevada beyond the Pancake Range into western Nevada. In the area studied, the formation covers about 9,000 square miles. Because of Mackin's work in Utah, an additional 4,000 square miles is known. In Nevada this formation is well exposed in the southern Egan Range (section SE, fig. 7), near Forest Home (FN), and in the Fortification Range (FR, fig. 5). Its average thickness measured in 21 Nevada sections is 617 feet. Volume represented by the map (fig. 14) is estimated at 1,050 cubic miles.

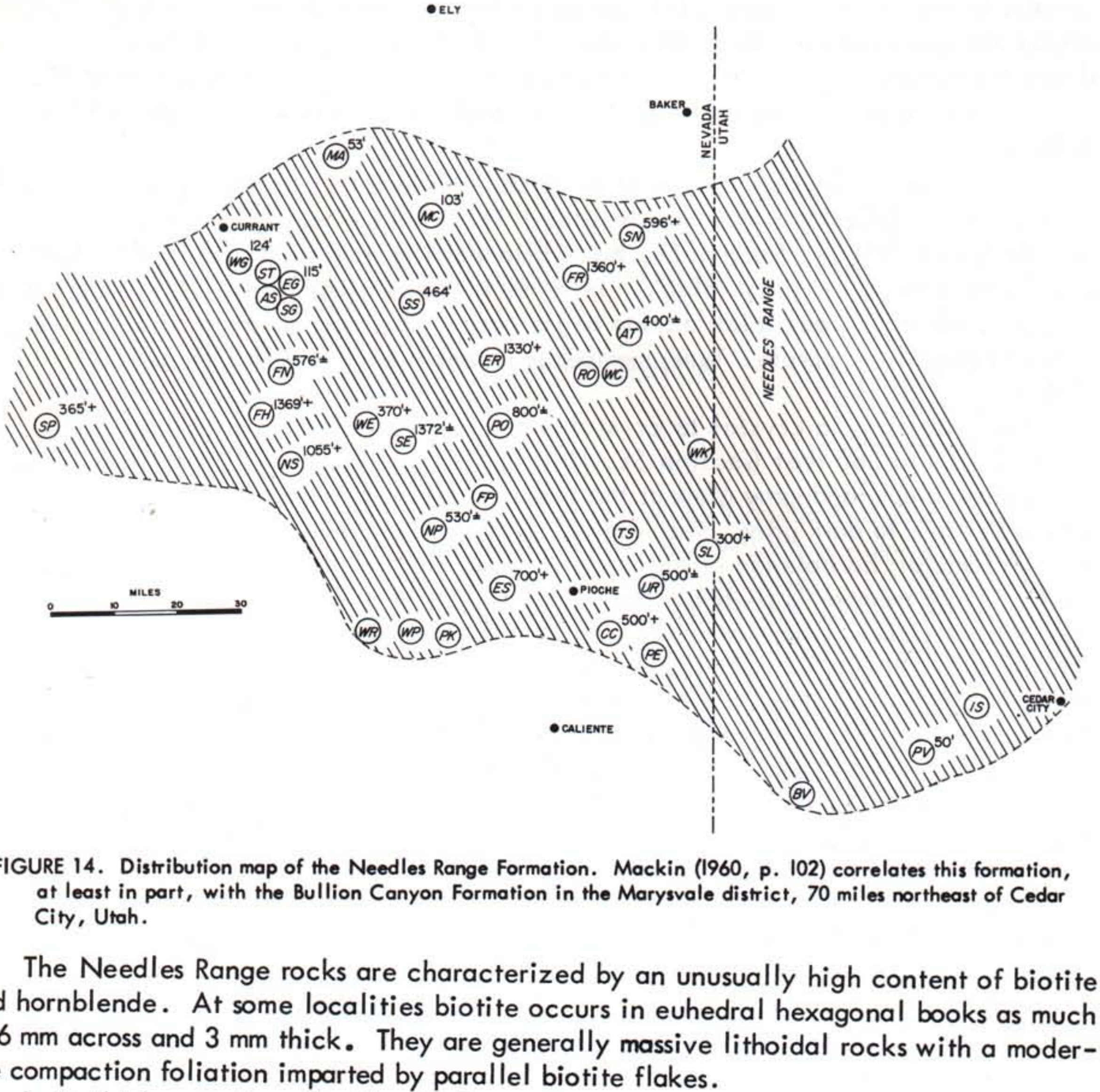


FIGURE 14. Distribution map of the Needles Range Formation. Mackin (1960, p. 102) correlates this formation, at least in part, with the Bullion Canyon Formation in the Marysvale district, 70 miles northeast of Cedar City, Utah.

The Needles Range rocks are characterized by an unusually high content of biotite and hornblende. At some localities biotite occurs in euhedral hexagonal books as much as 6 mm across and 3 mm thick. They are generally massive lithoidal rocks with a moderate compaction foliation imparted by parallel biotite flakes.

In its thicker sections the Needles Range Formation consists of as many as five lithologically distinct but closely similar members. Each appears to be a single ignimbrite.

The histograms (fig. 3) demonstrate the similarity of the members; in figures, they are:

Tvnr_5 - 12/0/76/12//2

Tvnr_4 - 18/5/52/25//16

Tvnr_3 - 24/8/46/22//10

Tvnr_2 - 7/0/62/31//17 (Minersville Tuff)

Tvnr_1 - 14/0/63/23//25 (Wah Wah Springs Tuff)

Except for Tvnr$_5$, this group of ignimbrite giants consists of biotite-rich crystal to crystal-vitric tuff. At least one of the units (Tvnr$_2$), however, has more hornblende than biotite, and even Tvnr$_1$ has almost as much hornblende as it has biotite. Average crystal content of the three younger units, based on study of thin sections with a petrographic microscope (see comment about differences in crystal percentage as determined on stained slices for histograms and as determined by thin-section counts - caption to figure 3) is 50 percent; crystal content decreases to 35 percent in Tvnr$_4$, and to about 10 percent in Tvnr$_5$.

Tvnr$_1$ member consists of crystal to crystal-vitric tuff, containing euhedral biotite in books and flakes to 6 mm in diameter. This member ranges: in thickness from 15 feet (MC) to 1,000 feet (section ER, fig. 5); in welding from lightly to highly welded; in color from pink to gray and black. In three sections black glass, with subconchoidal fracture, up to 50 feet thick occurs at its base. The most common colors are grayish pink and grayish red purple. Tvnr$_1$ member is probably the WahWah Springs Tuff of Mackin (1960).

Tvnr$_2$ member, a crystal to crystal-vitric tuff, ranges in thickness from 30 feet (section MC) to 380 feet (section SE, fig. 7). In four sections it has 10 to 35 feet of lenticulate black-and-gray glass at the base. The colors range from grayish orange pink and red purple to dark gray. The largest crystals of biotite in this member are about 2.5 mm in diameter; hornblende crystals are as much as 4 mm in length; both are black and shiny. Tvnr$_2$ member is probably the Minersville Tuff of Mackin (1960).

Tvnr$_3$ member, a crystal-vitric tuff, ranges in thickness from 60 to 820 feet. Pink and nonwelded in its thinnest section (section FR, fig. 5), this ignimbrite in its thickest section (section NS) shows a vertical gradation from a 70-foot black-glass base upward into lenticulite, then into moderately to lightly welded, light gray tuff.

Quartz, which is more abundant in this ignimbrite than in any other Needles Range member, is smoky and up to 4 mm in diameter. Most of the biotite is under 1.5 mm. Figure 25 is a detailed description of this member as it occurs in the Forest Home North (FN) section. Although the member here is only 68 feet thick, it is highly welded except in the upper 7 feet and the lower 13 feet: either the thickness has very little to do with degree of welding in this unit, or considerable tuff has been removed by erosion. Occurence of moderately welded (instead of lightly welded to nonwelded) tuff at the top of the unit and the overlying bedded tuffaceous shale and sandstone suggest erosion as the answer; on the other hand, the specific gravity curve suggests that the present top is probably not far below the original top of the ignimbrite. Note that the crystal content of the rock is more or less proportional to the degree of welding, that the size of crystals increases downward, and that quartz is much less abundant in the lower half of the unit than in the upper half.

A thin layer of conglomerate appears at the base of Tvnr$_3$ in one section (NS); in another (FR) it is underlain by flow breccia and lahar material.

Tvnr$_4$ member also consists of crystal-vitric tuff. Although thick, it is nonwelded to lightly welded and ranges in color from almost white to pink. Upper limits on crystal size are 3 mm for quartz, 3.5 mm for hornblende, and 2 mm for biotite. A thick section at South Egan (SE) contains abundant vague lenticles and earthy spheroid to 8 inches in diameter.

In the Fortification Range, what is thought to be Tvnr$_4$ is pale red purple, contains abundant biotite books to 5 mm in diameter, and has dark lenticles or discoids to several inches in length and half an inch in thickness.

Only two measured sections contain a Needles Range type of ignimbrite above Tvnr4. In both sections the unit has been called Tvnr5 member although correlation of the two is uncertain. In the Forest Home North (FN) section Tvnr5, 152 feet thick, is made up of lightly welded, grayish orange pink; moderately welded, pink; and highly welded, grayish red vitric-crystal tuff. Sparse feldspar crystals less than 2 mm in diameter and biotite flakes smaller than 1.5 mm speckle the lithoidal groundmass. In the South Egan (SE) section a thin, highly welded, dull black, vitric ignimbrite with hollow lithophysae occupies the Tvnr5 position; although the rock looks nothing like Tvnr5 at Forest Home North, the two have similar histograms.

From potassium-argon biotite dates obtained on specimens of Needles Range ignimbrites from Condor Canyon, from the Grant Range, and from the Needles Range, Armstrong (1963, p. 71) estimates the age of the formation as 28 or 29 million years.

Pahrock Sequence

Composition

Between the Needles Range Formation and the Leach Canyon Tuff is a group of relatively thin rock units called, for want of a better term, the Pahrock sequence. Most of the rock units in the Pahrock sequence are highly welded vitric ignimbrites. But also represented are other kinds of ignimbrites; flows; a lahar; and some lacustrine limestone. The sequence is best exposed in the Pahrock Range (section PK, fig. 6, and section PR, fig. 7). This sequence is stratigraphically equivalent to the Isom Formation of southwest Utah, but is lithologically different and contains no known ignimbrites common to both.

Only two of the units in this sequence, of which there are as many as 18 in the Pahrock Range, are extensive and distinctive enough to warrant description here. And the correlation of one of these, the Petroglyph Cliff Ignimbrite, is so uncertain that no distribution map has been prepared.

Petroglyph Cliff Ignimbrite

The Petroglyph Cliff Ignimbrite is a sheet of tuffbreccia and eutaxite in the lower part of the Pahrock sequence. Type section is near a cliff on the east side of the Seaman Range, a mile or so north of White River Narrows, on which are some Indian petroglyphs. Between the petroglyph cliff, approximately in section 15, T. 1 S., R. 62 E., and White Rock Spring, 2.5 miles north, the ignimbrite is continuously exposed (the thin dark unit lower right in figure 29-A). If the identification of this unit in other sections is correct, it extends over an area of about 1,800 square miles and has an average thickness of only 50 feet. Although it may seem incredible that a unit so thin could be present over such a wide area, this correlation is supported by the fact that only one highly welded vitric-lithic tuff or tuffbreccia unit, with a peculiar phenocryst composition (average: 4/17/69/10//4)[5] appears in approximately the same stratigraphic position in a number of contiguous sections (SL, WK, UR, CC, FP, PE, PK, WR, fig. 1) that seem to outline an east-west zone of distribution. The volume represented by the postulated extent and measured thicknesses is only 20 cubic miles.

---

[5] Martin, who has done considerable petrographic work on the Petroglyph Cliff Ignimbrite, (1963, written communication) would question any analysis showing visible quartz or sanidine in this ignimbrite.

At White Rock Spring, the Petroglyph Cliff Ignimbrite, 67 feet thick, and consisting mainly of strongly welded tuffbreccia, has been well described by Martin (1957, p. 38-44) from whose work the following description is condensed (see also fig. 28).

The uppermost part of the Petroglyph Cliff Ignimbrite at White Rock Spring consists of moderately welded, pale brown tuffbreccia containing abundant glass lenticles and blocks as large as 10 inches long in a matrix of vitric-lithic tuff. This upper zone grades down into black-and-brown mottled eutaxite, which in turn gives way to rock with irregular orange lithoidal lenticles in a dense black matrix, below which is reddish eutaxite containing wispy gray discoids, grading toward the base of the ignimbrite into dark gray, nonresistant felsitic tuff. Just above the base is a zone of incoherent gray, granular,vitric tuff two feet thick.

The crystal fragments, which make up 7 percent of the rock, are largely labradorite, diopsidic augite, hypersthene, and biotite. The index of refraction of glass from the upper part of the unit is 1.531, suggesting a composition more basic than that of the other ignimbrites, probably dacitic or even andesitic. Small angular fragments of purple and gray andesite are scattered throughout the rock. The orange lenticles in the orange-and-black eutaxite are porous, as is the matrix of the red massive eutaxite. Similar pin-hole porosity also occurs in specimens from other localities.

Shingle Pass Ignimbrite

In the upper part of the Pahrock sequence, another thin ignimbrite, which also has an areal extent remarkable for its thickness, is the Shingle Pass Ignimbrite. Its type section is at Shingle Springs, just west of the dirt road that leads through Shingle Pass in the Egan Range, in section 8, T. 8N., R. 63 E., Lincoln County (section SS, figs. 5, 7). Other good sections are East Grant (EG, fig. 5) and South Egan (SE, fig. 7).

The area of distribution (fig. 15), about 4,200 square miles, is a roughly north-south zone confined to eastern Nevada. Average thickness in 13 measured sections is 130 feet; estimated volume is 100 cubic miles.

The percent distribution of the phenocryst minerals in this vitric-crystal ignimbrite is 11/58/29/2//7. Crystal content, determined in thin section, ranges from 10 to 25 percent; the crystals, which are under 3 mm, consist mainly of clear feldspar. Most outcrops show sparse lithic fragments to 5 or 7 mm in diameter. At the type section the ignimbrite is 125 feet thick; it has a pale red-purple moderately to highly welded upper zone that grades down into a red-purple highly welded, crumbly weathering zone in the lower part of which there appear gray discoids, and this medial zone in turn gives way downward to a basal zone of grayish-red rock with irregular, subparallel slots on weathered surfaces. In several sections the main part of the unit is pale red-purple and in several it has orange to brown-black glass at the base. The unit is hard and resistant; in some outcrops the lower grayish-red to brownish-red rock breaks with subconchoidal fracture.

In five sections, all in the northern third of the outcrop area, the Shingle Pass Ignimbrite directly overlies the Needles Range Formation, even though stratigraphic relations show it to be rather high in the Pahrock sequence.

The Shingle Pass Ignimbrite is the youngest named volcanic unit in the northern part of the region studied. A few thin ignimbrites, mostly vitric, overlie the Shingle Pass in portions of the Egan and Grant Ranges; what seem to be the same units crop out in the northern portions of the Hot Creek, Monitor, and Toiyabe Ranges. These thin sheets represent the latest extensive ignimbrite volcanism in the northern part of east-central Nevada. In the southern part of east-central Nevada, as well as in southwest Utah, the Pahrock sequence is overlain by the Leach Canyon Tuff.

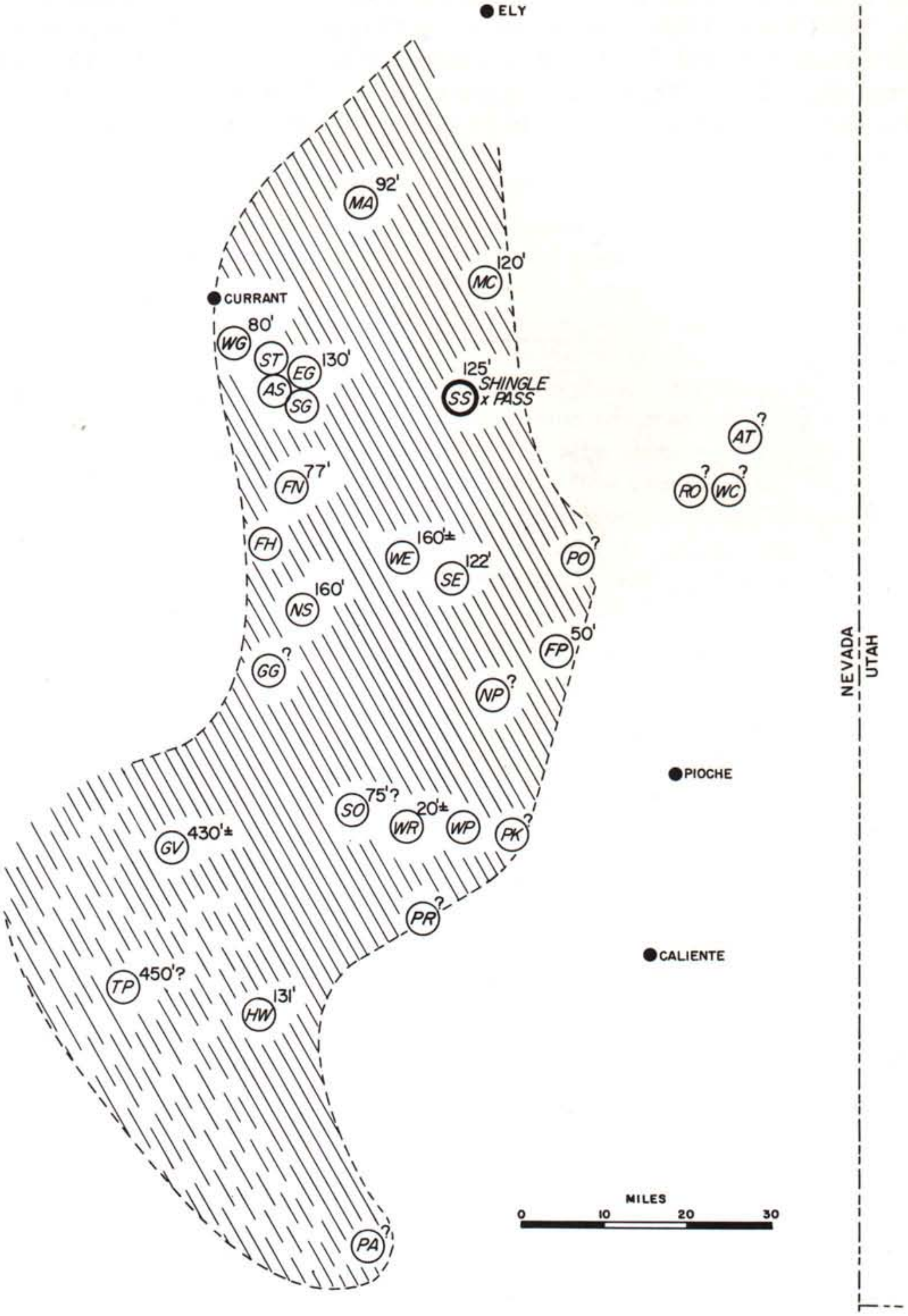


FIGURE 15. Distribution map of the Shingle Pass Ignimbrite.

Leach Canyon Tuff

The Leach Canyon Tuff, named by Mackin (1960, p. 90-91) for exposures in Leach Canyon, Iron County, Utah, is well exposed in Condor Canyon (CC), near Ursine (UR), at Black Canyon (BC), and in White River Narrows (WR, see fig. 6). The area represented by the map (fig. 16) is 5,000 to 7,000 square miles, but the formation extends farther into Utah than shown. Average thickness in 13 sections is 460 feet; estimated volume represented is over 500 cubic miles.

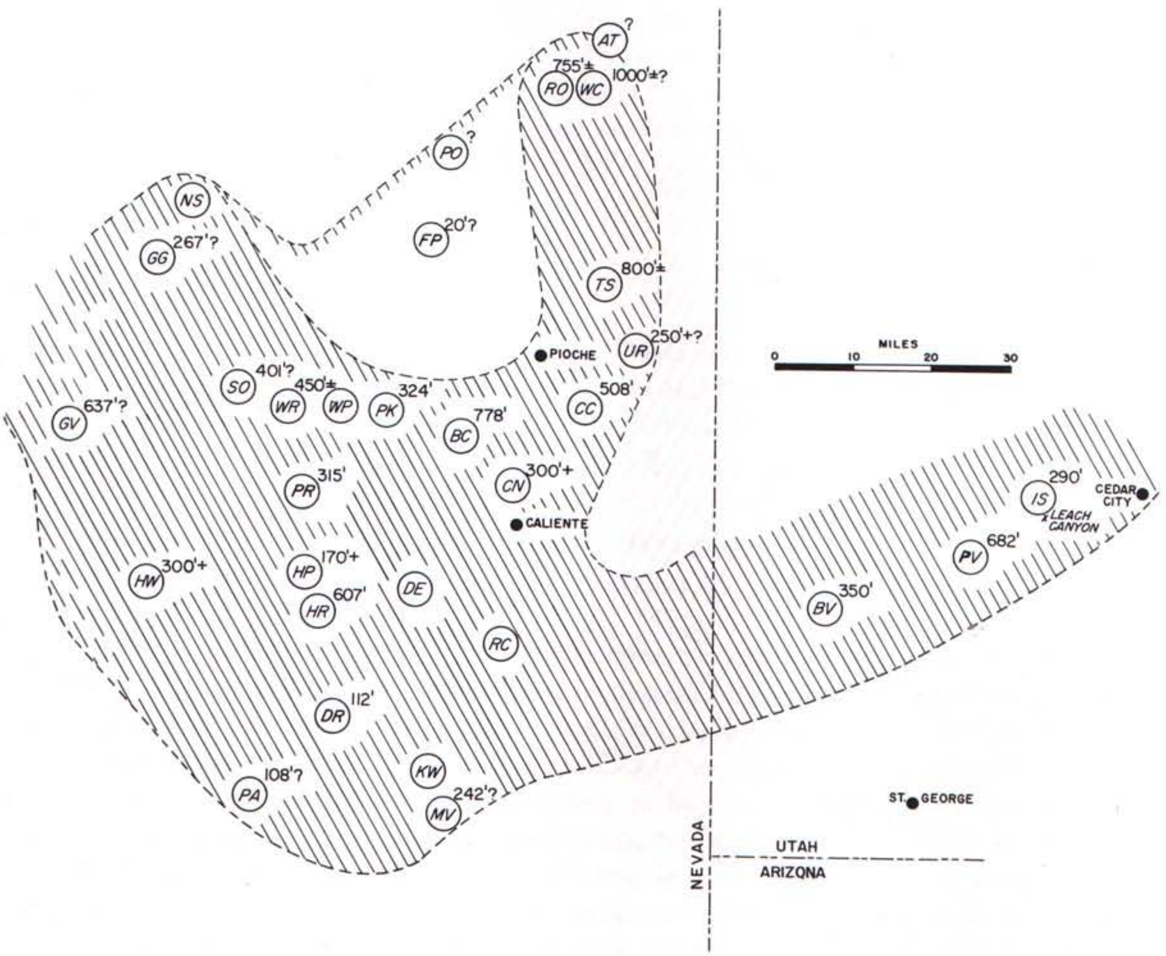


FIGURE 16. Distribution map of the Leach Canyon Tuff.

The Leach Canyon Tuff, in the Pahrock and Hiko Ranges, consists of at least three ignimbrites, each of which may have its own characteristic degree of welding. In the Hiko Range section (HR, fig. 7) the three units are, from bottom to top: (1) gray lithic-vitric sillar, 315 feet thick; (2) grayish pink, moderately welded lithic-crystal tuff, 220 feet thick; and (3) gray lithic-vitric sillar, 72 feet thick. In the East Pahrock section (PK, fig. 6), the sequence is: (1) 96 feet of gray pumice sillar at the base, overlain by

(2) 78 feet of moderately welded, light brownish gray, crystal-lithic tuff, which in turn is surmounted by (3) 150 feet of lightly welded, pale purple, lithic-vitric tuff.

Fairly abundant, small, red, angular, lithic fragments are more or less characteristic of the Leach Canyon Tuff, especially of the moderately welded portions or units, in which thin cream-colored alteration haloes surround many of the fragments; these lithic fragments are a striking feature of the surfaces along which the rock breaks. Several sections of the Leach Canyon Tuff have a zone of black glass at or near the base.

In most of the sections in which it occurs, the Leach Canyon Tuff rests on ignimbrites of the Pahrock sequence, but in others it directly overlies Paleozoic limestone, basaltic andesitic flows, or Tertiary nonvolcanic limestone.

At the type locality, Mackin (1960, p. 90-91) describes the Leach Canyon Tuff as:

> "...a single depositional unit, remarkably uniform in lithology through a thickness of 450-500 feet. Except at the base and near the top the rock consists of a matrix with the texture of unglazed porcelain, gray to flesh in color, enclosing fragments of dark red felsite, light gray pumice, and other rocks, and crystals of quartz, feldspar, biotite, and other pyrogenic minerals, mostly broken....The fragments make up as much as 10 percent of the rock, and the pyrogenic minerals range from 15 to 25 percent...some favorably situated faces exhibit a poorly developed foliation paralleling the base of the unit....The absence of lineation indicates that the foliation is a compaction structure, not a flow structure....
>
> "The stony-textured material grades downward...into...vitrophyre which ranges from zero to several tens of feet in thickness....There may or may not be a layer of pulverulent ash as much as ten feet thick at the base."

Condor Canyon Formation

Main features

Overlying the Leach Canyon Tuff is the Condor Canyon Formation, consisting, in different sections, of from one to five highly welded vitric to vitric-crystal ignimbrites. Two of the members, the Swett Ignimbrite and the Bauers Ignimbrite, make up the entire formation in southwest Utah, where they were named by Mackin (1960) and given member status in his Quichapa Formation. Because the number of ignimbrites in the sequence between the Leach Canyon Tuff and the Harmony Hills Tuff increases to three in the Pahrock Range and to five in the Hiko Range, and because they are lithologically similar to each other but differ greatly from the units above and below, these ignimbrites are here designated the Condor Canyon Formation, whose type section (section CC, fig. 6) is in Condor Canyon along the Pioche Branch of the Union Pacific Railroad, in sections 22, 23, 24, 26, and 27 of T. 1 S., R. 68 E.

The two named members are by far the most extensive; the map (fig. 17) shows that the Swett Ignimbrite extends about 3,500 square miles in the area studied, and the Bauers Ignimbrite covers about 6,000 square miles. Both units extend farther into Utah than shown. The estimated volume of the Condor Canyon Formation in the area shown is 300 cubic miles.

Swett Ignimbrite

In the sections measured, the Swett Ignimbrite ranges in thickness from 30 feet (WR, fig. 6, 7, 17) to 450 feet (TS), averaging 130 feet. Its average histogram is 0/0/95/5//5. The additional members of the Condor Canyon Formation that appear in the southern Pahrock and Hiko Ranges have similar histograms. The Swett Ignimbrite is 164 feet thick in Condor Canyon and has three zones that are typical of both the Swett and Bauers ignimbrites: a lower black-glass zone about 25 feet thick; a middle lithoidal zone streaked with parallel gray lenticles, about 125 feet thick; and an upper, structureless, pale purple, lithoidal zone, about 15 feet thick. The lithoidal zones are flecked with bronze biotite flakes.

At the Hiko Perlite (HP, fig. 7) locality were seen three units having the same phenocryst composition as the Swett Ignimbrite. In ascending order, they are: (1) an ignimbrite, composed of moderate red nonwelded tuff, grading down to lightly welded vitric tuff, 78 feet thick; (2) an ignimbrite, composed of pale red purple, highly welded vitric tuff with wispy lenticles and flow structure in its medial portion and black glass at its base, 450 feet thick; and (3) an ignimbrite composed of pale orange pink, moderately welded tuff at the top to moderate red highly welded vitric tuff at the base, with lithic fragments throughout, 53 feet thick.

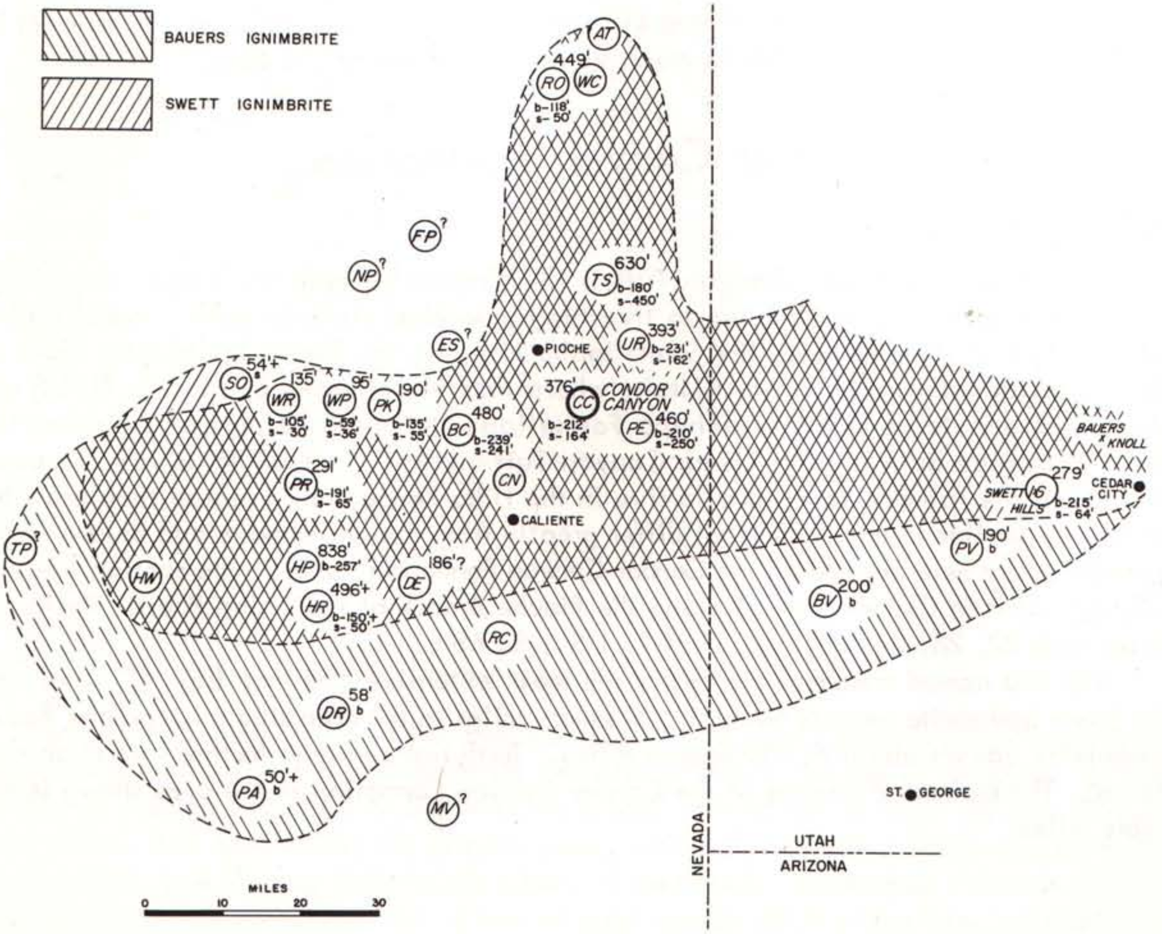


FIGURE 17. Distribution map of the Condor Canyon Formation. Thickness of the Bauers (b) and Swett (s) Ignimbrites at some localities is indicated beneath or to right of location symbols.

In the Hiko Range section (HR, fig. 7) the Swett-type ignimbrites, from bottom to top, consist of: (1) 21 feet of reddish brown, highly welded vitric tuff with lithic fragments; (2) 50 feet of reddish brown to dark gray, highly welded vitric tuff containing lithic fragments, with black glass at its base; (3) 175 feet of dull dark gray to black highly welded vitric tuff with a glassy basal zone; and (4) 100 feet of pale red moderately welded vitric tuff with lithic fragments, grading down into basal glass zone.

The Swett Ignimbrite (where single) is highly welded and has a black-glass base even in its thinnest sections.

Bauers Ignimbrite

In the measured sections the Bauers Ignimbrite has an average phenocryst composition of 0/36/60/4//10, serving to distinguish it from the Swett Ignimbrite (they look alike) even where the Bauers Ignimbrite is found alone. The Bauers Ignimbrite ranges in thickness from 58 to 257 feet, averaging 165 feet. Its thickness does not change so much from section to section as does that of the Swett. The Swett probably filled the low places in a more uneven surface; when the Bauers erupted there was virtually no relief. Nevertheless, relations in several places show there was some local deformation and even erosion between Swett and Bauers volcanism.

In Condor Canyon the Bauers Ignimbrite, 212 feet thick, consists of highly welded, red purple, vitric-crystal tuff with about 16 feet of black glass at its base; a foliated lithoidal middle zone; and a thin, pale purple lithoidal upper zone. In the upper part of the glassy zone are many cobble-sized lithophysae.[6] This feature is common in the Bauers Ignimbrite.

Only slight variation from the typical vertical section is seen in any locality. In the northern part of the Hiko Range (section HP) the Bauers Ignimbrite is 257 feet thick; its upper portion is pale purple moderately welded vitric tuff that grades down into highly welded vitric-crystal tuff that forms cliffs and has a rude columnar structure; there is a black glass zone at the base. In the Pine Valley Mountains of southwest Utah the Bauers is 190 feet thick; it has a similar nonfoliated pale purple upper zone over a foliated, strongly welded moderate red zone that forms most of the unit, and a 7-foot zone of basal black glass. The Bauers Ignimbrite as it appears in White River Narrows is shown in figure 27. The high percentage of lenticles and lithophysal features in the lower part of the medial zone is mirrored in an unusual low-density segment of the specific gravity curve, just above the high-density glass zone. In outcrops where the base is exposed, a thin layer, a few inches to 2 feet thick, of nonwelded to lightly welded tuff lies below the glass and forms the actual basal zone of the unit.

The foliation in the medial zone is commonly expressed by the presence of light gray discoids up to 6 inches in diameter and one inch in thickness (most are much thinner but not much smaller in diameter). All gradations exist between such discoids and subround lithophysae.

---

[6] The large, hollow, bubblelike or roselike spherulites, usually with a radial and concentric structure, that occur in certain rhyolites, obsidians, or related rocks.

Harmony Hills Tuff

Immediately overlying the Condor Canyon Formation in most areas, but separated from it by a thick unit of andesitic flowbreccia in southwest Utah and by units of basalt and sillar in part of the Nevada area, is the Harmony Hills Tuff, named by Mackin (1960, p. 90) for exposures in the Harmony Hills, Iron County, Utah. In Nevada good exposures of this unit may be seen at Condor Canyon (CC), Black Canyon (BC), and in the Delamar Range (DR).

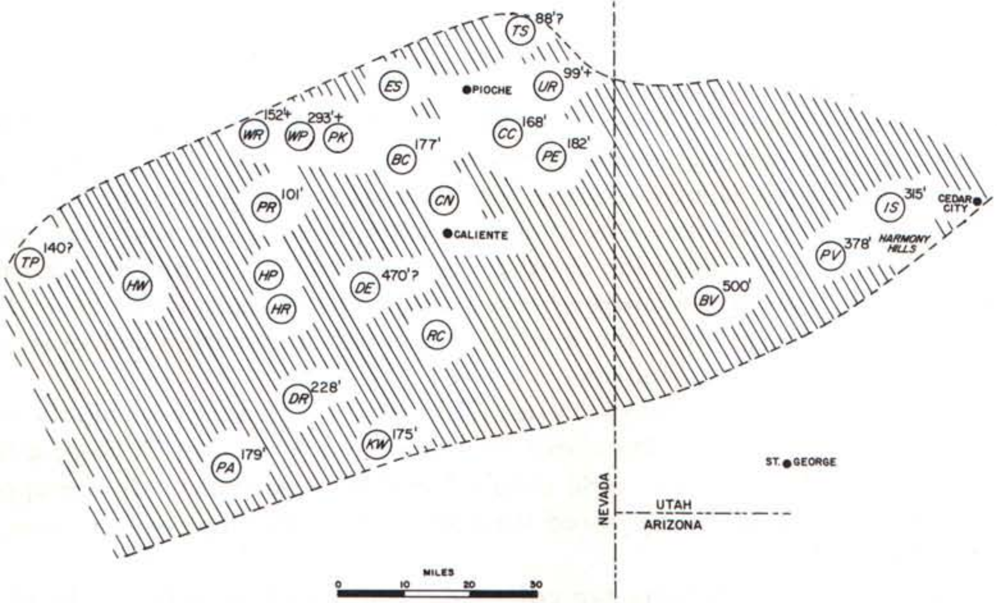


FIGURE 18. Distribution map of the Harmony Hills Tuff.

Known extent of the Harmony Hills Tuff (fig. 18) is more than 6,000 square miles; average thickness is about 250 feet, and the estimated volume in the area mapped is about 280 cubic miles. The composition of the phenocrysts is: $6/0/74/\frac{19}{11}//25$. Its color is grayish pink, pinkish red, to pale purple.

The unit as it appears in the Pine Valley Mountains of southwest Utah (Cook, 1957a, p. 40) is:

> "...lightly to moderately welded, dacitic or quartz latitic crystal tuff... 60 to 70 percent crystalline; most of the crystals are plagioclase but about one-fourth are biotite flakes, conspicuous in hand specimen...and arranged in eutaxitic foliation. A fresh surface of the tuff is red brown to purplish brown."

Although in most sections the Harmony Hills Tuff seems to be a single ignimbrite, in some areas it consists of two or three similar ignimbrites.

The Harmony Hills Tuff overlies the Little Creek Breccia in southwest Utah; a basalt flow in the Black Canyon section northwest of Caliente; and an extensive unnamed vitric-crystal nonwelded ignimbrite in southeastern Nevada. In other sections it rests directly on the Bauers Ignimbrite.

In most of the southeastern Nevada sections, the Harmony Hills Tuff is overlain by the Hiko Tuff, but over a large area in southwestern Utah a complex of welded tuff and flows between the Harmony Hills Tuff and the Hiko Tuff forms a thick lens that is known as the Rencher Formation.

Rencher Formation

The Rencher Formation (Cook, 1957a, p. 57-59) is a complex assemblage of welded crystal tuff and tuffbreccia, mudflow breccia, flows and flow-breccia, volcanic-derived sandstone, limestone, and conglomerate, all of which accumulated during a time of great intrusive deformation in southwestern Utah (and probably part of southeastern Nevada).

Most of the Rencher tuff, resembling the tuff of Harmony Hills Formation both in appearance and composition, is pale orange brown and biotite-rich.

The lower Rencher rocks fill depressions in a surface of folded and eroded older volcanic rocks; the upper Rencher rocks spread unconformably across the truncated edges of units deformed by intrusion and partially removed by erosion from the flanks of intrusive domes. It is now thought (Armstrong, 1963, p. 72) that the Rencher Formation may transgress the Oligocene-Miocene boundary.

Page Ranch Formation

General statement

The Page Ranch Formation (Cook, 1957a, p. 61-63) was named for exposures near Page Ranch in Iron County, Utah (section PV, fig. 6). Mackin (1960, p. 97) distinguished a lower, Irontown Member from an upper member he named the Kane Point Tuff. In Nevada, the stratigraphic position of the Kane Point Tuff is occupied by a unit here named the Hiko Tuff.

Irontown Member

In the area studied the Irontown Member consists of waterlaid tuff, lahar deposits, sillar, sandstone, and flows. It is found in all sections in which the Page Ranch Formation is present, except Delamar Range and Condor Canyon, where the Hiko Tuff lies directly on the Harmony Hills Tuff.

Hiko Tuff

The Hiko Tuff is, in the type locality, a single, extraordinarily thick, crystal-vitric to crystal ignimbrite. It makes up a large part of the Hiko (or Hyco) Range; the type section (HP, fig. 7) is on the east side of the Range about six miles south of U. S. Highway 93, in section 3, T. 5 S., R. 62 E., Lincoln County. Other sections with good exposures of the Hiko Tuff are Delamar Range and Pahranagat (sections DR and PA respectively, fig. 7).

The Hiko Tuff originally blanketed an area of more than 5,000 square miles (fig. 19) and had a volume on the order of 500 cubic miles. Thickness of the complete unit ranges from 213 to 1,135 feet; if the correlation with the Racer Canyon Tuff of Blank (1959) is correct, the unit reaches 1,500 feet in the Bull Valley district.

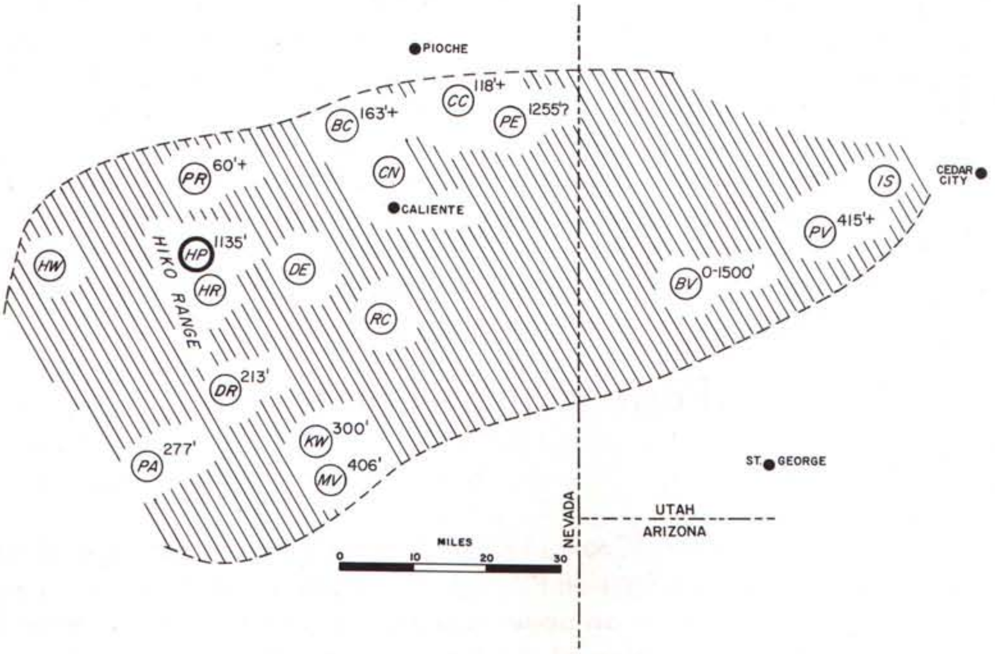


FIGURE 19. Distribution map of the Hiko Tuff Member of the Page Ranch Formation.

The average phenocryst composition is 24/27/37/12//15. Maximum grain sizes are: quartz, 4 mm; feldspar, 3 mm; biotite, 2 mm. At the type section (for more detailed description see fig. 26) the upper part of the unit is a red purple, crumbly, highly welded crystal tuff containing 40 to 50 percent crystals. It grades downward into highly welded, pale red purple tuff or lenticulite that contains 50 to 60 percent crystals, encloses fragments of flow rock as large as 4 inches in diameter, and is characterized by dark glassy lenticles and large rude columns. Below the glassy lenticulite zone the rock grades rather abruptly into lightly welded, grayish orange pink crystal-pumice tuff and then into a basal zone, 200 feet thick, of nonwelded grayish pink pumice-rich lithic-crystal tuff that contains many fragments of dark flow rock. Rock below the lenticulite zone strongly resembles nonwelded or lightly welded specimens of Leach Canyon Tuff (no correlation intended). The Hiko Tuff rests on a rudely bedded sequence of volcanic sandstone and pumice sillar, recognized as part of his Hells Bells Canyon Formation by Dolgoff (1963, p. 878, 882, 884-5); this sequence may be equivalent to the Irontown Member of the Page Ranch Formation.

Under the microscope few shards are seen above the highly welded lenticulite zone, but there is abundant crystal dust and ash in a partly microcrystalline groundmass. In the glassy lenticulite zone excellent compacted-shard structure features a vitroclastic groundmass not at all crystallized; both crystals and lithic fragments are more abundant in the highly welded zone than in the upper zone. Below the lenticulite zone small crystal fragments abound in a pumice-rich groundmass.

A potassium-argon date of 24^{+4}_{-2} million years was obtained by Armstrong (1963, p. 72) on biotite from the Hiko Tuff.

Kane Wash Formation

General features

The Kane Wash Formation, comprising at least eight members, crops out extensively in the Meadow Valley Mountains and in the Delamar Range on both sides of Kane Springs Wash, a prominent northeast-trending fault trough. The type section, Delamar Range (section DR, fig. 7) is at the west end of the Delamar Range, approximately in section 5, T., 9 S., R. 63 E., Lincoln County. The formation also crops out extensively on both sides of the Pahranagat Valley. Another good section is Kane Wash (KW) on the southeast side of Kane Springs Wash about 1 mile north of Kane triangulation station and above Grapevine Spring, approximately in section 34, T. 9 S., R. 65 E.

Judged on present outcrops, the Kane Wash Formation probably had an original extent of more than 6,000 square miles, extending in a broad arc, slightly convex southward, from the Bull Valley district in southwestern Utah to the Nevada Test Site in southern Nevada (fig. 20). Volume represented is more than 750 cubic miles.

The Kane Wash Formation is the youngest of the extensive ignimbrite formations in eastern Nevada. It rests either disconformably on the Hiko Tuff or with angular unconformity on Paleozoic sedimentary rocks.

Members of the formation vary widely in mechanical composition and considerably in mineralogy. On the other hand, they have these features in common: plagioclase is rare; quartz and sanidine are found in all; at least three of the thicker units are characterized by chatoyant sanidine.

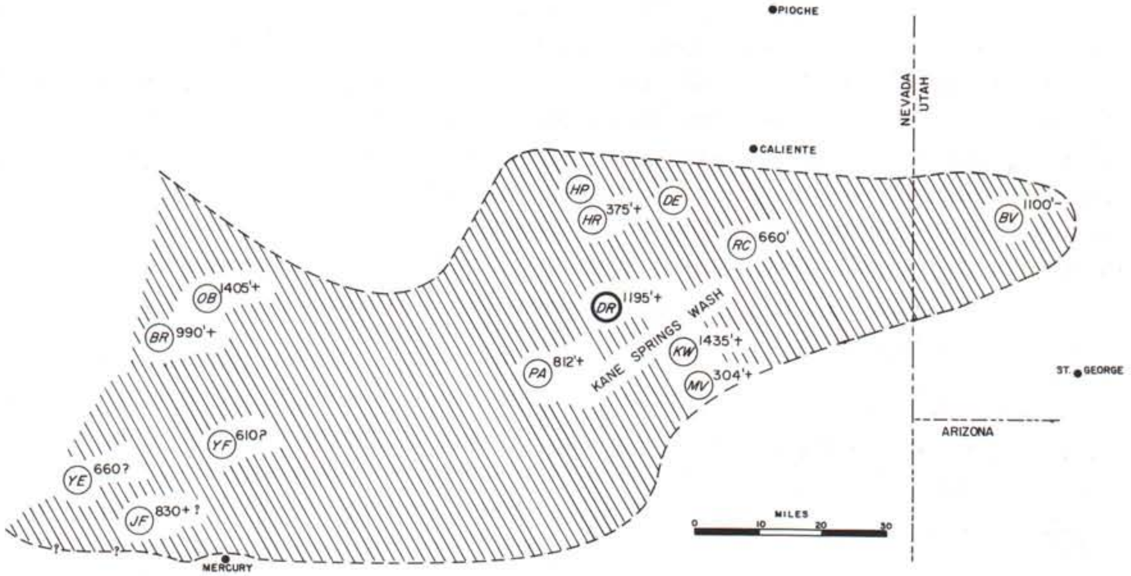


FIGURE 20. Distribution map of the Kane Wash Formation.

Lithology

The Kane Wash Formation in its type section includes all rock units above the Hiko Tuff. The basal unit in the type section consists of 172 feet of black, vesicular, basalt that contains some white amygdules. The basalt is overlain by a thin vitric ignimbrite

(Tvk1) which forms the base of the formation in most sections; it is 14 to 260 feet thick, resistant, and has an average phenocryst composition of 53/47/0/0//6. The highly welded portions weather tan to dark brown, and the sanidine in some outcrops is chatoyant. At the type section this ignimbrite, 50 feet thick, contains sparse crystals of quartz and sanidine under 1 mm in diameter, and conspicuous, flattish, red brown lithic fragments to 20 mm in length, oriented subparallel in a eutaxitic structure. The upper part of the unit, grayish orange pink, contains abundant small relict pumice fragments; the main part is pale pink. Under the microscope sharply defined, flattened shards are seen to compose a groundmass enclosing angular fragments of quartz and sanidine, as well as lithic fragments, some of which appear to be basalt.

Above Tvk1 in the type section is an unnamed vitric-crystal sillar unit (phenocryst composition 14/86/0/0//7) 49 feet thick. In the same stratigraphic position in the central Hiko Range is a thin, lightly welded, pale red, vitric-crystal tuff (phenocryst composition 1/92/0/$\overset{0}{\cancel{7}}$//14.)

A composite ignimbrite 455 feet thick overlies the unnamed sillar at the type section. The lower and major portion (Tvk2) of the unit consists of grayish pink, vitric-lithic sillar that contains many small pumice fragments and many angular lithic fragments, mostly red-brown, to 20 mm in maximum dimension. This lower zone or unit, whose phenocryst content in all measured sections averages 49/51/0/0//11, and whose thickness ranges from 272 to 545 feet, is 375 feet thick in the Delamar Range (DR) section. Near its top the unit becomes coherent, lightly, then moderately, welded, and grades abruptly into Tvk2x, a highly welded, resistant zone or unit, 80 feet thick, with an average phenocryst content in all sections of 45/49/2/$\overset{0}{\cancel{4}}$//10.

Tvk2, especially in the central Hiko Range, is a prominent feature of the landscape because of its striking pale orange-brown weathering color. The lower part, 100 feet or more thick, is bedded. Here the unit contains much silky pumice and abundant fragments of volcanic rock. Fragments decrease in size and abundance upward.

Tvk2x, which ranges in thickness from 40 to 100 feet and in color from grayish orange pink and moderate pink to pale blue and light gray, has much less abundant lithic fragments than the underlying zone; wispy to streaky dark lenticles to 20 mm in length are locally prominent in a felsitic matrix of vitric-crystal composition. The unit has chatoyant sanidine to 2 mm and rather sparse lithic fragments to 8 mm.

Another rhyolitic ignimbrite (Tvk3) overlies Tvk2x. At the type section, Tvk3 is 88 feet thick, consists of grayish purple, vitric sillar at the top which grades down into highly welded, purple, very resistant vitric tuff at the base. The average phenocryst composition for Tvk3 is 17/66/14/3//4. This member may correspond to the Grouse Canyon Member of the Indian Trail Formation (see "Correlation") which at Oak Spring Butte (OB, fig. 1) is highly welded and vitric in its upper part, grading from light gray lenticulite (the lenticles are dark, porous, parallel, up to 25 mm long and 4 mm thick) down to black perlitic glass; the rock contains sparse sanidine crystals, some chatoyant, up to 4 mm.

The four younger units in the type section, from bottom up, are:

(1) An ignimbrite 20 feet thick, composed of highly welded, pale blue to pale yellowish brown vitric-crystal tuff with lithic fragments; phenocryst composition 53/47/0/0//12.

(2) An ignimbrite 15 feet thick, composed of lightly to moderately welded, pale orange pink vitric-crystal tuff; phenocryst composition--18/77/0/5//11.

(3) An ignimbrite 5 feet thick, composed of moderate orange pink, crystal-vitric sillar; phenocryst composition--0/73/27/0//5.

(4) A high-temperature ignimbrite or rhyolite flow, 260 feet thick, consisting of pale yellowish brown, pale red, and medium dark gray lithoidal, hard, rudely columnar rock with black and tan glass at the base. The rock contains chatoyant feldspar and green, strongly pleochroic hornblende. The cryptocrystalline groundmass reveals neither shard nor fluidal structures. The unit forms a broad dip slope in the northwest part of the Meadow Valley Mountains. Average phenocryst composition is $37/50/0/\frac{0}{13}//13$.

Correlation of the upper four units in the Kane Wash section with those of the Delamar Range section is reasonably secure.

Correlation

The Oak Spring Group of the Nevada Test Site (Poole and McKeown, 1962) is here correlated with the Kane Wash Formation. Although no unit is known to be common to both the Oak Spring Group and the Kane Wash Formation, lithologic similarity and stratigraphic position suggest that the Grouse Canyon Member of the Indian Trail Formation (the lower of the two formations comprising the Oak Spring Group) may be equivalent to Tvk$_3$, described below. It may well transpire with further work that the Kane Wash Formation should be raised to group status as the former Oak Spring Formation of Johnson and Hibbard (1957, p. 367-369) was changed to the Oak Spring Group of Poole and McKeown.

The Alamo Range Formation of Dolgoff (1963, p. 888-890), mapped by him on both sides of the Pahranagat Valley, appears to be equivalent to the Kane Wash Formation.

In the Bull Valley district of southwestern Utah, the Kane Wash Formation appears to be represented by the Ox Valley Tuff, and by the Cedar Spring Member and the Pilot Creek Basalt of the Cove Mountain Formation of Blank (1959).

FEATURES OF EASTERN NEVADA IGNIMBRITES

General Statement

Ignimbrites have been described from many parts of the world. Ross and Smith (1961) summarize the principal features of ash-flow tuffs (ignimbrites), and describe in detail the characteristics that identify such deposits. Although the eastern Nevada ignimbrites show wide variation in mechanical or fragmental composition as well as in texture and structure, most of their features have counterparts in ignimbrites in other volcanic provinces. Features of the Nevada ignimbrites will be discussed here mainly as they compare or contrast with the general concept of what an ignimbrite is.

Shape and Size

Typically, an eastern Nevada ignimbrite is a thin sheet whose maximum linear dimension exceeds its maximum thickness by 500 to 2,000 times. It thins over, or wedges out against topographic highs; if found within a pre-existing valley, it shows a sag due to differential compaction, the lowest part of which follows the valley axis. Although no true distal margin of an ignimbrite has been identified in outcrop, the manner in which these pyroclastic sheets thin toward their margins, and the way in which highly welded units wedge out against topographic barriers, strongly suggest: (a) that Steiner's (1960, p. 29) visualization of the stubby margin of an ignimbrite sheet is not valid for the Nevada ignimbrites, and (b) that the volume of material erupted had relatively little to do with the extent of the resulting deposit--if, at the time of the eruption, relief is small, the ignimbrite will probably be extensive. Volume of material erupted had a lot to do with thickness of the deposit, but extent appears to have been determined largely by the nature of the basin or depression in which the ignimbrite formed.

Extent seems to bear no recognizable relation to composition or degree of welding: units that are virtually coextensive are, for example, a crystal tuff (Harmony Hills), nonwelded to moderately welded; two highly welded vitric to vitric-crystal ignimbrites (Swett and Bauers); and a vitric-crystal to vitric-lithic tuff (Leach Canyon), nonwelded to lightly welded.

Several Nevada ignimbrites have been identified in sections more than 100 miles apart; some of these units had an original extent of 5,000 to 10,000 square miles or more. The maximum volume of compacted pyroclastic material represented by any one of these ignimbrites is on the order of 500 cubic miles (Table 1). As Smith (1960a, p. 814) points out, figures generally quoted for area and volume are for pyroclastic fields and not for individual depositional or cooling units; consequently, comparisons of individual ignimbrites from different regions are not yet possible. The total volume of pyroclastic material in the 20,000 square miles studied in eastern Nevada and southwestern Utah (see fig. 35) is more than 5,000 cubic miles.

TABLE 1

Estimates of extent, average thickness, and volume of ignimbrite formations

Formation	Number of ignimbrites	Extent, square miles	Average thickness, feet	Volume, cubic miles
Kane Wash Formation	at least 8	6,000+	650	750+
Hiko Tuff	1	5,000	550	500
Harmony Hills Tuff	up to 3	6,000	250	280
Bauers Ignimbrite	1	6,000	165	190
Swett Ignimbrite	1	3,500	130	90
Leach Canyon Tuff	up to 3	6,000+	460	500+
Shingle Pass Ignimbrite	1	4,200	130	100
Petroglyph Cliff Ignimbrite	1	1,800	50	20
Needles Range Formation	4-5	13,000+	620	1,350
Windous Butte Formation	2	5,000	490	450+
Stone Cabin Formation	2	2,500	730	350

Eastern Nevada ignimbrites in measured sections range from less than 10 feet in thickness to about 1,135 feet; the average thickness is about 200 feet. The thickest ignimbrite so far described in the literature is the Superior dacite (Peterson, 1959) of the Globe-Superior area in Arizona, which is as much as 1,500 feet thick. The thicker Nevada ignimbrites are crystal-rich; the crystal-poor units tend to be thin. To put it another way, no vitric ignimbrite is known to exceed 450 feet in thickness; in most sections, such units are less than 250 feet thick. The only thick ignimbrite formation described here which is not crystal-rich is the Leach Canyon Tuff, locally 800 feet thick.

This formation, however, is composed of three separate ignimbrites, none of which exceeds 400 feet in thickness. Overall degree of welding in the Nevada ignimbrites does not seem related to thickness: there are both thin and thick highly welded ignimbrites, as well as thin and thick nonwelded ignimbrites.

Composition

Eastern Nevada ignimbrites are generally within the rhyolite-dacite composition range. Classified by crystal content, they range from pheno-rhyolite to pheno-andesite, although the index of refraction of their groundmass glass is commonly near 1.500, typical of rhyolites. An exception is the Petroglyph Cliff Ignimbrite, which appears on the basis of phenocryst composition and index of refraction to be more basic.

In most of the Nevada ignimbrites in which quartz phenocrysts are sparse or absent, the index of the groundmass glass suggests a more acidic composition than do the phenocrysts. Very few chemical analyses of the ignimbrites herein described are available. Four are given in Table 2.

TABLE 2

Partial chemical analyses of some ignimbrite specimens

	Ox Valley Tuff [1]	Windous Butte Formation [2]	Racer Canyon Tuff [3]	Rencher Formation [4]
SiO_2	73.80	70.42	69.40	63.4
Al_2O_3	16.04*	13.95	18.98*	17.85*
Fe_2O_3	----	1.93	----	----
FeO	----	1.11	----	0.39
Fe (total)	1.1		1.8	3.6
MgO	0.20	0.95	1.08	2.45
CaO	0.60	2.57	2.60	4.20
Na_2O	1.57	2.49	1.18	1.16
K_2O	3.70	3.71	3.38	3.38
TiO_2	----	0.41	----	----
Ti	0.61	----	1.27	1.08

* not correct for Ti

[1] Blank, 1959, p. 36. Possible equivalent of part of Kane Wash Formation.

[2] Faust and Callaghan, 1948.

[3] Blank, 1959, p. 36. Possible equivalent of the Hiko Tuff.

[4] Blank, 1959, p. 36.

Although some units contain crystals up to 5 or 6 mm in diameter, most of the phenocrysts are below 2 mm in size. The smaller grains are mainly angular crystal fragments (see fig. 21). Sanidine is the most common euhedral mineral. Quartz in some units is in large euhedral crystals, but is more common as embayed or corroded grains and irregular angular fragments. The phenocryst content as given in the histograms ranges from 2 to 30 percent, and probably represents fairly closely the volume in each unit occupied by phenocrysts over 1/4 mm in diameter; crystal percentages determined by thin-section study, in contrast, range from 5 to 65 percent. The groundmass in most of the crystal-tuff ignimbrites is highly charged with crystal fragments less than 1/4 mm in diameter. Lithic fragments may include both material torn from the walls of vents (andesite, latite, welded tuff) and material swept up from the ground (quartzite, chert, argillite).

The petrography of the Nevada ignimbrites needs much more attention than was possible in this primarily stratigraphic study.

Textural and Structural Features

The flattening and alteration of pumice fragments within the welded zones of ignimbrites, described in detail by Ross and Smith (1961, p. 24-28), has produced, in the Nevada ignimbrites, irregular discoids, both light-colored and dark, as well as lithophysae lined with secondary minerals. The discoids are up to 2 or 3 feet in diameter and as much as an inch or two in thickness, although most are much smaller; they are arranged in plane parallel manner so that, viewed in cross-section, they look like lenses, streaks, or wisps (see fig. 22). In strongly welded zones the pumice discs become black and glassy. Vapor-phase crystallization of collapsed pumice (Ross and Smith, 1961, p. 27) is common in some zones of Nevada ignimbrites, and results in discoidal cavities lined with small crystals.

FIGURE 21. Angular crystal fragments in welded crystal tuff of the Windous Butte Formation (upper member). Crossed nicols.

FIGURE 22. Collapsed pumice fragments in welded crystal-vitric tuff of the Windous Butte Formation (lower member). Plane light.

Planar compaction (eutaxitic) structure is a distinctive feature of moderately to highly welded zones in most of the ignimbrites, whether expressed by the pumice discoids described above; in the parallelism of biotite flakes; or in the parallel orientation of platy fragments other than pumice.

Columnar jointing, a common feature of many ignimbrites (Ross and Smith, 1961, p. 28), is not a characteristic of most of the eastern Nevada ignimbrites. It is found in certain nonwelded to lightly welded ignimbrites (in contradistinction to nonwelded to lightly welded zones), but is not usually seen in highly welded ignimbrites. Perhaps the best-formed columns in eastern Nevada are in the Leach Canyon Tuff in White River Narrows.

Microscopically, the two most distinctive features of the eastern Nevada ignimbrites--as with those from other parts of the world--are shard structure (see figs. 23 and 24) and fractured crystals. The structure of flattened glass shards and pumice fragments that drape over and are compressed under crystals and lithic fragments may be obscured by crystallization or, in strongly welded rocks, rendered difficult to determine by intense compaction and homogenization into a pseudofluidal structure. The groundmass of most specimens is highly charged with angular crystal fragments.

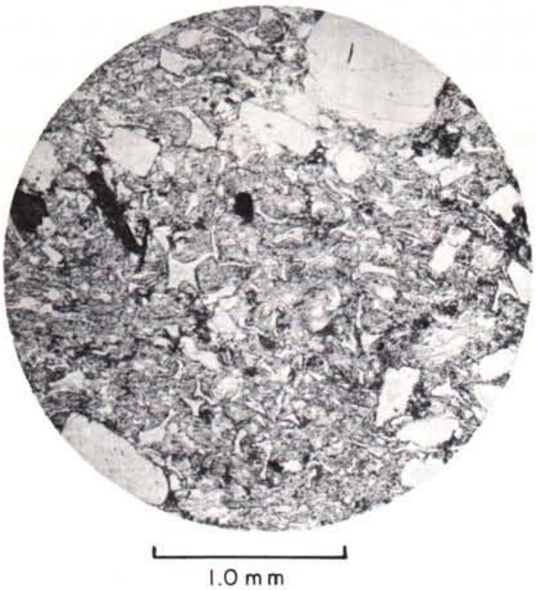


FIGURE 23. Shards, not compressed, in nonwelded crystal-vitric tuff (sillar) from an ignimbrite in the Pahrock sequence, exposed in the PR section (sillar below basalt flows). Plane light.

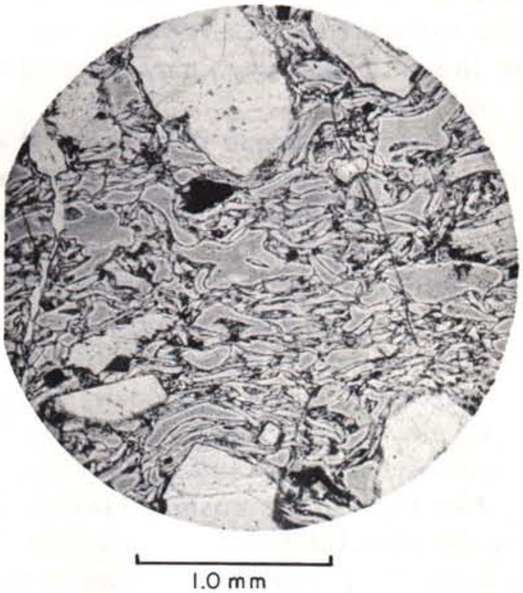


FIGURE 24. Compressed shards in moderately welded crystal-vitric tuff, from an ignimbrite in the Pahrock sequence exposed in the PR section (second ignimbrite below basalt flow). Plane light.

Vertical Variations

The principal vertical variation is in degree of welding. Thick ignimbrites of eastern Nevada show a zoning in section, starting at the top with a zone of soft, incoherent ash and lapilli among which are abundant pumice fragments, passing downward either gradually into a thick, lightly to moderately welded zone (in crystal and crystal-vitric ignimbrites) or abruptly into a moderately to highly welded zone (in vitric and vitric-crystal units); and then passing abruptly into a highly welded dark gray or black lenticulite or vitrophyric zone 10 to 100 feet thick and then, abruptly again, into a nonwelded basal zone of pulverulent tuff from a few inches to over 100 feet thick.

In many outcrops, however, the nonwelded top is not found. Only under exceptional circumstances could it long persist; in most places it has either been eroded off or swept up into the succeeding pyroclastic flow. One of the rare Nevada examples of a "complete top" is in the southern Pancake Range (section SP, fig. 5), where the entire Windous Butte lower ignimbrite was preserved by the almost immediate deposition of the upper ignimbrite; the *nuée* of the upper ignimbrite seems to have been fully loaded, for it swept up and incorporated into itself little if any of the soft tuff beneath. In the Grant Range, on the other hand, there is no nonwelded tuff either at the top of the lower ignimbrite or at the base of the upper ignimbrite: the *nuée* of the upper unit appears to have swept up the insulating blanket of nonwelded *material* from the top of the recently emplaced lower unit, and then, as the fragmental burden of the *nuée* settled onto the still hot main portion of the lower ignimbrite, the two deposits were *welded* together.

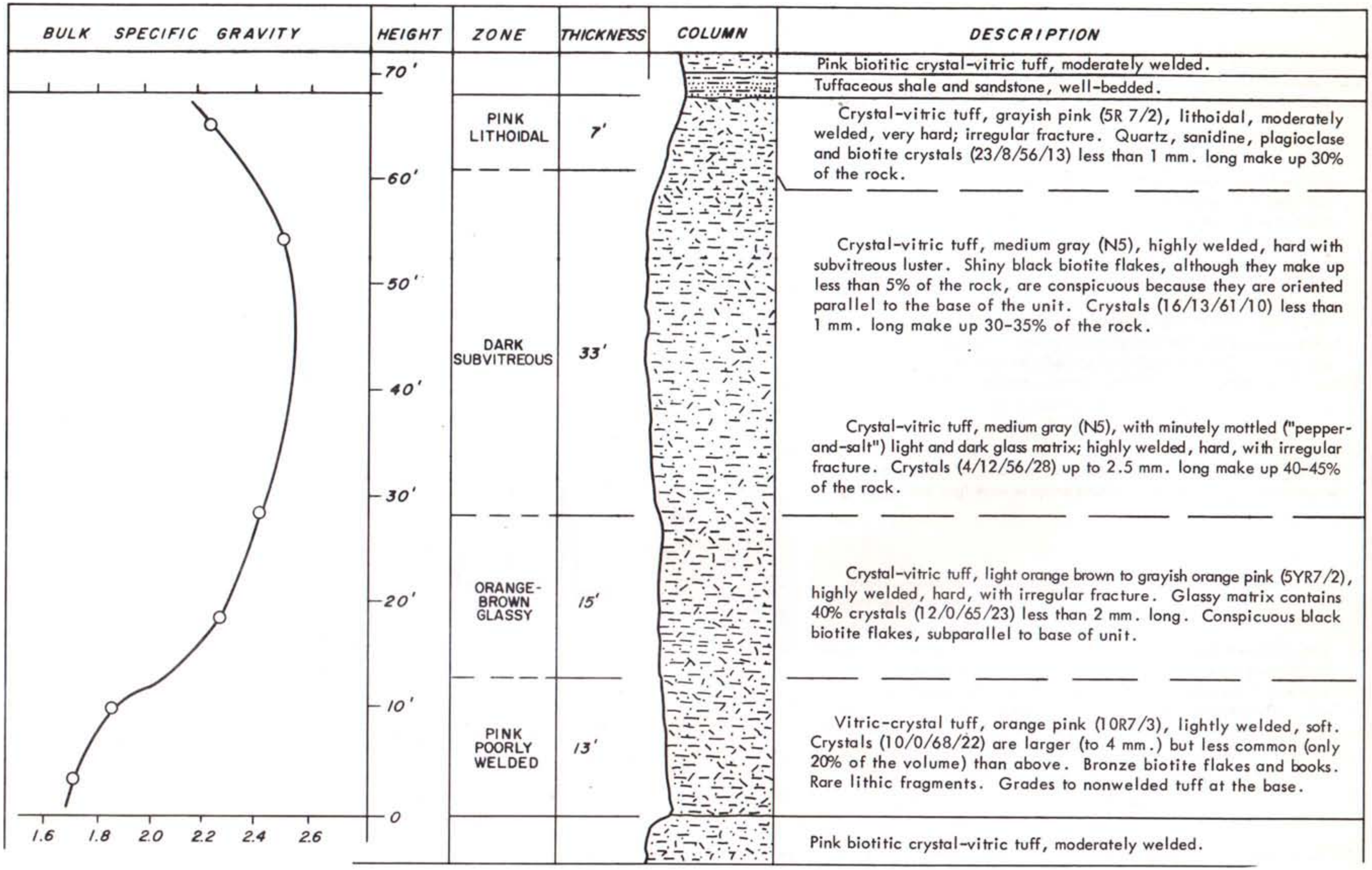
Except for those rare units that consist mainly of vitrophyre, zones of dense welding (vitrophyre and glassy lenticulite) in eastern Nevada ignimbrites are in the lower portions of the ignimbrites. Only rarely does the vitrophyric zone extend to the base of the unit; in such places there may be fused tuff (Ross and Smith, 1961, p. 26) at the top of the unit below.

During the Nevada field work, it was noted that the ignimbrites with the greatest thickness of nonwelded basal zone (like the Hiko Tuff, fig. 26, which has 240 feet of nonwelded tuff grading abruptly up into lenticulite) commonly overlie bedded ash that appears to be waterlaid. Bedded ash below ignimbrites is common, but has generally been ascribed to ash fall. For example, Ross and Smith (1961, p. 21) suggest that

> "...the nonsorted tuff immediately above and transitional with the bedded tuff is also ash-fall material that was deposited in such large volume by eruptions of increasing intensity that gravity sorting was inhibited. The ash fall was then followed by ash flows of the same composition and the contacts between the nonsorted fall tuff and the flow tuff are not discernible."

Nowhere in the eastern Nevada sections has any contact within the nonsorted, nonwelded basal material or between it and the overlying welded tuff or tuffbreccia been "discerned." It may be that none of this basal material--including the bedded ash--is of air-fall origin. The following is put forward as a working hypothesis which will be strengthened or thrown over by later field work. A *nuée* of 65 percent gas content (by volume) would be lighter than water and would float *on* any lake in its path. One can probably safely assume that most *nuées* contain at least that much gas; even after deposition, the nonwelded upper *portions of* ignimbrites have a minimum porosity of 50 percent (Smith, 1960a, p. 827). Chilled ash, crossing the phase boundary and settling in ponded water, might produce finely laminated deposits until there was no more opportunity for settling--when the available water was fully dispersed into interstices of the deposit. How far the chilling effect of water overflowed by a *nuée* might extend upward in the resulting deposit is a moot question, but it does seem *possible* that a deposit of glassy ash, itself a poor heat conductor, laid down at a temperature of 600 to 900° C, requiring some time to be welded, might lose enough heat to relatively cool water vapor (which at 300 psi water-vapor pressure, for example, couldn't be heated above 214° C while still in contact with liquid water)--streaming up into the deposit and displacing the original gases upward--to inhibit welding a considerable distance above the base of the deposit.

Some vertical variations in typical eastern Nevada ignimbrites studied by Martin (1957, 1959) are described in figures 25 to 28; the written descriptions have been slightly modified to incorporate the results of later work.



Pink biotitic crystal-vitric tuff, moderately welded.

Tuffaceous shale and sandstone, well-bedded.

Crystal-vitric tuff, grayish pink (5R 7/2), lithoidal, moderately welded, very hard; irregular fracture. Quartz, sanidine, plagioclase and biotite crystals (23/8/56/13) less than 1 mm. long make up 30% of the rock.

Crystal-vitric tuff, medium gray (N5), highly welded, hard with subvitreous luster. Shiny black biotite flakes, although they make up less than 5% of the rock, are conspicuous because they are oriented parallel to the base of the unit. Crystals (16/13/61/10) less than 1 mm. long make up 30-35% of the rock.

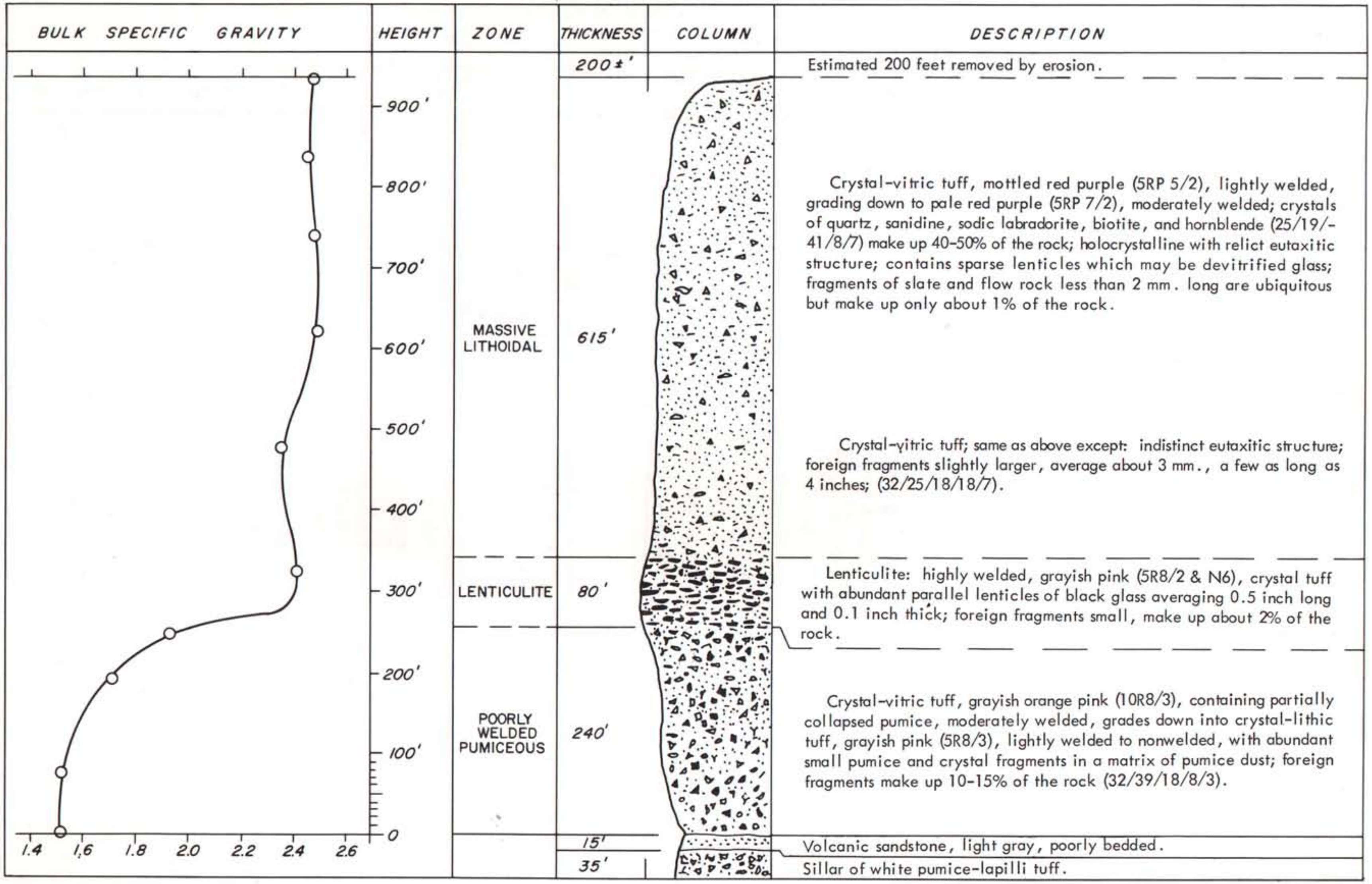
Crystal-vitric tuff, medium gray (N5), with minutely mottled ("pepper-and-salt") light and dark glass matrix; highly welded, hard, with irregular fracture. Crystals (4/12/56/28) up to 2.5 mm. long make up 40-45% of the rock.

Crystal-vitric tuff, light orange brown to grayish orange pink (5YR7/2), highly welded, hard, with irregular fracture. Glassy matrix contains 40% crystals (12/0/65/23) less than 2 mm. long. Conspicuous black biotite flakes, subparallel to base of unit.

Vitric-crystal tuff, orange pink (10R7/3), lightly welded, soft. Crystals (10/0/68/22) are larger (to 4 mm.) but less common (only 20% of the volume) than above. Bronze biotite flakes and books. Rare lithic fragments. Grades to nonwelded tuff at the base.

Pink biotitic crystal-vitric tuff, moderately welded.

FIGURE 25. Vertical variation in a thin crystal-vitric ignimbrite: data of Tvnr$_3$ member of the Needles Range Formation near Forest Home, Lincoln County, Nevada (revised from Martin, 1957, pl. 9).



Estimated 200 feet removed by erosion.

Crystal-vitric tuff, mottled red purple (5RP 5/2), lightly welded, grading down to pale red purple (5RP 7/2), moderately welded; crystals of quartz, sanidine, sodic labradorite, biotite, and hornblende (25/19/-41/8/7) make up 40-50% of the rock; holocrystalline with relict eutaxitic structure; contains sparse lenticles which may be devitrified glass; fragments of slate and flow rock less than 2 mm. long are ubiquitous but make up only about 1% of the rock.

Crystal-vitric tuff; same as above except: indistinct eutaxitic structure; foreign fragments slightly larger, average about 3 mm., a few as long as 4 inches; (32/25/18/18/7).

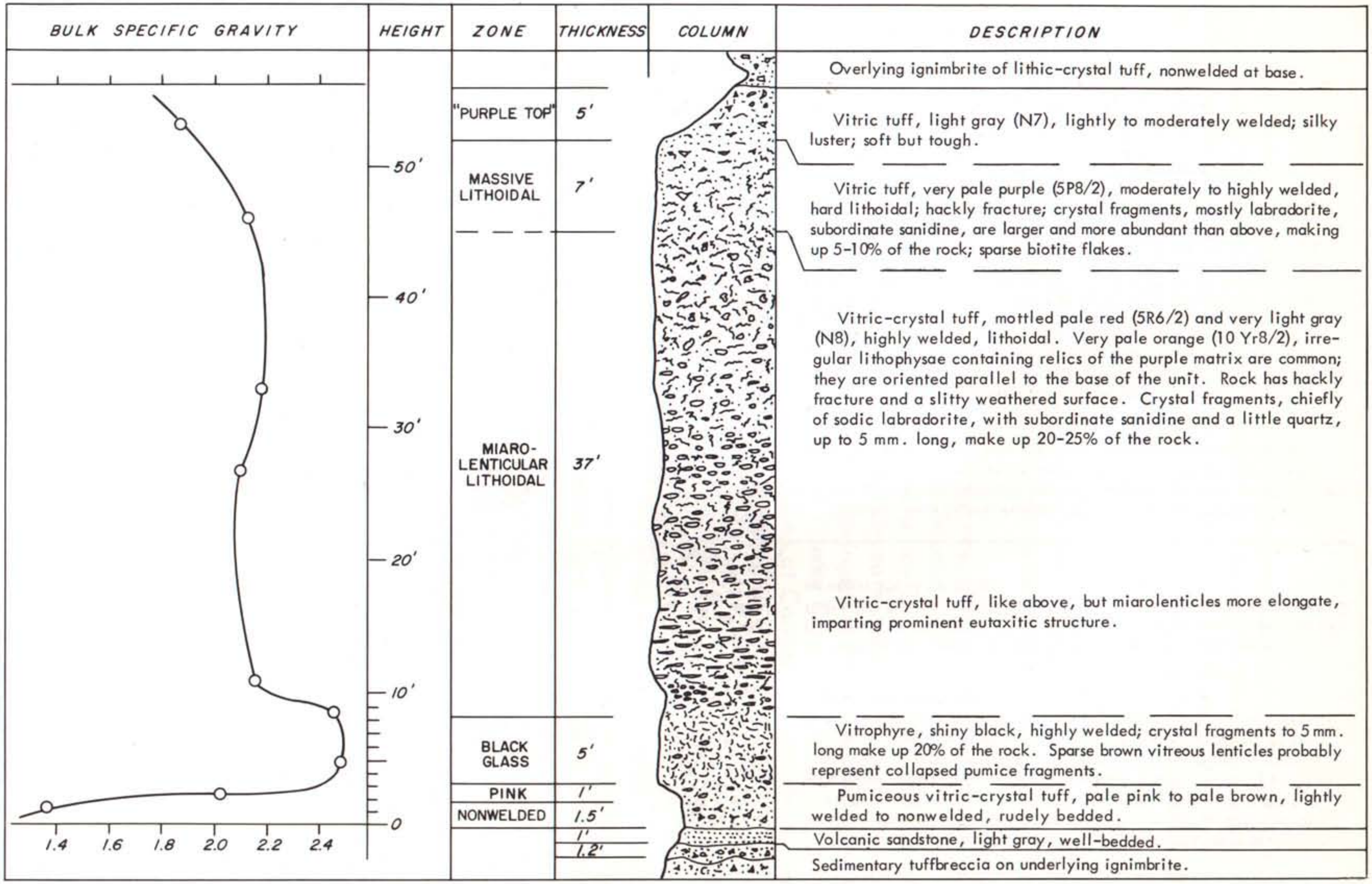
Lenticulite: highly welded, grayish pink (5R8/2 & N6), crystal tuff with abundant parallel lenticles of black glass averaging 0.5 inch long and 0.1 inch thick; foreign fragments small, make up about 2% of the rock.

Crystal-vitric tuff, grayish orange pink (10R8/3), containing partially collapsed pumice, moderately welded, grades down into crystal-lithic tuff, grayish pink (5R8/3), lightly welded to nonwelded, with abundant small pumice and crystal fragments in a matrix of pumice dust; foreign fragments make up 10-15% of the rock (32/39/18/8/3).

Volcanic sandstone, light gray, poorly bedded.

Sillar of white pumice-lapilli tuff.

FIGURE 26. Vertical variation in a thick crystal-vitric ignimbrite: data of the Hiko Tuff at its type section (revised from Martin, 1957, pl. 11).



Overlying ignimbrite of lithic-crystal tuff, nonwelded at base.

Vitric tuff, light gray (N7), lightly to moderately welded; silky luster; soft but tough.

Vitric tuff, very pale purple (5P8/2), moderately to highly welded, hard lithoidal; hackly fracture; crystal fragments, mostly labradorite, subordinate sanidine, are larger and more abundant than above, making up 5-10% of the rock; sparse biotite flakes.

Vitric-crystal tuff, mottled pale red (5R6/2) and very light gray (N8), highly welded, lithoidal. Very pale orange (10 Yr8/2), irregular lithophysae containing relics of the purple matrix are common; they are oriented parallel to the base of the unit. Rock has hackly fracture and a slitty weathered surface. Crystal fragments, chiefly of sodic labradorite, with subordinate sanidine and a little quartz, up to 5 mm. long, make up 20-25% of the rock.

Vitric-crystal tuff, like above, but miarolenticles more elongate, imparting prominent eutaxitic structure.

Vitrophyre, shiny black, highly welded; crystal fragments to 5 mm. long make up 20% of the rock. Sparse brown vitreous lenticles probably represent collapsed pumice fragments.

Pumiceous vitric-crystal tuff, pale pink to pale brown, lightly welded to nonwelded, rudely bedded.

Volcanic sandstone, light gray, well-bedded.

Sedimentary tuffbreccia on underlying ignimbrite.

FIGURE 27. Vertical variation in a vitric-crystal ignimbrite: data of the Bauers Ignimbrite in White River Narrows, Lincoln County, Nevada (revised after Martin, 1957, pl. 13).

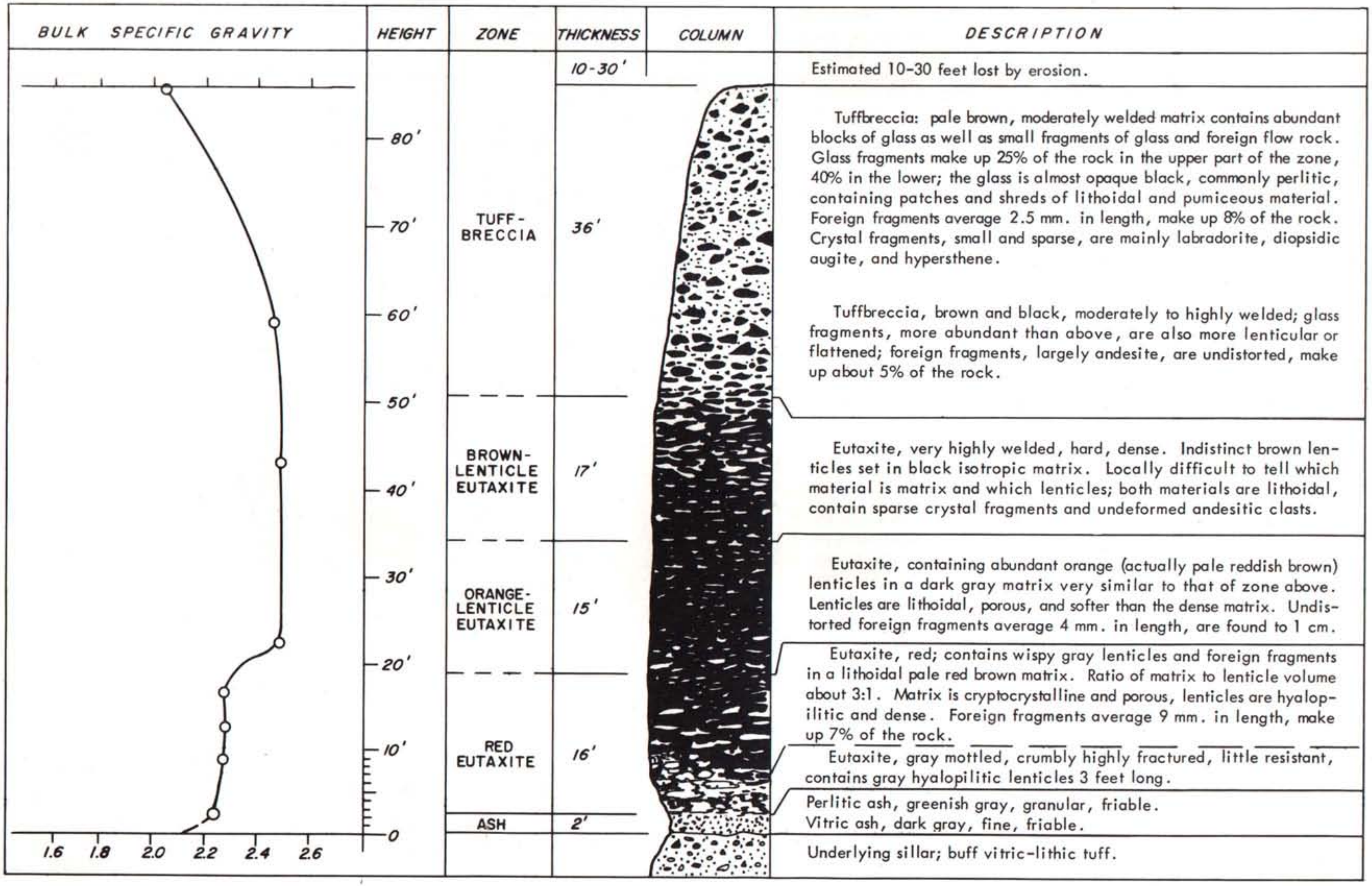


FIGURE 28. Vertical variation in a welded tuffbreccia ignimbrite: data of the Petroglyph Cliff Ignimbrite at White Rock Spring, Lincoln County, Nevada (revised after Martin, 1957, pl. 12).

Lateral Variations

Lateral variations in the eastern Nevada ignimbrites have not been studied in detail. A few inferences may be drawn, but their validity hinges on the correctness of the correlations made between sections. Lateral changes in welding, for example, seen in units like the Leach Canyon Tuff, which consists of hard, resistant welded tuff in the Iron Springs district, but is a soft nonwelded tuff in Condor Canyon 60 miles to the west, may be explained in several ways:

(1) Loss of heat away from the source (presumably nearer Iron Springs than Condor Canyon) prevented welding of the sheet at Condor Canyon.

(2) The two sections represent different ignimbrites, petrographically similar except for the degree of welding.

(3) Lateral variation in welding due to differences in thickness, illustrated by Smith's (1960b, pl. 20-D) description of zonal variations in welded ash flows. This change in degree of welding with change in thickness may be seen in the Leach Canyon Tuff at Petroglyph Cliff (see fig. 29). In this hypothesis a thick nonwelded zone has been eroded from the formation in the Iron Springs district; the welded zone there is due to an original thickness greater than at Condor Canyon.

(4) Some unknown factor inhibited welding at Condor Canyon--or induced it at Iron Springs.

(5) The correlation is incorrect.

Lateral variations in the Windous Butte Formation indicate that it is a composite sheet (for a discussion of composite sheets see Smith, 1960a, p. 812 -813; 1960b, p. 158). In the Egan and Grant Ranges the two ignimbrites of the formation cooled in such a way that the contact is within welded tuff; in some places it is a clear contact, in others gradational. In the southern Pancake Range, the same contact, within nonwelded tuff, shows that the two ignimbrites in that locality are separate and distinct cooling units.

Lateral variation studies of Great Basin ignimbrites are needed, to define the limits of variability of physical and chemical properties (which knowledge would provide a basis for evaluating correlation techniques), and to determine whether some physical property like the size of crystals or lithic fragments may show a pattern of variability that would lead to recognition of source areas (source is not known for any of the eastern Nevada ignimbrites: feeder dikes have not been found; the highest isopach for any unit outlines the lowest spot in the area of deposition, but does not necessarily indicate the source area).

ORIGIN OF THE IGNIMBRITES

Review of Hypotheses

Petrographers and field geologists have long been puzzled by the physical aspects of volcanic rock units that seem to grade from lava rock into tuff and, locally or overall, share the characteristics of both rock types.

The excellent reviews by Smith (1960a, p. 801-810) and by Ross and Smith (1961, p. 8-14) of the development of concepts of origin of such deposits make it unnecessary to more than briefly sketch existing hypotheses and their historical background.

The outbursts of Mont Pelé in Martinique in 1902, and the descriptions of the pyroclastic flows that Lacroix (1902, p. 1305) named "nuées ardentes" provided geologists with a possible explanation of the lava-tuff deposits. Within a few years, rocks in Wales, France, Germany, Japan, and Italy were interpreted as deposits of "Péléan origin." Many geologists remained unwilling to extrapolate the Péléan phenomena to cover the origin of large rhyolite and dacite sheets. After the interpretation in Péléan terms of the Katmai "sand flow" by Fenner (1920), however, realization began to spread that certain features of the large acidic sheets might be explained by a nuée origin. In New Zealand the sheet rhyolites of the North Island were named ignimbrites (fiery cloud rocks) by Marshall (1932) who postulated a Katmaian eruptive origin for them. Since the early 1930's many papers have been written describing deposits of "nuée ardente," "tuff flow," "ash flow," "glowing avalanche," or "pyroclastic flow" origin.

No matter what the name preferred, the eruptive mechanism is visualized as a hot, rapidly expanding, turbulent, highly mobile magmatic gas flow which, erupting from a volcano or from a fissure (or even several fissures simultaneously), carries with it intratelluric crystals and liquid droplets from the exploding magma, as well as rock fragments torn from the vent or swept up from the ground surface. At least the lower part of such a flow consists of a density or turbidity current, which carries by far the greater part of the pyroclastic matter and from which rises a continuously dissociating cloud of gas and fine particles. The ground-hugging density current, impelled by gravity, moves swiftly, seeking out depressions; its competence to carry material in suspension is a function both of turbulence and density (or viscosity), but probably is primarily dependent upon high turbulence. The solid, plastic, and liquid components of the current, upon dissociation of the gas, collapse together, and in the case of the hotter flows may become more or less firmly welded together.

The principal opposing hypothesis of origin for ignimbrites is that they result from either highly gaseous or pumice-charged lava flows or both.

Puzzling features of the "tufflavas" of Armenia were ascribed by Abich (1882) to the consolidation of a "frothy" flow. Iddings (1899) explained clastic texture in some Yellowstone Park rhyolites as either the result of collapse of pumice fragments in a liquid flow or of the formation of pumice and shards by vesiculation at and near the surface of the flow. Kennedy (1955) held that the same Yellowstone rocks, called welded tuffs by Boyd (1961) and C. S. Ross (1955), are "collapsed froth flows." Grange (1934, 1937) regarded the New Zealand ignimbrites as flow rocks; Steiner (1960) believed them to be the consolidated products of heterogeneous, immiscible acid lavas. Hausen (1954) regarded welded tuff in Oregon and Idaho as the result of "expanding lava" rather than condensing pyroclastic material.

Favorskaya (1956, p. 192-93; 1957) considered certain ignimbrites in eastern Siberia to be true flow rocks in which the characteristic parallel lenticular inclusions represent plastic fragments flattened in a viscous flowing mass. Vlodavets (1953, 1957) and Beliankin (1952) also supported a flow origin for ignimbrites.

The arguments of these opponents of the nuée ardente or ash-flow hypothesis may be summarized as follows: (1) no historic nuée has been known to leave a welded deposit; (2) all historic nuées issued from volcanoes and left relatively small, andesitic deposits, whereas the large, sheet ignimbrites were probably derived from fissure eruptions and are mainly rhyodacitic; (3) no one has ever seen a nuée of anything like the size that would be required to form an extensive ignimbrite; and (4) the features of ignimbrites - they assert - can be produced in other ways.

Analysis of Evidence From Eastern Nevada

Evidence from field and laboratory studies of the ignimbrites of eastern Nevada strongly indicates that most of these ignimbrites represent the deposits of nuées ardentes[7] and that lava flows played no part in their origin.

The strongest evidence is the orderly downward gradation within a single unit from nonsorted, incoherent ash and lapilli closely resembling deposits of historic nuées, into hard lava-like rock showing, under the microscope, progressive flattening and fusion of glass shards as the degree of hardness of the rock increases. The nonwelded basal zones common to most of the ignimbrites are compelling evidence, for they are not explained by the frothy or autovesiculating lava-flow hypothesis; this nonwelded basal zone is probably a chill facies composed of material which, although plastic or even liquid in the cloud, was quenched so quickly by contact with a cool surface beneath the nuée that individual particles could not cohere; the zone is in sharp contrast to the glassy, brecciated basal chill zone of a lava flow.

There is neither banding nor lineation in the typical eastern Nevada ignimbrite, again in contrast to the characteristics of most lava flows of similar composition. It is only fair to say, however, that some of the most highly welded units in the Great Basin locally show lineation, like that described by Kuellmer (1954, p. 48) from a "tuffaceous rhyolite" in New Mexico, and that some of the thicker units lack vitroclastic texture, like the dacitic ignimbrite described by Peterson (1959) from Arizona.

Such lineation is probably the result of local flowage after deposition of extremely hot units; ignimbrites with a history of flowage after deposition have been described and called rheo-ignimbrites (Rittmann, 1958, p. 528). Lack of vitroclastic texture probably results from destruction of the shard outlines by crystallization.

Amount of Compaction

A measure of the amount of compaction that takes place upon dissociation of the gas in a pyroclastic flow may be had from simple calculations based on the relations of volcanic units at Petroglyph Cliff[8], north of the narrows of White River on Nevada Highway 38 in Lincoln County (fig. 29), where a thick trachyte flow with a stubby margin has been covered by three ignimbrites, each of which thins over the topographic high created by the lava flow. The degree of thinning is greatest in the oldest of the three and least in the youngest; the percentage of thinning decreased because the relief was reduced after the deposition of each ignimbrite. Differential compaction of each ignimbrite kept the topographic high in existence, although successively reduced in height.

If we assume horizontality of the surface of each of the flows just before settling, we may calculate a compaction factor from the formulas

---

[7] Nuee ardente is used here in a loose, but widely accepted, sense. The dual nature of the moving mass that results from a nuee ardente type of eruption was clearly recognized by Lacroix (1904, p. 350) who described (a) the large cloud of gas and fine particles that rises from (b) a much denser turbidity current or pyroclastic flow. Ross and Smith (1961, p. 6) emphasize both the importance of this basal portion of the nuee in the formation of "ash-flow tuffs" and the fact that it is the "noncloud portion of a glowing cloud."

[8] The significance of this outcrop was first recognized by J. H. Mackin in 1955.

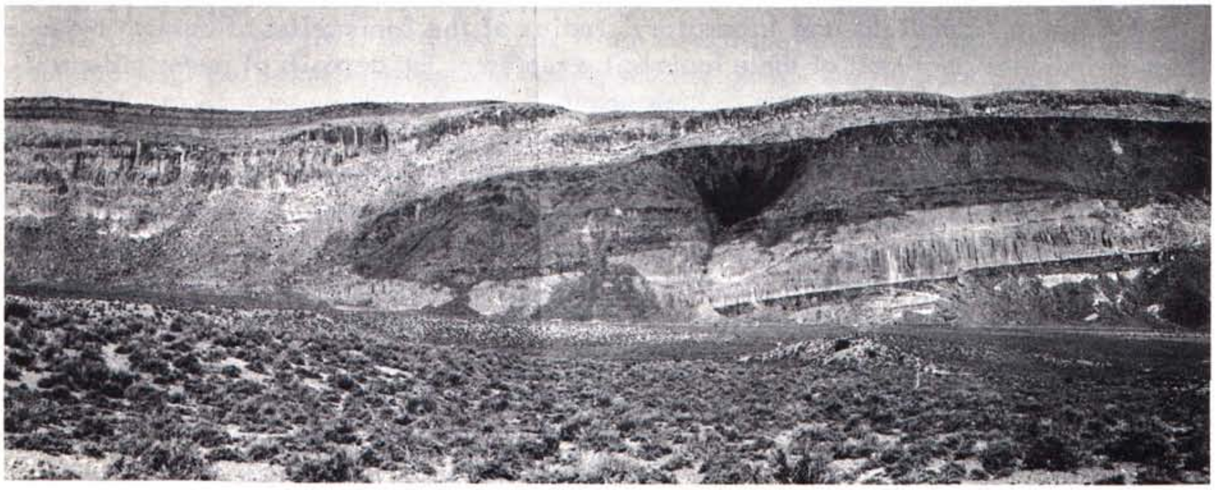
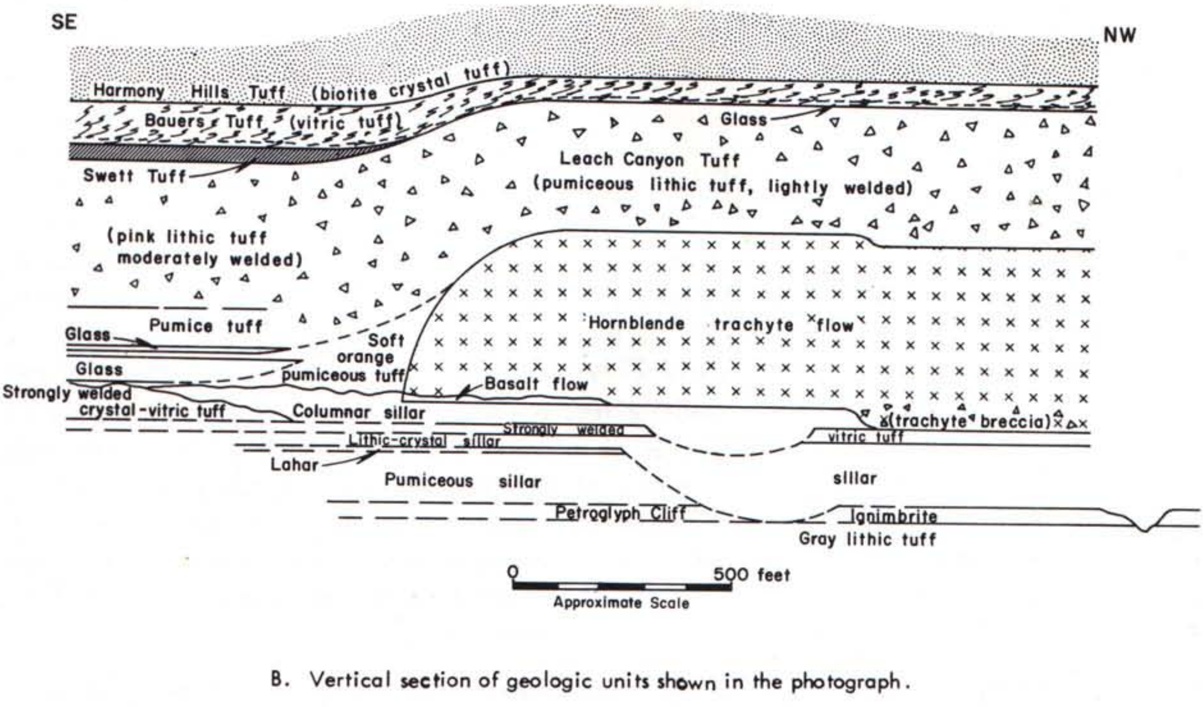


FIGURE 29. A. Photograph of geologic relations at Petroglyph Cliff, north of White River Narrows, Lincoln County, Nevada.



B. Vertical section of geologic units shown in the photograph.

$$(T_n - H)\ c = T_h$$

$$T_n c = T_1$$

where T_n = thickness of the pyroclastic flow

H = height of topographic obstacle

c = compaction factor

T_h = thickness of ignimbrite over the high

T_1 = thickness of ignimbrite over adjacent low

In the case of the Leach Canyon Tuff, $H = 287$ feet, $T_h = 300$ feet, and $T_1 = 440$ feet. Solution of the two equations for T_n gives 900 feet as the thickness of the pyroclastic flow. Substitution of that figure in either equation gives 0.49 for *c*, representing a compaction to slightly more than half the "original" thickness.

Compaction factors can be calculated only for the Leach Canyon and Bauers units. Because the Swett Ignimbrite was unable to surmount the rise that faced it, only a minimum figure for *c* can be caluclated for it. The results are:

Unit	c	Percent compaction
Bauers Ignimbrite (highly welded vitric-crystal tuff)	0.375	59
Swett Ignimbrite (highly welded vitric tuff)	0.26 min.	77 max.
Leach Canyon Tuff (lightly to moderately welded crystal-lithic tuff)	0.49	51

There is some uncertainty as to which horizon represents the base of the Leach Canyon Tuff on the left (southeast) side of the cross-section. Assumption that the base is the top of the "pumice tuff" (instead of its bottom) would give a c of 0.205 and a compaction of 81 percent; in light of the result obtained for the highly welded Bauers tuff, which seems to be more strongly compacted than the Leach Canyon Tuff, this high compaction appears improbable. On the other hand, degree of welding does not have to be a direct function of compaction (defined as decrease in thickness from original flow of gas-solid emulsion to resulting compacted deposit) and probably is not. A suspension capable of carrying lithic fragments of some size probably requires a considerable quantity of turbulent gas per fragment, more so than a cloud carrying only light magma bubbles and droplets; consequently, compaction *could* be greater in a nonwelded deposit of tuff-breccia than in a highly welded vitric ash tuff. It should be remembered that there are two phases of compaction in an ignimbrite: (1) disengagement of gas as the particles fall together, and (2) expulsion of gas as the particles are flattened and welded; only the latter phase is reflected in flattened pumice and compacted shards.

STRUCTURAL IMPLICATIONS OF THE VOLCANIC RELATIONS

Progressive Subsidence

The volcanic column has been divided arbitrarily into four volcanic "groups"of about equal thickness in order to study any changes in distribution that may have occurred with time. These groups will not be given formal names here because they contain unnamed formations (see Amer. Comm. Strat. Nomenclature, 1961).

Successively younger groups show progressive displacement or offlap (fig. 30) toward the south and southeast. Although this displacement can be seen in a line of sections (fig. 6), which clearly indicates that the older formations were deposited in the north and that younger formations were deposited each in its turn farther south, the full picture is better shown by isopach maps of the four groups.

Group A (fig. 31), the oldest, is restricted to the northern half of the area studied. The isopachs show two axes of greatest thickness, one N 50-60°E, the other N 30°W. Because the units involved are mainly ignimbrites, the axes of greatest thickness are also axes of greatest basin depth. A valid inference is that subsidence along these axes either prior to volcanism, during volcanism, or both, created the topographic depressions in which the ignimbrites accumulated. There is no north-south trend in this map.

Group B (fig. 32) in its depositional basin is displaced to the southeast from Group A, although there is a large area of overlap. The group B isopachs show only a northeast trend.

The thickest part of group C (fig. 33) lies south of the group B basin. For the first time, one north-south element appears, at the east end of what seems to be a curved axis of depression.

The axis of group D (fig. 34), the youngest and southernmost, parallels the outer convex boundary of the ignimbrite province, trending roughly N 50-70°E.

The composite isopach map of eastern Nevada Tertiary volcanic rocks (fig. 35) shows no clear pattern. Although some of the north-south fracture lines that now dominate the present structure of eastern Nevada may have originated during ignimbrite volcanism, the main trend of subsidence during the volcanism was N 50-60°E. Modern basin-range topography originated after the extrusion of the ignimbrites.

The foregoing discussion is based on the concept that ignimbrites tend to follow and fill depressions rather than to build up around centers of eruption. It follows that displacement of the area of ignimbrite accumulation during geologic time means progressive subsidence rather than migration of eruptive centers - although the two may well have been coincident.

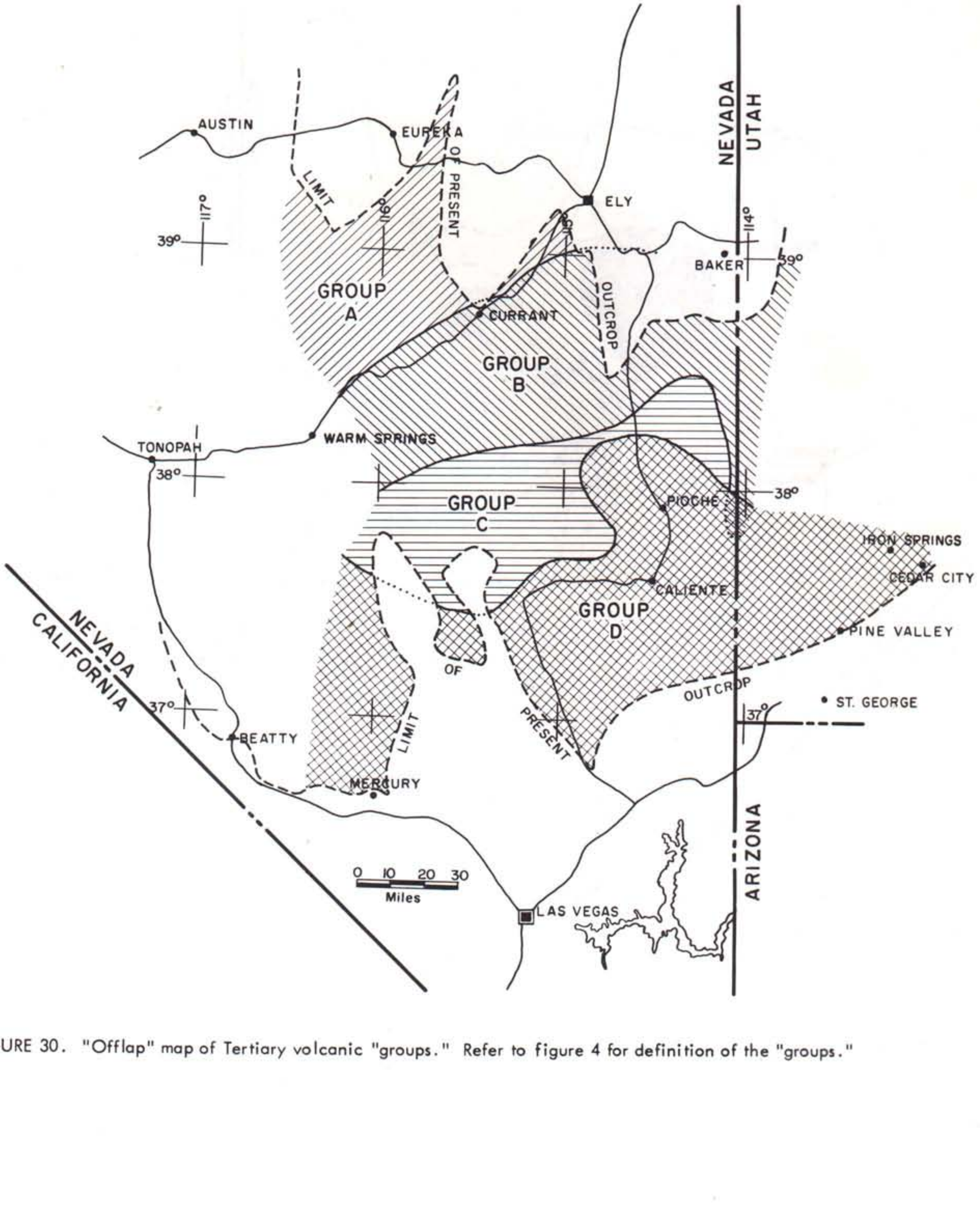


FIGURE 30. "Offlap" map of Tertiary volcanic "groups." Refer to figure 4 for definition of the "groups."

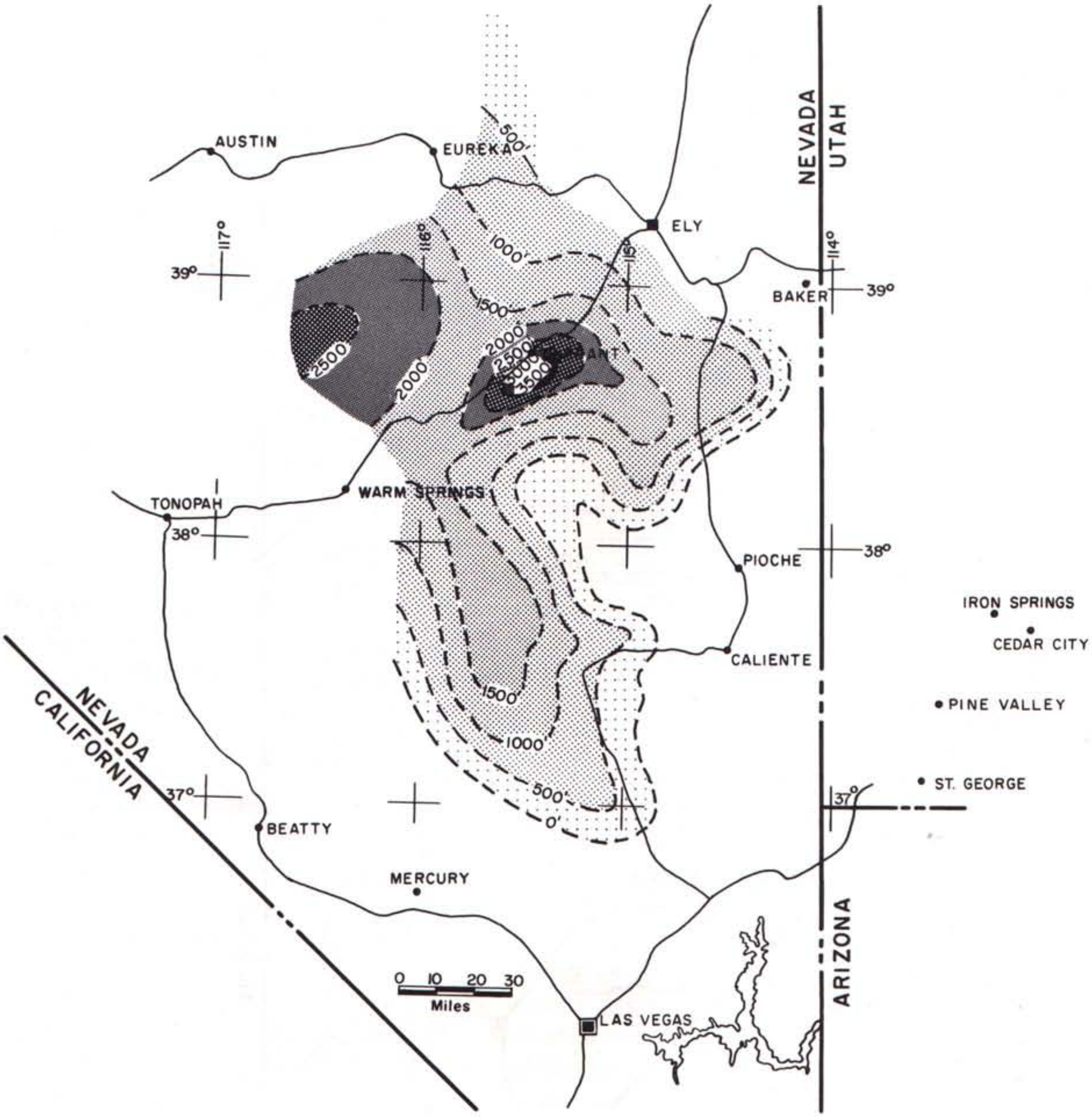


FIGURE 31. Isopach map of Tertiary volcanic group A -- the Stone Cabin and Windous Butte Formations.

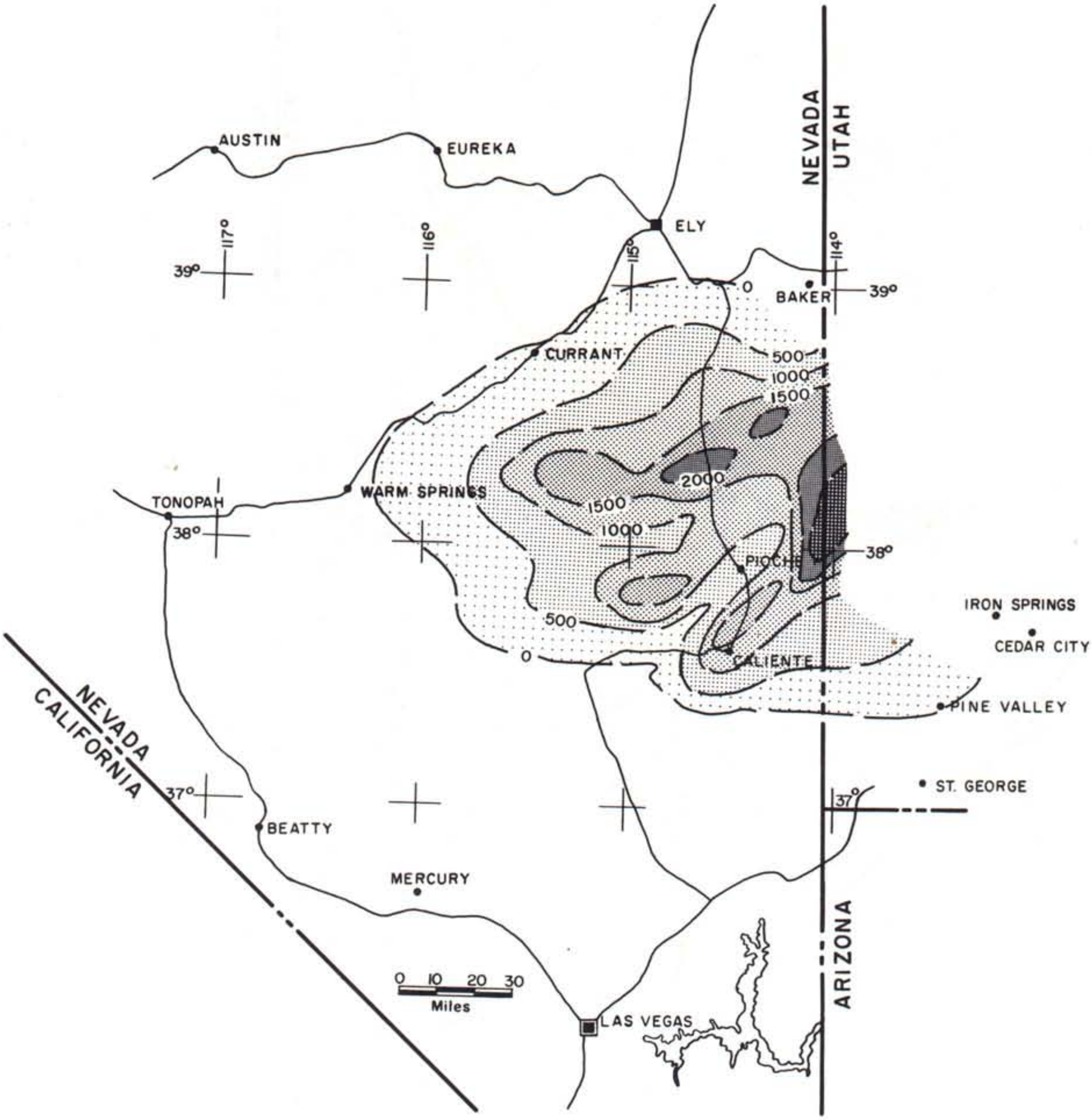


FIGURE 32. Isopach map of Tertiary volcanic group B -- the Needles Range Formation and Pahroc Sequence.

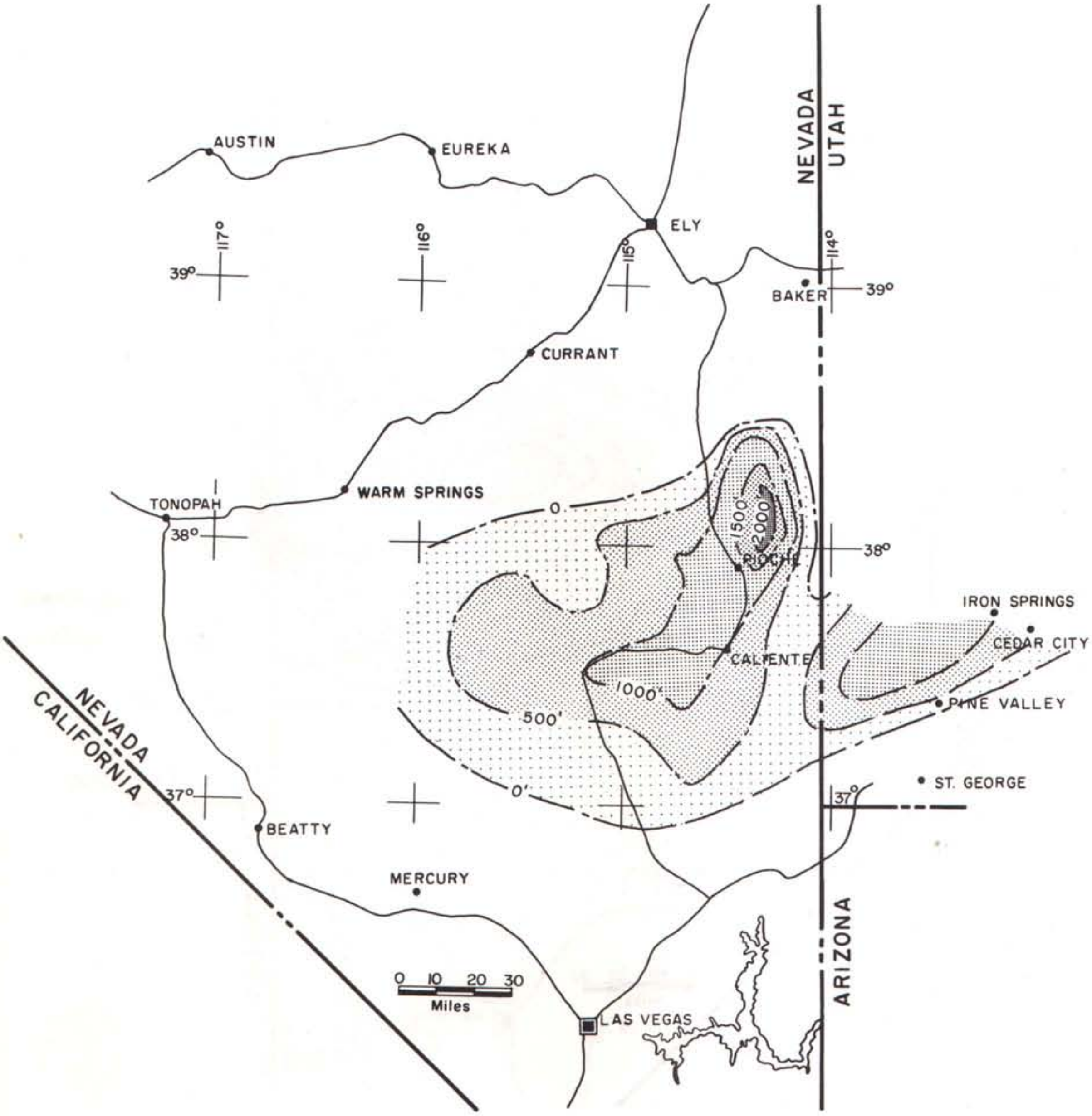


FIGURE 33. Isopach map of Tertiary volcanic group C -- the Leach Canyon Tuff, Condor Canyon Formation, Harmony Hills Tuff. This group equals the Quichapa Formation in southwestern Utah.

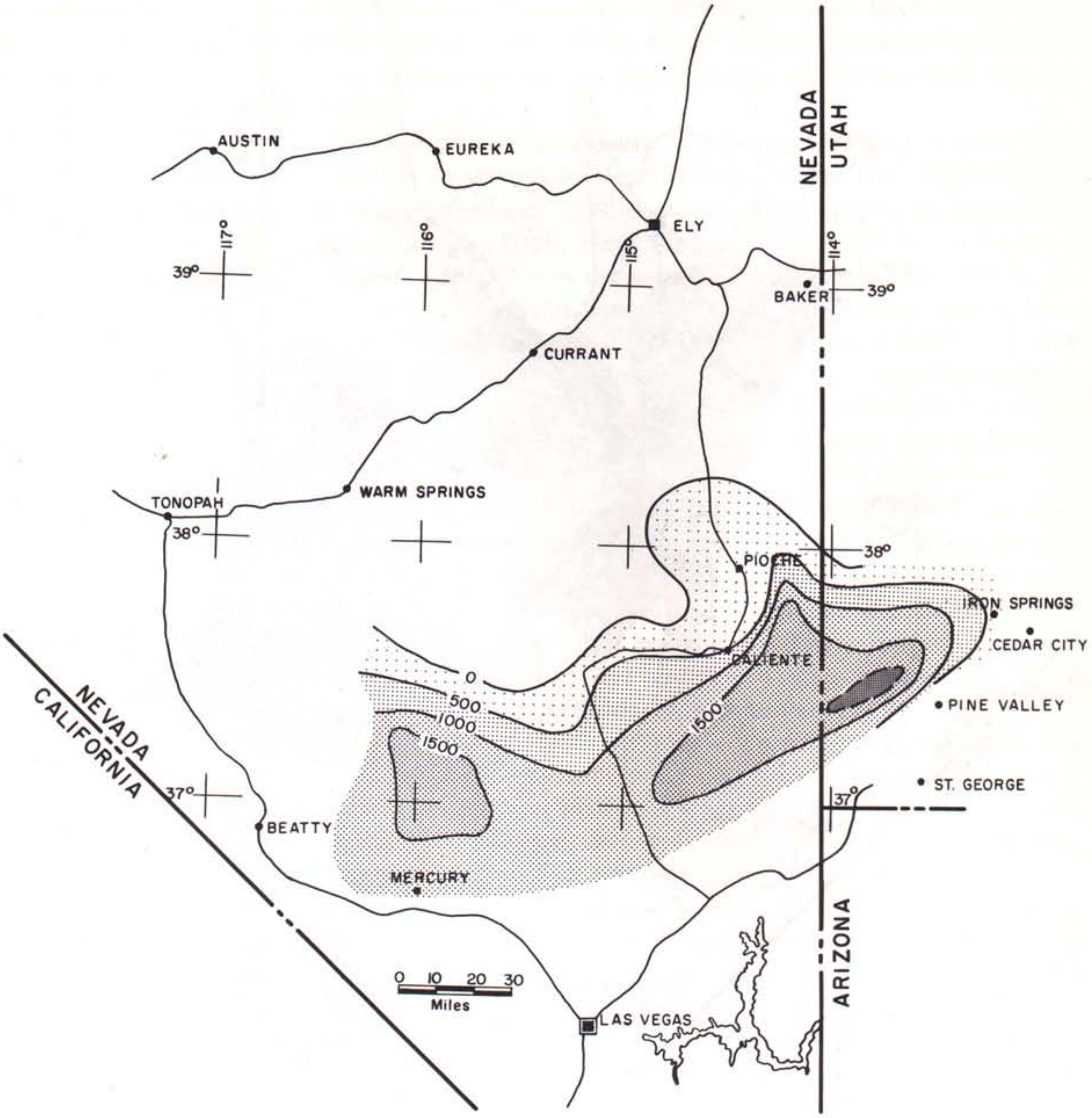


FIGURE 34. Isopach map of Tertiary volcanic group D -- the Rencher Formation, Page Ranch Formation, and Kane Wash Formation.

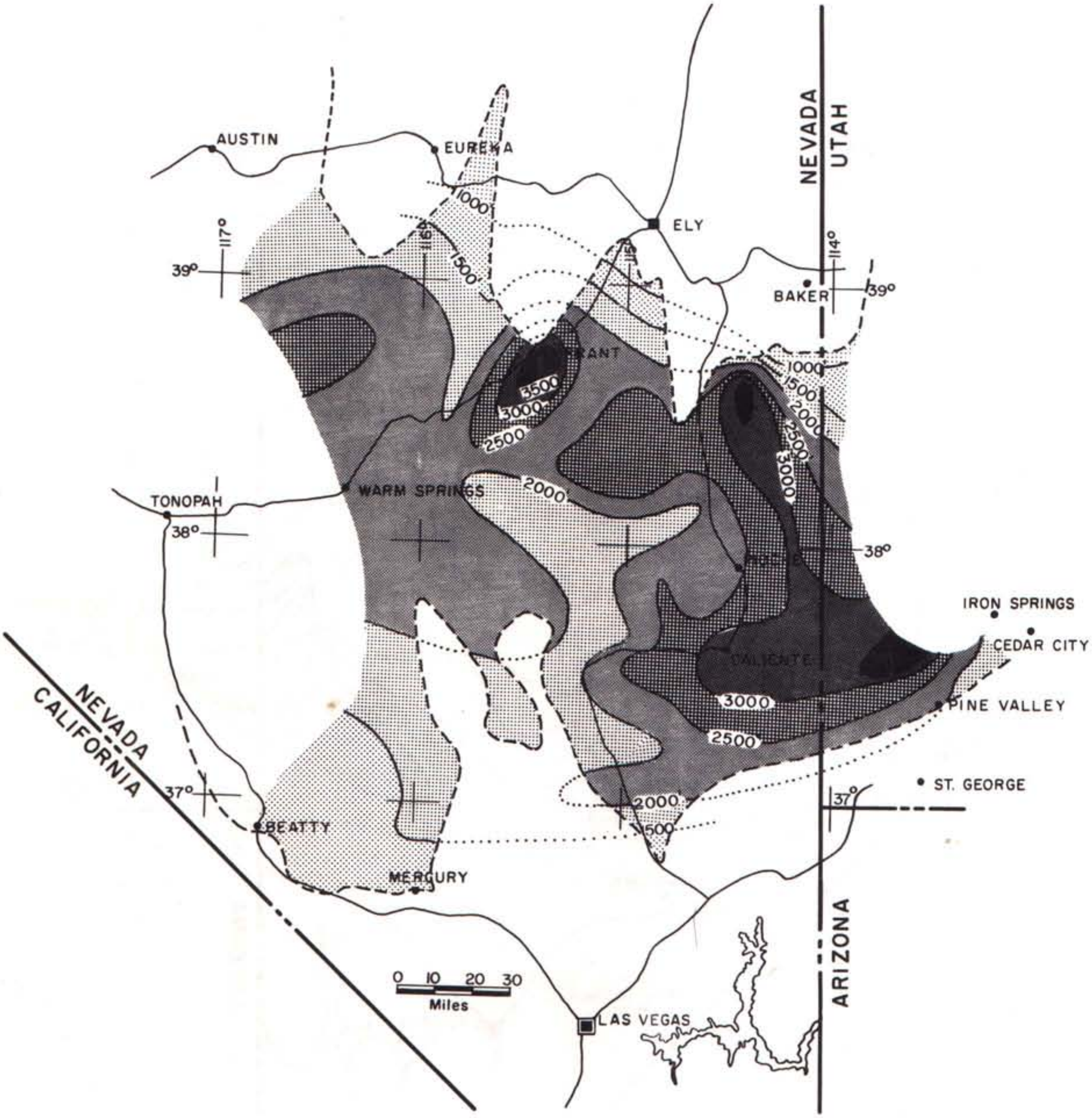


FIGURE 35. Composite isopach map of Tertiary volcanic rocks of eastern Nevada.

Coincidence of Subsidence with Volcanism

Mackin (1960, fig. 3, p. 100) points out that the Claron sediments in southwest Utah were derived chiefly from Laramide thrust ranges to the northwest, and that the eruptions which produced the Needles Range ignimbrites must have been immediately preceded or accompanied by foundering of these thrust ranges, because the Needles Range ignimbrites are thicker in some places on the old highland terrain than they are on the Claron farther southeast.

Study of ignimbrite stratigraphy in southeastern Nevada and southwestern Utah along a line of sections extending west from the Iron Springs district (fig. 36) indicates a similar abrupt subsidence of western highlands coincident with early ignimbrite volcanism.

In northwestern Washington County, Utah, near the Bull Valley district, a Laramide thrust sheet is clearly the source of the Claron sediments in that area (Cook, 1960b, p. 32). The position of a thin unit of the Needles Range Formation within the upper Claron Formation shows that Claron sedimentation continued undisturbed for a short time after Needles Range volcanism. To the west in Nevada, the Needles Range Formation is considerably thicker and in most sections rests directly on Lower Paleozoic rocks: unless this part of Nevada had exterior drainage from which the Claron basin was isolated by a continuous divide, subsidence here had already started in Needles Range time. But subsidence couldn't have started long before the Needles Range eruptions, for in most of the southeast Nevada sections the Needles Range Formation lies on a clean erosion surface cut on Paleozoic rocks, without the sediments that would be expected from subsidence, especially from subsidence that either accentuated or produced a basin of interior drainage. There can be little doubt that such a basin existed at least from the onset of volcanism; otherwise, the ignimbrites would not have been so well contained within areas whose boundaries can be plotted with considerable assurance.

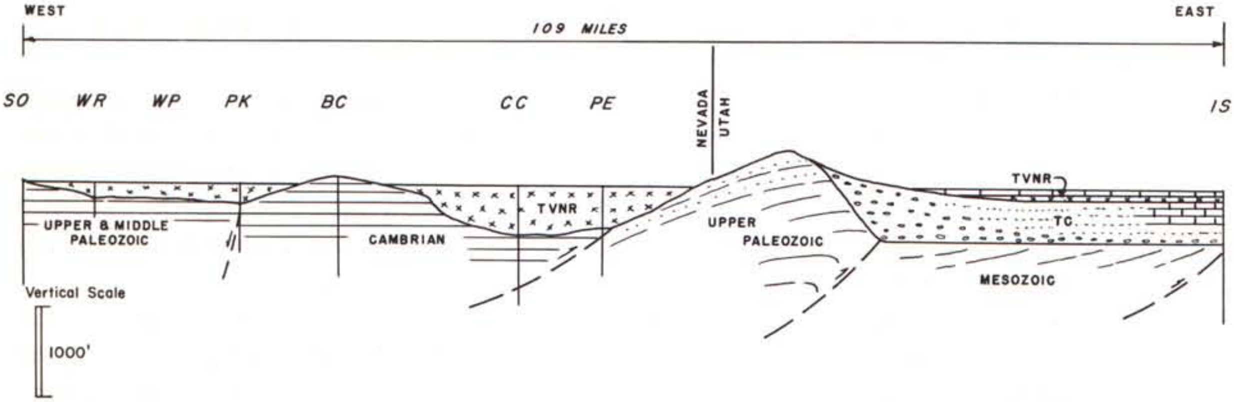
Following Needles Range volcanism, steptoes of Paleozoic rocks, standing above the ignimbrite plain, continued to provide limy sediments that accumulated in low places on the plain. This sedimentation was not confined to the Claron area of southwest Utah; far to the west in the Seaman Range of Nevada, white lacustrine limestone (section WR, fig. 6) and limestone conglomerate (section SO) overlies Needles Range tuff.

The Pahrock sequence, thin or absent in the Iron Springs district, thickens greatly but erratically westward in Nevada, where it extends beyond the area of Needles Range deposits. The conclusion seems inescapable that rapid subsidence provided the uneven-floored basin in which the Pahrock volcanic rocks accumulated in eastern Nevada. Abrupt changes in thickness of the Pahrock sequence suggest differential foundering along faults.

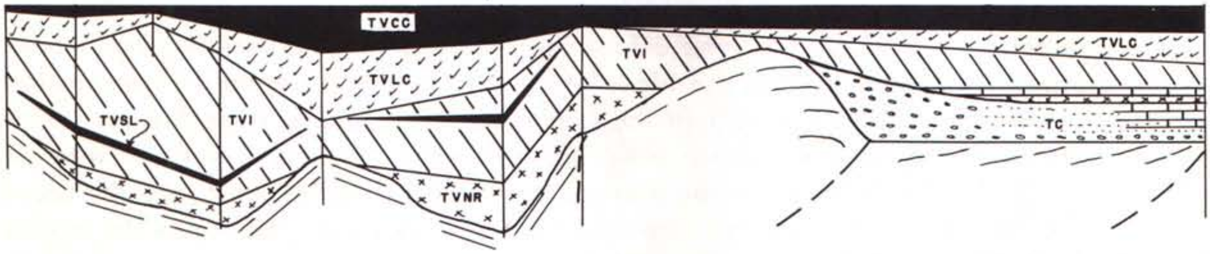
Relief produced by differential subsidence was obliterated by Pahrock volcanism, for the Leach Canyon Tuff and the thin Swett and Bauers Ignimbrites extend unbroken from the Colorado Plateau across southeastern Nevada, an extent that can only be explained in terms of a relatively flat pre-Leach Canyon surface.

Reflection of Subjacent Structure

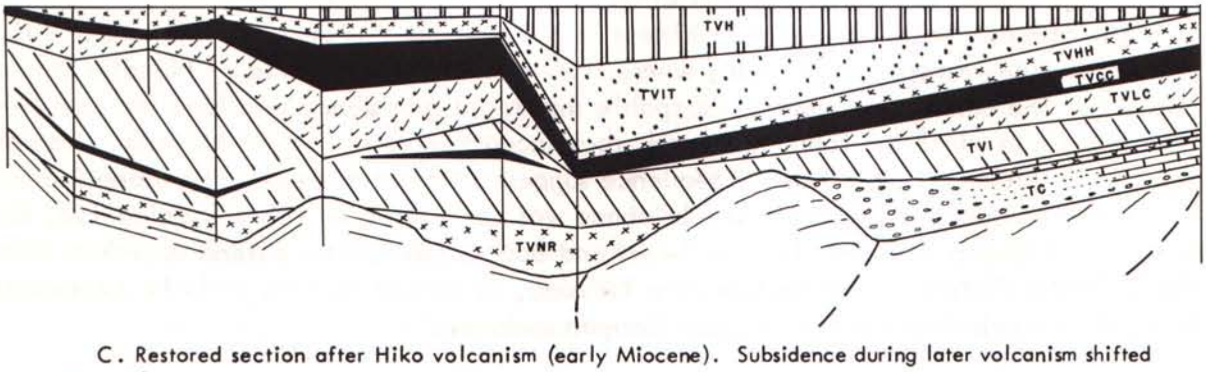
In eastern Nevada the Tertiary volcanic rocks rest on sedimentary "basement" rocks ranging in age from Cambrian to Triassic. Because prevolcanism deformation was sharply localized along axes that trend east of north, leaving between the narrow belts of deformation broad areas of undeformed Paleozoic rocks, the ignimbrites in many sections



A. Restored section at close of Needles Range time (late Oligocene). Some subsidence of the Nevada portion of this section immediately preceded the deposition of the Needles Range tuff, which rests directly on Paleozoic rocks in Nevada but is interbedded with penecontemporaneous sediments in Utah. The vertical scale is greatly exaggerated. The highland of Upper Paleozoic rocks is a Laramide thrust range; the fault beneath it is the Castle Cliff thrust. The two faults farther west are inferred, in order to explain changes in age of the Paleozoic rocks beneath the volcanic rocks.



B. Restored section after Condor Canyon volcanism. Subsidence in west greater than in east since Needles Range volcanism.



C. Restored section after Hiko volcanism (early Miocene). Subsidence during later volcanism shifted eastward.

FIGURE 36. Restored sections across Southeast Nevada and Southwest Utah. Reconstructions are based on measured sections shown in Figure 6. Units shown are Hiko Tuff - Tvh; Irontown member of the (early Miocene) Page Ranch Formation - Tvit; Harmony Hills Tuff - Tvhh; Condor Canyon Formation - Tvcc; Leach Canyon Tuff - Tvlc; Pahrocksequence - Tvp; Petroglyph Cliff Ignimbrite - Tvsl; Needles Range Formation - Tvnr; Claron Formation - Tc.

are essentially parallel to the underlying sedimentary rocks - although the hiatus represented by the contact in some cases spans most of the Paleozoic and all of the Mesozoic era. In other words, the attitude of the volcanics in many places reflects the attitude of the subjacent sedimentary rocks; locally, however, where prevolcanism folds were beveled by erosion before the volcanism, the angularity of the unconformity is great.

These relations do not imply complete crustal quiescence between the last Laramide movement and the ignimbrite volcanism. Faulting did occur within this time span, and there may have been regional uplift, but the vertical component of such movements did not vary much from place to place - in other words, there was very little tilting.

In the northwestern part of the area studied - in the central Egan Range, the Grant Range, the White Pine Mountains, and the Pancake Range - the regional disconformity (except where Laramide structural features are overlaid) at the base of the volcanic sequence changes into an angular unconformity. In most places in these ranges, however, the angularity is not great: the volcanic rocks commonly dip in the same direction as the underlying Paleozoic rocks but at somewhat lesser angles.

Prevolcanism Faults

In the Egan Range, Kellogg (1960, p. 195-196) recognizes two groups of northeasterly trending faults: one that originated before deposition of the Eocene sedimentary rocks in the range, the other during the initial stages of uplift "in the latest Eocene or earliest Oligocene." In other ranges, prevolcanism northeasterly structural trends are reflected by local valley fills of Wasatch-type sediments and early ignimbrites. Difficulties encountered in tracing ignimbrites from south to north, contrasted with the facility with which they may be followed from east to west, strongly suggest that some of these northeast-trending faults were active during volcanism; the trends of the axes of thickest ignimbrite accumulation in the isopach maps of the four volcanic groups lend support to the hypothesis.

In the Egan Range, movement took place on the Shingle Pass fault, which strikes slightly north of east where it can most accurately be mapped, just before the start of the ignimbrite volcanism; large exotic blocks of limestone slid from the new fault scarp into a lake basin north of the fault (Kellogg, 1960, p. 196), to be buried soon after by tuffaceous sediments and ignimbrites.

One cannot help being struck by the evidence of coincidence of northeast to east faulting and ignimbrite volcanism. The complex intrusive and extrusive rocks of the Robinson (Ruth) mining district near Ely, which mark that area as one of the most likely sources of the Group A ignimbrites, are in an easterly trending zone. But even if regional faulting did accompany volcanism, the "chicken-egg" question - did the flatulent magmas forcibly rupture their roof, thereby producing the faults, or did faulting of some other origin release the magmas - is far from solved.

Post-volcanism Horizontal Displacements

Although in several places in eastern Nevada and southwest Utah, Tertiary volcanic rocks have moved laterally on low-angle faults, and in a few places pre-Tertiary rocks rest upon Tertiary volcanic rock, nowhere has unequivocal evidence been presented that the volcanic rocks have participated in thrust faulting. Most of these occurrences can equally well or better be explained by gravity sliding.

At Iron Mountain, in the Iron Springs district of southwestern Utah, lateral movements of blocks and slices of Tertiary ignimbrites and the underlying Claron Formation are ascribed by Mackin (1960, p. 119-122) to gravity sliding from an intrusive dome. In the northern Schell Creek Range, northeast of Ely, Nevada, Young (1960, p. 168) interprets structural relations to indicate that Tertiary volcanics are in local thrust contact on older rocks, but cautions that "...more work is required on this relationship in order to prove or disprove it." Westgate (Westgate and Knopf, 1932, p. 42-43) described a post-volcanic thrust plate of greatly brecciated dolomite and quartzite which dips toward the valley between the West and Bristol Ranges, northwest of Pioche, and noted that "...the thorough brecciation of the overthrust block suggests that it was not under a heavy load at the time of faulting". Tschanz (1960), who maps this same block as part of an extensive "post-volcanic thrust plate" in northern Lincoln County, points out (p. 206) that "Westgate's explanation must be accepted unless the relations...can be explained by gravity sliding of portions of a Laramide thrust plate that became unstable during uplift of the Bristol Range." Portions of such a thrust plate that did slide from an unstable slope are found in the Welcome Spring area of extreme southwestern Utah (Cook, 1960b), where some of them overlie gravel containing Tertiary ignimbrite clasts. In the areas surrounding the Highland Range and the Pioche Hills (both west of Pioche), as well as on the east flank of the Schell Creek Range north of Patterson Pass (Tschanz, 1960, p. 206), brecciated Cambrian rocks overlie Tertiary volcanic rocks. Paul Gemmill (oral communication) explains the relations on the flanks of the Highland Range and the Pioche Hills by gravity sliding; Tschanz (1960, p. 206) thinks it likely that the Schell Creek relations can be explained by downslope gravity movement of brecciated masses.

Folds in the layered volcanic rocks of eastern Nevada are few. Some of them are of intrusive origin; others may be. Some are drag folds caused by faulting. Very few, if any, appear to be of compressive origin. The layered, block-faulted slabs have relatively low dips that can readily be ascribed to tilting. In the few places where the volcanic rocks have moved, or been overridden, along low-angle faults, the movement may have been caused by either gravity or compression.

The volcanic rocks of eastern Nevada lend little support to any hypothesis of post-ignimbrite low-angle faulting of a compressive origin.

REFERENCES

Abich, H., 1882, Geologische Forschungen in den Kaukasischen Landern, II. Geologie des Armenischen Hochlandes, I. Westhalfte: Vienna, A. Holder.

American Commission on Stratigraphic Nomenclature, 1961, Code of stratigraphic nomenclature: Am. Assoc. Petroleum Geologists Bull., v. 45, no. 5, p. 645-655.

American Geological Institute, 1957, Glossary of geology and related sciences: Natl. Research Council Pub. 501.

Armstrong, R. L., 1963, Geochronology and geology of the eastern Great Basin: unpublished Ph.D. thesis, Yale University.

Beliankin, D. S., 1952, On the problem of the tuffaceous lavas of Armenia (in Russian): USSR Acad. Sci. Proc., geol. ser., no. 3, p. 141-144.

Blank, H. R., Jr., 1959, Geology of the Bull Valley district, Washington County, Utah: unpublished Ph.D. thesis, University of Washington.

Boyd, F. R., 1961, Welded tuffs and flows in the rhyolite plateau of Yellowstone Park, Wyoming: Geol. Soc. America Bull., v. 72, p. 387-426.

Callaghan, Eugene, 1939, Volcanic sequence in the Marysvale region in southwestern-central Utah: Am. Geophys. Union Trans., 20th Ann. Mtg., pt. 3, p. 438-452.

Cook, E. F., 1955, Nomenclature and recognition of ignimbrites [abs.]: Geol. Soc. America Bull., v. 66, p. 1544.

______, 1957a, Geology of the Pine Valley Mountains, Utah: Utah Geol. and Mineralog. Survey Bull. 58.

______, 1957b, Stratigraphic and structural utility of layered volcanic rocks: Internat. Geol. Cong., 20th, Mexico City 1956, Proc., sec. 1, v. 1, p. 189-203.

______, 1960a, Great Basin ignimbrites in Guidebook to the geology of east-central Nevada: Intermountain Assoc. Petroleum Geologists, 11th Ann. Field Conf., 1960, p. 134-141.

______, 1960b, Geologic atlas of Utah-Washington County: Utah Geol. and Mineralog. Survey Bull. 70.

______, 1960c, Breccia blocks (Mississippian) of the Welcome Spring area, southwest Utah: Geol. Soc. America Bull., v. 71, p. 1709-1712.

Cotton, C. A., 1952, Volcanoes and landscape forms: Christchurch and London, Whitcombe and Tombs, 416 p.

Dolgoff, Abraham, 1963, Volcanic stratigraphy of the Pahranagat area, Lincoln County, southeastern Nevada: Geol. Soc. America Bull., v. 74, p. 875-900.

Evernden, J. F., Savage, D. E., Curtis, G. H., and James, G. T., 1964, Potassium-argon dates and the Cenozoic mammalian chronology of North America: Am. Jour. Sci., v. 262, p. 145-198.

Faust, G. T., and Callaghan, Eugene, 1948, Mineralogy and petrology of the Currant Creek magnesite deposits and associated rocks of Nevada: Geol. Soc. America Bull., v. 59, p. 11-47.

Favorskaya, M. A., 1956, Upper Cretaceous and Cenozoic magmatism of the eastern slopes of Sikhote-Alinya (in Russian): U.S.S.R. Inst. Geol. Mineral Deposits Trans., fasc. 7, 306 p.

______, 1957, On the problem of the mechanism of formation of some tufflavas (in Russian): Volcanological Laboratory [U.S.S.R.] Trans., Issue 14, p. 26-35.

Fenner, C. N., 1920, The Katmai region, Alaska, and the great eruption of 1912: Jour. Geology, V. 28, p. 569-606.

______, 1940, Geologia de los alrededores de Arequipa [Peru]: Rev. Univ. San Agustin de Arequipa, ano 13, p. 169-206.

______, 1948, Incandescent fuff flows in southern Peru: Geol. Soc. America Bull., v. 59, p. 879-893.

Fisher, R. V., 1960, Proposed classification of volcaniclastic rocks [abs.]: Geol. Soc. America Bull., v. 71, p. 1864-1865.

Grange, L. I., 1934, Rhyolite sheet flows of the North Island, New Zealand: New Zealand Jour. Sci. Tech., v. 16, no. 2, p. 57-67.

______, 1937, Geology of the Rotorua-Taupo subdivision: New Zealand Geol. Survey Bull. 37.

Hausen, D. M., 1954, Welded tuffs of Oregon and Idaho: Mississippi Acad. Sci. Jour. 1951-53, v. 5, p. 209-220.

Iddings, J. P., 1899, Geology of the Yellowstone National Park: U. S. Geol. Survey Mon. 32, pt. 2 (esp. p. 404-406).

Johnson, M. S., and Hibbard, D. E., 1957, Geology of the Atomic Energy Commission Nevada Proving Grounds area, Nevada: U. S. Geol. Survey Bull. 1021-K, p. 333-384.

Kellogg, H. E., 1960, Geology of the southern Egan Range, Nevada, in Guidebook to the geology of east-central Nevada: Intermountain Assoc. Petroleum Geologists, 11th Ann. Field Conf., 1960, p. 189-197.

Kennedy, G. C., 1955, Some aspects of the role of water in rock melts: Geol. Soc. America Spec. Paper 62, p. 489-504.

Kuellmer, F. J., 1954, Geologic section of the Black Range at Kingston, New Mexico: New Mexico Bur. Mines and Mineral Resources Bull. 33.

Lacroix, A., 1902, Nouvelles observations sur les eruptions volcaniques de la Martinique: Acad. sci. (Paris) Comptes rendus, v. 135, p. 672-674 and p. 1301-1307.

______, 1904, La Montagne Pelee et ses eruptions: Paris, Masson et Cie.

Mackin, J. H., 1952, Hematite veinlets in an ignimbrite in the Iron Springs district, southwestern Utah [abs]: Geol. Soc. America Bull., v. 63, p. 1337-1338.

______, 1960, Structural significance of Tertiary volcanic rocks in southwestern Utah: Am. Jour. Sci., v. 258, p. 81-131.

Mackin, J.H., Cook, E. F., and Threet, R. L., 1954, Stratigraphy of early Tertiary volcanic rocks in southwestern Utah [abs]: Geol. Soc. America Bull., v. 65, p. 1280.

Mackin, J. H., and Nelson, W. H., 1950, Early Tertiary welded tuffs in the Iron Springs district, southwestern Utah [abs.]: Geol. Soc. America Bull., v. 61, p. 1528.

Marshall, P., 1932, Notes on some volcanic rocks of the North Island of New Zealand: New Zealand Jour. Sci. Tech., v. 13, no. 4, p. 198-202.

______, 1935, Acid rocks of the Taupo-Rotorua volcanic district: Royal Soc. New Zealand Trans., v. 64, pt. 3, p. 323-366.

Martin, R. C., 1957, Vertical variations within some eastern Nevada ignimbrites: unpublished M. S. thesis, University of Idaho.

______, 1959, Some field and petrographic features of New Zealand and American ignimbrites: New Zealand Jour. Geol. Geophys., v. 2, p. 394-411.

Marwick, J., 1946, The geology of the Te Kuite subdivision: New Zealand Geol. Survey Bull. 41.

Misch, Peter, 1960, Regional structural reconnaissance in central-northeast Nevada and some adjacent areas: observations and interpretations, in Guidebook to the geology of east-central Nevada: Intermountain Assoc. Petroleum Geologists, 11th Ann. Field Conf., 1960, p. 17-42.

Misch, Peter, and Easton, W. H., 1954, Large overthrusts near Connors Pass in the southern Schell Creek Range, White Pine County, eastern Nevada [abs.]: Geol. Soc. America Bull., v. 65, p. 1347.

Peterson, D. W., 1959, Origin of the dacite near Superior and Globe, Arizona [abs.]: Geol. Soc. America Bull., v. 70, p. 1740.

Poole, F. G., and McKeown, F. A., 1962, Oak Spring Group of the Nevada Test-site and vicinity, Nevada: U. S. Geol. Survey Prof. Paper 450-C, p. 60-62.

Rittmann, Alfred, 1958, Cenni sulle colate di ignimbriti: Boll. Accad. Gioenia Sci. nat. Catania, ser. 4, p. 524-533.

Ross, C. S., 1955, Provenience of pyroclastic materials: Geol. Soc. America Bull., v. 66, p. 427-434.

Ross, C. S., and Smith, R. L., 1961, Ash-flow tuffs: their origin, geologic relations, and identification: U. S. Geol. Survey Prof. Paper 366.

Smith, R. L., 1960a, Ash flows: Geol. Soc. America Bull., v. 71, p. 795-842.

______, 1960b, Zones and zonal variations in welded ash flows: U. S. Geol. Survey Prof. Paper 354-F, p. 149-159.

Steiner, A., 1960, Origin of the ignimbrites of the North Island, New Zealand: a new petrogenetic concept: New Zealand Geol. Survey Bull., 68.

Tschanz, C. M., 1960, Geology of northern Lincoln County, Nevada in Guidebook to the geology of east-central Nevada: Intermountain Assoc. Petroleum Geologists, 11th Ann. Field Conf., 1960, p. 198-208.

Vlodavets, V. I., 1953, On some Semiachinsk tufflavas and their origin (in Russian): USSR Acad. Sci. Proc., geol. ser., no. 3, p. 96-106.

______, 1957, On the origin of the rock usually called tufflava and ignimbrite (in Russian): Volcanological Laboratory [U.S.S.R.] Trans., Issue 14, p. 3-16.

Wentworth, C. K., and Williams, Howel, 1932, The classification and terminology of the pyroclastic rocks: Nat. Research Council Bull. 89, Rept. Comm. Sedimentation 1930-32, p. 19-53.

Westgate, L. G., and Knopf, Adolph, 1932, Geology and ore deposits of the Pioche district, Nevada: U. S. Geol. Survey Prof. Paper 171.

Williams, P. L., 1960, A stained slice method for rapid determination of phenocryst composition of volcanic rocks: Am. Jour. Sci., v. 258, p. 148-152.

Winfrey, W. M., Jr., 1958, Stratigraphy, correlation, and oil potential of the Sheep Pass Formation, east-central Nevada: Am. Assoc. Petroleum Geologists, Rocky Mtn. Sec., Geological Record, Apr. 1958, p. 77-82; also in Guidebook to the geology of east-central Nevada: Intermountain Assoc. Petroleum Geologists, 11th Ann. Field Conf., 1960, p. 126-133.

Young, J. C., 1960, Structure and stratigraphy in north central Schell Creek Range in Guidebook to the geology of east-central Nevada: Intermountain Assoc. Petroleum Geologists, 11th Ann. Field Conf., 1960, p. 158-172.