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Little Drum Mountains, an Early Tertiary Shoshonitic Volcanic Center in Millard County, Utah*

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ABSTRACT.—The Little Drum Mountains represent a deeply eroded Eocene-Oligocene volcano, consisting of a vent complex which erupted mafic flows and flow breccias, accompanied by lahars. Flows are dominated by members of the shoshonite suite and contain up to 3.95 percent K_2O, mainly occult in K-rich glass, with K_2O/Na_2O ratios greater than 1.0. In a few interbedded flows, apparently of the calc-alkaline series, Na_2O predominates over K_2O. The lavas contain phenocrystic hornblende and/or pyroxene with varying amounts of plagioclase in a fine-grained groundmass of plagioclase, mafic minerals, and interstitial glass.

An ash-flow tuff of the Oligocene Needles Range Formation unconformably overlies the volcanic sequence.

Contemporaneous eruptions of calc-alkaline and shoshonitic lavas are possibly related to different depths of magma derivation corresponding to two mid-Cenozoic imbricate subduction zones beneath the western United States.

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*A thesis presented to the Department of Geology of Brigham Young University in partial fulfillment of the requirements for the degree Master of Science, April 1973. Myron G. Best, thesis chairman.

INTRODUCTION

Eocene-Oligocene volcanism in the Little Drum Mountains (Text-fig. 1) typifies the subductive phase of the plate-tectonic evolution of the western United States. Subduction of the Farallon plate beneath the North American plate is represented in early and middle Cenozoic calc-alkaline volcanism (Atwater, 1970; McKee, 1971; Scholz et al., 1971; Lipman et al., 1972), whereas subsequent late Cenozoic basaltic volcanism is associated with crustal extension and block-faulting (Leeman and Rodgers, 1970; Christiansen and Lipman, 1972).

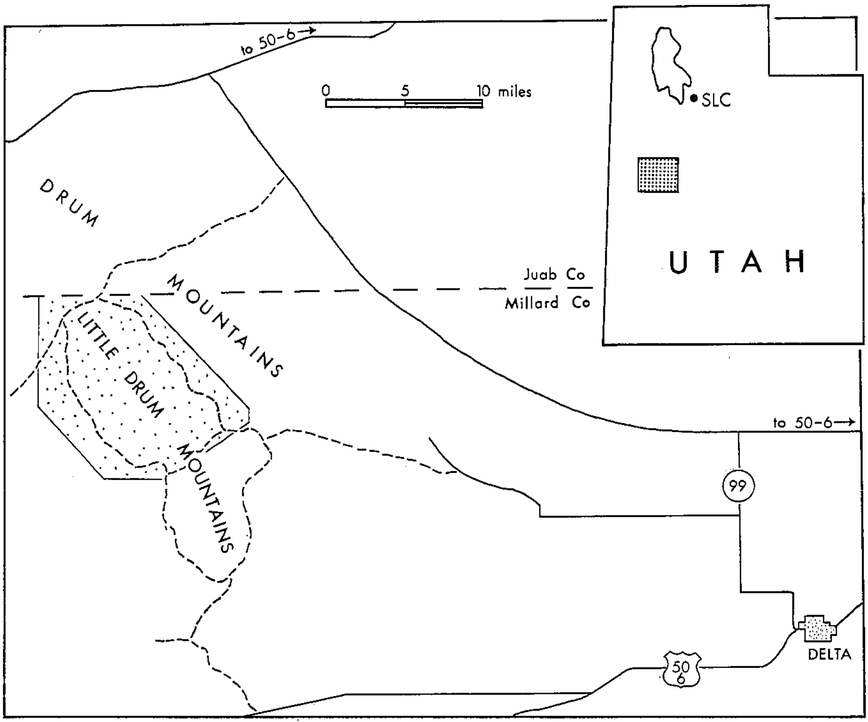
It has long been recognized that potassium increases relative to silica and sodium in Cenozoic volcanic rocks from the continental margin eastward into Utah (Merriam and Anderson, 1942; Moore, 1962). Further studies have related regional variations in alkali contents, especially potassium, of continental-interior Cenozoic igneous rocks to the depth of magma generation associated with Benioff zones, utilizing composition—focal-depth patterns in modern island arc trenches (Dickinson and Hatherton, 1967; Dickinson, 1968; Hatherton and Dickinson, 1969; Lipman et al., 1972).

Hogg (1972) found that mafic flows in western Utah north of the present study belong to the potassic shoshonite series of Joplin (1968). The Little Drum Mountains constitute a well-defined volcanic center for contemporaneous eruption of shoshonitic lavas with a few interbedded calc-alkaline (?) flows.

The principal purposes of this study are: (1) to map in detail the rock units of the volcanic sequence comprising the Little Drum Mountains, (2) to document the petrographic and chemical nature of the mafic flows, (3) to document critical age relationships radiometrically and stratigraphically, and (4) to gain insight into the origin of the magmatic association, particularly as it relates to the Cenozoic plate-tectonic evolution of the eastern Great Basin.

Previous Work

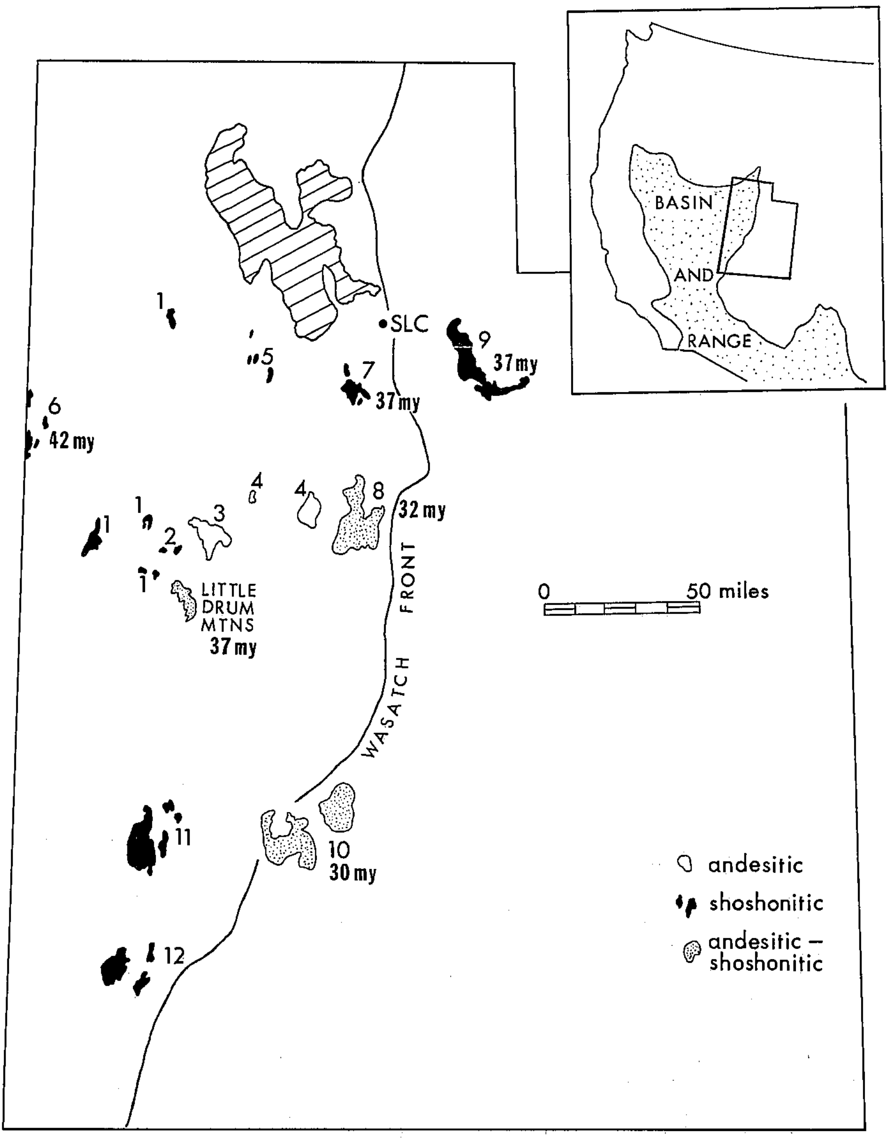
The only previous study of the Little Drum Mountains was made by Davis and Prince (1959), who mapped the area on aerial photographs at a



TEXT-FIGURE 1.—Index map of study area in Little Drum Mountains, Millard County, Utah.

scale of 1:62,500 (later reduced to 1:250,000) for the Utah State Mapping Project. Mackin (1963) correlated ash-flow tuffs in the prominent east-facing escarpment of the Little Drum Mountains with the Oligocene Needles Range Formation (Pierce, 1974).

Several studies of Tertiary andesitic and latitic volcanic rocks have been made elsewhere in western Utah (Text-fig. 2). Staatz and Carr (1964) recognized an older group of latitic flows exposed on the south end of Spor Mountain and in the Thomas Range. Two predominately andesitic volcanic sequences on opposite flanks of the Stansbury Mountains were described briefly by Rigby (1958) and in greater petrographic detail by Davis (1959). Andesite flows exposed on the flanks of the Simpson and Sheeprock Mountains in Tooele County were briefly described by Cohenour (1959). Erickson (1963) visualized four separate eruptive centers in western Juab County and attempted to relate andesites and latites occurring in the Keg Mountains with those in the Thomas and Simpson Ranges. The Keg Mountains are the topic of a master's thesis currently in progress by Ann Staub at the University of Utah. In a reconnaissance study of central Juab County, Shaw (1972) separated, on the basis of intensity of deformation and alteration, an older assemblage of mafic flows into two groups representing two major episodes of volcanism. The petrographic and chemical nature of latitic flows were described in the Gold Hill Mining District by Nolan (1935), in the Tintic



TEXT-FIGURE 2.—Locations of early Tertiary calc-alkaline and shoshonitic flows in western Utah: 1. Fish Springs Flat, Honeycomb Hills, Grayback Mountain; 2. Thomas Range; 3. Keg Mountains; 4. Simpson and Sheeprock Mountains: 5. Stansbury Mountains; 6. Gold Hill District; 7. Bingham District; 8. East Tintic District; 9. Park City-Alta District; 10. Marysvale region; 11. San Francisco District; 12. Iron Springs District.

Mining District by Lindgren and Loughlin (1919) and Morris (1957), and in the Oquirrh Mountains by Gilluly (1932).

General Description

The Little Drum Mountains represent a small, deeply eroded composite volcano built upon a west-dipping surface of moderately low relief underlain by Cambrian quartzites, limestones, and minor shales of the Drum Mountain sequence (Crittenden, 1961). Basin-range faulting subsequently uplifted and tilted the Little Drum—Drum Mountains block, and created alluvial-filled valleys to the east and west (Text-fig. 1).

The eroded volcano consists of a vent complex with flanking flows spreading laterally into adjacent valleys on either side. The Little Drum Mountains are arbitrarily divided into a north and south portion. The northern portion, which contains the eruptive center and is dominated by porphyritic mafic flows and flow breccias with interbedded lahars, is the subject of this study. The southern portion is composed of lahars and ash-flow tuffs stratigraphically lower than the northern sequence, plus a few interbedded mafic flows (Pierce, 1974).

Method of Study

Detailed mapping of the volcanic units utilized aerial photographs at scales of 1:20,000 and 1:24,000; the Topaz Mountain 15-minute topographic sheet; and preliminary Antelope Mountain 1NE, 1NW 7½-minute topographic sheets.

Representative samples were collected from each significant flow unit within the sequence. Thin sections were prepared to determine mineralogical and textural relationships. Whole-rock major-element analyses of thirteen specimens were obtained by X-ray fluorescence (XRF), and verified by atomic-absorption spectrophotometry (AA). Whole-rock potassium-argon dates were obtained on two specimens with a Nier 6-inch mass spectrometer at the Analytical Laboratory Branch of the United States Geological Survey in Menlo Park, California, by James Hoover. Electron microprobe analyses by M. G. Best were performed on hornblende and pyroxene.

Acknowledgments

The writer wishes to express appreciation to a number of individuals who contributed to this study, particularly Myron G. Best, for his counsel and genuine interest in this study, Willis H. Brimhall for his advice on atomic-absorption techniques, and Lehi F. Hintze for his counsel on stratigraphic relationships. The writer would also like to thank James Hoover for his assistance in X-ray fluorescence techniques, and his undaunted efforts to obtain age-date determinations. Special thanks are extended to my wife, Kathy, for her moral support and continual encouragement throughout this study.

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STRUCTURE

The Little Drum Mountains form a homocline that generally strikes N50° W, and dips 10° to 30° to the southwest (Pl. 1), although locally bedding may dip inward or outward away from eruptive centers. Crittenden (1961) believes that flanking flows derived from the Little Drum Mountains rest on a gentle westward-dipping eroded surface that was developed on the Paleozoic bedrock of the Drum Mountains subsequent to major faulting of the range.

A similar westward-dipping surface of probably not more than 10° underlies the Little Drum Mountains and is reflected in the northeast thinning of the eruptive sequence. The inclined prevolcanic surface precludes the development of typical quaquaversal dips away from eruptive vents, except where laharic breccias overcame the biasing effect of the slope and covered preexisting northeast-facing escarpments of viscous lava flows.

Determination of the original structure of the volcano is dependent upon resolving the amount of regional tilting after extrusion of the sequence. Viscous lava flows exhibiting 15° to 20° dips to the southwest in eastern escarpments are best explained by the addition of a 10° to 15° postvolcanic regional tilt to the 5° to 10° prevolcanic surface upon which the flows were extruded. This tilt is further substantiated by the 10° to 15° dip of the initially flat-lying Needles Range Formation on the western flanks. Therefore, extensive flows in adjacent valleys displaying homoclinal dips of 30° on western flanks and 10° on eastern flanks correspond to initial 15° to 20° quaquaversal dips off the volcano.

Subsequent tilting of the Little Drum Mountains is presumably related to basin-range faulting, which was initiated in the mid-Miocene (Stewart, 1972). The primary evidence for a basin-range fault block comprised of the Little Drum and Drum Mountains is a north-south-trending, deeply eroded fault-line scarp on the east side of the Drum Mountains (Crittenden, 1961). A western boundary fault is presumably covered by the alluvium of Whirlwind Valley. The existence of lava flows (Tf_s, Tf_{un}) covering Oldroyd Valley (named after the pre-existent Oldroyd reservoir) and lapping onto the flanks of the Drum Mountains suggests that Oldroyd Valley was a Paleozoic lowland filled with lava as the Little Drum Mountain volcano was erected on an inclined highland to the west. The inferred paleogeography does not necessitate, nor prove, a westward-tilted Little Drum Mountain fault block separate from the Drum Mountain block.

Two sets of transverse faults presumably related to basin-range faulting and that cut the volcanic sequence in the Little Drum Mountains are similar to those described by Crittenden (1961) in the Drum Mountains. One set of parallel faults, striking N 20° E in the aa shoshonite flows, Ts_3, is inferred mainly from aerial photographs, although a few eroded scarps and offset streams are also evident on the ground. The other set, striking N 40° W, is represented by a steeply dipping fault with 250 m of measurable displacement. Staatz and Carr (1964) believe that numerous transverse and strike-slip faults affecting the Thomas Range were activated in early Miocene time.

STRATIGRAPHY

Nomenclature

Nomenclature for volcaniclastic rocks used in this report is derived from Fisher (1960), Wright and Bowes (1963), Cook (1965), and Parsons (1967). Volcanic breccia is defined as a rock containing predominately angular fragments greater than 64 mm of any rock type, the brecciation and emplacement of which resulted from volcanic action. Breccias are subdivided, according to the primary origin of their fragmentation, as autoclastic, pyroclastic, or epiclastic. "Autoclastic" refers to fragments produced during movement of flows; "pyroclastic" fragments are explosively produced and aerially transported before deposition; and "epiclastic" involves weathering and erosion of already lithified or solidified volcanic rocks.

The following varieties of volcaniclastic rocks, which are discussed in succeeding sections, are defined as follows:

Flow breccias.—Flow breccias associated with massive flows result from autoclastic fragmentation initiated by frictional movement of partially solidified unconfined lavas (Fisher, 1960).

Pyroclastic flows.—Pyroclastic flows and breccias are explosively produced suspensions of liquid and/or semisolidified fragments.

Block-avalanches.—Block-avalanches, containing solidified fragments greater than 32 mm, are a variety of flow breccia that result from nonexplosive eruptions, and brecciate as they move downslope by gravity flow.

Ash-flows.—Ash-flows are explosively produced mixtures of gas and solidified ash and lapilli that, when consolidated, form ash-flow tuffs.

Laharic breccias.—Laharic breccias are deposited by volcanic mudflows originating in several different ways (Pierce, 1974).

Field Relations and Description of Rock Units

Mafic flows.—Tls_1, Ts_2, Ts_3, Tl_2, Tl_3, Ta_1, Tlb_2f.—Volcanic deposits of the northern Little Drum Mountains (Text-fig. 3) are dominated by mafic flows that belong to the potassic shoshonite series of absarokite-shoshonite-banakite-latite, originally described by Iddings (1895) and more recently discussed by Joplin (1968) and Nicholls and Carmichael (1969).

Shoshonites (Tls_1 [sample 5-5], Ts_2, Ts_3) contain phenocrystic hornblende and/or pyroxene in a fine-grained groundmass of subtrachytic to trachytic plagioclase microlites, oxide grains, and interstitial glass.

Plagioclase-rich latitic lavas (Tls_1 [samples 5-52], Tl_2, Tl_3) exhibit varying amounts of phenocrystic phases, including pyroxene, hornblende, and biotite, in a groundmass composed entirely of glass, or of glass and alkali feldspar (RI less than balsam) and microphenocrysts of hornblende, pyroxenes, and oxides.

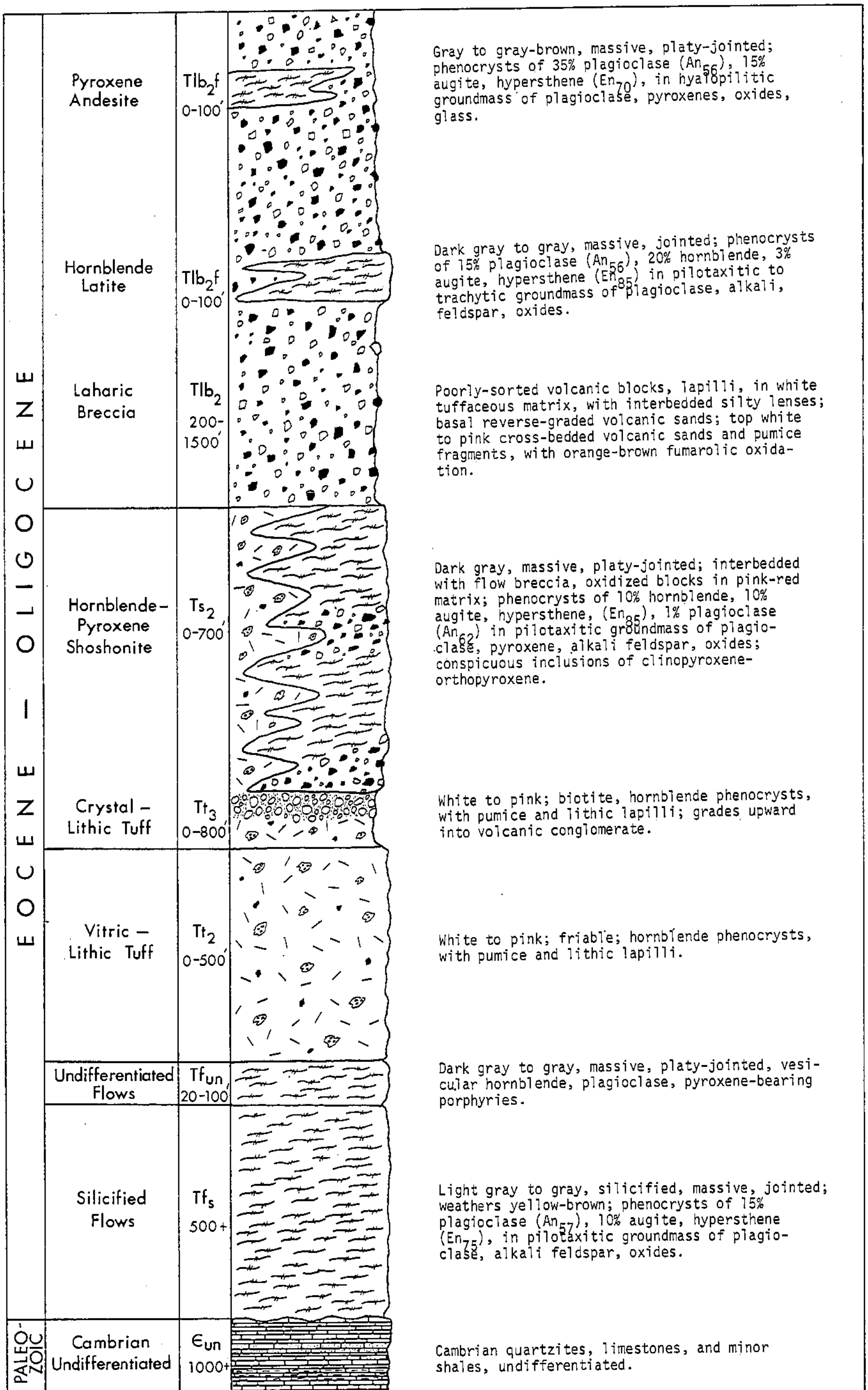
Two interbedded flows, Tlb_2f, Ta_1, which presumably represent the calc-alkaline series, are dominated by phenocrystic pyroxenes in a nearly holocrystalline groundmass of plagioclase microlites, pyroxenes, and oxides, with small amounts of residual glass.

Lava flows vary from massive, in blocky outcrops, to more typical platy-jointed sheets. Flow layering is expressed in glassy portions of flows by selective devitrification, creating alternating black and maroon laminae, and by some parting. Lava flows may grade upward or downward from massive lava into lenticular or irregular slabby masses and locally into flow breccias.

Welded breccias weather into cavernous outcrops (Pl. 2, fig 3) whereas less consolidated breccias are fully exposed only at the base of steep talus-covered slopes where stream channels have undercut the slope.

AGE	FORMATION	SYMBOL THICKNESS	LITHOLOGY	DESCRIPTION
Quaternary	Alluvium	Qal 0–100′		Gravel, sand, silt; includes older alluvial fans and slope wash, and recent drainages.
PLIOCENE?	Rhyolite Flow	Trf 50-100′		Pink, weathers white, jointed, flow-banded; aphyric.
OLIGOCENE	Needles Range	Tnr 50-100′		Dark gray to black basal vitrophere with obsidian lenses; light pink-gray to red-orange in less-welded portions; biotite, hornblende, plagioclase phenocrysts, with lithic lapilli.
EOCENE — OLIGOCENE	Hornblende – Pyroxene Latite	Tl_3 100–500′		Dark gray to black, glassy, flow-banded, massive, platy-jointed; interbedded with flow breccias, oxidized blocks in pink-red, white, or orange matrix; phenocrysts of 20% plagioclase (An_{54}), 5% hornblende, 4% augite, hypersthene (En_{70}) in pilotaxitic to trachytic groundmass of plagioclase, alkali feldspar, pyroxenes, oxides.
	Laharic Breccia	Tlb_3 0-100′		Poorly-sorted angular to sub-angular blocks and lapilli in light gray tuffaceous matrix with pumaceous layers.
	Pyroxene Andesite	Ta_1 0-500′		Gray to black, massive, platy-jointed, vesicular; phenocrysts of 20% plagioclase (An_{60}), 15% augite, hypersthene (En_{80}) in trachytic groundmass of plagioclase, oxides.
	Vitrophere Breccia	Tvb 0-300′		Poorly-sorted angular to sub-rounded blocks and lapilli of black vitrophere in pink to pink-orange matrix.
	Pyroxene Latite	Tl_2 0-500′		Dark-gray to black, glassy, flow-banded; gray to gray-brown, massive, platy-jointed; interbedded with flow breccia, oxidized blocks in pink-red to orange matrix; phenocrysts of 40% plagioclase (An_{57}), 10% augite, hypersthene (En_{83}), in hyalohyaline to pilotaxitic groundmass of plagioclase, alkali feldspar, glass.
	Latite – Shoshonite	Tls_1		Core- pink-orange; phenocrysts of plagioclase (An_{58}), 15% hornblende, 5% biotite, 1% pyroxenes in pilotaxitic groundmass of plagioclase, alkali feldspar, oxides. Border- dark-gray, platy-jointed; phenocrysts of 10% hornblende, 3% augite, hypersthene, 1% plagioclase in trachyitic groundmass of plagioclase, alkali feldspar, oxides.
	Pyroxene Shoshonite	Ts_3 50–1000′		Gray to black, oxidized red to red-orange; massive, platy-jointed, vesicular to scoracious; phenocrysts of 15% plagioclase (An_{63}), 20% augite, hypersthene (En_{85}), in hyalopilitic groundmass of plagioclase, pyroxenes, oxides, brown glass; grades into lower dark-gray, massive, platy-jointed basal flow.

TEXT-FIGURE 3.—Stratigraphic units in northern Little Drum Mountains, Utah.



TEXT-FIGURE 3. (continued)

Extensive shoshonite aa lava flows (Ts_3) are characterized by vesicular to scoracious, jagged surfaces which are locally autoclastic and reddened by oxidation.

Thicknesses of individual flow-units are highly variable, although massive flows interbedded with laharic breccias tend to be more uniform. Flows capping erosional mesas thin rapidly to the northeast and thicken to the southwest in response to the southwest-dipping surface upon which the flows were extruded (Pl. 2, fig. 2).

Vitric-lithic tuff, Tt_2.—This unit is exposed primarily in the lower portion of the escarpment at North Butte. "North Butte" is the name used herein for the prominent butte occurring in the northeastern portion of the Little Drum Mountains (Pl. 1). The tuff underlies low hills extending into Oldroyd Valley and unconformably overlies silicified flows (Tf_S). Other limited exposures of vitric-lithic tuff form subdued white to pink outcrops adjacent to recent stream channels at the contact of the unconformably overlying shoshonite flow (Ts_3). To the south the tuff is locally interbedded with an underlying laharic breccia, Tlb_1 (Pierce, pers. comm., 1972).

The tuff consists of 10 percent andesine and hornblende, with 40 percent lithic and devitrified pumice fragments, in a semi-opaque matrix of fine ash and pulverized rock material. The absence of biotite distinguishes this unit from the overlying biotite-rich tuff. (Tt_3).

Crystal-lithic tuff, Tt_3.—This unit occurs in a few isolated exposures beneath alluvial-covered ridges within the intervening drainages of the eastern flanks of the range but primarily in the prominent east-facing escarpment to the south where it directly overlies a vitric-lithic tuff (Tt_2) (Pierce, pers. comm., 1972). Overlying laharic breccias and interbedded flows (Tlb_2, Tlb_2f) constitute the upper portion of the southern escarpment. This distinctive contact is likewise concealed under flanking alluvium and is inferred at the break in slope between elongate talus-covered ridges underlain by laharic breccias and adjacent slope wash fans.

The light pink to white, slightly indurated to well cemented tuff contains 10 percent phenocrystic biotite, up to 4 mm across, 10 percent hornblende, 20 percent andesine, 5 percent embayed quartz, and 3 percent lithic fragments, all in a dark gray matrix of pumice lapilli and glass shards. The 10 percent chalky pumice fragments are up to 10 cm and contain a similar mineralogy to matrix phenocrysts. The 5 percent lithic lapilli and blocks are similar to underlying mafic flows but also include Paleozoic (?) sandstones and shales.

EXPLANATION OF PLATE 2

EXPOSURES OF VOLCANIC ROCKS, NORTHERN LITTLE DRUM MOUNTAINS

FIG. 1.—Laharic breccia (Tlb_2) composed of basal volcanic sand overlain by blocks and lapilli of flows in tuffaceous matrix.

FIG. 2.—View towards southeast of latite flows (Tl_2) capping erosional mesas of vitrophyre breccia (Tvb) and thinning from approximately 150 feet at right to 30 feet at left, in a northeast direction.

FIG. 3.—Cavernous weathering of welded flow breccia (Tl_2).

FIG. 4.—Vitrophyre breccia (Tvb) composed of fragmented welded ash-flow in crystal-rich matrix.

PLATE 2

1

2

3

4

Separating the overlying shoshonite flow breccia, Ts_2, from the underlying tuff, Tt_3, is a volcanic conglomerate 20 m thick. The conglomerate consists of subangular to well-rounded boulders and cobbles, dominated by pyroxene-bearing mafic flows (similar to Ts_2) in a brownish white reworked matrix with interbedded lenses of tuffaceous sandstone and angular volcanic fragments. Only limited exposures of the conglomerate occur adjacent to recent drainages that have removed the overlying alluvium.

Laharic breccias, Tlb_2, Tlb_3.—A series of laharic breccias were deposited as broad sheets over a surface of low relief, forming the most voluminous and widespread volcaniclastic rock units in the Little Drum Mountain sequence. Typically, the breccias are composed of poorly sorted, angular to subangular blocks and lapilli of mafic lava in a sandy, tuffaceous, well-cemented matrix of broken angular phenocrystic phases, orange brown pumaceous glass, lithic fragments, and finely comminuted rock debris. Distributed throughout the matrix are water-reworked silty, tuffaceous lenses exhibiting a few rip-up clasts. The lahars consist of three portions: basal reverse-graded sandstone, a dominant central portion of blocks and lapilli as described above, and an upper portion of cross-bedded sandstone (Pl. 2, fig. 1). In the field, successive lahars are distinguished by the erosional niche cut into less-resistant sandstone. Blocks and lapilli are dominated by hornblende-plagioclase similar to massive interbedded latitic flows (Tlb_2f), indicating a contemporaneous eruptive origin. However, lahars become heterolithologic with a variety of green, brown, and maroon aphyric and porphyritic lavas laterally away from the eruptive centers.

Vitrophyre breccia, Tvb.—This unit forms prominent, locally cavernous cliffs and elongate erosional mesas on underlying laharic breccias, Tlb_2. The breccia consists of angular to subrounded, poorly sorted fragments, up to 60 cm, of a dense, black vitrophyre in a pink orange to light pink crystal-rich matrix (Pl. 2, fig. 4). The matrix, varying from 30 to 70 percent, contains euhedral to broken, angular labradorite; pyroxene altered to tremolite-actinolite; sparse oxyhornblende and biotite, with 30 percent lithic and pumice fragments; and pulverized rock debris. In addition, the breccia contains up to 10 percent lithic lapilli and blocks of latite and aphyric lava clasts from the underlying laharic breccias.

Individual vitrophyre fragments contain 40 percent phenocrystic labradorite, 10 percent hypersthene and augite, and 1 percent hornblende and Fe-Ti oxides. The matrix is composed of eutaxitic shards in an orange brown glass, with axiolitic intergrowths in devitrified pumice fragments. Mineralogically and chemically the vitrophyre is similar to the pyroxene latite (Tl_2) with which it is interbedded, and appears to be gradational into the vitrophyric base of the overlying latite.

Needles Range Formation, Tnr.—Flanking the western side of the Little Drum Mountains is a crystal tuff, probably correlative with the widespread Needles Range Formation of southwestern Utah and eastern Nevada (Cook, 1965; Mackin, 1960) with an average K-Ar date of 29 m.y. (Armstrong, 1970). The ash-flow tuff comprises low, linear, somewhat cavernous outcrops unconformably overlying mafic flows and laharic breccias.

Foliation in the tuff ranges from 5° to 15° west. Color varies from light pink gray to red orange in less-welded portions, to dark gray to black in basal areas of intense welding. This unit contains euhedral to broken crystals of biotite, up to 4 mm, 10 percent; amphibole 10 percent; pyroxene 2 percent; plagioclase 30 percent; and quartz 3 percent. The eutaxitic matrix includes compacted pumice fragments and red lithic lapilli and blocks, including mafic lavas and Paleozoic (?) sandstone and shales.

Although additional paleomagnetic and radiometric data are necessary for a conclusive correlation with the Needles Range Formation, the petrography and relative age relationships are compatible.

Rhyolite flow, Trf.—This aphyric flow unconformably overlies the shoshonite aa flows, Ts_3, in a single exposure on the northwest flanks of the Little Drum Mountains. The flow has well-developed vertical joints that produce flaggy low-lying outcrops. Distorted flow-layering defined by alternating reddish brown and light green laminae are reflected petrographically by alternating quart-rich bands (extensively replaced by calcite) and finer-grained bands of devitrified glass containing microfelsitic quartz and feldspar. Trains of magnetite, possibly from replacement of mafic minerals, are concentrated along laminae.

Similar ryholitic flows occur in the Thomas Range, where they are presumed to be Pliocene in age (Staatz and Carr, 1964). Petrographic and age relationships of the rhyolite flow in the Little Drum Mountains suggests a probable correlation with the Thomas Range rhyolites.

Age Relations

Recent geochronologic studies of the Cenozoic igneous rocks of the western United States attempt to correlate petrologic types with the subduction zone resulting from the interaction of the Farallon and North American plates (Armstrong et al., 1969; Atwater, 1970; McKee, 1971; Scholz et al., 1971; Christiansen and Lipman, 1972; Lipman et al., 1972). These studies establish calc-alkaline magmatic activity beginning in late Cretaceous (approximately 70 m.y.) and continuing into middle Miocene (approximately 20 m.y.). Armstrong et al. (1969), McKee (1971), and Scott et al., (1970) showed that mid-Tertiary silicic volcanism began in the eastern Great Basin, with subsequent activity shifting south and west toward the margins of the Great Basin.

Any temporal pattern along the eastern margin of the Great Basin in west-central Utah is obscure. However, several isolated centers that have been dated indicate the commencement of volcanic activity at approximately 40 m.y. in western Utah. Intrusions in the Gold Hill area dated at 42 m.y. are followed elsewhere in western Utah by a group of nearly coincident events occurring at approximately 37 m.y. (late Eocene-early Oligocene) (Text-fig. 2).

In the Little Drum Mountains, K-Ar dates on the oldest and youngest flows in the sequence (Appendix A, Tables 1 and 3) are both 37.3 ± 0.4 m.y., which substantiates the relative age of the flows inferred from regional stratigraphic relationships. On the west flanks of the Mountains the Oligocene Needles Range Formation dated at 29 m.y. underlies low hills existing as embayments in a dissected topography. The tuff unconformably overlies laharic breccias and flows including the youngest age-dated latite, Tl_3. The unconformable relationship suggests that the entire volcanic sequence comprising the Little Drum Mountains was extruded and initially eroded prior to deposition of the Needles Range Formation approximately 29 m.y. ago.

Mode of Emplacement of Volcaniclastic Rocks

Flow breccias.—In the Little Drum Mountains, flow breccias grade upward and downward into massive lava. According to Curtis (1954) discontinuous unbrecciated layers at the base or within the breccia, and transitional stages between massive and brecciated portions are evidence for fragmentation after extrusion of the flow. He suggests that fragmentation in nonvesicular lava is initiated by rotation of jointed sheets, producing strong differential pressure that triggers a chain reaction of rapid brecciation with little additional movement.

Laharic breccias.—Laharic breccias in the Little Drum Mountains originated from major magmatic eruptions presumably accompanied by heavy rains that mobilized volcaniclastic debris accumulated on the flanks of the volcano. Conventially, torrential rains are believed to originate from condensation of steam in eruptive gas clouds with convective air rise over the volcano, plus ordinary storm activity (Macdonald, 1972). The limited extent of the Little Drum Mountain lahars would indicate that they were derived from hot block avalanches, which could have been initiated by mild gas-poor eruptions, collapse of domal spines, or slides of accumulated debris (Mullineaux and Crandell, 1962). Block avalanches were initially mobilized by gravity and attendant heat from entrapped gases, as evidenced by the glassy pumaceous matrix, and fumarolic oxidized upper surface of each lahar. Hot, dry avalanches became hot lahars as they accumulated water from streams or heavy rains on lower slopes.

Typically, block-avalanche lahars consist of a basal zone composed of reverse-graded volcanic sands sharply overlain by a massive central portion of blocks and lapilli in a coarse sand-pebble matrix (Pl. 2, fig. 1). Schmincke (1967) suggests that the basal zone may result from an inertia flow whereby shearing between grains causes larger grains to drift toward zones of least shear-strain (i.e., upward into higher velocity zones), and smaller grains toward greater shear strain near the base. The Little Drum Mountain lahars appear to have originated in this manner, starting as homogenous mixtures of very coarse clasts and medium-coarse sand, which were mechanically differentiated as they moved downslope, allowing coarser blocks and lapilli to move toward the surface, and medium sand to concentrate at the base. Alternatively, the basal reverse-graded bedding could also be attributed to a gradual increase in energy of an eruption during genesis of a lahar. This size sorting is commonly observed in stratified cinder cones associated with strombolian eruptions (Parsons, 1967). An upper zone in the lahars, consisting of fine to medium, cross-bedded sands and elongated, flattened pumice pebbles, probably represents a brief reworking of the upper surface of each lahar prior to burial by a succeeding one. The reworking can be attributed to flooding of lahar surfaces by ponded waters dammed behind lahar-choked river channels (Schmincke, 1967). Stream channels scoured into upper surfaces of lahars are probably related to this sheet-wash activity. The stratified pumaceous pebbles represent either reworked pumice flows or aerially deposited pumice ejecta (Kuno, 1941).

Vitrophyre-breccia.—This unit represents a semi-solidified, welded ash-flow that was fragmented by gravitational movement downslope as a hot block-and-ash avalanche. The block-and-ash avalanche presumably originated in a manner similar to that of the Merapi type of avalanche described by Williams (1957).

Volcanic conglomerate.—Volcanic conglomerates in the Little Drum Mountains were probably deposited by streams on flanking alluvial fans built up during periodic cessations in eruptive activity. Similar conglomerates are found interbedded with lava flows, laharic breccias, and tuffs in the Absaroka Volcanic Field (Rouse, 1940).

THE LITTLE DRUM MOUNTAINS VOLCANO

Recognition of the Volcanic Center

Recognition of ancient volcanoes is based on structural and stratigraphic relationships derived from modern day analogs. Criteria used for recognition of eruptive centers include radial distribution and outward dips of flows, lateral variations in volcanic breccias, and lateral facies changes (Rouse, 1947; Chadwick, 1966; Prostka, 1968; Schultz, 1968; Smedes, 1968).

Identification of the Little Drum Mountains composite volcano is complicated by modified eruptive events, and subsequent structural and erosional events. The characteristic circular plan and symmetrical profile imposed by a single summit vent was modified by a shift in main vent position and by the development of a series of independent vents along a presumable fissure. Initial quaquaversal dips related to vent structures were altered by a westward dipping prevolcanic surface, local attendant collapse of in-filled vents, and subsequent regional tilting.

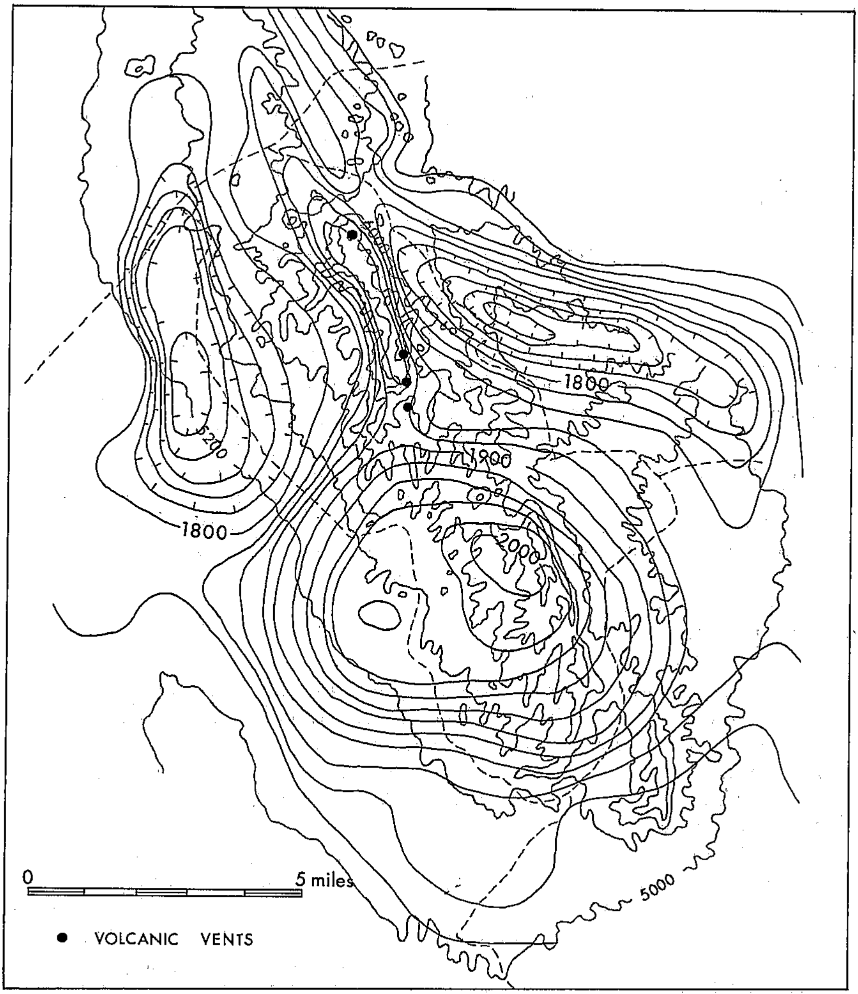
The most diagnostic criterion for recognition of the Little Drum Mountain volcanic center is the aerial distribution and variation in thickness of the flows shown on the map and cross sections of Plate 1. The more extensive flows are thickest in the range itself and thin markedly toward adjacent valleys. Other flows are distributed either concentrically or semicircularly about eruptive centers.

Laterally away from an eruptive center, near-vent flow breccias and lahars may grade into epiclastic lahars, which in turn grade into alluvial volcanic sediments (Prostka, 1968, Smedes, 1968). In the Little Drum Mountains angular blocks in near-vent flow breccias are welded together (agglutinated), but blocks gradually become smaller and more separated by a fine-grained attrited matrix farther from the vent area. Flow breccias grade outward into monolithic lahars characterized by a larger proportion of tuffaceous matrix and an absence of associated discontinuous layers of unbrecciated flow. Away from the vent, clasts in lahars become more heterogenous with an epiclastic matrix of interbedded, well-sorted tuffaceous layers. Ultimately, laharic breccias grade into possible alluvial fanglomerates at the southern base of the Little Drum Mountains slope (Pierce, pers. comm., 1972).

An aeromagnetic survey of west-central Utah provides indirect evidence for the volcanic center in the form of two positive magnetic anomalies that correlate closely with the postulated eruptive vents (Text-fig. 4).

Volcanic History

Pre-Needles Range volcanism in the Little Drum Mountains probably transpired over a relatively brief period of time during the late Eocene—early



TEXT-FIGURE 4.—Aeromagnetic map of the Little Drum Mountains area, Utah.

Oligocene, as only 0.8 m.y. is allowed at a maximum in the analytical uncertainties of the two available radiometric dates.

The volcanic complex is composed of two spatially and chronologically separate eruptive centers, distinguished by the nature and composition of their lavas. Eruptions from the southern center yielded blocky andesite, shoshonite, and latite flows from a series of north-south trending vents. The northern center produced predominately shoshonite aa lavas, which were subsequently intruded by shoshonite-latite plug domes.

Volcanic activity in the Little Drum Mountains area commenced with extrusion of latitic flows (now silicified, Tf_s) into Oldroyd Valley, presumably from a distant source to the north (Text-fig. 5). Overlying flows (now occurring as erosional outliers, Tf_{un}) originated primarily from initial vents of the Little Drum Mountains volcano. Contemporaneous eruptions from an unknown, but probably southerly and westerly, source emplaced a sequence of ash-flows (Tt_2, Tt_3), exposed primarily in east-facing escarpments to the south (Pierce, pers. comm., 1972). The ash-flows were laid down unconformably on the slightly inclined Paleozoic bedrock surface.

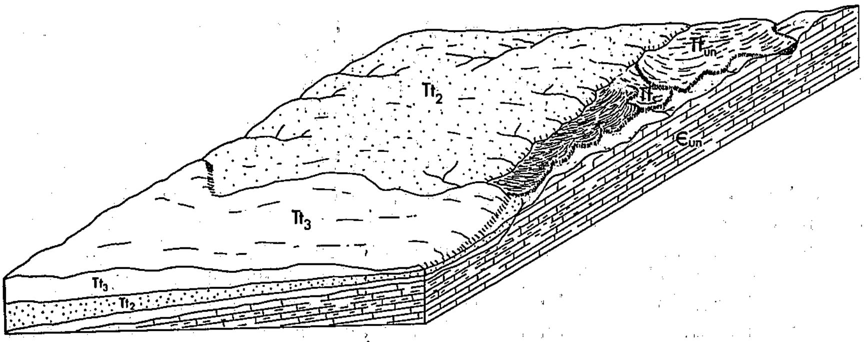
Following a brief period of erosion, as evidenced by lahar-filled stream channels carved in the upper surface of the uppermost ash-flow, Tt_3, major eruptions from an undetermined number of vents effused calc-alkaline and shoshonitic-flows (Ts_2, Tlb_2f) and flow breccias (Text-fig. 6). Intermittent collapse of unstable cone flanks resulted in landslides of accumulated debris, forming hot, dry block avalanches. The avalanches and flow breccias were in turn transformed into interbedded hot volcanic mudflows or lahars (Tlb_2), presumably by accompanying heavy rains.

Eruptions from a group of northern vents poured shoshonite aa flows (Ts_3) into a drainage system on the western flank, forming the present inverted valleys, and southeastward onto the southwest flanks of the Drum Mountains. This activity centered around a lava-filled vent (North Butte, vent 4) that was erupting concurrently and was attended by torrential rains, forming interbedded lahars (Tlb_2) (Pl. 3, fig. 3). The shoshonite flows subsequently were intruded by a northeast-southwest trending series of plug domes that possibly represent conduit fillings. The plug domes (Tls_1) are bordered by a chilled envelope of vertically jointed shoshonite and are cored by a later-intruded massive latite.

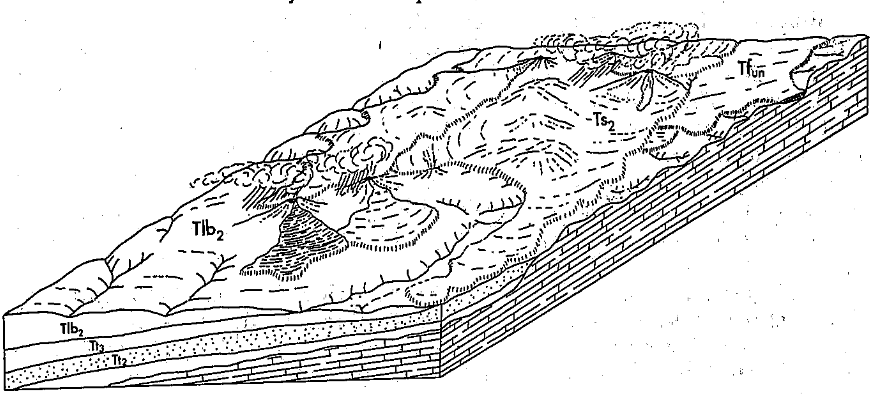
Subsequent extrusion of latitic flows and flow breccias (Tl_2, Tvb, Ta_1, Tl_3) defined a series of two, and possibly three, north-south-trending vents that presumably were fissure controlled (Text-fig. 7). Although there was a northerly shift in activity of the vents as the fissure opened, eruptions were more or less simultaneous.

Two of the vents (vents 1 and 2) are distinguished by prominent buttes that are latite (Tl_3) dome in-fillings resulting from the differential erosion's removal of the original cone structure. Attendant collapse of the domes (Ta, Tvb) is attributed to withdrawal of lava and gas pressure during waning stages of eruption. Similar topographic features are described in Lassen Volcanic National Park (Williams, 1932) and the Absaroka Volcanic Field (Rouse, 1940).

The southernmost vent (vent 1) is defined by nearly concentrically distributed flows, flow breccias and lahars (Tl_2, Ta_1, Tlb_3) encircling an elongate lava butte (Pl. 3, fig. 1). Youngest latitic flows (Tl_3) breached the crater rim and poured into a major stream channel carved into the southwest flank of the cone during a period of quiescence, subsequently forming an inverted valley (Text-fig. 8). Immediately to the north another vent area (vent 2) is defined by inward-dipping vitrophere breccia (Tvb) surrounding a similar butte composed of latitic flows and flow breccia (Tl_3) (Pl. 3, fig. 2). Lava from it escaped through a breached crater on the southwest side; ran down drainage ways; and formed, after erosion, inverted valleys. The breaching and erosion of deepest stream channels on the southwest flanks of the cones is attributed to the biasing effect of the southwest-dipping prevolcanic slope. A third vent (vent 3) is inferred from a small outcrop of tuffaceous breccia (Tlb_3) confined to a ridge summit directly north of the previously described



TEXT-FIGURE 5.—Block diagram showing flows in Oldroyd Valley flanking the Drum Mountains and overlain by ash-flow sequence.



TEXT-FIGURE 6.—Block diagram illustrating subsequent major vent eruptions and interbedded lahars.

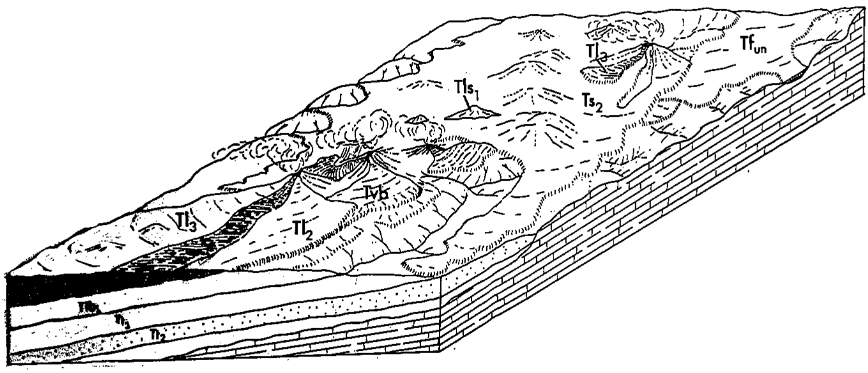
vent area and surrounded by unique interbedded flows (Tl_2). However, a definite relationship to a pre-existent vent structure is not discernible. Nearly contemporaneous activation of the dormant North Butte vent produced similar latitic flows (Tl_3) which in-filled that cone structure.

After cessation of the Little Drum Mountain volcanism and effective stream dissection, the Needles Range Formation (Tnr) was deposited on the western flanks, probably from remote sources to the southwest. Rhyolitic flows (Trf) deposited on the northwest flank of the Little Drum Mountains presumably were related to Pliocene volcanic activity in the Thomas Range area to the north.

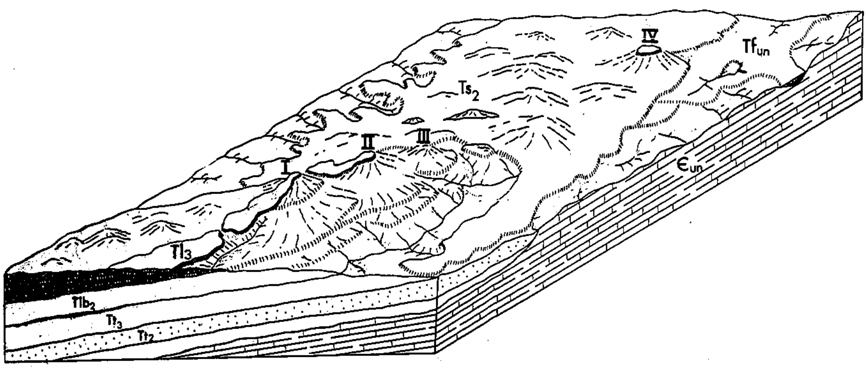
PETROCHEMISTRY OF THE LAVAS

Introduction

The chemical compositions of the lavas extruded from the Little Drum Mountains volcano appear to be separable into two groups representing the calc-alkaline and shoshonite magma series. Chemical ratios and oxide variations for most samples are similar to those of the potassic shoshonite series proposed by Joplin (1968). Two samples of interbedded pyroxene andesite



TEXT-FIGURE 7.—Block diagram depicting additional eruptions from series of north-south vents (vents 1, 2, 3) and reactivation of vent 4.



TEXT-FIGURE 8.—Block diagram illustrating prolonged erosional effects producing inverted valleys and prominent buttes.

units, Ta_1, Tlb_2f, seem to possess contrasting chemical parameters that are compatible with the calc-alkaline series. As the petrography and the mineralogy of the two series are similar, the shoshonitic suite is most readily recognized by chemical means: its high potassium content is occult in interstital glass and/or alkali feldspar.

The nomenclature utilized in this paper is based on chemical classifications proposed by Taylor (1969) for the calc-alkaline suite and by Joplin (1968) and Nicholls and Carmichael (1969) for the shoshonite series.

The shoshonite series, first described in Yellowstone National Park, Wyoming (Iddings, 1895), is characterized mineralogically by coexisting groundmass plagioclase and sanidine, and chemically by a high potassium content relative to sodium. The obvious mineralogical difference between the Wyoming shoshonites and those of the Little Drum Mountains is the presence of phenocrystic hornblende in the latter. Nicholls and Carmichael (1969) state that although the trachyandesites of Nelson and Pierce (1968) are chemically similar to shoshonites, they are not petrographic members because of their hornblende phenocrysts. It appears that Nicholls and Carmichael are biasing their nomenclature petrographically rather than relying on chemical criteria for membership in the shoshonite suite. Amphibole-bearing shoshonites have been described from New Guinea (Jakes and White, 1969), Fiji (Dickinson, 1968), and west-central Utah (Hogg, 1972).

Jakes and White (1972) compared the major element characteristics of the calc-alkaline and the shoshonitic magma series and related their differences to island-arc evolution. Principal oxide variations at increasing distances from the arc include an increase in K_2O at given SiO_2 contents, an increase in K_2O/Na_2O ratio, and a decrease in iron enrichment. Calc-alkaline lavas display a positive correlation of K_2O with increasing silica content, whereas shoshonitic lavas show little, or an antithetic change, with increasing silica. The K_2O/Na_2O ratio varies from 0.35 to 0.75 for the calc-alkaline series to 1.0 or greater for the shoshonite kindred (Jakes and White, 1972). Both the calc-alkaline and the shoshonite series exhibit high but variable Al_2O_3 content as well as little or no iron enrichment.

Jakes and White (1972) emphasize that in island-arc settings there are compositional gradations between the two suites. Moreover, successions of the calc-alkaline suite followed by the shoshonite series may be reflected in the stratigraphy of an erupting volcanic complex over a prolonged period (Jakes and Smith, 1970; Jolly, 1971). Similar successions may be paralleled laterally at increasing distances from island arcs and with decreasing age of the lavas (Joplin, 1968; Jakes and White, 1969; Gill, 1970). However, continental (Andean) calc-alkaline suites consistently have high K contents, and spatial variations between the calc-alkaline and shoshonitic suites are not as distinct.

Petrography and Mineralogy

Shoshonites.—The shoshonites of the Little Drum Mountains may be divided into two petrographic groups, olivine-clinopyroxene shoshonites (Ts_3) and hornblende-pyroxene shoshonites (Ts_1, Ts_2). The olivine-clinopyroxene shoshonite (Ts_3) contains 35 percent phenocrysts of labradorite (An_{62}), orthopyroxene, and clinopyroxene and traces of olivine as phyllosilicate pseudomorphs, in a fine-grained groundmass of subtrachytic plagioclase microlites, and dark brown glass (Pl. 4, fig. 1). The majority of the phenocrystic phases, which vary in size from 0.5 to 4 mm, exhibit embayed margins and internal sieve textures, suggesting disequilibrium at the time of eruption. They should properly be considered xenocrystic. Euhedral unaltered pyroxenes (Appendix, Table 3) exhibit strong normal zoning with more Fe-rich rims.

EXPLANATION OF PLATE 3

FIELD AND PETROGRAPHIC RELATIONS OF LAVAS IN THE NORTHERN LITTLE DRUM MOUNTAINS

FIG. 1.—Vent 1 butte viewed from east, showing vent filling (Tl_3) with portion of inverted valley to the left.

FIG. 2.—Vent 2 butte viewed from southeast, showing latite (Tl_3) capping inward-dipping vitrophyre breccia (Tvb).

FIG. 3.—North Butte, vent 4, viewed from southeast, capped by latite (Tl_3) and underlain by laharic breccia (Tlb_2) and ash-flow tuff (Tt_2). Flanking shoshonite flows (Ts_3) at right.

FIG. 4.—Pyroxene andesite (Tlb_2f).

PLATE 3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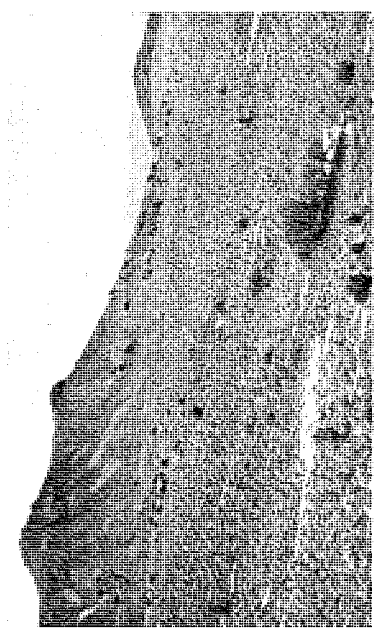
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Hornblende-pyroxene shoshonites (Ts_1, Ts_2) contain from 10 to 20 percent phenocrystic phases in a holocrystalline groundmass of subtrachytic to strongly trachytic microlites and anhedral alkali feldspar (Pl. 4, fig. 2). Strongly zoned clinopyroxene and orthopyroxene may dominate one over the other in different flows. Phenocrystic hornblendes (Appendix, Table 3) ranging in size from 0.5 to 3 mm, are euhedral to anhedral and have characteristic opaque reaction rims. Hornblende-pyroxene shoshonites characteristically contain glomeroporphyritic clusters up to 5 cm, consisting either of clinopyroxene-orthopyroxene or of clinopyroxene-orthopyroxene-plagioclase.

The texture of the phenocrysts in the shoshonites appears to be governed by the nature and degree of crystallization of the groundmass. Flows containing greater proportions of glass exhibit extensively reacted xenocrysts, whereas flows from which glass is absent display essentially unreacted phenocrysts.

Latites.—Feldspar-rich latites contain up to 45 percent phenocrystic hornblende, pyroxene, and biotite, ranging in size from 1 to 4 mm. The groundmass varies from holohyaline, with partially devitrified brown glass and crystallites, to an intergranular mixture of crystalline material and plagioclase lathes (Pl. 4, fig. 4). In most latitic lavas plagioclase phenocrysts, An_{58} to An_{64}, exhibit xenocrystic sieve features; however, in the more glass-rich pyroxene latites (Tl_2), they occur as essentially unreacted euhedral phenocrysts. A few euhedral hypersthene crystals are partially jacketed by augite shells. Hornblende phenocrysts vary from euhedral crystals with some plagioclase reaction rims in hornblende latites, to completely reacted pseudomorphs of pyroxene, plagioclase, and opaques in pyroxene latites. In the biotite-bearing latite, hornblende and plagioclase phenocrysts exhibit extensive resorptive sieve textures (Pl. 4, fig. 3).

Glomeroporphyritic clusters in latites consist predominately of plagioclase with varying amounts of pyroxene, hornblende, and opaques.

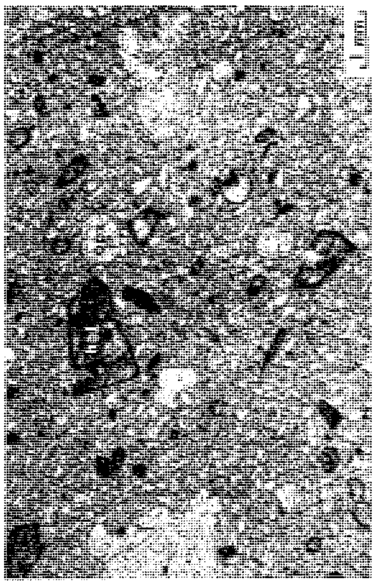
Calc-alkaline lavas (Tlb_2f, Ta_1).—Andesitic lavas contain from 25 to 45 percent phenocrysts of clinopyroxene, orthopyroxene, and trace hornblende in a fine-grained groundmass of plagioclase, pyroxene, and iron-titanium oxide granules and 5 to 10 percent interstitial glass (Pl. 3, fig. 4). Groundmass plagioclases vary from strongly trachytic microlites to euhedral unoriented laths. Phenocrystic plagioclases, An_{58} to An_{52}, ranging from 15 to 25 percent, exhibit varying degrees of internal sieve texture. Trace phenocrystic hornblendes occur as anhedral grains with opaque reaction rims. Pyroxene phenocrysts ranging in size from 0.5 to 3 mm, are dominated by clinopyroxene. The lavas also contain glomeroporphyritic clusters similar to those found in shoshonite flows.

EXPLANATION OF PLATE 4
PHOTOMICROGRAPHS OF LAVAS

FIG. 1.—Pyroxene shoshonite (Ts_3).
FIG. 2.—Hornblende-pyroxene shoshonite (Ts_2).
FIG. 3.—Hornblende-biotite latite (Tls_1).
FIG. 4.—Hornblende-pyroxene latite (Tl_3).

PLATE 4


1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Analytical Methods

Whole-rock major-element analyses of the various lavas extruded from the Little Drum Mountain volcano were made utilizing both atomic-absorption spectrophotometry and x-ray fluorescence. Thirteen samples were prepared for AA utilizing the technique developed by Brimhall and Embree (1971).

Fe_2O_3/FeO ratios were determined for selected samples utilizing the technique of Riechen and Fahey (1962).

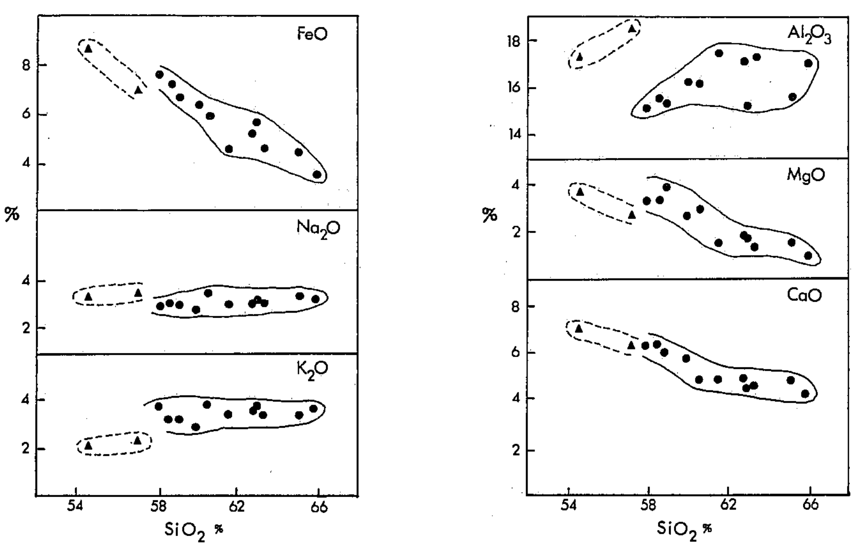
Ignition losses were ascertained by heating approximately 1g of rock powder in an oven at 120°C for 12 hours and measuring the resultant weight loss.

Chemical compositions, CIPW norms, and modal percentages are tabulated in the Appendix.

Oxide Variations

Harker variation diagrams (Text-fig. 9) reflect progressive changes in composition of the lavas that, at first glance, could be expected from fractional crystallization. Elements such as Mg, Ca, Ti, and Mn, which are normally depleted by fractionation, decrease systematically throughout the series; however, Na and K, which are typically concentrated, remain constant. The two interbedded andesite flows, which are chemically identifiable with the calc-alkaline series, are distinguished by markedly different trends only in Al_2O_3 and K_2O. For the remainder of the elements, calc-alkaline samples appear to be at least chemically gradational into the shoshonite series.

The principal chemical distinction between the two lava series is in the proportion of alkali contents. Shoshonitic lavas have a high but fairly constant K_2O content with K_2O/Na_2O ratios of 1.0 or greater. By contrast, the

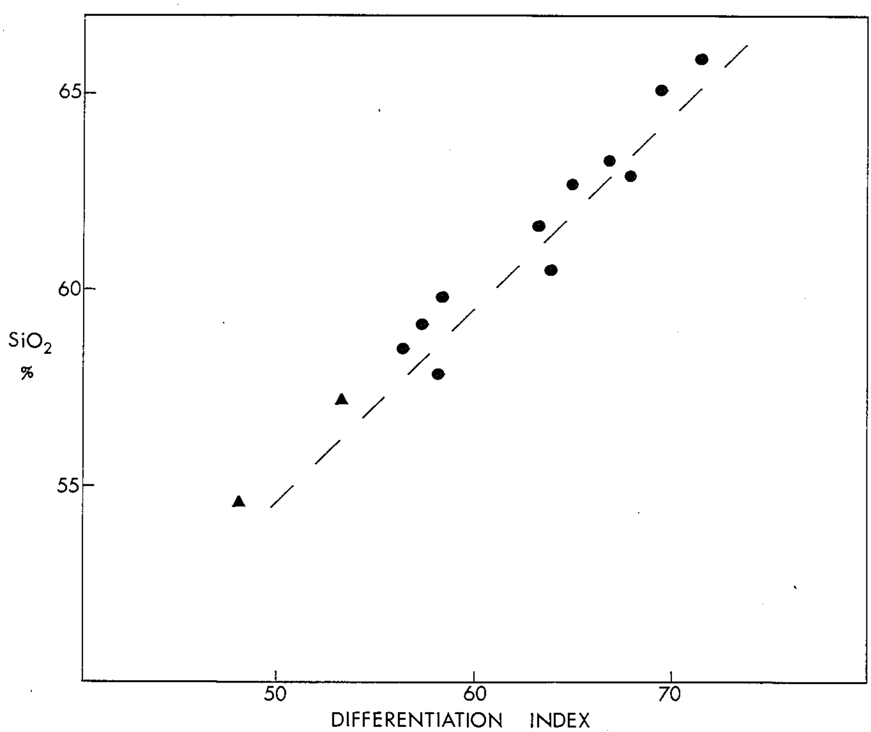


TEXT-FIGURE 9.—SiO_2 (Harker) variation diagrams for shoshonitic lavas (●) and calc-alkaline lavas (△) of the Little Drum Mountains. Trends for shoshonitic lavas (>) and calc-alkaline lavas (<).

two presumable calc-alkaline lavas are less potassic, with K_2O/Na_2O ratios near 0.6, Na_2O exceeding K_2O. Comparison of the K_2O/SiO_2 trend determined by Joplin (1968) with the Little Drum Mountain shoshonitic suite reveals that Joplin's (1968) suite contains slightly higher (1 to 2 percent) potassium contents throughout the series. However, in contrast to the characteristic flat to negative K_2O/SiO_2 slope exhibited by the shoshonite series, Joplin's (1968) data display a slight positive increase in K_2O with SiO_2, revealing latites with almost twice the potassium content of those observed in latites of western Utah. Compositions of the shoshonitic flows lie within the ranges of only the shoshonite and the latite members of the shoshonite series proposed by Joplin (1968). The calc-alkaline lavas are represented by a low-silica andesite, Ta_1, and a basaltic andesite Tlb_2f.

Silica exhibits a linear increase with the differentiation index (DI= sum of normative *q or, ab, ne*) of Thornton and Tuttle (1960) from the low-silica andesite to the latites (Text-fig. 10).

All of the lavas are silica saturated, containing up to 22 percent normative quartz, and the majority are hypersthene normative. The high potassium content occult in residual groundmasses of the shoshonitic suite is reflected in the normative orthoclase content, which averages about 20 percent throughout the suite. Calc-alkaline lavas, with lesser amounts of potassium and



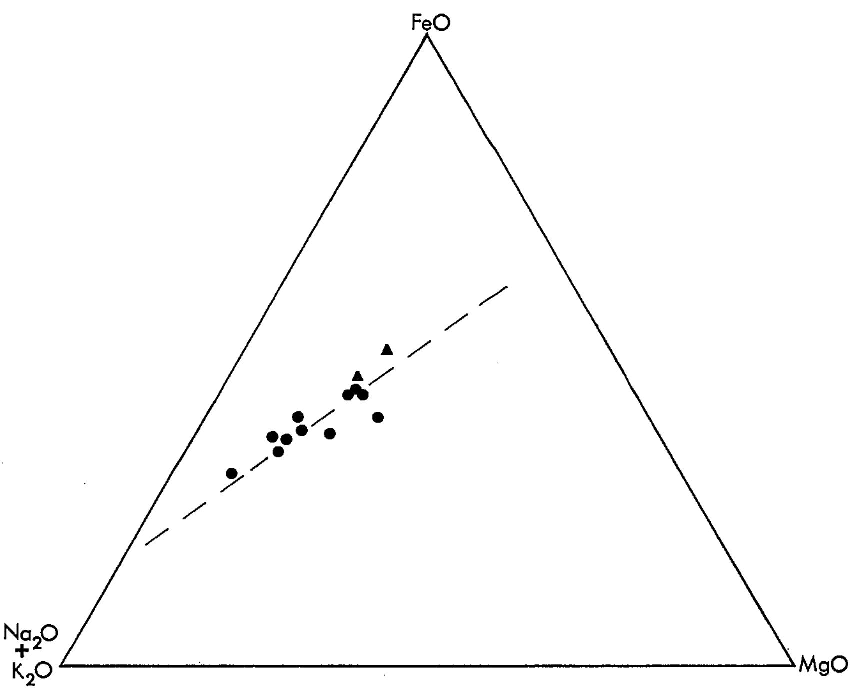
TEXT-FIGURE 10.—SiO_2 versus differentiation index (DI) diagram for shoshonitic lavas (●) and calc-alkaline lavas (△) of the Little Drum Mountains.

slightly greater amounts of sodium, exhibit slightly higher percentages of normative albite and significantly lower percentages of normative orthoclase. Strongly peraluminous samples with Al_2O_3 in excess of alkalies plus calcium, include corundum in their norms. Because of the high Fe_2O_3/FeO ratios determined for the lavas of the shoshonite suite, both normative magnetite and hematite exist, with corresponding smaller amounts of normative ilmenite.

The AFM diagram (Text-fig. 11) exhibits a slight trend away from iron enrichment with increasing alkalies, a trend recognized in other investigations of shoshonitic suites (Jakes and White, 1969; Jakes and Smith, 1970; Hogg, 1972). This trend, in addition to the calc-alkaline trend of Daly (1933), is consistent with the observation that in island-arc environments iron enrichment decreases with increasing K_2O content (Jakes and White, 1972).

PETROGENESIS

The major oxide variation diagrams (Text-figs. 9, 10) seemingly indicate that the Little Drum Mountain conduits were tapping a single continuously fractionating magma. The shoshonitic suite exhibits a gradational change in composition, from shoshonites to latites, that is paralleled closely by decreasing ages for the lavas. This unique correlation enhances the possibility of a solitary derivative magma. However, the relative lack of K_2O and Na_2O enrichment poses a perplexing problem concerning the genetic link between



TEXT-FIGURE 11.—AFM diagram for shoshonitic lavas (●) and calc-alkaline lavas (△) of the Little Drum Mountains. Trend (- - -) for calc-alkaline series from Daly (1933).

the individual members of the shoshonite series. Alternatively, the magma chamber might have been replenished periodically by influxes of new magma and allowed to fractionate further, each successive eruption being slightly more depleted, or enriched, in a particular element than in the preceding one.

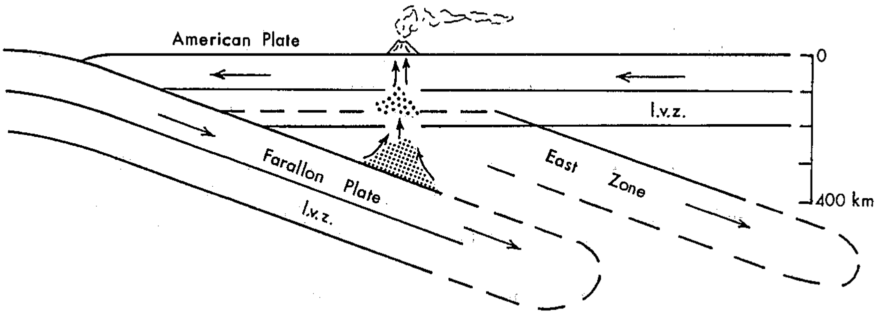
In a comparison of the chemical analyses of the least differentiated shoshonitic lava, Ts_2, according to the differentiation index trend (Text-fig. 10) with proposed parent magmas for various calc-alkaline assemblages (Nockolds and Allen, 1953), the only significant dissimilarity, other than SiO_2, is the strong K_2O enrichment of the shoshonitic suite. Whatever the scheme for K_2O enrichment in derivation of shoshonitic magmas, whether fractional crystallization of calc-alkaline magma or partial melting of peridotite, the existence of a low-temperature potassic phase appears compulsory in explaining the high K/Na ratios for the shoshonite suite. Various hypotheses devised to explain the origin of potassic rocks are reviewed by Bell and Powell (1969).

Applying the two models of Green and Ringwood (1968), relative enrichment of K_2O in the calc-alkaline series can be related to the effective shallow-level (15 to 45 km) fractionation of amphibole in crystal-rich lavas and the retention of amphibole in the liquid phase at greater depths (45 to 80 km). Recent studies by Green (1972) indicate that high-K, calc-alkaline lavas may be produced at depths greater than 150 km, where partial melting, controlled by ecologite fractionation could result in silica and potassium enrichment through wall-rock reaction and breakdown of phlogopite as the magma ascends.

There appears to be no realistic combination of mineral phases that would allow calc-alkaline lavas to originate from fractionating shoshonitic magmas, or vice versa, with all the critical elements, excluding K, remaining constant. Nicholls and Carmichael (1969) point out a similar problem within the shoshonite series in attempting to derive the highly feldspathic banakite member from the more mafic absarokite member. Jakes and White (1972) suggest that differences in trace elements between calc-alkaline and shoshonitic rocks of the same SiO_2 content imply they were not produced by mere fractionation of one parent magma.

Based on these conclusions, recent studies involving shoshonitic suites attempt to relate their origin to hybrid assimilation of an earlier magmatic phase by later, presumably differentiated, melts (Bell and Powell, 1969; Prostka, 1973). Petrographic studies of the shoshonite suite in the Absaroka Volcanic Field indicate a hybrid origin, involving assimilation of gabbro by a high-temperature syenitic magma (Prostka, 1973). Although the textural evidence for Prostka's shoshonites appears to be compatible with a hybrid origin, it should not be presumed that all shoshonite suites are similarly derived. In particular, the association of syenite and gabbro magmas in the Little Drum Mountains is totally hypothetical. Mantle-derived inclusions occurring in absarokites (Babkine et al., 1968) indicate that primary potassic-rich mafic magmas presumably exist in the upper mantle.

The disequilibrium phenocrystic phases occurring in the Little Drum lavas are possibly the result of a complex history of magmatic interactions between ascending partial melts resupplied by a subducting oceanic plate, and overlying fractionating upper-mantle magma chambers. Additional interactions could be expected between ascending fractionated shoshonitic melts and



TEXT-FIGURE 12.—Schematic cross section of inferred imbricate middle Cenozoic subduction zones across western United States, depicting contemporaneous calc-alkaline and shoshonitic magma generation from the Little Drum Mountains volcanic center (modified from Lipman et al., 1972).

postulated overlying calc-alkaline magmas related to two imbricate subduction zones (Text-fig. 12.) Still another possibility is that the "xenocrystic" grains represent high-pressure precipitates formed in magmas which ascended to the surface too rapidly to maintain equilibrium. The presence of glassy groundmasses in these lavas and not in others might suggest rapid quenching of "superheated" residual liquids upon extrusion.

REGIONAL CONSIDERATIONS AND CONCLUSIONS

The Little Drum Mountains volcanic complex is part of a large volcanic province related to a presumed mid-Tertiary subduction zone in the western United States. A significant portion of this province in western Utah belongs to the shoshonite series. Hogg (1972) found that mafic flows in Fish Springs Flat, Honeycomb Hills, Grayback Mountain, and the Stansbury Mountains belong to the shoshonite series. Examination of the analytical data for previously described latitic lavas in the Tintic District, the Park-City District, the San Francisco District, the Iron Springs District, and the Marysvale region indicate that low-silica samples have shoshonitic affinities (Text-fig. 2). Pre-Pliocene latites overlain by Quaternary tholeiitic basalts in the Black Rock Desert (Hoover, pers. comm., 1973) are also shoshonitic.

Recent studies concerning island-arc evolution establish a correlation between the potassium content of lavas and the depth to the underlying inclined Benioff zone (Kuno, 1966; Dickinson and Hatherton, 1967; Dickinson, 1968). In island arcs early tholeiitic eruptions on the oceanic side are succeeded inland by calc-alkaline rocks, and finally by shoshonitic lavas at increasing distances from the arc (i.e., with increasing depth to the subduction zone) (Jakes and Smith, 1970; Jakes and White, 1969; Gill, 1970; Jolly, 1971). Using K_2O/SiO_2 variation diagram of Dickinson (1968), Lipman et al. (1972) inferred the existence of two imbricate subduction zones during early and middle Cenozoic time in the Great Basin.

The estimated depth, based on my data, to the western of these two subduction zones beneath the Little Drum Mountain volcanic center ranges between 150 and 350 km. The uncertainty in depth is related to the range of potassium contents in the shoshonitic and the presumed calc-alkaline lavas, and to the slight inclination of the K_2O/SiO_2 variation diagram (Text-fig. 16). The shoshonitic lavas, which contain between 2.8 and 3.4 percent K_2O at 60 percent SiO_2, correspond to a depth of 250 to 350 km, whereas calc-alkaline values indicate much shallower depths of 100 to 150 km. The accuracy of the depth derived from the latter values is diminished because of the limited number of samples. It must be emphasized that these values give only the apparent depths to the Benioff zone in the Dickinson model. The actual depth of magma generation is not specified and is likely shallower.

Jakes and White (1972) propose two complementary evolutionary models for the potassic lavas of island arcs. One model derives magmas from the partial melting of the upper part of the descending oceanic slab with a contributing lower melting phase, presumably alkaline sediments, being dragged along the subduction zone. In the other model the underthrust oceanic crust merely supplies volatiles and hydrated siliceous fluids to the overlaying upper mantle where partial melting occurs. In both models subsequent fractionation of the ascending magma is complementary to partial melting.

In addition to occurrences in the Little Drum Mountains, occurrences of temporal and spatial mingling of calc-alkaline and shoshonitic lavas are found in the Absaroka Volcanic Field (Chadwick, 1970), in Papua (Jakes and Smith, 1970), and Puerto Rico (Jolly, 1971). Two complementary models have been proposed to account for such occurrences. In the first model, Jakes and Smith (1970) believe that early fractionation of a low-temperature potassic phase, presumably biotite, produces low-Si, potassium-enriched, crystal-rich lavas (high-K calc-alkaline, and absarokite-shoshonite lavas) and residual silica-rich liquids depleted in potassium (banakite-latite lavas). In a second model, Jakes and Smith (1970) and Jolly (1971) postulate that similar lava associations could be produced contemporaneously by varying degrees of partial melting of dehydrated tholeiites of the oceanic lithosphere along the Benioff zone.

Strong fractionation of rare-earth elements in calc-alkaline and shoshonitic rocks indicates that the high-K series may originate from a slight degree of partial melting of more primitive mantle material (Jakes and White, 1972). Inclusions of lherzolite, amphibole lherzolite, and ariégite (garnet-pyroxene-spinel) occurring in an absarokite from Pouget, France (Babkine et al., 1968), indicate a mantle derivation of this lava. The contemporaneous eruption of calc-alkaline and shoshonitic lavas from the same vents in the Little Drum Mountains may indicate that a conduit was tapping two independently fractionating magmas derived from the upper mantle.

Shallow dips of 20° to 25° inferred from subduction zones in the western United States (Lipman et al., 1972) preclude contemporaneous generation of the Little Drum magmas at increasing depths along the upper surface of one subducing oceanic plate. However, magma derivation could conceivably correspond to two sites along each of the two inferred imbricate subduction zones. The shoshonite magmas could be associated with depths of 250 to 350 km along the western Benioff zone. Depths of 100 to 150 km for the calc-alkaline lavas correspond to the low-velocity zone, in which contemporaneous decoupling of the overlying eastern zone might have occurred (Text-fig. 12).

In this study, an early to mid-Cenozoic shoshonitic volcanic province has been confirmed and extended in western Utah. Additional radiometric and petrologic investigations of numerous known mafic flows associated with isolated volcanic centers in west-central Utah would help to define the nature and geographical limits of the province. Trace element and isotope studies of documented centers would aid in determining the nature and origin of their source magmas related to the volcanic-tectonic evolution of the eastern margin of the Great Basin. Experimental research involving the magmatic processes and possible "primitive" potassic phases responsible for the unique characteristics of the shoshonitic kindred could confirm a possible genetic link to the calc-alkaline series. Research devoted to the nature of the mineralogy and phase equilibria of the shoshonitic series would shed light on the genetic relationship between phenocrystic phases and chemical characteristics of the individual members of the series.

In addition, geophysical research related to the kinematics involved in decoupling subducing plates could aid in recognizing possibly related mid-Tertiary calc-alkaline-shoshonite magma associations in western Utah.

APPENDIX

TABLE 1
CHEMICAL AND NORMATIVE COMPOSITIONS AND MODAL ANALYSES

Spec. no.	5-8	5-3	5-5	5-1	5-42
Map Unit	Ta_1	Tlb_2f	Tls_1	Ts_2*	Ts_3
Name	Pyroxene Andesite	Pyroxene Andesite	Hornblende Shoshonite	Hornblende Pyroxene Shoshonite	Pyroxene Shoshonite
SiO_2	54.54	57.08	57.80	58.54	59.08
TiO_2	1.22	.81	1.44	1.22	.96
Al_2O_3	17.29	18.43	15.15	15.54	15.36
Fe_2O_3	5.20			6.10	
FeO	3.94	6.85^{+}	7.67^{+}	1.60	6.61^{+}
MnO	.15	.11	.90	.10	.11
MgO	3.59	2.69	3.20	3.28	3.86
CaO	6.74	6.16	6.25	6.28	6.02
Na_2O	3.21	3.38	2.92	3.05	3.02
K_2O	2.04	2.26	3.75	3.20	3.19
Ign. loss	n.d.	n.d.	n.d.	1.52	1.68
Total	97.92	97.77	98.27	100.43	99.89
Q	9.17	11.46	11.30	12.78	13.02
or	12.06	13.36	22.16	18.91	18.85
ab	27.10	28.54	24.65	25.75	25.50
an	26.08	27.73	16.73	18.78	18.46
di	5.28	1.67	10.78	9.25	8.51
hy	7.66	7.16	2.97	3.88	5.67
mt^{++}	7.54	5.96	1.79	1.95	2.48
hm			5.32	4.76	3.94
il	2.32	1.54	2.73	2.32	1.82
K_2O/Na_2O	.64	.67	1.28	1.05	1.06
TTI	48.33	53.35	58.11	56.41	57.37
Phenocrysts					
Plagioclase	18.7		0.7	2.3	15.4
Olivine			2.7		0.2
Augite	6.5		0.6	2.2	12.3
Hypersthene	2.6		8.2	3.1	7.3
Amphibole	0.1		0.2	7.3	
Biotite			2.9		
Fe-Ti oxides	3.2			2.2	
Groundmass	68.9		84.7	82.9	65.0

* Whole-rock potassium-argon age date, 37.3 ± 0.4 million years.

† Total Fe reported as FeO.

†† Fe_2O_3/FeO ratios for normative calculations based upon ratios determined in this report for selected shoshonite, latite, and andesite.

TABLE 2
CHEMICAL AND NORMATIVE COMPOSITIONS AND MODAL ANALYSES

Spec. no.	5-2	5-41	5-7	5-100	5-52
Map unit	Tlb_2f	Ts_3	Tvb	Tl_3	Tls_1
Name	Hornblende Latite	Pyroxene Latite	Latite Vitrophere	Hornblende Pyroxene Latite	Hornblende Biotite Latite
SiO_2	59.80	60.48	61.44	62.78	62.91
TiO_2	.80	.95	.50	.68	.95
Al_2O_3	16.35	16.32	17.50	17.24	15.23
FeO^+	6.29	5.90	4.51	5.05	5.67
MnO	.12	.06	.13	.08	.08
MgO	2.54	2.91	1.56	1.84	1.78
CaO	5.72	4.88	4.82	4.93	4.52
Na_2O	2.86	3.46	3.05	3.02	3.13
K_2O	2.88	3.95	3.37	3.52	3.76
Ign. loss	n.d.	n.d.	n.d.	n.d.	1.51
Total	97.36	98.71	96.88	99.14	99.54
Q	17.21	11.82	18.20	18.74	19.28
or	17.02	23.34	19.93	20.80	22.22
ab	24.15	29.21	25.75	25.50	26.43
an	22.69	17.48	23.32	22.51	15.99
di	3.97	4.89		1.06	4.68
hy	4.48	4.98	3.88	4.09	2.26
mt^{++}	3.55	2.57	4.35	2.67	2.44
hm	2.64	3.01	.54	2.26	2.92
il	1.52	1.80	.96	1.29	1.80
C			.06		
K_2O/Na_2O	1.01	1.14	1.10	1.17	1.20
TTI	58.38	64.37	63.88	65.04	67.93
Phenocrysts					
Plagioclase					16.5
Augite					0.5
Hypersthene					0.3
Amphibole					11.4
Biotite					1.9
Fe-Ti oxides					2.0
Groundmass					67.4

* Whole-rock potassium-argon age date, 37.3 ± 0.4 million years.
† Total Fe reported as FeO.
†† Fe_2O_3/FeO ratios for normative calculations based upon ratios determined in this report for selected shoshonite, latite, and andesite.

TABLE 3
CHEMICAL AND NORMATIVE COMPOSITIONS AND MODAL ANALYSES

Spec. no.	5-6	5-9	5-101	5-1P	5-8P
Map Unit	Tl_2	Tl_3*	Tl_3	Ts_2	Ts_3
Name	Pyroxene Latite	Hornblende Pyroxene Latite	Hornblende Latite	Hornblende Phenocryst	Orthopyroxene Phenocryst
SiO_2	63.34	65.10	65.93	43.61	51.51
TiO_2	.46	.56	.40	2.75	0.79
Al_2O_3	17.35	15.67	17.17	11.22	3.17
Fe_2O_3		3.47			
FeO	4.45	1.14	3.43	10.58	8.55
MnO	.12	.08	.03		
MgO	1.32	1.61	.87	15.58	15.66
CaO	4.60	4.81	4.23	11.37	20.38
Na_2O	3.11	3.29	3.25	2.04	0.35
K_2O	3.43	3.44	3.59	1.15	0.04
Ign. loss	n.d.	1.49	n.d.		
Total	98.18	100.66	98.90	98.30	100.44
Q	20.31	21.40	22.94		
or	20.27	20.33	21.21		
ab	26.26	27.78	27.44		
an	22.25	17.39	20.46		
di		4.69			
hy	3.29	1.83	2.17		
mt	2.93	2.31	1.94		
hm	1.59	1.88	1.43		
il	.87	1.06	.76		
C	.16		.25		
K_2O/Na_2O	1.10	1.05	1.10		
TTI	66.83	69.51	71.59		
Phenocrysts					
Plagioclase	40.4	19.8			
Augite	4.9	1.3			
Hypersthene	3.0	2.0			
Amphibole	0.1	3.1			
Fe-Ti oxides	3.9	1.6			
Groundmass	47.7	72.2			

* Whole-rock potassium-argon age date, 37.3 ± 0.4 million years.
† Total Fe reported as FeO.
†† Fe_2O_3/FeO ratios for normative calculations based upon ratios determined in this report for selected shoshonite, latite, and andesite.

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