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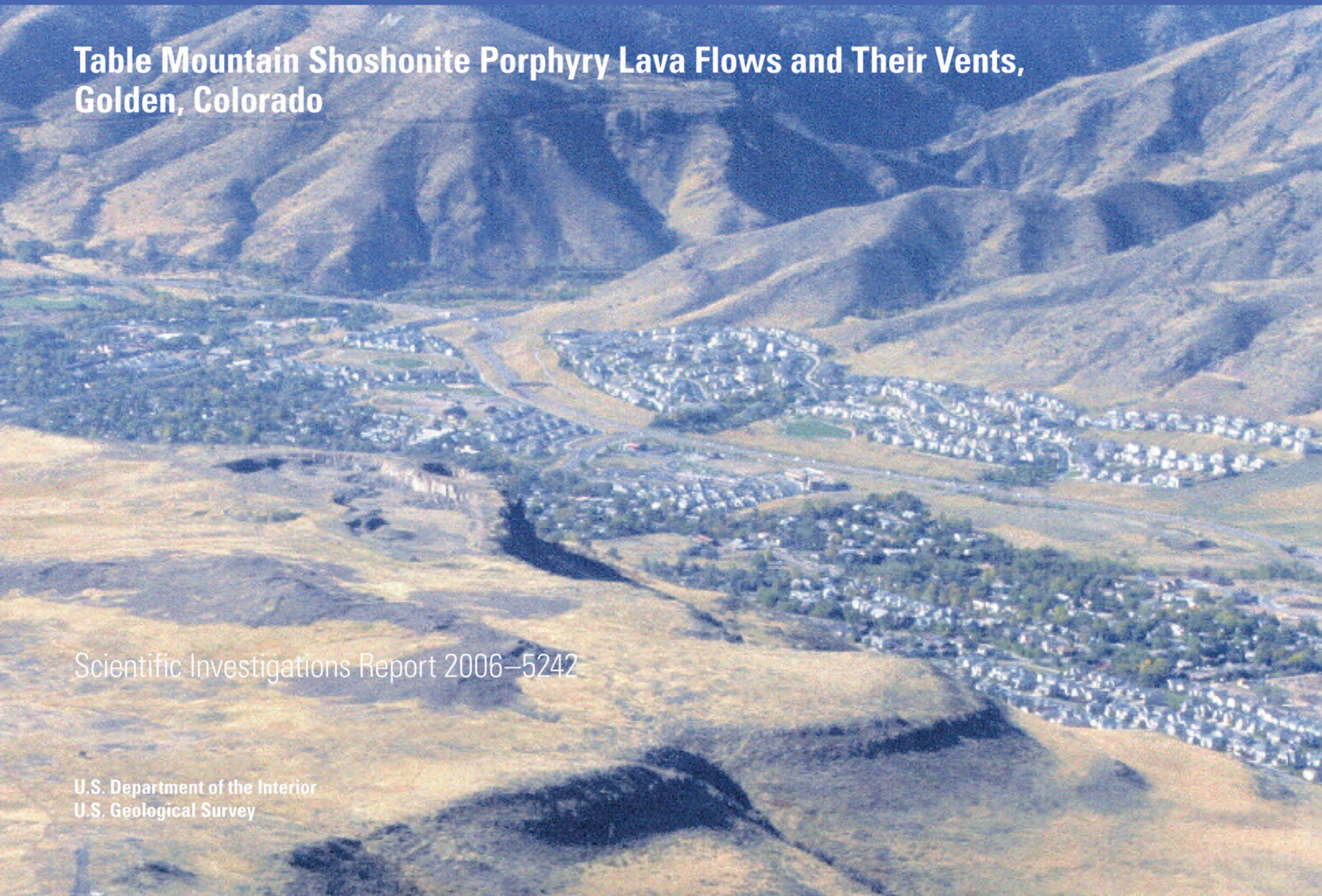
Table Mountain Shoshonite Porphyry Lava Flows and Their Vents, Golden, Colorado



Scientific Investigations Report 2006–5242

U.S. Department of the Interior
U.S. Geological Survey

Cover. North Table Mountain, Golden, Colo., looking south. Photograph by Shawn Steigner.

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By Harald Drewes

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Volume	
cubic mile (mi^3)	4.168	cubic kilometer (km^3)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Volume	
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)

Table Mountain Shoshonite Porphyry Lava Flows and Their Vents, Golden, Colorado

By Harald Drewes

Abstract

During early Paleocene time shoshonite porphyry lava was extruded from several plugs about 5 km north of Golden, Colo., to form lava flows intercalated in the upper part of the Denver Formation. These flows now form the caps of North and South Table Mountains. Detailed field and petrographic studies provide insights into magma development, linkage between vents and flows, and the history of the lava flows.

The magma was derived from a deep (mantle) source, was somewhat turbulent on its way up, paused on its way up in a shallow granite-hosted chamber, and near the surface followed the steep Golden fault and the thick, weak, steeply dipping Upper Cretaceous Pierre Shale. At the surface the lava flowed out of several plug and dike vents in a nonexplosive manner, four times during a span of about 1 m.y. Potassium-rich material acquired in the shallow chamber produced distinctive textures and mineral associations in the igneous rocks.

Lava flows 1 (the lowest) and 2 are channel deposits derived from the southeastern group of intrusions, and flow 1 (a composite, multiple-tongued flow) lies about 50 m below the capping flows. Provisionally, the unit termed flow 1 is considered to include older, felty-textured flows that are distinguished from a blocky-textured unit, flow 1a. Flow 2, newly recognized in this study, lies immediately beneath the capping flows. Lava flows 3 and 4, more voluminous than the earlier ones, were derived from a plug vent 1–2 km farther north-northwest and flowed south-southeast across a broad alluvial plain. This plug is a composite body; the rim phase fed flow 3, and the core phase was the source of flow 4. During the time between the effusion of the four flows, the composition of the shoshonite porphyry magma changed subtly; the later flows contain more alkali, as shown by higher proportions of sanidine.

On North Table Mountain, lava flows 3 and 4 form an elongate tumulus above a stream channel that carried water at the time of their eruption. On South Table Mountain, lava flow 3 forms a low, broad dome that forced flow 4 into channels now restricted to the west and northeast flanks of that mesa.

Mesa-capping lava flows 3 and 4 are broken by many small normal faults and are warped into open synclines, probably in response to local stresses associated with the settling of piedmont deposits into the Denver Basin. Mid-Tertiary deposits are inferred to have covered the upper part of the Denver Formation and its lavas; these deposits could thus have been instrumental in changing the stream flow direction to the east before the onset of Neogene uplift and consequent canyon cutting across the flows. Other younger deposits may also have covered the area, to be linked to this consequent canyon cutting.

Introduction

During the early Paleocene the area of Golden, Colo., lay at the foot of the Laramide Rocky Mountains, much as the town now is at the front of the present Rocky Mountains. However, some geologic conditions changed between that time and the present. During the earlier time of mountain building, uplift was accompanied by tilting and faulting of the sedimentary sequence. Not only were there abundant andesitic eruptions to the west, but a shoshonite porphyry volcanic system developed locally. The present uplift has been unaccompanied by volcanism, and reactivation of the Golden fault is suggested by only very limited evidence.

The present study focuses on the volcanic rocks and their vents (fig. 1); the lava flows are dated as 64–63 Ma (mega-annum, or millions of years). The magma reached the surface along the Golden fault and flowed south-southeastward along the paleo-drainage system. Although a considerable body of knowledge about these rocks has already accumulated, most past studies were aimed at stratigraphy, surficial geology, and zeolite mineralogy. Thus, the present study—based on more detailed mapping, structural geology emphasis, and petrographic considerations—permits new interpretations and raises new questions.

Previous Work and Methods Used in This Study

Earlier studies, such as the work of Johnson (1925), explained aspects of the structure of the Golden area, and the regional concepts of Drewes (1991a,b) suggest

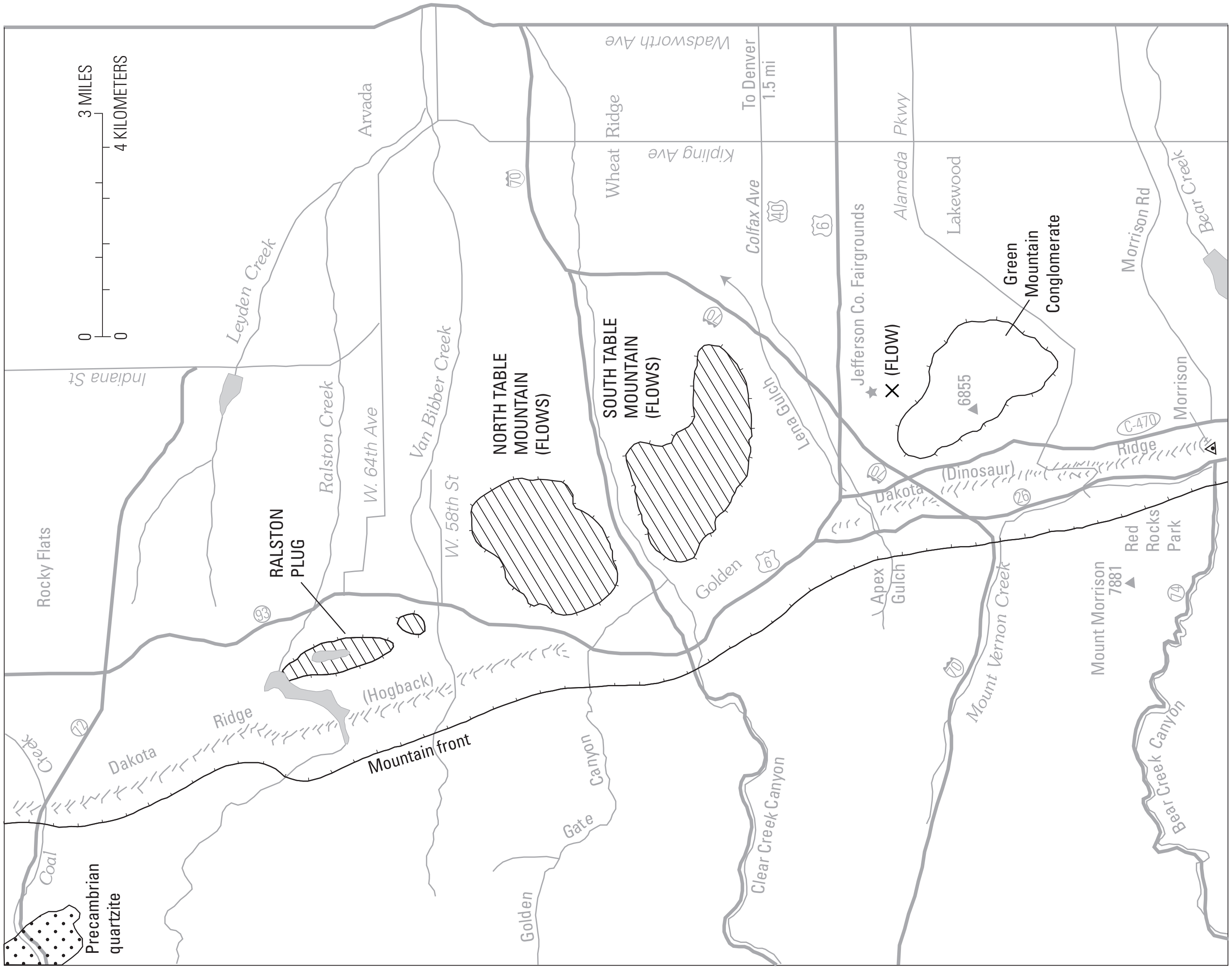


Figure 1. Location of igneous rocks (patterned areas) along western margin of Denver Basin near Golden, Colo.

that the effects of the Laramide orogeny might be viewed as a young foreland phase of a more regional Cordilleran orogeny. A more regional interpretation emphasizes an east-west–oriented compressional stress field in which the local steep structures, such as the Golden fault, may be shallow-level "sled-runner" structures or even backthrusts.

The initial effort of the present study was the preparation of 1:6,000 to 1:12,000 geologic maps of key areas. Base maps were prepared from the Golden and Morrison 7½-minute U.S. Geological Survey topographic maps of 1965, which were also the base maps used by Van Horn (1972) and Scott (1976). Their geologic maps provided a valuable foundation to my initial effort. Rock samples were collected in the mapping effort of 2001–03.

Petrographic study followed the mapping and was based on 48 thin sections of selected rocks. These sections were cut and some also stained for potassium feldspar by the Western Petrographic Company of Provo, Utah. The thin sections were studied during 2003–04.

Structural features encountered in the Cretaceous and Tertiary sedimentary formations were recorded during the present study. The stratigraphic units associated with the lava flows are the Cretaceous Pierre Shale and the Cretaceous and Tertiary Denver Formation. The stratigraphy and sedimentology of these units were not studied for this report; however, brief descriptions of them are included. For further data on stratigraphy see Van Horn (1957, 1972), Scott (1976), and Weimer (1996), and for details on the Paleocene Green Mountain Conglomerate see Drewes and Townrow (1999). Older works of note include Johnson (1925), Van Tuyl and others (1938), and Waage (1953), and those of historic interest include LeConte (1868), Hayden (1873), and Emmons and others (1896).

Overview of the Igneous Rocks

The igneous rocks are unquestionably closely related; intrusive and extrusive rocks alike are shoshonite porphyry (a potassium-rich basalt) having small phenocrysts of plagioclase, pyroxene, and olivine. The lava flows are dated as 64.2±1.1 to 63±1.7 Ma, as reported by Obradovich (2002). Intrusive bodies north-northwest of the Table Mountain lava flows consist of one large composite plug, now being quarried, and a cluster of smaller dikes, sills, and another plug. Known as the Ralston intrusive bodies or the Ralston dike or plug, these are hosted in the Pierre Shale.

About 2 km south-southeast of the nearest small intrusive body (a small plug) is North Table Mountain, on which four levels of lava flows are recognized. The flows are numbered sequentially upward. Small flows at the same stratigraphic level are given one number, 1, except for one with a unique texture here designated 1a. Flow 1 is considered in this study to be a composite, multiple-tongued flow, and where the tongues can be distinguished, they have been mapped as flow 1 or flow 1a. Lava flow 2 is newly recognized as a distinct flow in this study; previously it had been assigned to flow 3 (or to unit Tv2 of Van Horn, 1972). Flows 1 and 2 are channel flows; flow 1 occupied three or four channels and flow 2 a single channel. Flow 1 lies about 50 m below flow 3 (with Denver Formation intervening), whereas flow 2 has little or no sedimentary material separating it from flow 3. The mesa-capping flows are 3 and 4. On North Table Mountain these flows are separated from each other by small lenses of conglomerate and sandstone.

The kilometer-wide Clear Creek Canyon separates North from South Table Mountain. Only lava flows 3 and 4 reached South Table Mountain. No intervening sedimentary lenses have been found between these flows on South Table Mountain. However, there may be remnants of downfaulted sedimentary rocks overlying flow 4 at two sites, described subsequently. Furthermore, only a small volume of flow 4 reached South Table Mountain, where it filled two local channels flanking a domal core on flow 3.

Lava flow 3 reached the north flank of Green Mountain about 2 km south of South Table Mountain. The intermittent stream in Lena Gulch now flows through the broad, shallow gap. Until about 1990 there was a single outcrop of flow 3 accessible just above (south of) the Jefferson County Fairgrounds, but that site was then "suburbanized" (that is, scraped off and covered).

Cretaceous and Tertiary Sedimentary Rocks

Among the host rocks pertinent to this investigation are the Upper Cretaceous Pierre Shale and the Cretaceous and Tertiary Denver Formation. The Pierre Shale—a medium-gray clay shale or mudstone and some silty shale—is about 1,880 m thick. It generally does not weather out, even as flakes. Where the Pierre is naturally exposed, it generally appears as layered mud, but it typically is thickly covered by colluvium or by terrace deposits. Inevitably, exposures of Pierre Shale in this area are the result of excavations. In the area of the Ralston intrusive bodies, which is also disturbed by the north-trending Golden fault, the vertical to steep eastward dips of the Pierre reflect the up-arching of the whole sedimentary sequence over the Rocky Mountains. Locally, however, the shale dips anomalously westward. Fossils of pelecypods and orthocerids (cephalopods) were found at only two real outcrops; yet Van Horn (1972) reported fossils in sufficient abundance and sequential order so as to infer structure from them, although the fossils come mainly from colluvial areas that are heavily grass covered. No effort was made to verify Van Horn's recorded observations; his structural interpretations therefore are simply accepted in the present study.

The upper part of the Denver Formation, in which the lava flows are intercalated, is poorly consolidated, pale-yellowish-brown to light-yellowish-gray or, rarely, nearly white siltstone, sandstone, and some conglomerate. Clast sorting is poor to moderate, and clasts are subrounded. Stream-type crossbedding, channel deposits, and mudflow beds are common. Most clasts are of andesitic rock; these include various porphyries, aphanitic rock, and some vesicular rock. At the southeast end of South Table Mountain, andesitic scoria is present in a bed about 50 m below flow 3. Conspicuous by their absence are shoshonite ejecta. Biotite from these clasts was dated by the K-Ar method, using modern decay constants, as 65.8±1.4 Ma (Evernden and others, 1964; Obradovich and Cobban, 1975). Although the cited authors discussed the relationship of this bed to the nearby Cretaceous-Tertiary boundary, I suspect their date simply supplies the age of the volcanic source rocks of the Denver Formation, a source that lay perhaps a few tens of kilometers to the northwest. The date thus has only an indirect bearing on the age of the overlying lava flow.

The dark crystals within the clasts of the Denver Formation are amphibole (those in the dated scoria were biotite, however). In only a few places were clasts of shoshonite porphyry found; either these places were at the level of, and downstream from, the distal end of a part of flow 1, or they were near lava flows 3 or 4.

Fossil wood fragments are common in the Denver Formation, but most are surface finds and possibly lag concentrates. Most of this wood is medium gray to nearly white and not very siliceous. Charcoal chips are abundant in a 20-cm-thick mudflow bed (within the Denver Formation at site P in fig. 6) that is 3 m below flow 3 on the west flank of South Table Mountain.

All signs indicate that the Pierre Shale was a marine deposit and that the Denver Formation was a fluvial channel deposit. To judge by the thickness of the mud deposited by the Pierre sea, its floor must have been dropping slowly but steadily. At the end of Pierre time, at about 80 Ma, the region started to rise, and by Denver Formation time a moderately high area lay to the west. Streams from this upland drained east-southeastward as seen on Green Mountain (Drewes and Townrow, 1999) and as will be shown in this study.

Field Observations

Ralston Intrusive Bodies

The Ralston shoshonite porphyry intrusive bodies comprise one large composite plug to the northwest and a small plug plus many small dikes and sills to the southeast. The large plug has previously been referred to as the “Ralston dike,” but its oval shape (2 km long and 1 km wide) suggests the term “plug.” Perhaps the poorly exposed center of the intrusive body gave the impression that only the narrow eastern and western ridges were dikes (fig. 2). In this plug a core phase and a rim phase are recognized.

Ralston Plug

At the time of this study quarrying was in progress in the rim-phase rock of the western higher ridge, in which seven levels have been cut. Although this quarry provided excellent fresh outcrops, the sample sites have already vanished or will soon. Smaller inactive quarries and tunnel entrances offer other sites of fresh rock. On the other hand, artificial fill covers some parts of the plug.

The topography of the northwestern plug is instructive; its edges are high, whereas its elongate core forms a basin. With the aid of some small earthen dams, much of this core area has been turned into a reservoir, Upper Long Lake. The remainder of the basin is largely covered by colluvium. Tunnels through the eastern and western ridges bring water into the lake and then out of it to a lower reservoir, Lower Long Lake.

In projecting the Golden fault along the north-northwest–trending axis of the Ralston plug, I concur with the mapping of Van Horn (1972). Other branches of that fault are based on fossil distribution (Van Horn) and on structural anomalies (this study).

The rim phase is very hard, medium-gray to dark-gray rock that is cut by widely spaced, steep, east-northeast–trending joints. This trend is approximately normal to the axis of the plug. Its outer contact with Pierre Shale dips inward, more steeply west of the western ridge and more gently east of the eastern ridge. The net effect is that the plug has the shape of an upright, elongate, eastward-tilted funnel. Of course, magma did not go down the funnel, but rather as it rose the confining pressure decreased more rapidly on the east side than the west side of the plug. Trace amounts of pyrite in veinlets and tiny pockets were seen in two places near the outer contact on the west and north sides of the plug.

The core phase resembles that of the rim phase in many ways; yet it is subtly different. It weathers browner and is cut by closely spaced joints that mostly dip gently inward. This difference in jointing and weathering intensity explains the contrasting topographic habits of plug rim and core. The contact between rim and core rocks is chiefly covered but in the quarry is gradational across tens of meters. This observation suggests that the rim-phase rocks were still hot when the core-phase magma came through; the arrivals of the two magma phases were separated only by a small span of time.

The Ralston plug is surrounded by an altered, or “baked,” zone of Pierre Shale. Along the western ridge, where the baked zone is well exposed by quarry operations, it is 10–15 m wide. This width extends around the north end of the plug, but it thins slightly along the eastern ridge and is concealed to the south. In the baked zone the mudstone is sufficiently hardened to weather into flakes or even plates. Its color is also changed from gray to pale yellowish brown. Although the core-phase rock near the outer contact becomes finer grained, it is not vitreous.

Several small dikes crop out northwest of the Ralston plug (Van Horn, 1972) but are now beneath the water of the Ralston Reservoir or beyond the area of figure 2. They appear to lie closer to the projected western branch of the Golden fault than to the main fault.

Southeastern Group of Intrusive Rocks

The southeastern group of intrusive rocks lies mainly between the quarry access road to the north and Van Bibber Creek to the south (fig. 2). Most of these elongate bodies are a few tens to a few hundreds of meters in length and seem randomly scattered. Several western bodies are roughly aligned, although in detail they are en echelon and are steeply inclined, perhaps near a fault. Certain features of the eastern intrusions suggest that they have gently inclined contacts; the small bodies seem to curve around the topography like sills, whereas the small plug just north of the creek has an exposed contact dipping 5°–30° W. This small plug is about 0.5 km in diameter and is generally subcircular in plan but with some prongs heading northward. The gently westward dipping features along these eastern bodies again suggest that the rising magma expanded more freely eastward.

The recurrence of this inferred eastward expansion of rising magma at both plugs may support Van Horn's (1972) interpretation that the mass of Pierre Shale east of Highway 93 is a thrust flap in the area of the intrusive rocks, rather than a Quaternary landslide. Such eastward expansion at least permits Van Horn's thrust-flap interpretation, whereas the preservation of faunal zones requires it.

Probably few of the southeastern group intrusive bodies reached the Paleocene surface. Those most likely to have done so are the small plug and maybe one of the western dikes, on the basis of their size. It is noteworthy that none of these bodies has surrounding baked zones. Apparently, insufficient magma passed up these vents to provide the necessary heat to bake the wall rock.

North Table Mountain Lava Flows

Shoshonite porphyry lava flows crop out at four levels on North Table Mountain. The distribution of the flows on North Table Mountain is shown in figure 3. The lower two levels are channel flows; the upper two flows spread across a broad south-southeast–sloping valley plain. Lava flow 2 (site A in fig. 3) is newly identified in this study; previously it had been mapped as part of flow 3 (or of Tv2 of Van Horn, 1972), the lower of the mesa-capping flows. Many of these features are shown in the photograph of North Table Mountain (fig. 5).

To judge by the relative thickness of sedimentary beds between the flows, considerable time elapsed between extrusion of flows 1 and 2 but only a little time separated extrusion of the other flows. The dates on flows 1 and 4 are only about 1 m.y. apart; thus the time between extrusion of flows 1 and 2 may have been as much as 0.95 m.y., and the spread between the extrusion of the others would then be measurable in tens of thousands of years at most. This statement is speculative, however, because the margin of error for the dates of the flows is such that their date ranges overlap and are therefore statistically identical.

The lava-flow foliation on North Table Mountain generally dips 3°–5° SE. However, at the highest part of the mesa along its northeastern edge, dips are 5°–7° SW., thereby suggesting an open, southeast-plunging syncline. Additionally, flows 3 and 4 are cut by about 25 small normal faults, some of which control the predominant, southeast-flowing drainage on the mesa top. Offsets range from 1 m to a few tens of meters. Likely, both the fold and faults were formed as the foreland-basin deposits settled in the Denver Basin, thereby generating local stresses.

Some modifications have been made to the North Table Mountain mapping of Van Horn (1972). The small lens of lava flow 1 on the northwest flank of the mesa (fig. 3, near site B) has been extended southwestward to the gully just east of flow 2 (fig. 3, near site C). Also, only three, not four, lenses of flow 1 crop out on the south flank of North Table Mountain; the westernmost one as previously shown (fig. 3, site D) is thought to be a patch of slump material derived from overlying flows. Additionally, the contact between flows 3 and 4 is considered to have been eroded back from the mesa edge between the northern end of the mesa and the communications building (fig. 3, site E). This interpretation is based on tracing the top of the red, oxidized, amygdaloidal upper zone of flow 3 along the base of a low cuesta. It is this mapping that led to the recognition of flow 2 (unit Tf2) at site A (fig. 3).

Lava Flow 1

Lava flows 1 and 1a form several small lenses around the flanks of North Table Mountain, where they occupy three or four shallow channels about 50 m beneath the mesa-capping flows. These flows are at most 15 m thick and are weakly columnar jointed. All are heavily oxidized, and most are amygdaloidal. Their source is a small plug northwest of the intersection of Highway 93 and 58th Street.

Lava Flow 2

Lava flow 2 appears only at site A (fig. 3), where it has a thick eastern part and a thin western one, about 15 and 9 m thick, respectively. The change in thickness takes place abruptly along a steep contact that is not a fault; rather, it appears to be

LIST OF MAP UNITS IN AREA AROUND RALSTON INTRUSIVE BODIES

Unit	Description
Qa	Younger alluvium (Quaternary)
Qaf	Artificial fill (Quaternary)
Qc	Colluvium (Quaternary)
Qls	Landslide deposits (Quaternary)
Qao	Older alluvium (Quaternary)
	Terrace deposits (Quaternary)
Qb	Broadway Alluvium
Qlo	Louviers Alluvium
Qs	Slocum Alluvium
Qv	Verdos Alluvium—Queried where scraped off for construction purposes
Qrf	Rocky Flats Alluvium
TKd	Denver Formation (Paleocene and Upper Cretaceous)
	Shoshonite porphyry (Paleocene)
Tsc	Core phase
Tsr	Rim phase
Tss	Southeastern group
Ka	Arapahoe Formation (Upper Cretaceous)
Kl	Laramie Formation (Upper Cretaceous)
Kf	Fox Hills Formation (Upper Cretaceous)
Kp	Pierre Shale (Upper Cretaceous)
Kpa	Altered zone
Kn	Niobrara Formation (Upper Cretaceous)
Kfh	Fort Hays Limestone Member
Kb	Benton Shale (Upper Cretaceous)
Kd	Dakota Group (Lower Cretaceous)
Kds	South Platte Formation
Kdl	Lytle Formation
Jm	Morrison Formation (Upper Jurassic)
p€-Ŧo	Older rocks (Triassic to Precambrian)

Contact—Showing dip. Dotted where concealed

Fault—Showing dip and lineation (half arrow); bar and ball on downthrown side where known. Dotted where concealed

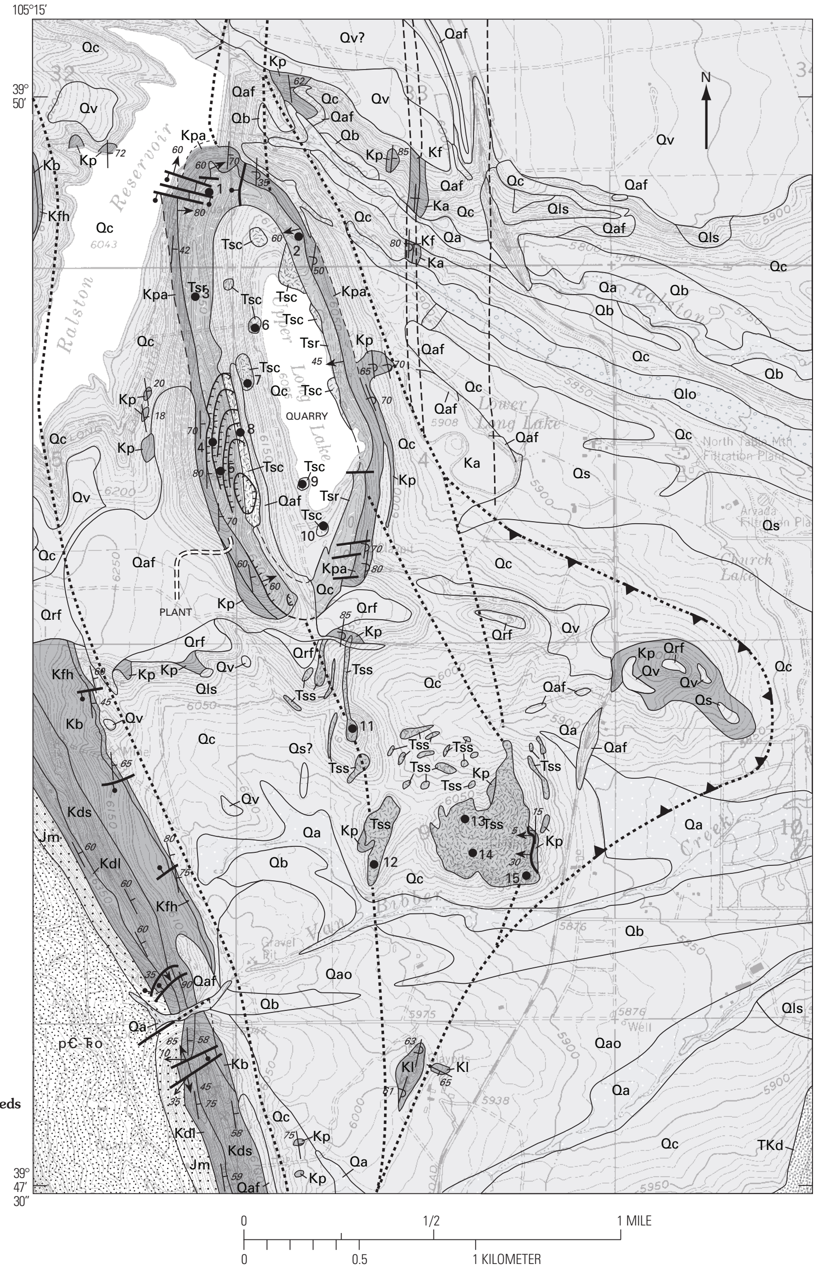
Concealed thrust fault—Sawteeth on upper plate

Quarry wall—Showing levels. Hachures point toward lower level

Trail

Strike and dip of beds
- Inclined
- Vertical
- Overturned

Sample locality—Showing sample number



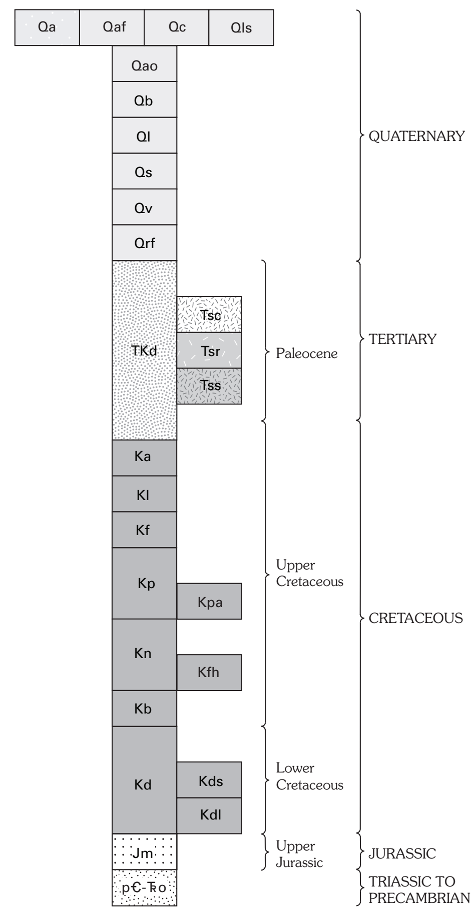
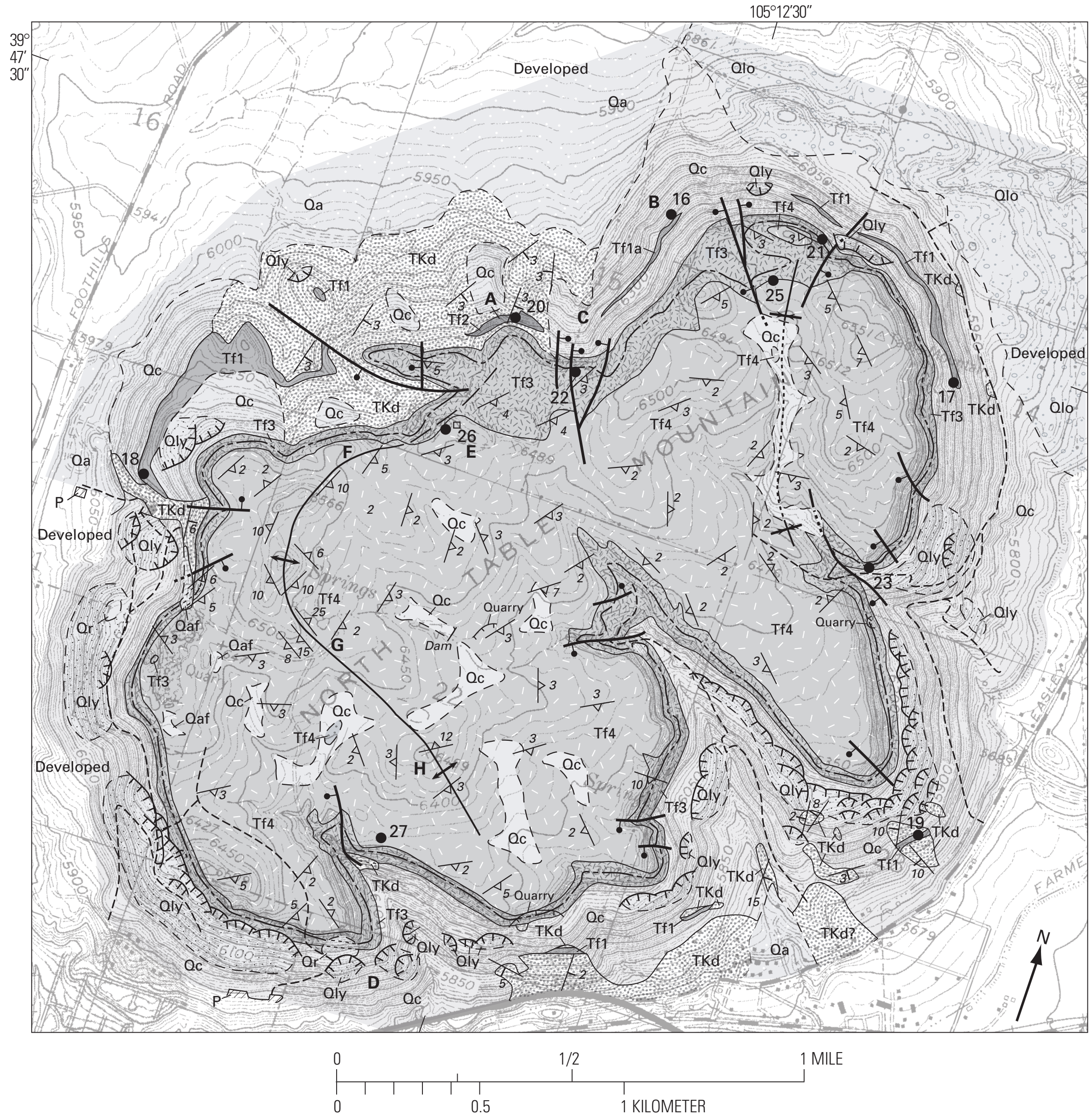


Figure 2. Geologic map of area around Ralston intrusive bodies, 5–8 km north of Golden, Colo. Sites 1–15 provided samples that were point counted. Base from U.S. Geological Survey, 1:24,000, Golden, 1965 (photorevision as of 1980).



EXPLANATION

Tf1 **Map unit**—Qa, younger alluvium; Qc, colluvium; Qr, rock-fall deposits; Qly, younger landslide deposits; Qaf, artificial fill; Qao, older alluvium; Qlo, older landslide deposits; Tf1–4 and Tf1a, lava flows 1–4 and 1a; TKd, Denver Formation. See figure 4 for correlation and description of map units

Contact—Dashed where inferred or gradational; dotted where concealed

Supplemental horizon—Base of amygdaloidal zone of lava flow 3. Dotted where concealed

Fold—Showing dip of limbs. Dotted where concealed

Anticline

Syncline

Trace of inferred stream channel beneath flow 3 (unit Tf3)

Landslide scarp headwall

Fault—Bar and ball on downthrown side where known. Dashed where approximately located; dotted where concealed

Trail or jeep track, supplements that on base map

10 **Strike and dip of inclined beds**

2 **Strike and dip of inclined flow foliation**

Quarry—Hachures point toward quarried area

17 **Sample locality**—Showing sample number as referenced in text

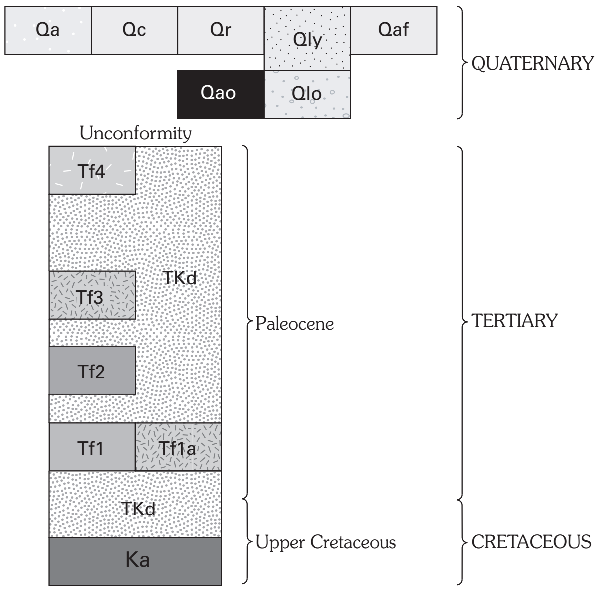
A **Site described in text**

P **Public parking area**

Building not shown on base map

Figure 3. Geologic map of North Table Mountain, 1–4 km northeast of Golden, Colo. Mapped at scale of 1:12,000 and here shown slightly reduced. Sites 16–23 and 25–27 provided samples that were point counted. Sites A–H are referred to in text: A, flow 2; B and C, flow 1 lens mapped by Van Horn (1972) and now extended to the southwest; D, previously interpreted flow 1 lens now seen as a patch of slump material derived from overlying flows; E, communications building; F–H, line of tumuli on flows 3 and 4; F, possible southern extension of subsurface channel containing flow 2; G, channel flow (Van Horn, 1972); H, low dome in flow foliation. See figure 4 for correlation and description of map units. Base from U.S. Geological Survey, 1:24,000, Golden, 1965 (photorevision as of 1980).

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS FOR NORTH AND SOUTH TABLE MOUNTAINS

Qa **Younger alluvium (Quaternary)**—Of undesignated terraces

Qc **Colluvium (Quaternary)**—Mainly 1–2 m thick on mesas; may be thicker on mesa flanks

Qr **Rock-fall deposits (Quaternary)**

Qly **Younger landslide deposits (Quaternary)**

Qaf **Artificial fill (Quaternary)**—Typically road fill and quarry dumps

Qao **Older alluvium (Quaternary)**—Caps a small knoll southeast of South Table Mountain; may be Rocky Flats Alluvium

Qlo **Older landslide deposits (Quaternary)**—Probably inactive

TKd **Denver Formation (Paleocene and Upper Cretaceous)**—Mainly pale-yellowish-brown volcaniclastic siltstone, sandstone, grit, and conglomerate; some cobble conglomerate and mudflow deposits. Poorly sorted and crossbedded; mainly derived from andesites, locally also of shoshonite of Tf1–4 and rarely of older rocks; contains chips of petrified wood and rarely of charcoal. Lava flows intercalated at four levels

Tf4 **Lava flow 4 (Paleocene)**—Shoshonite porphyry, augite, plagioclase, and some olivine and orthoclase phenocrysts. Has an upper amygdaloidal zone, largely eroded, columnar joints, and flow foliation

Tf3 **Lava flow 3 (Paleocene)**—Shoshonite porphyry; columnar jointed and flow foliated. Zone at top of flow contains zeolite amygdules; weak weathering; uppermost red, oxidized scoria zone 1–2 m thick; locally, scoria blocks are pressed into base of unit Tf4; elsewhere, thin conglomerate lenses of unit TKd are present between units Tf3 and Tf4

Tf2 **Lava flow 2 (Paleocene)**—Shoshonite porphyry containing abundant zeolite amygdules, pods, and veins; 10 m beneath lava flow 3; weakly columnar jointed

Tf1 **Lava flow 1 (Paleocene)**—Shoshonite porphyry; mainly felty texture; several lenses on flanks of North Table Mountain about 35 m beneath lava flow 3; weakly columnar jointed

Tf1a **Lava flow 1a**—Low-level lava flow having mainly blocky texture

Ka **Arapahoe Formation (Upper Cretaceous)**—Nearly white quartzose sandstone and pebble conglomerate

Figure 4. Correlation and description of map units for North (fig. 3) and South (fig. 6) Table Mountains, Golden, Colo. Radiometric ages: Unit Tf4, 63.5±1.2 Ma; unit Tf3, 64.2±1.1 Ma; unit Tf1, 63.0±1.7 Ma. These ages are as reported by Obradovich (2002); they are not in normal stratigraphic sequence but are correct within the stated margin of error.

Figure 5. North Table Mountain, Golden, Colo., looking south. E, communications building; F–H, line of tumuli. Photograph by Shawn Steigner.

the edge of a deep channel or gully, with a terrace on its west side. The flow filled the channel to a level above that of the terrace. Flow 2 shows strong zeolitization; the zeolites and calcite not only filled vesicles but also larger cavities and veinlets. This strong zeolitization may have been facilitated by water in the channel that the lava flow followed.

The top of lava flow 2 underlies a small bench between the cliffs formed by the lower parts of flows 2 and 3. Stronger alteration and greater vesiculation than found in the lower parts of flows 2 and 3 have made this bench-forming zone weak. The zeolitization and alteration end abruptly upward at the base of flow 3, thereby marking a disconformity. The colluvial cover on this bench contains some rounded fragments of shoshonite; these may be pebbles, but the rounded fragments could alternatively have been weathered round from the underlying rock. In figure 3 a thin sheet of sedimentary rocks (unit TKd) is shown to lie between flows 2 and 3 to highlight the presence of a disconformity there.

At the cliff outcrop (fig. 3, site A), the channel that contains lava flow 2 is seen to head only southward, but as described subsequently I suggest that it trends southwestward toward the communications building (figs. 3 and 5, site E) and onward to site F (figs. 3 and 5), where capping flows 3 and 4 provide some features that support the presence of the channel and its contained lava flow 2.

Lava Flow 3

Lava flow 3 is the most extensive one on North Table Mountain. It is about 24 m thick to the northeast and thins slightly to the south. The flow base is mostly covered and, where exposed, directly overlies the typical sandstone or siltstone beds of the Denver Formation, altering them but little. The main part of flow 3 is strongly columnar jointed. Fresh rock is dark gray, and weathered surfaces are brownish gray. The top 6–9 m of the flow is strongly oxidized and amygdaloidal and underlies a narrow bench between two cliffs. This amygdaloidal zone is absent from the southeastern part of South Table Mountain, again owing to erosion. However, in this rather thin area of flow 3, the entire flow is slightly amygdaloidal.

Lava Flow 4

Lava flow 4 closely resembles the lower part of flow 3. Flow 4 has no upper amygdaloidal or vesicular zone, but one was probably originally present and has been removed through more extensive erosion than the underlying, protected flows have been subject to. Some of the original lateral extent of flow 4 has also been reduced by erosion, as described at the beginning of this section. Flow 4 is strongly columnar jointed, and on the top of the mesa the many bare rock surfaces are laced with the hexagonal fracture system of these columns. The attitude of these bare rock surfaces of the mesa top is controlled by a flow foliation, which provides useful structural information in several places, as described next. Also seen in places on the mesa surface is a knobby weathering product on a centimeter scale; the weathered-out spherules, like so many oversized rabbit pellets, may be spherulites, which represent an incipient crystallization of glassy (or near-glassy?) material.

At site F (figs. 3 and 5) is the north end of a 1-km-long, low, arcuate (concave to the east) ridge in flow 4. The flow foliation along this ridge shows it to be an anticline whose flanks dip mostly about 10° but locally as much as 25°. Half a kilometer southeast of the end of the ridge (figs. 3 and 5, site H) is a low dome whose flanks dip 5°.

The ridge and dome are tumuli formed in the lava when it was already marked by the flow foliation but not quite cooled and hardened. The process was driven by pressure from steam that was generated when the flows heated the water in an underlying channel. This pressure was sufficient to bow up the covering flows, yet not enough to explode, as at a maar. As the steam pressure decreased, lava filled in any voids. The incorporated water may have allowed the development of the flow's exceptionally abundant zeolites. The arcuate trend and narrowness of the ridge suggest that the water was present in a drainage, and the ridge's position suggests that the drainage was the same one used by flow 2. Flow 2 probably ended where the north end of the arcuate ridge begins; the water along the lower reaches of the drainage remained to be turned into steam, except perhaps along the gap between the tumulus ridge and the tumulus dome.

Human Use of the Lava Rocks

The ridge surface is marked by scores of topographic depressions, half circles in plan view and surrounded by cusplike edges. The depressions are about 10 m across on the downhill side and are rounded uphill; they have a cut depth of 1–1.5 m. I suggest that these features are miniature quarries from which rock slabs were obtained, though to date no historical records have been found to support this interpretation. The up-arched flow foliation of the arcuate ridge would have made it possible for workers to pry up slabs for use in house or foundation construction, probably in Golden during its pioneer days. The size restraints may have been determined by a lease unit, reflecting the common need at that time for, say, the walls of a single foundation. The uphill rounding and depth control were determined by how deeply one could pry up slabs by using muscle power and pry bar. Because prying up the slabs would have been difficult in corners, a rounded headwall inevitably remained.

Support for the inference that these depressions are not natural features comes from additional field observations. For one thing, a few stockpiles of the quarried blocks survive; however, most of the material was removed from the small quarries and nothing was constructed on the mountain. Furthermore, lichen abundance, size, and variety on the walls of the miniature quarries are reduced compared to those lichen characteristics on nearby unquarried rock surfaces. This contrast is greater on the south-facing quarry walls than on the north-facing ones, likely reflecting a difference in growth rate due to a variation in moisture. Also, small (10–40 cm long) debris fragments on the ground surfaces away from the miniature quarries are commonly subrounded to subangular and carry lichens. The quarry floors and the ground surfaces near the quarry edges carry about equal amounts of such lichen-covered, subrounded to subangular debris fragments and angular blocks and slabs (coming from the quarries, as waste) with few or no lichens. Finally, should an alternative explanation such as periglacial processes be considered, it is difficult to indicate why periglacial features are absent elsewhere on the mesas, as well as in the nearby Front Range.

At another quarry on the south side of North Table Mountain in flow 3, cobblestones were produced, probably for use in downtown Denver early in the twentieth century, perhaps at a time when trolley tracks were laid. The lava columns were first split into slabs along the flow foliation and then cut into 10-cm cubes or blocks of 10×10×20 cm. Likely, such skill required European stonecutters already practiced in this craft.

South Table Mountain Lava Flows

Only lava flows 3 and 4 reached the area of South Table Mountain. The volume of flow 1 and flow 1a was insufficient to bring them south of the present Clear Creek gap. However, a lens of channel gravel carrying shoshonite porphyry clasts crops out beneath flow 3 at site I (fig. 6). The level of this outcrop is appropriate for an interpretation that the lens lies just down-channel from the distal end of a lobe of flow 1 now eroded away by Clear Creek.

Lava flow 3 spread widely across the area of South Table Mountain (fig. 6), but flow 4 was more restricted; indeed, flow 4 covered much less area than mapped by Scott (1976). At the north end of South Table Mountain, flow 3 developed a low, broad dome such that the lava is 18–21 m thick on the dome's top and only 9–13 m thick on its flanks to the east or west. Flow 3 to the south and southeast of this dome gradually thins to 2–5 m. This thin part of flow 3 is slightly amygdaloidal throughout its thickness, rather than only in its upper third. Flow foliation delineates the dome; off-dome dips to the west (fig. 6, site J) exceed 30° in places, and those to the northeast (fig. 6, site K) are as much as 17°, but mostly somewhat less. The northern part of the dome has been eroded away by Clear Creek.

The south and southeast flanks of the dome dip more gently (3°–5°) but are modified by six subordinate, short pressure ridges (sites marked L, M, and N in fig. 6). Some of these features are shown in figure 7. The ridges are about 100 m broad and a few hundred meters long with east- to south-trending axes. Flow foliation dips 5°–10° off the flanks and ends of the ridges but grades northward or westward toward the main dome (fig. 6). These features suggest that the dome represents a local thickening ("inflation") of lava flow 3, rather than a normal flow cover over a raised subflow terrain. Although the flow crust cooled and stiffened, its core lava retained fluidity, and pressure in the dome built up as more lava accumulated. The ridge structures provided a local release of this pressure. Perhaps a final surge southeastward permitted the thin amygdaloidal part of flow 3 to extend farther down the broad plain.

At its maximum southward extent, lava flow 3 reached the north flank of the present Green Mountain (Scott, 1976; Drewes and Townrow, 1999) on the first rise south of the Jefferson County Fairgrounds (fig. 1). The outcrop there was small and consisted of heavily oxidized, amygdaloidal shoshonite porphyry. In about 1990, the outcrop was scraped off and covered by soil around new houses. Although I did get to see the outcrop in time, I lacked the foresight to sample it. Other lava outcrops have been reported on this part of Green Mountain (Reichert, 1952) but found wanting in the present study. Some reported sites of lava outcrops might be boulder concentrations in channels or boulder piles pushed together by builders; others remain enigmatic.

Lava flow 4 is found only on the west and northeast flanks of the dome formed by the underlying flow 3 of South Table Mountain. Flow 4 was less voluminous than flow 3, so when it reached the dome it divided and followed lower ground on flow 3. Streams seem not to have run along this low ground; no sedimentary lenses separate the flows. The base of flow 4 immediately overlies the blocks of the oxidized upper crust of flow 3. The western prong of flow 4 is fairly straight and about 1 km long (fig. 7). The northeastern prong is sinuous and at least 1.5 km long. Both extend onto the mesa to the zones of steepened flow foliation on the flanks of the dome on flow 3. Although an upper oxidized and amygdaloidal zone is seen at the top of flow 3 along cliff faces that cut the dome, such a zone has not been seen within flow 3 on the dome flanks. Perhaps the dome rock cooled more slowly than the thinner parts of flow 3 on the flanks of the dome, which were covered by flow 4 before oxidation and vesiculation of the underlying thin part of flow 3 were far advanced. Another possibility that would explain the difference in lava character is that the volatile elements could have been concentrated upward into the dome. With fewer volatile elements in the flank lavas, oxidation and amygdule formation in those lavas would have been impaired.

As described, flows 3 and 4 on both North Table Mountain and South Table Mountain usually consist of a lower columnar type of structure overlain by an amygdaloidal, noncolumnar type. The lava flows on South Table Mountain are slightly deformed in the manner of those on North Table Mountain, but in places they are

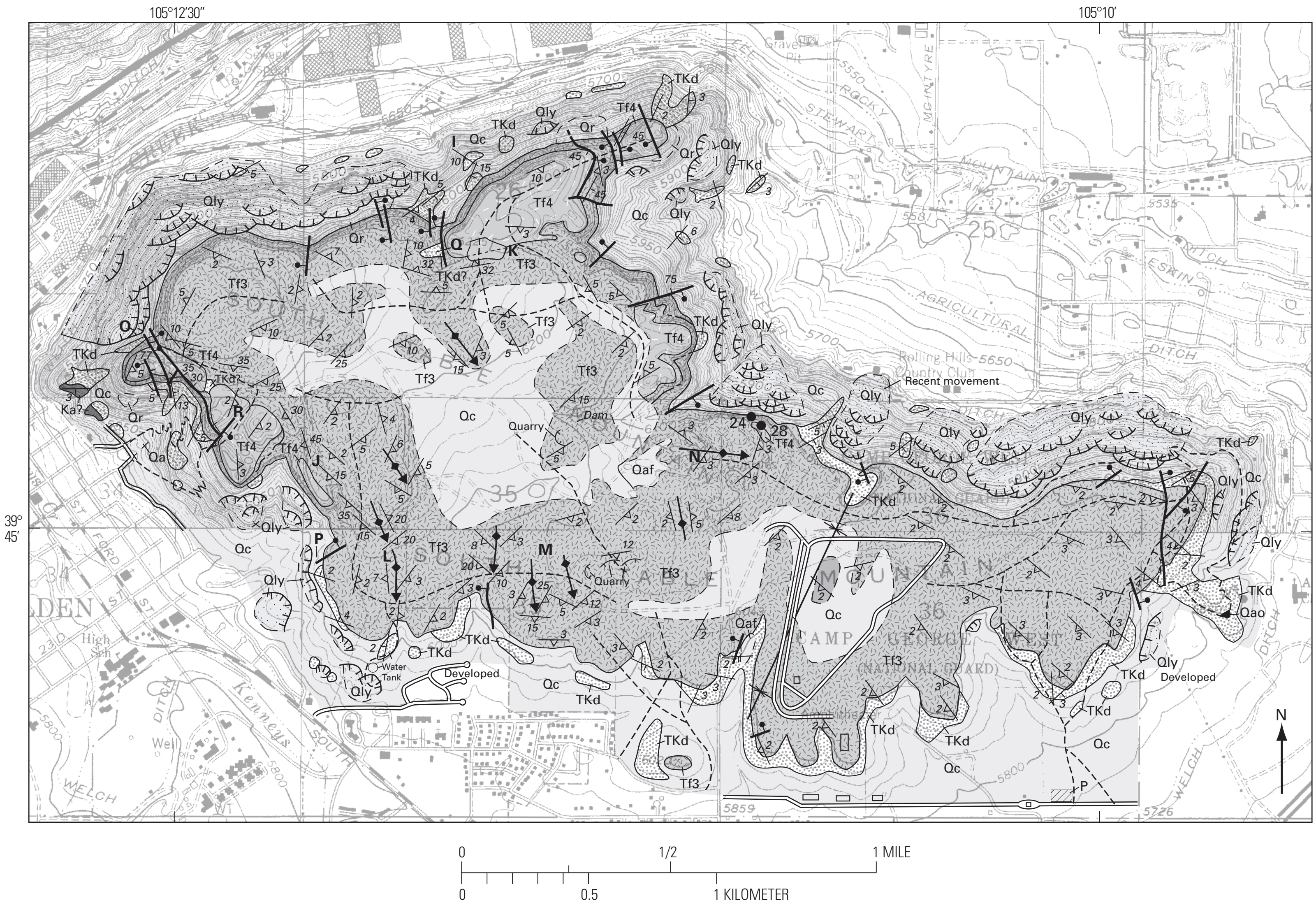


Figure 6. Geologic map of South Table Mountain, 1–6 km southeast of Golden, Colo. Mapped at scale of 1:6,000 and here shown reduced. Sites 24 and 28 provided samples that were point counted. Sites I–R are referred to in text: I, shoshonite porphyry clast–bearing channel gravel; J, zone of steeply dipping flow foliation on west side of dome in flow 3; K, zone of moderately dipping flow foliation on northeast side of dome; L–N, areas of pressure ridges; O, Castle Rock; P, charcoal-bearing mudflow deposit within Denver Formation (unit TKd) 3 m below flow 3; Q and R, small weathered patches of silt and clay, probably remnants of Denver Formation overlying the lava flows. See figure 4 for correlation and description of map units. Base from U.S. Geological Survey, 1:24,000, Golden and Morrison, 1965 (photorevision as of 1980).

EXPLANATION

Tf1 **Map unit**—Qa, younger alluvium; Qc, colluvium; Qr, rock-fall deposits; Qly, younger landslide deposits; Qaf, artificial fill; Qao, older alluvium; Tf3–4, lava flows 3–; TKd, Denver Formation; Ka, Arapahoe Formation. See figure 4 for correlation and description of map units

Contact—Dashed where inferred or gradational; dotted where concealed

Supplemental horizon—Base of amydaloidal zone of lava flow 3. Dotted where concealed

Fold—Showing dip of limbs. Dashed where approximately located; dotted where concealed

Anticline

Syncline

Pressure ridge—Showing fold axis and plunge of nose

Landslide scarp headwall

77 **Fault**—Showing dip where known. Bar and ball on downthrown side where know

Gravel road

Trail or jeep track

10 **Strike and dip of inclined beds**

2 **Strike and dip of inclined flow foliation**

Quarry—Hachures point toward quarried area

24 **Sample locality**—Showing sample number as referenced in text

K **Site described in text**

P **Public parking area**

Building not shown on base map

also internally deformed by flow turbulence. In addition, at Castle Rock (site O in figs. 6 and 7) both the northern ends of the channelized flow 4 and the adjacent flow 3 show structural irregularities. The flows are broken into several small sheets, and south of Castle Rock, the bold prominence overlooking Golden, flow breccia is found in place of the usual columns. Likely, the dome is linked to these irregularities in some way not yet clear.

About 20 small faults cut the lava flows of South Table Mountain, and near the southeastern end of South Table Mountain another open, south-plunging syncline is developed in the flow foliation. Displacement on the faults is normal, and dips are commonly steep. Southeast of Castle Rock (site O in fig. 6) several faults dip gently to moderately. This fold and these faults are also viewed as responses to the settling of deposits in the Denver Basin.

A few local sedimentary features near the flows on South Table Mountain are of interest. The charcoal-bearing mudflow bed in the underlying Denver Formation lies about 3 m below flow 3 at site P in figure 6. At sites Q and R are small bodies of siltstone, likely of the Denver Formation, over the lava flows.

Problems in Interpreting the Lava Flows

The field study of the shoshonite porphyry lava flows and intrusive bodies not only provides a more complete picture of their origin and emplacement history but also raises some questions. From which vent did the flows come? How far did the flows once spread? Why and when did the southeast-flowing Paleocene streams shift to the present east-flowing ones? And why are the broadest gaps between segments of the igneous system located where today's crosscutting streams are smallest (fig. 8)?

The question of the source vents of the lava flows has been raised before (Allan, 1922; Ahmad, 1971). The conventional wisdom of the recent decades would place the source of the flows as the "Ralston dike" because their rocks are much alike and the flows thin away from that proposed source.

The field study shows that the southeastern group of intrusive bodies is probably linked to channel flows 1 and 2; the low volume of these flows is compatible with a vent or vents lacking the heat to alter its host rocks. In contrast, the field study shows that the Ralston plug may have been the source of flows 3 and 4. Their larger volume is compatible with a vent having a wide altered zone. One objective of the petrographic study described later in this report was to determine whether the rocks might verify this field-based interpretation.

The question of the past extent of the lava flows remains speculative, but one observation is useful. The outcrops of flow 3 that now are found on North and South Table Mountains are parts of an originally much larger flow area. These remnants were once connected across the canyon at Clear Creek but are now separated by a

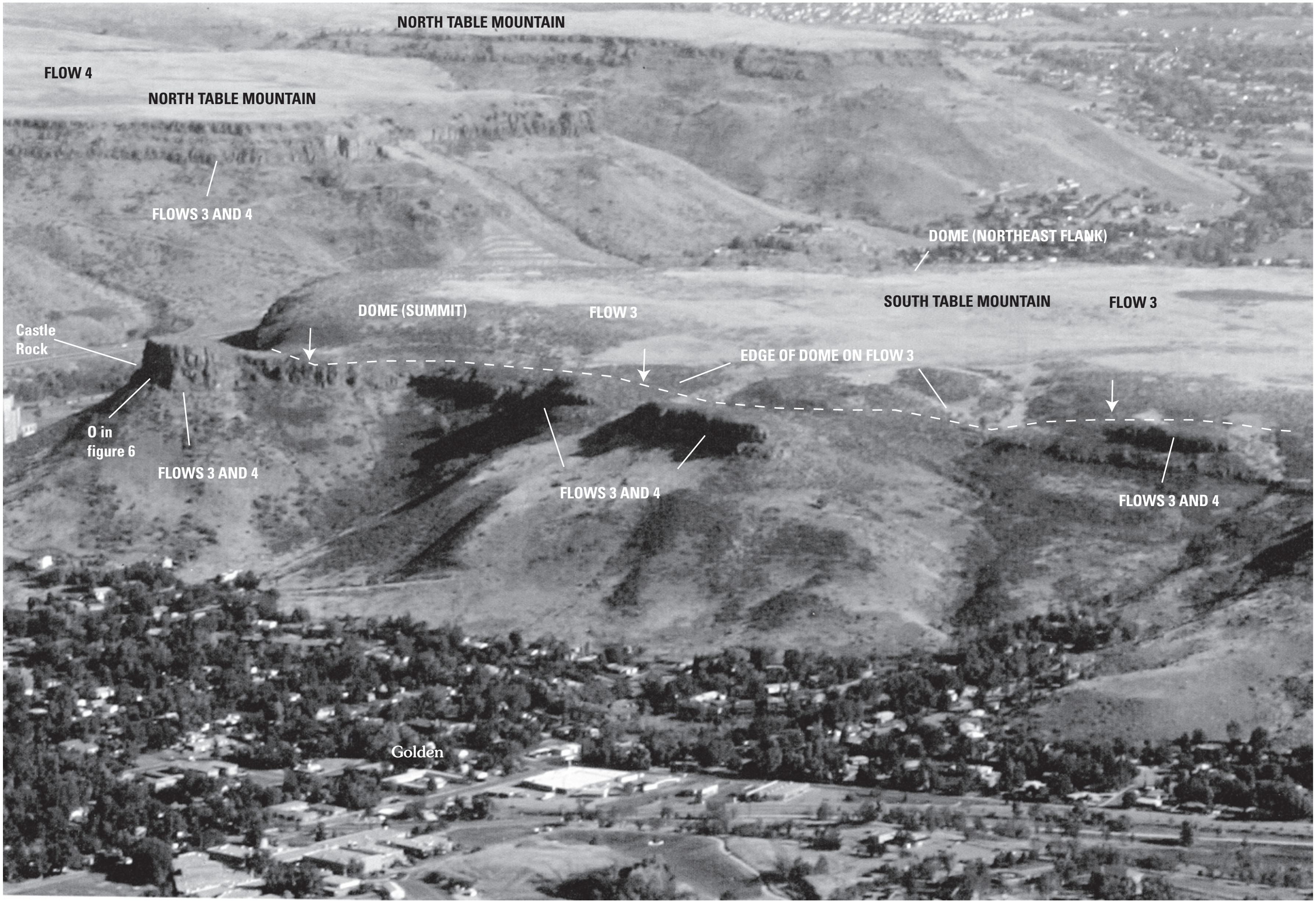


Figure 7. South Table Mountain, Golden, Colo., looking northeast, with North Table Mountain in distance. Arrows show direction of dip of flow foliation. Photograph by Shawn Steigner.

0.5- to 0.7-km-wide gap. The same is true of flow 4. Since canyon incision began, therefore, each mesa edge has retreated about 0.3 km. One might surmise that the degree of erosion was similar east and west of the mesas, where flow thicknesses were the same as on the nearby mesas. Should the east side of the broad valley plain on which flows 3 and 4 poured have been higher laterally (because of the presence of an erosional remnant), thinner flows might have spread there, permitting more rapid erosion, other factors remaining constant. However, other factors did not remain constant. Since the present drainage system was established, the tributary drainages east and west of the mesas were much smaller than Clear Creek and so had a much lower capability for erosion These considerations suggest that the eastern and western edges of the mesas were eroded less than the amount removed at Clear Creek Canyon.

This question on lava flow erosion intrigued Waldschmidt (1939), who proposed that lava flows 3 and 4 extended west of the mesas to the position of the Dakota Ridge, a distance of 0.8–1.5 km, although the Dakota Sandstone (now Dakota Group) is largely faulted out. Because he offered no basis for his proposal, I here favor the more conservative distance of lateral erosion of about 0.2–0.3 km, somewhat less than half of the width of Clear Creek Canyon; a larger stream erodes more than a smaller one.

Lava flow thickness is an important factor in judging the likely erosion history of the flows. To the north near their source at the narrow part of the plain, flows 3 and 4 together may have been 20–30 m thick (as seen in the cliff heights in fig. 7). To the south, flow 3, the only flow there, was only 2–5 m thick and was spread across a wide plain. Again, given transverse drainages of the same size, the southern part of the lava field should erode more rapidly.

With these considerations of the past extent of flows in mind (fig. 8), their combined total volume is estimated to have been about 0.7–0.8 km^3.

The general south-southeastward flow direction implies that higher ground lay to the east-northeast. This high ground need only have been slightly higher than the valley in which the lava flowed, not a major upland. Most likely, this minor upland was underlain by an older part of the Denver Formation. The surface of the valley beneath flow 3 would then have become a local disconformity within the Denver Formation. It is easier to envision the larger Clear Creek cutting the gap in flow continuity between North Table Mountain and South Table Mountain than it is to picture the cutting of the broader gap between North Table Mountain and the intrusive bodies (Van Bibber Creek gap) and that between South Table Mountain and Green Mountain (Lena Gulch gap). The Van Bibber Creek gap is probably wide because all flows that the creek crossed were channelized this close to the vents, thus offering less resistance to erosion. The Lena Gulch gap is probably wide because the distal end of flow 3 was thin and amygdaloidal. Furthermore, projecting flow 3 southward from South Table Mountain using the prevalent dip, or even half that dip, leads to a misfit with the level of the Green Mountain outcrop site (the projection using the flow 3 dip is lower than the Green Mountain outcrop), suggesting that some faulting in this gap has further weakened the lava and facilitated erosion.

The fault that is proposed to run through the Lena Gulch gap area would have its south block raised a few tens of meters. In figure 8 the proposed fault is given a northwest strike to mimic another such structure mapped a short distance south of the Green Mountain lava outcrop (Drewes and Townrow, 1999); the position of the proposed fault is only broadly constrained.

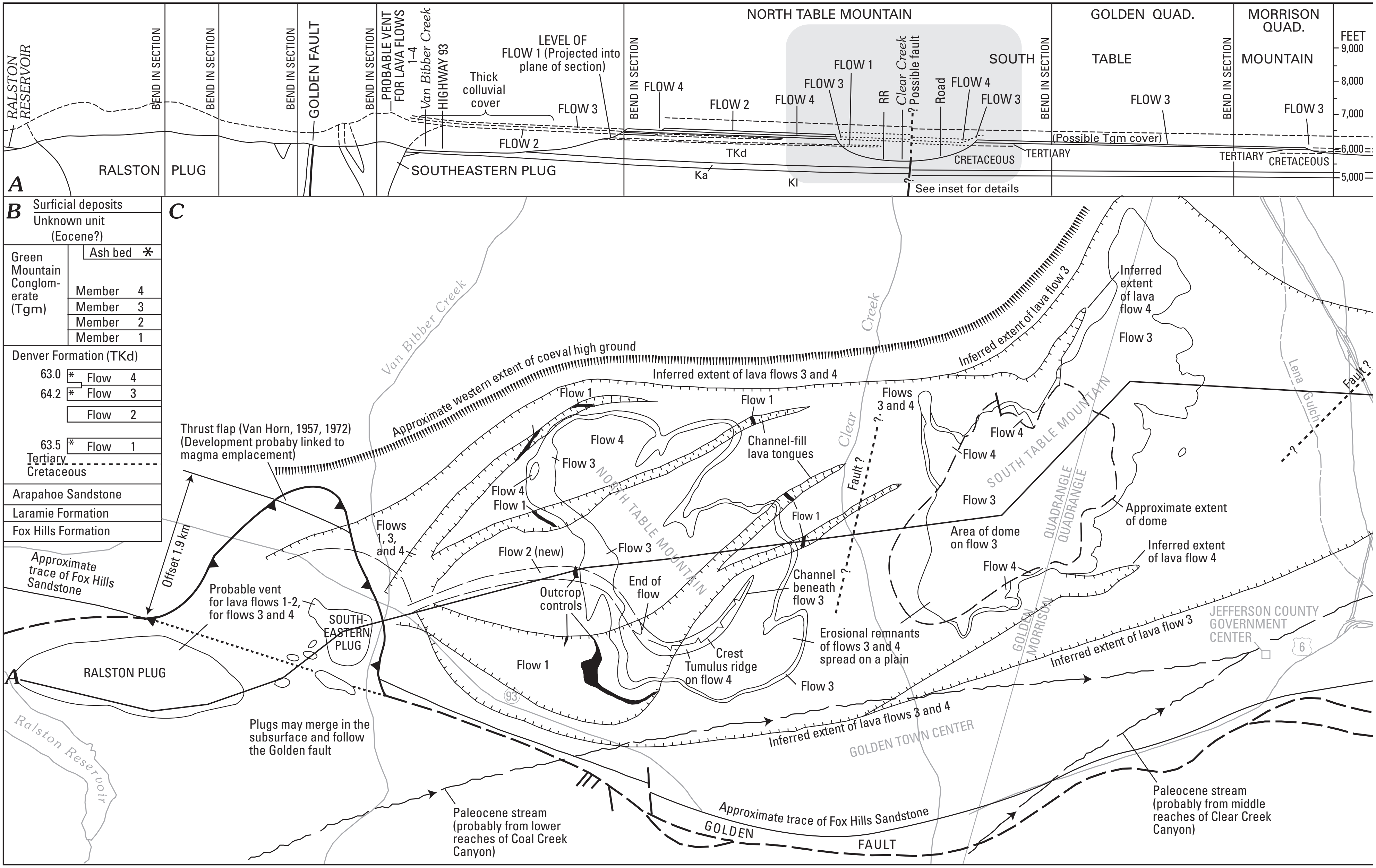
Finally, how and when did the local river systems change their courses and what was needed geologically to bring about this change? The basic answer, of course, is textbook geomorphology. Streams are superposed from a covering layer during uplift and erosion. The shift in flow direction of streams would be enhanced by a slight northward tilt of the region before incision began. Such tilting would less likely have occurred during the Paleocene, when east-west compression was the main regional stress, than during the mid-Tertiary, when the Rocky Mountains were worn low and unconsolidated formations, such as the White River Formation of the Colorado-Kansas border area, were deposited (fig. 9).

Figure 9 shows the White River Formation as it may have been distributed along an east-west profile during mid-Tertiary time. It is Miocene in Kansas and Oligocene farther north, and its proposed extension to the Golden area is also likely to have been Oligocene. The proposed extension of the White River may have lapped onto the residual uplands to the west. This unit is likely to have been fine grained, moderately well sorted, and unconsolidated. Although a few small patches of Tertiary rocks are known to exist west of Golden, the deposits are undated; those that consist of coarse gravels may be too old—possibly Green Mountain Conglomerate (Paleocene) equivalents. The proposed mid-Tertiary formation X of figure 9 might easily have been mistakenly assigned to older or younger piedmont deposits, if indeed any formation X remnants still exist.

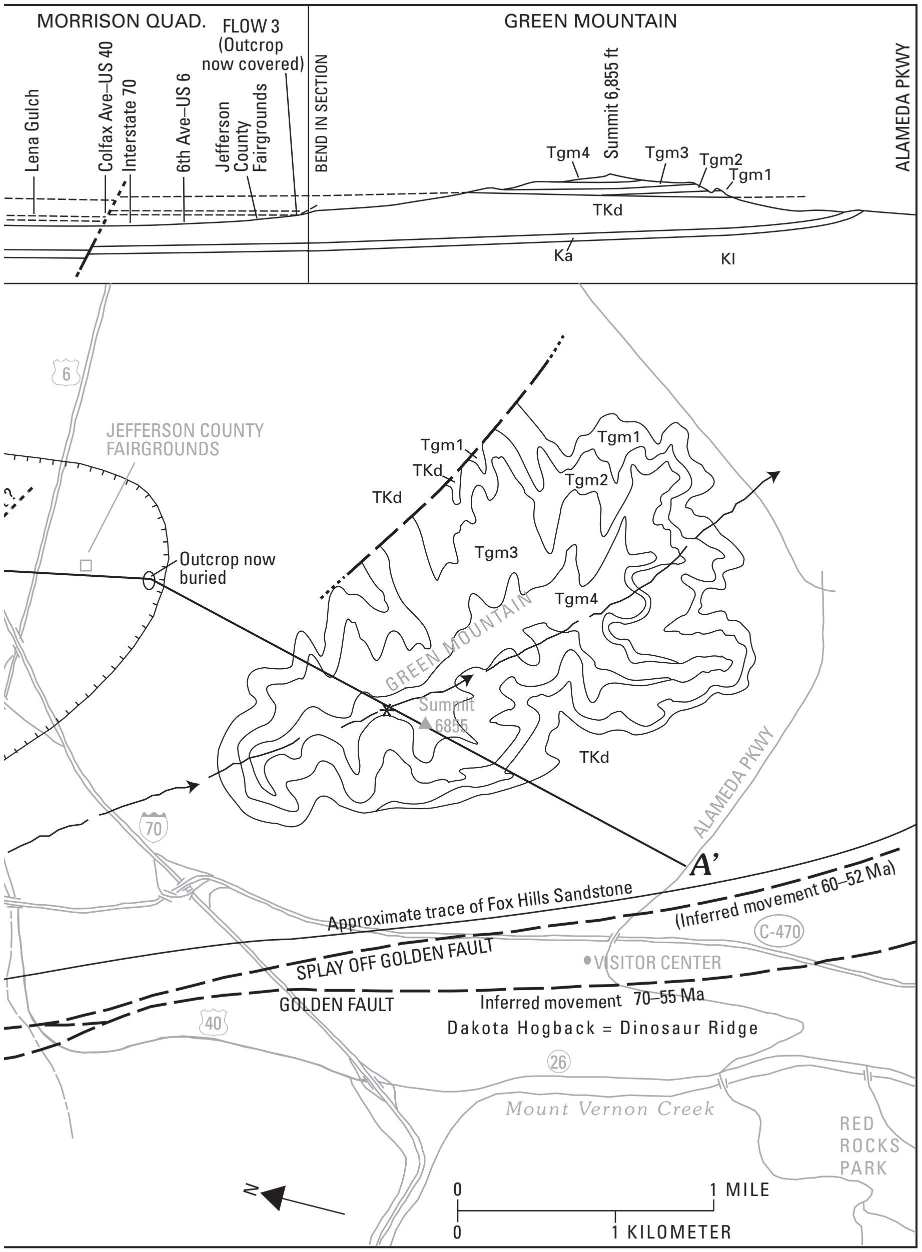
Geophysical Data

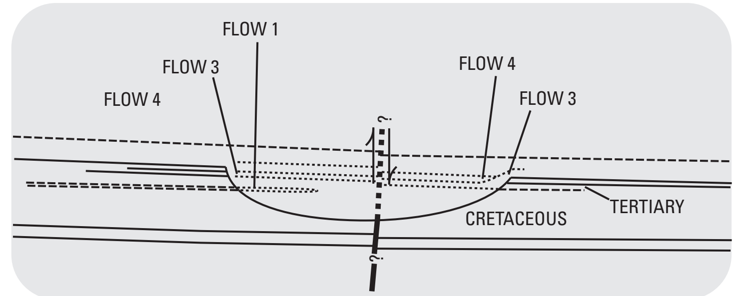
Several geophysical studies have been made in the area of the intrusive bodies; one of them provides only raw data, but the others provide data and diverse interpretations without reaching a clear consensus. Although these studies deserve attention, they must be approached with circumspection.

Of greatest interest in these studies is the recurring idea that the Ralston plug narrows downward. The ground magnetic data of Hasbrouck and others (1975) are herein interpreted to show that the body narrows downward to the form of a dike approximately aligned along the western shore of Upper Long Lake. The gravity



*63.9 (Obradovich, 2002)





EXPLANATION

TKd — **Map unit—**Tgm1–4, members 1–4 of Green Mountain Conglomerate; Tfl–4, lava flows 1–4; Tkd, Denver Formation; Ka, Arapahoe Formation; K1, Laramie Formation

Outcrop of lava flow 1—Mapped for control

Contact

Approximate trace of Fox Hills Sandstone—Concealed in most places

Inferred extent of lava flow

Crest of tumulus ridge

Approximate extent of dome on South Table Mountain

Approximate western extent of coeval high ground

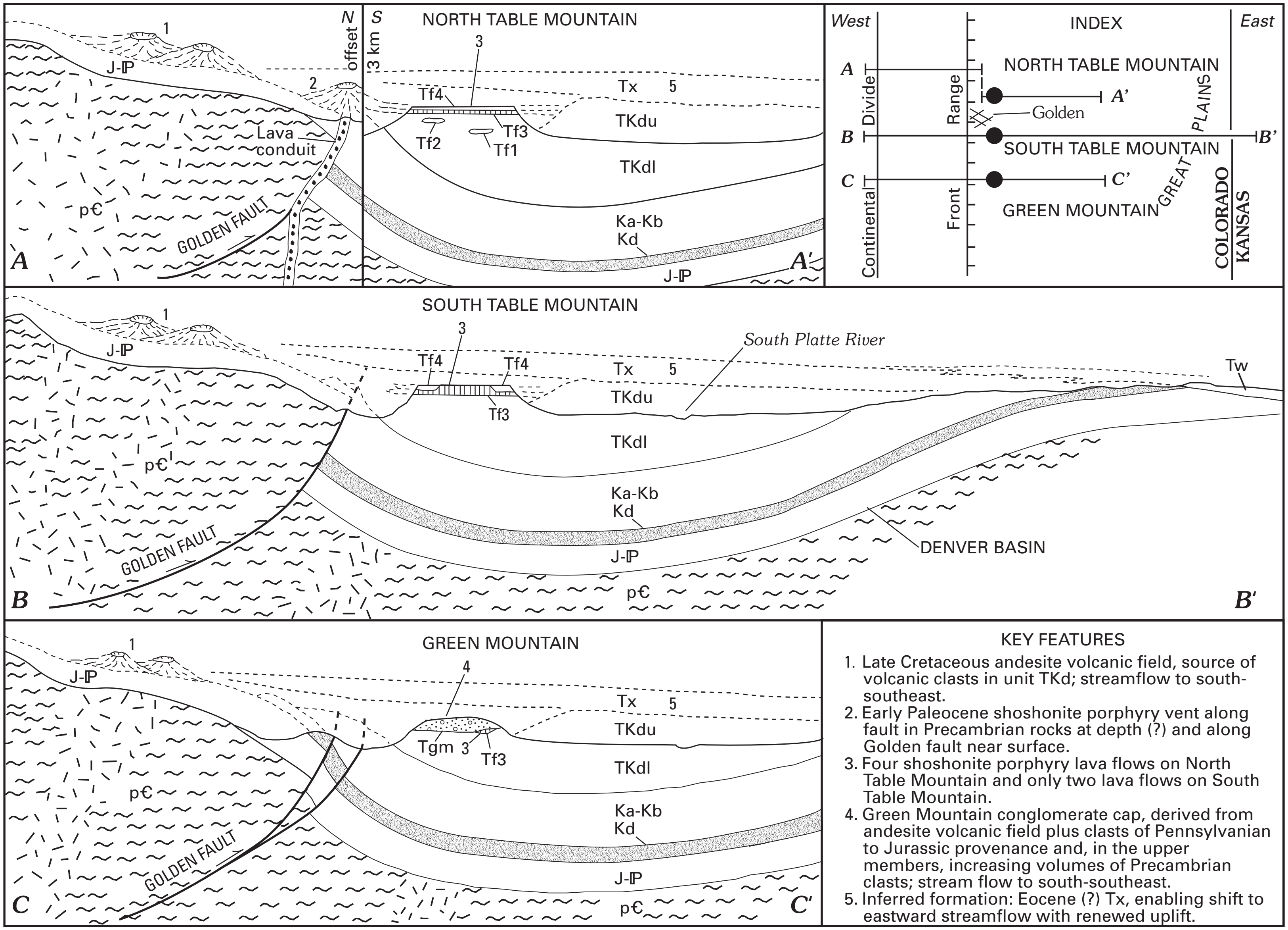
Paleocene stream—Arrow shows direction of flow

Fault—Dashed where approximately located; dotted where concealed; queried where location uncertain

Inferred thrust fault—Sawteeth on upper plate

Lava flow contact—Projected above present surface

Figure 8. Map and profile of lava flows from source vents to North and South Table Mountains and to Green Mountain, near Golden, Colo. A, North-northwest to south-southeast profile. Vertical scale exaggerated; some contacts near intrusive bodies projected to their probable positions beneath colluvial cover. B, Stratigraphic chart, abbreviated to show only units germane to interpretation of lava flows. C, Map of area from Ralston plug to Green Mountain, showing units key to study of lava flows, in part from Drewes and Townrow (2005).



Not to scale
Vertical exaggeration about 50×

Figure 9. Diagrammatic cross sections across the Front Range, North and South Table Mountains, Green Mountain, and the Denver Basin to the Colorado-Kansas border.

EXPLANATION

Tf1 **Map unit—**Tw, Tertiary White River Formation; Tx, unknown Tertiary (Eocene (?) unit x; Tgm, Tertiary Green Mountain Conglomerate; Tf1–4, Tertiary lava flows 1–4; TKdu, inferred upper part of Tertiary and Cretaceous Denver Formation; TKdl, lower part of Tertiary and Cretaceous Denver Formation; Ka–Kb, Upper Cretaceous sequence (Arapahoe Formation to Benton Shale); Kd, Lower Cretaceous sedimentary rocks; J–ℙ, Jurassic to Pennsylvanian sedimentary rocks; pЄ, Precambrian granite and metamorphic rocks

Lava flow—Showing columnar jointing

Topographic profile showing present-day surface

Contact—Dashed where projected above present-day surface

Fault—Arrow shows direction of movement. Dashed where projected above present-day surface

study of Stanlav and Morrison (1952) led them to infer that most of the plug's mass lies above a level of about 60 m below the lake level and that the bottom of the plug gradually deepens below that level to the west. The seismic (vibroseis) study of Shuck (1976) along an east-west trace across the southern part of the plug led him to infer that the intrusive body is a rootless and faulted sill dipping gently eastward.

The magnetic field study of Levings (1932), covering the area of the Ralston plug and the southeastern group of intrusive bodies, was set up to dispel the idea that the anomalies are solely related to the impressing of the Earth's magnetic field on cooling igneous rocks. His results show magnetic highs and lows in and near the intrusive bodies. Although variously explained by Levings, the subsurface shape of the intrusive bodies was not considered.

Additional structural interpretations have also been offered by the Colorado School of Mines students mentioned previously (Levings, 1932; Shuck, 1976; Stanlav and Morrison, 1952; and Hasbrouck and others, 1975). However, these interpretations are based on minimal geophysics, no field mapping, and much speculation on issues of particular interest during their school years. Where is the vent that fed the lava flows? Does the Golden fault dip gently or steeply? Is the structural flap of Pierre Shale east of Highway 93 a thrust slice or a gravity-impelled slide? The issue of the vent sites has already been addressed in this report. The structural issues remain beyond the scope of this report. Clearly, a comprehensive, detailed geophysical study tied to mapping and petrography is still to be made.

Petrographic Observations

The igneous rocks of the Ralston intrusive bodies and the Table Mountain lava flows are generally accepted to be of one family, if not identical. Once the issue of an appropriate petrologic name was settled, however, the rocks attracted little further attention in the literature. Past petrographic studies, for instance, provide little more than a rock description, a modal analysis, and a chemical analysis. Lacking are information on sample localities, whether the sample is single or composite, and which flow or intrusive body is represented. Only the zeolite minerals have been given further attention, and this interest is for their mineralogy rather than for their information about lava flow history (Johnson and Waldschmidt, 1925; Kile and Modreski, 1988). The reports of Allan (1922), Waldschmidt (1939), Ahmad (1971), and Kile (2004) best summarize the past work on these igneous rocks; they reflect the needs and working styles of their times.

The present study was undertaken with two objectives in mind. First, it was desirable to describe the rocks more systematically and tie them to field maps. They might tell a bit more of their history than already known. Second, with such a start it might be possible to test the links between vents and lava flows inferred from field observations. As much like one another as the rocks seem to be, it was clear that this second objective would require meticulous observations, systematic procedures, and large counts, not only of mineral kinds and abundance, but of textures and alteration as well. In order to make the modal counts of minerals as objective as possible, then, 2,000-point counts were taken, following identical grid patterns in each thin section. Thin sections for which modes had been determined at the beginning of the petrographic study were recounted once specific identification skills became routine. Thin sections stained for potassium feldspar were point counted for modal analysis first, unstained and unaltered rocks next, and slightly altered rocks last.

Textures

All the rocks are porphyritic; phenocrysts are 1–4 mm long and make up 15–20 percent of the rocks. The phenocrysts include plagioclase, pyroxene, olivine, and magnetite. The groundmass is mainly blocky but has some felty texture. The groundmass grain size is in the range of 0.1–0.5 mm, except along the few sampled chilled margins, where it was even finer, and thus impractical to determine the mode. Sample 15 (fig. 2), from the southeasternmost point of the small plug of the Ralston intrusive bodies, has an entirely felty groundmass. In some rocks, crystals having a felty texture are faintly flow aligned or ophitic.

Most samples have a blocky groundmass that contains 5–10 percent interstitial crystals, chiefly anhedral sanidine but also some biotite, both of which are remarkably unaltered. Some specimens from the core of the Ralston plug have large interstitial sanidine anhedra; in one rock (sample 6) they even reach the size of the phenocrysts. In this specimen, biotite forms beautiful subhedral crystals (half of hexagonal platelets) attached to some groundmass blocky crystals. These biotite crystals resemble crystals lining cavity walls. Although not implying that groundmass cavities existed in the intrusive rock, the subhedral biotite crystals nevertheless suggest a period of late crystallization from a highly fluid residual liquid. In contrast, the phenocrysts probably crystallized earliest, as suggested by the cores of some plagioclase phenocrysts that are strongly altered to clay minerals and by other phenocrysts that are bent or crystallographically distorted.

All transparent crystals are laced with trace amounts of acicular microlites. Some of these are apatite; others are probably plagioclase and many are undetermined. Their presence in both early-formed phenocrysts and late-formed interstitial crystals needs further explanation.

Several noteworthy textural features were observed sparingly in most specimens, and one of them was seen only in the intrusive rocks; they bear describing because they indicate a bit about the development of the magma. Most noticeable are scattered rounded grains, chiefly of magnetite, but also of pyroxene, olivine, and rarely of apatite. They range in abundance from about 10 to 50 per square centimeter of thin section, and they were seen among phenocrysts and groundmass alike. Some small rounded grains are included in phenocrysts. Among the intrusive rocks they seem to be most abundant in the core phase and least common in the southeastern group of the small plug, dikes, and sills.

Even less common are strongly fragmented pyroxene phenocrysts—crystals that literally look chewed up. They have been found in only a few intrusive and lava flow specimens and then in only a few phenocrysts of a specimen. Chewed-up grains are broken up into small subrounded segments that are slightly rotated relative to their neighbors. Crystals were found showing various stages of development of this texture. Some have only incipient curved fractures; others are completely fractured, but the segments are not rotated. Next in sequence are grains having the rotated segments. In all these stages the original pyroxene crystal outline is retained. Perhaps the ultimate stage of development is patches of clustered small pyroxene crystals no longer retaining a phenocryst outline and admixed with a few small crystals of other minerals. Resorption as a result of a change in magma chemistry is not indicated, because resorbed crystals typically show embayments along fractures and cleavage planes. No such embayments were observed in the igneous rocks studied here.

In a single case, a small ring of such subrounded small pyroxene crystals, each having its own orientation, was seen. The usual groundmass mixture both fills and surrounds the ring.

Taken together, these special textural features suggest that conditions of magma and lava flows were turbulent, a not-surprising situation. What remains surprising, however, is the scarcity of these features. Furthermore, finding signs of limited turbulence encapsulated in phenocrysts attributed to deep-level crystallization along with similar signs in a groundmass that probably crystallized at a higher level is interesting; mildly turbulent conditions persisted.

The groundmass material provides a different message. These crystals are undeformed and unaltered. Magma movement at this late stage of crystallization surely was not turbulent. The magma may even have stopped moving. The last fluid, with its higher alkali content giving it a lower temperature of crystallization, may simply have moved through a mush of phenocrysts and groundmass crystals.

Some of the intrusive rocks show narrow reaction rims or partial rims of biotite around pyroxene or magnetite; less common are rims of pyroxene around olivine. Rare as they are, reaction rims are most common in rocks of the Ralston plug. Fewer than half the samples of the southeastern group intrusive rocks have reaction rims.

Reaction rims are signs of a chemical disequilibrium, a condition of these rocks long known through the association of olivine with sanidine and biotite. The scarcity of these reaction rims in the intrusive rocks and their apparent absence in the lava flows need explanation. Perhaps the reaction rims formed late in the vents after most of the magma had surfaced. They may also be so scarce because very little potassium-bearing material was incorporated by the magma.

Minerals

The major minerals of the shoshonite porphyry are andesine plagioclase, augite pyroxene, and olivine. Accessory minerals are magnetite and apatite, and in a few samples sphene was suspected but not proved. Additionally, all rocks contain interstitial sanidine and biotite. Secondary minerals include alteration products and zeolites. Alteration products are mainly clay minerals, sericite, iron oxides and hydroxides, iddingsite, and antigorite. The zeolite minerals commonly seen in thin section are analcime, thomsonite, and chabazite; many more zeolite minerals are reported present by Kile and Modreski (1988). Calcite and pyrite veinlets cut through the rocks in a few places. Because most samples were taken from cliff faces, quarry walls, and excavation spoil piles, surface weathering was minimal; only a few samples could not be point counted because of such alteration, and these were mostly from South Table Mountain.

Plagioclase phenocrysts are white, as much as 3.5 mm long, euhedral to subhedral, and compositionally zoned. Most phenocryst cores and some zones are altered to clay minerals, and others are bleary (having indistinct extinction-angle effects, possibly stressed). Nevertheless, compositions were usually obtainable by using the *mp* (that is, crystallographic and cleavage planes 010 and 001) section method, which is more precise than the usually applied Michel-Levy method. Both phenocryst and groundmass plagioclase are calcic andesine; in some samples groundmass crystals are sodic andesine, and rarely phenocrysts from the southeastern group intrusive rocks are sodic labradorite. Groundmass plagioclase is subhedral to anhedral and 0.1–0.5 mm long.

Pyroxene crystals appear black in the rock but in thin section are pale green. They show a faint pleochroism from a grayish green to a pale brownish green. Phenocrysts are as much as 4 mm long and largely euhedral; groundmass grains are anhedral. Extinction angles are 44°–45°. Cleavage is orthogonal. These characteristics are indicative of augite. Although most rocks contain unaltered augite, many from South Table Mountain samples are altered to FeO-bearing secondary minerals.

Some of the dark crystals are olivine. Olivine phenocrysts are rarely more than 2 mm long and form euhedral crystals; groundmass olivine is subhedral or anhedral. The mineral has its distinctive high relief and birefringence as well as alteration to iddingsite or antigorite along crystal margins and fractures. Generally, groundmass olivine is completely altered. The intensity of the alteration increases toward the distal ends of lava flows 3 and 4.

Magnetite is present as small phenocrysts but mainly as groundmass grains. It reflects the lavender-gray color of titaniferous magnetite. Grain shapes range widely from euhedral to anhedral. Some magnetite is clustered with pyroxene and apatite.

Apatite is clear in thin section and mostly euhedral, but some grains are rounded. The larger crystals are delicately striated. It has a parallel extinction, a feature of about one-fourth of the microlites. Therefore, these are interpreted to be apatite.

Sanidine is interstitial and hence anhedral. Although it typically is a pale pinkish-orange in the rock, it is clear in thin section. Usually these crystals are small, but in sample 6 they reach 1–2 mm long. They have a diagnostic low relief, an absence of polysynthetic twins, and a negative $2V$. Sanidine is fresh in the intrusive rocks, slightly altered to kaolinite on North Table Mountain, and strongly altered to kaolinite on South Table Mountain.

Biotite is typically small and subhedral or anhedral; in sample 6, however, biotite crystals reach 1 mm in diameter and appear as incomplete hexagonal platelets. Biotite is pleochroic from pale brown to moderate brown and has a very low to zero extinction angle. Toward the distal ends of lava flows it is altered to sericite.

Mineral Modes

Having now examined the shoshonite porphyry in the field and under the microscope, I turn to the second objective. Might the rocks themselves show a connection between particular lava flows and certain intrusive bodies? If any connection were found, would it support the correlation inferred from the field study? Already mentioned was the concern that, because anticipated differences in modes (mineral counts) would be subtle, counting procedures would require special care.

In brief, more points were counted (2,000) per thin section than is commonly done. The eyes were first “fine-tuned” through counting several thin sections purely for practice and discarding those results; then counting, in order, thin sections stained for potassium feldspar, unstained thin sections of unaltered samples, and finally thin sections of slightly altered samples. Except for lava flow 2, modes were made of four or five thin sections of each group, and the results averaged. Procedural systematics is recorded but is too lengthy to warrant description here. A tabulation of 28 modes appears in tables 1 and 2.

Once modal averages were obtained, typically of 8,000–10,000 points per rock unit, 5 minerals (pyroxene, olivine, magnetite, apatite, biotite) and feldspars as a group were selected from the 11 tallied in order to avoid those that still gave some concern during the counting. For example, despite the care taken, distinguishing the two feldspars from one another remained more uncertain than other routine decisions, not only in comparing the feldspar counts of one half-slide with those of the other, but also in comparing the counts within a group. Overlapping wedges of small groundmass grains might lead to uncertainties, even among the stained thin sections. Accordingly, combined feldspar was tabulated. Likewise, phenocryst counts remained suspect because of problems in distinguishing small cross sections through tips or keels of phenocrysts from cross sections through middles of groundmass grains.

From averages obtained for each of the 6 parameters (5 minerals and the feldspars as a group), then, comparisons were made between each of the 4 lava flows and each of the 3 intrusive units, a total of 12 comparisons. The percentage deviation between, say, modal pyroxene in the rim phase of the Ralston plug and modal pyroxene in flow 1 was totaled with the deviations of the other five parameters, and that total deviation was compared with the total deviation of the other flows. The lowest total deviation registers the best fit, or likeliest correlation. The deviation comparisons are illustrated in figure 10.

The results of the mineral counts provide only partial support for the inferences made through field and petrographic observation. The reason for this lack of full confirmation remains unclear. Perhaps chemical analyses remain more reliable than modes (mineral counts), no matter the effort put into the counting. Overall, the potassium content increases from 0.4 to 3.1 percent for biotite and from 0.0 to 14.8 percent for sanidine (fig. 11).

The petrographic study also suggests that the southeastern plug is multiphased, but field evidence to support this inference has not yet turned up. Apparently, samples 15 (fig. 2) and 16 (fig. 3) are related; the former was taken from the southeast corner of the southeastern group plug, whereas the latter is from channel lava flow 1 nearest to that plug. These two samples alone are entirely felty textured, and they

Table 1. Mineral modes of intrusive rocks of the Golden, Colo., area.

										Phenocrysts		
Sample no.	**Field no.**	**Plagioclase (andesine)**	**Pyroxene (augite)**	**Olivine**	**Magnetite**	**Apatite**	**Biotite**	**Sanidine**	**Total**	**Pyroxene**	**Plagioclase**	**Feldspar (composite)**
					Rim phase of Ralston plug							
1	23D03	56.1	15.4	7.0	4.1	0.9	3.8	12.7	100.0	8.6	6.7	68.8
2	22D03	65.5	12.4	8.2	4.7	1.0	2.1	6.1	100.0	2.1	7.9	71.6
[1]3	17D03	37.8	15.2	7.7	4.2	0.7	2.1	32.3	100.0	11.9	7.1	70.1
4	2D03	57.5	18.4	5.8	5.9	0.7	3.5	8.3	100.1	9.2	10.7	65.8
5	15D03	49.2	18.8	9.1	3.8	0.4	2.5	16.2	100.0	8.1	3.3	65.4
1–5	Average	53.2	16.0	7.6	4.5	0.7	2.8	15.1	100.0	10.0	7.1	68.3
					Core phase of Ralston plug							
[2]6	16D03	33.7	18.4	8.1	3.0	0.2	3.7	32.9	100.0	4.3	4.7	66.6
7	10D03	63.5	17.0	5.7	4.0	0.8	2.3	6.7	100.0	6.5	9.2	70.2
[1]8	13D03	40.5	22.2	10.1	4.1	0.8	4.2	20.1	100.0	7.5	9.2	60.6
9	8D03	62.7	16.2	5.6	4.5	0.9	3.1	7.0	100.0	3.8	3.8	69.7
10	19D03	62.0	18.0	6.2	4.8	1.3	2.2	7.5	100.0	8.5	9.5	69.5
7–10	Average	57.2	18.0	6.9	4.4	0.9	3.0	10.3	100.0	6.6	7.9	67.5
					Southeastern group of intrusive rocks							
11	24D03	42.8	19.6	7.4	5.8	1.0	2.4	21.0	100.0	9.5	9.0	63.8
12	33D03	55.2	15.7	9.1	4.6	0.7	2.0	12.7	100.0	10.8	9.0	67.9
13	29D03	66.6	12.8	8.9	4.6	1.1	1.3	4.7	100.0	10.7	9.2	71.3
[1]14	30D03	23.8	16.1	6.4	5.8	1.1	2.4	44.4	100.0	10.8	9.5	68.2
[3]15	35D03	70.1	14.5	9.4	4.1	0.4	0.4	1.1	100.0	4.8	7.4	71.2
11–14	Average	47.4	16.1	8.0	5.2	1.0	2.0	20.7	100.1	10.7	9.2	67.8

[1]Stained for potassium feldspar.

[2]Not in average; probably laden with residual fluid; thus atypical.

[3]Not in average; atypical felty textured, low potassium-mineral content, early phase; probably associated with sample 16.

have had little or no potassium-rich material added (that is, they contain little or no biotite or sanidine). The channel lava flow at site 16 is provisionally viewed as flow 1a; the other channel flows at this level, not all of which have been closely examined, are accepted as flow 1. Probably little time elapsed between the effusion of flows 1a and 1, and much more time separated the effusion of those flows and flow 2.

Petrogenesis of the Lava Flows

The development of the magma is inferred from both its mineral assemblage and textures. The magma originated probably as basalt from a deep source (the mantle), possibly including a scattering of labradorite, augite, olivine, and magnetite phenocrysts formed early and felty-textured plagioclase following soon thereafter. On moving upward, minor turbulence is indicated by the presence of rounded phenocrysts. At a higher crustal level, perhaps 5–8 km deep, the magma paused in its progress, forming a chamber in granitic host rock. The heat of the magma was sufficient to melt a small amount of its host rock, thereby acquiring an alkali component. A blocky-textured groundmass began to crystallize before the magma resumed its upward journey. A chemical equilibrium between early crystals and alkali-contaminated melt had not yet been reached. Some of the early crystals were stressed, altered, and rounded, because minor turbulence was again part of the upward movement. Near the surface, magma egress was facilitated by a steep segment of the Golden fault and ultimately also by a thick zone of nearly upended, weak

Table 2. Mineral modes of lava flows of North and South Table Mountains, near Golden, Colo.

Sample No.	Field No.	Plagioclase (andesine)	Pyroxene (augite)	Olivine	Magnetite	Apatite	Biotite	Sanidine	Total	Phenocrysts: Pyroxene	Phenocrysts: Plagioclase	Feldspar (composite)
						Flow 1						
[1]16	45D03	60.7	14.9	10.2	7.6	0.8	0.0	5.8	100.0	9.5	10.0	66.5
17	01D13	55.3	16.8	8.0	6.4	0.7	(2)	12.8	100.0	7.5	10.7	68.1
18	01D21	55.4	20.6	7.8	3.3	0.8	0.4	11.7	100.0	14.1	13.3	67.1
19	01D5	56.2	17.7	6.4	4.9	0.8	1.0	13.0	100.0	9.7	10.3	69.2
17–19	Average	56.9	18.4	7.4	4.9	0.8	0.7	10.8	100.0	10.2	11.1	68.1
						Flow 2						
20	01D18	65.1	14.3	6.2	5.2	0.7	0.9	7.6	100.0	11.3	10.3	72.7
						Flow 3						
21	01D14	61.4	13.6	6.9	8.5	0.6	1.1	7.9	100.0	11.4	9.3	69.3
22	01D17	51.7	19.7	7.3	5.8	0.9	1.0	13.6	100.0	9.4	10.6	65.3
23	01D1	60.0	17.2	4.0	5.0	1.0	0.6	12.2	100.0	18.8	11.1	72.2
24	02D9	55.2	13.6	8.5	5.7	1.0	0.5	15.5	100.0	11.7	8.0	70.7
21–24	Average	57.1	16.0	6.8	6.3	0.9	0.8	12.3	100.0	12.8	9.8	69.4
						Flow 4						
25	01D15	63.9	15.5	3.8	4.8	0.1	1.0	10.4	100.0	14.4	9.2	74.3
26	01D19	57.7	13.6	6.6	6.0	0.9	0.4	14.8	100.0	9.5	8.3	72.5
27	01D12	59.0	14.8	4.3	5.2	0.6	0.9	15.2	100.0	11.0	8.6	74.2
28	02D8	60.7	12.6	6.1	5.1	0.9	0.5	14.1	100.0	12.6	6.7	74.8
25–28	Average	60.3	14.1	5.2	5.3	0.7	0.7	13.6	100.0	11.9	8.2	74.0

[1]Not in average; atypical felty textured; low potassium-mineral content, early phase, probably associated with sample 15. Stained for potassium feldspar.

[2]Not in average; probably laden with residual fluid; thus atypical.

Pierre Shale. At first the magma pressure was barely enough to generate a few small channel flows. No explosive activity is recorded by scoriaceous ejecta in contemporaneous beds of the Denver Formation; a low dome over the small southeastern plug and possibly a fissure vent over the small western dikes supplied lava flows 1 and 1a.

A pause in volcanic activity of perhaps most of the million-year age span permitted magma pressure to build up again and gave the magma a chance to melt more granitic material around the high magma chamber, slightly changing the magmatic composition again. The lava flows are dated at 64.2±1.1 to 63±1.7 Ma, as reported by Obradovich (2002). The statistical errors ±1.1 and ±1.7 indicate that the ages could range from as old as 65.3 Ma to as young as 61.3 Ma. Nevertheless, other factors suggest that a 1-m.y. range is the most reasonable. A few tens of meters below flow 3 on the southeast side of South Table Mountain, an ash-bearing bed in the Denver Formation was dated at 65.8±1.4 Ma (Evernden and others, 1964; Obradovich and Cobban, 1975). Furthermore, near the top of member 4 (the uppermost member) of the Green Mountain Conglomerate, another ash-rich bed provided an age of 63.94±0.28 Ma (Obradovich, 2002). During this short span of time, much happened—deposition of much of the Denver Formation and most of the Green Mountain Conglomerate. Therefore, interpreting a narrow age span of 64–63 Ma for the Table Mountain lava flows is reasonable.

Although the first magma of the renewed upward surge followed the old passageway, the increased pressure soon forced a new passageway a bit farther northwest but along the same structural controls. Perhaps the structure involving the Pierre Shale was changing at that time because of movement on the Golden fault. Abundant shoshonite porphyry lava now poured forth at the Ralston plug, skirting the earlier vent mounds in a large channel at first and then surging across the broad reaches of a

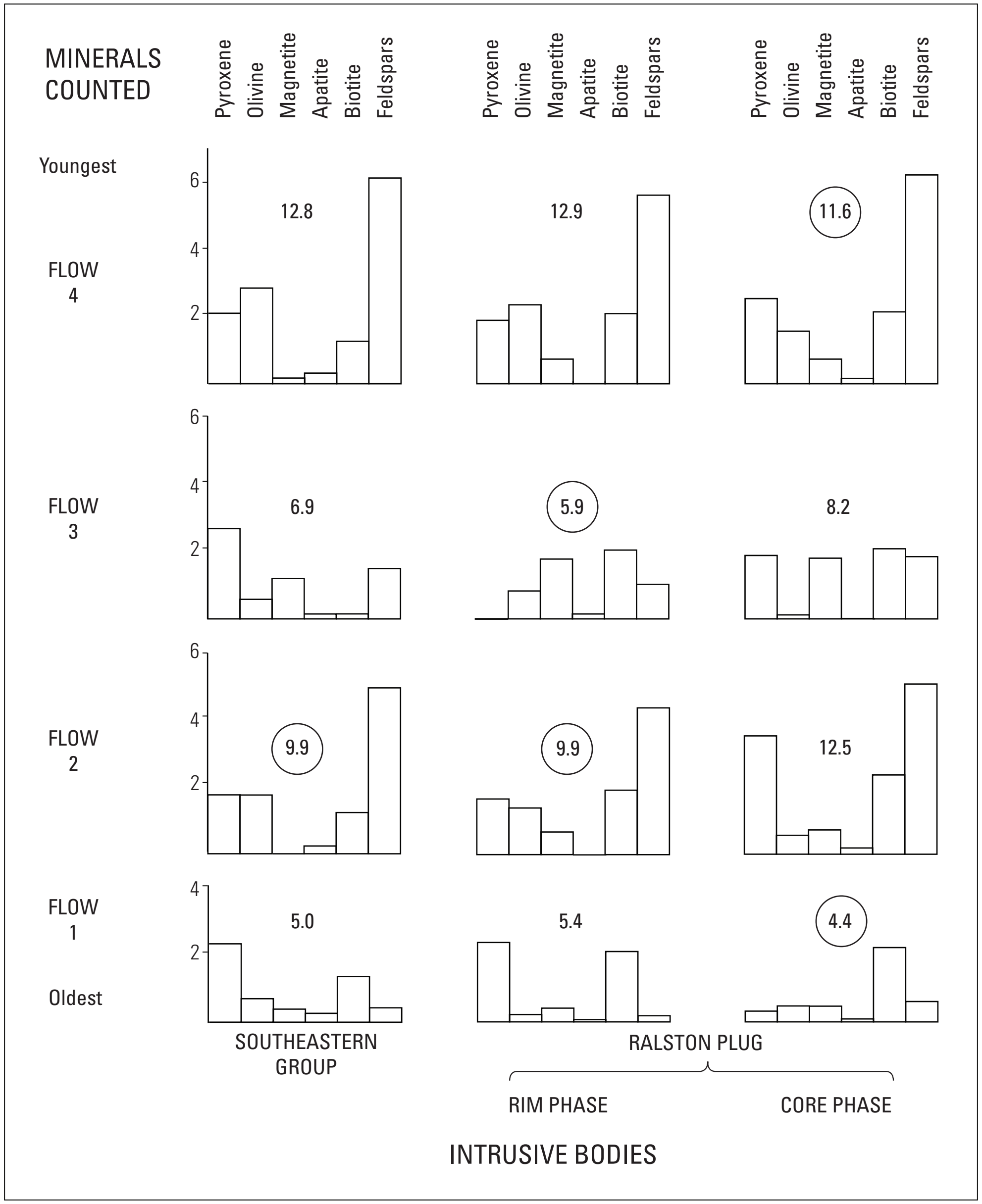


Figure 10. Summary histograms of six parameters (mineral modes) used in correlating lava flows with intrusive rocks, using averages of several samples each. Deviations between average percentages of a mineral in a given flow and average percentages of the same mineral in the samples from each possible source vent were compared, as described in the text. The lowest total deviation for each flow (circled numbers) registers the best fit, or likeliest correlation, with a source vent. For data on which these calculations are based, see tables 1 and 2.

valley sloping down to the south-southeast. Only a brief pause separated the emplacement of flows 3 and 4. On their way south they covered the lower part of flow 2 and the gully it followed. Steam generated in the lower, un-lava-filled part of this channel bowed up the overlying parts of flows 3 and 4. With the dissipation of this local steam pocket, other lava filled in the space (which at any one time need never have been large) in a matter of hours, if not just minutes.

Upon reaching an area 2–3 km south of the elongate tumulus, lava flow 3 formed a broad, low dome for unknown reasons. During the brief interval between the outpouring of flows 3 and 4, stream deposits covered a bit of the northern end of the broad plain, but none of the southern part near the dome. Flow 4 was diverted into two prongs by this dome. Soon thereafter lava extrusion ceased. The Pierre Shale around the Ralston plug had been hot enough long enough to bake the shale. The last fluids in the flows and vents deposited the interstitial crystals, and those fluids in the vent even interacted with some of the older crystals to make the sparse reaction rims.

Summary of Conclusions

Some conclusions reached through this study confirm ideas already in print, whereas others are newly offered herein. Inevitably, new questions are raised; such is the nature of our science.

1. During its upward movement the shoshonite porphyry magma had a complex history.
2. Magma extrusion at 64–63 Ma was nonexplosive; low domed or fissure vents formed, rather than a large volcano.
3. One or several of the southeastern group of vents supplied the earlier channel lava flows, of small volume. Provisionally, the composite channel flow 1 is seen as comprising two phases, a slightly older, felty-textured flow 1a and several slightly younger, mainly blocky-textured flows termed flow 1.

Figure 11. Amounts, in percent, of the potassium-rich minerals, biotite and sanidine, in the intrusive and extrusive rocks of the shoshonite porphyry. The composite shows an overall increase in the younger rocks. Subset of the two plugs and flows shows a general increase in potassium-rich minerals from older to younger rocks.

Intrusive bodies	Biotite	Sanidine
Composite:		
Core of Ralston plug -------------------------	3.1	14.8
Rim of southeastern plug and nearby dikes	0.4	1.1
Ralston plug:		
Core---	3.1	14.8
Rim --	2.8	15.1
Southeastern plug and nearby dikes:		
Core and nearby dikes -----------------------	2.0	20.7
Rim --	0.4	1.1

Younger ↑ / Older

Extrusive bodies: Flow	Biotite	Sanidine
4	0.7	13.6
1a	0.0	5.8
4	0.7	13.6
3	0.8	12.3
1	0.7	12.5
1a	0.0	5.8

4. A fourth lava flow, number 2 in rising sequence, is herein recognized.
5. Lava flows 3 and 4 came from the Ralston plug (not a dike at the present surface). Flow 3 is correlated with the rim phase of that plug and flow 4 with its core phase.
6. A linear tumulus was formed over the channel used by flow 2 below its distal end, at what is now the western part of North Table Mountain.
7. At the position that later became the northern part of South Table Mountain, a broad, low dome was formed on flow 3. Flow 4 parted around the dome and continued in channels now appearing as benches upon flow 3 along the mesa flanks.
8. General settling of deposits into the Denver Basin produced open synclinal sags and many small normal faults affecting flows 3 and 4.
9. Sedimentation continued, at least intermittently, through Paleogene time. A proposed Oligocene or Miocene deposit, possibly an extended part of the White River Formation, covered the Golden area. Likely, at that time a slight northward regional tilting shifted the local streams from a south-southeast–flowing direction to an east-flowing direction.
10. Renewed uplift through the Neogene led to stream incision that now erodes vents from flows and segments of flows from each other.
11. This study also supports a proposal that the source of the andesite detritus making up the Denver Formation and the contaminated basalt of the Table Mountain lava flows may be genetically linked. Consider that in the underlying asthenosphere the leading edge of a Pacific plate descended eastward. As the plate descended, it was heated up enough to melt the less refractory part of the plate and andesite magma rose and fed the volcanic field lying west or northwest of Golden. Andesite detritus was shed into a basin farther east. As the plate remnant descended farther, temperature rose some more and the more refractory basaltic remnant of the plate also melted. This slightly younger and more easterly magma source then fed the lava flows intercalated in the upper part of the Denver Formation.

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References Cited

Ahmad, M.D., 1971, Study of genetic relationship between the Ralston intrusive bodies and the Table Mountain lava flows near Golden, Jefferson County, Colorado: Golden, Colorado School of Mines, M.S. thesis, 124 p.

Allan, R.J., 1922, Basaltic rocks of the Golden area, Colorado: Golden, Colorado School of Mines, M.S. thesis, 18 p.

Drewes, Harald, 1991a, Description and development of the Cordilleran orogenic belt in the Southwestern United States and Northern Mexico: U.S. Geological Survey Professional Paper 1512, 92 p.

Drewes, Harald, 1991b, Mesozoic and early Tertiary orogenesis in the Southwestern United States—Understanding its development, nomenclature and age: Geological Society of America Abstracts with Programs, v. 23, no. 4, p. 1718.

Drewes, Harald, and Townrow, John, 2005, Trailwalker's guide to the Dinosaur Ridge, Red Rocks and Green Mountain Area (2nd ed.): Morrison, Colo., Friends of Dinosaur Ridge, 86 p., map scale about 1:18,000.

Emmons, S.F., Cross, Whitman, and Eldridge, G.H., 1896, Geology of the Denver Basin: U.S. Geological Survey Monograph 27, 556 p.

Evernden, J.F., Savage, D.E., Curtis, G.H., and James, G.T., 1964, Potassium-argon dates and Cenozoic mammalian chronology of North America: American Journal of Science, v. 262, p. 145–198.

Hasbrouck, W.P., Botsford, M.L., and Jennings, W.P., 1975, Data from ground magnetic survey of the Ralston Dike, Jefferson County, Colorado: U.S. Geological Survey Open-File Report 75–97, 43 p.

Hayden, F.V., 1873, Publication of the Hayden Survey: Washington, D.C., Government Printing Office, 844 p.

Johnson, J.H., 1925, The geology of the Golden area: Quarterly of the Colorado School of Mines, v. 20, no. 3, 25 p.

Johnson, J.H., and Waldschmidt, W.A., 1925, Famous Colorado mineral localities—Table Mountain and its zeolites: American Mineralogist, v. 10, p. 118–120.

Kile, D.E., 2004, Zeolites and associated minerals from the Table Mountains near Golden, Jefferson County, Colorado: Rocks & Minerals, v. 79, no. 4, p. 218–238.

Kile, D.E., and Modreski, P.J., 1988, Zeolites and related minerals from the Table Mountain lava flows, near Golden, Colorado: Mineralogical Record, v. 19, p. 153–184.

LeConte, J.L., 1868, Notes on the geology of the survey for the Union Pacific Railroad from Smoky Hill River to the Rio Grande: Philadelphia, Review Printing House, 76 p.

Levings, W.S., 1932, A magnetic survey of the Ralston Dike, Jefferson County, Colorado: Quarterly of the Colorado School of Mines, v. 27, no 3, p. 31–41.

Obradovich, J.D., 2002, Geochronology of Laramide synorogenic strata in the Denver Basin, Colorado: Rocky Mountain Geology, v. 37, no. 2, p. 165–171.

Obradovich, J.D., and Cobban, W.A., 1975, A time scale for the Late Cretaceous of the Western Interior of North America: Geological Association of Canada Special Paper 13, p. 31–54.

Reichert, S.O., 1952, Geology of the Golden–Green Mountain area, Jefferson County, Colorado: Golden, Colorado School of Mines, Dr.Sci. dissert., 136 p.

Scott, G.R., 1976, Geologic map of the Morrison Quadrangle, Jefferson County, Colorado: U.S. Geological Survey Geological Investigations Map I–790–A, scale 1:24,000.

Shuck, E.L., 1976, A seismic survey of the Ralston dike area, Jefferson County, Colorado: Golden, Colorado School of Mines, M.S. thesis, 45 p.

Stanlav, F.M., and Morrison, L.S., 1952, Gravity survey of the Ralston dike, Jefferson County, Colorado: Golden, Colorado School of Mines, M.S. thesis, 54 p.

Van Horn, Richard, 1957, Bedrock geology of the Golden quadrangle, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ–103, scale 1:24,000.

Van Horn, Richard, 1972, Surficial and bedrock geologic map of the Golden quadrangle, Jefferson County, Colorado: U.S. Geological Survey Geologic Quadrangle Map I–761–A, scale 1:24,000.

Van Tuyl, F.M., Johnson, J.H., Waldschmidt, W.A., Boyd, James, and Parker, B.H., 1938, Guide to the geology of the Golden area: Quarterly of the Colorado School of Mines, v. 33, no. 3, 22 p.

Waage, K.M., 1953, Dakota Group in the northern Front Range foothills, Colorado: U.S. Geological Survey Professional Paper 274–B, p. 15–51.

Waldschmidt, W.A., 1939, The Table Mountain lavas and associated igneous rocks near Golden, Colorado: Quarterly of the Colorado School of Mines, v. 34, no. 3, p. 3–62.

Weimer, R.J., 1996, Guide to the petroleum geology and Laramide orogeny, Denver Basin and Front Range, Colorado: Colorado Geological Survey, Department of Natural Resources Bulletin 51, 127 p.

Glossary

A

acicular Needlelike; commonly refers to tiny crystals, highly elongate, that are found in larger ones.

amygdaloidal An igneous-rock texture in which gas bubble holes are filled with late-deposited minerals, commonly zeolites or calcite.

andesite An igneous rock having a composition intermediate to that of rhyolite (high silica and alkali minerals) and basalt (low silica and alkali minerals).

anhedral Under the microscope, a mineral not showing crystal form.

B

backthrust A local or subordinate thrust fault on which the upper plate of rock moved toward, rather than away from, the source of compressional stress.

basalt An igneous rock low in silica and alkali minerals.

C

columnar joints In sheets of igneous rock, sets of cooling fractures typically forming columns with hexagonal cross sections 1–2 m across.

cuesta A ridge with a gentle side and a steep side formed by the differential weathering of a gently dipping, erosionally resistant rock layer and adjacent weak layers.

D

dike A tabular-shaped (long and thin) intrusive body.

M

Michel-Levy method A procedure using one crystallographic plane to obtain the general composition of plagioclase feldspar; the commonly used method.

microlite A tiny crystal included in a large one; may be acicular.

mp method A procedure using two crystallographic planes to obtain the precise composition of plagioclase feldspar; the rarely used method.

O

orogeny The complex processes that structurally deform rocks on a large scale, including folding, faulting, igneous intrusion, metamorphism, and volcanism.

P

periglacial Features formed near a glacial margin.

phenocryst Crystals larger than those of the groundmass.

pleochroic Under the microscope, the effect of changing colors of certain minerals upon rotating the platform on which the thin section lies; useful in mineral identification.

plug A cylindrically shaped (round or oval in section), middle-sized (about 0.1–10 km) pipelike intrusive body.

porphyry An igneous-rock texture of scattered large crystals among many small ones.

pumice A finely porous volcanic rock, commonly less dense than water so it floats until it becomes water logged.

R

reaction rim A ring of one mineral around another, usually seen in thin section but sometimes visible to the naked eye.

S

scoria A coarsely porous volcanic rock that is denser than pumice.

shoshonite A petrographer's name for an alkali-rich basalt.

T

thrust flap A local wedgelike thrust plate.

tumulus On a lava flow, an upward-bulged structure formed by moderate steam pressure.

V

vesicular Having small gas bubble holes, for example, in a lava flow.

vibroseis A seismic method that puts vibrational energy into the ground; the returning energy is analyzed to determine the structure of layers below the ground surface

W

wall rock The rock immediately adjacent to an intrusive body, as distinct from "host rock," the rock generally intruded.

Z

zeolite A family of minerals, mainly alkaline, that are associated with the latest stage of lava cooling or with the early stage after lava has cooled.