Previous section
Volume contents

Geology of the Tertiary Intrusive Centers of the La Sal Mountains, Utah—Influence of Preexisting Structural Features on Emplacement and Morphology

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CONTENTS

Abstract........ 62
Introduction........ 62
Acknowledgments........ 62
Regional Geologic Setting........ 62
Geology of the La Sal Mountains........ 67
Field Relationships of the La Sal Mountains Intrusive Centers........ 69
  Northern La Sal Mountains Intrusive Center........ 69
  Southern La Sal Mountains Intrusive Center........ 76
  Middle La Sal Mountains Intrusive Center........ 77
Structural Control for the La Sal Mountains Intrusive Centers........ 77
Surface Faults in the La Sal Mountains Region........ 79
Conclusions........ 80
References Cited........ 81

FIGURES

1. Map showing selected magmatic and structural features of the Colorado Plateau... 63
2. Maps showing geologic and geographic features of the La Sal Mountains and vicinity........ 65
3. Photograph of view to southeast up Castle Valley, showing northern La Sal Mountains........ 67
4. Photograph of La Sal Mountains as seen from Dead Horse State Park........ 68
5. Simplified geologic maps and cross sections of the northern La Sal Mountains...... 70
6. Photograph of La Sal Peak and Castle Mountain in the northern La Sal Mountains, as seen from Horse Mountain........ 74
7. Map showing structural and magmatic features and interpreted subsurface faults of the La Sal Mountains region........ 78

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ABSTRACT

The results of geologic mapping and subsurface data interpretation, combined with previous regional gravity and magnetic surveys, define the structural setting and emplacement history of the late Oligocene intrusive centers of the La Sal Mountains, Utah. The La Sal Mountains contain three intrusive centers: northern, middle, and southern; they are located on a broad dome, which has about 600 meters of relief across a diameter of about 32 kilometers. The intrusions are estimated to have been emplaced at shallow levels ranging between 1.9 and 6.0 kilometers. The intrusions are holocrystalline and porphyritic and have a very fine- to fine-grained groundmass. Each of the centers consists predominantly of hornblende plagioclase trachyte emplaced as laccoliths, plugs, sills, and dikes. The northern mountains intrusive center contains additional bodies of quartz plagioclase trachyte, peralkaline trachyte and rhyolite, and nosean trachyte that intrude the earlier hornblende plagoclase trachyte.

The northern and southern intrusive centers were emplaced into preexisting anticlines cored by salt diapirs. Geophysical and drill-core data suggest that older rocks beneath these salt diapirs are offset by northwest-striking, high-angle faults that influenced the location and development of the diapirs during the late Paleozoic and early Mesozoic. These northwest-striking en echelon faults may be connected by a northeast-striking fault or ramp-monocline structure. The northwest-striking faults and northeast-trending connecting structures form a structural boundary that separates a southern region of shallower level pre-salt rocks from a northern region of deeper level pre-salt rocks. The intrusions of the La Sal Mountains were emplaced along a kink in the structural boundary that separates these two parts of the late Paleozoic Paradox Basin. The ascending magmas for the La Sal Mountains intrusions appear to have exploited the preexisting zone of structural weakness in the upper crust during their ascent.

Most surface faults in the area around the La Sal Mountains postdate magma emplacement: the surface faults formed during late Tertiary to Quaternary collapse of the crests of the salt-cored anticlines. The collapse of the salt-cored anticlines was caused by dissolution of the salt and salt flowage.

INTRODUCTION

The La Sal Mountains of southeastern Utah are one of several mountain ranges in the central Colorado Plateau that contain hypabyssal intrusion-cored domes (fig. 1). In general, these intrusions have similar morphologies, lithologies, and chemical compositions (Eckel and others, 1949; Hunt and others, 1953; Hunt, 1958; Witkind, 1964; Ekren and Houser, 1965). A common form for these shallow intrusions is a laccolith, as initially described by Gilbert (1877) in the Henry Mountains. Therefore, the intrusive centers are commonly referred to as laccolithic centers. Previous workers (Kelley, 1955; Hunt, 1956; Shoemaker, 1956; Witkind, 1975; Warner, 1978) have speculated about whether structures represented by lineaments may have influenced the distribution and form of the conspicuous and prominent intrusive centers of the Colorado Plateau. The problem I will address in this report is: Did northwest-striking subsurface faults and associated salt-cored anticlines of the northern Paradox Basin control the location and form of the La Sal Mountains intrusive centers? If so, what is the geological and geophysical evidence to support this hypothesis?

Peale (1877; 1878) originally described the La Sal Mountains. Gould (1926) and Hunt (1958) mapped the mountains at a reconnaissance scale and studied the mineral deposits. Uranium and petroleum exploration during the 1950’s and 1960’s prompted additional geologic mapping (1:24,000 scale) in the middle and southern La Sal Mountains (Carter and Gualtieri, 1957, 1958; Weir and Puffet, 1960; Weir and others, 1960). Case and others (1963) conducted regional gravity and magnetic surveys in the area.

This report presents some of the results of recent (1988–92) 1:24,000-scale geologic mapping of the northern La Sal Mountains by the Utah Geological Survey and a synthesis of the previous investigations. The report will focus on the general structural geology of the La Sal Mountains intrusive centers and the possible influence of subsurface faults and salt-cored anticlines on the emplacement and morphology of the intrusions.

ACKNOWLEDGMENTS

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REGIONAL GEOLOGIC SETTING

Geophysical studies suggest that the Colorado Plateau is underlain by 40- to 50-km-thick Precambrian cratonic crust (Thompson and Zoback, 1979; Allmendinger and others, 1987). Surface exposures of the Precambrian basement in the plateau region suggest that it consists of gneissic rocks of Early Proterozoic age (1,800 to 1,600 Ma) and granitoid rocks of Middle Proterozoic age (1,400 to 1,500 Ma) (Tweto, 1987; Bowring and Karlstrom, 1990; Case, 1991). East-northeast of the La Sal Mountains, on the

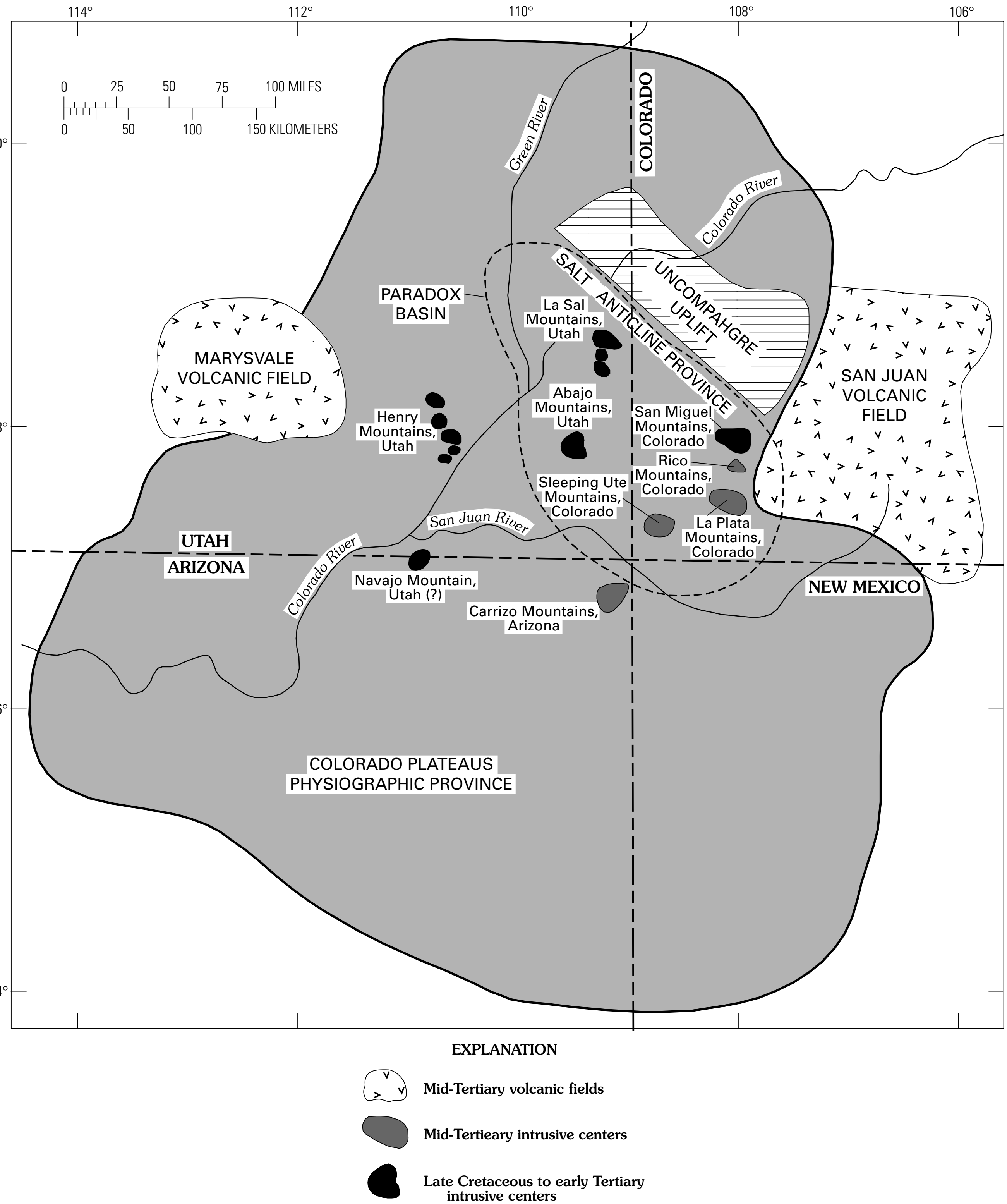


Figure 1. Selected magmatic and structural features of the Colorado Plateau (modified from Woodward-Clyde Consultants, 1983, Figure 6–1, p. 136).

Uncompahgre Plateau, the basement rocks contain northwest-striking faults that show evidence of Proterozoic shearing (Case, 1991). Farther east, in the mountains of central Colorado, Proterozoic rocks contain both northwest-striking and northeast-striking fault zones that also show evidence of Proterozoic movement (Hedge and others, 1986; Tweto, 1987). In the southwestern part of the Colorado Plateau the basement rocks are faulted by northeast-striking Proterozoic shear zones (Bowring and Karlstrom, 1990). Subsurface data indicate that a 600-m-thick sequence of Cambrian to Mississippian epicontinental sedimentary rocks overlies the Proterozoic basement rocks of the central Colorado Plateau (Hintze, 1988).

During the late Paleozoic, regional tectonism formed the ancestral Rocky Mountains and associated basins (Woodward-Clyde Consultants, 1983). The Paradox Basin formed on the southwest side of the ancestral Uncompahgre Uplift during this tectonism (fig. 1). The basin is asymmetric, having its northwest-trending axis along its northeastern margin adjacent to the faulted ancestral uplift. Drilling and seismic data show that the uplift is bounded along the Paradox Basin by a high-angle reverse fault (Uncompahgre fault). The fault accommodated approximately 6,100 m of vertical offset and 9 km of horizontal offset during the late Paleozoic (Frahme and Vaughn, 1983; White and Jacobson, 1983; Potter and others, 1991). The amount of subsidence and sedimentation was greatest in the northeastern part of the basin adjacent to the uplift.

During the Middle Pennsylvanian, a sequence of cyclic evaporites (chiefly halite, gypsum, and anhydrite), fine-grained siliciclastics, and carbonates of the Paradox Formation were deposited in the basin. In the northeastern part of the basin, later flowage of the evaporites formed northwest-trending elongated salt diapirs, which may be referred to as salt walls (Jackson and Talbot, 1991). In the vicinity of the La Sal Mountains, the salt diapirs form three near-parallel rows: the Moab Valley–Spanish Valley–Pine Ridge salt diapir system, the Castle Valley–Paradox Valley salt diapir system, and the Salt Valley–Cache Valley–Fisher Valley–Sinbad Valley salt diapir system (fig. 2). Some early workers in the Paradox Basin suggested the existence of faults and (or) folds in the underlying rocks that controlled the locations and development of the salt diapirs (Harrison, 1927; Stokes, 1948). Data from drilling and geophysical surveys in the region strongly suggest the existence of high-angle, large-displacement, northwest-striking faults in the Pennsylvanian and older rocks below some of the salt diapirs (Shoemaker and others, 1958; Case and others, 1963; Baars, 1966; Woodward-Clyde Consultants, 1983). These faults strike subparallel to the Uncompahgre fault.

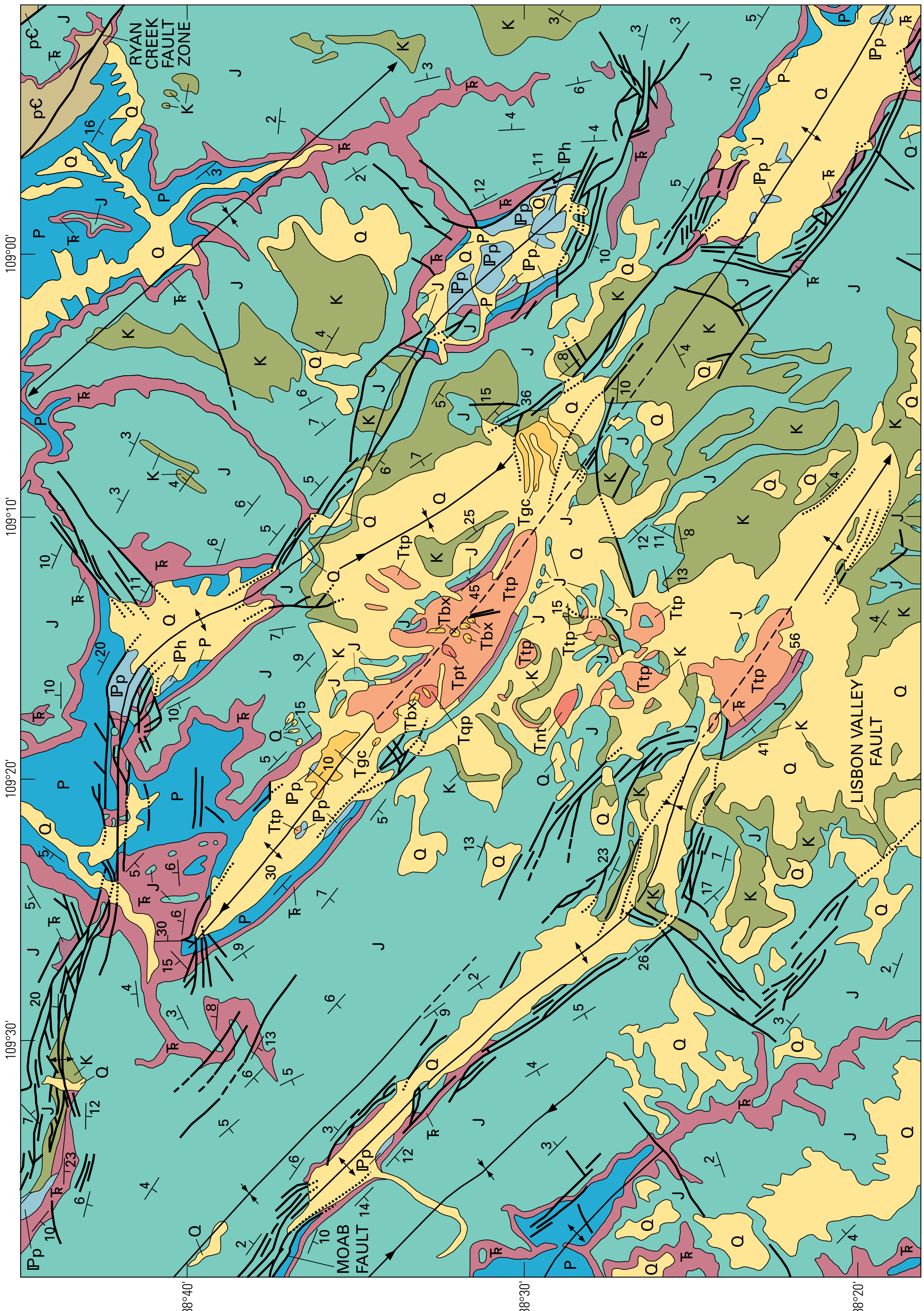
The growth of the Paradox Basin salt diapirs affected the deposition of synkinematic Upper Pennsylvanian to Upper Triassic sediments and caused considerable variation in the stratigraphic thickness of these units (Shoemaker and others, 1958; Cater, 1970; Doelling, 1988). Localized salt flowage along some of the diapirs continued until the Late Jurassic (Shoemaker and others, 1958; Cater, 1970; Tyler and Ethridge, 1983). Synkinematic Upper Pennsylvanian to Upper Jurassic formations are thin or absent over some salt diapirs, but are significantly thicker in the rim synclines that formed adjacent to the salt diapirs during salt flowage. The piercement, thinning, and folding of strata over the salt diapirs produced the salt-cored anticlines.

Northeast-southwest compressive stress of the Laramide orogeny affected the region during the Late Cretaceous to Eocene (McKnight, 1940; Cater, 1970; Baars and Stevenson, 1981; Heyman and others, 1986). Some structures were reactivated and formed large uplifts. The Uncompahgre Plateau, for instance, rose on the site of the Paleozoic Uncompahgre Uplift. North-northwest-striking high-angle faults and monoclines formed in association with these uplifts (Cater, 1970; Jamison and Stearns, 1982). North-northwest-trending, gentle folds are also interpreted to have formed during this orogenic period (Cater, 1970; Johnson, 1985). Broad folds may have been superimposed on the preexisting salt-cored anticlines and adjacent rim synclines (fig. 2)(Cater, 1970; Doelling, 1988). The crustal structural fabric produced during these periods of deformation may have influenced the emplacement of the Colorado Plateau intrusive centers.

Even though the Colorado Plateau intrusive centers have structural and geochemical similarities, recent isotopic dating (Sullivan and others, 1991; Nelson, Heizler, and Davidson, 1992; Nelson, Davidson, and Sullivan, 1992) combined with previous studies (Armstrong, 1969; Cunningham and others, 1977) indicates that the centers form two temporally and spatially distinct belts (fig. 1). A northeast-southwest-trending belt of Late Cretaceous to early Tertiary intrusive centers extends from the Four Corners region into Colorado. An east-west-trending belt of late Oligocene to early Miocene magmatic centers extends across the Colorado Plateau from the Marysvale volcanic field to the San Juan volcanic field (fig. 1), including several intrusive centers (Best, 1988; Nelson, Davidson, and Sullivan, 1992). The La Sal Mountains magmatic activity occurred in the late Oligocene and is part of the east-west belt (Nelson, Davidson, and Sullivan, 1992).

The Colorado Plateau has undergone epeirogenic uplift during the late Cenozoic (Hunt, 1956; Lucchitta, 1979; Johnson and Finn, 1986), and regional erosion has been pronounced. However, the salt-cored anticlines remain distinct physiographic features because of late Cenozoic collapse along their crests. The collapse transformed most of them into steep-walled valleys, which are generally floored by Quaternary deposits (figs. 2 and 3). Collapse of the crests along marginal faults of the salt-cored anticlines was caused by salt dissolution or salt flowage.

Figure 2 (following pages). Geologic and geographic features of the La Sal Mountains, Utah and vicinity. *A*, Simplified geologic map, modified and reduced from the 1:250,000 map of Williams (1964). For the locations of geologic features not labeled above, compare this to the geographic map on the following page, which is at the same scale. *B*, Notable geographic features in and near the La Sal Mountains, Utah.


RYAN CREEK FAULT ZONE
MOAB FAULT
LISBON VALLEY FAULT
109°00'
109°10'
109°20'
109°30'
38°40'
38°30'
38°20'

A

EXPLANATION

Q	**Quaternary deposits (includes some Pliocene fan gravels)**
	Tertiary rocks:
Tgc	**Geyser Creek Fanglomerate (Pliocene?)**
Tnt	**Nosean trachyte** — youngest (Oligocene)
Tbx	**Breccia** (Oligocene)
Tpt	**Peralkaline trachyte** (Oligocene)
Tqp	**Quartz plagioclase trachyte** (Oligocene)
Ttp	**Hornblende plagioclase trachyte** — oldest (Oligocene)
K	**Cretaceous strata:**
J	**Jurassic strata:**
TR	**Triassic strata:**
P	**Cutler Formation (Lower Permian)**
₱h	**Honaker Trail Formation (Upper and Middle Pennsylvanian)**
₱p	**Paradox Formation (Middle Pennsylvanian)**
p€	**Precambrian rocks**

Contact

Fault—Dashed where approximate; dotted where covered

23 **Strike and dip**

Anticline axial trace—Dashed where approximate or covered

Syncline axial trace—Dashed where approximate or covered

0 5 10 15 20 KILOMETERS

GEOLOGY OF THE LA SAL MOUNTAINS

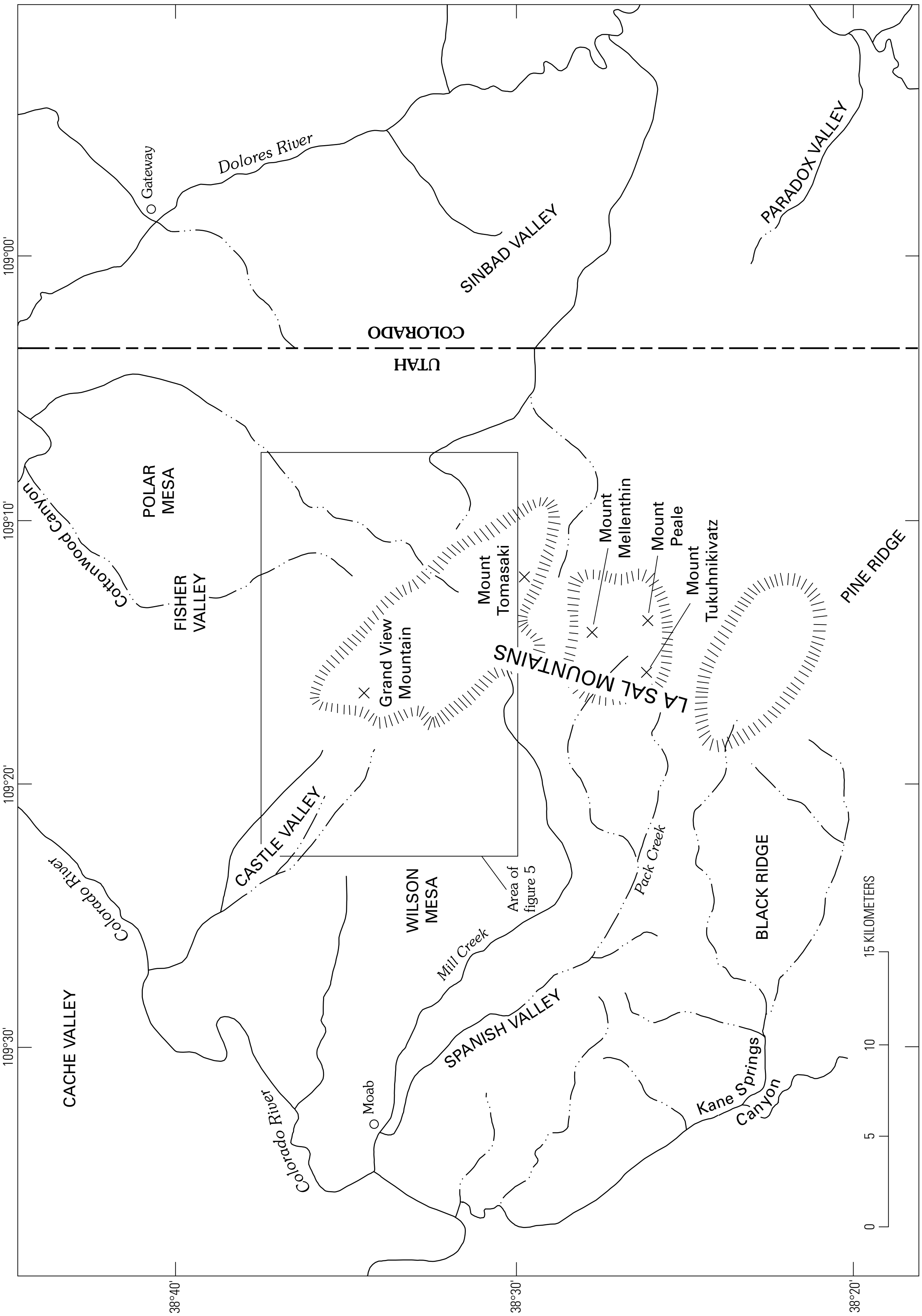
The La Sal Mountains consists of three distinct clusters of peaks separated by high passes: the northern, middle, and southern La Sal Mountains (fig. 4). Each of the mountain clusters is an intrusive center consisting of hypabyssal intrusions of trachyte and rhyolite porphyries emplaced as laccoliths, plugs, sills, and dikes.

The three intrusive centers in the La Sal Mountains intruded upper Paleozoic and Mesozoic sedimentary rocks and have a north-south alignment (fig. 2). As first recognized by Gould (1926), both the northern and southern mountains are cored by large elliptical igneous intrusions elongated northwest-southeast. The northern mountains are elongated along the Castle Valley–Paradox Valley salt-cored anticline system. The southern mountains are elongated along the Moab Valley–Spanish Valley–Pine Ridge salt-cored anticline system. The elongation of these intrusive centers suggests that shallow-level magma emplacement was influenced by the preexisting salt-cored anticlines. The intrusions of the middle mountains form several laccoliths, plugs, and sills in a circular cluster arrangement. These were emplaced into subhorizontal sedimentary rocks between the two salt-cored anticline systems.

The La Sal Mountains intrusive centers are on a broad dome that has approximately 600 m of relief across a diameter of about 32 km. Regional magnetic data suggest there is no large intrusion in the subsurface below the La Sal Mountains from which the intrusive centers were supplied. The magnetic low at the La Sal Mountains indicates that no such intrusion is present within 11–14 km beneath the mountains (Case and others, 1963). It is possible, though, that one could be present at greater depth.

Hunt (1958) interpreted each of the La Sal Mountain intrusive centers as consisting of a central stock surrounded by outward-radiating laccoliths. In his view, the stocks forced up the individual domes and the laccoliths were injected laterally from the stocks. This interpretation is identical to his conclusions on the physical injection of stocks and laccoliths for the Henry Mountains. The mechanism of emplacement of the Henry Mountains laccoliths is disputed. Research by Johnson and Pollard (1973), Pollard and Johnson (1973), Jackson and Pollard (1988a), and Corry (1988) in the Henry Mountains indicates that a large central laccolith, not a discordant stock, formed the intrusive domes of the Henry Mountains. The laccoliths were probably fed by a network of radiating dikes, but the data does not rule out the possibility of a stock at depth (Jackson and Pollard, 1988a). Jackson and Pollard (1988a,b), Hunt (1988), and Corry (1988) discuss the two opposing interpretations at length. No field evidence demonstrates convincingly that any of the La Sal Mountains centers are cored by discrete central stocks that have fed magma outward to radiating laccoliths. Surficial deposits, frost wedging, hydrothermal alteration, and poor bedrock exposures make detailed structural analysis of the La Sal Mountains intrusives problematic.

Igneous rocks of the La Sal Mountains are holocrystalline and porphyritic and have a very fine- to fine-grained groundmass. Chemically, the igneous rocks are mildly subalkaline to alkaline and contain 59–71 percent SiO_2. Based on the Total Alkali-Silica classification of LeBas and others (1986), rocks of the La Sal Mountains consist of various types of trachyte and some rhyolite (Ross, 1992). Mapping (figs.


Dolores River
Gateway
SINBAD VALLEY
PARADOX VALLEY
COLORADO
UTAH
POLAR MESA
Cottonwood Canyon
FISHER VALLEY
Mount Tomasaki
Mount Mellenthin
Mount Peale
Mount Tukuhnikivatz
PINE RIDGE
Grand View Mountain
LA SAL MOUNTAINS
CASTLE VALLEY
Colorado River
WILSON MESA
Area of figure 5
Pack Creek
BLACK RIDGE
Mill Creek
CACHE VALLEY
SPANISH VALLEY
Moab
Kane Springs Canyon
0
5
10
15 KILOMETERS
109°00'
109°10'
109°20'
109°30'
38°40'
38°30'
38°20'

B

Figure 3. View to the southeast up Castle Valley, Utah, showing the northern La Sal Mountains. Note the high cliffs along the valley margins. Round Mountain is in the center of the valley (foreground).

Figure 4. The La Sal Mountains, Utah, as seen from Dead Horse Point State Park, about 40 km west of the mountains. Northern mountains are on the left, middle mountains are in the center, and southern mountains are on the right. Photograph by Craig Morgan, Utah Geological Survey.

2 and 5) shows the following lithologic units in the La Sal Mountains (in order from oldest to youngest): hornblende plagioclase trachyte (Ttp), quartz plagioclase trachyte (Tqp), peralkaline trachyte (Tpt), peralkaline rhyolite (Trp), and nosean trachyte (Tnt).

Hornblende plagioclase trachyte is the predominant igneous rock type in the La Sal Mountains. It contains phenocrysts of plagioclase (20–50 percent) and hornblende (≤15 percent), ≤5 percent). The plagioclase phenocrysts are subhedral to euhedral laths, some complexly zoned, ranging from 1 to 8 mm. The hornblende phenocrysts are subhedral to euhedral and generally range from 2 to 7 mm. The clinopyroxene forms equant microphenocrysts. Accessory minerals are apatite, opaque oxides, sphene, otite, and spicuous amphibolite xenoliths, and some of the hornblende crystals are xenocrysts derived from disintegration of those xenoliths (Nelson, Davidson, and Sullivan, 1992). Quartz plagioclase trachyte is largely similar to the hornblende plagioclase trachyte, except that its phenocryst assemblage includes ≤10 percent anhedral (resorbed?) quartz.

The peralkaline trachyte contains 20–70 percent phenocrysts of alkali feldspar, plagioclase, and microperthite, along with aegirine-augite (≤10 percent), ≤5 percent). The alkali feldspar forms large (0.5–2.0 cm) equidimensional euhedral crystals that are complexly zoned and twinned. Some crystals have plagioclase cores. Aegirine-augite forms euhedral microphenocrysts (≤3 mm) scattered in the groundmass, which consists of alkali feldspar and minor quartz, apatite, opaque oxides, and zircon. The texture of the peralkaline trachyte varies from seriate to porphyritic. Conspicuous protoclastic(?) and filter-pressing textures are locally present.

The peralkaline rhyolite contains 5–40 percent phenocrysts of subhedral to euhedral feldspar. Feldspar phenocrysts are commonly plagioclase, but some are complexly zoned, having plagioclase cores and alkali feldspar rims. Sanidine forms phenocrysts in certain rhyolite intrusions. Quartz (≤10 percent) and aegirine-augite (≤5 percent) may be phenocrysts. The groundmass is feldspar-rich and also includes some quartz, clinopyroxene, apatite, zircon, and opaque oxides.

The nosean trachyte is a distinct rock because it contains abundant large (0.5–5.0 cm) equidimensional multiphase feldspar megacrysts and glomerocrysts. The megacrysts are complexly zoned albite, perthite, and alkali feldspar. Besides the megacrysts, the rock contains 30 percent euhedral plagioclase and alkali feldspar (0.2–1.0 cm), 10 percent subhedral to euhedral nosean (≤2 mm), and 2–5 percent subhedral to euhedral aegirine-augite (≤4 mm) as phenocrysts. Microphenocrysts of anhedral melanite garnet, commonly in small clusters with aegirine-augite and opaque oxides, compose about 2 percent of the rock. Sphene, biotite, and opaque oxides are accessory minerals. The groundmass is feldspar-rich and trachytic.

Based on $^{40}Ar/^{39}Ar$, K/Ar, and fission-track geochronology, magmatic activity in the La Sal Mountains ranged in age from 25.1 to 27.9 Ma (Nelson, Heizler, and Davidson, 1992). This timing is contemporaneous with magmatic activity in the Henry and Abajo Mountains (Nelson, Davidson, and Sullivan, 1992).

FIELD RELATIONSHIPS OF THE LA SAL MOUNTAINS INTRUSIVE CENTERS

NORTHERN LA SAL MOUNTAINS INTRUSIVE CENTER

The northern La Sal Mountains intrusive center consists of a large composite pluton forming an elliptical structural dome, 13.7x4.8 km, surrounded by several smaller satellite laccoliths and sills (fig. 5). The main intrusive dome shows about 1,520 m of structural relief along the base of the Lower Jurassic Glen Canyon Group sandstones across the short axis of the dome (fig. 5, section *A–A′*). Preliminary restoration of the cross section *A–A′* prior to intrusion suggests about 300 m of relief was present on the base of the Glen Canyon Group over the preexisting salt-cored anticline. The salt diapirs in the core of the Castle Valley–Paradox Valley salt-cored anticlines have near-vertical margins and height-to-width ratios greater than one. The estimated height of the Castle Valley salt diapir is between 2,700 and 3,000 m. The estimated height of the Paradox Valley salt diapir is between 2,400 and 4,600 m (Shoemaker and others, 1958; Case and others, 1963; Cater, 1970).

Hornblende plagioclase trachyte is the oldest and most voluminous igneous rock type at northern intrusive center. The exact shape and size of the hornblende plagioclase trachyte intrusion or intrusions that form the main pluton (within the preexisting salt-cored anticline) are poorly understood. Field observations and petrographic and geochemical analyses have not produced sufficient information to determine if the main pluton is formed by one or several intrusions. Even the pluton’s shape and original size cannot be determined because its roof rocks have been removed by erosion, its floor is not exposed, and only a few outcrops show its marginal contacts. Though conclusive evidence is lacking, the main hornblende plagioclase trachyte pluton probably consists of several coalesced laccoliths that were emplaced in the upper part of the salt diapir below its contact with the overlying country rock.

Hunt (1958) used flow banding, linear hydrothermal alteration zones, sheeted joints, xenolithic blocks of contact-metamorphosed country rock, and the eroded shape of

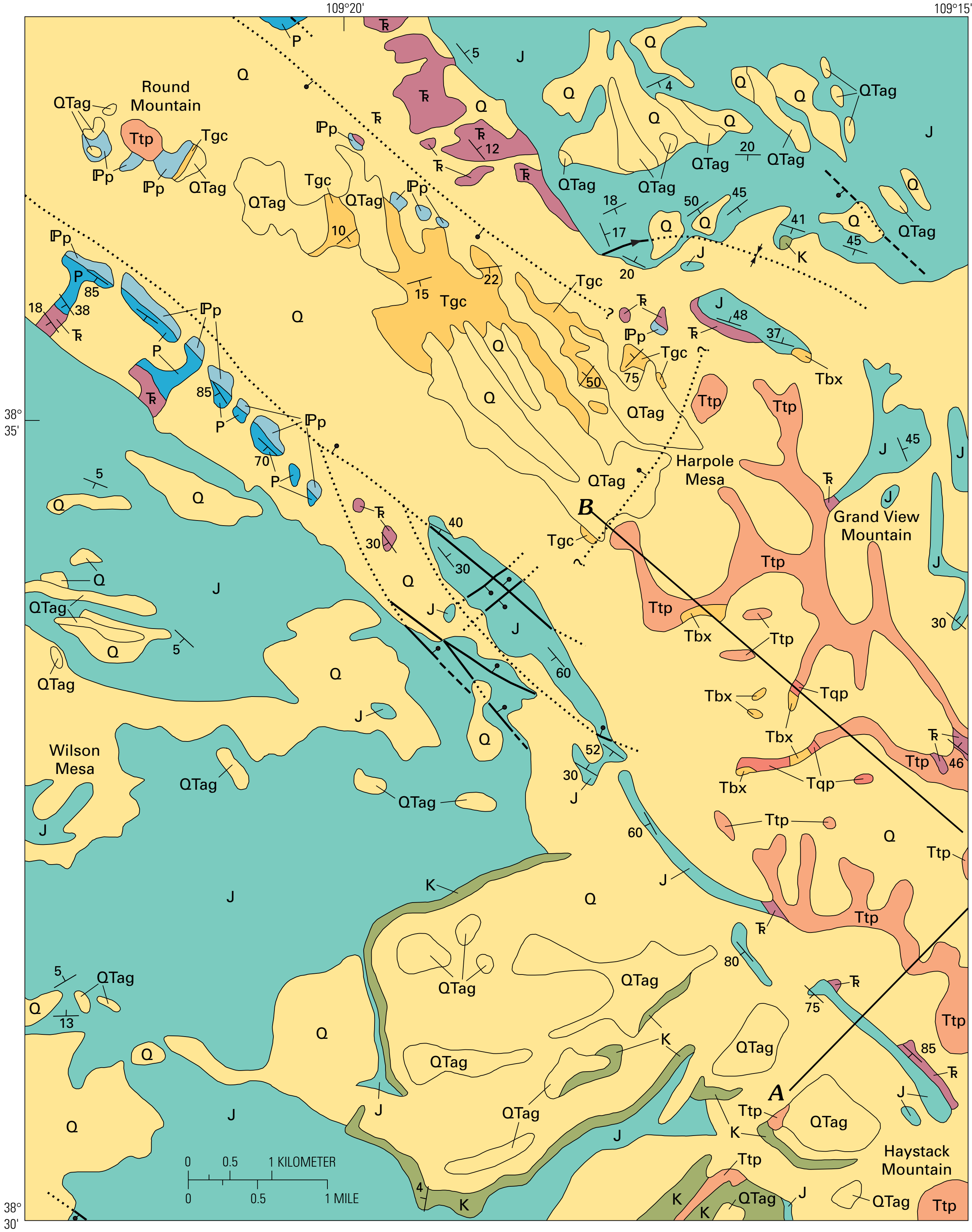
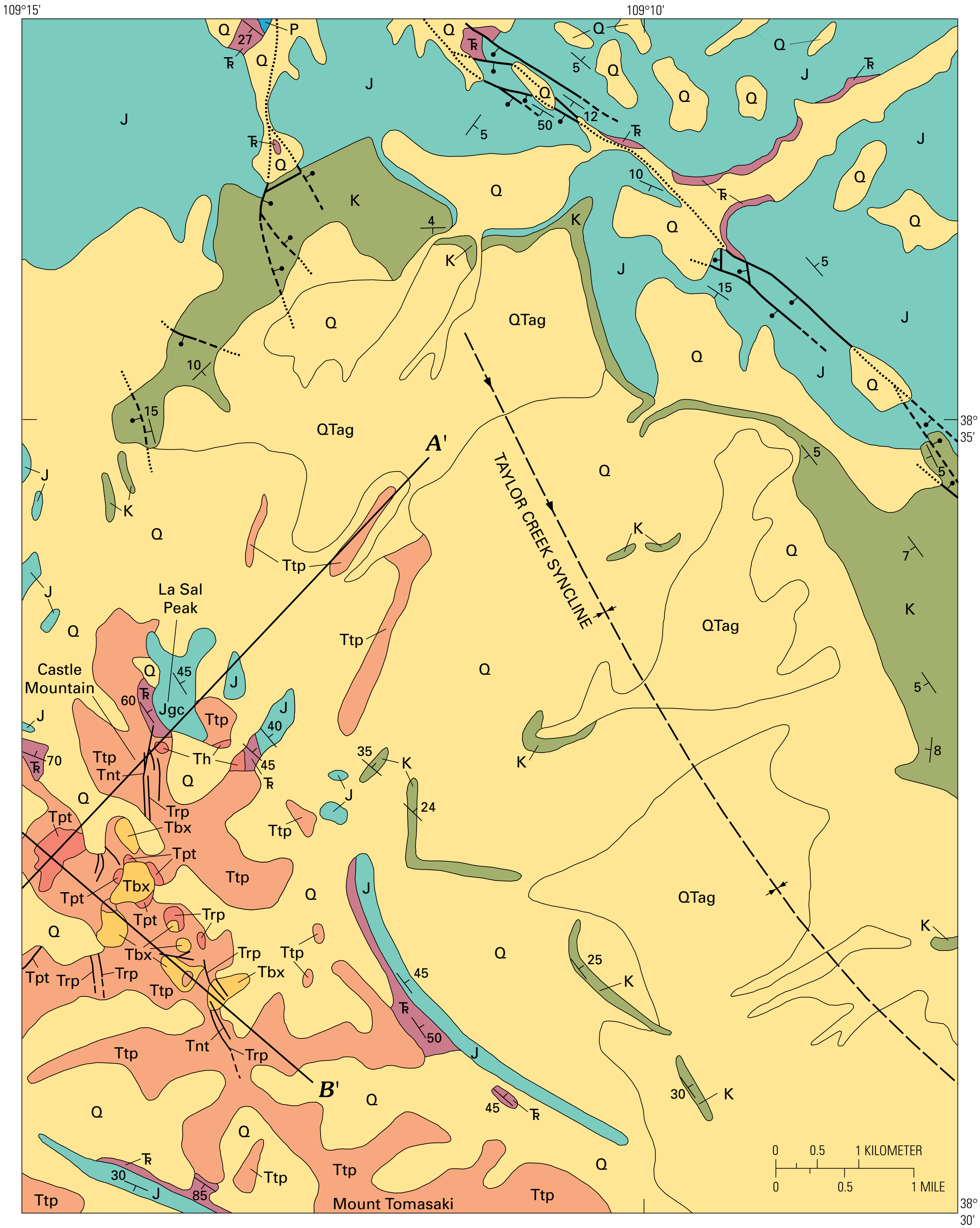


Figure 5 (above and following pages). Simplified geologic maps and cross sections of the northern La Sal Mountains, Utah. Maps above show the Warner Lake (left) and Mt. Waas (right) 7.5-minute quadrangles. See following pages for explanation and cross sections.


109°15'
109°10'
38° 35'
38° 30'
A'
B'
TAYLOR CREEK SYNCLINE
La Sal Peak
Castle Mountain
Mount Tomasaki
QTag
Q
J
K
Ꞧ
P
Ttp
Tpt
Tnt
Trp
Tbx
Th
Jgc
0 0.5 1 KILOMETER
0 0.5 1 MILE

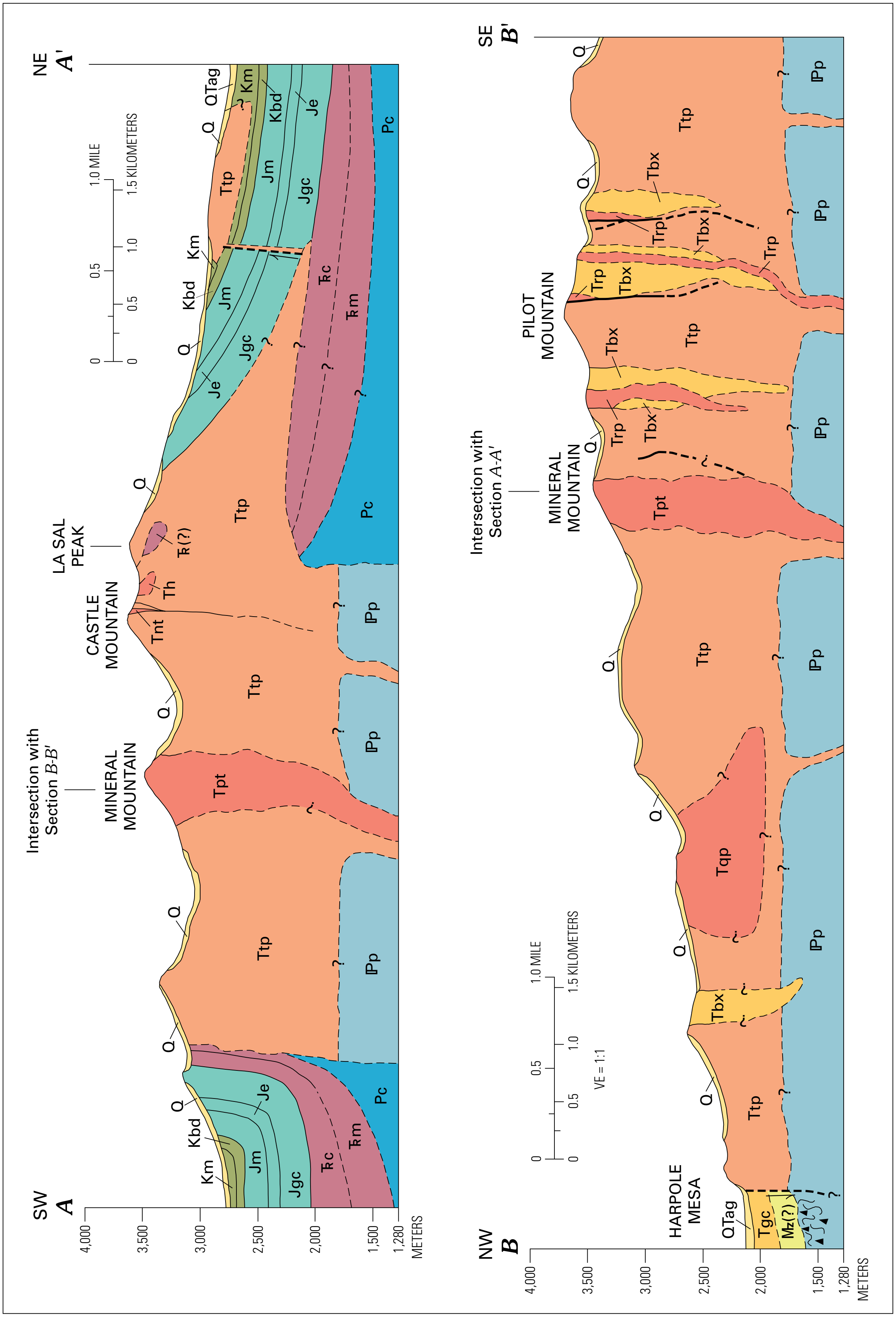


Figure 5 (above and following page). Interpretive cross sections through the Warner Lake and Mt. Waas Quadrangles. See maps on the preceding pages for lines of section. No vertical exaggeration.

EXPLANATION FOR MAPS AND CROSS SECTIONS

Q	**Quaternary deposits**
QTag	**Pleistocene and Pliocene alluvial fan gravels**
	Tertiary rocks
Tgc	**Geyser Creek Fanglomerate (Pliocene?)**
Th	**Hornfels** (youngest)
Tnt	**Nosean trachyte**
Trp	**Peralkaline rhyolite**
Tbx	**Breccia** (Oligocene)
Tpt	**Peralkaline trachyte**
Tqp	**Quartz plagioclase trachyte**
Ttp	**Hornblende plagioclase trachyte** (oldest)
Mz	**Mesozoic rocks, undifferentiated**
K	**Cretaceous strata**
Km	**Mancos Shale (Upper Cretaceous)**
Kbd	**Dakota Sandstone (Upper Cretaceous) and Burro Canyon Formation (Lower Cretaceous)**
J	**Jurassic strata**
Jm	**Morrison Formation (Upper Jurassic)**
Je	**Entrada Sandstone (Middle Jurassic)**
Jgc	**Glen Canyon Group (Lower Jurassic; includes Navajo Sandstone, Kayenta Formation, Wingate Sandstone)**
TR	**Triassic strata**
TRc	**Chinle Formation (Upper Triassic)**
TRm	**Moenkopi Formation (Middle and Lower Triassic)**
P	**Cutler Formation (Lower Permian)**
IPp	**Paradox Formation (Middle Pennsylvanian)**

Contact

Normal fault—Dashed where approximate; dotted where covered; bar and ball on downthrown side

23 **Strike and dip**

Anticline axial trace—Dashed where approximate or covered

Syncline axial trace—Dashed where approximate or covered

mountain peaks of igneous rocks to define the axial trends of "laccoliths that radiate from the central stock." However, in remapping the area I have found that (1) the hydrothermal alteration and fractures are peripheral to and related to the emplacement of later peralkaline trachyte and rhyolite intrusions and breccia pipes; (2) the metamorphosed xenolithic blocks are small isolated roof pendants that have no systematic distribution; and (3) the conical eroded peaks in the core of the northern mountains are not the tops of individual laccoliths.

On the southwest flank of the northern mountains dome, the sedimentary rocks are abruptly folded from a dip of 5° to dips of 60°–90° southwest, forming a northwest-trending monocline (fig. 5, section *A–A'*). Triassic strata are in near-vertical contact with the hornblende plagioclase trachyte pluton along the entire flank. A thin contact-metamorphic aureole of hornfels indicates minimal baking of the country rock along the contact. At several locations, Triassic strata adjacent to the pluton form thin breccia zones. This clast-supported breccia has well-indurated clasts in a matrix of calcite and crushed rock. Many of the frost-heaved Lower Jurassic Glen Canyon Group sandstone blocks that cover the large flatiron ridge of the monocline have slickenside surfaces and cataclastic shear bands. The breccia zones, slickensides, and shear bands suggest near-bedding-plane faulting and stretching of the sedimentary rocks as they were arched across the main igneous pluton. Similar features have been described on the flanks of the laccolithic domes in the southern Henry Mountains (Johnson and Pollard, 1973; Jackson and Pollard, 1988a).

Along most of the northeast flank of the northern mountains, Triassic and Jurassic strata dip about 45°–50° and 45°–60° northeast, respectively (fig. 5). The pluton–country rock contact along this flank appears to be nearly vertical or to dip slightly northeast. At La Sal Peak, the structure is complex because the hornblende plagioclase trachyte intrusion breached the flank of the anticline and was injected as much as 1.7 km into the flanking rocks (fig. 5, section *A–A'*). Exposures in this area (fig. 6) shows that hornblende plagioclase trachyte cuts discordantly across the Triassic and Glen Canyon Group strata. Small dikes and sills penetrate several meters into the country rock beyond the main contact. Triassic strata are unmetamorphosed to variably baked, forming an irregular hornfels zone. Some areas of well-developed hornfels may be partially stoped blocks.

The elevation of the floor of the hornblende plagioclase trachyte pluton in the northern mountains is problematic. Case and others (1963) suggested, on the basis of gravity and magnetic data, that the northwest part of the main pluton (Grand View Mountain area) and the southeast part (Mount Tomasaki area) both extend outward over thickened masses of salt (fig. 5). By modeling the geophysical data, they suggested that the floor of the pluton is approximately 2,700 m above sea level at the northwest and southeast ends and drops to about 2,100 m near the center. Hunt (1958) estimated that the maximum thickness of the laccoliths in the northern mountains is about 600–900 m, indicating that the floor of the main pluton is at an elevation of 2,400–2,700 m. However, outcrops of hornblende plagioclase trachyte are

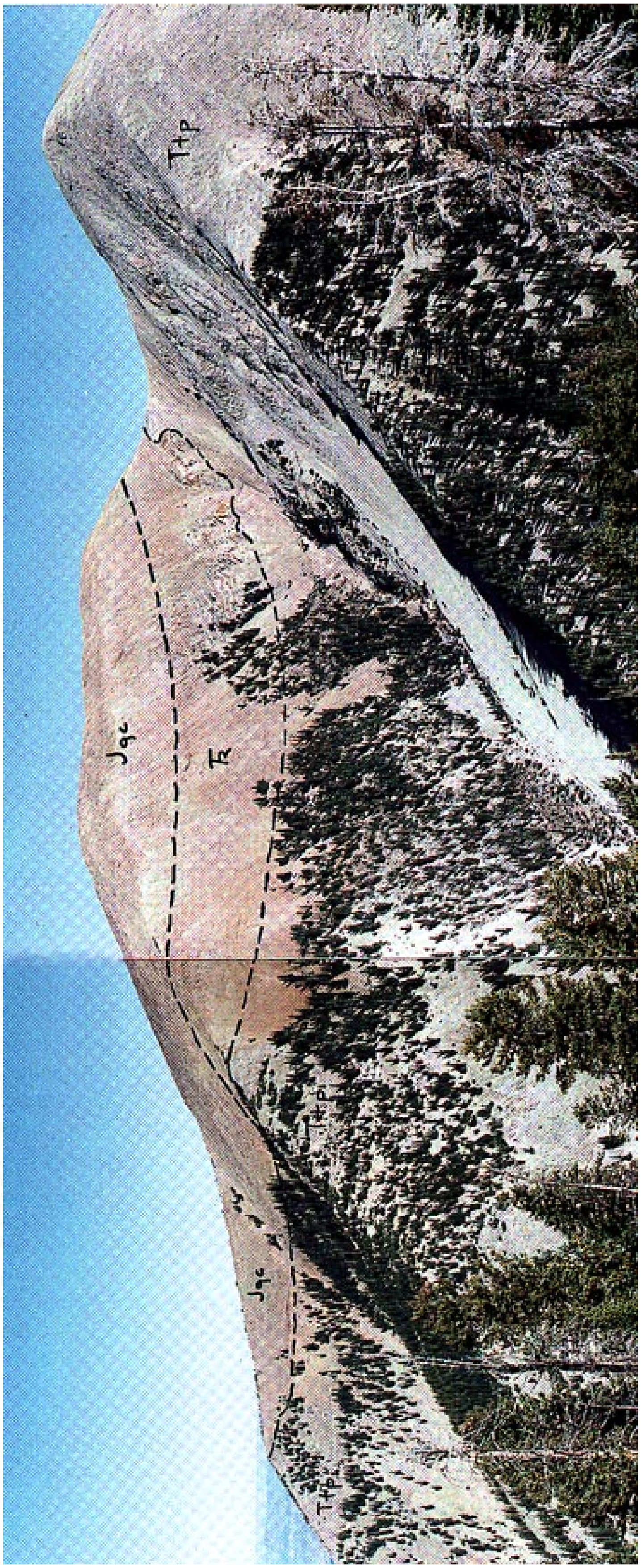


Figure 6. La Sal Peak (left) and Castle Mountain (right) in the northern La Sal Mountains, Utah. View is to the east from Horse Mountain. Castle Mountain and the flanks of La Sal Peak are composed of hornblende plagioclase trachyte (Ttp) and several dikes of nosean trachyte and peralkaline rhyolite (not labeled). La Sal Peak is capped by Mesozoic strata. Dashed lines mark approximate locations of contacts between the Triassic (₮) strata (Chinle and Moenkopi Formations), the Jurassic (J) strata (Glen Canyon Group), and the intrusive rocks.

present at elevations as low as 2,100 m at the base of Grand View Mountain. The outcrop thickness of hornblende plagioclase trachyte at Grand View Mountain is about 1,000 m. At the southeast end of main pluton the lowest hornblende plagioclase trachyte outcrops are at about 2,700 m, but colluvium and glacial deposits cover bedrock below this elevation.

The best inference for the elevation of the pluton's floor may be one that derives from the observation that the underlying salt diapir does not appear to have dissolved. If it had, it would have caused collapse of the extended parts of the pluton. In the adjacent Castle Valley, late Cenozoic dissolution of the upper part of the salt diapir has lowered the upper surface of the diapir to elevations between 1,200 and 1,900 m for most of the valley (based on drilling records from water wells and on well cuttings and geophysical logs from two petroleum wells: Gold Bar Resources, Castle Valley #1 and Grand River Oil & Gas, Sid Pace #1, sec. 16, T. 25 S., R. 23 E.). An elevation of 2,400–2,700 m for the floor of the main pluton would be significantly higher (>500 m) than the level of collapse and the upper surface of the salt diapir in adjacent Castle Valley. If the pluton's floor were that much higher, then the salt dissolution in Castle Valley would have undermined the northwestern part of the pluton, and the igneous rocks there should show collapse structures, such as faults, folds, and open-fracture zones, like those in adjacent sedimentary strata that were subject to salt-dissolution-induced collapse. In fact, collapse appears to wrap around the intrusion at Grand View Mountain (fig. 5). These data suggest that the base of the pluton is at an elevation below the current level of salt dissolution. Thus, I estimate that the floor of the hornblende plagioclase trachyte pluton in the northern mountains is at an elevation of about 1,800 m (fig. 5, section *B–B′*), which is slightly lower than the lowest igneous outcrops at Grand View Mountain and the upper surface of the diapir in the upper part of Castle Valley. Assuming the pluton's contact with the underlying salt diapir is generally subhorizontal and yet locally complex, then its minimum thickness is about 1,800 m at the center of the northern mountains. At Grand View Mountain the pluton is estimated to be 1,400 m thick.

If this interpretation of the main hornblende plagioclase trachyte pluton is correct, then in cross section the pluton may resemble a cluster of coalesced mushrooms (laccoliths) with thin vertical feeder stalks rooted through the salt diapir (fig. 5, sections). As the laccoliths grew, the intervening evaporite rocks were pushed aside until the intrusions coalesced and the margins of the individual laccoliths became indistinguishable. A concentrated network of stalks would be located at the center of the northern mountains, where additional intrusions were emplaced.

Hornblende plagioclase trachyte samples from the northern, middle, and southern La Sal Mountains have similar weight-percent concentrations of Na_2O, K_2O, total alkalies, CaO, and Rb. These data suggest that during emplacement into the salt diapir and coalescence of the intrusions, the magma assimilated little or no material from the evaporite rocks.

Several satellite hornblende plagioclase trachyte laccoliths and sills are present around the northern La Sal Mountains dome. The satellite intrusions may connect at depth to the feeder system of the main pluton or may have their own feeder systems. Field observations and geophysical data are inconclusive about their relations to the main pluton. Round Mountain consists of an intrusion of hornblende plagioclase trachyte in contact with the contorted cap rock of the salt diapir in Castle Valley (fig. 5). Several small roof pendants of cap rock are preserved on its top. The base of the intrusion is not exposed and the marginal contacts are nearly vertical. Chill-zone rock at its margin locally shows randomly oriented slickensides, suggesting that the intrusion is fault bounded. Hunt (1958) and Corry (1988) interpreted the faults as having formed during emplacement. I believe the faulting postdates emplacement and occurred during salt dissolution of the diapir and collapse of cap rock and country rock around the rooted Round Mountain intrusion (fig. 3).

Northeast of the northern mountains dome are two small, poorly exposed laccoliths(?) of hornblende plagioclase trachyte that are elongated to the northeast (fig. 5, section *A–A′*). A thin sill probably connects them. These laccoliths(?) were emplaced in gently dipping Cretaceous strata (fig. 5).

To the southwest, the Haystack Mountain laccolith was emplaced in Upper Jurassic and Cretaceous strata at the lower hinge of the monocline that marks the steep southwest flank of the northern mountains dome (fig. 5). At the base of the mountain along its south side are scattered outcrops of strata that dip steeply away from the laccolith (Carter and Gualtieri, 1958; Weir and Puffet, 1960), suggesting that the floor of the laccolith is not exposed. Two thin sills are also present in the Upper Cretaceous strata in this area.

The later trachytes, rhyolites, and breccia pipes in the northern La Sal Mountains either intrude or are in gradational(?) contact with the hornblende plagioclase trachyte (fig. 5). Quartz plagioclase trachyte forms a bulbous or sill-like mass in gradational(?) contact with hornblende plagioclase trachyte. Peralkaline trachyte and peralkaline rhyolite intrude hornblende plagioclase trachyte as plugs and dikes and lie at the center of a synmagmatic hydrothermal alteration system that also includes calcite-quartz breccia pipes (Ross, 1992). The breccias found in the intrusive pipes range from crackle breccia to matrix-supported breccia. The matrix is predominantly calcite and includes subordinate amounts of quartz, crushed rock, and opaque grains. Quartz veins, stockworks, and pods are locally present. Hematite pseudomorphs after various sulfides are common. At the northwest end of the northern mountains, other discrete areas of similar breccias are present near the margins of the main pluton and adjacent to the quartz plagioclase trachyte body. In these breccias clast types are variable: some contain only fragments of either Triassic rock and (or) Glen Canyon Group sandstone, some have only fragments of hornblende plagioclase trachyte or quartz plagioclase trachyte, and at least one contains a mixture of both sedimentary and igneous rock fragments. The breccia formed at the sedimentary-igneous contact because of either forceful emplacement of magma or the release of volatile-rich fluids. The hydrothermal alteration mineral assemblages that formed during emplacement of the later intrusions and breccia pipes range from mainly argillic to propylitic to locally phyllic.

Several late-stage peralkaline rhyolite and nosean trachyte dikes, trending generally northward (N. 15° W. to N. 10° E.), cut most of the intrusive phases (fig. 5). Previous studies (Price and Henry, 1984; Best, 1988) have used the orientation of dikes in slightly older host rocks to determine the paleostress orientations at the time of dike emplacement. Following the assumptions used in these studies, the orientation of the late-stage rhyolite and nosean trachyte dikes suggests an overall east-west direction of horizontal least principal stress during their emplacement. The overall north-south alignment of the La Sal Mountains intrusive centers also supports an east-west direction of horizontal least principal stress during their emplacement in the late Oligocene. Best (1988) suggested that a northerly least-principal-stress orientation for the Western United States rotated to an east-northeast direction during the latest Oligocene to early Miocene. Even though the La Sal Mountains data set is small and only qualitative, the observations are worth noting.

Determining the depth of emplacement for the intrusions in the northern mountains is problematic due to episodic growth on the Castle Valley–Paradox Valley salt diapirs. (See Shoemaker and others, 1958; Cater, 1970; Doelling and Ross, 1993.) Surface geologic mapping and subsurface petroleum well data indicate that only the Middle to Upper Pennsylvanian, Permian, and Triassic strata show significant variations in stratigraphic thickness in the area around the northern La Sal Mountains, Castle Valley, and Fisher Valley (Shoemaker and others, 1958; Goydas, 1990; Doelling and Ross, 1993; H.H. Doelling, unpublished data; M.L. Ross, unpublished data). Jurassic and Cretaceous strata in the same area have relatively uniform stratigraphic thickness, with some local variation. Construction of preliminary restored cross sections across the salt diapir at Castle Valley and the northern La Sal Mountains (prior to emplacement of the intrusions) suggests that Upper Pennsylvanian and Permian strata were not preserved across the crest of the diapir. A relatively thin section of Triassic strata rested on the cap rock. Supporting this hypothesis is the fact that Triassic rocks are the oldest strata continuously exposed along the margins of the northern mountains dome.

Taking into account the effects of salt diapir movement, the reconstructed stratigraphic section of Lower Triassic (base of the Moenkopi Formation) to Upper Cretaceous (top of the Mancos Shale) strata (compiled from Hintze, 1988; Doelling and Ross, 1993; M.L. Ross, unpublished data; and Willis, 1991) is approximately 1.9 km thick near the La Sal Mountains. When the northern La Sal Mountains intrusions were emplaced, this section was probably overlain by a sequence comprising the Upper Cretaceous Mesaverde Group through the Eocene Green River Formation. This sequence would have added about 0.76 km to the section, based on its present thickness in the Book Cliffs, about 70 km north of the area (compiled from Willis, 1991; Willis, unpublished data; and Franczyk and others, 1992), and on thickness modifications suggested by G.C. Willis (oral commun., February 1993). According to these estimates, approximately 2.7 km of sedimentary rocks covered the crest of the salt diapir at the time the main intrusions and the Round Mountain intrusion were emplaced. The other satellite intrusions have an estimated depth of emplacement of about 1.9 km. These estimates assume a minimal amount of erosion from post-Green River Formation time to the late Oligocene.

SOUTHERN LA SAL MOUNTAINS INTRUSIVE CENTER

The southern La Sal Mountains intrusive center is structurally similar to that of the northern mountains in that it was emplaced into a salt-cored anticline (fig. 2). However, the intrusive dome is smaller (8.0 x 4.4 km), and hornblende plagioclase trachyte is the only igneous rock exposed.

Salt-dissolution-induced collapse of the Moab–Spanish Valley salt-cored anticline formed the northwest-trending Pack Creek syncline and many high-angle normal faults that terminate near the margin of the pluton. Wells drilled in the Pine Ridge salt-cored anticline southeast of the southern intrusive center (fig. 2) indicate that strata as young as the Chinle Formation locally rest on Paradox Formation cap rock (Hite and Lohman, 1973). The southwest margin of the dome is a steep (40°–85°) southwest-dipping monocline in Permian to Lower Cretaceous strata. The hornblende plagioclase trachyte pluton is in apparent discordant contact with the Lower Permian Cutler Formation along this side. (See Weir and Puffet, 1960, and Weir and others, 1960, for details.) Carter and Gualtieri (1958) and Hunt (1958) interpreted the intrusion to be in concordant contact with the Cutler along part of its northeast flank, forming a 45˚–60˚ northeast-dipping monocline. Along the northeast flank the sedimentary rocks have been breached by several small sill-like intrusions that cut discordantly across the Upper Jurassic and Cretaceous strata (Hunt, 1958; Weir and Puffet, 1960). I estimate that the structural relief on the base of the Lower Jurassic Glen Canyon Group across the short axis of the southern mountains dome is 1,500–1,700 m. Taking into consideration the effects of salt diapir growth on the post-Paradox strata, the estimated depth of emplacement for the southern La Sal Mountains intrusions is between 2.60 and 2.74 km.

MIDDLE LA SAL MOUNTAINS INTRUSIVE CENTER

The middle La Sal Mountains consist of three prominent mountains: Mount Mellenthin, Mount Peale, and Mount Tukuhnikivatz, each underlain by hornblende plagioclase trachyte intrusions (fig. 2). Smaller satellite intrusions of hornblende plagioclase trachyte are adjacent to the three larger ones. Mount Mellenthin is capped by a laccolith emplaced in the Mancos Shale. The floor of the laccolith is about 60 m above the underlying Burro Canyon Formation and the Dakota Sandstone. Several irregular feeder dikes to the laccolith, striking N. 20°–25° E., are exposed in a glacial valley on the southwest side of the mountain (Gould, 1926; Hunt, 1958; Corry, 1988). Northeast of the mountain a smaller discordant intrusion was emplaced in the Upper Jurassic Morrison Formation (Carter and Gualtieri, 1958; Hunt, 1958).

Mount Peale consists of a large laccolith, which has faulted marginal contacts that are discordant with the country rock (Carter and Gualtieri, 1958). The level of emplacement for the Mount Peale laccolith is uncertain. Hunt (1958) showed the laccolith as being emplaced into the Morrison Formation; however, Carter and Gualtieri (1958) mapped the floor of the laccolith as being at the Kayenta Formation–Navajo Sandstone contact. They also mapped the Navajo Sandstone, Entrada Sandstone, and Morrison Formation in a large roof pendant.

The intrusions at Mount Tukuhnikivatz appear to have a complex morphology. The main intrusion, which forms the highest peak, cuts discordantly across Jurassic strata along its margins, and its floor is not exposed (Hunt, 1958; Weir and Puffet, 1960). Because of the lack of information on the base of this intrusion, its form has been interpreted as a plug (Gould, 1926), a bysmalith (Hunt, 1958), or a “punched laccolith” (Corry, 1988). On the northwest flank of the mountain are two intrusions previously described as laccoliths. Hunt (1958) and Weir and Puffet (1960) show the intrusions as having floors (basal contacts) that cut discordantly across northwest-dipping strata and extending laterally from the main Mount Tukuhnikivatz intrusion. (See cross section *B–B′* in Weir and Puffet, 1960.) As mentioned previously, recent work by Jackson and Pollard (1988a) in the Henry Mountains and by Corry (1988) indicate that the intrusive relations illustrated and discussed by Hunt (1958) and Weir and Puffet (1960) for the Mount Tukuhnikivatz intrusion(s) are unlikely and difficult to reconcile with current mechanical models. The level of emplacement of the Mount Tukuhnikivatz intrusion(s) is also uncertain. Hunt (1958) showed the intrusion(s) as being emplaced into the Morrison Formation. Weir and Puffet (1960) showed the intrusion(s) as being emplaced a different horizons within Jurassic strata.

An intrusion of nosean trachyte in the Morrison Formation is located in the northwest part of the middle mountains. The contact between the intrusion and the Morrison Formation is poorly exposed. The intrusion appears to be sill-like with a northwest dip subparallel to the dip of the Morrison Formation exposures nearby.

Exxon Corporation drilled the Gold Basin Unit #1 well (sec. 15, T. 27 S., R. 24 E.) near the center of the middle mountains (fig. 7). Geophysical and drilling logs indicate multiple levels of intrusions in the subsurface down to about 1,100 m below sea level. The lowest intrusions appear to be near the base of the Paradox Formation. The maximum thickness of an individual igneous rock horizon in the well was about 300 m. The intrusions in the middle mountains appear to have been emplaced at multiple stratigraphic horizons from the Paradox Formation to the Mancos Shale, resulting in a Christmas tree-like appearance in cross section. Using the data from the Exxon well and the structural relationships of Weir and Puffet (1960) the estimated overall range for depth of emplacement of the intrusion of the middle La Sal Mountains is 1.9–6.0 km.

STRUCTURAL CONTROL FOR THE LA SAL MOUNTAINS INTRUSIVE CENTERS

The northern and southern La Sal Mountains intrusive centers were emplaced into preexisting salt-cored anticlines. The salt-cored anticlines influenced the form of the main hornblende plagioclase trachyte plutons. Northwest-trending faults that offset the Paradox Formation and older rocks controlled the localization, linear form, and northwest-trending parallel belts of the salt diapirs that core the folds of the northern Paradox Basin. Northwest-trending high-angle faults, which displace Pennsylvanian and older rocks, have been identified in the subsurface beneath several of the salt-cored anticlines (Shoemaker and others, 1958; Case and others, 1963; Cater, 1970; Parker, 1981; Woodward-Clyde Consultants, 1983). Baars (1966) interpreted west-northwest-trending fault blocks of Proterozoic and Paleozoic rocks in the San Juan Mountains as southeastward continuations of the northwest-trending subsurface faults of the Paradox Basin. The west-northwest-trending basement faults in the San Juan Mountains show evidence for episodic movement from the Late Proterozoic to the Late Permian. The subsurface faults of the northern Paradox Basin are believed to have a similar history of repeated movements (Baars, 1966; Stevenson and Baars, 1987). Many northwest-striking and several east-west-striking faults cutting Proterozoic and Phanerozoic rocks have been mapped in the Uncompahgre Plateau and the eastern Paradox Basin region (Tweto, 1987; Case, 1991). The predominance of northwest-striking faults indicates a pervasive northwest-trending structural fabric for the region.

Geophysical data (Joesting and Byerly, 1958; Joesting and Case, 1960) and well data (Case and others, 1963)

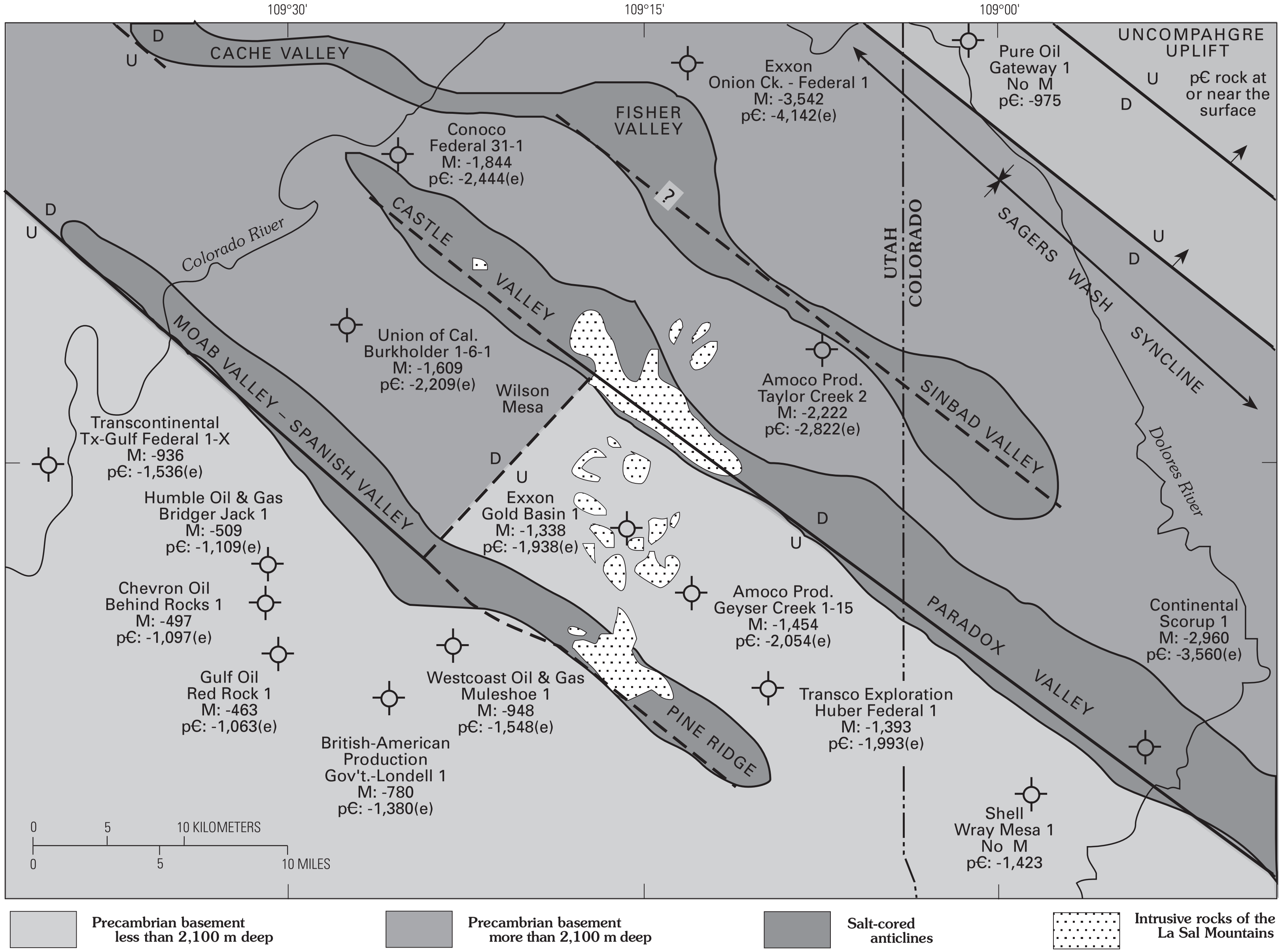


Figure 7. Structural and magmatic features in the La Sal Mountains region and the approximate locations of interpreted subsurface faults. Dashed lines are inferred faults. Subsurface faults on the southwest flank of the Uncompahgre Uplift are high-angle reverse faults. The locations of selected petroleum wells that penetrate pre-Paradox Formation rocks are shown. Subsurface elevations are given, in meters, for tops of the Mississippian (M) and Precambrian (p€) rocks. For wells not reaching the Precambrian, an estimated (e) thickness of 600 m (Hintze, 1988) was used for the Precambrian to Mississippian stratigraphic interval. Modified from Case and others (1963).

indicate that one of the Paradox Basin subsurface faults is along the southwest flank of the Paradox Valley salt-cored anticline (fig. 7). Steep northeastward gradients in both gravity and magnetic data (Paradox Valley regional gradient of Case and others, 1963) coincide with a vertical offset of about 1,800–2,100 m in the Proterozoic and Paleozoic rocks (Elston and others, 1962; Case and others, 1963). The zone of steep geophysical gradients extends northwestward to a point just beyond the northern La Sal Mountains. Figure 7 shows the estimated location and trend of the subsurface fault. The fault may continue northwestward along the southwest flank of Castle Valley, where the estimated vertical offset decreases to about 300 m (Doelling and Ross, 1993). Case and Joesting (1972) suggested that basement faults having as much as 300 m of displacement could exist in the salt-cored anticline region without causing an obvious gravity or magnetic anomaly.

Another pair of coincident northwest-trending gravity and magnetic gradients occurs subparallel to the southwest flank of the Moab–Spanish Valley salt-cored anticline (fig. 7) (Case and Joesting, 1972). Termed the Spanish Valley regional gradient, it trends west-northwest from Spanish Valley to the area between the Colorado and Green Rivers. Elevations of the tops of the Mississippian strata in the widely separated petroleum wells around Spanish Valley indicate an elevation difference of at least 1,100 m on pre-Paradox Formation rocks across the steep geophysical gradients, which most likely results from a subsurface fault or faults along the flank of the salt-cored anticline. However, the distance between wells is about 11.3 km, and a north-northeast dip of 6° on pre-Paradox Formation rocks could produce the same amount of elevation difference. If a fault does exist, geophysical data and well information suggest that displacement on the fault decreases gradually to the southeast of Spanish Valley.

At the southeast end of Spanish Valley the geophysical gradients change direction and trend northeast for 16–24 km along the west-northwest flank of the La Sal Mountains, transverse to the northwesterly regional gravity and magnetic trends. This segment of steep northeast-trending gradients (termed the Wilson Mesa gradient of Case and others, 1963) connects the Spanish Valley and Paradox Valley regional gradients. Both gravity and magnetic values decrease to the northwest along the Wilson Mesa gradient, and information from wells drilled since the geophysical study indicate a possible offset, down to the northwest, of about 300 m in the pre-Paradox Formation rocks across the Wilson Mesa gradient (fig. 7). The presence of the geophysical gradients and the apparent offset in pre-Paradox rocks suggest a buried fault, but the data are inconclusive. The distance between wells is large enough (22.5 km) that a northwest dip of about 2° in pre-Paradox Formation strata could also produce the same amount of elevation difference.

Case and others (1963) interpreted the Wilson Mesa gradient to be a major structural and lithologic discontinuity in the Proterozoic basement rocks. Other workers (Hite and Lohman, 1973; Hite, 1975) interpreted the coincidence of the Wilson Mesa gradient and the apparent left-lateral offset of both the Moab–Spanish Valley–Pine Ridge salt-cored anticline system and the Fisher Valley–Sinbad Valley salt-cored anticline system (fig. 2) as indications of a northeast-striking basement fault with left-lateral displacement. However, the Castle Valley–Paradox Valley salt-cored anticline system crosses the inferred basement fault with no offset, suggesting that the alignment of features is coincidental. Permian and younger strata in the area do not show any evidence for lateral offset. No large northeast-striking faults have been mapped in the Proterozoic basement or younger rocks on the Uncompahgre Plateau (Heyman, 1983; Heyman and others, 1986; Tweto, 1987; Case, 1991).

In summary, the coincidence of the geophysical gradients with displacement of the Paradox Formation and older rocks strongly supports the existence of a subsurface fault beneath Paradox Valley that extends to the northern La Sal Mountains (fig. 7). In the Moab–Spanish Valley area, the coincidence of steep geophysical gradients, a salt-cored anticline, and a large elevation difference for pre-Paradox rocks also suggests that a subsurface fault exists. Evidence for the existence of a subsurface fault coincident with the Wilson Mesa gradient is less conclusive. However, a fault or flexure in the pre-Paradox rocks along the Wilson Mesa geophysical gradient cannot be ruled out. Case and others (1963) suggested that (1) the subsurface faults are high-angle; (2) they separate a southern region of shallower, uniformly magnetized Proterozoic basement from a downthrown northern region of deeper, more heterogeneous Proterozoic basement; and (3) the geophysical gradients are manifestations of these faults. The sparse well data do support the correlation with geophysical gradients and the separation of a southern region of shallower Proterozoic basement from a northern region of deeper basement (fig. 7).

The locations of the La Sal Mountains intrusive centers along the trend of subsurface faults and possibly at the intersections of these faults suggest that the faults were avenues of weakness for the ascent of magma in the upper crust. This is especially true for the northern and southern centers.

SURFACE FAULTS IN THE LA SAL MOUNTAINS REGION

Most of the exposed faults around the La Sal Mountains strike northwesterly and formed by salt-dissolution-induced collapse after emplacement of the intrusions (fig. 2). The collapse-related faults are closely spaced, discontinuous to splaying, and generally short, and they form swarms or networks on or near the salt-cored anticlines. The fault networks form narrow, fault-block slivers that trend parallel to the length of the collapse valley. Most fault blocks are successively downdropped toward the valley. At several locations, seismic data show that the faults die out in the salt diapirs and do not displace pre-Paradox Formation strata. Previous studies (Colman, 1983; Harden and others, 1985; Oviatt, 1988; Goydas, 1990) and recent field mapping and geochronology (Doelling and Ross, 1993; Ross, unpublished data) suggest that salt-dissolution-induced collapse and faulting are Pliocene to Quaternary age for the Castle Valley, Moab–Spanish Valley, Fisher Valley, and Cache Valley salt-cored anticlines (fig. 2) and also for the Salt Valley salt-cored anticline (just northwest of area of fig. 2). Most collapse-related faults, like those at Moab and Spanish Valley, strike northwesterly. However, some collapse-related faults strike northeasterly, such as the Cottonwood graben at Fisher Valley (fig. 2). The amount of displacement on the graben boundary faults increases toward the Fisher Valley collapsed salt diapir, indicating that collapse of the diapir produced the graben (Goydas, 1990).

Some faults in the La Sal Mountains region are not related to salt tectonic movements. The Ryan Park fault zone, along the southwest flank of the Uncompahgre Plateau (northeast corner of the area of fig. 2), is part of a network of faults that formed during the Laramide orogeny and the late Cenozoic uplift of the Uncompahgre Plateau (Shoemaker, 1956; Cater, 1970; Heyman, 1983). The location and orientation of the Ryan Park fault zone was controlled by the late Paleozoic Uncompahgre fault(s), which formed during uplift of the ancestral Uncompahgre Uplift (Heyman and others, 1986).

Two northwest-striking normal faults near the La Sal Mountains, which are at the surface, offset strata across the crests of two salt-cored anticlines and are the result of regional extension and not late Cenozoic salt-dissolution-induced collapse. The Moab fault (western edge of the area of fig. 2) and the Lisbon Valley Fault (southern edge of the area of fig. 2) are both long (32–39 km) and have large displacements (800–1,800 m) (Parker, 1981; Doelling, 1988). Both have been interpreted as high-angle northeast-dipping listric faults that die out in the underlying salt diapirs. This interpretation was based on surface and well data for the Lisbon Valley fault (Parker, 1991) and on surface and seismic data for the Moab fault (D.M. Rawlins, Exxon Corp., oral commun., 1993). Both faults approximately overlie subsurface faults in pre-Paradox Formation rocks but are separated from them by the salt diapirs. In addition, both faults offset Upper Cretaceous and older strata, suggesting they are Tertiary age. McKnight (1940) interpreted the Moab fault to be a tectonic fault that formed in response to post-Laramide Tertiary extension. The Moab and Lisbon Valley faults may have formed in response to movement on the subsurface faults and salt diapirs during late Tertiary epeirogenic uplift of the Colorado Plateau. However, Hite and Lohman (1973) and Woodward-Clyde Consultants (1983) interpreted the Moab and Lisbon Valley faults as salt-dissolution-induced collapse structures because they believed the faults did not extend below the salt diapirs (now known to be the case).

In summary, most of the numerous surface faults around the La Sal Mountains intrusions postdate emplacement of the intrusions and represent shallow structural deformation resulting from salt dissolution or salt flowage of the diapirs.

CONCLUSIONS

No field evidence supports the hypothesis of Hunt (1958) that the individual La Sal Mountains intrusive centers consist of discrete central stocks surrounded by outward radiating laccoliths. Evidence once believed to define the central stock in the northern mountains is now interpreted to be the result of later emplacement of trachyte and rhyolite porphyry intrusions and breccia pipes. The main plutons in both the northern and southern La Sal Mountains probably consist of coalescent laccoliths of hornblende plagioclase trachyte. Intrusions in the middle La Sal Mountains were emplaced between salt-cored anticlines; surface structures and subsurface data suggest these laccoliths and sills are vertically stacked at various stratigraphic horizons from the Paradox Formation to the Mancos Shale.

Intrusions of the La Sal Mountains were probably emplaced at depths ranging between 1.9 and 6.0 km. These depths of emplacement are consistent with emplacement depths for the Henry and Abajo Mountains laccoliths (Witkind, 1964; Jackson and Pollard, 1988a).

The elliptical shape of the northern and southern La Sal Mountains intrusive centers and their positioning along two salt-cored anticline systems indicates that magma emplacement was controlled, in part, by the preexisting salt diapir and anticline. Geophysical data (Case and others, 1963) suggest that the extremities of the main pluton in the northern mountains overlie a thickened mass of salt. Field mapping in the northern mountains supports the geophysical data, indicating that thickened salt is present around the Grand View Mountain intrusion. The intersections between a possible concealed northeast-striking fault and the northwest-striking faults that underlie and controlled the salt-cored anticlines of the Castle Valley–Paradox Valley system and the Moab Valley–Spanish Valley–Pine Ridge system appear to have been magma conduits for the La Sal Mountains intrusions. The northeast-striking fault (or fold ramp) may be a connecting structure between the two northwest-striking en echelon faults. The La Sal Mountains intrusive centers are located along the structural boundary between deepest part of the Paradox Basin and slightly shallower area to the south.

Most surface faults in the area around the La Sal Mountains postdate magma emplacement and formed during late Tertiary to Quaternary salt-dissolution-induced collapse of the crests of the salt-cored anticlines.

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Next section