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Abstract

Twelve distinct laccoliths can be identified in the Ortiz porphyry belt. The laccoliths are composed of plagioclase-orthoclase-hornblende-quartz porphyry, which can be classified as quartz andesite by its modal assemblage. Laccoliths from 33.2 to 36.2 Ma and related sills in the Ortiz porphyry belt, which intrude the entire range of the approximately 3-km-thick (1.9-mi-thick) Phanerozoic stratigraphic section, predate mid-Tertiary movement on the Tijeras–Cañoncito fault system and 27.9–31.4 Ma stocks, dikes, and base- and precious-metal mineralization.

The range of depth of formation of concordant intrusions in the Ortiz porphyry belt is about three times that commonly observed in other laccolith groups. Two hypotheses are proposed to explain this feature: (1) Pre 34-Ma movement on the Tijeras–Cañoncito fault system placed laccolith-hosting Pennsylvanian and Permian strata on the southeast side of the fault system to the same elevation as Mesozoic strata on the northwest side, allowing the laccoliths and sills to intrude in a narrower depth range; and (2) Growing volcanic edifices, contemporaneous with the intrusion of laccoliths and sills, caused the range of neutral buoyancy, in which concordant intrusive bodies would form, to rise over time. Both of these models may have worked together.

The transition from Laramide east-west-directed compressional regional stress field (with vertical least compressive stress) to the Rio Grande rift-related extensional stress field (horizontal least compressive stress) is constrained by the ages of the older laccoliths and the younger stocks, and by their field relations. Igneous rocks of the Ortiz porphyry belt straddle the transition. Laccoliths intruded near the waning of the Laramide stress regime during the interval from 33.2 to 36.2 Ma and may have occupied Laramide structures such as folds and arches. Post-laccolith movement on the Tijeras–Cañoncito fault system and subsequent intrusion of 27.9–31.4 Ma discordant stocks and dikes indicate a change in regional stress fields, constraining the timing of the transition to the period from 31.4 to 33.2 Ma.

Introduction

This report describes the stratigraphic and structural settings, and field relationships of laccoliths of the Ortiz porphyry belt. Theoretical concepts of laccolith formation are reviewed, with attention paid to the development of the concept in the Ortiz porphyry belt. Models to account for the anomalously large range of depths of laccolith emplacement in the Ortiz porphyry belt are advanced and discussed. Finally, the transition from the early laccolithic (concordant) style of intrusion to the later stock (discordant) style of intrusion in the area is discussed in the context of the transition from Laramide to Rio Grande rift tectonics.

Location and geologic setting

The mountain group consisting of South Mountain, the San Pedro Mountains, the Ortiz Mountains, and the Cerrillos Hills in Santa Fe County, New Mexico, composed of mid-Tertiary intrusive rocks and their hosts, comprise the Ortiz porphyry belt. Rocks associated with the Ortiz porphyry belt are also exposed in the La Ciénega area (Fig. 1). Roadcut exposures of laccolithic rocks can be viewed along NM–14, at points 5.0 mi (8 km) and 7.4 mi (12 km) north of Golden; and at Devil's Throne, 0.8 mi (1.3 km) west of Cerrillos on County Road 55. The Cerrillos Hills laccolith is well exposed on hiking trails in the Cerrillos Hills Park in the southwestern part of the Cerrillos Hills. All other outcrops are on private land. Land owner permission is required to visit them.

The roughly north-south trending Ortiz porphyry belt occupies the structural high between the Hagan and Santo Domingo Basins and the Sandia uplift on the west, and the southern part of the Española Basin and the Estancia Basin on the east. The porphyry belt is cut by strands of the Tijeras–Cañoncito fault system in its South Mountain and San Pedro and Ortiz Mountains portions.

Definition

A laccolith has been defined as "A concordant igneous intrusion with a convex-up roof and known or assumed flat floor" (*Glossary of Geology*, 4th edition, 1997, J. A. Jackson, ed.). Laccoliths were first described by Gilbert (1877) in his studies of the Henry Mountains of Utah as being formed by magma that "insinuated itself between two strata, and opened for itself a chamber by lifting all the superior beds" (Fig. 2A). Since Gilbert's work, laccoliths have come to be viewed as having the following characteristics listed by Corry (1988; after Daly 1933):

a) Laccoliths are formed by forcible intrusion of magma and initially are entirely enclosed by the invaded formations except along the relatively narrow feeding channel. b) Like sills, laccolith contacts commonly follow a bedding plane, though many instances are known where the intrusion cuts across bedding. The plane of the intrusion remains sensibly parallel to the Earth's surface at the time of the intrusion, although the floor of large intrusions may sag as the intrusion grows. c) In cross section, the ideal laccolith of Gilbert (Fig. 2A) has the shape of a plano-convex, or doubly convex, lens flattened in the plane of the bedding of the invaded formation. The lens may be symmetrical or asymmetrical in profile; circular, elliptical, or irregular in plan view. d) There is a complete gradation between sills and laccoliths, with no clearly defined point at which a sill becomes a laccolith. e) A laccolith lifts its roof as a result of the forcible injection of magma. Hunt and Mabey (1966) point out that the presence of concordant roof pendants, which are borne upward from shallow depths, implies a floored, laccolithic intrusion.

Corry restricts the use of the term laccolith to bodies greater than 30 m (98 ft) thick (Corry 1988, appendix A). Corry's thickness criteria are used in this study.

Laccolith models

Cross-sectional diagrams of various laccolithic models are presented in Figure 2. Gilbert's (1877) original laccolithic model (Fig. 2A) was modified by Jackson and Pollard (1988a) and placed into a stratigraphic context (Fig. 2B). The Christmas Tree laccolith, a series of multiple concordant intrusions connected by narrow feeder dikes (Fig. 2C), and the punched laccolith (Fig. 2D) may be considered to be end-member cases of laccolithic forms (Corry 1988).

Feeders for laccoliths have been considered by most investigators to be dikes or narrow pipelike conduits situated centrally underneath the laccolithic mass (e.g., Gilbert 1877; Jackson and Pollard 1988a). Laboratory models of laccolithic formation generally start with the centrally located dike or conduit as well (e.g., Kerr and Pollard 1998; Roman-Berdiel et al. 1995; and Dixon and Simpson 1987).

Hyndman and Alt (1987) documented laccolith feeder dikes that are tangential with respect to laccoliths in the Adel Mountains of central Montana. The feeder dikes are members of radial swarms that apparently were controlled by an overlying central volcano (Hyndman and Alt, 1987, fig. 3).

Feeders as central stocks with laccoliths growing laterally as tongue-shaped masses have been posited in the Henry Mountains (Hunt 1953, 1988). Jackson and Pollard (1988a,b) disputed Hunt's interpretation, citing structural relations of the overlying sedimentary rocks, and concluded that the source of the laccoliths was

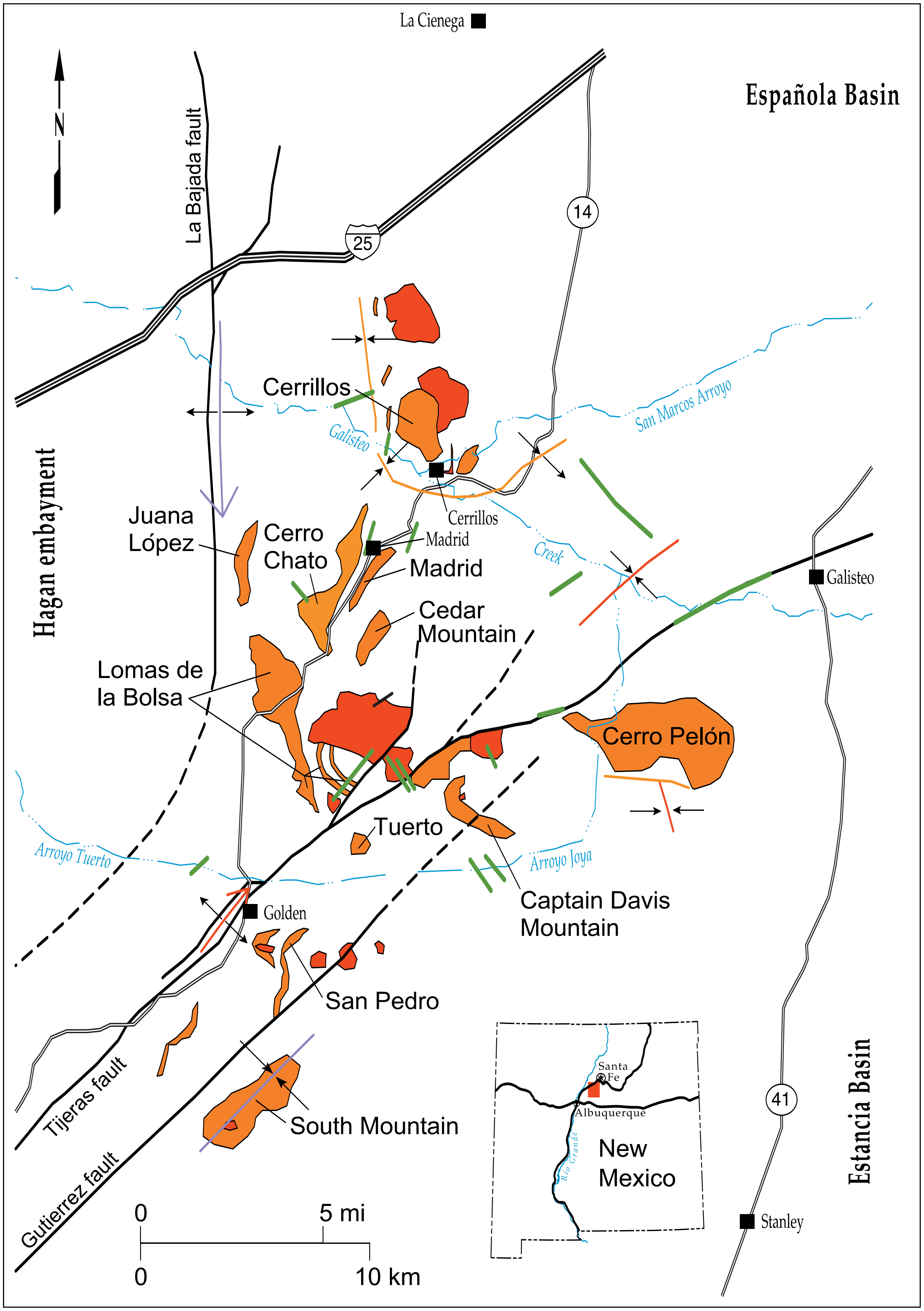


FIGURE 1—Simplified geologic map of the Ortiz porphyry belt, showing laccoliths in orange, later intrusive rocks in red, and late dikes in green. Fold axial traces: orange = laccolith related (mid-Tertiary), magenta = Laramide, and lavender = Rio Grande rift related. Faults are black.

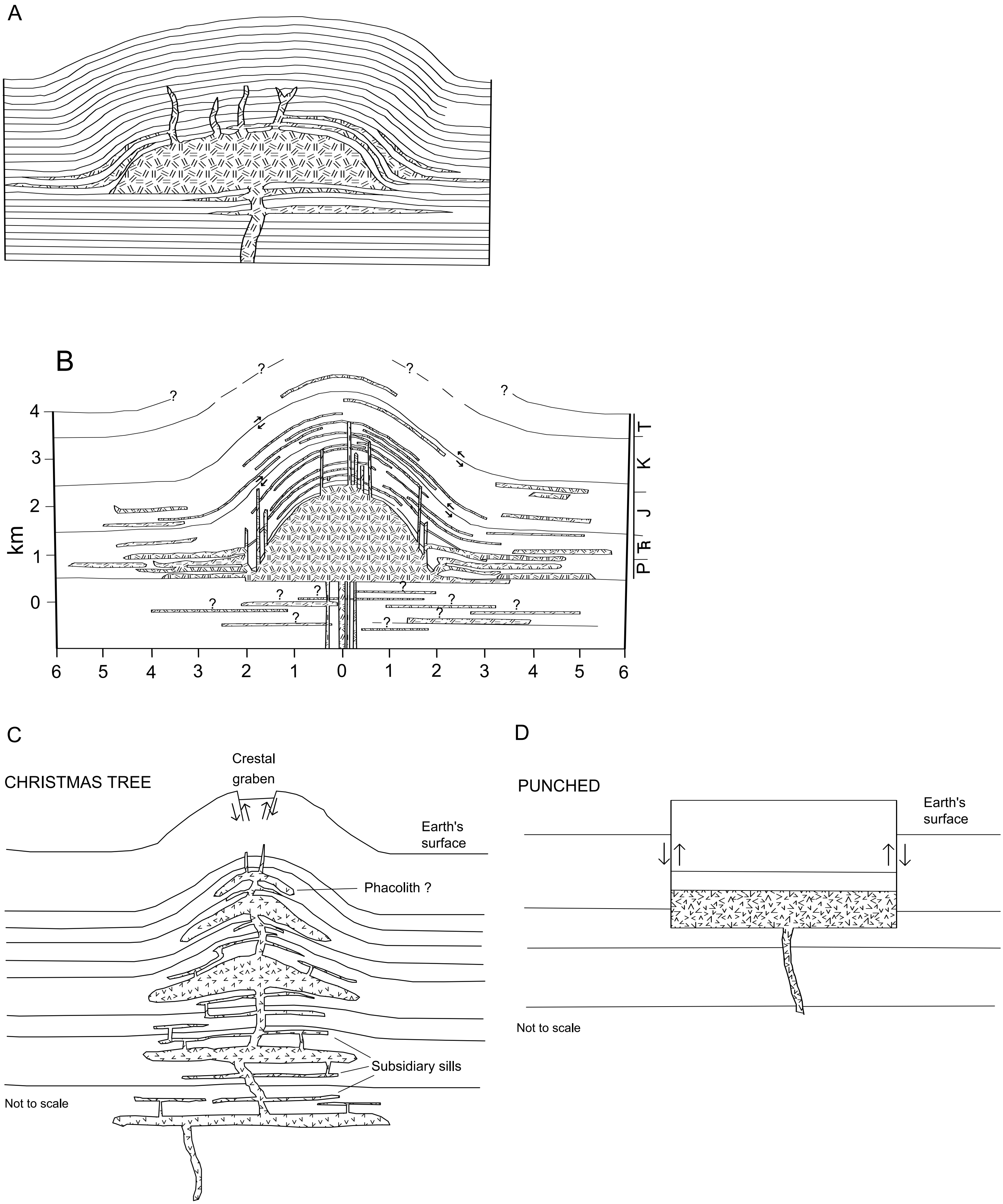


FIGURE 2—Laccolith models. **A**) Gilbert's schematic cross section of a laccolith (Gilbert 1877); **B**) model of Henry Mountain laccolithic structure (Jackson and Pollard 1988a); note depths of emplacement and flexural slip of overlying beds; **C**) "Christmas Tree" laccolith model (Corry 1988); **D**) Punched laccolith (Corry 1988).

probably narrow dikes centrally located under the laccolithic masses.

Stress field

In an isotropic medium, tabular intrusions form perpendicular to the axis of least stress sigma 3. Therefore laccoliths must form in a stress environment characterized by a vertical sigma 3; vertical dikes form in a regime of horizontal sigma 3. Magma may propagate along a plane that is perpendicular to the axis of least stress, sigma 3. Horizontal intrusions are therefore unexpected in areas undergoing extension, and dikes would tend to be the rule.

Vertical range of intrusion

The vertical range in which magma may spread horizontally is a function of the variation in density of the country rock with depth. Corry's model (Corry 1988, fig. 25, p. 25) indicates that magma with a density of 2,500 ± kg/m^3 may be neutrally buoyant over a vertical range of approximately 1 km (0.6 mi). This is roughly compatible with field observations of emplacement levels of many laccolith groups (Corry 1988; Mudge 1968). In a survey of laccoliths, mainly in the western United States, Mudge (1968) noted that concordant igneous masses occurred in sedimentary rocks under 900–2,300 m (~0.5–1.4 mi) of cover. Jackson and Pollard (1988) quantified depths of 1–2.5 km (0.6–1.5 mi) for emplacement of Henry Mountains laccoliths (Fig. 2B).

Host rocks

It appears that the existence of anisotropies, particularly horizontal parting surfaces such as bedding planes or unconformities, of the host rocks, rather than their ductility is the more important factor for emplacement of horizontal intrusions (Corry 1988; Mudge 1968). Field studies and modeling further indicate that the presence of a soft layer in the laccolith's roof is also a significant factor (Mudge 1968; Roman-Berdiel et al. 1995). The susceptibility of parting surfaces to intrusion may be enhanced by horizontal compression, producing arched beds that lift the overlying strata, as suggested by Keyes (1918) in the Ortiz porphyry belt.

Stages of laccolithic growth

Corry (1988) divides the process of emplacement and growth of laccoliths into four stages: (1) movement of magma vertically through the lithosphere, (2) reorientation of magma from vertical climb to horizontal spreading, (3) cessation of horizontal spreading and commencement of thickening, and (4) large-scale deformation of the overburden by thickening of the intrusion. Magma rises in cracks until the weight of the magma above the neutrally buoyant elevation balances the magma driving pressure. Some mechanism must allow magma to spread horizontally, forming "protolaccoliths" or sills.

Dixon and Simpson (1987) present a four-stage model of laccolith formation, based on observations of centrifuge modeling using silicone putty: (1) The *sill* stage is represented by the spread of putty from a vertical conduit to form a concordant intrusion of low aspect ratio (amplitude/diameter). The putty continues to spread until its surface area is large enough so that upward force exerted by the putty can lift the overburden. (2) The *bending laccolith* stage begins at the initiation of uplift and the increase of aspect ratio, forming a sinusoidal profile. (3) The *cupola* stage is initiated with a change from the sinusoidal profile to a dome shape with a sharp kink in the overlying layers above the edge of the intrusion. As the diameter and amplitude increase with the injection of more material, the hinge line of the kink migrates outward radially. (4) The last, *kink laccolith*, stage begins with the formation of a second kink at the top of the flanks of the intrusion. During the last stage the top of the laccolith flattens.

Laccolith concept in the Ortiz porphyry belt

Laccoliths were first described in the Ortiz porphyry belt at the beginning of the twentieth century (Johnson 1903; Ogilvie 1905, 1908; Lindgren and Graton 1906; Keyes 1909, 1918, 1922). The early workers did not distinguish between different types of intrusive rocks. Ogilvie (1905, 1908) considered that the laccoliths formed after regional tilting. Keyes (1909, 1918, 1922) noted that the laccoliths in the Ortiz porphyry belt occurred in discrete parts of the sedimentary section and at regular intervals in a north-south direction. Early investigators (Lindgren and Graton 1906; Keyes 1909; Ogilvie 1905) thought the entire igneous masses of the Cerrillos Hills, Ortiz Mountains, and San Pedro Mountains to be laccoliths of monzonite porphyry (Fig. 3).

Using the Ortiz Mountains as an example, Keyes (1918) postulated that laccoliths form in a tectonic setting characterized by profound faulting and orographic flexing. Certain arched rigid beds would carry the load of overlying beds, thereby allowing the invasion of magma.

In the middle part of the twentieth century, investigators divided the igneous rocks in the porphyry belt and recognized that the laccolithic rocks are older (Stearns 1953a; Disbrow and Stoll 1957; Peterson 1958; McRae 1958; Atkinson 1961; Thompson 1964; Fig. 4). Griswold (1950) alluded to different igneous rock types in the Ortiz Mountains and emphasized the sill-like nature of much of the intrusive rock. Peterson (1958) and McRae (1958) described laccolithic intrusions in the Ortiz Mountains.

Recent quadrangle-scale and more detailed geologic mapping allows for more detailed descriptions of individual laccoliths and recognition of the traits common to all parts of the Ortiz porphyry belt (Ferguson et al. 1999; Maynard 2000; Maynard et al. 2001; Lisenbee and Maynard 2001; Maynard et al. 2002).

Ortiz porphyry belt laccoliths

The distribution of the 12 distinct laccoliths in the Ortiz porphyry belt is shown in Figure 1. In the Cerrillos Hills, the Ortiz Mountains, the San Pedro Mountains, and South Mountain, younger stocks, plugs, and dikes intrude the laccoliths and complicate their original configurations. The laccoliths are listed in Table 1. Following the definition proposed by Corry (1988) the term laccolith is reserved for floored or concordant intrusive bodies greater than 30 m (98 ft) thick. Many thinner sills of andesite porphyry, generally presumed to be apophyses of larger laccoliths, have been mapped.

Geologic mapping for this study and comparison to studies in adjacent areas (Table 1 and Fig. 1) show that andesite porphyry forms 12 laccoliths or laccolithic centers in the Ortiz porphyry belt. The South Mountain, San Pedro, Captain Davis Mountain–Lone Mountain, Lomas de la Bolsa, and Cerrillos Hills laccoliths were intruded by later stocks and dikes. The entire Ortiz porphyry belt was tilted in a monoclinal fashion to the east (though markedly less in the case of the Cerro Pelón laccolith). In the Ortiz porphyry belt, tilting, subsequent intrusions, and local faulting have complicated or obscured the characteristic rounded dome appearance associated with laccoliths (Corry 1988). It is questionable whether all the bodies described in this report began with domal forms.

The most extensive laccoliths in the Ortiz porphyry belt intrude the most ductile parts of the sedimentary section, such as mudstones of the Chinle Group and the Mancos Shale. Laccoliths also intrude more rigid formations, however, such as limestone of the Madera Formation and sandstone of the Dakota Formation.

Composition and geochemistry. The composition of laccolith-forming rocks in the Ortiz porphyry belt is strikingly constant with only minor variations in texture and composition. Laccoliths of South Mountain, the San Pedro Mountains, and the Cerrillos Hills have been described as monzonite, monzonite porphyry, latite porphyry, or hornblende monzonite porphyry (Thompson 1964; Atkinson 1961; Disbrow and Stoll 1957; Stearns 1953a,b).

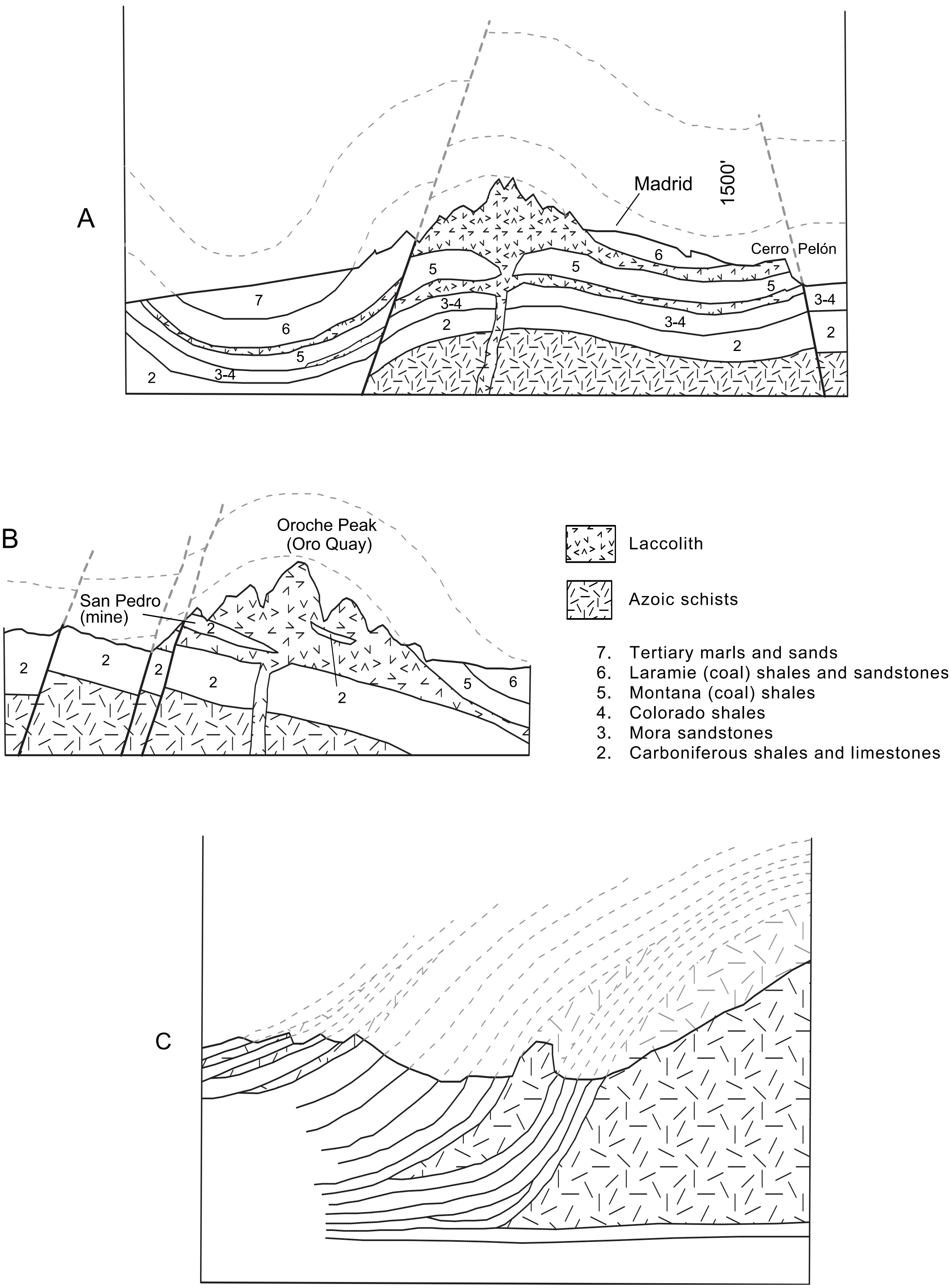
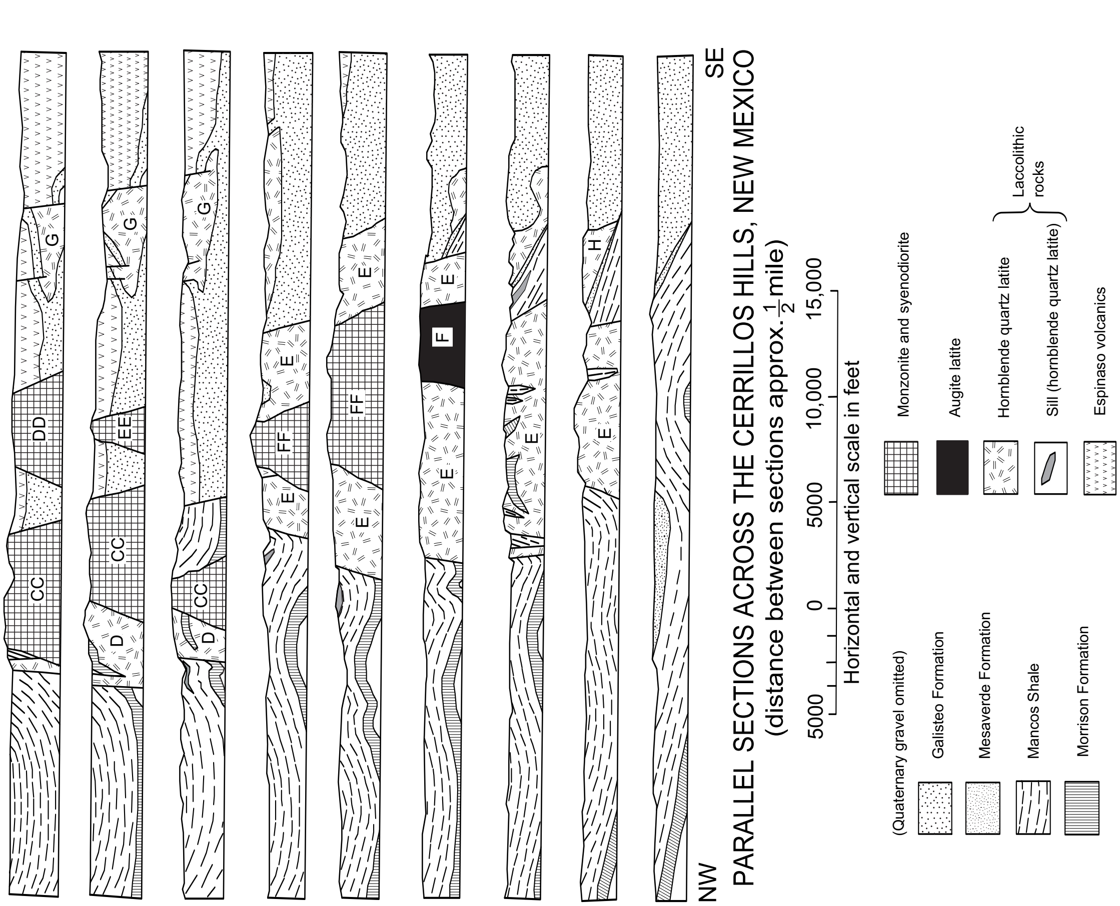
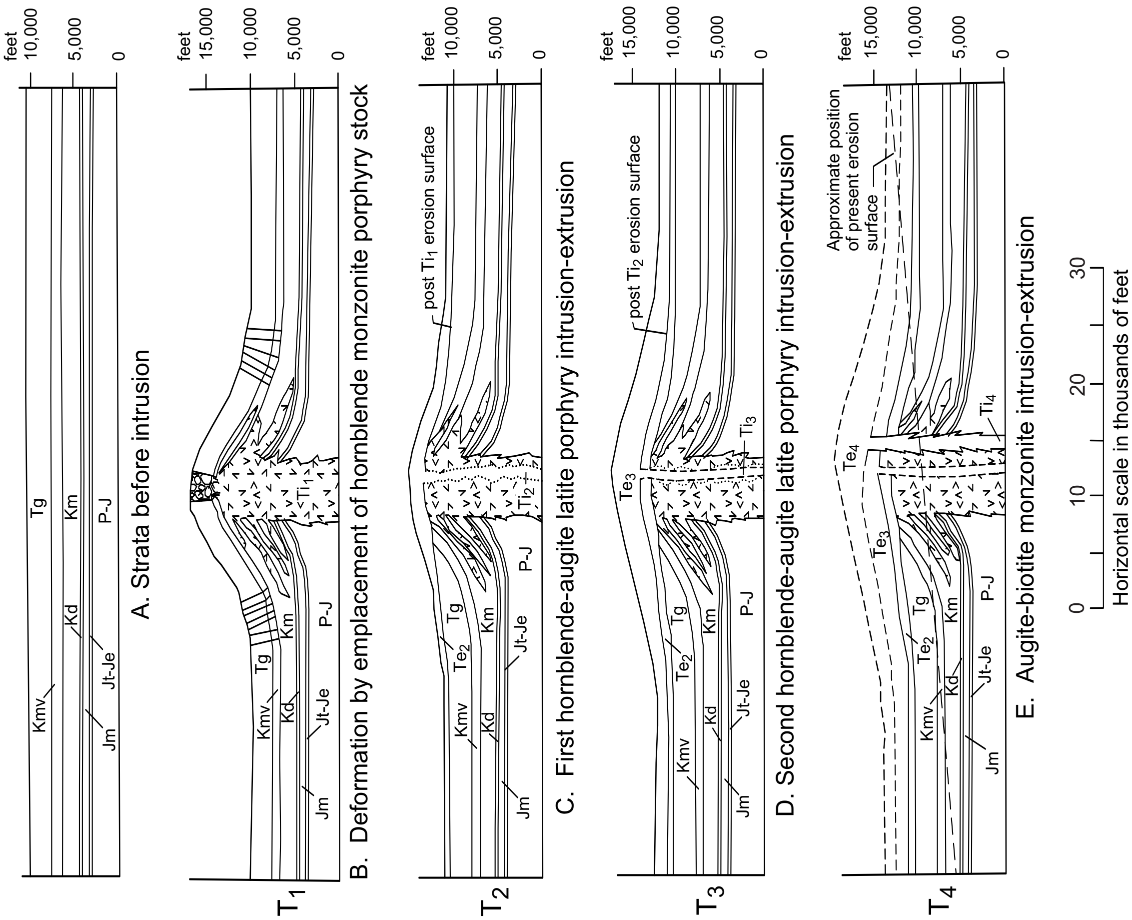


FIGURE 3—Diagrammatic east-west cross sections (not to scale) showing early ideas of laccoliths in the Ortiz porphyry belt. **A**) Ortiz Mountains – Cerro Pelón. (Keyes 1909). **B**) San Pedro Mountains (Keyes 1909). Note that the Cerro Pelón laccolith is shown connected to the mass of the Ortiz Mountains and that the Ortiz Mountains laccolith is shown extending into the Hagan Basin, offset by a basin-bounding fault. Keyes envisaged the igneous rocks of the San Pedro and Ortiz Mountains as monolithic laccolithic complexes. **C**) Cerrillos Hills laccolith as depicted by Johnson (1903). Note the pronounced bend of overlying sediments.



A
PARALLEL SECTIONS ACROSS THE CERRILLOS HILLS, NEW MEXICO
(distance between sections approx. 1/2 mile)
NW
SE
1
2
3
4
5
6
7
8
9
CC
DD
D
EE
G
E
FF
F
H
5000
0
5000
10,000
15,000
Horizontal and vertical scale in feet
(Quaternary gravel omitted)
Galisteo Formation
Mesaverde Formation
Mancos Shale
Morrison Formation
Monzonite and syenodiorite
Augite latite
Hornblende quartz latite
Sill (hornblende quartz latite)
Espinaso volcanics
Laccolithic rocks



B
feet
15,000
10,000
5,000
0
A. Strata before intrusion
Kmv
Tg
Kd
Km
Jm
Jt-Je
P-J
B. Deformation by emplacement of hornblende monzonite porphyry stock
T1
Ti1
C. First hornblende-augite latite porphyry intrusion-extrusion
T2
post Ti1 erosion surface
Te2
Ti2
D. Second hornblende-augite latite porphyry intrusion-extrusion
T3
post Ti2 erosion surface
Te3
Ti3
E. Augite-biotite monzonite intrusion-extrusion
T4
Approximate position of present erosion surface
Te4
Ti4
0
10
20
30
Horizontal scale in thousands of feet

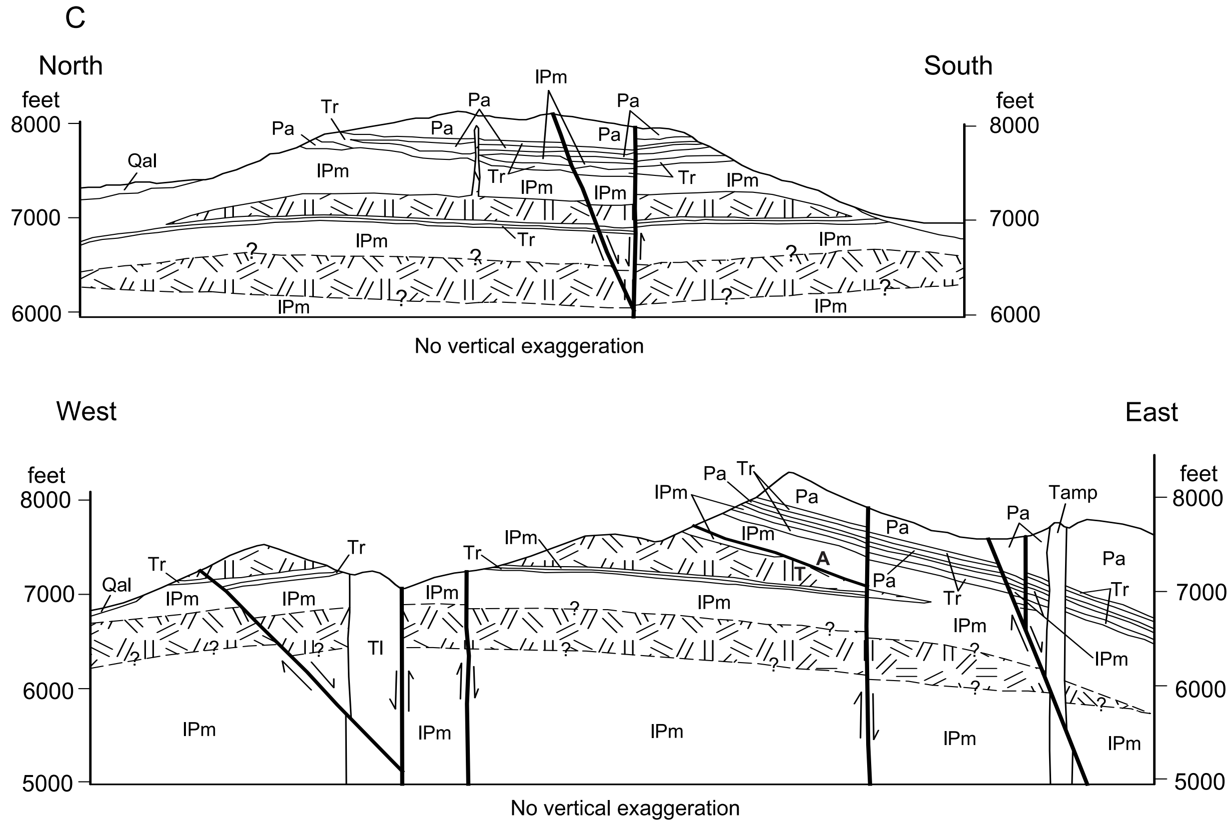


FIGURE 4—Mid-twentieth century representations of the relationship of early laccoliths to later intrusions in the Ortiz porphry belt. **A**) Stearns' (1953a) series of sections of the Cerrillos Hills; **B**) Schematic section of the Cerrillos Hills, showing igneous succession (Disbrow and Stoll 1957); **C**) Cross section of the San Pedro Mountains (Atkinson 1961); **Qal** = alluvium; **Tamp** = augite-monzonite porphyry; **Tr** = rhyolite; **Tl** = latite; **Pa** = Abo Formation; **IPm** = Madera Formation. **A** = movement away from the viewer; **T** = movement toward the viewer. Atkinson posited no central stock as the source of the laccolithic masses in the San Pedro Mountains.

Lisenbee and Maynard (2001) described the Cerro Pelón laccolith as diorite porphyry. In the Ortiz Mountains, the laccolith-forming rocks have been described as latite-andesite porphyry (Peterson 1958; McRae 1958), andesite (Kay 1986), and quartz andesite porphyry (Coles 1990).

Generally, laccolith-forming rocks are composed of 30–60% subhedral to anhedral feldspar phenocrysts and 10–15% black to green hornblende needles. In samples from the Ortiz Mountains, andesine makes up approximately 75% of feldspar phenocrysts. Quartz phenocrysts may compose as much as 5% of the rock. Hornblende-rich, rounded inclusions ranging from 2 to 15 cm in diameter are observed in laccolithic rocks in all parts of the Ortiz porphyry belt. Xenoliths of basement-derived granitic gneiss ranging in size from 10 cm to 1 m have been observed in the South Mountain (Thompson 1964) and Cerrillos laccoliths.

Laccolith- and sill-forming rocks from the Ortiz Mountains plot in the quartz andesite field on a QAPF modal minerals classification diagram (Streckheisen 1979; Coles 1990; Fig. 5). Whole-rock analytical data (Table 2) plotted on an alkali-silica classification grid of Le Bas et al. (1986) show the laccolithic rocks ranging from andesite through latite to trachyte (Fig. 6).

Similarity of composition is widely reported throughout individual laccolith groups, and implies temperature and chemical similarity of melts (Corry 1988). The Ortiz porphyry belt can be viewed as a laccolithic group in the sense of Gilbert (1877) and Cross (1894), as noted by Johnson (1903), Ogilvie (1905, 1908), and Keyes (1909, 1918, 1922).

Contact metamorphism. Thermal metamorphism of sedimentary rocks surrounding laccolithic rocks is limited to a narrow contact zone usually less than 10 cm wide, though locally as wide as 1 m (3.3 ft; Fig. 7). Thermal metamorphism associated with the Madrid laccolith resulted in the anthracitization of two of the important coal seams at Madrid: the White Ash bed, which directly underlies the Madrid laccolith, and the Ortiz Arroyo bed, which lies above the Madrid laccolith (Beaumont 1979). In certain areas of the Ortiz and San Pedro Mountains, hornfels and garnet skarn are widely developed near contacts with stocks (Atkinson 1961; Schroer 1994).

South Mountain laccolith

Thompson (1964) and Ferguson et al. (1999) confirmed Keyes' (1909) observation that a simple laccolith forms South Mountain. In plan, the laccolith forms an ellipse 6.1 km by 2.4 km (3.8 by 1.5 mi). It is floored by the Permian Abo Formation and the lowest part of the Yeso Formation (Meseta Blanca Member). The roof of the laccolith, where preserved, is Yeso Formation and Glorieta Sandstone (Thompson 1964; Ferguson et al. 1999). A narrow feeder dike under the laccolith is postulated by Ferguson et al. (1999). The laccolith occupies the keel of a syncline interpreted by Ferguson et al. (1999) as formed in response to movement on the Gutierrez fault before laccolith emplacement (Fig. 8).

San Pedro laccolith group

The San Pedro laccolith, as mapped by Atkinson (1961), Ferguson et al. (1999), and Maynard (2000), is composed of two concordant bodies of andesite porphyry in the western part of the San Pedro Mountains (Fig. 4C). Only one of the intrusive bodies is exposed. A lower sill is implied by the high position of Pennsylvanian Madera Formation in the San Pedro Mountains with respect to Permian and Triassic strata exposed in Tuerto Arroyo to the north. Smaller, irregular masses of andesite por-

TABLE 1—Principal laccoliths of the Ortiz porphyry belt. Estimated depths of emplacement are calculated using the sums of known or estimated thicknesses of Phanerozoic rocks in the area. Not counted is the thickness of the Espinaso volcanics, part of which may be extrusive equivalent of the laccolithic intrusions. **TCFS** = Tijeras–Cañoncito fault system.

Laccolith group	Host strata	Present elevation range (m)	Estimated depth of emplacement (m)	Present areal extent (km^2)	Comments	References
South Mountain	Permian	2,160–2,260	2,600	14.5	Single simple laccolith	Thompson (1964), Ferguson et al. (1999)
San Pedro	Pennsylvanian	1,830–2,100	3,000–3,200	5.7	Christmas Tree laccolith, feeders not identified. Three main sills. Later orthoclase porphyry latite stocks and dikes.	Atkinson (1961), Ferguson et al. 1999), Maynard (2000)
Tuerto	Triassic	1,830–1,890	2,200–2,400	6.4	Poorly exposed. Magnetic studies suggest large extent.	Atkinson (1961), Ferguson et al. (1999), Maynard (2000)
Captain Davis Mountain	Cretaceous (Mancos Shale)	2,010–2,100	1,400–1,900	15.5	Concordant and discordant contacts; complex, strongly faulted by TCFS. Possibly originally Christmas Tree laccolith. Intruded by younger granodiorite stock.	Maynard (2000), Lisenbee and Maynard (2001), this study
Cerro Pelón	Cretaceous (Mesaverde Group), Paleocene and Eocene	1,920–2,100	1,000–1,200	15.5	Single simple laccolith. Feeder not identified.	Lisenbee (1967), Lisenbee and Maynard (2001), Lisenbee (1999)
Lomas de la Bolsa	Jurassic and Cretaceous	1,980–2,410	1,000–2,000	52	Christmas Tree laccolith. Discordant contacts mainly in Lomas de la Bolsa–Crooked Canyon area. Sills cut by TCFS. At least 10 distinct sills.	Maynard (2000)
Juana López	Cretaceous (Mancos Shale)	1,830–1,920	1,800	1.2		Maynard et al. (2001)
Cerro Chato	Cretaceous (Mesaverde Group)	1,860–2,100	1,200	6.0		Maynard et al. (2001)
Madrid	Cretaceous (Mesaverde Group)	1,860–1,980	1,100	1.2	Madrid sill altered bituminous coal to anthracite.	Maynard et al. (2001)
Cedar Mountain	Mesaverde Group–Diamond Tail Formation	1,980–2,230	1,000	2.5	Intrudes Mesaverde Group–Diamond Tail Formation contact	Maynard (2000), Maynard et al. (2001)
Cerrillos Hills	Jurassic, Cretaceous, Paleocene	1,740–1,890	1,100–2,000	30	Punched or Christmas Tree laccolith in western part. Single laccolith in southeast part. Strata strongly domed.	Stearns (1953a,b), Disbrow and Stoll (1957), Maynard et al. (2001), Maynard et al. (2002)
La Ciénega	Cretaceous				Faulted and poorly exposed.	

phyry also crop out in the eastern part of the range. Poorly exposed andesite porphyry intrudes Triassic strata in the valley between the San Pedro and Ortiz Mountains. The two principal sills of the San Pedro laccolith intrude limestone and shale of the Pennsylvanian Madera Formation and range in thickness from 0 to 60 m (0 to 200 ft). Strata and sills in the San Pedro Mountains are tilted to the east, except along the western flank of the range, where they are near horizontal (Atkinson 1961; Ferguson et al. 1999; Maynard 2000). Connecting feeder dikes between the sills have not been clearly identified, though poor exposures of andesite porphyry southwest of the village of Golden, along a major strand of the Tijeras–Cañoncito fault system, suggest a feeder there, with a Christmas Tree, or half-Christmas Tree laccolith centered adjacent to the fault.

Rhyolite sills and irregular masses crop out in the central and eastern part of the San Pedro Mountains. Stocks and dikes of augite monzonite and orthoclase-porphyry latite intrude the complex.

Cerro Pelón laccolith

Keyes (1909) postulated a subterranean connection between the Cerro Pelón laccolith and the Ortiz laccolith (Fig. 3A). Mapping by Lisenbee (1967), Bachman (1975), Lisenbee (1999), and Lisenbee and Maynard (2001), shows the Cerro Pelón laccolith to be a body separated from the Ortiz Mountains by the Tijeras–Cañoncito fault system. The Cerro Pelón laccolith comprises a single, 150-m (500-ft) thick concordant body invading the Cretaceous Mesaverde Group (Fig. 9; Lisenbee 1967, 1999; Lisenbee and Maynard 2001). The buried northern edge of the Cerro Pelón laccolith forms a pronounced and easily mapped monocline.

The Cerro Pelón laccolith is described by Lisenbee and Maynard (2001) as diorite porphyry and medium gray to light tan on fresh surfaces. It weathers very light gray to very light tan and is fine grained with euhedral phenocrysts of biotite, hornblende, and feldspar. Trachytic texture and hornblende lineation are common. Thin sections reveal sericitic alteration of feldspar. Hornblende crystals show strong alignment (A. Lisenbee pers. comm.).

Lomas de la Bolsa laccolith

The Lomas de la Bolsa laccolith comprises andesite porphyry masses that make up the bulk of Las Lomas de la Bolsa, the sills exposed on the western and south-central parts of the Ortiz Mountains, and sills encountered in drill holes at Lukas and Carache Canyons. In the western and south-central Ortiz Mountains, the sills intrude Jurassic through Cretaceous strata. Andesite porphyry sills and dikes in the Paleocene Diamond Tail Formation in the Ortiz graben and near the Cunningham Hill mine may represent the highest levels of the Lomas de la Bolsa laccolith. In the vicinity of Las Lomas de la Bolsa and the adjacent part of the Ortiz Mountains (where NM–14 crosses the range at Stagecoach Canyon), andesite porphyry appears in map pattern to form a large irregular intrusive mass. Large sections of the Jurassic–Cretaceous stratigraphic succession are missing. In contrast, to the north and south, the andesite porphyry forms discrete concordant bodies, and the stratigraphic section is complete, though "inflated" by the intrusive bodies. It is inferred therefore that the Stagecoach Canyon area is the central feeder zone of the Lomas de la Bolsa laccolith (Fig. 10).

In the Ortiz Mountains andesite por-

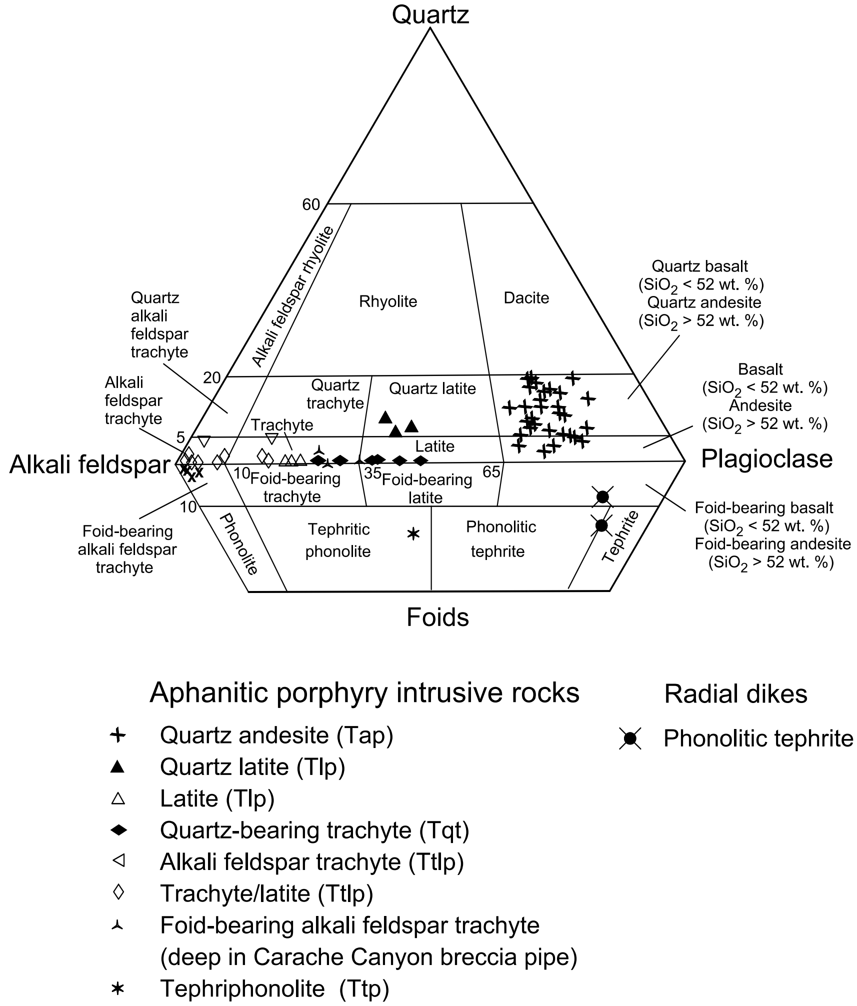


FIGURE 5—QAPF modal mineral rock classification diagram (Streckheisen 1979) with plots of laccolith- and sill-forming rocks from the Ortiz Mountains. Data are from Coles (1990). Coles' modal estimates were based on 500 point counts on thin sections stained for potassium, using sodium cobaltinitrate.

TABLE 2—Selected whole-rock analytical data from laccolith-forming rocks in the Ortiz and San Pedro Mountains. Fe_2O_3 and FeO analyses are reported as total iron by Kay (1986). Sample from Lindgren and Graton (1906) was subjected to a partial analysis only. * = wt % oxides; ** = ppm.

	Ortiz Mountains (Lomas de la Bolsa laccolith)										San Pedro Mts.	
Source	Coles (1990)						Kay (1986)		Ogilvie (1908)		Lindgren and Graton (1906)	Average values
Sample	IG-32	IG-66	IG-91	IG-94	IG-95	IG-97	BK-42	BK-43	1	3		
*SiO_2	61.60	59.98	63.70	58.80	61.96	61.15	62.4	61.3	63.11	62.48	62.08	61.69
*TiO_2	0.46	0.98	0.48	0.81	0.78	0.69	0.52	0.68	0.80	0.60	–	0.68
*Al_2O_3	17.20	17.32	17.77	16.78	16.47	17.43	17.4	17.5	16.75	18.07	–	17.27
*Fe_2O_3	1.45	3.45	2.25	3.55	1.21	3.00	4.64	3.98	2.68	2.61	–	2.88
*FeO	2.75	1.75	1.55	1.95	2.95	1.70	4.64	3.98	1.39	1.97	–	2.00
*MnO	0.13	0.19	0.12	0.16	0.13	0.07	0.07	0.09	0.11	0.17	–	0.12
*MgO	1.60	1.51	0.99	1.75	1.23	1.65	1.51	1.66	1.22	1.34	–	1.45
*CaO	5.19	5.17	4.03	5.68	4.70	5.46	5.21	6.18	3.88	4.67	4.62	4.98
*Na_2O	4.34	4.67	5.23	3.82	4.61	4.75	4.45	4.64	4.76	4.69	4.76	4.61
*K_2O	1.94	3.59	2.52	2.67	3.50	2.42	2.79	2.39	3.48	2.16	2.84	2.75
*P_2O_5	0.40	0.31	0.18	0.31	0.22	0.27	0.22	0.29	0.25	0.28	–	0.27
*Cr_2O_3	–	–	–	–	–	–	0.01	0.01	–	–	–	–
*BaO	–	–	–	–	–	–	–	–	0.16	0.09	–	–
*S	–	–	–	–	–	–	–	–	0.03	0.03	–	–
LOI	1.40	1.00	1.01	3.17	1.25	0.96	1.00	1.54	1.41	0.64	–	1.34
Totals	98.46	99.92	99.83	99.45	99.01	99.55	100.22	100.26	100.03	99.80	–	
$(Na_2O+K_2O)/SiO_2$	0.10	0.14	0.12	0.11	0.13	0.12	0.12	0.11	0.13	0.11	0.12	0.12
$(Na_2+K_2O)/CaO$	1.21	1.60	1.92	1.14	1.73	1.31	1.39	1.14	2.12	1.47	1.65	1.52
**Rb	43	81	51	51	93	24	50	60				57
**Sr	810	820	1020	665	800	710	950	1010				848
Rb/Sr	0.053	0.099	0.050	0.077	0.116	0.034	0.053	0.059				0.068

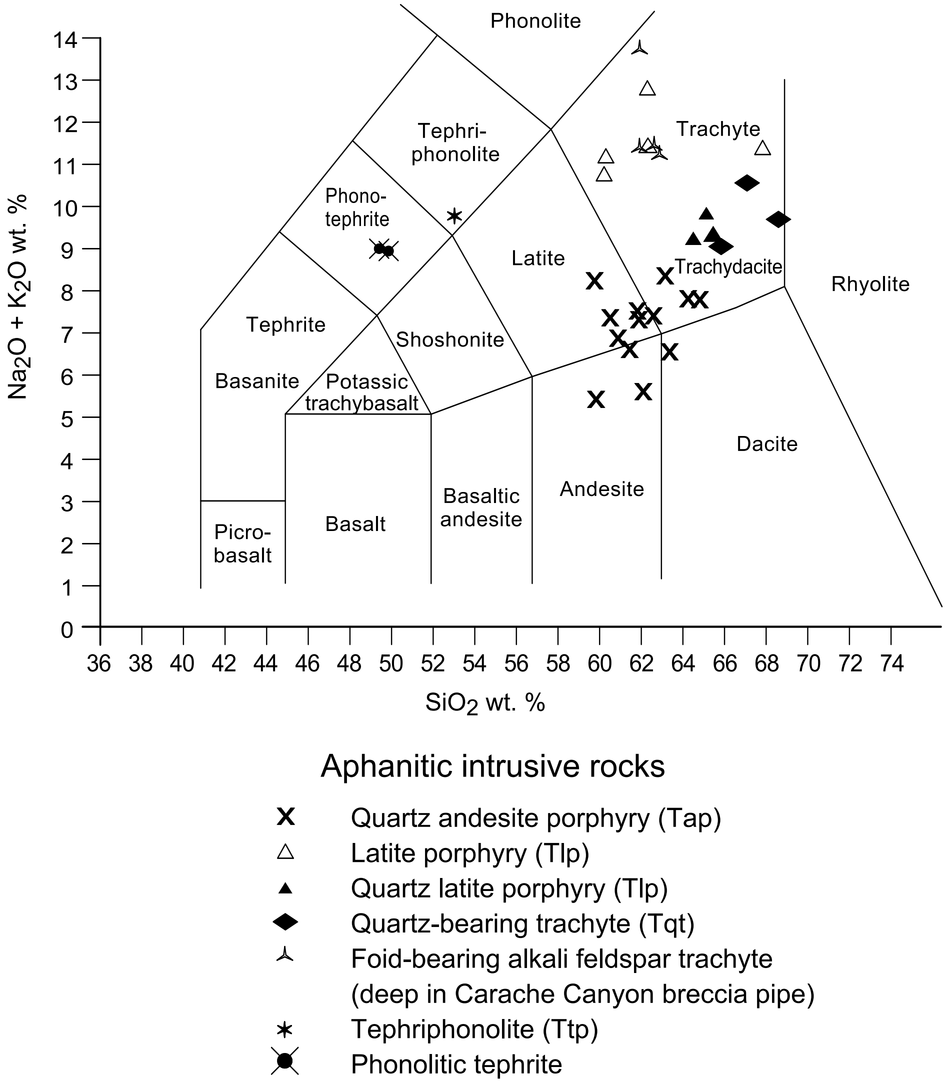


FIGURE 6—Alkali-silica plot of selected fresh samples of laccolith- and sill-forming rocks in the Ortiz Mountains and San Pedro Mountains. Classification scheme of Le Bas et al. (1986).

FIGURE 7—Contact of andesite-porphyry sill with Mancos Shale.

phyry is grayish green to gray on fresh surfaces, fine to medium grained, and porphyritic. Phenocrysts of plagioclase, lesser hornblende, and rare quartz make up 40–60% of the rock. Groundmass is gray and aphanitic. Subhedral andesine plagioclase makes up about 75% of the phenocrysts and ranges from 0.5 to 2 mm. Black euhedral hornblende phenocrysts (0.6–5 mm) constitute nearly all the rest of the phenocryst assemblage. Clear, highly resorbed quartz makes up perhaps 1% of the phenocrysts. Plagioclase, orthoclase, and quartz, and trace allanite, zircon, and rutile form the groundmass. Hornblende-rich (augite-cored?) xenoliths 2–10 cm in diameter are commonly found in the andesite porphyry and are interpreted as co-magmatic cumulates (Coles 1990).

Captain Davis Mountain laccolith

A large faulted mass of andesite porphyry intruding Cretaceous Mancos Shale lies adjacent to the Tijeras–Cañoncito fault system at Captain Davis Mountain and Lone Mountain to the east of the main mass of the Ortiz Mountains (Fig. 11; Lisenbee and Maynard 2001). Faulting and the later intrusion of a granodiorite stock on the eastern end of Captain Davis Mountain and an augite monzonite plug on Lone Mountain obscure the original configuration of the andesite porphyry body in map pattern. Contacts of individual sills are commonly observed to be parallel to bedding, especially on the south and east sides of Lone Mountain. A central feeder system is likewise obscure but may be inferred to lie along the Tijeras–Cañoncito fault system, because of the greatest abundance of andesite porphyry in this area.

Cerro Chato, Madrid, Cedar Mountain, and Juana López laccoliths

Three separate concordant andesite porphyry laccoliths, Cerro Chato, Madrid, and Cedar Mountain, intrude Mesaverde Group sedimentary rocks and form prominent ridges from the north flank of the Ortiz Mountains to the town of Madrid (Fig. 12). A fourth laccolith, the Juana López laccolith, intrudes the lower part of the Mancos Shale. No dikes or other feeder structures connect the individual bodies. Such connecting structures may exist at depth, or they may have been eroded away. Johnson (1903) hypothesized that the laccoliths propagated from the Ortiz Mountains. However, the greatest thickness of each of these bodies appears to lie some distance away from the Ortiz Mountains, suggesting that the centers of the laccoliths (or feeding structure of a Christmas Tree laccolith) are also outside of Ortiz Mountains.

Cerrillos Hills laccolith

Recent mapping (Maynard et al. 2001, 2002) shows a large mass of andesite porphyry (intrusion E of Stearns 1953a) with

FIGURE 8—Cross section of the South Mountain laccolith (Ferguson et al. 1999). No vertical exaggeration. Ferguson et al. (1999) interpreted the syncline beneath the floor of the South Mountain laccolith to be a pre-intrusive, Laramide structure.

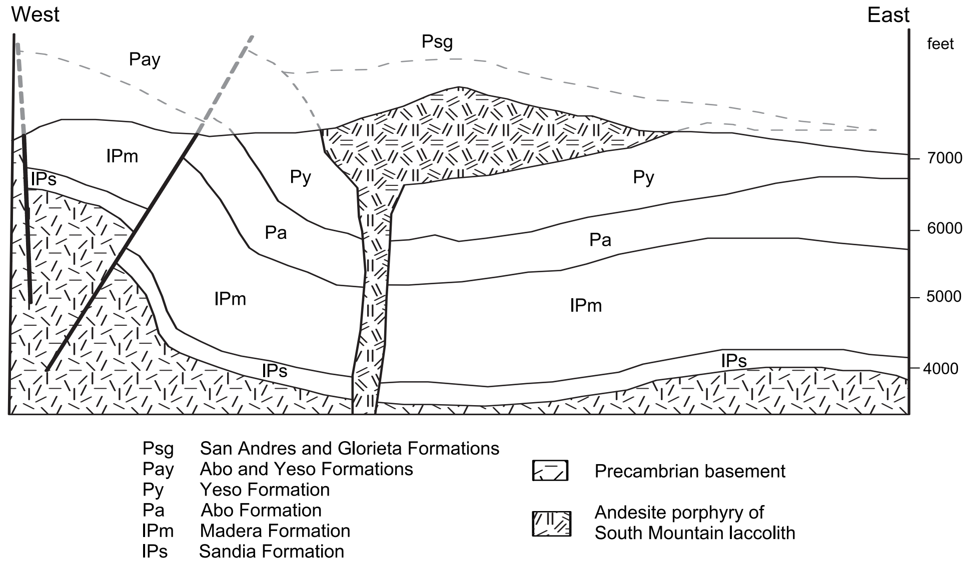
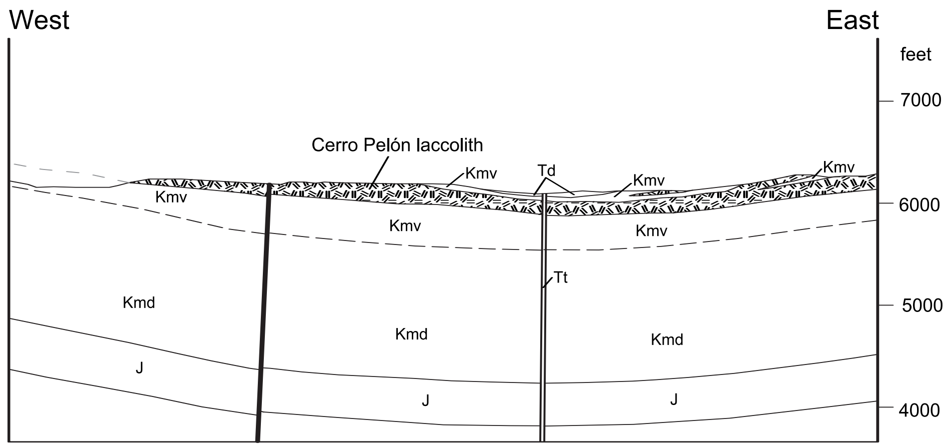


FIGURE 9—Cross section of the Cerro Pelón laccolith modified from Lisenbee (1999) and Lisenbee and Maynard (2001). No vertical exaggeration. **Tt** = trachytic dike; **Td** = Diamond Tail Formation; **Kmv** = Mesaverde Group; **Kmd** = Mancos Shale and Dakota Sandstone; **J** = Jurassic rocks.



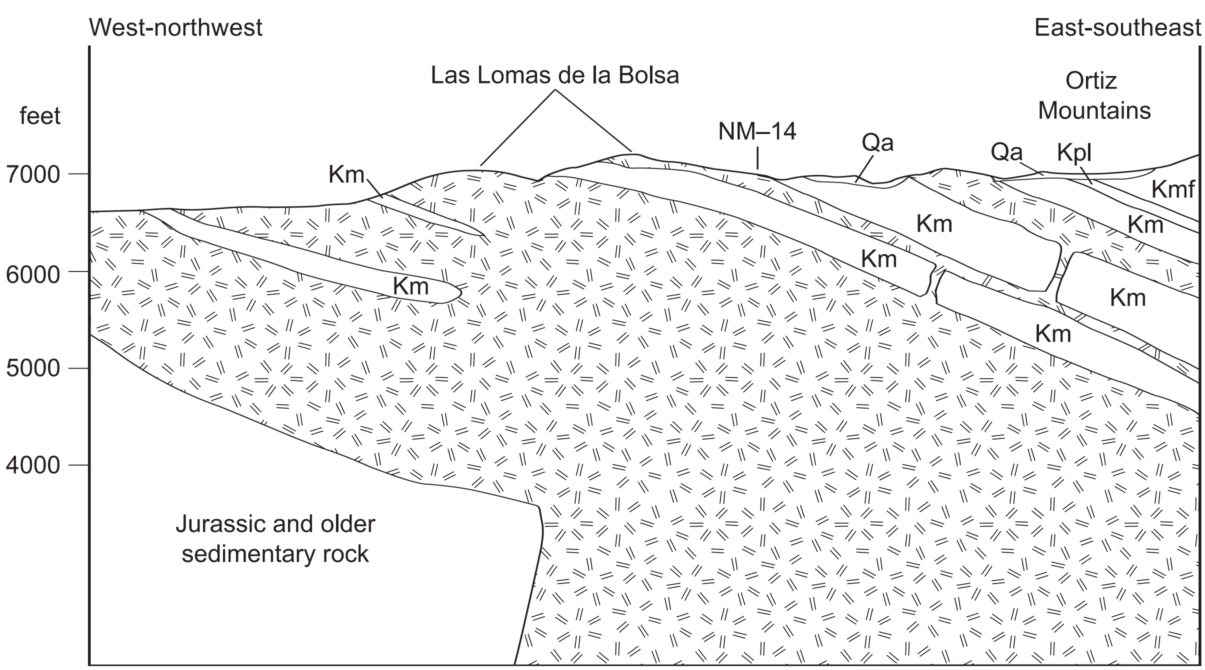


FIGURE 10—Cross section of the Lomas de la Bolsa laccolith (modified from Maynard 2000). No vertical exaggeration. Sections of the Jurassic and Cretaceous stratigraphy are missing in the Lomas de la Bolsa area, suggesting that the intrusion is not floored. **Km** = Mancos Shale; **Kpl** = Point Lookout Sandstone; **Kmf** = Menefee Formation; **Qa** = Quaternary alluvium and colluvium.

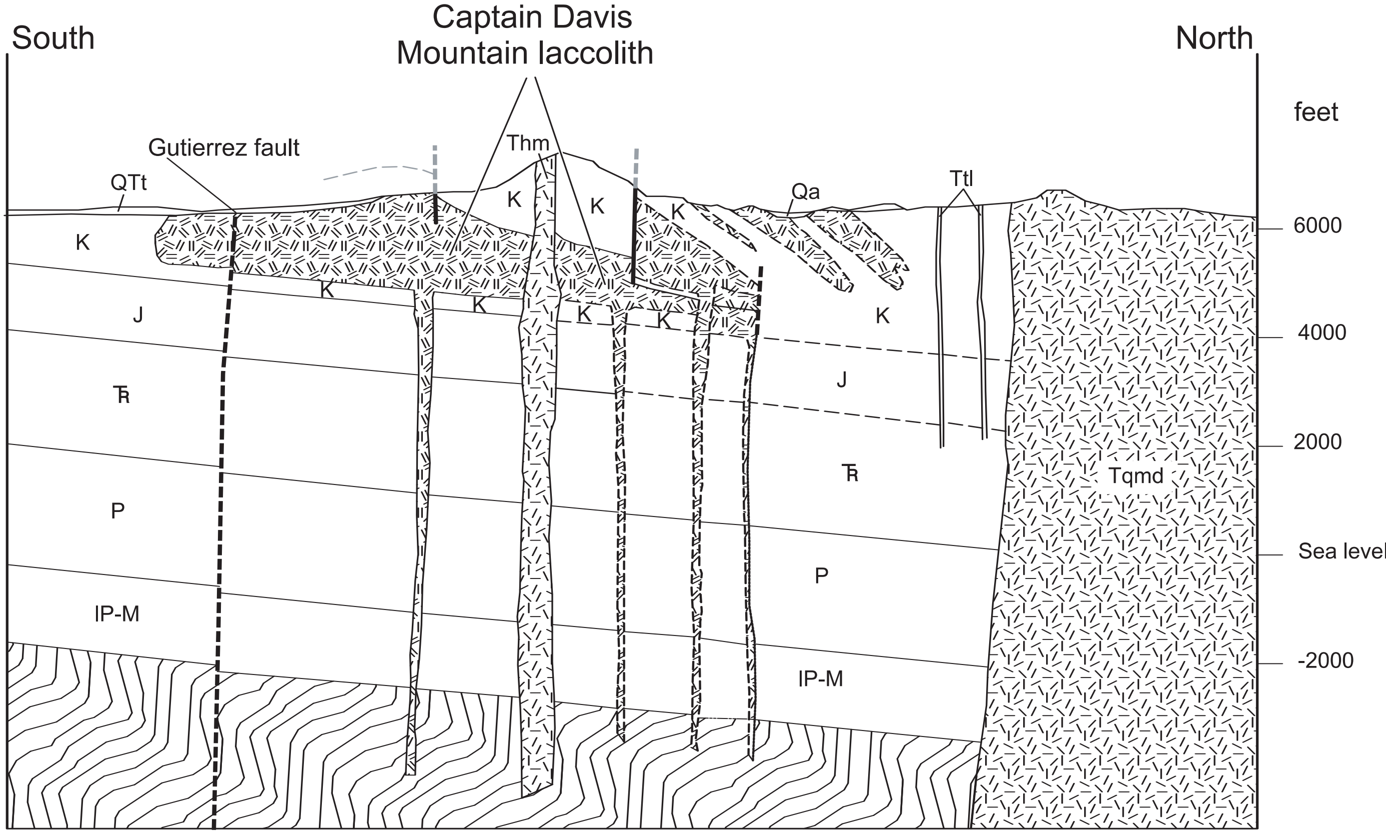


FIGURE 11—Cross section of the Captain Davis Mountain laccolith (Lisenbee and Maynard 2001). No vertical exaggeration. **Thm** = hornblende monzonite stock; **Tqmd** = quartz monzonite stock; **Ttl** = trachyte latite dike; **Qa** = alluvium; **QTt** = Tuerto Gravel. **K**, **J**, **TR**, **P**, and **IP–M** = Cretaceous, Jurassic, Triassic, Permian, and Pennsylvanian–Mississippian strata, respectively. Wood grain pattern = Precambrian basement.

discontinuous outcrops of Jurassic Morrison Formation and Cretaceous Dakota Formation and Mancos Shale in the southwestern part of the Cerrillos Hills. Most contacts of this andesite porphyry body are concordant with respect to bedding; discordant contacts, although present, cannot be traced more than a few tens of meters. Mancos Shale, Dakota Formation, and Morrison Formation dip to the southwest, in structural continuity with sedimentary rocks outside the main intrusive mass. This group of sedimentary rocks indicates a northeast-trending horst block in the center of the intrusive mass. The horst may be related to doming caused by later intrusive activity. Although no floor to the intrusive mass was observed, the predominance of concordant contacts suggests that the intrusion is essentially laccolithic (Fig. 13).

Smaller, concordant intrusions invade Mancos Shale and Mesaverde Group sedimentary rocks in the northwestern and southeastern parts of the Cerrillos Hills, representing Stearns' (1953a) intrusions D and H, respectively. The latter intrusion appears to strongly deform overlying sedimentary rocks near NM–14. Thin (<30 m; <98 ft) sills of andesite porphyry intrude Mancos Shale in the west-central part of the Cerrillos Hills, northwest of Grand Central Mountain. Sills in the Mancos Shale form the prominent Devil's Throne (Fig. 14) and Buffalo Mountain, west of Cerrillos. At Devil's Throne the intrusion is near vertical, as are the host rocks. These sills can be interpreted as lesser sills related to a Christmas Tree laccolith forming Stearns' intrusion E.

A smaller laccolith, here included with the Cerrillos laccolith, intrudes Cretaceous

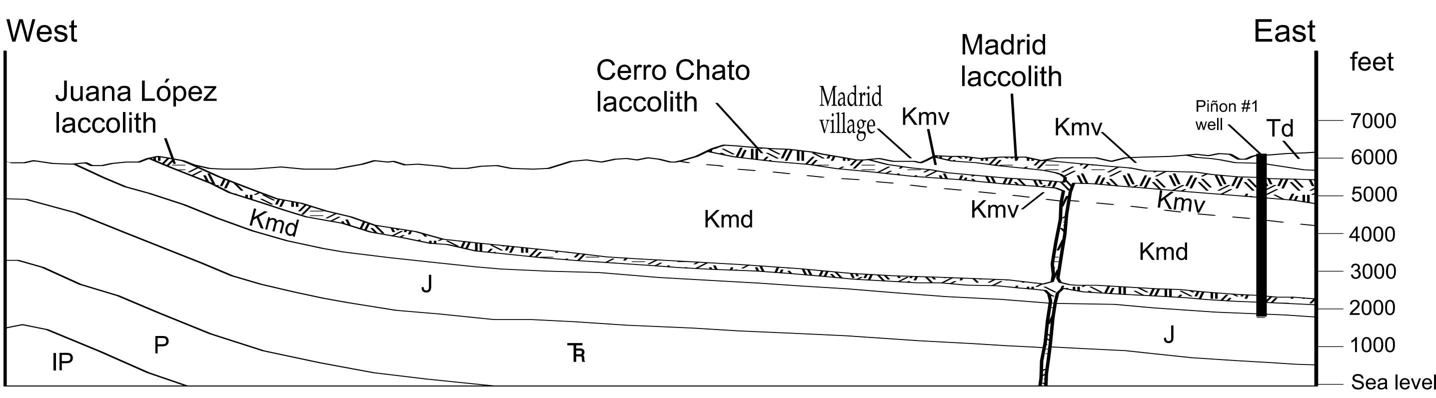


FIGURE 12—Cross section showing the Juana López, Cerro Chato, and Madrid laccoliths. No vertical exaggeration. From Maynard et al. (2001). **Td** = Diamond Tail Formation; **Kmv** = Mesaverde Group; **Kmd** = Mancos Shale and Dakota Formation; **J**, **TR**, **P**, and **IP** = Jurassic, Triassic, Permian, and Pennsylvanian strata, respectively. Anticline at western end of section is associated with the La Bajada fault.

Mesaverde Group and Paleocene Diamond Tail Formation sediments in the southeastern part of the Cerrillos Hills. The concealed southeastern edge of the intrusion deformed the overlying beds, pushing them into a vertical to overturned orientation in the area known as Garden of the Gods, on the west side of NM–14 approximately 2 mi (3.2 km) east of Cerrillos (Fig. 15).

Johnson (1903) and Keyes (1918) first described laccoliths in the Cerrillos Hills. Johnson (1903) observed the concordant contacts of andesite porphyry with sedimentary rocks dipping away from the center of the range. Johnson failed, however, to clearly recognize that the augite-hornblende (-biotite) monzonite bodies that form the highest peaks in the Cerrillos Hills represent separate intrusions with stocklike geometries. Johnson's interpretation was that the laccoliths were tongues that emanated from a central stock.

Stearns' (1953a) investigation of the Cerrillos Hills area divided the igneous rocks into three intrusive units, plus the extrusive Espinaso volcanics. Stearns, pointing out that no floor had been observed for Johnson's proposed laccolith(s), proposed an alternate structure for two of the three main andesite-porphyry bodies in the Cerrillos Hills, describing them as a central stock with sheetlike, inward-dipping dikes intruding steeply tilted sedimentary rocks on its margins. Stearns stated that the concordant contacts noted on the south and west sides of the Cerrillos Hills would probably give way to discordant contacts at depth.

Disbrow and Stoll (1957) agreed with Stearns' separation of older and younger intrusive units, but favored the model of tongue laccoliths emanating from a central stock for the first group, as Hunt (1953) proposed in the Henry Mountains of Utah. Disbrow and Stoll (1957) described hornblende monzonite (Ti_1 in their designation) of the Cerrillos Hills as a gray porphyry with equant plagioclase and elongate black hornblende phenocrysts in a dark, fine-grained groundmass.

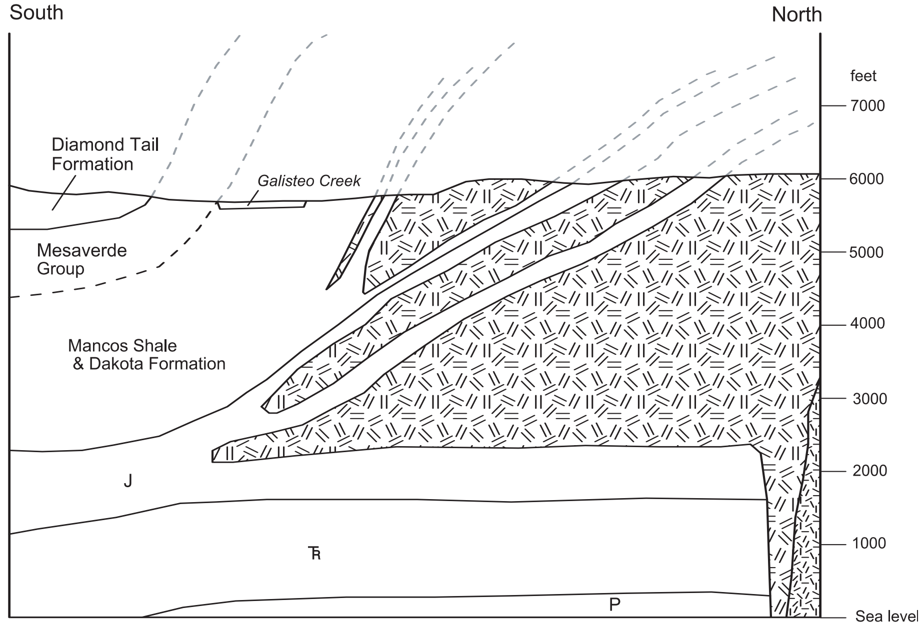


FIGURE 13—Cross section of the southern part of the Cerrillos Hills. No vertical exaggeration. Main Cerrillos Hills laccolith showing the laccolithic doming of Tertiary (Diamond Tail Formation), Cretaceous, and Jurassic sedimentary rocks. Note similarity to Johnson's (1903) interpretation (Fig. 3C). **J**, **Ꞧ**, **P**, and **IP** = Jurassic, Triassic, and Permian strata, respectively. From Maynard et al. (2001).

Vertical range of laccolith emplacement in the Ortiz porphyry belt

The laccoliths of the Ortiz porphyry belt described in this report are emplaced over a vertical stratigraphic range of approximately 2.2 km (1.3 mi). In addition, 10–15-m-thick (35–50-ft-thick) sills of similar material intrude the Diamond Tail and Galisteo Formations, giving a total vertical stratigraphic range of approximately 3 km (1.9 mi) to the laccolith group. Stratigraphically deepest known laccoliths are in the southern part of the belt. The shallowest laccoliths are in the central and northern parts. The apparent stratigraphic distribution may be only the result of depth of exposure. Assuming that the same thicknesses of the Phanerozoic rocks prevailed over the entire Ortiz porphyry belt, it remains to be explained why laccoliths were emplaced over a vertical range about three times that commonly observed in laccolith groups. Two hypotheses may be considered to explain this anomalously large range of emplacement depths. It appears likely that they operated in concert (Fig. 16).

Pre-existing fault model

Pre-34 Ma movement on the Tijeras–Cañoncito fault system may have uplifted the southeastern area, corresponding to the San Pedro Mountains and South Mountain, with respect to the northwestern area. Such movement would have brought the Paleozoic strata into a depth range similar to that of Mesozoic rocks on the northwest side. Pre-34 Ma (Laramide) movement on the Tijeras–Cañoncito fault is consistent with the model proposed by Abbott et al. (1995) for formation of the Galisteo Basin. According to their model, synorogenic Eocene and Paleocene strata were deposited in a northeast-southwest-elongate basin controlled by the Tijeras–Cañoncito fault. Maximum offset of the

FIGURE 14—Devil's Throne, on the left side of the road, is approximately 1 mi west of Cerrillos. Devil's Throne is composed of a sill of the Cerrillos laccolith.

TABLE 3—Summary of isotopic ages of rocks from the Ortiz porphyry belt. Units are listed from oldest to youngest, based on field relations. Samples yielding poor isochron data or whose data conflict with field relations are excluded.

Unit	Study/Sample	Age (Ma)	Method, type	Comment
Andesite porphyry, Ortiz Mountains	Bachman and Mehnert (1978)	34.0 ± 2.2	K-Ar hornblende	
	McIntosh (2000)/Ig-30	34.29 ± 0.21	$^{40}Ar/^{39}Ar$, hornblende, isochron	fair isochron
	Sauer (1999)/K97-9-25F/3/KD9	34.3 ± 0.3	$^{40}Ar/^{39}Ar$, hornblende, isochron	
	Sauer (1999)/K97-9-25C/2/KD9	35.9 ± 0.09	$^{40}Ar/^{39}Ar$, hornblende, isochron	
	Sauer (1999)/K97-9-25E/8/KD9	36.2 ± 0.8	$^{40}Ar/^{39}Ar$, hornblende, isochron	
	Sauer (1999)/K97-9-25B/4/KD9	33.3 ± 0.09	$^{40}Ar/^{39}Ar$, hornblende, plateau	
Andesite porphyry, San Pedro Mountains	Sauer (1999)/SP-2-BS/5/KD9	33.7 ± 0.1	$^{40}Ar/^{39}Ar$, hornblende, plateau	
Augite (hornblende) monzonite, Ortiz Mountains	Armstrong (1975)/1222155-61	33.9 ± 1.2	K-Ar hornblende	
	Kay (1986)	29.6 ± 1.5	K-Ar hornblende	
	Sauer (1999)/O-4-BS/14/KD9	31.3 ± 0.3	$^{40}Ar/^{39}Ar$, hornblende, Tmax?	
Augite (hornblende) monzonite, San Pedro Mountains	Sauer (1999)/SP-1-BS/20/KD9	30.6 ± 0.5	$^{40}Ar/^{39}Ar$, hornblende, isochron	
	Sauer (1999)/SP-1-BS/7/KD9	30.94 ± 0.06	$^{40}Ar/^{39}Ar$, hornblende, plateau	
Augite monzonite, La Cienega area	Sauer (1999)/CA-4BS/17/KD9	29.40 ± 0.05	$^{40}Ar/^{39}Ar$, biotite, plateau	
Augite and hornblende monzonites from Cerrillos Hills	Sauer (1999)/K97-9-23A/19/KD9	28.7 ± 0.1	$^{40}Ar/^{39}Ar$, K spar, isochron	augite-biotite monzonite
	Sauer (1999)/K97-9-23B/15/KD9	28.27 ± 0.07	$^{40}Ar/^{39}Ar$, biotite, plateau	augite-biotite monzonite
	Sauer (1999)/K97-9-24D/16/KD9	28.4 ± 0.04	$^{40}Ar/^{39}Ar$, biotite, isochron	hornblende-biotite monzonite
	Sauer (1999)/K97-9-24D/13/KD9	28.2 ± 0.3	$^{40}Ar/^{39}Ar$, K spar, isochron	hornblende-biotite monzonite
Volcanic rocks of Dolores Gulch, Ortiz Mountains	Kay (1986)/NMO-13,1072'	34.2 ± 1.4	K-Ar hornblende	
	McIntosh (2000)/Eg-13	31.31 ± 0.27	$^{40}Ar/^{39}Ar$, K spar	fair to good isochron
	McIntosh (2000)/Eg-27	31.48 ± 0.19	$^{40}Ar/^{39}Ar$, K spar	fair to good isochron
Espinaso volcanics, Hagan Basin	Kautz et al. (1981)/base	34.3 ± 0.8	K-Ar	
	Kautz et al. (1981)/middle	34.6 ± 0.7	K-Ar	
	Kautz et al. (1981)/top	26.9 ± 0.6	K-Ar	from mafic flow in lowest Santa Fe Group beds
Subvolcanic latite plug	Kay (1986)/ OR-9	35.1 ± 1.4	K-Ar feldspar	
Trachytic latite dikes	Kay (1986)/ OR-10	30.7 ± 1.2	K-Ar feldspar	
	Kay (1986)/ OR-12	30.3 ± 1.2	K-Ar biotite	
	Kay (1986)/ OR-11	29.9 ± 1.2	K-Ar whole rock	
	Kay (1986)/ OR-8	33.1 ± 0.8	K-Ar feldspar	
	Kay (1986)/ OR-13	35.1 ± 1.4	K-Ar feldspar	
	Kay (1986)/ OR-7	31.6 ± 1.2	K-Ar biotite	
	McIntosh (2000)/ Eg-68	31.69 ± 0.20	$^{40}Ar/^{39}Ar$, K spar	fair to good isochron
	McIntosh (2000)/ Eg-70	31.91 ± 0.18	$^{40}Ar/^{39}Ar$, K spar	fair to good isochron
	McIntosh (2000)/ Wg-12	31.83 ± 0.18	$^{40}Ar/^{39}Ar$, sanidine	well behaved
Granodiorite stock of Candelaria Mountain, Ortiz Mountains	McIntosh (2000)/ Ig-68	31.10 ± 0.63	$^{40}Ar/^{39}Ar$, K spar	fair to good isochron; unit is cut by trachytic latite dikes
Mineralization-associated minerals	Kay (1986)/ OR-2	32.0 ± 1.2	K-Ar sericite	
	McIntosh (2000)/ OC-43, 564'	32.20 ± 0.38	$^{40}Ar/^{39}Ar$, adularia	
	McIntosh (2000)/ OC-43, 554'	31.56 ± 0.12	$^{40}Ar/^{39}Ar$, adularia	

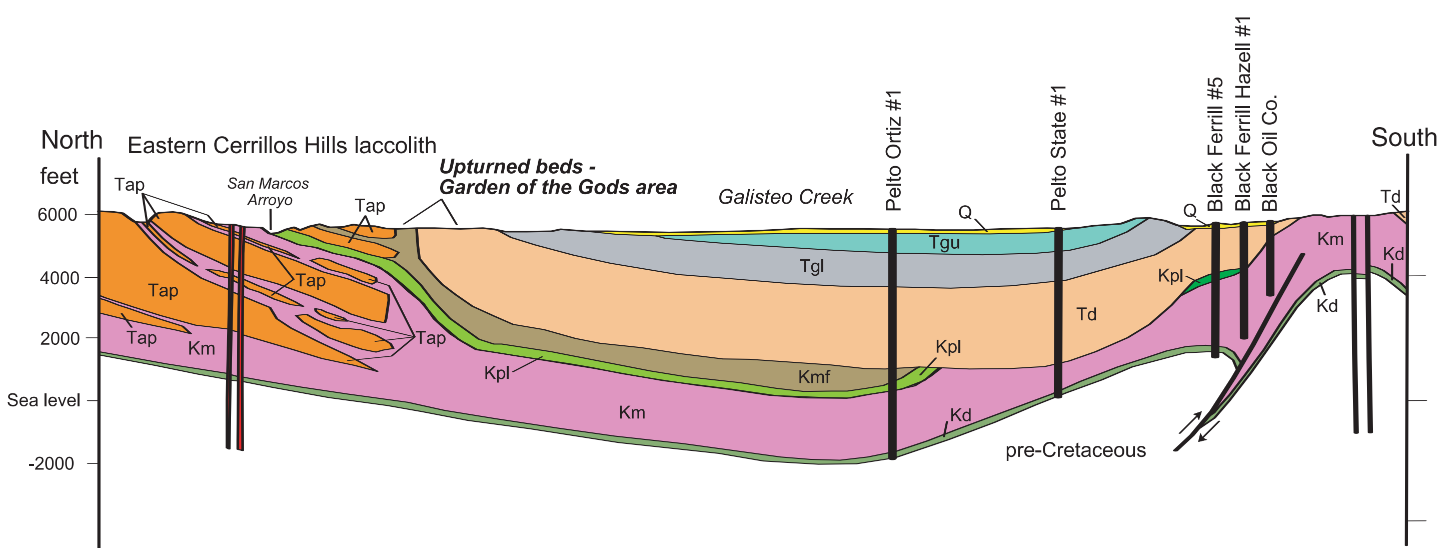


FIGURE 15—East Cerrillos Hills laccolith, showing doming of Cretaceous and Tertiary rocks. No vertical exaggeration. **Q** = Quaternary deposits; **Tap** = andesite porphyry; **Tgu** = upper Galisteo Formation; **Tgl** = lower Galisteo Formation; **Td** = Diamond Tail Formation; **Kmf** = Menefee Formation; **Kpl** = Point Lookout Sandstone; **Km** = Mancos Shale; **Kd** = Dakota Formation. From Maynard et al. (2002).

fault is equivalent to the combined thickness of the Galisteo strata, approximately 1,300 m (4,265 ft). The pre-existing fault model also is consistent with the observation that andesite-porphyry dikes intrude strands of the Tijeras–Cañoncito fault system in the Ortiz Mountains. The pre-existing fault model does not, however, account for the remaining 700 m (2,300 ft) or so of anomalous range.

Growing volcanic edifice model

The zone of neutral buoyancy would have moved upward during the period of intrusion of the laccolith group because of the construction of volcanic edifices on the porphyry belt. As the volcanic superstructure grew, country rock densities would have increased. Continuing intrusion of magma would have found neutral buoyancy at higher stratigraphic levels. The volcanic pile would have had to be 1–2 km (0.6–1.2 mi) thick to produce the observed vertical range of laccolith emplacement.

The calc-alkaline laccolith group was emplaced before the alkaline stocks. Volcanic rocks coeval with the porphyry belt, known as the Espinaso Formation, are best exposed in the Hagan Basin and in the southern part of the Española Basin, east of the Cerrillos Hills, and in a few other isolated exposures. Although volcanic vents have been identified in the northeastern part of the Cerrillos Hills (Stearns 1953b; Disbrow and Stoll 1957) and in the eastern part of the Ortiz Mountains (McRae 1958; Peterson 1958; Kay 1986; Maynard 1995), these vents appear to be related to later alkaline activity. Studies of the Espinaso Formation (Erskine and Smith 1993; Kautz et al. 1981) suggest that the lower part of the unit contains calc-alkaline rock types that may be the product of the earlier, laccolithic phase of magmatism.

Spatial relationship of laccoliths to stocks and dikes in the Ortiz porphyry belt

Twelve distinct laccoliths form most of the areal extent of exposed igneous rock in the Ortiz porphyry belt, approximately 125 km^2 (49 mi^2; Fig. 1, Table 1). In the Cerrillos Hills, Ortiz Mountains, San Pedro Mountains, and South Mountain, younger stocks, plugs, and dikes intrude the laccoliths and complicate their original configurations. The younger intrusive rocks in the Cerrillos Hills, Ortiz Mountains, and San Pedro Mountains are more varied in composition than the laccolithic rocks, but share general characteristics. Resistant medium-grained, equigranular augite ± hornblende ± biotite monzonite to monzodiorite form steep-sided discordant stocks and plugs and underlie the highest peaks in each range. Smaller stocks and dikes of latite porphyry with prominent euhedral feldspar crystals are present in various locations in the Ortiz porphyry belt. Geologic mapping shows that stocks cut the laccoliths in the Cerrillos Hills, Ortiz Mountains, and San Pedro Mountains (Stearns 1953a,b; Disbrow and Stoll 1957; Peterson 1958; McRae 1958; Atkinson 1961; Coles 1990; Maynard unpublished mapping).

In the Ortiz Mountains, major faulting along the Tijeras–Cañoncito fault system cuts the laccoliths, but predates younger calc-alkaline to alkaline stocks and base- and precious-metal mineralization (Maynard 1995). Miocene tilting, subsequent erosion, and Pliocene–Pleistocene cover further obscure the laccolithic forms.

Radial arrays of dikes of a range of compositions, distinct in appearance from the laccolith-forming andesite porphyry, have been mapped radiating from the Cerrillos Hills, the Ortiz Mountains, and, less markedly, from the San Pedro Mountains. Trachytic latite dikes cut laccolithic rocks in the Carache Canyon area in the Ortiz Mountains (Schutz 1995; Schutz and Nelsen 1990) and on the southern flank of Captain Davis Mountain (Lisenbee and Maynard 2001). Euhedral feldspar porphyry latite dikes cut laccolithic rocks in the southern part of the Cerrillos Hills (Stearns 1953a; Disbrow and Stoll 1957; Maynard et al. 2001, 2002).

Isotopic dating and age relationships

In the Ortiz porphyry belt laccolithic rocks have yielded isotopic ages ranging (including the error margins) from 33.2 to 36.2 Ma (Table 3). Crosscutting augite- and hornblende-monzonite stocks have been dated in the range from 27.9 to 31.4 Ma. No overlap appears between these two intrusive groups, confirming the field relationships.

Volcanic rocks of the Espinaso Formation have yielded isotopic ages ranging from 31.04 to 31.67 Ma in the volcanic vent at Dolores Gulch in the Ortiz Mountains. K-Ar dating of the Espinaso Formation in the Hagan Basin (Kautz et al. 1981) showed ages ranging from 33.5 to 35.3 Ma. These latter ages appear to belong to volcanic products of the earlier laccolithic event. The younger ages from Dolores Gulch come from rocks that appear related to the younger alkalic magmatic events associated with metallic mineralization in the Ortiz Mountains.

Smaller stocks and dikes of more alkalic composition (or at least poorer in quartz) intrude the andesite porphyry laccoliths and augite and hornblende monzonites in many locations in the porphyry belt. Isotopic age data for these units and for minerals associated with mineralization in the Ortiz Mountains range from 29.9 to 31.91 Ma. Error margins on the available data permit the interpretation of overlapping igneous events. However, field relationships indicate that laccolithic rocks predate all stocks and dikes (with the exception of the "Golden Dike" at Carache Canyon in the Ortiz Mountains).

Major movement on the Tijeras–Cañoncito fault system in the Ortiz Mountains, resulting in formation of the Ortiz graben, postdates the formation of the Lomas de la Bolsa and Captain Davis Mountain laccoliths. An augite-monzonite stock and the Cunningham Gulch subvolcanic stock and Dolores Gulch volcanic vent invade the Ortiz graben, with minor later movement. The relative timing of the igneous and structural events is depicted in Figure 17.

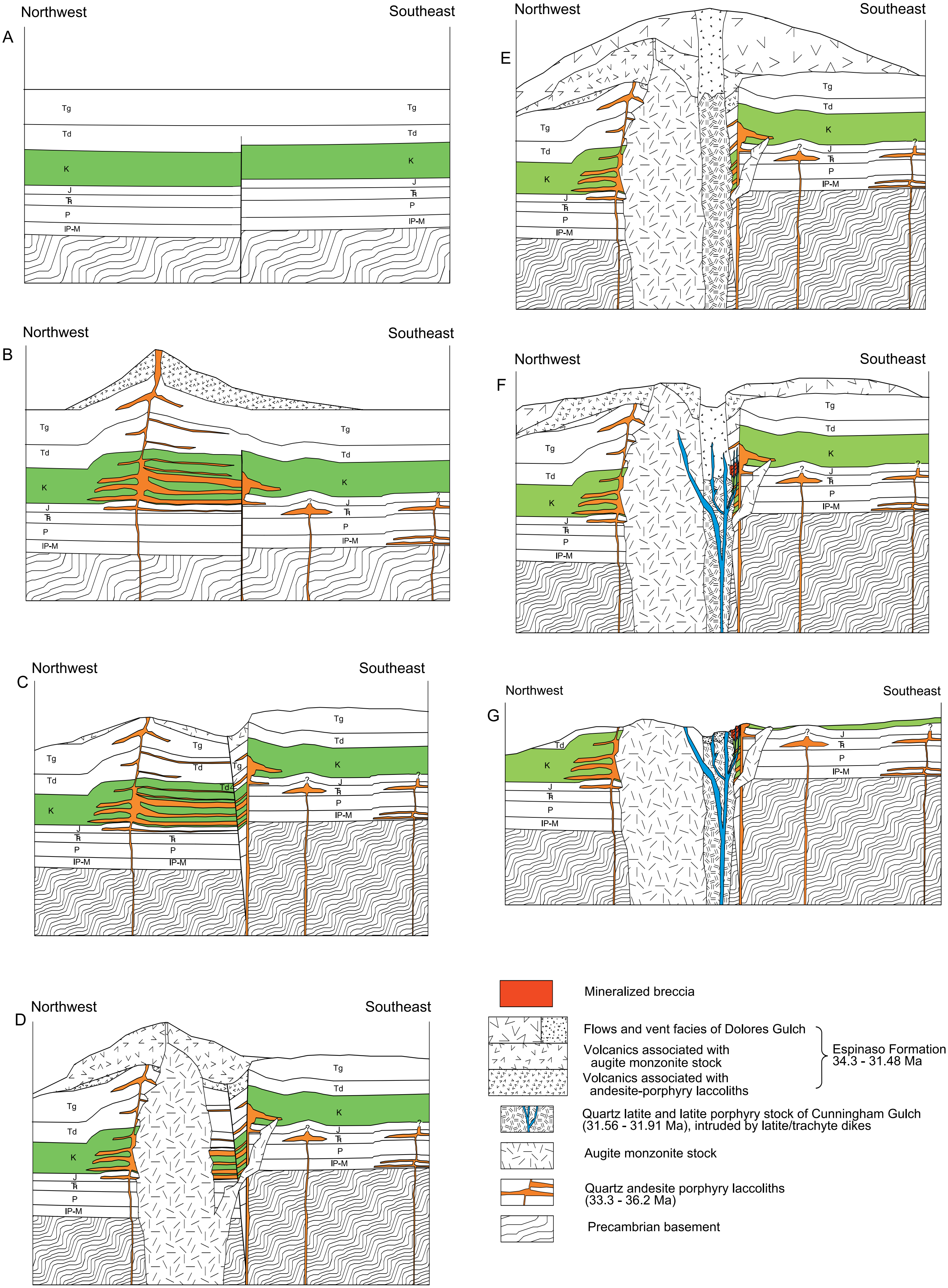
Orientation of intrusive bodies

With the exceptions of the Cerro Pelón and Captain Davis Mountain laccoliths, laccoliths of the Ortiz porphyry belt are oriented north-south over a distance of more than 40 km (25 mi). Younger, crosscutting stocks occur in clusters of varying orientation. In the Ortiz Mountains a series of stocks are aligned roughly parallel to strands of the Tijeras–Cañoncito fault system. In the San Pedro Mountains, stocks form a line roughly west to east. In the Cerrillos Hills stocks form an irregular pattern.

Dikes of a variety of compositions radiate from the Cerrillos Hills, the Ortiz Mountains, and the San Pedro Mountains. In the Ortiz Mountains orientations parallel and nearly perpendicular to principal strands of the Tijeras–Cañoncito fault system dominate. It is tempting to consider them as feeders for the laccoliths; however, their composition, texture, field relationships with laccoliths, and isotopic ages indicate that they postdate the laccoliths. Geochemical information further suggests that they are more akin to the quartz-poor stocks.

Volcanic rocks

The intrusive centers of the Ortiz porphyry belt represent the lower parts of volcanic edifices that produced the volcanic and volcano-sedimentary rocks of the Espinaso Formation. The Espinaso Formation has been described by various investigators in exposures east of the Cerrillos Hills and in the Hagan Basin (e.g., Stearns 1953a; Disbrow and Stoll 1957; Kautz et al. 1981; Erskine and Smith 1993). Volcanic breccias, in part interpreted to be vent breccias, are exposed in the northern parts of the Cerrillos Hills (Stearns 1953a; Disbrow and Stoll 1957) and in the Dolores Gulch area in the eastern part of the Ortiz Mountains (Griswold 1950; Kay 1986). Erskine and Smith (1993) concluded that the Espinaso Formation had a lower part containing volcanic clasts of calc-alkaline affinity, and an upper part containing calc-alkaline clasts and alkaline clasts. From this it is inferred that the laccolithic phase of magmatism pro-



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Mineralized breccia
Flows and vent facies of Dolores Gulch
Volcanics associated with augite monzonite stock
Volcanics associated with andesite-porphyry laccoliths
Espinaso Formation 34.3 - 31.48 Ma
Quartz latite and latite porphyry stock of Cunningham Gulch (31.56 - 31.91 Ma), intruded by latite/trachyte dikes
Augite monzonite stock
Quartz andesite porphyry laccoliths (33.3 - 36.2 Ma)
Precambrian basement

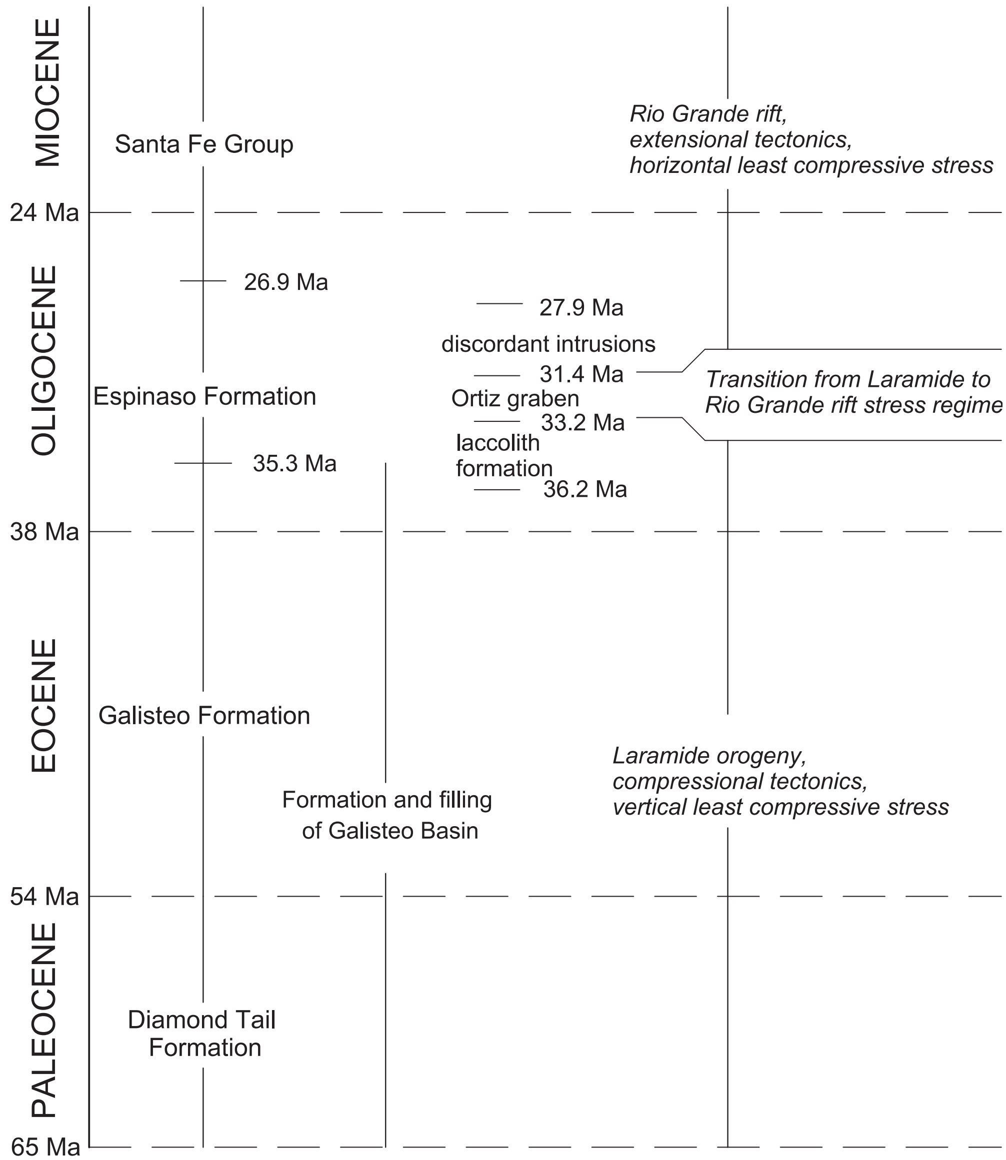

FIGURE 17—Correlation chart depicting the relationships of the Ortiz porphyry belt igneous rocks, the Espinaso volcanics, early Tertiary sedimentary rocks, and the timing of the transition from the Laramide to Rio Grande rift stress fields.

FIGURE 16—Schematic cross sections depicting evolution of laccoliths in the Ortiz porphyry belt. **A**) Down-to-the-north displacement on the Tijeras–Cañoncito fault system and deposition of early Tertiary Diamond Tail and Galisteo Formation sediments. Displacement brings Paleozoic sedimentary rocks on the south side of the Tijeras–Cañoncito fault system to the same elevation range as Jurassic and Cretaceous rocks on the north side. **B**) Laccoliths form in the range from 1,000 m to 2,000 m (from 3,280 ft to 6,560 ft) below the surface. **C**) As laccolith-related magma penetrates to the surface, resulting in volcanic edifices, the zone of neutral buoyancy rises, allowing laccoliths and sills to form at higher stratigraphic levels. **Tg** = Galisteo Formation, **Td** = Diamond Tail Formation, **K**, **J**, **TR**, **P**, and **IP–M** = Cretaceous, Jurassic, Triassic, Permian, and Pennsylvanian–Mississippian strata, respectively. **Orange** = laccoliths, **green** = Cretaceous strata and **wood grain** = Precambrian basement. Vertical exaggeration about 3.5x. **D)** Reactivation of the Tijeras–Cañoncito fault system and formaton of the Ortiz graben followed by intrusion of the augite monzonite stock. **E)** Intrusion of the Cunningham Gulch quartz latite and latite prophyry stock. Eruption from the Dolores Gulch vent partially occupies Ortiz graben. **F)** Intrusion of latite/trachyte dikes associated with gold mineralization. **G)** Present-day erosion level.

duced a volcanic edifice, which was nearly entirely removed by erosion, leaving only the flanking pyroclastic and volcano-sedimentary aprons.

Transition from Laramide to rift-related tectonic regimes

Later intrusions of the Ortiz porphyry belt form discordant dikes and stocks, as opposed to concordant intrusions, because of a change in regional stress patterns during the period 31.4–33.2 Ma. Laccoliths and sills require sigma 3 to be vertical; therefore, they are likely to have intruded in a compressional stress field. The elongate north-south orientation of the laccolithic array of the Ortiz porphyry belt suggests that the overall compression was approximately west-east during the time of intrusion of the laccoliths.

Laramide movement on the Tijeras–Cañoncito fault system has been documented and inferred in many locations along its trace (e.g., Abbott et al. 1995; Lisenbee 1967; Ferguson et al. 1999). Laramide-age north-south-trending folds, or arches, may have provided favorable sites for intrusion of the laccoliths, as first suggested by Keyes (1918). Laramide-aged folding has been interpreted at South Mountain, where the South Mountain laccolith is interpreted to have intruded a pre-existing syncline (Ferguson et al. 1999). Laramide folding and thrusting has been interpreted near the Tijeras–Cañoncito fault system where it crosses Galisteo Creek. The Captain Davis Mountain and Cerro Pelón laccoliths may have formed by virtue of their location adjacent to the Tijeras–Cañoncito fault system. Cerro Pelón laccolith may partly occupy a Laramide-age warp in this area.

In general, however, the relationship between specific Laramide faults and folds and the position of laccolithic masses is obscure, largely because of the effects of folding of beds near the margins of buried laccolithic bodies (e.g., the margins of the Cerrillos Hills), and because of tilting of most of the porphyry belt in response to opening of the Rio Grande rift during the early Miocene.

The mid-Tertiary movement on the Tijeras–Cañoncito fault system, specifically the formation of the Ortiz graben, signaled a significant change in the regional stress field from compression to extension. Faults bounding the Ortiz graben cut the laccolithic rocks and are cut in turn by an augite-monzonite stock, constraining the formation of the Ortiz graben to the 31.4–33.2 Ma interval. The younger, more alkalic, intrusive rocks tended to form stocks, plugs, and dikes in response to the reorientation of least compressive stress (sigma 3) to a horizontal orientation. The orientation of the younger intrusive bodies was strongly affected by pre-existing structures, as stated previously. More important regionally, the overall stratigraphic separation across the Tijeras–Cañoncito fault system in the Ortiz Mountains, is approximately 500 m (1,640 ft) down on the north side.

The radial pattern of dikes present around the Ortiz Mountains and the Cerrillos Hills may be related to: (1) the least stress direction perpendicular to fault strands, allowing them to dilate, and (2) development of radial fractures as a result of the load of volcanic edifices.

The use of field relations and isotopic data from the Ortiz porphyry belt serves as a tight constraint on the transition from Laramide to rift-related stress regimes discussed by Abbott et al. (2004) and Erslev (2001). They constrained the transition from Laramide- to rift-related tectonism in north-central New Mexico to some time between the late Eocene (upper part of the Galisteo Formation, perhaps 35–40 Ma, that was deposited in a Laramide basin and affected by northeast–north-northeast compression) and the earliest Miocene, about 24 Ma. Thus laccoliths formed near the time of the waning of Laramide east-west directed compression stress field with vertical sigma 3 (33.2–36.2 Ma), possibly concentrating in arches formed in earlier Laramide time. The regional stress field changed radically during the period 31.4–33.2 Ma, resulting in the reorientation to a horizontal and west-east sigma 3 and extensional movement on the Tijeras–Cañoncito fault system, signaling the beginning of regional extension and the development of the Rio Grande rift. In the Ortiz porphyry belt, further magmatic activity in the newly reoriented stress field formed dikes and roughly cylindrical discordant stocks.

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References

Abbott, J. C., Cather, S. M., and Goodwin, L. B., 1995, Paleogene synorogenic sedimentation in the Galisteo Basin related to the Tijeras–Cañoncito fault system; *in* Bauer, P. W., Kues, B. S., Dunbar, N. W., Karlstrom, K. E., and Harrison, B. (eds.), Geology of the Santa Fe region, New Mexico: New Mexico Geological Society, Guidebook 46, pp. 271–278.

Abbott, J. C., Goodwin, L. B., Kelley, S. A., and Maynard, S. R., 2004, The anatomy of a long-lived fault system—structural and thermochronologic evidence for Laramide to Quaternary activity on the Tijeras fault, New Mexico; *in* Cather, S. M., McIntosh, W. C., and Kelley, S. A. (eds.), Tectonics, geochronology, and volcanism of the Southern Rocky Mountains and Rio Grande rift: New Mexico Bureau of Geology and Mineral Resources, Bulletin 160, CD-ROM.

Armstrong, 1975, K-Ar dates from the Ortiz Mine Grant: unpublished report to Conoco, Inc.

Atkinson, W. W., Jr., 1961, Geology of the San Pedro Mountains, Santa Fe County, New Mexico: New Mexico State Bureau of Mines and Mineral Resources, Bulletin 77, 49 pp.

Bachman, G. O., 1975, Geologic map of the Madrid quadrangle, Santa Fe and Sandoval Counties, New Mexico: U.S. Geological Survey, Geologic Quadrangle Map GQ-1268, scale 1:62,500.

Bachman, G. O., and Mehnert, H. H., 1978, New K-Ar dates and the late Pliocene to Holocene geomorphic history of the central Rio Grande region, New Mexico: Geological Society of America, Bulletin, v. 89, no. 2, pp. 283–292.

Beaumont, E. C., 1979, Geology of the Cerrillos coal field, Santa Fe County, New Mexico; *in* Ingersoll, R. V., Woodward, L. A., and James, H. L. (eds.), Guidebook of Santa Fe country: New Mexico Geological Society, Guidebook 30, pp. 269–274.

Coles, D. W., 1990, Alteration and mineralization of the Carache Canyon gold prospect, Santa Fe County, New Mexico: Unpublished M.S. thesis, Colorado State University, Fort Collins, 183 pp.

Corry, C. E., 1988, Laccoliths; mechanics of emplacement and growth: Geological Society of America, Special Paper 220, 110 pp.

Cross, W., 1894, The laccolithic mountain groups of Colorado, Utah, and Arizona: U.S. Geological Survey, 14th Annual Report, Part IId, pp. 165–241.

Daly, R. A., 1933, Igneous rocks and the depths of the earth: McGraw-Hill, New York, 508 pp.

Disbrow, A. E., and Stoll, W. C., 1957, Geology of the Cerrillos area, Santa Fe County, New Mexico: New Mexico State Bureau of Mines and Mineral Resources, Bulletin 48, 73 pp.

Dixon, J. M., and Simpson, D. G., 1987, Centrifuge modeling of laccolith intrusion: Journal of Structural Geology, v. 9, no. 1, pp. 87–103.

Erskine, D. W., and Smith, G. A., 1993, Compositional characterization of volcanic products from a primarily sedimentary record: Geological Society of America, Bulletin, v. 105, no. 9, pp. 1214–1222.

Erslev, E. A., 2001, Multistage, multidirectional Tertiary shortening and compression in north-central New Mexico: Geological Society of America, Bulletin, v. 113, no. 9, pp. 63–74.

Ferguson, C. A., Osburn, G. R., and Allen, B. D., 1999, Geology of the San Pedro 7.5-minute quadrangle, Santa Fe County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Geologic Map, OF-GM 29, scale 1:24,000.

Gilbert, G. K., 1877, Geology of the Henry Mountains, Utah: U.S. Geographical and Geological Survey of the Rocky Mountain Region, 160 pp.

Griswold, C. T., 1950, Report on the mineral possibilities of the Ortiz Mine Grant: private report prepared for G.W. Potter of Joplin, Missouri.

Hunt, C. B., 1953, Geology and geography of the Henry Mountains region, Utah: U.S. Geological Survey, Professional Paper 228, 234 pp.

Hunt, C. B., 1988, The laccolith-stock controversy—new results from the southern Henry Mountains, Utah: Discussion: Geological Society of America, Bulletin, v. 100, no. 10, pp. 1657–1659.

Hunt, C. B., and Mabey, D. R., 1966, Stratigraphy and structure, Death Valley, California: U.S. Geological Survey, Professional Paper 494A, 162 pp.

Hyndman, D. W., and Alt, D., 1987, Radial dikes, laccoliths, and gelatin models: Journal of Geolo-

gy, v. 95, no. 6, pp. 763–774.
Jackson, J. A., ed., 1997, Glossary of geology, 4th edition: American Geological Institute, 784 pp.
Jackson M. D., and Pollard, D. D., 1988a, The laccolith-stock controversy—new results from the southern Henry Mountains, Utah: Geological Society of America, Bulletin, v. 100, no. 1, pp. 177–139.
Jackson, M. D., and Pollard, D. D., 1988b, The laccolith-stock controversy—new results from the southern Henry Mountains, Utah: Reply: Geological Society of America, Bulletin, v. 100, no. 10, pp. 1657–1659.
Johnson, D. W., 1903, The geology of the Cerrillos Hills, New Mexico: Colorado School of Mines Quarterly, v. 24, pp. 173–246, 303–350, 456–500; v. 25, pp. 69–98.
Kautz, P. F., Ingersoll, R. V., Baldridge, W. S., Damon, P. E., and Shafiqullah, M., 1981, Geology of the Espinaso Formation (Oligocene), north-central New Mexico, part 2: Geological Society of America, Bulletin, v. 92, no. 12, pp. 2318–2400.
Kay, B. D., 1986, Vein and breccia gold mineralization and associated igneous rocks at the Ortiz mine, New Mexico, USA: Unpublished M.S. thesis, Colorado School of Mines, Golden, 179 pp.
Kerr, A. D., and Pollard, D. D., 1998, Toward more realistic formulations for the analysis of laccoliths: Journal of Structural Geology, v. 20, no. 12, pp. 1783–1793.
Keyes, C. R., 1909, Garnet contact deposits of copper and the depths at which they are formed: Economic Geology, v. 4, pp. 365–372.
Keyes, C. R., 1918, Mechanics of laccolithic intrusion (abs.): Geological Society of America, Bulletin, v. 29, p. 75.
Keyes, C. R., 1922, New Mexican laccolithic structures: Pan-American Geologist, v. 37, no. 2, pp. 109–120.
Le Bas, M. J., Le Maitre, R. W., Streckheisen, A., and Zanettin, B., 1986, A chemical classification of volcanic rocks based on the total alkali silica diagram: Journal of Petrology, v. 27, no. 3, pp. 745–750.
Lindgren, W., and Graton, L. C., 1906, A reconnaissance of the mineral deposits of New Mexico: U.S. Geologic Survey, Bulletin 285, pp. 74–86.
Lisenbee, A. L., 1967, Geology of the Cerro Pelón–Arroyo de la Jara area, Santa Fe County, New Mexico: Unpublished M.S. thesis, University of New Mexico, 112 pp.
Lisenbee, A. L., 1999, Geology of the Galisteo 7.5-min quadrangle, Santa Fe County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Geologic Map, OF-GM 30, scale 1:24,000.
Lisenbee, A. L., and Maynard, S. R., 2001, Geology of the Captain Davis Mountain 7.5-min quadrangle, Santa Fe County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map, OF-GM 48 , scale 1:24,000.
Maynard, S. R., 1995, Gold mineralization associated with mid-Tertiary magmatism and tectonism, Ortiz Mountains, Santa Fe County, New Mexico; *in* Bauer, P. W., Kues, B. S., Dunbar, N. W., Karlstrom, K. E., and Harrison, B. (eds.), Geology of the Santa Fe region, New Mexico: New Mexico Geological Society, Guidebook 46, pp. 161–166.
Maynard, S. R., 2000, Geology of the Golden 7.5-min quadrangle, Santa Fe and Sandoval Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Geologic Map, OF-GM 36, scale 1:24,000.
Maynard, S. R., Lisenbee, A. L., and Rogers, J., 2002, Geology of the Picture Rock 7.5-minute quadrangle, Santa Fe County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map, OF-GM-51.
Maynard, S. R., Sawyer, D., and Rogers, J., 2001, Geology of the Madrid 7.5-min quadrangle, Santa Fe and Sandoval Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map, OF-GM 40, scale 1:24,000.
McIntosh, W. C., 2000, $^{40}Ar/^{39}Ar$ isotopic age determinations from the Ortiz Mountains: New Mexico Bureau of Geology and Mineral Resources memorandum.
McRae, O. M., 1958, Geology of the northern part of the Ortiz Mountains, Santa Fe County, New Mexico: Unpublished M.S. thesis, University of New Mexico, 112 pp.
Mudge, R. M., 1968, Depth control of some concordant intrusions: Geological Society of America, Bulletin, v. 79, no. 3, pp. 315–322.
Ogilvie, I. H., 1905, The high-altitude conoplain—a topographic form illustrated in the Ortiz Mountains: American Geologist, v. 36, pp. 27–34.
Ogilvie, I. H., 1908, Some igneous rocks from the Ortiz Mountains, New Mexico: Journal of Geology, v. 16, pp. 230–238.
Peterson, J. W., 1958, Geology of the southern part of the Ortiz Mountains, Santa Fe County, New Mexico: Unpublished M.S. thesis, University of New Mexico, 115 pp.
Roman-Berdiel, T., Gapais, D., and Brun, J. P., 1995, Analogue models of laccolith formation: Journal of Structural Geology, v. 17, no. 9, pp. 1337–1346.
Sauer, R. R., 1999, Petrochemistry and geochronology of plutons relative to tectonics in the San Pedro–Ortiz porphyry belt, New Mexico: Unpublished M.S. thesis, University of Colorado, Boulder, 115 pp.
Schroer, G., 1994, Geology of the Greenhorn Au-Cu skarn deposit, Lukas Canyon, Ortiz mining district, New Mexico: Unpublished M.S. thesis, Colorado State University, Fort Collins, 115 pp.
Schutz, J. L., 1995, Gold mineralization associated with alkaline intrusives at the Carache Canyon breccia pipe prospect, Ortiz Mountains, New Mexico; *in* Bauer, P. W., Kues, B. S., Dunbar, N. W., Karlstrom, K. E., and Harrison, B. (eds.), Geology of the Santa Fe region, New Mexico: New Mexico Geological Society, Guidebook 46, pp. 167–174.
Schutz, J. L., and Nelsen, C. J., 1990, Geology and gold mineralization of the Carache Canyon breccia pipe, Ortiz Mountains, New Mexico; *in* Hausen, D. M. (ed.), Gold '90: Proceedings of the Gold '90 Symposium, Salt Lake City, Utah, pp. 65–81.
Stearns, C. E., 1953a, Early Tertiary vulcanism in the Galisteo–Tonque area, north-central New Mexico: American Journal of Science, v. 251, no. 6, pp. 415–452.
Stearns, C. E., 1953b, Tertiary geology of the Galisteo–Tonque area, north-central New Mexico: Geological Society of America, Bulletin, v. 64, no. 4, pp. 459–508.
Streckheisen, A., 1979, Classification and nomenclature of volcanic rocks, lamprophyres, carbonatites, and melilitic rocks—recommendations and suggestions of the IUGS subcommission on the systematics of igneous rocks: Geology, v. 7, pp. 331–335.
Thompson, T. B., 1964, The geology of the South Mountain area, Bernalillo, Sandoval, and Santa Fe Counties, New Mexico: Unpublished M.S. thesis, University of New Mexico, 69 pp.