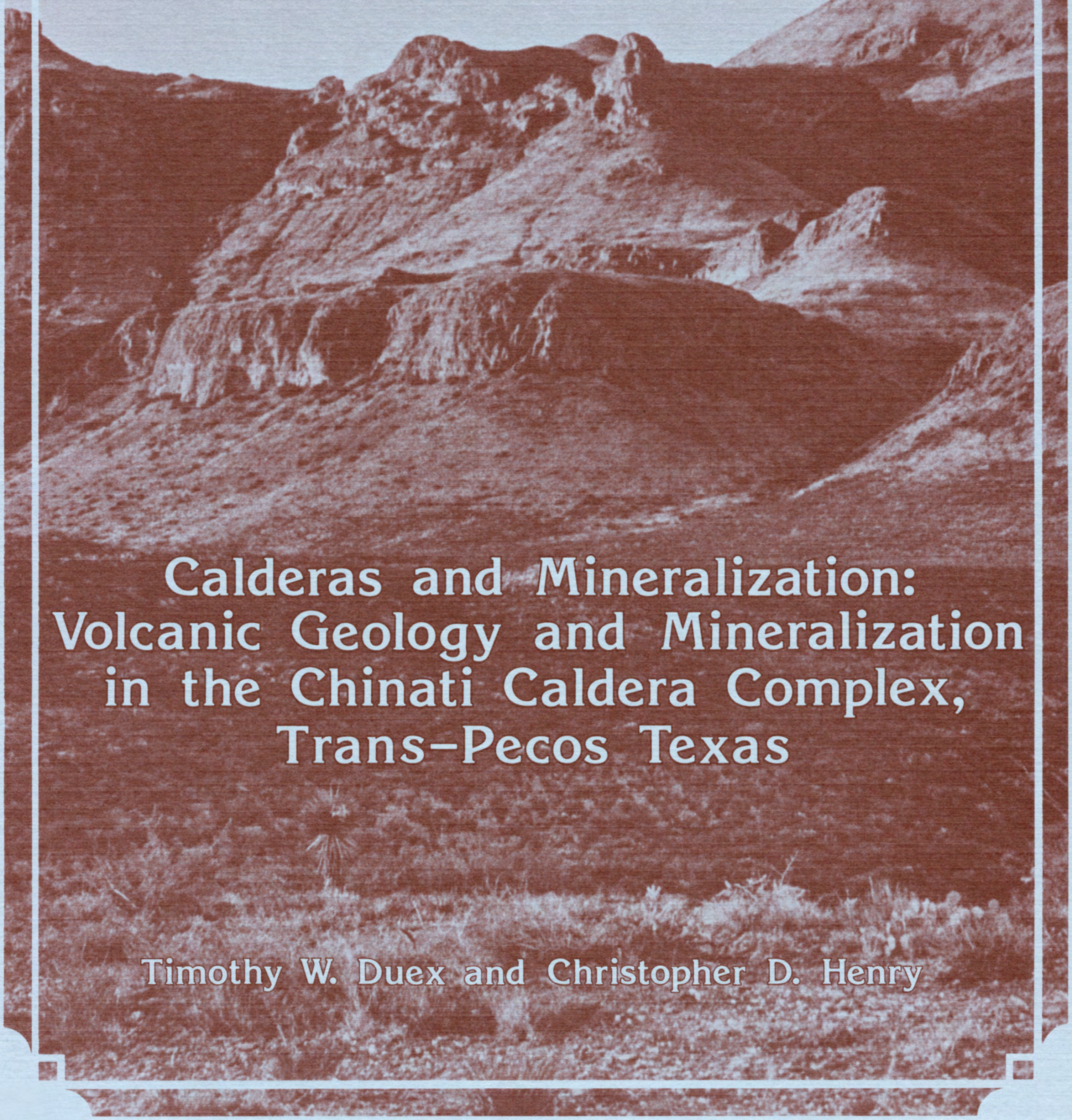
Geological Circular 81-2



Calderas and Mineralization: Volcanic Geology and Mineralization in the Chinati Caldera Complex, Trans-Pecos Texas

Timothy W. Duex and Christopher D. Henry

Bureau of Economic Geology W. L. Fisher, Director • 1981

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INTRODUCTION

This report describes preliminary results of an ongoing study of the volcanic stratigraphy, caldera activity, and known and potential mineralization of the Chinati Mountains area of Trans-Pecos Texas. Many ore deposits are spatially associated with calderas and other volcanic centers. A genetic relationship between calderas and base and precious metal mineralization has been proposed by some (Albers and Kleinhampl, 1970) and denied by others (McKee, 1976, 1979). Steven and others (1974) have demonstrated that calderas provide an important setting for mineralization in the San Juan volcanic field of Colorado. Mineralization is not found in all calderas but is apparently restricted to calderas that had complex, postsubsidence igneous activity. A comparison of volcanic setting, volcanic history, caldera evolution, and evidence of mineralization in Trans-Pecos to those of the San Juan volcanic field, a major mineral producer, indicates that Trans-Pecos Texas also could be an important mineralized region. The Chinati caldera complex in Trans-Pecos Texas contains at least two calderas that have had considerable postsubsidence activity and that display large areas of hydrothermal alteration and mineralization. Abundant prospects in Trans-Pecos and numerous producing mines immediately south of the Trans-Pecos volcanic field in Mexico are additional evidence that ore-grade deposits could occur in Texas.

The Chinati caldera complex is located in Presidio County about 40 km (25 mi) southwest of Marfa, Texas (fig. 1). A simplified geologic map, cross section, and

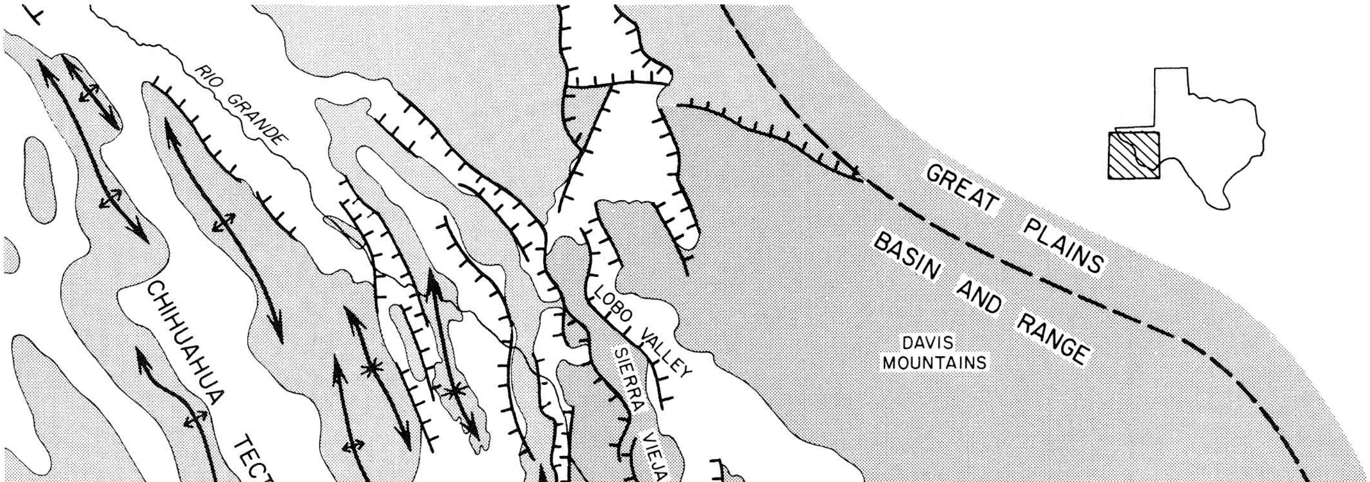

Figure 1. Index map of Trans-Pecos Texas showing location of generalized geologic map of figure 2.

stratigraphic column showing relative age relationships are shown in figures 2, 3, and 4. The Chinati caldera complex lies in the southern Basin and Range Province and is bounded on the southwest by several postvolcanic normal faults that parallel the north-northwest trend of the Rio Grande Valley. The Chinati caldera complex, as defined here, includes at least two calderas that were eruptive centers for thick accumulations of volcanic strata. It also includes several sequences of volcanic rock for which sources are currently unknown.

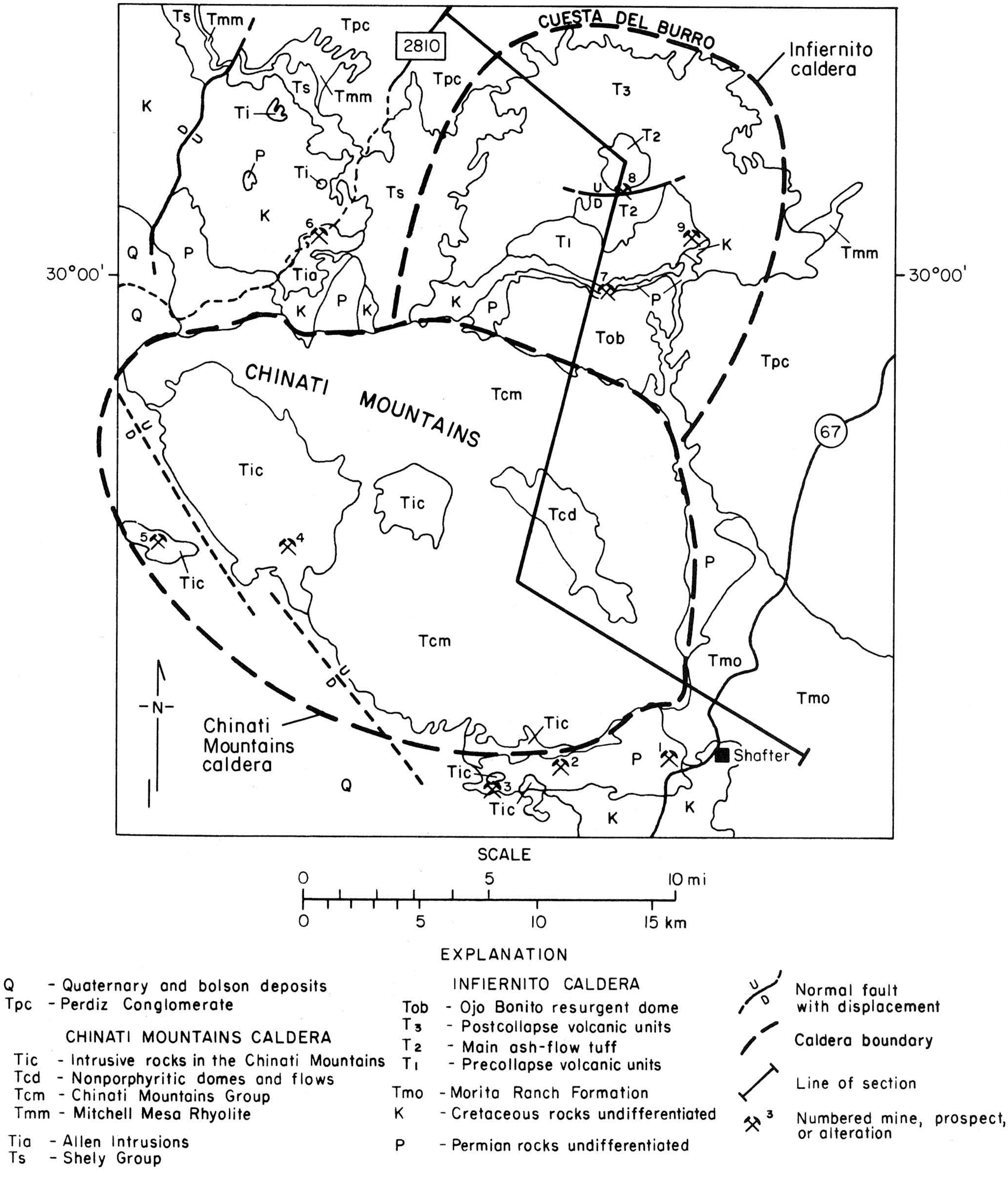

Figure 2. Generalized geologic map of the Chinati caldera complex, Trans-Pecos Texas (modified from Rix, 1953; Amsbury, 1958; Dietrich, 1966; Cepeda, 1977; and Barnes, 1979).

The Chinati Mountains caldera is the largest and best documented caldera in Trans-Pecos Texas (Cepeda, 1977, 1979). It is the probable source of the Mitchell Mesa Rhyolite, a widespread marker bed throughout Trans-Pecos, and of at least 1,000 m (3,300 ft) of lava flows and tuffs within the caldera. This caldera formed between 32 and 31 m.y. ago.

As defined in this paper, the Infiernito caldera, the second caldera of the complex, includes those rock units exposed between the Chinati Mountains on the south and the Cuesta del Burro on the north (fig. 2). It is named after Cerro Infiernito, a prominent landmark within the caldera. The Infiernito caldera is clearly older than the Chinati Mountains caldera because its southern half was destroyed by the formation of the Chinati caldera; however, no isotopic ages are currently available to document its absolute age.

The Chinati caldera complex is entirely within the Trans-Pecos alkalic igneous province described by Barker (1977). The volcanic rocks of the Chinati Mountains caldera vary systematically with decreasing age from metaluminous to peralkaline, according to whole-rock chemical analyses (Cepeda, 1977). Complete whole-rock chemical data are not available for rocks of the Infiernito caldera, but they are not peralkaline because many of them contain biotite.

Rix (1952, 1953) mapped the Chinati Peak Quadrangle and described the Chinati Mountains volcanic series as well as a group of rocks in the eastern part of the area that he correlated with the Buck Hill volcanic series of Goldich and Elms (1949). In the Presidio area, Dietrich (1966) reinterpreted the latter group of rocks as a distinct volcanic sequence, which he named the Morita Ranch Formation. No source area is known for these rocks. Cepeda (1977) studied the Chinati Mountains in detail and interpreted them as a caldera, but he did not extend his map beyond the Chinati caldera ring-fracture zone on the north where it truncates rocks of the Infiernito caldera. The geologic history of the Infiernito caldera is described in this report.

Amsbury (1958) named the Shely Group, a series of volcanic rocks on the Shely Rim. The Shely Group overlies rocks of the Infiernito caldera on its western edge and is also truncated by the Chinati Mountains caldera. Barnes (1979) extrapolated the Shely units into the Infiernito area. This report, however, shows that the Infiernito rocks are distinct from and older than the Shely Group and probably formed during development of a resurgent caldera.

STRATIGRAPHY

Pre-Tertiary Rocks

The oldest rocks exposed in the Chinati Mountains area are Upper Pennsylvanian and Permian carbonates. They crop out along the northern, eastern, and southern borders of the Chinati caldera (Skinner, 1940; Rigby, 1953; Rix, 1953; Amsbury, 1958). In the northern and northwestern parts of the area, the carbonates are silty and sandy, but in the southern parts they contain less detrital material. In the Shafter area, along the southern border of the Chinati caldera, they are the host rocks for silver and lead-zinc mineralization. Cretaceous marine carbonates and terrigenous clastics overlie the Permian rocks around the edges of the Chinati caldera and are thickest in the Loma Plata anticline.

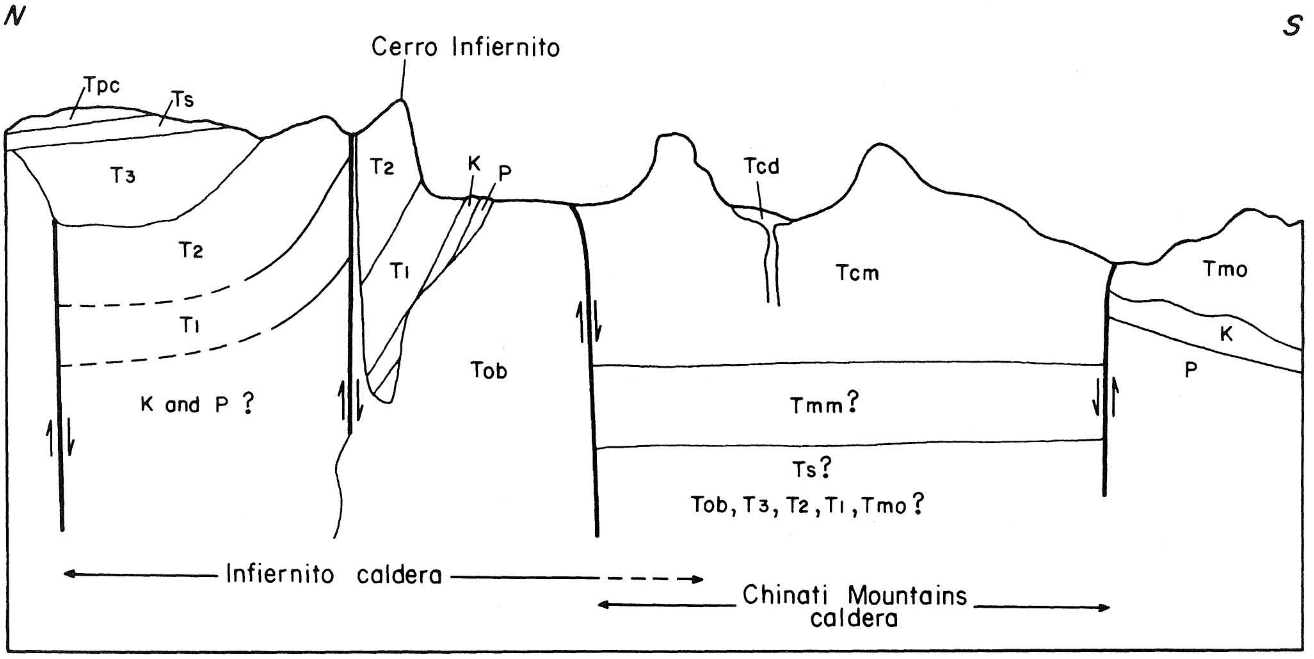

Figure 3. Schematic cross section through Infiernito and Chinati Mountains calderas. Symbols are from figure 2.

Tertiary Volcanic Rocks

Several distinct sequences of volcanic rocks that were erupted from various volcanic centers during Tertiary time overlie the Permian and Cretaceous sedimentary rocks. Relative age relationships among some volcanic sequences are not everywhere straightforward, and isotopic age data are incomplete, but the relative ages of different volcanic strata, from youngest to oldest, are shown schematically in figures 3 and 4. In the following section, the major units in each sequence are described, and relationships among separate sequences are discussed. The volcanic rocks of the Infiernito and Chinati calderas are discussed in relation to mineralization later in the text.

The two oldest and possibly coeval volcanic sequences are exposed adjacent to the Chinati Mountains caldera. They are the Morita Ranch Formation and the rocks of the Infiernito caldera. Both sequences lie disconformably on the aforementioned pre-Tertiary rocks and are unconformably overlain at least in part by the Perdiz Conglomerate. Both sequences are truncated by the Chinati caldera ring-fracture zone. However, they are nowhere in contact and have no units in common; therefore, the relative age relationship between the two series cannot be directly established (fig. 4).

Morita Ranch Formation

Shafter Area

A sequence of volcanic rocks that crop out north and east of Shafter (fig. 2) was initially assigned to the Buck Hill volcanic series by Rix (1952, 1953). Later, more extensive mapping throughout Trans-Pecos Texas revealed that the rocks formed a distinct series, which was renamed the Morita Ranch Formation by Dietrich (1966). In the Presidio area he defined the Morita Ranch Formation to include all flow and sedimentary rocks that crop out between pre-Tertiary strata and Perdiz Conglomerate. In exposures southeast of Shafter, he described four members of the formation and equated them with units that Rix mapped. The four members are Tm2 (unit T2 of Rix), black porphyritic basalt with abundant large feldspar phenocrysts; Tm3a (unit T3 of Rix), thick sequence of rhyolitic flows and tuffs; Tm3b (lower part of unit T4 of Rix), rhyolitic ash-flow tuff with abundant feldspar and minor quartz phenocrysts; and Tm4 (correlative at least in part with the upper part of unit T4 of Rix), medium- to fine-grained olivine basalt (fig. 5).

In addition, Rix (1952, 1953) noted layers of tuff and olivine basalt below Tm2 (his unit T2), which he labeled unit T1. These strata pinch out both north and south of Shafter and were not recognized by Dietrich (1966) in the Presidio area. In reconnaissance work done as part of this study, we identified a sequence of rocks just east of the boundary of the Chinati Mountains caldera and north of Shafter that is at least partly correlative with what Rix describes and maps as unit T1 (fig. 5). The lowest volcanic layer observed in this study is a lithic, moderately welded, rhyolitic ash-flow tuff that has been faulted and possibly folded along with the underlying Permian and Cretaceous sedimentary rocks. This unit, or part of it, is most likely what Rix (1953) refers to as basal tuff. On top of the ash-flow tuff is a thick but laterally discontinuous porphyritic rhyolite flow with a thick autobreccia zone at its base. Rix refers to the base as a flow breccia but maps the upper part of the body as an intrusion. The breccia and more massive upper part are interpreted here to be parts of a single flow.

The next unit observed above the porphyritic rhyolite is a thin, poorly exposed sequence of bedded tuffs and

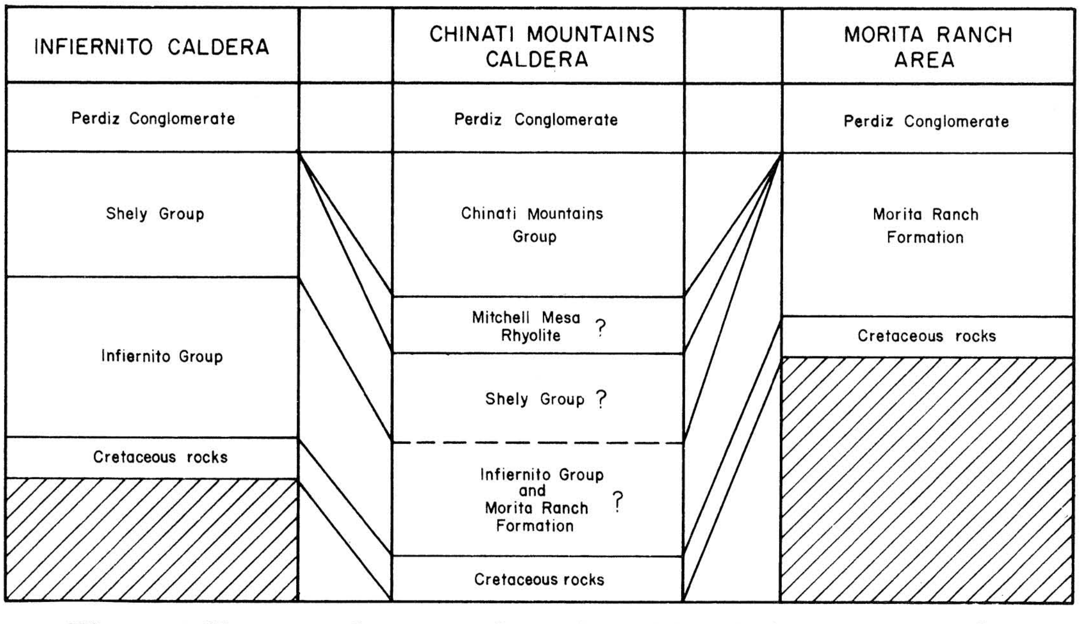

Figure 4. Known and suspected stratigraphic relations among rocks of the Chinati caldera complex.

minor mud flows. Rix does not mention these beds in his description of unit T1. The stratigraphically highest part of unit T1 observed in this area is a thick flow-banded rhyolite that Rix identified and correlated with more massive outcrops along U. S. Highway 67. Rix describes olivine basalt in the upper part of unit T1, but it was not observed in the area investigated for this report. The rest of the section (Rix's units T2 through T4 and Dietrich's units Tm2 through Tm4) is similar to what we observed and to what is summarized in figure 5.

In summary, the Morita Ranch Formation is a significant and distinctive sequence of volcanic rocks that does not correlate with the Buck Hill volcanic series to the east or with the rocks of the Infiernito or Chinati calderas to the west. The presence of biotite in several units of the Morita Ranch Formation serves to distinguish it from the Chinati Mountains Group and from other more alkaline igneous rocks of Trans-Pecos Texas that have no biotite. The presence of biotite, which also occurs in rocks of the Infiernito caldera, and the relative stratigraphic position

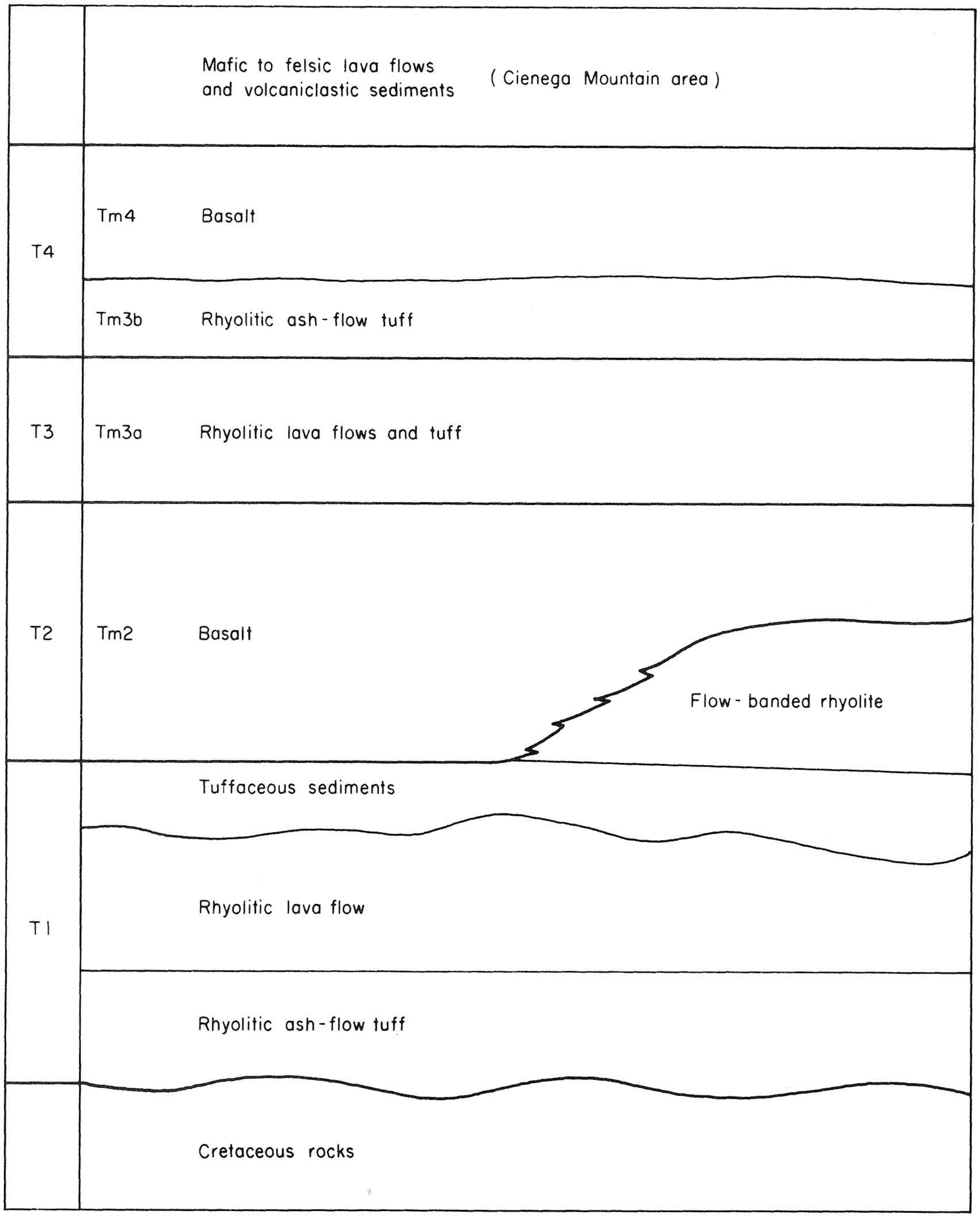

Figure 5. Stratigraphy of the Morita Ranch Formation near Shafter, derived from Rix (1952, 1953), Dietrich (1966), Hardesty (in progress), and this study. Designations T1, T2, T3, and T4 are from Rix; designations Tm2, Tm3a, Tm3b, and Tm4 are from Dietrich.

of both sequences suggest possible correlation of the Morita Ranch Formation and rocks of the Infiernito caldera. However, the source area for volcanic rocks of the Morita Ranch Formation and their relation to the Infiernito caldera cannot now be precisely established.

Cienega Mountain Area

Hardesty (in progress) has mapped an area east of Shafter in the vicinity of Cienega Mountain. He identified the upper members of the Morita Ranch Formation and a sequence of overlying mafic to felsic lava flows and volcaniclastic sediments that we are tentatively including within the Morita Ranch Formation. He also noted numerous small intrusions and a large riebeckite rhyolite intrusive dome that forms the main mass of Cienega Mountain. These units are nowhere in contact with rocks of the Chinati Mountains, but they are probably also older than the Chinati Mountains Group. Their relationship to the Infiernito caldera or to the Shely Group is uncertain. At least a few of the flows originated locally, but the source for most of them is unknown.

Infiernito Caldera

The geologic history of the Infiernito caldera is best explained by grouping the rocks into four genetic sequences: precollapse volcanic strata (T_1 of figs. 2 and 6),

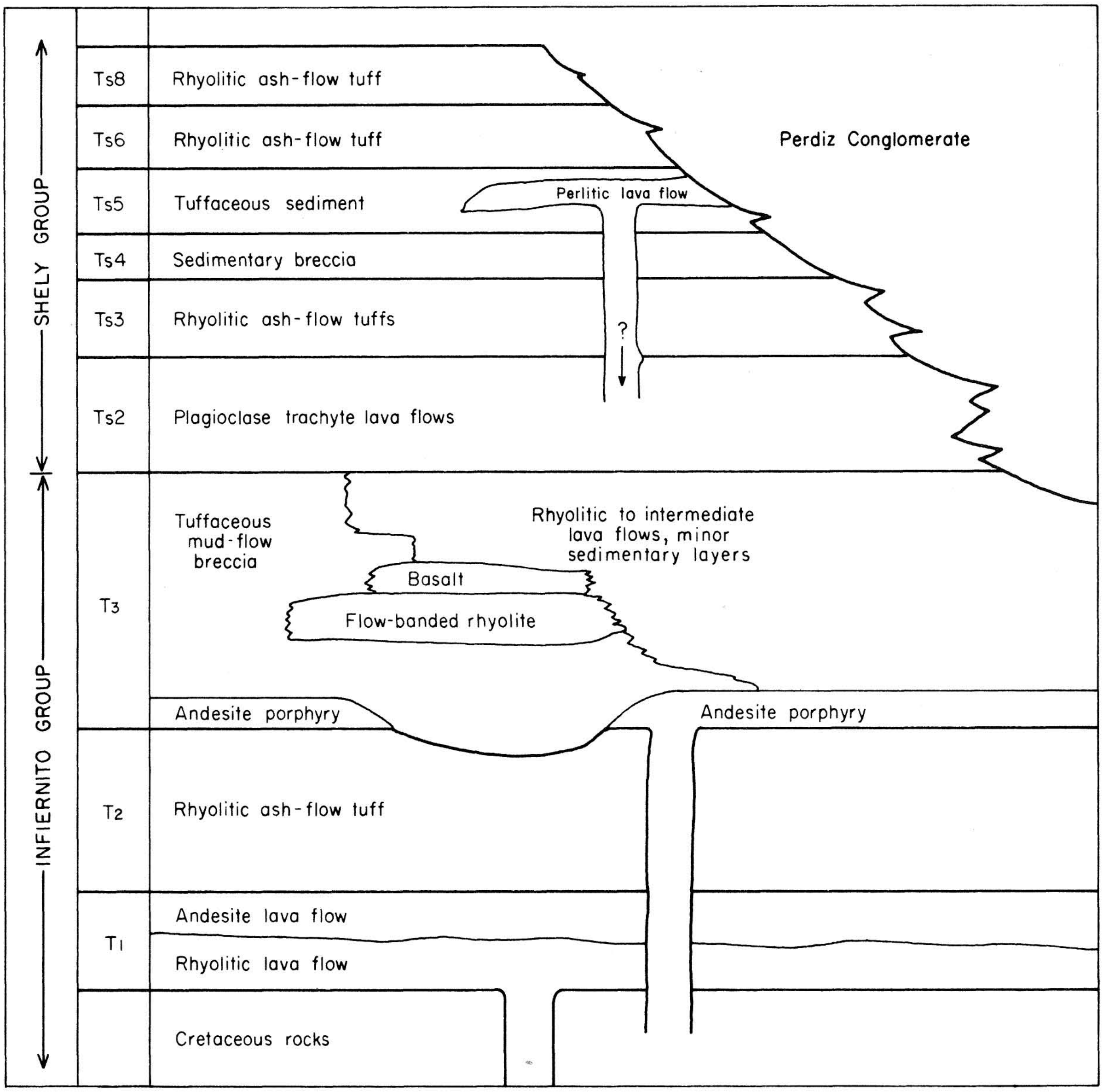

Figure 6. Stratigraphy of the Shely and Infiernito Groups in the Infiernito caldera area, northern Chinati Mountains, derived from Amsbury (1958) and this study. Ts designations are from Amsbury (1958).

ash-flow tuffs of the main eruptive event (T2), postcollapse volcanic units (T3), and intrusion of the Ojo Bonito resurgent dome (Tob). The first two units have been tilted to the north by intrusion of the resurgent dome. Postcollapse units dip gently and symmetrically away from the main ash-flow tuff to the east, west, and north. Collapse of the Chinati caldera truncated the southern half of the Infiernito caldera and presumably concealed it beneath lava flows that fill the Chinati caldera. Therefore, only the northern half of the Infiernito caldera is exposed. The caldera boundary fault is buried beneath postcollapse volcanic units, but its inferred position is shown in figures 2 and 3.

Precollapse Volcanic Rocks

The precollapse units consist of a basal rhyolite lava flow overlain by a slightly porphyritic andesite flow (fig. 6, T1). They overlie, seemingly conformably, Cretaceous and Permian sedimentary rocks and are overlain by the main ash-flow tuff. The precollapse units are exposed in low dissected hills and dip 20 to 30° in a northerly direction. Exact thicknesses and precise contacts of these flows with the overlying unit and with each other are not clear because hydrothermal alteration has destroyed primary structures and textures over large areas. At least some of the rhyolite is intrusive. Other outcrops display excellent contorted flow banding and tabular subhorizontal autobreccia zones typical of lava flows. Several areas are light- to dark-gray perlite, but most exposures are light-gray to white, fine-grained, aphyric, and devitrified rhyolite. The andesite flow overlying the rhyolite flow is light gray to gray and contains about 3 percent white, chalky feldspar phenocrysts in a fine-grained matrix. Flow structures are rare, but the consistent appearance of the andesite between the rhyolite below and the ash-flow tuff above indicates that it is a lava flow and not an intrusion.

Ash-Flow Tuff

Eruption of a thick (up to 300 m, 1,000 ft) lithic ash-flow tuff was responsible for the formation of the Infiernito caldera. It is best exposed on a steep-sided hill, referred to as Cerro Infiernito by local residents, in the center of the caldera. An equal thickness of ash-flow tuff is repeated by normal faulting on the hill just to the north (fig. 2). The ash-flow tuff is restricted to the two hills, where it forms steep cliffs and rugged terrane, and to two north-trending stream valleys immediately west and east of the hills.

Rock on Cerro Infiernito and on the hill to the north is densely welded but relatively featureless and difficult to identify as an ash-flow tuff. In places, deep weathering has etched the surface of some exposures and brought out prominent eutaxitic textures that are otherwise too subtle to observe. Compressed pumice and fine-grained gray to red lithic fragments constitute as much as 20 percent of the rock. In addition, 3 to 5 percent feldspar phenocrysts are present in a dark-gray, fine-grained, densely welded groundmass that rarely displays ghosts of flattened shards in thin sections. The same unit in the stream valleys is more distinctly an ash-flow tuff. Eutaxitic structure is more prominent, and the rock contains abundant (up to 50 percent) lithic fragments.

As many as four or five distinct layers are present on the northeastern margin of the ash-flow tuff outcrop, where it is in contact with postcollapse volcanic units. These thin ash-flow tuffs have moderately welded bases with poorly welded tuffaceous tops and are laterally continuous with the exposures on the massive cliffs. The welding zonation and lateral continuity indicate that either the ash-flow tuff is a single cooling unit composed of numerous individual flows or the less-welded layers were minor ash-flow tuff eruptions in the latter stages of caldera development that are seen only near the top of the section. Along its eastern side, the ash-flow tuff outcrop displays steeply dipping (up to 45°) eutaxitic banding, partly caused by resurgence and possibly by a large amount of differential compaction. The ash-flow tuff may have ponded against an abutment or in a depression. This may have been a primary or secondary collapse zone associated with the eruption of the ash-flow tuff. The ash-flow tuff beyond the two hills in the center of the volcanic pile is buried beneath younger rocks of the postcollapse unit.

Additional evidence for a caldera wall, revealed by detailed mapping, includes discontinuous outcrops of Permian and Cretaceous rocks through more than 90° of arc around the northeast side of the proposed caldera. These scattered thin outcrops occur at or just inside the limit of the ash-flow tuff outcrop. However, these outcrops could also be interpreted as large megabreccia blocks that slumped off an outer caldera wall and were incorporated in the ash-flow tuff, a less favored prospect because no large blocks of volcanic rocks are visible in the tuff. Regardless of the exact location of the caldera wall, the thick ash-flow tuff is significant because it is the product of a previously unknown major eruption.

Postcollapse Volcanic Rocks

A thick sequence of volcanic flows and sediments unconformably overlies the ash-flow tuff of the Infiernito caldera and underlies the Perdiz Conglomerate or the Shely Group (fig. 6). We have included within this sequence only rocks genetically related to caldera activity. From oldest to youngest these strata are andesite porphyry, tuffaceous mud-flow breccia and agglomerate, and a thick sequence of rhyolitic lava flows with minor lenses of volcaniclastic sediments and mafic lavas (fig. 6).

The andesite porphyry crops out adjacent to the main ash-flow tuff. The general outcrop pattern indicates that it is dominantly a lava flow; however, the andesite porphyry shows several different contact relationships with the ash-flow tuff. In areas of low relief, the andesite porphyry overlies the ash-flow tuff. Where the contact is well exposed in stream valleys, it is commonly steeply dipping (60 to 75°); in places the andesite porphyry even dips underneath the ash-flow tuff. The variety of relationships suggests that the andesite porphyry is in part intrusive. Lithologically similar andesite porphyry dikes up to 20 m

(65 ft) wide and more than 1,500 m (5,000 ft) long cut overlying rocks.

The andesite porphyry contains 20 to 25 percent large (5 to 15 mm) plagioclase phenocrysts in a gray fine-grained groundmass. In a few fresh outcrops, trace amounts of small (1 to 2 mm) biotite flakes can be seen in the groundmass; however, the biotite commonly has weathered to small brown rusty spots. No flow banding or flow textures are seen. Exposures are generally massive with large rounded boulders that weather along fractures.

Tuffaceous breccia and agglomerate overlie the andesite porphyry (fig. 6). This unit is extremely thick (greater than 100 m, 330 ft) on the western side of the caldera, is thinner in the northern part, and pinches out on the eastern side of the caldera. It contains a variety of rock types. Sandstones and conglomerates are obviously water laid because stream channels can be seen in several places. In other places, distinct sedimentary layers, containing boulders up to 1.5 m (5 ft) in diameter, dip up to 45° off the andesite porphyry. These well-bedded layers are rare, but consistently dip away from the Ojo Bonito intrusion.

The most common lithologies are mud-flow breccia and agglomerate. These deposits contain fragments of volcanic rocks that range from sand and gravel size up to 4.5 m (15 ft) in diameter. Boulders of flow-banded rhyolite are abundant and form resistant knobs where they weather out of the softer yellow-brown tuffaceous matrix. Andesite porphyry and basalt fragments are locally abundant. Layering in the breccia and agglomerate is not well defined, but the entire unit dips gently away from the hills of ash-flow tuff and beneath rhyolitic lava flows. This rock unit was formed from coarse pyroclastic debris shed from the caldera walls and the resurgent central part of the caldera into a moatlike depression that was deepest on the western side.

Rhyolitic and basaltic volcanism was contemporaneous with deposition of the breccia unit. In the northern part of the caldera, a thick mound of flow-banded rhyolite is sandwiched between thin breccia layers. The rhyolite consists of contorted flow-banded obsidian, perlite, and spherulitically devitrified rhyolite. Thin, irregular mafic lava flows are also found within the breccia. The largest outcrop of mafic flow is on the northern side of the caldera and stretches for about 3 km (1.8 mi). It rests directly on the flow-banded rhyolite and is overlain by the breccia unit. Smaller flows are perhaps remnants of once larger, more continuous flows that filled in low spots around the edges of the caldera. The flows consist of massive to amygdaloidal, fine-grained, reddish-brown basalt. The rhyolite and basalt flows indicate that volcanism was relatively continuous during the erosion and sedimentation that occurred after eruption of the ash-flow tuff. Such flows may represent ring-fracture volcanism.

A series of thick rhyolitic lava flows overlies the breccia-agglomerate unit. The flows extend from midway along the western side of the exposed part of the caldera, where they also abut agglomerates that filled in against the southern edge of the rhyolites. From there, the flows continue around to the eastern side of the caldera where they are truncated by the Chinati caldera. On the northeastern side of the caldera they rest directly on the flow-banded rhyolite and mafic flow. On the eastern side where the breccia pinches out they lie on top of andesite porphyry. The flows vary in number and character in different parts of the caldera. In general, the lowest layers are rhyolites; flows higher in the section are more intermediate in composition. In the eastern part of the area, at least two and up to five distinct flows occur beneath a cap of the Perdiz Conglomerate. In the western part of the area, two main flow groups are present: a lower rhyolitic group and an upper rhyodacitic group. These two flows underlie plagioclase trachyte lava flows (Ts2) of the Shely Group (Amsbury, 1958). The different flow units, including the trachyte, appear to form a continuous compositional sequence and may be genetically related. Where outcrops of the Shely units pinch out, the flows are capped by Perdiz Conglomerate.

The lowermost flow in the western part of the caldera is a massive rhyolite up to 100 m (330 ft) thick. It forms large cliffs below the northern Shely Rim but pinches out to the south where the Shely Group lies directly on the tuffaceous breccia unit. The steepness and the abrupt aspect of the pinch-out suggest high viscosity. Thick layers of black, glassy obsidian and gray perlite and minor amounts (up to 10 percent) of devitrification spherules are abundant in the lowest 10 m (33 ft) of the flow. In the upper 90 percent of the unit, devitrification is more common, and most of the rock consists of layers of intergrown devitrification spherules with no interstitial glass. The rock contains minor amounts of biotite and 1 to 5 percent white chalky feldspar phenocrysts in a gray-brown to red-brown fine-grained groundmass. The individual flow bands and the overall attitude of the unit indicate that it dips gently in a west-northwest direction.

Overlying flows are found below the Perdiz Conglomerate in the northwest part of the caldera; they pinch out to the south, but whether this is due to erosion or lack of deposition is not clear. They are generally about 50 to 60 m (160 to 190 ft) thick, dip to the west, and consist of lamellar flow-banded, noncontorted rhyolitic to dacitic lava. The gray to red-gray, fine-grained groundmass contains minor amounts of biotite and 5 to 10 percent plagioclase phenocrysts. Glassy layers and devitrification spherules are seen only near the base.

The eastern part of the caldera displays a sequence of volcanic rocks broadly similar to that of the western half, but the flows are thinner, less extensive, and more numerous. The lower layers are flow-banded obsidian and devitrified or crystalline rhyolite. The upper units are more intermediate and variable in composition, but commonly have minor amounts of biotite and 5 to 10 percent plagioclase phenocrysts in a gray to red-gray, fine-grained groundmass. Locally the flows are steeply dipping (50° to 60°) and intercalated with similarly inclined tuffs and agglomerates. Numerous faults and dikes are also apparent. All the foregoing evidence points to many local sources for the flows and pyroclastic debris in this area. We interpret the petrographic and structural evidence to indicate that the flows result from ring-fracture volcanism along the edge of the Infiernito caldera.

Ojo Bonito Pluton

The largest intrusive body in the Infiernito caldera is the Ojo Bonito pluton. The pluton crops out on the southernmost exposed part of the caldera where it abuts and is cut by the Chinati Mountains caldera (fig. 2). The intrusion may have been in the approximate center of the caldera before it was truncated by the younger caldera. It forms a roughly rectangular outcrop that is surrounded by Permian sedimentary rocks on the north, east, and west. Rix (1953, p. 131) called this the "Ojo Bonito laccolith" and described it as "a biotite hornblende alkali granophyre." It consists of about 35 percent microcline, 30 percent plagioclase, and 20 percent quartz; biotite, hornblende, magnetite, augite, and minor amounts of accessory minerals compose the remainder of the rock.

Little evidence indicates that the intrusion has the form of a laccolith. Instead, it is interpreted here as a resurgent dome for several reasons: (1) the Permian and Cretaceous sedimentary rocks, the precollapse volcanic rocks, and the main ash-flow tuff dip steeply away from the intrusion; (2) small plutons of the same rock type cut the ash-flow tuff; and (3) petrographically similar dikes cut the volcanic pile above and form a pattern radiating away from the central part of the caldera where the pluton is located. Most of the dikes are petrographically similar to the andesite porphyry in the postcaldera volcanics, but a few have biotite in a coarser groundmass and more closely resemble the rock of the Ojo Bonito intrusion. Boulders from the overlying conglomerate display a range of textures from obvious "granitic" Ojo Bonito rock, through those with progressively finer groundmass and less megascopic biotite, to those that are identical to andesite porphyry specimens. This is interpreted to indicate that the intrusive andesite porphyry and dikes are genetically related to, although perhaps not exactly contemporaneous with, the intrusion and doming associated with the Ojo Bonito emplacement. It is possible that the rocks came from a single parent magma but were emplaced over a considerable time interval. The postcollapse volcanic units are younger than the resurgent dome but are cut by some of the dikes.

The rising resurgent dome was broken by several normal faults. One set trends roughly north, and a single fault trends due east. The north-trending set extends into, but apparently disappears within, the pluton, which was probably still liquid at the time. The faults are manifested in the Permian and Cretaceous rocks as sharp flexures, involving as much as a 70° change in strike. The easternmost fault observed also clearly displaces lava flows of the precollapse volcanic units and may have served to localize intrusion of flow-banded rhyolite and hydrothermal fluids.

The east-trending fault separates the two outcrops of ash-flow tuff on Cerro Infiernito and the hill to the north. The actual fault trace has not been identified, but its effect on the ash-flow tuff is dramatic. The tuff on both hills dips approximately 15° north; the top of the unit on Cerro Infiernito is in line with the base of the tuff on the northern hill. This suggests about 300 m (1,000 ft) of displacement.

Flow-banded rhyolite forms additional small intrusive bodies. Petrographically similar rhyolite was emplaced over much of the caldera cycle. Some of the rhyolite was clearly emplaced as lava flows and some as intrusions. However, contact relationships are not clear for much of the flow-banded rhyolite, especially where it is extensively hydrothermally altered along the north-trending stream valley east of Cerro Infiernito. Most of the rhyolite in this area is probably intrusive and may have been emplaced along the north-trending normal faults.

Perdiz Conglomerate

After igneous activity ceased, the rocks of the Infiernito caldera were unroofed and eroded. The product of this episode of denudation is a boulder conglomerate that is exposed on the Cuesta del Burro and has been mapped as the Perdiz Conglomerate. The Perdiz Conglomerate (Ramsey, 1961) records the posteruptive erosion of the Chinati Mountains caldera (Walton, 1979) and thus is much younger than the Infiernito caldera. However, the conglomerate on Cuesta del Burro is composed dominantly of rock fragments from the Infiernito caldera and contains few, if any, clasts from the Chinati Mountains Group. The dominance of Infiernito clasts could indicate either that the conglomerate in this area is older than the defined Perdiz Conglomerate or that its source was almost entirely within the Infiernito area. The conglomerate on Cuesta del Burro is mapped as Perdiz because it is laterally continuous with known Perdiz outcrops.

Shely Rim Area

Shely Group

The Shely Group is a sequence of volcaniclastic sediments, rhyolitic ash-flow tuffs, and rhyolitic to trachytic lava flows (Amsbury, 1958) that overlie postcollapse volcanic units of the Infiernito caldera (fig. 6). The major outcrop of the Shely Group is along a north-trending ridge, the Shely Rim, along the western edge of the caldera (fig. 2). Amsbury observed and named eight distinct map units as follows: Ts1, fine- to coarse-grained tuff and conglomerate; Ts2, plagioclase trachyte lava flows; Ts3, light-colored densely welded, slightly porphyritic rhyolite ash-flow tuff, overlain by darker colored poorly to densely welded, fine-grained, slightly porphyritic, rhyolite ash-flow tuff; Ts4, sedimentary breccia; Ts5, light-gray tuff and tuffaceous conglomerate with local lenses of perlitic lava flow; Ts6, fine-grained, lithic, densely welded ash-flow tuff; Ts7, very fine grained, slightly porphyritic, densely welded, rhyolite ash-flow tuff; and Ts8, dense to pumiceous, flow-banded spherulitic rhyolite. Where we observed units Ts6, Ts7, and Ts8, they consisted of two densely to moderately welded ash-flow tuffs (fig. 6). Also, Ts1 does not occur in the vicinity of the Infiernito caldera; in this area Ts2 is the basal unit of the Shely Group.

Allen Intrusions

Amsbury (1958) also mapped a group of porphyritic to nonporphyritic rhyolite intrusions, including vitrophyre, perlite, intrusive breccia, and minor sedimentary breccia that he named the Allen Intrusive Complex (fig. 2). The Allen Intrusions crop out just west of the Shely Rim and just north of the Chinati caldera. Relations between individual intrusions and country rock are complex, but Amsbury found at least five distinct rock types. Field work during this project has shown that the Allen Intrusions are at least in part contemporaneous with the Shely Group. For example, one of the intrusive bodies (Ta4 of Amsbury, 1958) along the eastern side of the complex is laterally continuous into a perlite lava flow in unit Ts5 (unit Ts5p of Amsbury) (fig. 6). The Allen Intrusions were apparently shallow bodies producing both lava flows and pyroclastic material at the same time that the Shely Group was erupted.

Relations to the Infiernito Caldera

The Shely Group is a significant accumulation of volcanic material. However, its source area and genetic relation to older and younger volcanic rocks are not clear. Rhyolitic flows of the postcollapse volcanic units of the Infiernito caldera grade upward into more intermediate rocks and appear to form a continuous compositional sequence with unit Ts2, plagioclase trachyte. This association suggests that Ts2 is genetically related to the late Infiernito rocks; the complete sequence of rhyolitic to intermediate lava flows could represent sequential eruptions from a zoned or evolving magma chamber.

The transition from intermediate lava flows (Ts2) to dominantly rhyolitic ash-flow tuffs and tuffaceous sediments (Ts3 to Ts8) represents a marked change in style of eruption and chemical composition. Considerable local relief exists on the upper surface of Ts2, particularly along the southern part of Shely Rim. Ash-flow tuffs of units Ts3 and possibly Ts6 fill valleys cut into Ts2. The dominantly rhyolitic ash-flow tuffs and tuffaceous sediments of the upper part of the Shely Group may represent renewal of explosive volcanism in the Infiernito caldera, initial phases of pyroclastic activity in the Chinati caldera, or eruption from an as yet unidentified volcanic center. Most evidence indicates that the pyroclastic rocks of the Shely Group are not derived from the Infiernito caldera. Ash-flow tuffs of the Shely Group, most notably Ts6, both thicken and increase in number of flows toward the south (toward the Chinati caldera) rather than toward the Infiernito caldera to the east. Also, conglomerate lenses within Ts5 contain abundant coarse clasts of the Ojo Bonito intrusion. Much time must have elapsed between the initial emplacement of the intrusion and its subsequent unroofing, erosion, and deposition within Ts5. Thus the Shely Group above Ts2 may have been deposited long after cessation of activity in the Infiernito caldera. Possibly the Shely Group and the associated Allen Intrusions represent initial local activity of the developing Chinati Mountains caldera. Absolute ages to substantiate hypotheses are not available, however, and the exact significance of the Shely Group remains unclear.

"Shely Cauldron"

Cofer (1980) proposed that a large caldera exists in the area north and west of the Chinati Mountains. He relates volcanic and intrusive rocks from the area that encompasses much of the Infiernito caldera, the Shely Rim, the Allen Intrusions, and parts of the Sierra Vieja to the eruption, collapse, and resurgence of the "Shely cauldron." He recognizes neither the Infiernito caldera nor the relative timing of events in the volcanic history of the Chinati Mountains area as interpreted in this report. Therefore, the conclusions reached in this report and those of Cofer (1980) are largely incompatible.

Chinati Mountains Group

The Chinati Mountains Group is composed of more than 1,000 m (3,300 ft) of flows and tuffs within the Chinati Mountains caldera (figs. 2, 3). Stratigraphic nomenclature of previous works by Rix (1953), Amsbury (1958), and Cepeda (1977) is given in table 1. This report summarizes the stratigraphy as described by Cepeda (1977).

Table 1. Nomenclature of the Chinati Mountains Group.

RIX (1953)	AMSBURY (1958)	CEPEDA (1977)
T8 soda rhyolite	Tc6 rhyolite	upper rhyolite nonporphyritic domes and flows
T7 olivine augite andesine trachyte	Tc5 trachyte	upper trachyte
T6 soda rhyolite	Tc4 rhyolite	lower rhyolite
T5 quartz trachyte	Tc3 trachyte	middle trachyte
	Tc2 trachyte	lower trachyte
	Tc1 conglomerate	basal conglomerate

Mitchell Mesa Rhyolite

The Mitchell Mesa Rhyolite is the most extensive ash-flow tuff of the Trans-Pecos volcanic field. Eruption of the Mitchell Mesa resulted in the formation of the Chinati Mountains caldera, although it is not part of the Chinati Mountains Group (Cepeda, 1977). The Mitchell Mesa is not exposed within the caldera; however, a thick section of the tuff may be exposed beneath the lava flows of the Chinati Mountains Group (fig. 3). Collapse of the caldera took place along a well-defined zone that is exposed along the northern, eastern, and southern sides of the caldera (fig. 2). The caldera has been truncated by a major Basin-and-Range normal fault along the west side; the caldera boundary there is buried beneath approximately 1,000 m (3,300 ft) of basin fill.

Lower and Middle Trachytes

Both of these units form small outcrops near the margins of the caldera and together are approximately 250 m (850 ft) thick. They are porphyritic, containing up to 25 volume percent plagioclase, anorthoclase, and augite phenocrysts in a fine-grained groundmass of feldspar, opaques, and clinopyroxene. Magnetite, ilmenite, and apatite are common accessory minerals.

Lower Rhyolite

The lower rhyolite is the most widespread unit of the Chinati Mountains Group. It ranges in thickness from 20 m (65 ft) at the northern margin of the caldera to a maximum of 415 m (1,350 ft) along the western edge of the range. It is characterized by large (up to 1 cm, 0.4 inch, in diameter) anorthoclase phenocrysts, which constitute up to 15 percent of the rock. Quartz is the only other phenocryst and makes up 4 to 6 percent of the rock. In the east-central part, the lower rhyolite is abruptly cut off by a series of nonporphyritic domes and flows (fig. 2). Rounded cobbles of lower rhyolite within the nonporphyritic flows indicate that the lower rhyolite (and possibly the upper trachyte) is older than the nonporphyritic domes and flows.

Upper Trachyte

The upper trachyte so closely resembles the middle trachyte that it is distinguished only where the lower rhyolite is present. Its thickness varies from more than 400 m (1,300 ft) near Chinati Peak to about 20 m (65 ft) in its easternmost exposure, where it has been thinned by erosion. Two distinct textural variations are evident. Lower flows contain from 5 to 15 percent fine (1 to 2 mm) plagioclase phenocrysts. Upper flows contain about 25 percent larger (0.3 to 1 cm) phenocrysts. Vitrophyres, which are entirely lacking in the middle trachyte, occur at the base of several flows in the lower part of the upper trachyte north of Chinati Peak. The vitrophyres contain approximately 10 percent plagioclase up to 2 mm long, from 2 to 3 percent augite, 2 to 3 percent anorthoclase, and 1 to 2 percent generally equant opaque phenocrysts in a matrix of light-brown glass.

Nonporphyritic Domes and Flows

Four rhyolitic flow-banded domes form an arc concave to the south in the eastern part of the caldera. Flows extend south from the arc of domes and are as much as 50 to 60 m (165 to 200 ft) thick. Field observations suggest that (1) the arcuate trend of domes probably represents a ring-fracture zone on the boundary of a secondary collapse zone and that (2) collapse of this zone took place in more than one episode.

Upper Rhyolite

The upper rhyolite is a porphyritic gray to green lithic-crystal tuff with abundant (20 to 25 percent) small (1 to 3 mm) tabular anorthoclase phenocrysts. Exposures of this rock are largely restricted to a circular area approximately 5 km (3 mi) in diameter in the central part of the mountains, where it is estimated to be greater than 180 m (600 ft) thick. It contains approximately 10 percent resorbed quartz and 1 percent prismatic amphibole phenocrysts in addition to the anorthoclase phenocrysts. Aggregates of a dark to bright green, probably sodic, clinopyroxene, and granophyric-like textures are common in parts of the upper rhyolite. The upper rhyolite is interpreted as a peralkaline ash-flow tuff unit that accumulated predominantly in its own collapse zone and was the last major eruptive activity in the Chinati Mountains.

West Chinati Stock

The West Chinati Stock, the largest intrusive body in the Chinati Mountains (60 km^2, 20 mi^2, in area), is interpreted as a major resurgent dome. Two distinct rock types compose the intrusive mass: a dark plagioclase-rich quartz monzodiorite outer shell at least 250 m (850 ft) thick and a core of leucocratic porphyritic hornblende granite. Microgranite dikes and plugs up to several meters wide and hundreds of meters long intrude the quartz monzodiorite throughout its outcrop. The West Chinati Stock and ring-fracture intrusions along the southern boundary of the caldera are shown as Tic on figure 2.

Ring-Fracture Intrusions

Several types of small intrusive bodies occur around the margins of the Chinati caldera and are interpreted to be related to igneous activity along the ring-fracture zone. Aphyric dikes and plugs with contorted flow banding intrude the upper trachyte and the lower rhyolite in the northern part of the caldera but are too small to show on figure 2. The dikes range up to 5 m (17 ft) thick, and the plugs are as much as 100 m (330 ft) wide. A blue color is imparted to the plugs by small bluish-purple grains of amphibole, which suggests a peralkaline affinity.

Irregularly shaped sills, dikes, and stocks occur along the southern margin of the Chinati Mountains west of the town of Shafter. They occur between volcanic rocks of the Chinati Mountains Group and Permian strata, and within the Permian rocks. Mica and hornblende andesite porphyries are the most common rock types.

Geochemistry of the Chinati Mountains Group

Cepeda (1977) used whole-rock and mineral chemical data to show that crystal fractionation was an important mechanism in the chemical evolution of the extrusive rocks of the Chinati Mountains caldera. Mixing calculations show that it is possible to produce the more differentiated, peralkaline members of the volcanic series from the most mafic member by removal of various amounts of phenocryst minerals. For example, calculations show that 100 parts upper trachyte will yield 65 parts middle trachyte, 38 parts lower rhyolite, 22 to 25 parts upper rhyolite, or 23 parts Mitchell Mesa Rhyolite if variable percentages of plagioclase, olivine, augite, magnetite, and anorthoclase phenocrysts are removed. A parent magma having the composition of the upper trachyte would yield an amount of peralkaline (upper) rhyolite approximately one fifth its original amount. Actual percentages of minerals and mineral and rock composition are listed in Cepeda (1977).

The Mitchell Mesa was probably an early differentiate of the magma that produced the rocks of the Chinati Mountains Group. Eruption of the alkali- and silica-rich Mitchell Mesa left a more mafic and alkali-poor residual magma, probably similar to the trachytes in composition. Subsequent differentiation of the residual magma produced the lower and upper rhyolites.

Trace-element data given in Cepeda and others (in press) also show consistent trends for volcanic rocks of the Chinati Mountains. Uranium and thorium (and to a lesser extent, molybdenum, lithium, and beryllium) tend to increase systematically from the oldest, least evolved parental material to the youngest, most evolved products of differentiation of the Chinati Mountains Group. The most clear-cut trend is from upper trachyte through flow-banded nonporphyritic rhyolite to upper rhyolite and peralkaline dikes. Uranium, thorium, molybdenum, lithium, and beryllium all increase; the highest concentrations are in the vitrophyre of the upper rhyolite. Lower concentrations in some upper rhyolite samples probably reflect postmagmatic processes. Cepeda and others (in press) conclude that uranium concentrations in all the rocks of the Chinati Mountains Group are sufficiently high to make them adequate source rocks for uranium deposits.

MINERALIZATION IN THE CHINATI CALDERA COMPLEX

Mineralization in the Chinati Mountains area is spatially and probably genetically related to caldera structures, development, and activity. Theoretically, economic deposits could form in several stages of development of a caldera. The ring-fracture, or collapse, zone around the edge of the caldera provides an ideal pathway for percolation of hydrothermal fluids and subsequent mineral deposition either in the fracture zone itself or in adjacent rocks. Also, ring fractures remain zones of weakness along which late-stage, trace-element-enriched magmatic differentiates can intrude and create economically exploitable concentrations. A second potential site of mineralization is in or adjacent to the resurgent dome in the central part of a caldera. The most likely types of deposits in this environment are vein, disseminated porphyry, or contact metasomatic deposits. Finally, mobilization and enrichment of minor elements could occur at several stages in caldera development, including (1) differentiation and fractional crystallization of plutonic igneous bodies; (2) devitrification and vapor-phase crystallization of volcanic rocks; and (3) low-temperature weathering or diagenesis of any of the products of a caldera. The Chinati Mountains area displays excellent examples of these types of deposits.

Shafter Area

The largest silver-producing area in Texas occurs west of Shafter at the southern edge of the Chinati Mountains (Ross, 1943). Base metal deposits (Ross, 1943) of sphalerite, galena, and rare native lead occur with argentite in veins and mantos in Permian and Cretaceous limestones along east-west-trending normal faults (fig. 2, mines no. 1 and 2). The age of mineralization has not been established but is most likely post-early-Tertiary because igneous bodies of probable early Tertiary age that cut Cretaceous strata show the effects of mineralization (Ross, 1943, p. 89). We believe that mineralization resulted from hydrothermal activity generated by intrusions along the southern ring-fracture zone of the caldera. The east-west-trending fractures, which commonly control ore distribution, parallel the caldera margin and are probably part of the ring-fracture zone.

Just west of Shafter, disseminated copper-molybdenum mineralization occurs in intrusive rocks that may also be ring-fracture intrusions of the caldera (fig. 2, prospect no. 3) (McAnulty, 1976). The area has recently been explored, and unconfirmed reports indicate that a minable deposit was discovered.

San Antonio Canyon Area

Numerous prospects and small abandoned mine sites occur in the San Antonio Canyon area along the western side of the Chinati Mountains (fig. 2, prospects no. 4 and 5). Mineralization occurs dominantly in the West Chinati Stock. Two types of ore deposits are present (McAnulty, 1972): (1) lead, zinc, and silver minerals and fluorite in fissure veins, and (2) disseminated copper mineralization in a variety of rock types around the margin of the West Chinati Stock. Sporadic exploration and mining have occurred since the 1890's, and potentially commercial deposits of lead, zinc, silver, fluorspar, and copper exist. The San Antonio Canyon area is an excellent example of alteration and mineralization associated with resurgent doming of a caldera.

Chinati Mountains Group

Fractional crystallization of magma that formed the Chinati Mountains Group has produced late-stage differentiates, particularly peralkaline rhyolites, enriched in uranium, thorium, molybdenum, beryllium, and lithium (Cepeda and others, in press). Devitrification and vapor-phase crystallization of the volatile-rich upper rhyolite have released uranium, molybdenum, beryllium, lithium, and fluorine, probably as fluoride complexes in the vapor phase. Granophyric crystallization resulting from slow cooling of thick caldera-fill upper rhyolite has released thorium in addition to the other five elements, probably also as fluoride complexes but in a more hydrothermal phase. Cepeda and others (in press) conclude that hydrothermal uranium deposits could occur in the Chinati Mountains, particularly as uraniferous fluorite deposits. However, no such deposits have been found.

Allen Intrusions

Fracture zones in the Allen Intrusions (fig. 2, prospect no. 6) contain uranium mineralization consisting of secondary uranium minerals (autunite, metatorbernite, and tyuyamunite) and uraniferous iron-manganese oxyhydroxides (Henry and others, 1980). Amsbury (1958) states that 200 tons of ore, averaging 0.34 percent U_3O_8, were mined from a trench along a wide fracture zone; the ore was stockpiled nearby but never processed. Henry and others (1980) report U_3O_8 concentrations up to 1,430 ppm for samples from clay gouge along the trench, and they list the Allen Intrusions as a favorable environment for the formation of uranium deposits. The probable origin of the deposits consists of (1) release of uranium from rocks of the Allen Intrusions themselves or of the Shely Group, (2) transport of uranium in ground water, and (3) adsorption of uranium by iron-manganese oxyhydroxides along the fracture zones. The secondary uranium minerals result from supergene enrichment. It is possible that small-scale, low-tonnage deposits exist in the Allen Intrusions, but on the basis of inspection of diamond drill core, Henry and others (1980) concluded that uranium concentrations decrease with depth along fractures.

Infiernito Caldera

Abundant areas of hydrothermal alteration and possible mineralization occur within rocks of the Infiernito caldera. The most promising environments for potential economic deposits are (1) in and around the margins of the Ojo Bonito pluton and in small apophyses extending from it (fig. 2, prospects no. 7 and 8); (2) in large altered areas within precollapse volcanic units and flow-banded rhyolite (fig. 2, prospect no. 9); and (3) in altered areas associated with andesite porphyry bodies.

The most extensive hydrothermal alteration is associated with intrusion of the Ojo Bonito pluton during resurgent doming, but additional alteration is associated with the intrusive flow-banded rhyolites, many of which are highly altered. Abundant alteration occurs in the intrusion and in Permian rocks adjacent to it (fig. 2, prospect no. 7). Two altered areas occur in the main ash-flow tuff where it is intruded by small apophyses of Ojo Bonito (fig. 2, prospect no. 8). In some places, altered areas are associated with the andesite porphyry unit that may be genetically related to resurgence. Pyrite and other currently unidentified sulfides are commonly found within altered rocks. Mineralization in the Ojo Bonito pluton may be analogous to mineralization in the West Chinati Stock. Mineralization in the resurgent dome of the Chinati Mountains is more abundant and well exposed, perhaps because postcaldera faulting and subsequent erosion have combined to cut deeply into the pluton and uncover its mineralized parts.

Similarly, the ring-fracture zone of the Infiernito caldera is not as well exposed as that of the Chinati caldera, presumably because it is covered by postcollapse, ring-fracture volcanic rocks. The ring-fracture zone of the Chinati caldera places volcanic rock directly against well-exposed Permian and Cretaceous strata that are the host rocks for vein and manto deposits at Shafter. The ring-fracture zone of the Infiernito caldera is not as well exposed, and only small outcrops of Permian and Cretaceous rocks are seen. These sedimentary units do exist at depth, but they are covered by thick rhyolitic and basaltic flows. At one locality on the east side of the Ojo Bonito pluton where the Cieneguita Formation of Permian age is fairly well exposed, Rix (1953, p. 134) reports a pyroxenite sill that contains molybdenite, pyrite, galena, and sphalerite. The relationship of this sill to the Infiernito caldera is unknown, but it illustrates the potential for mineralization in and around the Infiernito. Similar mineralization elsewhere around the edge of the Infiernito caldera could be hidden beneath volcanic rocks.

Only speculative conclusions about mineralization in the Infiernito caldera are possible because only surface sampling has been done. However, two environments in which potentially economic ore deposits could form are (1) in the ring-fracture zone around the edge of the caldera, where mantos and veins could replace country rock, such as the mineralization at Shafter in the Chinati caldera; and (2) as vein or disseminated deposits within or adjacent to the Ojo Bonito resurgent dome, which would be analogous to mineralization in the San Antonio Canyon area of the Chinati caldera.

CONCLUSIONS

The Chinati caldera complex consists of at least two resurgent calderas. The youngest and best exposed is the Chinati Mountains caldera; its extrusive products show a systematic whole-rock and trace-element chemical variation that can be related to fractional crystallization of a parent magma. The Infiernito caldera, an older and previously unidentified volcanic center, occurs north of and is cut by the Chinati Mountains caldera. Several other sequences of volcanic rocks found in the region cannot be assigned definitely to either source and may imply the presence of additional calderas. Mineralization in the Chinati Mountains area can be genetically related to caldera structures and activity. The best targets for further exploration are (1) in ring-fracture zones around the edges of the calderas, and (2) in and around the margins of resurgent domes of the calderas.

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