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GEOLOGY OF THE NORTHERN VALLES CALDERA AND TOLEDO EMBAYMENT, NEW MEXICO

JAMIE N. GARDNER and FRASER GOFF
Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract—Detailed geologic mapping supported by geochronology and petrography shows that the northern Valles caldera records a complex history of pre-caldera volcanism and Rio Grande rift-related sedimentation, caldera collapse and mass wasting, ring-fracture volcanism and structurally focused volcanism within the Toledo embayment, and formation of intracaldera lacustrine deposits and alluvial terraces. The prominent northeastern grain of the Jemez lineament is locally defined by the Jemez fault zone, Redondo Creek graben, Toledo embayment, a structural discontinuity, the Embudo fault zone, and short faults in the map area. The main ring fracture collapse structures of the Toledo and Valles calderas were nearly coincident. Although the origin of the Toledo embayment is not entirely resolved, geologic arguments constrain its formation between 2.3 and 1.5 Ma. Based on geomorphic and other field relations of domes and flows, the structural history of the area, and timing constraints, we argue that the Toledo embayment formed during collapse of the Toledo caldera (1.61 Ma) along a structurally controlled zone that had hosted a northeasterly-elongated offshoot from the main Toledo caldera magma body. Field and laboratory data suggest that the hypabyssal rocks of the Cerro Rubio hills are shallow remnants of earlier Tschicoma volcanoes that covered the present area of the embayment before formation of Toledo caldera. The embayment became the site of structurally focused rhyolitic extrusions and explosive eruptions after caldera formation.

INTRODUCTION

The Jemez Mountains of northern New Mexico are the result of a volcanic and tectonic history that spans at least the last 16.5 Ma (Gardner et al., 1986). Particularly famous in this rich history are the two caldera-forming events that gave rise to the Otowi (1.61 Ma; Toledo caldera) and Tshirege (1.22 Ma; Valles caldera) members of the Bandelier Tuff (Smith and Bailey, 1966; 1968; Smith et al., 1970; Izett and Obradovich, 1994). Smaller volume, intracauldron volcanism followed each major caldera-forming event (Fig. 1), producing the Cerro Toledo Rhyolite (roughly 1.6 Ma to 1.23 Ma; Heiken et al., 1986; Spell et al., this volume) and the Valles Rhyolite (1.13 Ma to about 0.06 Ma; Spell and Harrison, 1993; Toyoda et al., 1995; Reneau et al., 1996).

The geology of the northern Valles caldera and the Toledo embayment (Fig. 1) is dominated by caldera collapse and mass wasting of the caldera walls, young volcanism, and fluvial and lacustrine sedimentation. The northern part of the caldera, in addition, affords some of the thickest

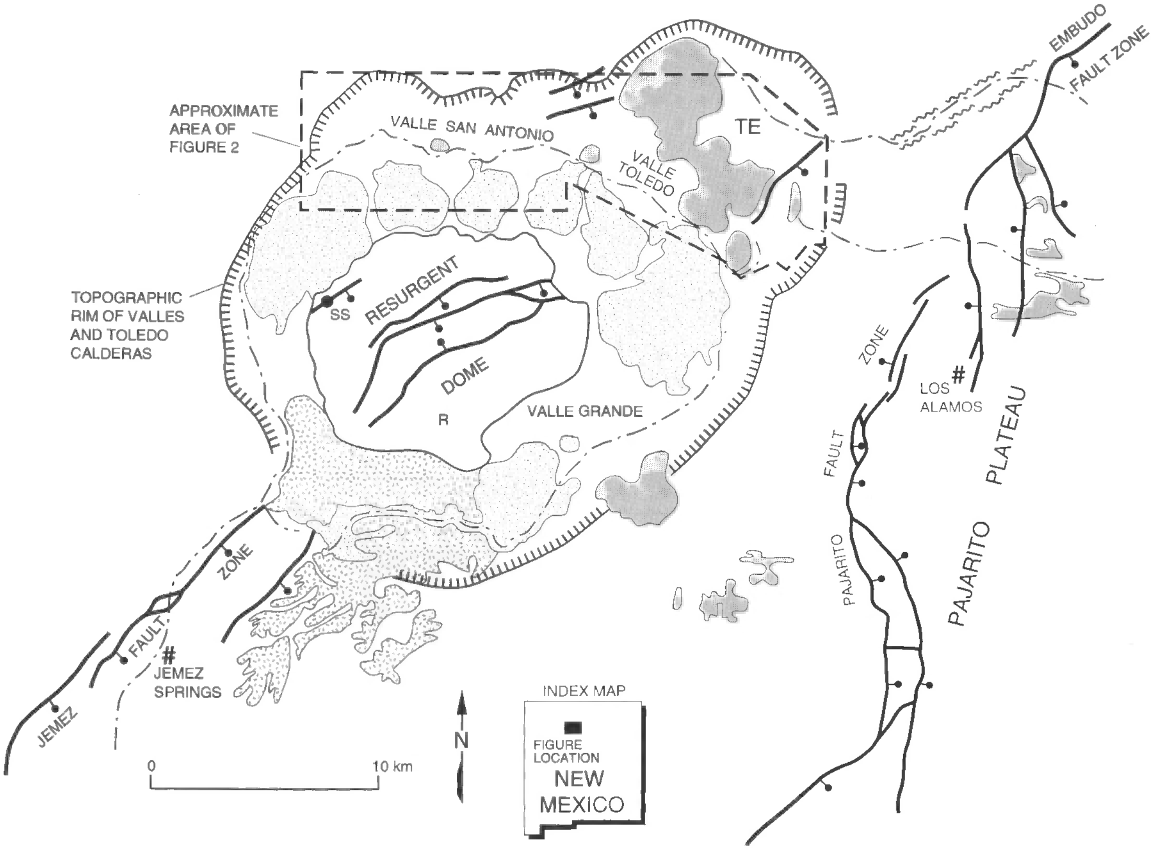

FIGURE 1. Location map showing general relations within the Valles/Toledo caldera complex, the Toledo embayment (TE), modern drainages from the caldera (dash-dot lines), major fault zones, distribution of Cerro Toledo Rhyolite (for post-Toledo caldera volcanics, shaded), distribution of major units of the Valles Rhyolite (post-Valles caldera volcanic rocks stipple is Valle Grande Member domes and flows; coarser, double-dash stipple is Banco Bonito, Battleship Rock and El Cajete members), resurgent dome of Valles caldera (R is Redondo Peak; long faults define Redondo Creek graben), area of Figure 2, and some localities mentioned in the text. SS is Sulphur Springs and the shears southwest of Embudo fault zone represent the structural discontinuity of Aldrich and Dethier (1990) along Santa Clara Canyon drainage. Base and general geology from Smith et al. (1970), with modifications from this work, Goff and Gardner (1980) and Goff et al. (1990).

exposures of pre-caldera volcanic rocks, important regional structural implications, and one of the few localities where syn-volcanic, coarse epiclastic gravels and debris flows can be found interfingered with basin-fill sandstones. Because of traditionally restricted access, there have been few studies that focus on the geology of the northern caldera, and those that exist have dealt mainly with aspects of Cerro Toledo Rhyolite volcanism (e.g., Heiken et al., 1986; Stix et al., 1988). Here we present a previously unpublished geologic map and discussion of the general geology of this fascinating and scenic area.

GEOLOGIC MAP

Geologic mapping at a scale of 1:24,000 was done in 1981 in support of stratigraphic and structural studies related to the early Continental Scientific Drilling Program efforts in the Valles caldera. Figure 2, of roughly the northern halves of the Valle Toledo and Valle San Antonio 7.5 minute quadrangles, is mostly original mapping by the authors, but because of access restrictions imposed on the field work, the western portion of the Valle San Antonio, and some of the Valle Toledo, have been modified from Smith et al. (1970) and Griggs (1964), respectively. Some contact relations between formations in the northern rim of Valles caldera are based on data of Gardner (1985).

Units

Paliza Canyon Formation (Tp): Dominantly multiple flows of two-pyroxene andesite with plagioclase the dominant phenocryst phase. Exposures of the andesites of this formation in the topographic rim of Valles caldera, north of the Valle San Antonio, are among the thickest in the Jemez Mountains. Placement of contacts with the overlying Tschicoma Formation, north of the Valle San Antonio, is significantly higher than depicted by Smith et al. (1970), but is supported by each unit's distinctive chemistry and petrography (Gardner, 1985; Gardner et al., 1986). No dates of fresh material from this unit in the map area have been obtained, but WoldeGabriel (1990) reported minimum ages on hydrothermally altered andesites in the area of about 7 Ma. Gardner et al. (1986) reported the age range of the Paliza Canyon Formation as >13 Ma to 7 Ma.

Tertiary Sediments (Ts): A thick sequence (over 200 m) of dominantly silicified arkosic sandstone with interbeds of subangular andesitic gravels occurs north-northwest of Trasquilar dome. The unit interfingers with some discontinuous Paliza Canyon andesite flows, and is capped with Tschicoma dacite. This unit, because of interfingering relations with the Paliza Canyon Formation, was depicted as Cochiti Formation by Gardner (1985), and lumped with the Paliza Canyon Formation by Smith et al. (1970). This unit represents the intercalation of Santa Fe Group basin-fill sands with what Gardner (1985), Gardner et al., (1986), and Goff et al. (1990) considered to be Cochiti Formation—dominantly detritus derived by erosion, which was essentially coeval with volcanism, of the Keres Group, as defined by Bailey et al. (1969). In light of the discussions of Smith and Lavine (this volume), we leave this unit unassigned, but in that it largely separates volcanic flows of the Paliza Canyon and Tschicoma formations only in the vicinity of the present Toledo embayment, it probably has structural, as well as time-stratigraphic, significance.

Tschicoma Formation (Tt): Dominantly flows and domes of coarsely porphyritic hornblende, two-pyroxene dacite with large (1 cm) phenocrysts of plagioclase. K-Ar dates indicate the formation ranges in age from 7 Ma to about 2 Ma (Gardner et al., 1986; Goff et al., 1989). Included in this unit, per the recommendations of earlier workers (Heiken et al., 1986; Gardner et al., 1986; Self et al., 1986), are the hills of Cerro Rubio dacite (of Griggs, 1964; Smith et al., 1970). Griggs (1964) inferred intrusive relations of Cerro Rubio into Cerro Toledo Rhyolite, and Smith et al. (1970) indicated that the north and south Cerro Rubio mounds intruded after, and extruded immediately before, Cerro Toledo Rhyolite volcanism, respectively. We concur with these workers that volcanic textures and poor exposures of contact relations might allow various interpretations, but dates (2.18 to 3.59 Ma) and geochemical similarity to the Tschicoma Formation dacites (Heiken et al., 1986; Gardner et al., 1986) suggest that inclusion of the Cerro Rubio hills as part of the Tschicoma Formation is appropriate. Furthermore, patches of Cerro Toledo Rhyolite, and, for that matter, Tshirege Member of the Bandelier Tuff, overlie both Cerro Rubio mounds. The stratigraphic relations with Cerro Toledo Rhyolite alone, therefore, indicate that both Cerro Rubio hills predate at least some (all?) Cerro Toledo volcanism.

Cerro Toledo Rhyolite (Qct): Dominantly domes and massive flows of mostly aphyric to slightly porphyritic rhyolite. A few domes and associated flows contain phenocrysts of sanidine (notably, Turkey Ridge dome and flows contain chatoyant sanidine), and sparse quartz. Included in this unit are minor pyroclastic fall and flow deposits, as well as pumiceous lavas. Dates for the formation range from about 1.62 to about 1.20 Ma (Doell et al., 1968; Izett et al., 1981; Heiken et al., 1986; Stix et al., 1988), but a "best" age range may be 1.54 to 1.23 Ma (Spell et al., this volume). We note, however, that the current re-dating effort (Spell et al., this volume) has apparently not sampled some potentially significant units. Also included in this unit, per the recommendations of Heiken et al. (1986) and Self et al. (1986), are the Warm Springs, Trasquilar (Fig. 3), and Los Posos domes, which were depicted by Smith et al. (1970) as Valles Rhyolite. Patches of Tshirege Member of the Bandelier Tuff can be found on the Los Posos domes, clearly indicating that they predated formation of the Valles caldera. Doell et al. (1968) reported K-Ar dates on the Warm Springs dome equivalent to Cerro Toledo Rhyolite age, but attributed the apparent pre-Valles age to hydrothermal alteration. Thus, we redated, or dated, these problematic domes, all of which yielded Cerro Toledo Rhyolite equivalent dates (reported in Heiken et al., 1986). These earlier K-Ar dates are well supported by the recent $^{40}Ar/^{39}Ar$ dates of Spell et al. (this volume). Patches of Cerro Toledo Rhyolite overlie the Cerro Rubio domes, and one Cerro Toledo Rhyolite vent lies on the northwest shoulder of Cerro Rubio.

Bandelier Tuff (Qbt): Mostly densely welded ignimbrites of the Tshirege Member in the map area. Some Otowi Member and other older units as shown by Smith et al., (1970) in the western wall of Valles caldera, at the western edge of the Valle San Antonio quadrangle, have not been broken out from this unit in Figure 2. Recent $^{40}Ar/^{39}Ar$ dates indicate the ages of the Otowi and Tshirege members of the Bandelier Tuff to be 1.61 Ma and 1.22 Ma, respectively (Izett and Obradovich, 1994; Spell et al., this volume). Conspicuously crystal rich with bipyramidal quartz and chatoyant sanidine, the Bandelier Tuff fills a paleocanyon between Turkey Ridge and the unnamed Cerro Toledo Rhyolite dome to the southeast, and apparently ponded in the topographic depression between the Cerro Toledo Rhyolite domes and Tschicoma Formation domes in the northeastern Toledo embayment. Patches of Tshirege Member overlie the Los Posos domes.

Landslide Deposits (Qls): This unit includes all types of post-caldera mass wasting deposits in the map area. As such, debris avalanche deposits, minor debris flows, and a large block slide complex north of Valle San Antonio, are all shown as Qls on Figure 2. Of particular interest, is the large block slide complex north of Valle San Antonio which Smith et al. (1970) depicted as a complex of arcuate faults on the caldera rim. The arcuate faults of Smith et al. (1970) mark the headwalls of massive, coherent block failures of the caldera wall. Lithologies in this unit are variable, but consist mostly of pre-caldera rocks, with minor Bandelier Tuff in the western part of the map area.

Valles Rhyolite (Qvr): Undivided flows, domes, and tephras of mostly the Valle Grande Member of the Valles Rhyolite, but the unit includes some Redondo Creek Member in the western Valle San Antonio quadrangle (Fig. 2) (Bailey et al., 1969; Smith et al., 1970). In the map area, Spell and Harrison (1993) reported the ages of the eruptive centers as follows: Cerro del Medio, 1.133 to 1.095 Ma; Cerro Abrigo, 0.973 Ma; Cerro Santa Rosa, 0.915 to 0.787 Ma; Cerro San Luis, 0.800 Ma; Cerro Seco, 0.800 Ma; and San Antonio Mountain, 0.577 Ma. As mapped, this unit is highly variable petrographically; however, although most eruptive centers have some aphyric phases, most are porphyritic with quartz, sanidine, plagioclase, biotite, and minor hornblende and pyroxene.

Lake Deposits (Qld): Finely laminated deposits of clay, silt, and very fine sand, derived by erosion of surrounding rock units, and deposited in intracauldron lakes. Deposits are commonly tuffaceous, and Griggs (1964) reported diatomaceous facies in Valle Grande. In the map area, the lacustrine units overlie the large mass wasting deposits and most commonly underlie a veneer of coarser alluvial material of the alluvial terraces. The lake deposits appear to interfinger with fan and colluvial material, and Smith et al. (1970) reported interbedded relations with tuffs of the Valle

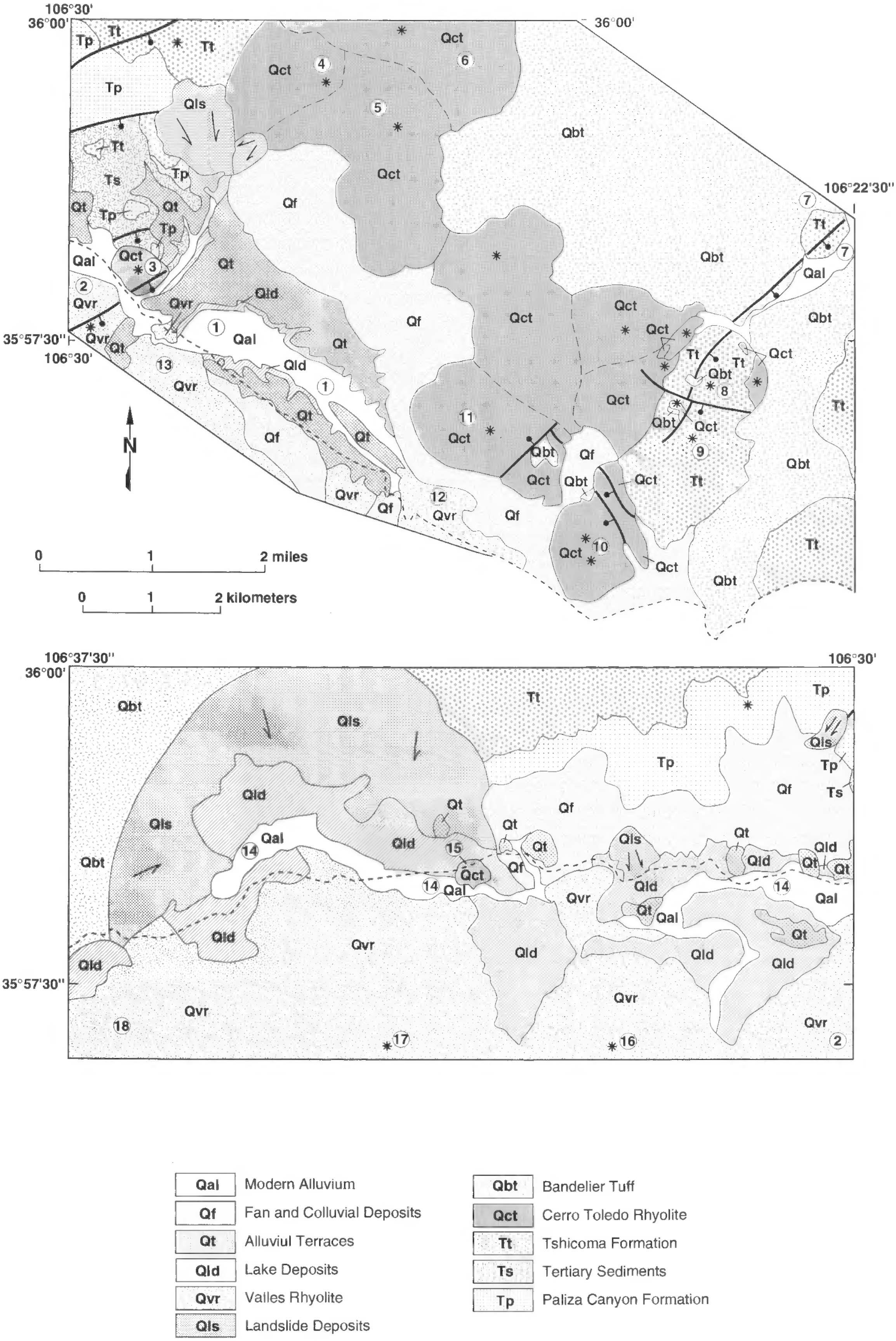

FIGURE 2. Upper and lower maps are reductions of previously unpublished geologic maps of the northern parts of Valle Toledo and Valle San Antonio 7.5 minute quadrangles, respectively. Map units are described in text. Short dash line is Pipeline Road, whereas long dash lines are contacts between Cerro Toledo Rhyolite dome and flow centers. Asterisks are volcanic vents. Geographic features (numbers) are, ordered in a roughly clockwise fashion on each part of the figure, as follows: 1 = Valle Toledo; 2 = Cerro Santa Rosa; 3 = Trasquilar dome; 4 = Indian Point; 5 = Turkey Ridge; 6 = Cerro Toledo; 7 = Santa Clara Canyon; 8 = Cerro Rubio dacite hill, north; 9 = Cerro Rubio; 10 = Los Posos dome, southeast; 11 = Los Posos dome, northwest; 12 = flow from Cerro del Medio; 13 = flow from Cerro Abrigo; 14 = Valle San Antonio; 15 = Warm Springs dome; 16 = Cerro San Luis; 17 = Cerro Seco; 18 = north flank of San Antonio Mountain.

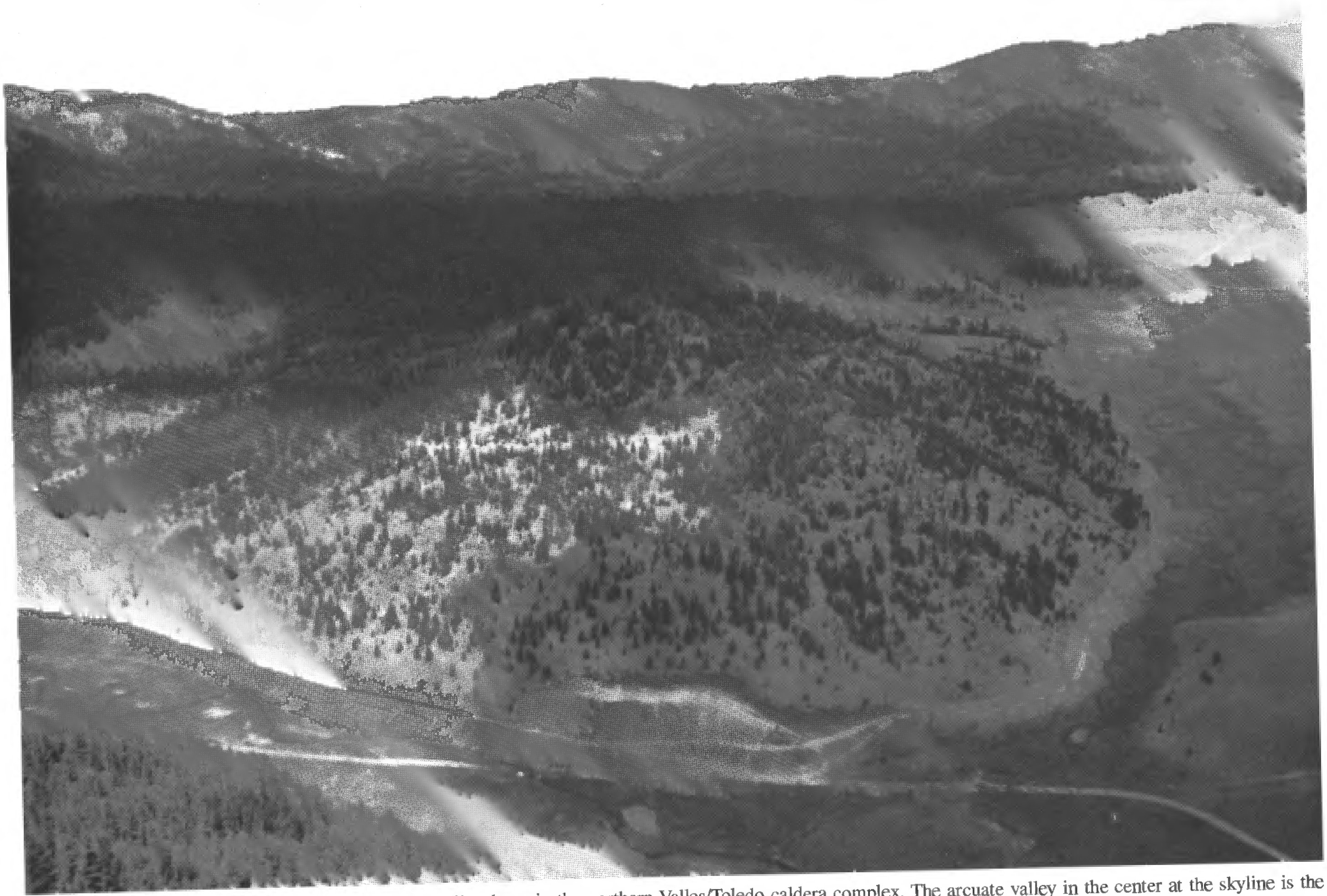

FIGURE 3. View looking north-northeast over Trasquilar dome in the northern Valles/Toledo caldera complex. The arcuate valley in the center at the skyline is the northwest boundary of the Toledo embayment and it separates pre-caldera volcanic and sedimentary rocks on the west (left) from domes of Cerro Toledo Rhyolite filling the embayment on the east (right). Trasquilar dome is interpreted to be part of a remnant arc of Toledo caldera ring fracture domes.

Grande Member of the Valles Rhyolite. We are fairly confident that the deposits of this unit shown on Figure 2 are roughly coeval and were deposited in the same lake, but, as discussed below, there were different lakes, at different times, in various portions of the caldera.

Alluvial Terraces (Qt): Prominent strath terraces, with about 1-2 m of coarse rhyolitic gravels, are cut on underlying lacustrine deposits, and, less commonly, on fan deposits, landslide material, and Valle Grande rhyolite flows. The terraces are a striking geomorphic feature of Valle Toledo, but persist downstream into central Valle San Antonio. Some of these terraces were mapped by Griggs (1964), who also recognized another, higher terrace set, not shown in Figure 2, which he interpreted as the remains of lake terraces.

Fan and Colluvial Deposits (Qf): Sand, gravel, and boulders derived by erosion of rock units composing the domes and caldera walls. These deposits form a mantle on steeper slopes and grade into alluvial fans which extend into the valleys. For the most part, these deposits are younger than the alluvial terraces, but in one locality northeast of Warm Springs dome the terraces are cut on an alluvial fan.

Modern Alluvium (Qal): Alluvial material in active channel and flood plain of San Antonio and Santa Clara creeks, composed of detritus derived from surrounding rhyolite domes and caldera walls.

DISCUSSION

Toledo embayment

It is perhaps unfortunate that what now is referred to as the Toledo embayment was called "Toledo caldera" by Ross et al. (1961) and Smith et al. (1970), because many later workers took this depiction quite literally in a very restrictive sense, even though Smith et al. (1970) clearly recognized Rabbit Mountain on the southern topographic rim of "Valles" (see below) caldera to be Cerro Toledo Rhyolite (Fig. 1). Ever since it was first pointed out that the Toledo caldera ring fracture was nearly coincident with that of the younger Valles caldera (Goff et al., 1984), the possible origins of the Toledo embayment have been the subject of much speculation (for example, Heiken et al., 1986; Self et al., 1986; Goff et al., 1989; Turbeville et al., 1989), but, in contrast to earlier workers, most of these authors suggested a pre-Toledo caldera age for the embayment's formation. Most of these authors tended to favor formation of the embayment by either collapse related to Tschicoma Formation volcanism or by mass wasting and/or erosion along the northeast-trending Jemez lineament grain that cuts through the caldera complex and volcanic field (Jemez fault zone, faults in the resurgent dome, structural discontinuity, and Embudo fault zone, all shown in Fig. 1). There are two issues that must be kept in mind when pondering the origins of the Toledo embayment: the structural and tectonic history of the area, and the age constraints on the topographic depression of the embayment.

Gardner and Goff (1984) postulated that the local rift boundary from >13 to about 6 Ma was a series of north-trending faults that bisect the volcanic field (and present caldera) west of the rift's modern boundary on the Pajarito and Embudo fault zones. Recent geophysical work (Baldridge et al., 1994), and the sequence of interfingered epiclastic gravels and rift-fill sandstones north of Trasquilar dome appear to support this hypothesis. Aldrich and Dethier (1990) argued that the Embudo fault zone and ancestral Santa Clara Canyon drainages, incised along their northeast-trending structural discontinuity, have existed since middle Miocene time. In contrast to the north-trending faults that became largely inactive around 6 Ma, the northeast-trending structures of the Jemez lineament grain remain active, exhibiting control of caldera structure, microseismicity, and Quaternary deformation (Gardner and House, 1987; Goff et al., 1989; Gonzalez and Dethier, 1991; Baldridge et al., 1994; House and Hartse, 1995). Thus, some incarnation of the Toledo embayment has existed as a structural trough or rift basin in the past, and the embayment area has a long history of rift-bounding tectonic activity and structurally influenced sedimentation and fluvial incision. At least locally, however, the northeast-trending faults have been the dominant structural elements since about 6 Ma.

The older limit for the age of the topographic depression of the Toledo embayment is provided by lavas that form its northern rim, the youngest of which are dated at 2.3 Ma (Goff et al., 1989). Some workers (e.g., Self et al., 1986) have argued that the embayment must predate the Cerro Rubio hills (3.59 and 2.18 Ma; Heiken et al., 1986), but this assertion is dependent on interpretation of the Cerro Rubio hills as extrusive domes. Heiken et al. (1986), however, described the hills as plugs, not domes. We support the interpretation of Goff et al. (1989) that the Cerro Rubio hills are shallow intrusive remnants of Tschicoma volcanoes that once formed pre-caldera highlands over the area, and that the Cerro Rubio plugs do not provide useful age constraints on the age of the embayment. On the other hand, all workers concur that at least some of the Cerro Toledo Rhyolite domes and lavas were clearly extruded into the embayment depression. The oldest, well-dated dome and flows that, without ambiguity, were extruded into the depression make up Indian Point, for which Spell et al. (this volume) report an age of 1.464 Ma. The embayment depression, therefore, must have formed between 2.3 and about 1.5 Ma. Furthermore, the field relations indicate that the Cerro Toledo and Indian Point domes and lavas flowed up against the topographic barrier of the northwest wall of the embayment and there is no evidence of previous mass wasting of the wall, suggesting that the embayment wall had formed shortly before extrusion of these Cerro Toledo Rhyolite domes.

All of these considerations lead us to conclude that the most probable origin for the Toledo embayment is collapse associated with development of the Toledo caldera. It seems likely that an apophysis of the Toledo (or Otowi) magma chamber elongated to the northeast along regional faults, and that, after evacuation of the apophysis, collapse occurred along these structures. Such controls on collapse structure and post-caldera volcanism would not be unusual. There are suggestions that eruptions of the pre-Bandelier San Diego Canyon ignimbrites (1.89 Ma; Spell et al., 1990; Turbeville and Self, 1988; T. L. Spell, unpublished data, 1995), from an area now occupied by the western and southwestern portions of Valles caldera, formed small collapse structures elongated in the northeastern direction (Nielson et al., 1989; Gardner et al., 1990; Hulen et al., 1991). Furthermore, the combined structure of the Valles and Toledo calderas, revealed by drilling and geophysics (Goff et al., 1989; Hulen et al., 1991), shows pronounced influence of collapse along northeast-trending faults surrounded by collapse on the main ring fracture system. Finally, Self et al. (1986) indicated that there are northeast-trending alignments of petrographic types among the Cerro Toledo Rhyolite domes in the embayment.

Toledo and Valles calderas

Goff et al. (1984) showed that the Toledo and Valles caldera ring fracture collapse structures are nearly coincident, and that, if anything, the Toledo caldera's structural margin is, in some places, out board of that of the Valles (see additional detail summarized in Goff et al., 1989). We note that the caldera moat is significantly wider in areas where Cerro Toledo Rhyolite domes are preserved: specifically, the Valle San Antonio, Valle Toledo-Toledo embayment, and Valle Grande areas (Fig. 1). This suggests that in these areas the topographic wall of what is generally called "Valles caldera" is probably the result of the formation of both the Toledo and Valles calderas. In contrast, in areas such as the western and southern moat zones, where Valles Rhyolite flows abut the topographic wall, the topographic wall is probably strictly "Valles" in origin.

Intracauldron lakes and terraces

Although many people envision a single, giant caldera-filling crater lake for the Valles caldera, it is evident that multiple intracauldron lakes filled different parts of the calderas at different times. Clearly, some of the Cerro Toledo Rhyolite (post-Toledo caldera) domes were erupted through water ponded in the northern moat zone of the caldera, as evidenced by the phreatomagmatic tuff ring that surrounds Warm Springs dome. Following formation of the Valles caldera, lakes that predated resurgent doming had formed, and left deposits that were involved in the structural doming event (Smith et al., 1970) within about 0.1 Ma of Valles caldera's formation (Spell and Harrison, 1993). Scientific core hole VC-2b, near Sulphur Springs on the west flank of the resurgent dome, penetrated 168 m of interbedded accretionary lapilli tuffs, coarse clastic breccias, and fine-grained lacustrine rocks that are only gently tilted (10-15°) and exhibit hydrothermal alteration that predated soft sediment deformation (Gardner et al., 1989). These relations suggest that a lake, with very high bottom temperatures, formed in this part of the caldera soon after collapse, but postdated most structural doming. While this lake developed, the newly formed caldera walls and dome were shedding debris flows into it, and small-volume eruptive activity continued. Lake deposits in the northern moat of the caldera (in Valle San Antonio and Valle Toledo) appear to postdate the major mass wasting of the caldera walls, show depositional relations on rocks at least as young as 0.8 Ma, and are not structurally deformed (Fig. 2). Griggs (1964) mapped flat-lying lake deposits in Valle Grande, and reported more than 300 m of caldera-fill deposits penetrated by a drill hole there.

In the Valle Toledo and Valle San Antonio areas, alluvial terraces are most commonly developed on the lake deposits. Comparison of the gradient of the terrace surfaces with that of the modern San Antonio Creek shows that the creek's gradient is much steeper, even where the modern stream meanders through Valle San Antonio. We believe these relations suggest that the terraces in the northern part of the caldera record alluvial beveling that accompanied draining of intracauldron lakes from the northern part of the caldera, and that, once the lakes were drained, continued incision by the creek, particularly in establishing a course around San Antonio Mountain, has lowered the base level. Some authors (e.g., Goff and Shevenell, 1987; Hulen and Nielson, 1988; Goff and Gardner, 1994) have suggested major breaching of the southwest caldera wall, rapid and deep incision, and dramatic changes in caldera hydrology, at about 0.5 Ma. This episode of breaching and incision, which is roughly coincident with large-volume dome eruptions in the southern and western moats, apparently occurred with the draining of lakes in the northern and western portions of the caldera, leading to the establishment of the drainage patterns that persist today.

CONCLUSIONS

The ring fault collapse structure of the Toledo caldera is roughly coincident with that of the younger Valles caldera, and is partially marked by a remnant arc of ring-fracture domes, consisting of the Warm Springs, Trasquilar, and Los Posos domes, of the Cerro Toledo Rhyolite. The Toledo embayment formed sometime between 2.3 and 1.5 Ma. In the embayment, Cerro Rubio dacitic rocks (3.6 to 2.2 Ma) form plug-like bodies that have survived from Tschicoma volcanism, and do not provide any useful constraints on the embayment's formation. We argue that the Toledo embayment formed during collapse of the Toledo caldera (at about 1.61 Ma) and that the embayment occurs in a zone of long-established weakness caused by local structural manifestations of the northeast-trending Jemez lineament. Before formation of Toledo caldera and the Toledo embayment, the area of the embayment had a long history of rift-bounding tectonic activity and structurally influenced sedimentation and incision. Cerro Toledo rhyolites (1.5 to 1.2 Ma) filled the embayment, and have locally intruded Cerro Rubio rocks.

Intracaldera lakes have been a common phenomenon in both Valles and Toledo calderas. Hydromagmatic rhyolitic ash beds are commonly associated with post-caldera volcanism. In Valles caldera some lacustrine deposits display hydrothermal alteration that occurred prior to soft sediment deformation. All lake deposits in the northern moat postdate mass wasting of the northern caldera wall and overlie post-Valles caldera rhyolite domes and flows. Prominent alluvial terraces in the northern moat apparently record alluvial beveling that accompanied drainage of these lakes at about 0.5 Ma.

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