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Compositionally zoned dikes of the Questa mine area, northern New Mexico: Magma mixing and the post-26 Ma evolution of the Questa magmatic system

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COMPOSITIONALLY ZONED DIKES OF THE QUESTA MINE AREA, NORTHERN NEW MEXICO: MAGMA MIXING AND THE POST–26 MA EVOLUTION OF THE QUESTA MAGMATIC SYSTEM

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Abstract—Mid-Tertiary compositionally zoned dikes are present in a 2 km by 4 km, east-west-trending dike swarm at the Questa mine, northern New Mexico. Dike emplacement occurred after deposition of the 26 Ma Amalia Tuff and prior to emplacement of molybdenum-bearing granites. Zoning consists of phenocryst-poor "mafic" dike margins which grade continuously inwards to phenocryst-rich "felsic" cores. Geochemical analysis and petrologic modeling reveal systematic intra-dike mineralogic and chemical zoning which originated through the mixing and cointrusion of andesite and rhyolite magmas. The Amalia Tuff and the younger molybdenum-bearing granites are plausibly related through the mixing event which formed the zoned dikes and subsequent crystal fractionation.

INTRODUCTION

Recent mapping at the Questa mine, in the Sangre de Cristo Mountains of northern New Mexico, has documented an extensive occurrence of compositionally zoned dikes (Jones, 1988). The intrusions exhibit a full compositional range from andesite to rhyodacite. This paper addresses the nature and origin of these dikes and their proposed relation to the post–26 Ma evolution of the Questa magmatic system.

GENERAL GEOLOGY

The granitic intrusions and molybdenum deposits of the Questa mine are part of a regionally extensive felsic magmatic system of mid-Tertiary age. The central volcanic feature of the region is the Questa caldera which formed at 26 Ma through the eruption of the Amalia Tuff rhyolite (Lipman, 1983). Subsequent to caldera formation, magmatic activity continued from 26 Ma to 18 Ma with the emplacement of granitic stocks and intermediate to felsic dikes (Lipman et al., 1986; Czamanske et al., 1990). Molybdenite deposition at Questa is dated at ∼24 Ma (Czamanske et al., 1990).

Six chemically and texturally distinct mid-Tertiary intrusive rock types are present in the Questa mine area. All are younger than the Amalia Tuff, and the relative ages of each are firmly established by crosscutting relations (Jones, 1988). From oldest to youngest, they are: (1) rhyolite dikes of Amalia Tuff affinity (Lipman, 1983); (2) compositionally zoned andesite to rhyodacite dikes; (3) pre-MoS_2 rhyodacite to rhyolite dikes; (4) syn-MoS_2 granite stocks and rhyolite dikes; (5) post-MoS_2 rhyolite dikes and stocks; and (6) quartz-latite and lamprophyre dikes. The compositionally zoned andesite to rhyodacite dikes crosscut the 26 Ma Amalia Tuff and are in turn cut by molybdenum-bearing granite intrusions dated at ∼24.6 Ma (Czamanske et al., 1990). The emplacement of zoned dikes thus occurred in a period of less than two million years between caldera formation and molybdenum mineralization.

COMPOSITIONALLY ZONED DIKES

Description and field relations

The zoned dikes constitute a heterogeneous array of variably porphyritic intrusions which, in hand sample, appear to be dominantly quartz latite to rhyolite in composition. The dikes occur as a 2–4 km wide swarm which trends east-west through the southern and northern mine area (Fig. 1). Dikes range in thickness from <5 to 15 m, averaging 10 m, and dip steeply to the north and south or are vertical. The original extent of the dike swarm in the central mine area is probably obscured by younger intrusions.

Dikes exhibit compositional variation on three levels of observation: (1) intra-dike, from contact to core of dike; (2) intra-dike, along strike; and (3) inter-dike. All variations represent transitions between apparent "mafic" and "felsic" end-member rock types. Compositional transitions are sufficiently abrupt on a mapping scale that a single dike may be variably identified as a latite, quartz latite or rhyolite depending on which part of the dike is observed. Dikes commonly exhibit the following macroscopic zoning characteristics: (1) both dike borders are dark-colored (mafic), fine-grained, magnetite-rich and phenocryst-poor relative to dike cores. Felsic cores are generally thicker than mafic borders, but either may constitute from <10% to >90% of dike thickness; (2) mafic and felsic zones exhibit no sharp or chilled crosscutting or contact relations in outcrop, drill core, or thin section; (3) quartz phenocrysts are most abundant in felsic cores; they decrease in abundance towards mafic borders, from which they are generally absent; and (4) sieve-textured plagioclase phenocrysts are common in mafic borders but are absent from felsic cores. Alkali feldspar phenocrysts are rare in borders but abundant in cores.

To determine the nature and origin of compositional variation in the zoned dikes, thin sections were cut and whole-rock geochemical anal-

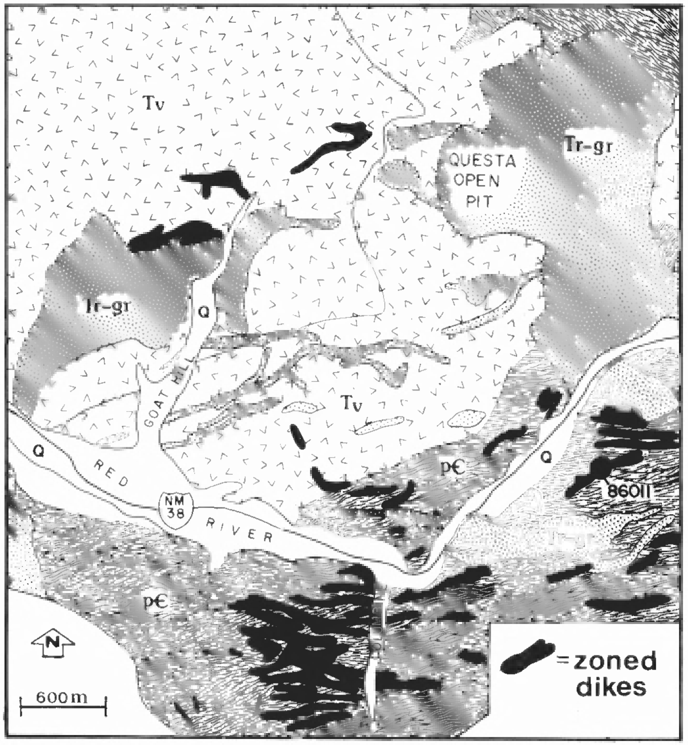

FIGURE 1. Simplified geologic map of the Questa mine area. Zoned dikes shown with exaggerated thickness. p€ = Proterozoic metamorphic rocks. Tv = Oligocene andesites and Miocene Amalia Tuff. Tr-gr = rhyolite to granite stocks and dikes (pre-, syn-, and post-MoS_2).

yses were obtained for 37 samples from 17 selected dikes (Jones, 1988). In thin section, dikes are strongly porphyritic (14–77 vol%, avg. 29%) with phenocrysts of plagioclase and alkali feldspar, quartz, biotite, magnetite, and hornblende. Zircon, apatite and titanaugite (rare) are present as accessory microphenocrysts. The groundmass ranges from very fine-grained in dike interiors to glassy (devitrified) at dike contacts.

Estimated phenocryst modes for over 100 hand samples indicate that the dikes span the andesite to rhyolite fields of the Streckeisen modal classification. Application of various normative and major and trace element classification schemes, one of which is shown in Figure 2, indicate the dikes span the andesite to rhyodacite-rhyolite compositional fields (Jones, 1988).

Zoning in dike 86011

Dike site 86011 (Fig. 1) was sampled in detail to determine the nature of intra-dike compositional zoning. The site is unique only with respect to excellent outcrop exposure across the full dike width. Sample selection was based on mapped variations of phenocryst type and abundance (Fig. 3).

Phenocryst mineralogy was determined by point-counting thin sections cut from representative portions of the analyzed samples. Phenocrysts increase in abundance from 20 vol% in the dike margins to over 35 vol% in the dike core. Phenocryst abundance directly correlates with an increase in both absolute and relative abundances of quartz phenocrysts and in the absolute abundance of feldspar phenocrysts. Euhedral to subhedral quartz phenocrysts are most abundant in the dike core and become increasingly less abundant and more resorbed towards the dike contacts.

Silica varies from 59.3% at the southern contact to 69.2% in the core, to 65.3% at the northern contact (Fig. 3). K_2O, Zr, Rb and Nb have a positive correlation with SiO_2 while other elements have a negative correlation or no apparent systematic variance.

Microprobe analyses of feldspar compositions (Fig. 4) reveal that An_{45-52} plagioclase is dominant in the mafic portions of the dike (86011a–b) while An_{5-10} plagioclase is dominant in the felsic portions (86011c). Compositions in the An_{45-52} range in 86011a–b represent small, clear, unzoned phenocrysts. In sections 86011a–b, and c, compositions in the An_{10-40} range represent complex normal and reverse zoning in large (7 mm), mottled and sieve-textured phenocrysts. These larger phenocrysts are commonly rimmed by clear An_{45-52} overgrowths.

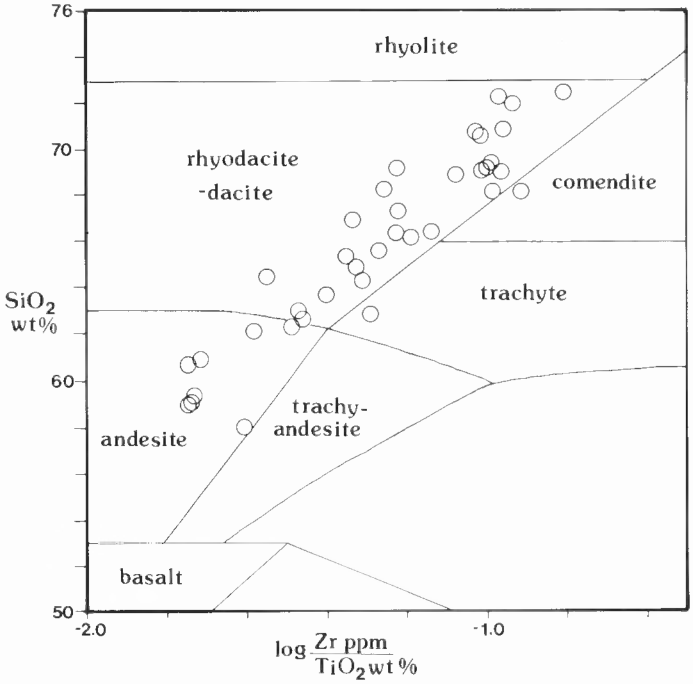

FIGURE 2. Chemical classification diagram for 37-zoned-dike-whole-rock analyses (after Winchester and Floyd, 1977).

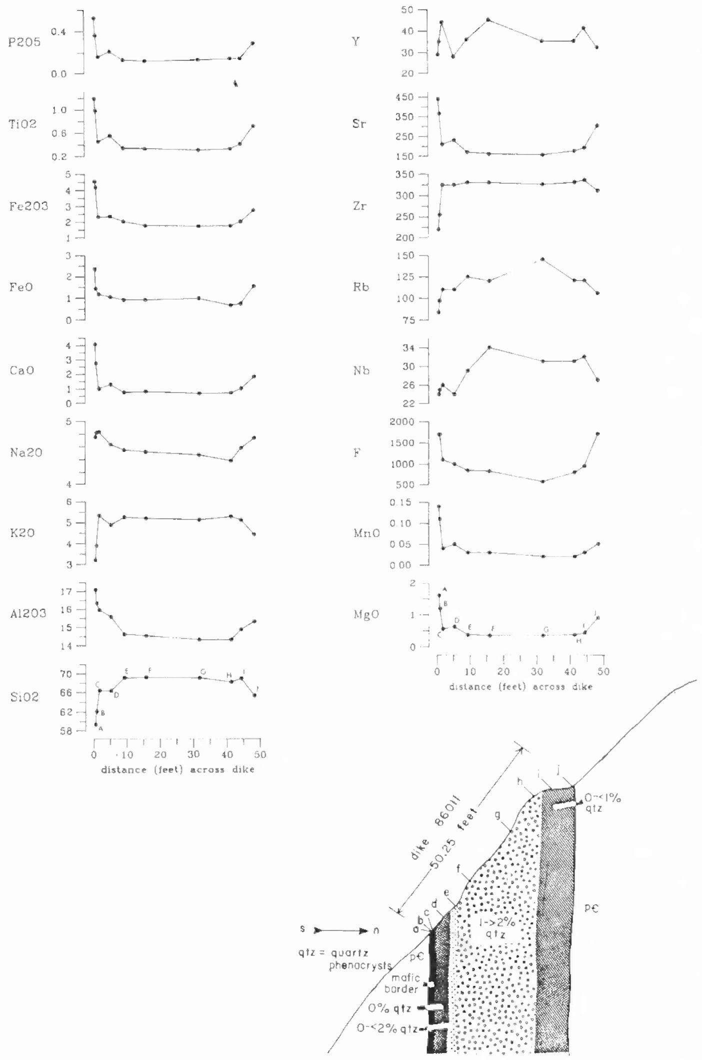

FIGURE 3. Geochemical profile of dike 86011. Oxides in weight percent. Trace elements in parts per million.

Zoning in other dikes

Systematic intra-dike mineralogic and chemical zoning is documented for all of the dikes shown in Figure 1 (Jones, 1988); the range of compositions for individual dikes is both greater and lesser than that observed at site 86011. For the 37 samples analyzed, SiO_2 ranges from a low of 58.0% to a high of 72.5% (Fig. 2). The greatest documented SiO_2 range across a single dike is 11.6% (59.0% margin; 70.6% core) and the least is 1.9% (62.9% margin; 64.8% core). Even though individual dikes may exhibit abrupt compositional variations over short distances (e.g., 86011), the variable range of SiO_2 from dike to dike is indicative of the full compositional continuity of mafic to felsic zoning (Fig. 2).

DISCUSSION

Origin of compositional zoning

Magmatic processes potentially capable of producing zoning in dikes include: crystal fractionation; wallrock assimilation; thermal diffusion; immiscibility; and magma mixing. Crystal fractionation, and related processes such as flow differentiation and filter-pressing, involve the separation of crystalline phases from a melt. If the zoned dikes formed in this manner, felsic cores would be derived from mafic borders through subtraction of a phenocryst assemblage more mafic than the bulk composition of the dike borders. However, mafic zones are volumetrically subordinate to felsic zones and complete removal of the phenocrysts present could not produce the felsic zones. Thus, relative volume considerations and phenocryst mineralogy and distribution preclude such a process.

Assimilation of mafic wallrock by a felsic melt can theoretically produce magma of intermediate composition (Bowen, 1928). For this to occur, a melt contaminated by assimilation of higher-temperature mineral phases would necessarily become more phenocryst-rich. Wallrock assimilation is precluded for the zoned dikes at Questa because the mafic dike margins are everywhere phenocryst-poor. Furthermore, petrologic modeling (Jones, 1988) indicates that assimilation of mafic wallrocks at Questa cannot account for chemical variation in the dikes.

In-situ thermal diffusion is not a plausible mechanism for dike zonation for two reasons. First, the fine-grained to glassy groundmass of the dikes indicates rapid quenching upon emplacement. Second, the antithetical variation of Na and K (Fig. 3) is opposite to that reported from studies on thermal diffusion (Lesher et al., 1982).

Immiscibility as a zoning mechanism requires the formation of physically and chemically discrete, thermally equilibrated magmas. This is implausible at Questa because dike zoning is continuous and the presence of sieve-textured plagioclase phenocrysts indicates thermal disequilibrium between the mafic and felsic magmas (Hibbard, 1981). One is therefore left with a magma mixing model to explain the formation of the compositionally zoned dikes.

Evidence for magma mixing

Magma mixing as a zoning mechanism for the Questa dikes is supported by several observations. First, the continuous zoning between mafic and felsic portions of the dikes indicates an end-member mixing process. Distinct end-member compositions are clearly indicated by the variable An content of plagioclase between border and core zones (Fig. 4). Second, sieve-textures in feldspar and embayment textures in quartz correlate with increasing mafic component in the dikes. Sieve and embayment textures are a common feature of mixed-magma occurrences (Walker and Skelhorn, 1966) and are interpreted here as indicating superheating of felsic magma by mafic magma. The fine-grained nature of the zoned dikes indicates rapid crystallization upon emplacement and requires that superheating of the felsic magma occurred prior to emplacement at current levels of exposure.

To evaluate a mixing hypothesis, potential end-members were tested against an extended Q-mode factor analysis model generated from a database of 37 dike analyses (Jones, 1988, table 3). The range of dike compositions is closely approximated by the mixing of a theoretical aphyric andesite and a rhyolite dike of Amalia Tuff affinity (Table 1). Estimated mixing proportions of these end-members for compositions at dike site 86011 are given in Table 2. This modeling exercise indicates that residual Amalia Tuff magmas, found as dikes crosscutting the Amalia Tuff throughout the mine area, are the most probable felsic end-member of the zoned dikes. The mafic end-member is proposed to be an andesite magma which underplated the Amalia Tuff magma chamber at depth.

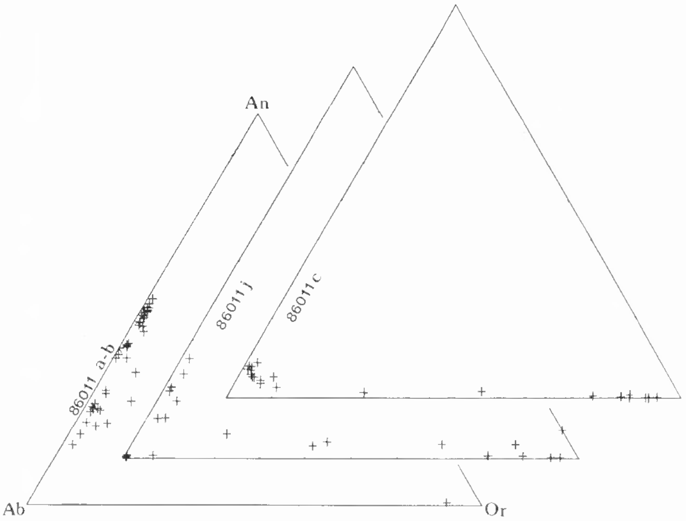

FIGURE 4. Ternary plots of microprobe-determined feldspar compositions for portions of dike 86011.

TABLE 1. Rhyolite and andesite end-member compositions derived from Q-mode factor analysis model of the zoned dikes (Jones, 1988).

	Rhyolite	Andesite
SiO2	75.30	54.02
TiO2	0.15	1.63
Al2O3	12.40	17.47
Fe2O3	1.95	4.85
FeO	0.25	3.45
MnO	0.04	0.21
MgO	0.16	2.47
CaO	0.20	4.84
Na2O	4.40	4.75
K2O	4.70	2.55
P2O5	0.02	0.70
LOI	0.28	2.66
Total	99.85	99.60
Rb(ppm)	140	119
Sr(ppm)	54	538
Zr(ppm)	485	137
Nb(ppm)	58	18
Y (ppm)	70	18
F (ppm)	930	3007

Site of magma mixing and nature of dike emplacement

The site and process of magma mixing, and the mechanism of dike emplacement, are complex and likely interrelated events. Several observations impose specific constraints on these processes.

TABLE 2. Mixing proportions of Table 1 end-members to approximate compositions of dike site 86011.

	proportion rhyolite	proportion andesite
86011a	.12	.88
86011b	.36	.64
86011c	.66	.34
86011d	.73	.27
86011e	.79	.21
86011f	.83	.17
86011g	.80	.20
86011h	.82	.18
86011i	.79	.21
86011j	.56	.44

Site of mixing

If magma mixing was purely a function of the mechanics of dike emplacement (Koyaguchi, 1985; Carrigan and Eichelberger, 1990) then two unique end-member magma compositions would be expected. No chemical variations would exist between dikes beyond the thoroughness of mixing each experienced. However, the dikes at Questa exhibit distinct inter-dike, as well as intra-dike, chemical variations (Jones, 1988, fig. 7). Petrologic modeling indicates these secondary variations reflect crystal fractionation, the degree of which appears to be unique for each dike (Jones, 1988). This constrains mixing to be at least partially independent of the emplacement process, and further indicates that this stage of mixing occurred prior to dike emplacement. Furthermore, sieve-textured feldspars and strongly embayed quartz phenocrysts indicate that significant heat exchange between the magmas occurred prior to dike injection.

It is likely that mixing first occurred when andesite magma initially underplated the Amalia Tuff magma chamber. Upon cooling, the andesite decreased in bulk density through volatile oversaturation and rose to turbulently mix with the overlying rhyolite magma (Eichelberger, 1980; Huppert et al., 1982). This mixing event likely produced two hybrids (Kouchi and Sunagawa, 1983), one andesitic and one rhyodacitic, which are represented by the most extreme compositions of the zoned dikes. These hybrids further mixed during dike emplacement.

Dike emplacement

The persistent mafic border to felsic core symmetry of the dikes indicates a zoning mechanism related to dike emplacement. Two such mechanisms have been proposed. Koyaguchi (1985) suggests that during volcanic eruptions viscosity contrasts allow underlying, less viscous mafic magmas to overtake highly viscous felsic magmas in the eruptive vents. Interrelated with this mechanism is that proposed by Carrigan and Eichelberger (1990), where viscosity segregation of co-erupted magmas causes mafic to felsic zonation. With either mechanism the final, chilled product is a dike which has mafic borders and a felsic interior. However, as discussed above, this mechanism alone cannot account for inter-dike chemical variations.

Implications for the evolution of the Questa magmatic system

The mixing events which generated the zoned dikes occurred between the eruption of the 26 Ma Amalia Tuff and the crystallization of 24.6 Ma molybdenum-bearing granites. Petrologic modeling (Jones, 1988) reveals the Amalia Tuff and the molybdenum-bearing granites are plausibly related through magma mixing and subsequent crystal fractionation. Figure 5 provides a means of visualizing the proposed evolutionary path of the mixed magmas in this temporal context. The zoned dikes occupy a field between the Amalia Tuff (and cogenetic dikes) and younger lamprophyre and quartz latite intrusions. Pre-, syn- and post-MoS_2 rhyolites and granites are respectively represented by their own fields (Fig. 5). Q-mode factor analysis modeling (Jones, 1988) indicates that the more felsic magmas of the zoned dikes could have evolved to compositions of the mineralizing intrusions through fractionation of phenocrysts present in the dikes. The vector representing this process is shown in Figure 5. The field of pre-MoS_2 intrusions represents magma crystallization at an intermediate stage of fractionation. Furthest along the fractionation vector lie compositions of the mineralizing intrusions of the Questa ore bodies. Interestingly, the field of post-MoS_2 intrusions projects back towards the mafic portion of the zoned dike field. This may represent late-stage injection of mafic magmas into the felsic magma chamber. Perhaps not coincidentally, in contrast with earlier granite-rhyolite bodies these late intrusions appear to have been explosively emplaced.

Preliminary Sr isotopic data support a process of combined magma mixing and crystal fractionation. Initial $^{87}Sr/^{86}Sr$ values for the Amalia Tuff (.70824–.71227: Johnson, 1986) decrease with inferred increasing depth in the magma chamber (i.e., higher levels in the tuff stratigraphy). This has been attributed to assimilation of radiogenic Precambrian rocks in the upper portions of the tuff magma chamber (Johnson, 1986, 1990). An alternative explanation is that the higher initial $^{87}Sr/^{86}Sr$ values reflect those of the original Amalia Tuff and that the increase in less radiogenic Sr with increasing depth reflects Sr uptake from underplated mafic magmas. Since the Amalia Tuff typically contains less than 20 ppm Sr, very little radiogenic Sr is required to significantly shift the isotopic values (Jones, 1988). This mechanism would account for the low initial $^{87}Sr/^{86}Sr$ values characteristic of the younger mineralizing granite intrusions at Questa (~.704–.706, S. Atkin, oral commun., 1985; Johnson, 1986). These granites have Sr concentrations up to an order of magnitude greater (10's ⟶ 100 ppm) than those reported for the Amalia Tuff. This negative correlation of Sr abundance with initial $^{87}Sr/^{86}Sr$ values is inconsistent with a theory of wallrock assimilation. Arguments for assimilation in the upper portions of the Amalia Tuff magma chamber based on U-Pb zircon dating (Johnson, 1990) fail to account for the possibility of rapid solid-state Pb diffusion in the presence of a thermal gradient established by underplating mafic magmas (B. Watson, oral commun., 1990). Thus, chemical variations in the Amalia Tuff may reflect mafic-felsic magma interactions which culminated with the emplacement of the zoned dikes.

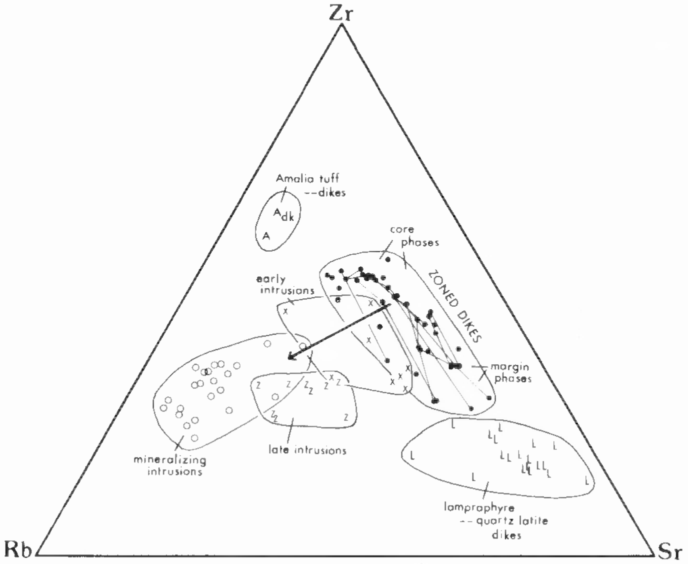

FIGURE 5. Zr-Rb-Sr ternary plot of selected rock types from the Questa mine area. Dots = zoned dikes (lines connect multiple samples from single dikes). A = average of 12 Amalia Tuff analyses. Adk = average of 6 dikes of Amalia Tuff affinity. X = pre-MoS_2 rhyodacites-rhyolites. Circles = Syn-MoS_2 granites-rhyolites. Z = post-MoS_2 rhyolites. L = lamprophyre and quartz latites. Vector represents proposed fractionation trend of zoned dike magmas.

CONCLUSIONS

Evidence for mixing between andesite and rhyolite magmas is preserved in a dike swarm at Questa. The hybrid dikes were emplaced after eruption of the Amalia Tuff and prior to intrusion of granitic magmas associated with the Questa molybdenum deposits. Caldera magmatism and the subsequent generation of molybdenum-bearing magmas are plausibly related through the combined effects of magma mixing and crystal fractionation. This is consistent with reported $^{87}Sr/^{86}Sr$ isotope variations within the Amalia Tuff and for the younger molybdenum-bearing intrusions at Questa. The mixing event(s) which formed the zoned dikes appear(s) to have significantly influenced the chemical and isotopic evolution of the Questa magmatic system.

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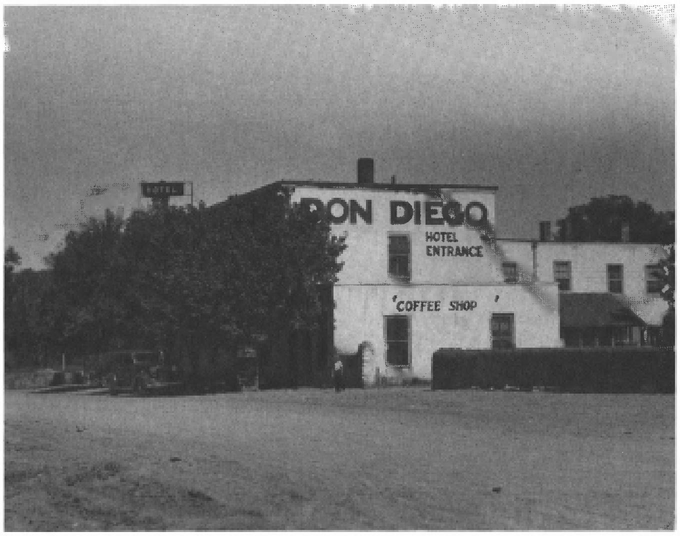
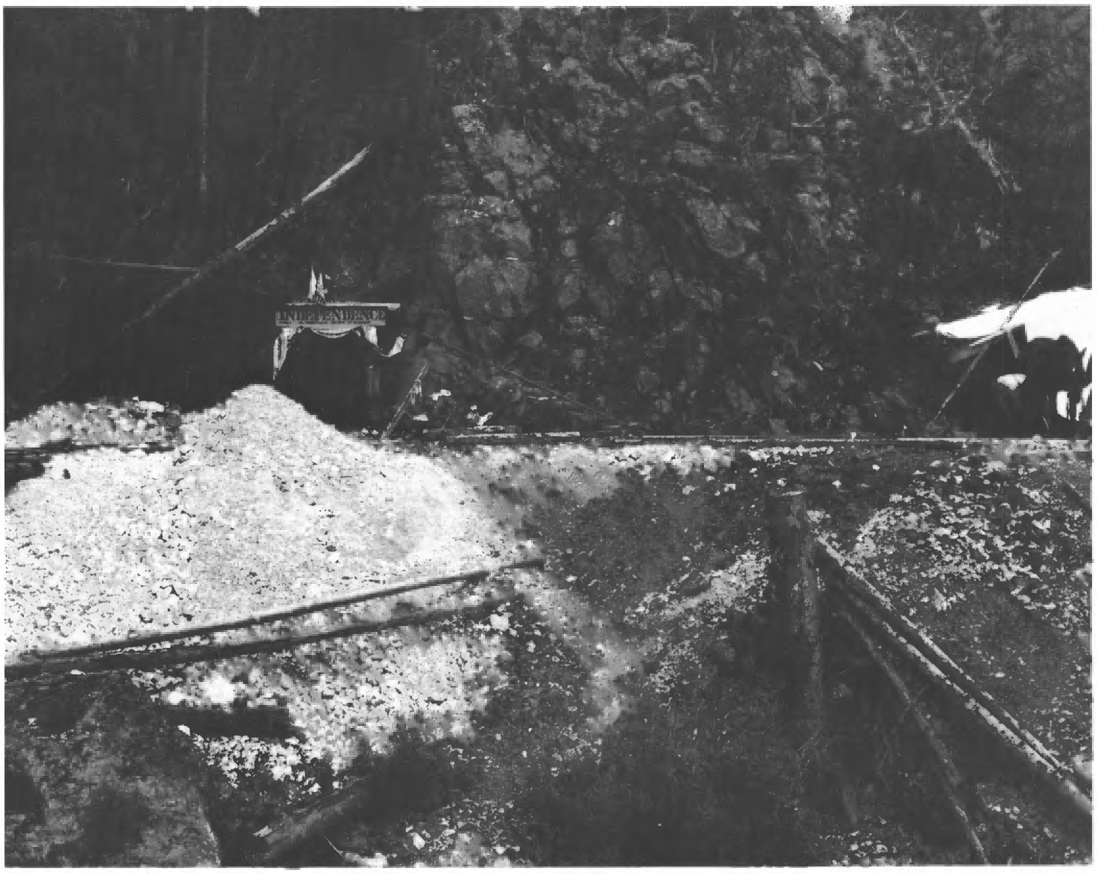


The St. James Hotel when it was named the Don Diego, circa 1925. Courtesy of Philmont Scout Ranch.



Independence mine, circa 1905, Red River District, Taos County, New Mexico. Possibly named because of a Fourth of July discovery (note flags and bunting), this mine is located on a branch of Bitter Creek about 6 mi NE of Red River. The discovery of an extremely rich (but small) gold deposit here in 1904–5 led to a rush into the area. Some of the ore assayed as high as $500 per ton and encouraged the driving of some 2000 ft of drift. Alas, no more rich pockets were found. Photo by L. C. Graton; courtesy of U.S. Geological Survey.