Age, chemistry, and geologic implications of tertiary volcanic rocks in the Last Chance Range and part of the Saline Range, northern Death Valley region, California

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AGE, CHEMISTRY, AND GEOLOGIC IMPLICATIONS OF TERTIARY VOLCANIC ROCKS IN THE LAST CHANCE RANGE AND PART OF THE SALINE RANGE, NORTHERN DEATH VALLEY REGION, CALIFORNIA

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Basalt, interlayered with flows of intermediate to felsic composition and felsic tuff, crops out in isolated masses on the flanks and crest of the Last Chance Range in eastern California. A few small coeval rhyolite intrusions also are present. The flows are interpreted to be part of the Saline Range volcanic field, which is widely exposed in the adjacent range to the southwest. We present here potassium-argon ages for two basalt flows, one in the Last Chance Range and one on the eastern flank of the Saline Range, and a $^{40}Ar/^{39}Ar$ age for a rhyolite intrusion in the Last Chance Range. The dated rocks are in the Last Chance Range 15′ quadrangle (fig. 1). The ages provide new evidence for the duration of volcanism in the Saline Range-Last Chance Range area and, together with four ages previously published (Elliott and others, 1984), offer a chronology for the geologic history of the eastern part of the volcanic field. The ages also help constrain the timing of mineralization that produced deposits of mercury, sulfur and gypsum, and possibly gold in the Last Change Range.

GEOLOGIC SETTING

The Last Chance Range is a northerly trending fault block composed mostly of tilted, folded, and thrust-faulted Paleozoic miogeoclinal strata (Wrucke and Corbett, 1990; Corbett and others, 1988). To the west is Eureka Valley, which is bordered at the south end by the Saline Range, an area 20 by 30 km containing gently east-tilted fault blocks capped mainly by basalt and trachyandesite flows with lesser amounts of rhyolite flows and tuff and intrusive trachyandesite (Ross 1967, 1970; Nelson, 1971). The flows in the Saline Range rest on Paleozoic strata and, from geophysical evidence, on alluvial fill deposited in a basin that once connected Eureka Valley with Saline Valley southwest of the range (Blakely and McKee, 1985). Flows from the Saline Range extend to the east and locally lap onto the western flank of the Last Chance Range. The oldest volcanic rocks in the Last Chance Range are basalt flows interlayered with sandstone and conglomerate. They occupy a paleovalley cut in the Paleozoic bedrock and are interpreted as having erupted from a volcano at the site of the northernmost cinder deposit shown in figure 1. Younger flows and tuffs farther south in the range may have blanketed a larger area coextensive with rocks exposed in the Saline Range. This former widespread distribution is strongly suggested by outcrops of volcanic rocks that make up nearly half of the exposed bedrock in the southern part of the Last Chance Range. Basalt flows and felsic tuff exposed low on the east flank in this part of the range lie on fanglomerate and basin deposits reported here to be as young as late Miocene in age and extend eastward into Death Valley.

Flows of basaltic and trachyandesitic composition are the most voluminous of the volcanic rocks in the Saline and Last Chance Ranges. Numerous small reddish cinder deposits, but no large volcano, mark the eruptive centers of these flows in the part of the Saline Range in the Last Chance Range quadrangle (fig. 1). In this part of the range, these flows and cinder deposits make up the entire section, which is at least 150 m thick compared to a maximum thickness farther south in the Saline Range of 300-400 m. In the Last Chance Range, the remnant volcanic section is no more than about 150 m thick. Two cinder deposits are preserved in the Last Chance Range, one of which is the small volcano mentioned earlier. Although only 0.38 km across as exposed but partly covered by younger deposits, this volcanic center is the largest in the Last Chance Range quadrangle.

DESCRIPTION OF THE ROCKS

Most of the dark flow rocks examined for this study are basalt. They consist of 5-10 percent olivine phenocrysts and commonly one to several percent each of clinopyroxene and plagioclase phenocrysts in an intergranular groundmass that contains abundant small olivine clinopyroxene, and magnetite grains scattered between aligned plagioclase laths. Olivine phenocrysts commonly are 0.4-2.0 mm across but are as large as 4.0 mm in diameter and have reddish-brown iddingsite rims in some specimens, but none in others. The clinopyroxene, probably augite, is in euhedral to rounded grains 0.4-2.2 mm long. It is pale green

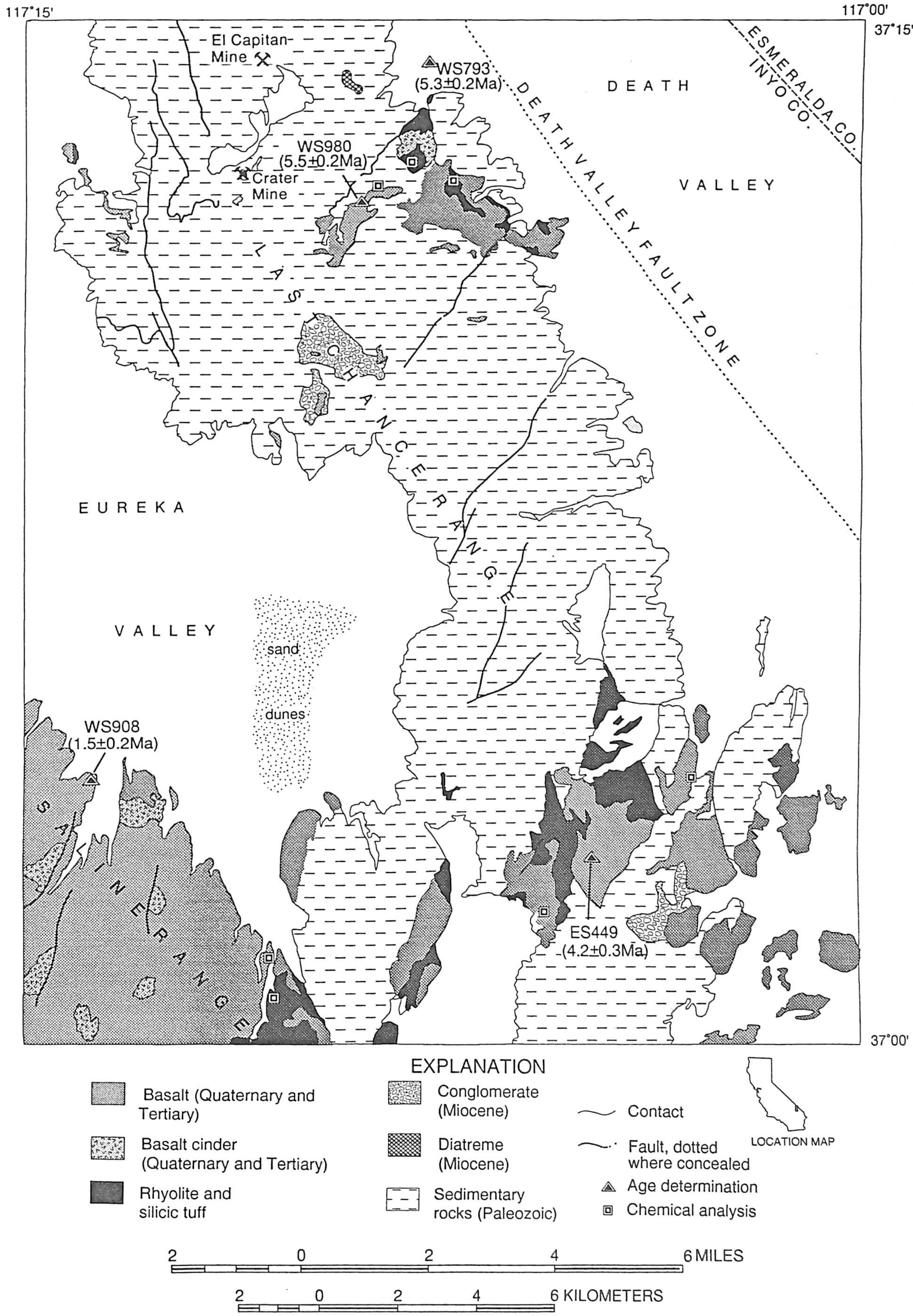

FIGURE 1. Simplified geologic map of the Last Chance Range quadrangle showing locations of samples collected for age determination and chemical analysis. Geology from Wrucke and Corbett (1990). Sample ES449 is from Elliott and others (1984).

in thin section and dark green in hand specimen. Although plagioclase commonly is subordinate in volume to other phenocryst phases, it is the most abundant phenocryst mineral in some rocks, where it is as much as 1.5 mm long. Large plagioclase crystals are zoned, and some zones are highly seived with glass. One olivine-bearing basalt has a few large highly resorbed quartz crystals.

The two trachyandesite samples we studied could not be distinguished from basalt in the field. Ross (1970) made the same observations for the dark flow rocks in the main part of the Saline Range, where trachyandsite is abundant. In our study area, one trachyandesite specimen has approximately 7 percent olivine, 5 percent clinopyroxene, and 1 percent plagioclase as phenocrysts in an intergranular groundmass, and the other specimen has less than one percent each of olivine and plagioclase phenocrysts. In thin section, these rocks differ from basalt in having smaller plagioclase laths in the groundmass and in containing a few highly resorbed plagioclase phenocrysts that are highly seived throughout or at the margins and may be exotic.

A trachydacite flow is interbedded with basalt in the south-central part of the Last Chance Range quadrangle. Because of its small size, the outcrop area of the trachydacite is not shown on figure 1, but it is at the site of the chemical analysis symbol shown as 1.8 km southwest of dated sample ES449. The rock is medium gray, about 60 m thick, and distinctly flow banded. It consists of about 5 percent rounded plagioclase with some highly seived zones, 3 percent rounded quartz, and 1 percent clinopyroxene as phenocrysts. Commonly the clinopyroxene crystals are clustered. Approximately one percent of the rock consists of rounded to embayed volcanic fragments, some with vague borders, all probably basalt. The fragments have a texture of felted plagioclase laths, and some contain olivine. The groundmass of the trachydacite is pale-brown devitrified glass highly charged with feldspar microlites or is microgranular. The only other flow we found in or near the study area that may be trachydacite is on the east flank of the Saline Range south of the Last Chance quadrangle. It is somewhat dissimilar to the flow just described in having 20 percent plagioclase phenocrysts, 5 percent biotite phenocrysts, and one percent augite phenocrysts but no quartz.

Rhyolite flows are exposed in the northeastern and southern parts of the Last Chance quadrangle (fig. 1). One flow on the eastern flank of the Saline Range south of the Last Chance quadrangle also was examined during this study. The flows are as much as 90 m thick and are interlayed with basalt. Interiors of the flows have about 10 percent plagioclase phenocrysts, commonly only 0.3-0.8 mm long, and 5 percent biotite phenocrysts mostly 0.2-0.5 mm across in a white to medium gray aphanitic to glassy groundmass. Broken fragments of clinopyroxene were found as small xenocrysts in one specimen. The groundmass may be perlitic, pumiceous, massive, or flow banded, or hyalopilitic.

Felsic tuff locally is abundant in the Saline and Last Chance Ranges. Rhyolite tuffs that crop out in the Saline Range were described by Ross (1970). No chemical analyses are available for the felsic tuffs in the Last Chance Range, but high quartz and biotite contents suggest that some of the tuff is rhyolite. It consists of white to light gray ash and pumice lapilli in deposits with a maximum thickness of about 70 m. Fine layering in some of the tuff suggests deposition by air-fall. Other sections have fine cross laminations interlayered with beds containing pebbles of Paleozoic rocks, pumice, basalt, and rhyolite that indicate deposition by water. Massive lapilli tuffs are thought to be ash flows.

CHEMISTRY

Volcanic rocks in the Last Chance and Saline Ranges have compositions in a nearly complete continuum from alkali-rich basalt to rhyolite, but some intermediate compositions are volumetrically minor (fig. 2, table 1). The basalts, with one exception, would plot in the alkalic field using K_2O versus SiO_2 of Peccerillo and Taylor (1976). All of the rocks have $Na_2O>K_2O$. Figure 2 shows that the volcanic rocks in the Last Chance Range are chemically similar to those in the Saline Range, thereby supporting evidence from their geographic distribution that all of them are part of the Saline Range volcanic field.

In an attempt to determine if fractional crystallization was a dominant process in the evolution of the rocks of the Saline Range volcanic field, a plot was made of Nb versus Zr (fig. 3). Plots using these elements provide a useful test of fractionation-controlled origins for magmatic rocks of widely varying silica contents (Wilson, 1989). Because of their incompatibility in mineral phases that crystallize in mafic and intermediate magmas, abundances of these elements should maintain a nearly constant ratio in rocks related by fractional crystallization. Figure 3 shows that our data for these elements do not plot on a straight line as they would if their ratio were constant. Plots of Ce versus Zr and Rb versus Zr give similar results. We conclude that some combination of magma mixing, contamination of magma by crustal materials, or magma generation at different mantle or crustal sources probably were important in the evolution of these rocks. The fragments of basalt(?) in the trachydacite flow, quartz in one olivine-bearing basalt, and seived plagioclase in

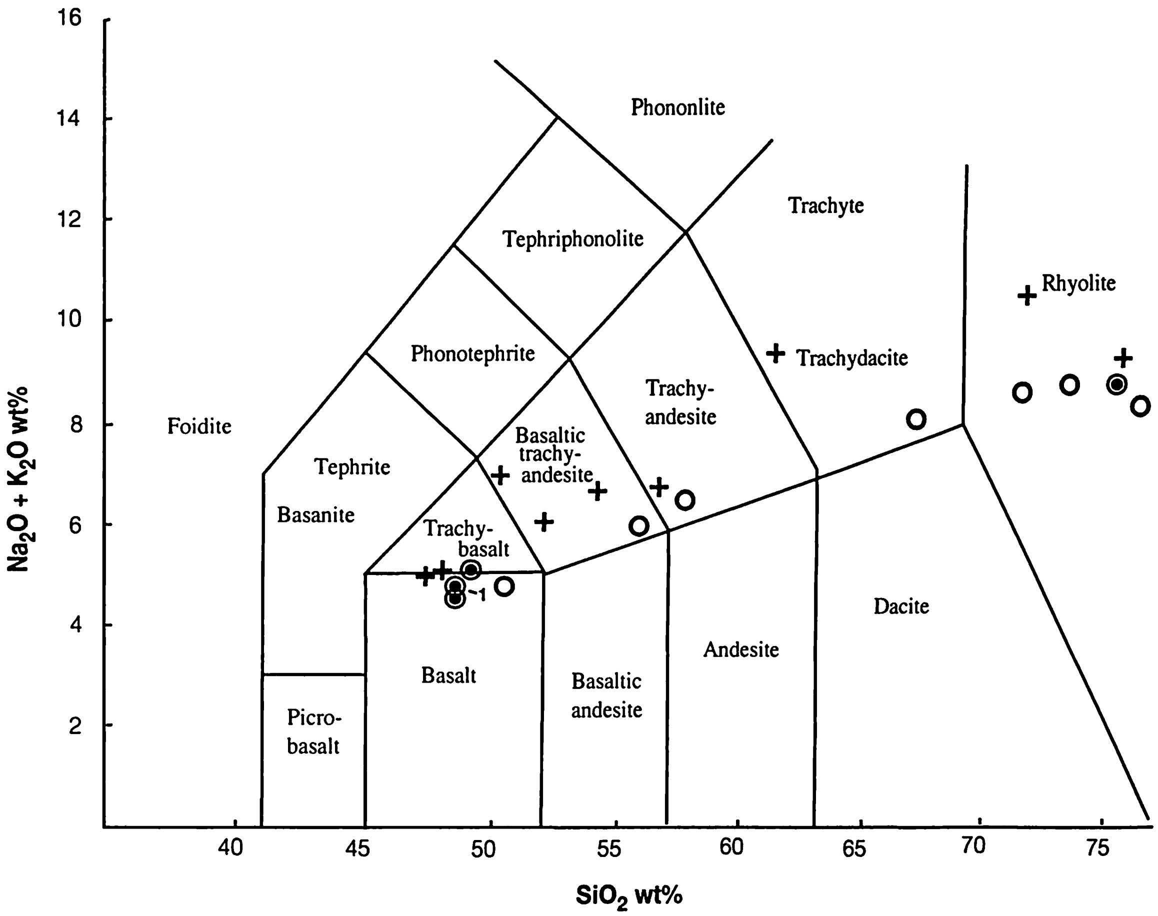

FIGURE 2. Diagram of weight percent total alkalies versus silica for volcanic rocks in the Last Chance and Saline Ranges. • Lithologic field boundaries and nomenclature from Le Bas and Streckeisen (1991).

◉ Age determination and chemical analysis this study (1, age from Elliott and others, 1984).

O Chemical analysis this study.

+ Chemical analysis from Ross (1970).

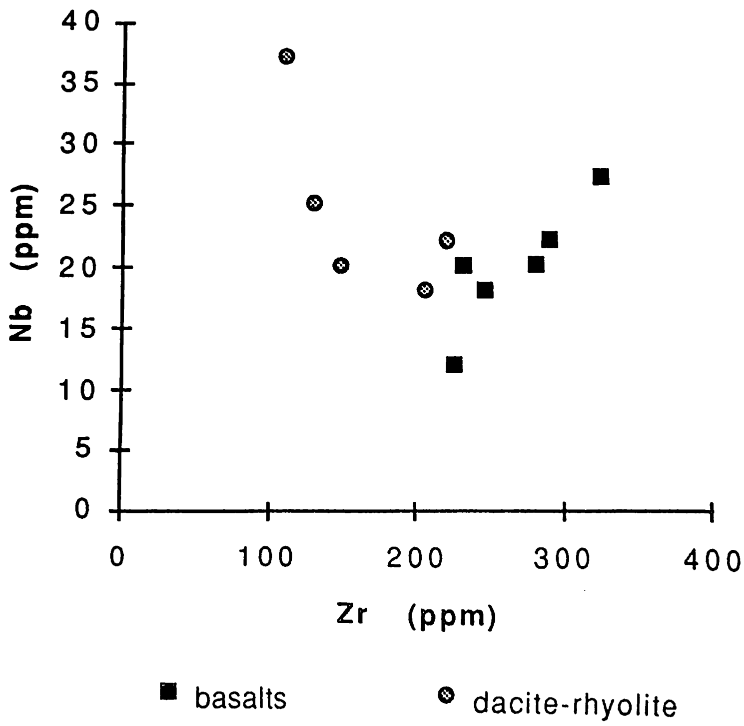

FIGURE 3. Diagram of niobium versus zirconium for volcanic rocks in the Last Chance Range quadrangle.

■ basalt and trachyandesite.

⊗ trachydacite and rhyolite.

rocks of all compositions except rhyolite provide support for this conclusion.

AGE DETERMINATIONS

Ages determined for this study show that the intrusive rhyolite and basalt flow from the Last Chance Range are latest Miocene in age and the basalt flow from the eastern flank of the Saline Range is early Pleistocene in age. Other ages reported for the Last Chance Range and eastern Saline Range fall in this time span. Elliott and others (1984) recorded a Pliocene age of 4.2 Ma for another locality (ES449) in the Last Chance Range (fig. 1) and ages of 4.6 to 2.5 Ma for rocks in the Saline Range south of the Last Chance quadrangle. When combined with ages reported by Conrad and others (1994) and Sternlof (1988), volcanism in the Saline Range volcanic field is documented as having extended into the late Pleistocene, taking place at numerous intervals and spanning the time between 5.5 and 0.6 Ma.

Sample preparation and argon and potassium analyses for the age determinations were carried out in the U.S. Geological Survey laboratories at Menlo Park, California. The basalt samples were crushed and sized to -30 to +60 mesh then split for analysis without further processing. Potassium analyses were performed by a lithium metaborate flux fusion-flame photometry method using lithium as an internal standard (Ingamells, 1970). Sanidine was separated from the rhyolite using magnetic and heavy-liquid separation techniques, then irradiated in the Los Alamos Omega West reactor at 6MW for 0.5 hr. The irradiated sample and flux monitors were loaded in conventional argon extraction lines for extraction and purification using techniques similar to those described by Dalrymple and Lanphere (1969). Argon composition for all samples was determined by standard isotope-dilution procedures using a 60°-sector, 15.2 cm radius, Neir-type mass spectrometer. The precision of the date is the estimated analytical uncertainty at the 95 percent confidence level (2 sigma) and is based on experience with replicated analyses in the Menlo Park laboratories. The decay constants used in the age calculations are: $\lambda_\varepsilon+\lambda_{\varepsilon'} = 0.581 \times 10^{-10} yr^{-1}$; $\lambda_\beta = 4.962 \times 10^{-10}$ yr^{-1}; and $^{40}K/K_{total} = 1.167 \times 10^{-4}$.

VOLCANIC AND TECTONIC HISTORY

When the oldest basalt flows of the Saline Range volcanic field erupted in the late Miocene in the Last Chance Range, the range was topographically high and bounded by extensional basins to the west and east. Eureka Valley to the west contained a thick section of Neogene alluvial deposits prior to volcanism in the Saline Range (Blakely and McKee, 1985; Conrad and others, in press), and conglomerates and other basin deposits were deposited in the Last Chance Range and on its eastern side (Wrucke and Corbett, 1990) before emplacement of the first basaltic flows in those areas. A paleovalley in the north-central Last Chance quadrangle was partly filled with sedimentary deposits when the oldest flows known in the Saline Valley volcanic field poured down to the south at about 5.5 Ma from the volcano on the present east side of the range (fig. 1). Rhyolite flows erupted concurrently in the same general area, probably from a center where rhyolite intrusive rocks are exposed today 1 to 2 km north of the basaltic volcano, and rhyolite flows and tuffs erupted from localities farther south in the Last Chance Range, possibly from sites where other intrusive rhyolite bodies are exposed. Rhyolite flows became abundant in the northeastern part of the Last Chance quadrangle and rhyolite tuffs in the southern part. Continued outpourings of basaltic rocks interlayered with at least one trachydacite flow and more numerous rhyolite flows and tuffs eventually blanketed large areas now exposed in the Last Chance Range.

The available isotopic ages between 5.5 and 0.6 Ma document that eruptions were numerous during extension in the Saline Range volcanic field. Extension in the area began before 4.6 Ma (Conrad and others, in press) and probably before 5.5 Ma, and it continued after volcanism ceased. Bodies of volcanic rocks stranded high in the Last Chance Range, some of which are 700 m above the base of flows in the Saline Range, show the great amount of offset that has taken place since volcanism began. Faulted alluvial fans along the western range front near the south border of the Last Chance quadrangle (Wrucke and Corbett, 1990) indicate that extension in the area has continued into the Holocene.

AGE OF MINERALIZATION

The timing of mineralization at the sulfur and gypsum deposit at the Crater Mine, the largest source of native sulfur in California from 1915 to 1953 (Branner, 1959) (fig. 1), and the possible gold deposit beneath it (Marsh and others, 1991), is suggested but not clearly resolved by the present data. The nearby mercury deposit at the El Capitan Mine (fig. 1) (Hill, 1972) is presumably of the same age (Marsh and others, 1991). No igneous rocks are exposed at these deposits, so the age of mineralization must be inferred. The nearest intrusive rocks to the Crater Mine would be below the diatreme 3.7 km to the northeast and at the basaltic

TABLE 1. Representative chemical analyses of Cenozoic volcanic rocks from the Last Chance and Saline Ranges.

Major oxides: Analysis by wave-length dispersive X-ray fluorescence spectrometry for most oxides (Taggart and others, 1987) and by classical whole rock and rapid rock techniques for FeO, H_2O^+, H_2O^-, and CO_2 (Jackson and others, 1987).
Trace elements: Analysis by energy dispersive X-ray fluorescence spectrometry (Johnson and King, 1987).
Rare earth elements: Analysis of samples WS798, WS811, and WS816 by inductively coupled plasma-atomic emission spectrometry (Lichte and others, 1987a); samples WS908 and WS1051 by inductively coupled plasma mass spectrometry (Lichte and others, 1987b), and samples WS833 and WS999A by instrumental neutron activation (Baedecker and McKown, 1987).

Sample No.	WS1051	WS908	WS811	WS816	WS999A	WS833	WS793
SiO_2	46.20	48.20	55.00	56.70	65.30	70.30	74.50
$A1_20_3$	13.70	17.40	15.70	16.10	14.10	13.10	13.40
Fe_2O_3	5.02	5.57	2.22	3.28	2.83	0.67	0.85
FeO	3.82	3.70	4.25	2.93	0.78	0.46	0.04
MgO	7.45	5.80	5.90	5.40	2.20	0.30	0.43
CaO	12.70	9.89	7.80	6.06	3.52	2.42	0.93
Na_2O	2.51	3.41	3.07	3.75	3.48	33.00	3.44
K_2O	2.03	1.57	2.80	2.62	4.37	5.06	5.19
H_2O^+	0.39	0.28	0.23	0.47	0.61	1.78	0.52
H_2O^-	0.42	0.38	0.21	0.58	1.25	0.26	0.44
TiO_2	1.22	1.79	1.20	0.96	0.53	0.20	1.61
P_2O_5	0.56	0.96	0.47	0.37	0.16	0.06	0.83
MnO	0.15	0.15	0.11	0.12	0.07	0.05	0.14
CO_2	2.64	0.41	<0.01	<0.01	0.40	0.94	<0.01
Trace Elements, ppm							
Nb	12.00	27.00	20.00	22.00	18.00	20.00	25.00
Ftb	40.00	27.00	57.00	55.00	75.00	116.00	160.00
Sr	1,100.00	1200.00	810.00	790.00	315.00	184.00	72.00
Zr	225.00	325.00	230.00	290.00	205.00	148.00	130.00
y	26.00	26.00	23.00	20.00	14.00	14.00	15.00
Ba	1,800.00	1200.00	1200.00	930.00	850.00	610.00	320.00
cu	59.00	44.00	32.00	37.00	23.00	<20	<20
Ni	108.00	50.00	120.00	120.00	44.00	<20	<20
Zn	77.00	89.00	70.00	76.00	47.00	30.00	34.00
Cr	240.00	68.00	220.00	230.00	90.00	<20	<20
Rare Earth Elements, ppm							
La	64.00	90.00	50.90	35.90	61.00	54.40	44.50
Ce	120.00	160.00	99.20	63.10	102.20	89.30	74.60
Pr	16.00	17.00	11.10	7.40			7.00
Nd	60.00	64.00	41.40	25.60	31-60	24.10	20-80
Sm	9.90	9.80	6.90	4.10	4.81	3.79	3.00
Eu	2.30	2.80	1.80	1.22	1.10	0.53	0.41
Gd	7.10	8.20	6.00	4.00			2.50
Tb	0.94	1.10	1.00	<1	0.45	0.37	<1
Dy	5.10	5.80	3.20	4.60			2.20
Ho	0.86	1.00	0.74	0.49			0.42
Er	2.50	2.80	2.00	1.40			1.30
Tm	0.35	0.37	0.31	0.23			0.22
Yb	2.10	2.30	2.00	1.40	1.66	1.57	1.50

volcano 4.8 km to the east-northeast (fig. 1). Other nearby igneous sources are the rhyolite intrusions 5.3 and 5.9 km northeast of the Crater Mine. The El Capitan Mine is a little closer than the mineral deposits at the Crater Mine to the diatreme and rhyolite intrusions. Although the diatreme has not been dated, its matrix of felsic shards and fragments of sanidine, plagioclase, quartz, and biotite suggest a possible genetic association with the rhyolite intrusions, one of which has an age of 5.3 Ma (fig. 1). The basaltic volcano east-northeast of the Crater Mine has a similar age of 5.5 Ma, judged by the age of one of its basaltic flows discussed earlier. Mineralization at the Crater and El Capitan Mines probably could have taken place anytime during igneous activity in the Saline Range volcanic field. However, it seems reasonable to assume

that heat from one of the nearby intrusive sources of late Miocene age likely was responsible for the deposits, suggesting that they formed about 5.5 Ma.

SAMPLE DESCRIPTIONS

1. *WS-793* $^{40}Ar/^{39}Ar$
Rhyolite intrusion (37°14′19″N, 117°37′54″W; Last Chance Range 15′ quadrangle, Inyo Co., CA). Light-gray, weakly flow-banded rock consisting of 10-15 percent sanidine and plagioclase phenocrysts commonly 0.5-1.0 mm long, and 1-2 percent biotite phenocrysts commonly about 0.6 mm long in a matrix of glass charged with feldspar microlites and abundant small irregular quartz crystals. *Collected by:* C.T. Wrucke. *Analyzed by:* R.J. Miller. *Analytical data:* $^{40}Ar^{rad}/^{39}Ar$ = 18.025; $^{37}Ar/^{39}Ar$ = 0.044; $^{36}Ar/^{39}Ar$ = 0.0369; K/Ca = 11.031; $^{40}Ar^{rad}/Ar^{tot}$ = 39.5%; J = 4.108×10^{-4}.
(sanidine) 5.3 ± 0.2 Ma

2. *WS-908* K-Ar
Basalt flow (37°03′49″N, 117°43′55″W; Last Chance 15′ quadrangle, Inyo Co., CA). Dark-gray fine-grained rock from one of the highest flows on the northeast flank of the Saline Range. Specimen missing. *Collected by:* C.T. Wrucke. *Analyzed by:* R.J. Miller. *Analytical data:* K_2O = 1.470%, 1.454%, 1.466%; $^{40}Ar^{rad}$ = 3.22×10^{-12} moles/g; $^{40}Ar^{rad}/Ar^{tot}$ = 12.7%.
(whole rock) 1.5 ± 0.2 Ma

3. *WS-980* K-Ar
Basalt flow (37°12′18″N, 117°35′46″W; Last Chance Range 15′ quadrangle, Inyo Co., CA). Dark-brownish-gray rock consisting of 20 percent olivine phenocrysts commonly euhedral with oxidized rims and 0.35-1.1 mm in length and 10 percent stubby euhedral to anhedral augite crystals 0.25-0.60 mm long in an intergranular matrix of aligned plagioclase laths and minute crystals of augite, oxidized olivine, and magnetite. *Collected by:* C.T. Wrucke. *Analyzed by:* R.J. Miller. *Analytical data:* K_2O = 1.724%; $^{40}Ar^{rad}$ = 1.38×10^{-11} moles/g; $^{40}Ar^{rad}/Ar^{tot}$ = 44.5%.
(whole rock) 5.5 ± 0.2 Ma

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The 1983 revision of this geologic time chart was prepared by the Geologic Names Committee for U.S. Geological Survey use. It supersedes the 1980 chart. Numerical ages of chronostratigraphic boundaries are subject to many uncertainties besides the analytical precision of the dating. The placement of boundary stratotypes and the achievement of international agreements on these ages is a slow process subject to much revision and review. Recent studies and revisions of the geologic time scale of especial interest are reported in *A geologic time scale,* by W. B. Harland, A. V. Cox, P. G. Llewellyn, C. A. G. Pickton, A. G. Smith, and R. Walters, 1982: Cambridge University Press, 132 p.; *The decade of North American geology 1983 geologic time scale,* by A. R. Palmer, 1983: Geology, v. 11, p. 503–504; and *The chronology of the geological record,* N. J. Snelling (ed.), 1985: Blackwell Scientific Publishers, The Geological Society, Memoir No. 10, 343 p.

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