THE LEONA RHYOLITE, ALAMEDA COUNTY, CALIFORNIA*

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Abstract

The Leona rhyolite crops out discontinuously for 21 miles along the front of the hills from Berkeley to a point 4 miles southeast of Hayward, Calif. Long ago, A. C. Lawson and C. W. Clark agreed that it represents a single extensive lava flow of late Tertiary, probably Pliocene age. Because so many large rhyolite extrusive rocks are being interpreted nowadays as welded tuffs, re-examination of the Leona is timely.

In its southern half, recently studied, the rhyolite belt exhibits continuous groundmass fabric with unfragmented phenocrysts and practically lacks pyroclastic debris, suggesting origin as lava. However, downward extension of several broad hill cappings into narrow feeder-like masses, the presence of rhyolite dikes, and other features suggest extrusion as a series of domes and short flows rising more or less simultaneously along subsidiary shears in a major fault zone rather than as a single flow.

Commonly, the rock is a weathered mixture of iron oxide-stained quartz and argillized feldspar. Where fresh, it typically contains a few corroded phenocrysts of sodic plagioclase and quartz in spherulitic glass or in a felted microcrystalline groundmass of quartz and albite. A little chlorite and altered biotite are the only ferromagnesian minerals. Pyrite crystals, many of them rounded but not altered chemically, are abundant in fresh rhyolite but extremely rare in the underlying rocks; the pyrite appears to be primary.

In previous descriptions, orthoclase and oligoclase have been identified as major components, and albite has not been reported. Despite the modified mineralogy, the name soda rhyolite, originally assigned by Lawson, still seems appropriate.

The formation is little deformed and thus apparently is younger than the intense regional post-Pliocene orogeny; it is overlain by Pleistocene sedimentary rocks. This and other indirect evidence favor emplacement of the rhyolite rather early in the Pleistocene. Since then, it has played an important role in the geomorphic development of the east side of San Francisco Bay.

Introduction

The hills that rise abruptly on the east side of San Francisco Bay are discontinuously capped with distinctive light-colored pyritic soda rhyolite. Lawson (1914) named the formation Leona rhyolite, from its impressive exposures at Leona Heights in Oakland, and concluded that it is the eroded remnant more than 21 miles long of a single great lava flow of late Tertiary, probably Pliocene age. Clark (1917) studied the formation shortly afterward and reached similar conclusions. Nowadays, many workers doubt that rhyolitic lava ever flows more than a few miles; an increasing number of rhyolitic rocks once thought to be extensive lava flows are turning out, upon close examination, to be welded tuffs. This doubt has originated perhaps, from recognition of the high viscosity of rhyolitic melts both in the field and in the laboratory. Restudy of the Leona may, then, be of interest. The southern half of the rhyolite belt

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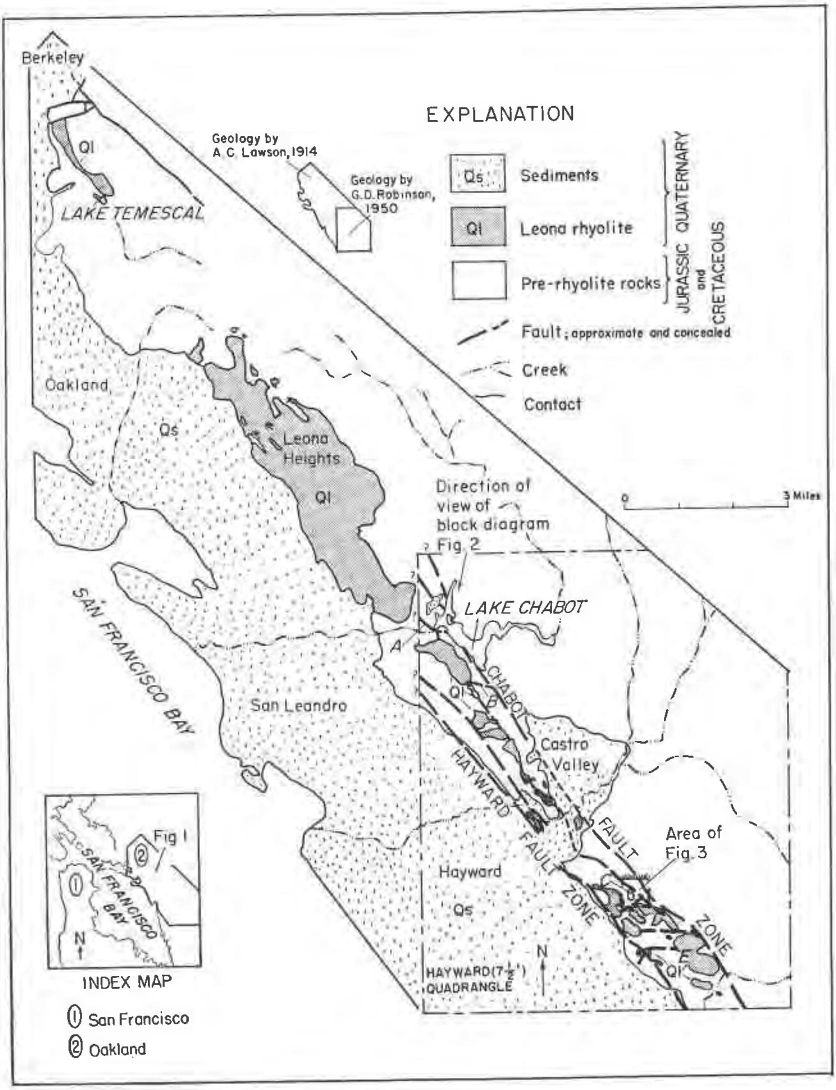

FIG. 1. Distribution of Leona rhyolite, Alameda County, California. The faults which are shown to terminate at the edges of the Hayward Quadrangle are believed to continue beyond it but have not yet been mapped.

crosses the Hayward $7\frac{1}{2}$-minute Quadrangle (see Fig. 1), which I recently mapped and briefly described (Robinson, in preparation). The present paper, which is an expansion of part of the quadrangle report, summarizes existing information on the Leona and presents some new data bearing on its origin and age. Information on the northern half is from Lawson and Clark.

W. T. Schaller's first publication (1903) described the secondary minerals at Leona Heights. Clarence Ross has pioneered in marshalling the evidence favoring the emplacement of large rhyolitic extrusive bodies as welded tuff. Thus it is fitting that a discussion of the Leona rhyolite appear in a publication dedicated to Schaller and Ross. This paper, however, lacks the systematic laboratory approach that characterizes their work. Rather, it is primarily a field study, supported only in small part by laboratory data.

The Leona is deeply altered in most places, and presents a cryptic and unappealing face to casual inspection, which is no doubt why it has been largely neglected since the days of Lawson and Clark. Whether or not the story it has to tell is convincing, this paper will have served its purpose if it stimulates others to undertake exhaustive laboratory studies of the Leona rhyolite.

Field Relations

The base of the rugged hills that face San Francisco Bay on the east is a fault- or fault-line scarp, marking the western edge of a zone, 1 to 2 miles wide, riven by a series of northwest-trending faults, linked by subsidiary transverse faults (Fig. 1). This faulted zone has been the site of repeated disturbances at least since the late Tertiary and probably since far back into the Mesozoic. The westernmost faults have had mostly Recent movement; the easternmost ones appear to have been long inactive. In the Hayward quadrangle, these faults have been designated the Hayward fault zone and the Chabot fault zone respectively. Within the faulted zone the principal bedrocks are Upper Jurassic sedimentary, volcanic, and plutonic rocks, overlain by the Leona rhyolite and by Pleistocene gravel.

Outcrops of the rhyolite extend for more than 21 miles between Hamilton Gulch in Berkeley and the southeast corner of the Hayward quadrangle. The rhyolite belt is nowhere more than 1½ miles wide and commonly is less than half a mile wide. It is broken by two major gaps, one 2½ miles long southeast of Lake Temescal in Berkeley, the other 1½ miles long southeast of Hayward. Elsewhere the rhyolite is almost continuous, cut through only by narrow stream canyons. Its highest altitude is about 1100 feet, at Leona Heights; it is exposed in many places less than 100 feet above San Francisco Bay. The original top is nowhere preserved. The present thickness varies abruptly and irregularly, with a maximum of 800 feet near Leona Heights. Most of the rhyolite remnants are less than 100 feet thick, but masses 300 to 400 feet thick are preserved at several places.

The rhyolite usually follows a fault contact between the Upper Jurassic Knoxville formation on the east and a complex assemblage of sedimentary and volcanic rocks of the Upper Jurassic Franciscan formation intruded by serpentine and gabbro on the west. Although largely underlain by Jurassic rocks, the rhyolite is underlain in at least one place by late Tertiary rocks. North of Hayward, in the hills above Hayward Union High School, a small body of siliceous mudstone, correlated with the middle Miocene Monterey group, is present between the serpentine and the rhyolite.

The base of the rhyolite is exposed in a few transverse canyons. These cross sections are V-shaped, as though the rhyolite had flowed down youthful stream valleys cut in the fault zone. In some of them, a few feet of pebble-cobble conglomerate in a rhyolitic tuff matrix underlies the Leona. The pebbles are predominantly Franciscan formation chert and greenstone, with minor amounts of biotitic sandstone from Cretaceous or Tertiary rocks; others are of siliceous shale and chert from the Monterey group.

No younger rocks overlie the Leona in the Hayward quadrangle. Just to the north, however, unconsolidated stream gravels lie on the eroded top of the rhyolite, far above the present valleys and trending athwart them (Clark, 1917, p. 363). Scattered at the highest altitudes in the Hayward area are similar isolated gravel patches, clearly of Pleistocene age, containing pebbles from recognizable Jurassic, Cretaceous, Miocene, and probably Pliocene formations.

The kind and degree of deformation of the Leona rhyolite is important in deducing its age. According to Lawson and Clark, the rhyolite has been much affected by faulting. Their maps show the Leona to be terminated on the north by a west-trending fault, severely displaced by several of the great northwest-striking regional faults, and notably offset by two smaller transverse faults west of Lake Chabot. In the Hayward quadrangle the only significant deformation of the rhyolite is several hundred feet of vertical displacement and perhaps 1200 feet of horizontal displacement on its western edge, in the Hayward fault zone. The two transverse faults west of Lake Chabot are in the Hayward quadrangle (A and B, Fig. 1). Their existence is not questioned, but, in my opinion, the rhyolite is not offset by them. The outcrop pattern of the rhyolite hill-capping that trends across B seems to be entirely erosional. The rhyolite at A, which forms the abutments of the Lake Chabot Dam far below the base of the nearest hill-capping of rhyolite, seems to be a dike, as do several other elongate rhyolite masses on the west side of Lake Chabot. Two of these are shown in a perspective block diagram (Fig. 2). The contacts of three of these masses are well exposed in places, and the rhyolite shows no signs of disturbance, although at the upper contact of the rhyolite exposed on the east side of the San Leandro Rock Co. quarry (see diagram) there is a few feet of black gouge, derived from Franciscan rocks. Apparently these dikes occupy earlier faults. There is no evidence that these bodies are slivers faulted down from a surface flow.

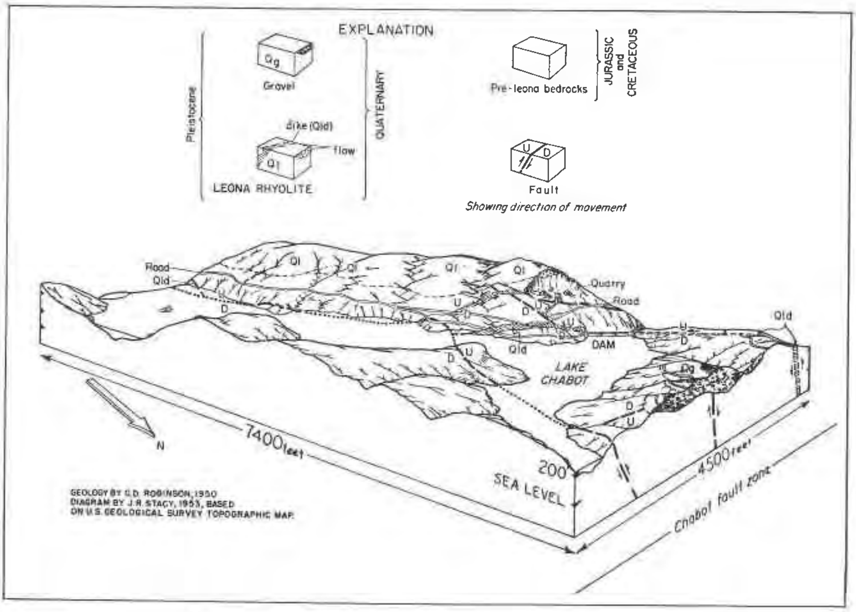

FIG. 2. Perspective block diagram of Leona rhyolite and adjoining formations near Lake Chabot, Hayward Quadrangle, California.

Interpreting the structure is complicated by the presence of old, presumably Franciscan, keratophyric volcanic rocks along much of the western edge of the rhyolite belt. In hand specimens, these rocks are characteristically similar to fresh Leona rhyolite, and they were included with the Leona by Lawson and by Clark. Where well exposed, however, and in thin section, the keratophyric rocks can usually be readily distinguished from the Leona. They have been intensely folded and faulted. If correlated with the Leona they would naturally lead to an exaggerated idea of its deformation.

Southeast of Hayward, on the east side of the belt, three broad rhyolite hill cappings (C, D, E, Fig. 1) narrow abruptly downward into feederlike masses in valleys, which are also the loci of pre-rhyolite faults. Figure 3 is an areal map of one of these (C). These bodies seem best interpreted as eroded domes or as the vent portions of individual short flows.

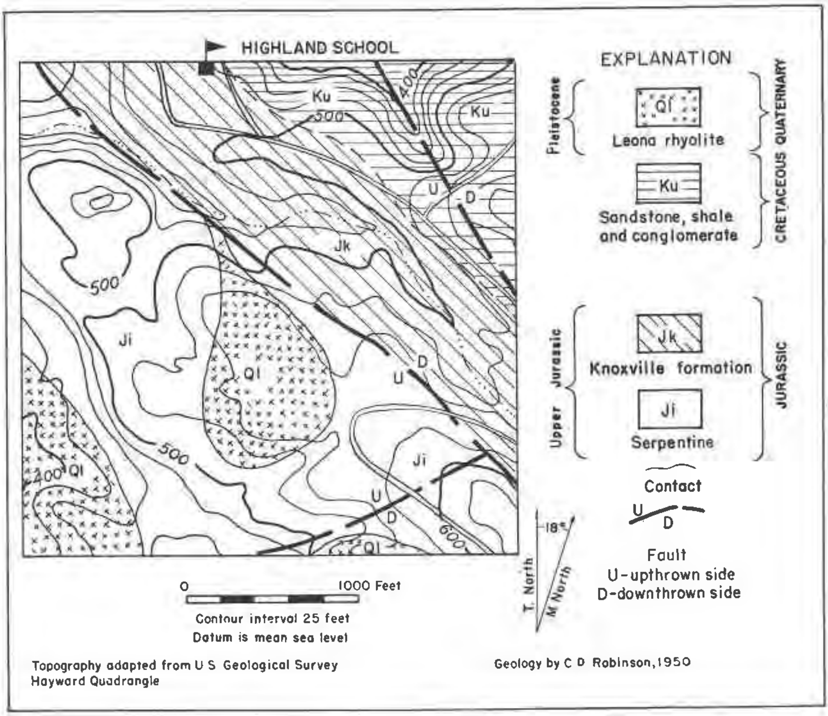

FIG. 3. Geologic detail near Highland School, Alameda County, California.

INTERNAL FEATURES

The rhyolite, though the most resistant rock in the area, with a tendency to form cliffs, is nearly everywhere deeply altered. Even in quarries, it is commonly a dense mottled, very pale orange to brownish-white mixture of quartz, argillized feldspar, clay, and wisps of chlorite, with iron-stained pits marking former pyrite grains. Innumerable closely spaced fractures are coated with reddish-orange and yellowish-brown iron stains, masking the predominantly light color of the altered rock. Sufficient use of the hammer will usually reveal comparatively fresh rhyolite under a thick carapace of alteration, and the alteration is most intense at higher altitudes and where fractures are most numerous. The alteration, therefore, seems to be largely due to weathering, possibly accelerated by sulfuric acid produced by oxidation of the original disseminated pyrite. The rock is massive, with no sign of layering even in the largest exposures. It is rarely amygdaloidal or vesicular and only locally flow-banded.

The intricate fracturing is apparently due mainly to cooling rather than to deformation. Many fractures are healed with glass or other groundmass material, the brecciation is widespread rather than confined to linear zones, and offsetting across fractures is trivial. Where the rhyolite has been affected by known faults it has cataclastic textures, both macroscopic and microscopic, and the shearing has linear, purely local, distribution. A few fractures are filled with veinlets of quartz or calcite.

Where fresh, the Leona rhyolite is medium bluish or greenish gray. About 30 thin sections from the Hayward quadrangle were studied. They exhibit a few per cent of small poorly oriented phenocrysts of plagioclase (sodic oligoclase to albite), quartz, and sporadically, orthoclase. The phenocrysts are commonly a little resorbed and cracked. Pyroclastic debris, such as broken crystals, glass shards, and relict lapilli, is very rare. The groundmass is typically a felted, locally granophyric, microcrystalline mixture of untwinned albite and quartz. Less commonly, the groundmass is spherulitic glass, in which the spherules are usually chalcedony but in places are feldspar or quartz. Locally the glass is riddled with poorly aligned feldspar microlites. The only ferromagnesian constituents are scattered shreds of chlorite and of biotite, marginally altered to chlorite. Cubes and pyritohedrons of pyrite are disseminated throughout. The mineral proportions vary widely, but the average fresh holocrystalline rock may be visualized as consisting of 60 per cent albite, 30 per cent quartz, 3 per cent oligoclase, 2 per cent each of orthoclase, chlorite, and pyrite, and accessory magnetite, apatite, sphene, zircon, and ilmenite.

The plagioclase, based on many measurements of maximum extinction angles and a few measurements in oils, seems to grade from sodic oligoclase, mostly in the phenocrysts, to somewhat calcic albite (γ 1.538–1.540), mostly in the groundmass. Most of the albite is untwinned, but that approaching oligoclase in composition occasionally exhibits rather broad albite twinning. Zoning was not seen. All of the plagioclase is evidently primary.

Chlorite appears in the freshest rhyolite, which also contains a little biotite, marginally chloritized. The chlorite probably formed during or soon after consolidation of the rhyolite by deuteric alteration of biotite.

In the northern part of the area the phenocrysts are larger and more abundant, making up 5 to 15 per cent of the rock, and the groundmass is more commonly glassy, with much local development of microlitic and spherulitic facies. The bulk mineral composition appears to be about the same as in the southern (Hayward) part.

Three chemical analyses exist from the time of Lawson and Clark; they are reproduced in Table 1 along with one of Daly's averages (1933) for comparison. No recent analyses have been made, but partial analysis of two fresh rhyolite samples for Na_2O and K_2O, made in 1952 in the

TABLE 1. CHEMICAL COMPOSITION OF LEONA RHYOLITE

	(1)	(2)	(3)	(4)
SiO_2	71.00	72.12	71.60	72.80
TiO_2	—	0.17	0.12	0.33
Al_2O_3	12.70	11.49	11.93	13.49
Fe_2O_3	0.66	2.77	3.00	1.45
FeO	2.44	2.30	3.40	0.88
MnO	—	0.10	0.09	0.08
CaO	0.90	0.94	0.52	1.20
MgO	1.39	0.85	1.33	0.38
Na_2O	6.45	5.28	4.62	3.38
K_2O	2.99	0.86	1.90	4.46
P_2O_5	—	0.88	0.62	0.08
SO_3	—	—	0.08	Nr
CO_2	—	1.15	0.38	Nr
FeS_2	—	0.03	—	Nr
H_2O (at 110° C.)	0.28	0.06	0.07	1.47
Ignition	1.56	0.96	0.55	
	100.37	99.96	100.21	100.00

(1) Analyst—C. P. Richmond. } From Clark (1917), p. 371, and Lawson (1914),
(2) and (3) Analyst—G. E. Colby } p. 12.
(4) Average of 126 analyses of rhyolite, from Daly (1933), p. 9.
Nr, not reported.

laboratories of the U. S. Geological Survey, confirm the proportions of these oxides reported by the earlier analysts.

Elaborate petrologic calculations and deductions based on these analyses would be idle: the data are few and they represent material that was "more or less altered" (Lawson, 1914, p. 12). Even allowing for this the analyses have some features strikingly at variance with the mineralogy as described by Lawson and by Clark. The most significant of these involve the composition of the feldspars. Clark (1917, p. 371) states that "orthoclase, plagioclase, mostly oligoclase, and quartz are the essential constituents of the original rock." But orthoclase and oligoclase cannot be major constituents of a rock containing only 1 to 3 per cent of K_2O and less than 1 per cent of CaO. The present identification of albite as the dominant feldspar, with minor amounts of oligoclase and orthoclase, brings the mineralogy into reasonable agreement with the chemical analyses. The dominance of albite is supported by two partial *x*-ray analyses, made by A. J. Gude, III, of the Geological Survey. Staining tests with sodium cobaltinitrate, made by Lyman C. Huff, also of the Geological Survey, confirm the observation that potash feldspar is sparse and sporadic. Despite this substitution of albite for most of the orthoclase and oligoclase in the mode, the name soda rhyolite applied by Lawson still seems appropriate.

Origin of the Pyrite

The ubiquitous pyrite deserves further discussion. Although pyrite is (or was) disseminated throughout the rhyolite, it is absent from the underlying rocks, even at their contacts with pyrite-rich rhyolite, except at one locality where keratophyric volcanics contain a little. It seems reasonable, on this basis alone, to regard the pyrite as a primary mineral in the rhyolite, as Lawson and Clark did. The behavior of pyrite under volcanic conditions, that is, at high temperature and low pressure, is not in conflict with such an origin. It is well-known that pyrite, in a vacuum, decomposes to pyrrhotite and sulfur vapor at about 500° C. But the pyrite-pyrrhotite reaction is reversible, according to Allen, Crenshaw, and Johnston (1912), and their work shows that under only 1 atmosphere of sulfur vapor pressure the dissociation of pyrite is sluggish and incomplete even at 750° C.; at falling temperature, pyrrhotite changes almost completely to pyrite at about 550° C. They found that pyrrhotite in hydrogen sulfide melts at 1183° C. The melting point of pyrite in air is 1171° C. (Handbook of Chemistry and Physics, 1952). The temperature of flowing rhyolite has never been measured, and few really pertinent laboratory experiments are recorded; published speculations range from as low as 600° C. to as high as 1260° C. A number of recent field measurements indicate that the extrusion temperature of basalt in Hawaii is in the range 1030 to 1080° C. (Macdonald and Finch, 1950; Macdonald, 1952); basalt extrusion temperatures near 1170° C. are suggested by recent laboratory experiments (G. C. Kennedy, oral communication). It is generally agreed that rhyolite issues at lower temperature than basalt. In the absence of excess oxygen, then, it would appear that iron sulfide can remain stable at the temperatures expected in rhyolite lava and be preserved as pyrite after cooling.

There is some basis for imagining the pyrite in the Leona to have crystallized early. Many of the pyrite crystals in the unaltered rock are rounded and embayed; some are nearly spherical. The degree of rounding varies widely, even in a single thin section. The surfaces of the rounded crystals have the characteristic luster of pristine pyrite. The possibility is worth considering that early-formed crystals of pyrite were marginally corroded by interaction with the melt, just as the silicate phenocrysts were.

Whether early formed or late, the pyrite does not vein or shoulder aside the other minerals of the rock, and seems syngenetic.

Near Leona Heights, large ovoid masses of pyrite, with very small amounts of chalcopyrite, bornite, sphalerite, and chalcocite, were formerly mined for use in making sulfuric acid. The workings have long been abandoned and inaccessible, but some have been described by Clark (1917) and others by Mace (1911). The pyrite bodies, some more than 100 feet long, appear to have been emplaced in fractures cutting the rhyolite, and the sulfide minerals, according to Clark, have replaced the rhyolite to some extent. The deposits examined by Clark were near the base of the rhyolite, but wholly within it; those studied by Mace were largely within the rhyolite but rested on carbonaceous shale. It was Clark's hypothesis that primary disseminated pyrite had been oxidized by ground water to form acid ferrous sulfate solutions, which were neutralized and reduced below the water table by the rhyolite itself, aided by the carbonaceous shale, to produce the pyrite masses. The process is somewhat difficult to visualize in detail, particularly with respect to the copper and zinc sulfides, and it seems more likely that the massive pyrite and its accompanying sulfides are hydrothermal, and derived originally from the same source as the pyritic rhyolite. Whatever its origin, the massive pyrite at Leona Heights is younger than the rhyolite, and is seemingly not to be correlated with the disseminated pyrite.

Emplacement of the Rhyolite

The field and laboratory observations, while far from exhaustive, indicate that most of the rhyolite was emplaced by extrusive flow. The rock fabric, with its continuous groundweb, consistently unfragmented phenocrysts, and paucity of pyroclastic debris, clearly suggests that the flowing material was lava and not hot ash. The suggestion of liquid origin is especially forceful where the groundmass is spherulitic glass. The presence of a little pyroclastic material is not unfavorable to this thesis. Incorporation of pyroclastic fragments in any lava flow is to be expected, for ash eruption generally accompanies lava outflow, and some windborne material falls on and mingles with the lava. In addition, the chilled margins of the flow are fragmented as extrusion continues, and these fragments may become widely distributed within the flow.

It does not necessarily follow that the lava issued from a single vent somewhere in the rhyolite belt and traveled for 10 miles or more. Another possibility is suggested by the rhyolite dikes and the three masses that taper downhill, viewed in relation to the regional fault system. Perhaps magma rose, more or less simultaneously, at many places along relatively open west-trending subsidiary fractures of the northwest-trending main fault system, to feed a series of domes and short flows. The main faults, of compressional type, were presumably too tight for magma to pass. Pre-rhyolite stream erosion along the main fault zones, however, provided channels for the lava once it reached the surface. Such a method of emplacement would account for the two long gaps in the belt and for the considerable differences in facies along it.

The proposed emplacement mechanism, in offering multiple vents and short travel for the rhyolite, at the same time provides fairly reasonable avenues for post-lava hydrothermal solutions to disseminate pyrite and, later, even to chloritize and argillize the rock. If so, the solutions were rigorously selective, for they failed to deposit pyrite in the neighboring rocks, although many of them offer environments seemingly as favorable as the rhyolite. Chlorite and clay are widely developed in the underlying rocks (they are abundant primary constituents of the sedimentary rocks, and the ferromagnesian minerals of the volcanic rocks of the Franciscan formation have been largely converted to chlorite), but these same rocks have also been silicified and carbonatized, whereas neither silica nor carbonates have been significantly added to the rhyolite; apparently the chlorite and clay in the rhyolite are not to be correlated with those in the country rocks. While favoring the multiple-extrusion hypothesis for the rhyolite, I prefer not to appeal to it as a mechanism for the hydrothermal introduction of pyrite or chlorite or clay. Pending more thorough study, it is tentatively concluded that the pyrite is primary, that the chlorite is largely deuteric, and that all the clay is the product of weathering.

Age and Regional Relations

The Leona rhyolite was dated as late Tertiary, probably Pliocene, by Lawson (1914) and Clark (1917). Subsequent regional studies, and this local one, provide evidence that its age is very likely early or middle-Pleistocene. The presence of bedrock of the Monterey formation and detritus below the rhyolite demonstrate that the rhyolite cannot be older than late Miocene. The very youngest Pliocene rocks throughout the Bay area are reported by all modern workers to be intensely deformed. On the other hand, strata in the Bay area known to contain earlier Pleistocene ("Irvingtonian") continental fauna have gentle dips; beds with unequivocal later Pleistocene ("Rancholabrean") fauna are essentially flat (Savage, 1951, pp. 288–289). Because the rhyolite is little deformed, it is probably post-Pliocene. Because it was deeply eroded before deposition of Pleistocene gravels, themselves now deeply eroded, it appears to be of fairly early Pleistocene age.

Patches of white rhyolite along the west front of the Berkeley Hills north of Berkeley, though similar chemically to the Leona and of about the same age, were considered to be remnants of a separate flow and were named Northbrae rhyolite by Lawson (1914), largely because they contain magnetite rather than pyrite. This difference is, I think, more striking than significant. The Northbrae rhyolite may well prove to be simply another of the many small closely related intrusive masses constituting the Leona rhyolite belt. To the south, near San José, an intrusive mass mapped and named Alum by Crittenden (1951, pp. 46–48) seems to be a correlative of the Leona rhyolite, as he suggests.

Geologic History

The Leona rhyolite is not mentioned in the section on geologic history in Lawson's San Francisco folio (1914), and Clark devotes but a curt paragraph to its geologic history. Doubtless they were prudent rather than negligent. Despite their example, I shall try to reconstruct the history of the rhyolite and its environs. Supporting evidence for details of the regional geology is omitted. These may be found in the Hayward quadrangle report (Robinson, in preparation) and in broader studies, such as those of Taliaferro (1941), Howard (1951) and Louderback (1951).

In late Pliocene time the rhyolite belt was probably dry land, but the nature of the rocks which directly underlay the land surface and the shape of that surface are unknown. At the end of the Pliocene, the region was intensely deformed along northwest-southeast axes. Tight folds were formed, and the Chabot and Hayward fault zones, which may have existed much earlier, were active, with mainly vertical displacement. The early Pleistocene streams tended to be consequent on the folds and faults, flowing northwestward to the ocean. When a ridge-and-valley stage of dissection had been reached, still in early Pleistocene or middle Pleistocene time, another, much milder, episode of deformation reactivated some of the older faults. Rhyolitic magma, from unknown sources, rose along relatively open segments of the faults, largely in complementary fractures rather than on the main breaks. Where magma reached the surface it formed domes or short flows, not more than a few miles long, channeled by the northwest-striking valleys. Probably no large eruption cones were formed, but there was a little explosive activity during the eruptive episode, and some rhyolitic ash was incorporated within and deposited ahead of the slow-moving lava, which subsequently covered it. Although the rhyolite was doubtless much thicker and more widespread than it is today, it probably did not form a continuous blanket of really imposing extent.

When the rhyolite was emplaced, it was about as close to sea level as now, but the shore line was nevertheless farther west, for San Francisco Bay did not yet exist. Extrusion of the rhyolite greatly modified the local drainage pattern, but not for long. Streams, still flowing northwestward, cut into the rhyolite and deposited gravel upon it. Deposition was the dominant process, and by late Pleistocene time the area was a graveled coastal plain. The rhyolite was buried by these gravels.

Then gentle regional tilting produced westerly surface dips, and consequent streams began to run athwart the buried northwest-trending structures and drainage courses. The Hayward fault zone became active, with dominantly vertical displacement. The east side remained stationary or rose slightly, the west side dropped at least 650 feet and possibly several times that much, permitting marine waters to enter here for the first time, perhaps, since the early Pliocene. (Eustatic changes may also have contributed to this invasion.) The west side and northern end of the rhyolite belt were involved in the faulting. The pyrite masses at Leona Heights may have been formed at about this time.

As a result of the very late Pleistocene tilting and faulting, most of the earlier Pleistocene gravels were stripped, and the streams became superposed. Westward tilting and submergence probably continued well into the Recent epoch, and a thick sequence of interbedded marine and stream deposits accumulated under what is now the Bay plain just west of the rhyolite belt. Still more recently westward tilting and submergence gave way to gentle uplift, exposing the Bay plain and entrenching the streams crossing it.

In Recent time, intermittent movements in the Hayward fault zone became mainly horizontal rather than vertical, and rhyolite on the west side of the zone was shifted northwestward.

Downcutting in some of the superposed streams was able to keep pace with uplift, especially where the rhyolite was thin, and canyons were cut across the rhyolite belt. Most streams were diverted by the resistant rhyolite, turning far to the northwest or southeast for outlet. A major outlet developed through the long gap in the rhyolite at Hayward. Gradually, valley cutting on the east and faulting on the west turned the old rhyolite-filled valleys into the rhyolite-capped ridges of today

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