POTASSIUM-ARGON AND FISSION-TRACK AGES OF THE SONOMA VOLCANICS IN AN AREA NORTH OF SAN PABLO BAY, CALIFORNIA

By

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INTRODUCTION

This map presents a compilation of potassium-argon and fission-track ages of lithologic units found within the Sonoma Volcanics. Also included are ages of other volcanic rocks in the vicinity of the Sonoma Volcanics and ages of tuff interbedded with nearby sedimentary rocks. The ages reported here (tables 1, 2, 4) are a compendium of data produced at the University of California (Berkeley) laboratory by Garniss H. Curtis and Robert J. Fleck, and at the U.S. Geological Survey (USGS) laboratory by Charles E. Meyer, Kenneth F. Fox, Jr., and their colleagues. The geologic map is modified from compilations by Blake and others (1971), Blake and others (1974), Fox and others (1973), and Sims and others (1973).

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The Sonoma Volcanics consist of complexly interleaved and much deformed lava flows, ash-flow tuffs, and pyroclastic deposits. Previous workers established that these rocks and the subjacent Tolay Volcanics, which we discuss in a following section, range in age from approximately 12 m.y. to 3 m.y. Based on chemical analyses, the composition of the Sonoma Volcanics ranges from silicic basalt through andesite, dacite, rhyodacite, quartz latite, and rhyolite. Silica content ranges from 48.5 to 77.1 percent (72 analyses). These rocks were erupted within a volcanic field whose erosional remnants now extend about 90 km in a northwest direction, and span about 40 km in the transverse direction.

Piecing together the stratigraphy and history of the Sonoma Volcanics has been difficult because of the lack of lithologic continuity and because of extensive deformation. The rocks are folded, in places overturned, and disrupted by major right-lateral fault systems. Despite this complexity, a crude stratigraphic sequence has been discerned. Before turning our attention to the age data, we consider the stratigraphic framework of the Sonoma Volcanics and other Miocene and Pliocene rocks nearby.

For the purpose of this report, we accept an estimated age of about 5 m.y. for the boundary between Miocene and Pliocene, and about 2 m.y. for the boundary between Pliocene and Pleistocene. These are the estimated ages currently in use by the USGS (Sohl and Wright, 1980).

ANALYTICAL METHODS

Fission-track analysis

Bulk samples were crushed, washed in water, and sieved. Zircon and other nonmagnetic heavy minerals in the -60 +140 and -140 +180 mesh fractions were concentrated by sinking in methyline iodide and then separated from magnetic constituents in a magnetic separator. Part of the zircon concentrate was then embedded in a teflon disc and ground down using successively finer abrasives, so as to expose and polish an interior surface of the zircon crystals (Gleadow and others, 1976; Naeser, 1976).

The zircons were etched in phosphoric acid using a modification of the process outlined by Fleisher, Price, and Walker (1964). In that process, cleaved zircons were immersed in phosphoric acid at a temperature of 375-500° C. With that method it is desirable to maintain constant circulation of the hot acid, in order to prevent under-etching because of build-up of an insoluble phosphatic incrustation around the zircon. We maintain constant circulation with the procedure outlined below.

A small quantity of the concentrated phosphoric acid is dehydrated by heating slowly to approximately 500° C in a platinum beaker and then cooled to room temperature, at which temperature the acid has a jelly-like consistency. A 2- to 3-mm-diameter loop formed in the end of a 20 gauge platinum wire is then dipped into the acid and the adhering bead of acid is removed. A glass rod, previously fused to the other end of the wire, serves as a handle.

Two to ten zircons are then detached from their teflon mount by prodding gently with a steel needle, and transferred on the end of a moistened toothpick to the interior of the phosphoric acid bead. The bead and included zircons are then inserted through a small aperture into a preheated furnace, and baked at 450 to 475° C for two to five minutes. While baking, slow twirling of the glass rod by hand (at roughly 30 to 40 rpm) circulates the acid with respect to zircons. The bead is then removed and the etched zircons are recovered by washing away the acid bead in hot water in a watch-glass. The zircons are transferred to a lexan mount and later irradiated (Kleeman and Lovering, 1967). Our samples were irradiated in the USGS reactor at Denver, Colorado. Irradiated sample detectors were etched and the induced tracks counted using standard procedures outlined by Naeser (1976).

As in other etching methods (Gleadow and others, 1976), optimum etching temperature and time vary from sample to sample, depending on age and uranium content of the zircons, hence a few trial runs were usually necessary. We found it helpful to imperfectly polish the ground zircons, leaving a few of the fine scratches produced by the coarser abrasives to aid in distinguishing interior from exterior surfaces of the zircon crystals.

The method as outlined above is effective, but requires much dexterity and patience in manipulation of the tiny zircon crystals.

Potassium-argon analysis

Argon and potassium contents of 27 samples were determined at the K-Ar laboratory of the Department of Geology and Geophysics at the University of California, Berkeley; 11 samples were tested at the geochronology laboratories at the USGS, Menlo Park, California. At both laboratories, argon determinations were made by using standard isotope-dilution techniques (Dalrymple and Lanphere, 1969) using Reynolds-type mass spectrometers. Potassium analyses were made by flame photometry.

STRATIGRAPHIC RELATIONS OF THE SONOMA VOLCANICS WITH OTHER MIOCENE AND PLIOCENE ROCKS

Based on stratigraphic relations with the sedimentary rocks and the age data presented here, the Sonoma Volcanics is divided into a lower member that is late Miocene and early Pliocene, and an upper member that is late Pliocene. In the Sonoma Mountains area, the lower part of the Sonoma Volcanics is underlain by and interleaved with sparsely fossiliferous marine and brackish water sedimentary deposits of the late Miocene Petaluma Formation. Southeast of Sonoma and in Bennett Valley on the northern flank of the Sonoma Mountains these older volcanic rocks are overlain by continental sedimentary deposits that were assigned to the Huichica Formation of Pliocene age (Fox, 1983). North and northeast of Santa Rosa, rocks correlated with the Huichica Formation are overlain by the upper member of the Sonoma Volcanics. This upper member is in turn overlain by unfossiliferous continental deposits of the Glen Ellen Formation.

One additional stratigraphic complexity must be noted. In the Sonoma Mountains area, the older member of the Sonoma Volcanics, though interlayered with beds assigned to the Petaluma Formation, also rests with apparent unconformity upon a considerable thickness of older rocks of the Petaluma Formation. Deep drill holes collared in the Petaluma Formation about 5 km east-northeast of Petaluma and west of what is presumed to be the base of the Sonoma Volcanics penetrated about 1200 m of chiefly marine sedimentary strata, and below that, another 1200 m of volcanic rocks that were named the Tolay Volcanics by Morse and Bailey (1935). The drill holes failed to reach the base of these volcanic rocks. The section penetrated by the Murphy No. 1 well (see map for location) was considered by Morse and Bailey (1935, p. 1442-1443) to be typical of the Tolay; consisting of basaltic to andesitic lava flows with interlayered tuff, breccia, and agglomerate that overlies dacite and dacite porphyry. The upper 40 to 50 m of the Tolay is interbedded with ostracode-rich shales of the Petaluma Formation (Morse and Bailey, 1935, p. 1445).

Thus, in the western part of the Sonoma Mountains area, there are two thick and lithologically similar sequences of volcanic rocks with a substantial intervening thickness of clay, silt, sand, and shale of the Petaluma Formation. Lacking a lithologic basis for distinguishing the two series of volcanic rocks from each other at the outcrop, it was common practice prior to Mankinen's (1972) study to designate all the volcanic rocks at the surface in this area as the Sonoma Volcanics. Mankinen, however, correlated the sequence of basalt flows in the Burdell Mountain area, which is southwest of the Sonoma Mountains, with the Tolay Volcanics. These basalts, which directly overlie rocks of the Franciscan Complex, were dated by Mankinen at 12.1±0.8 m.y. (see table 3).

DISCUSSION OF AGE DATA

Tolay Volcanics

Volcanic rocks that occupy a comparable stratigraphic position to the Burdell Mountain rocks and to the Tolay Volcanics at the Murphy No. 1 well -- that is, volcanic rocks directly overlying the Franciscan Complex or Great Valley sequence and that are overlain by the Wilson Grove or the Petaluma Formations -- are here assigned to the Tolay Volcanics. These include basalt flows near Petaluma and masses of rhyolite and basalt west of the Tolay fault in the Sears Point area. Ages of rocks from these areas (samples GHC-180A, GHC-180B, GHC-182, and GHC-183) range from 11.76±0.44 to 13.62±2.39 m.y. (table 2). Rocks nearly that old that crop out between the Rodgers Creek and Tolay faults north of Sears Point are also assigned to the Tolay Volcanics. Rocks in this area are demonstrably overlain by and/or interlayered with the Petaluma Formation, and well logs indicate that a substantial thickness of volcanic rocks and interlayered sediments is present in the subsurface. Samples from this area (samples GHC-178, GHC-179, GHC-611, GHC-616, and GHC-675) range in age from 8.52±0.18 m.y. to 10.64±0.27 m.y. (table 2). If these correlations are correct, our data indicate that the Tolay Volcanics range in age from about 14 m.y. to 8.5 m.y.

Petaluma and Wilson Grove Formations

Tuff beds intercalated within the Petaluma Formation were dated at three localities (samples SV-43A, GHC-658, table 1; sample SP-5, table 2). The oldest is sample SV-43A, dated at 11.33±0.88 m.y. This sample represents a 40- to 45-cm-thick bed of light-gray pumicitic (fine lapilli) tuff intercalated with thin beds of chalky white diatomite and pebbly silt. These beds, which are located about 3 km northeast of the Rodgers Creek fault, are overlain by light-brown silt and fine sand. The exposed thickness of this section is about 30 m. Nearby volcanic rocks are correlated with the andesite of Rodgers Creek, a member of the Sonoma Volcanics. The Tolay Volcanics present to the west of the Rodgers Creek fault, which is known to have a thickness exceeding 1200 m, is thus either absent or represented only by this thin tuff bed on the east side of this fault.

A sample of one of the younger tuffs (SP-5, table 2) in the Petaluma Formation was analysed and compared with other tuffs in the San Francisco Bay region by Andrei Sarna-Wojcicki. On the basis of chemical similarity, Sarna-Wojcicki correlated this tuff with a tuff in the Wilson Grove Formation at localities 37 and 40. Ages of the tuff are as follows:

Formation	Locality*	Age (m.y.)	Sample no.
PETALUMA	41	6.9±0.3	SP-5
	--	5.77±0.12	GHC-658
WILSON GROVE	37	5.83±0.68	KA-2321
	40	6.21±0.1	BH-11
	40	5.4±0.3	SV-782

*Locality as given by Sarna-Wojcicki, 1976, figs. 2 and 9 and table 1.

However, on the basis of the age data tabulated above, the tuff in the Wilson Grove Formation is probably somewhat younger than the tuff in the Petaluma at the locality of sample SP-5. The Wilson Grove tuff is roughly equivalent in age to a tuff in the Petaluma at Sears Point dated at 5.77±0.12 m.y. (sample GHC-658, table 2).

Sonoma Volcanics

Lower member

The lower member of the Sonoma Volcanics is here divided into five informal map units: the andesite of Rodgers Creek, the rhyolite of Arrowhead Mountain the rhyolite of Bismark Knob, the andesite of Atlas Peak, and the soda rhyolite of Sugarloaf Ridge.

Andesite of Rodgers Creek.--The andesite of Rodgers Creek is the most extensive map unit within the Sonoma Volcanics. To the east, 6 km east of Sonoma, the unit overlies older Miocene sedimentary rocks, and to the north and northwest the unit overlies the Franciscan Complex and Great Valley sequence (undifferentiated). In the central part of the map area, the unit locally overlies or is interlayered with the upper part of the Petaluma Formation.

On the basis of 11 dated samples, this unit ranges in age from about 8 m.y. to about 5.5 m.y. The ages of four additional samples are inconsistent with geologic relationship and remain to be explained. Sample S20 (9.1±4.5 m.y., table 3) is considered unreliable because of the large atmospheric argon content (see Mankinen, 1972, p. 2065). The age of sample GHC-187 (4.78±5.19 m.y., table 2) is suspect for the same reason. The age of sample 69-7-30C (3.80±.01 m.y., table 2) is much less than expected--and significantly less than any other part of the unit. If the age is real, it indicates that part of the andesite of Rodgers Creek is roughly equivalent in age to the Huichica Formation, whereas at contacts observed east of Sonoma, in Bennett Valley, and north of Santa Rosa the Huichica Formation unconformably overlies the andesite. The age of sample GHC-185 (4.26±0.27 m.y., table 2) is slightly younger than expected. Sedimentary rocks overlying the flow from which the sample was collected are mapped as Petaluma Formation.

Rhyolite of Arrowhead Mountain.--The rhyolite of Arrowhead Mountain includes a large dome at Arrowhead Mountain, two areas of flow rock north of the city of Sonoma, and several small plugs scattered along the western flank of the Sonoma Mountains. The flows and the dome are intercalated within the more mafic lava and tuff of the andesite of Rodgers Creek. A sample of the rhyolite from Arrowhead Mountain yielded an age of 7.5±1.8 m.y. (sample SV-287B, table 1). A sample of the small rhyolitic mass intruded along the Rodgers Creek fault in the southern part of the Sonoma Mountains yielded an age of 7.36±2.24 m.y. (sample SV-34 A-2, table 2). The rhyolitic plug cutting the Petaluma Formation south of Santa Rosa yielded ages of 7.20±0.26 m.y. (plagioclase) and 7.96±0.14 m.y. (K-feldspar) (both from sample GCH-188B, table 2).

Rhyolite of Bismark Knob.--The rhyolite of Bismark Knob includes plugs and domes overlying or cutting the andesite of Rodgers Creek. East and southeast of Kenwood, rhyolite flows belonging to this unit are probably overlain by the less silicic flows of the andesite of Atlas Peak. Although the rhyolite of Bismark Knob has not been dated by radiometric methods, the stratigraphic relations suggest it is 5 to 6 m.y. old.

Andesite of Atlas Peak.--The andesite of Atlas Peak overlies basement rock except for the erosional outlier east of Kenwood, where it unconformably overlies the andesite of Rodgers Creek and probably also overlies the rhyolite of Bismark Knob. On the basis of eight dated samples, the andesite of Atlas Peak ranges in age from about 5.5 m.y. to about 4 m.y. Sample S17, with a reported age of 1.4±0.8 m.y. (table 3) is also from this unit, but that age -- considered unreliable by Mankinen (1972, p. 2068) because of the large atmospheric argon content--is improbably young and inconsistent with other results. Samples 7-218-E-2 (3.37±0.23 m.y., table 2) and SV-628 (3.4±0.2 m.y., table 1) also may be too young based on geologic correlations with other dated units. Sample 7-218-E-2 was collected from a thick ash-flow sequence correlated with the 4.1 m.y.-old Lawler Tuff on the basis of chemical similarity (Sarna-Wojcicki, 1976, localities 19-21, p. 17), whereas sample SV-628 represents a dacitic ash-flow tuff, partially welded in its central part, that underlies a large rhyolitic mass to the south correlated with the rhyolite of Mount George (in the upper member of the Sonoma Volcanics), which is probably about 3.7 to 4.1 m.y.old based on K/Ar isotopes.

Soda rhyolite of Sugarloaf Ridge.--The soda rhyolite of Sugarloaf Ridge is a tabular body about 7 km in exposed length, and 1.5 km in width and intercalated within the lavas and tuffs of the andesite of Atlas Peak. The rhyolite crops out in the area centered about 3 km north of Kenwood. Although the contacts of the rhyolite with enclosing strata were not observed, the rhyolite is judged to be extrusive on the basis of its vesicularity and fine-grained texture.

The rhyolite has not been dated directly. However, Mankinen's (1972) sample S8, dated at 5.4±0.2 m.y., which represents the part of the andesite of Atlas Peak stratigraphically below the rhyolite, establishes an older limit. His sample S14, dated at 4.1±1.2 m.y., represents rocks believed to be stratigraphically higher than the rhyolite, hence establishes a younger limit on the age of the rhyolite.

Upper member

The upper member of the Sonoma Volcanics consists of five informal map units: the rhyolite of Mount George, the tuff-breccia of Napa, the andesite of Tulucay Creek, the tuff of the Petrified Forest, and the rhyolite of Calistoga. The rhyolite of Mount George forms the base of the succession in the Napa area. To the west and northwest, the basal unit is the tuff of Petrified Forest, which interfingers with continental sediments that form the upper part of the Huichica Formation.

Rhyolite of Mount George.--The rhyolite of Mount George unconformably overlies lava and tuff of the andesite of Atlas Peak, and forms the summit area of the mountainous highland east of Napa.

The unit includes a persistent zone of welded to partially welded eutaxitic tuff at the base that locally is as much as 50 m in thickness. At least two rhyolitic flows are stacked above this basal welded tuff at Mount George. Three samples of the unit have been dated, yielding ages of 3.73±1.23 m.y. (sample 676-SH-1, table 2), 3.89±0.01 m.y. (sample GHC-176, table 2) and 4.3±0.1 m. y. (sample S5, table 3). Sarna-Wojcicki (1976) referred to the flow at locality S5 as dacite and the flow at location GHC-176 (located 3 km to the east of S5) as rhyolite. Based on mapping by Fox (see Sims and others, 1973) and unpublished analytical data, the two localities seem to be discontinuous erosional remnants of the same flow. The age given for sample S5, collected from a black vitrophyre at the base of the flow, may be slightly greater than the real age of the rhyolite, because at locality GHC-176 the flow overlies an ash-flow tuff correlated by chemical fingerprinting with the 4.1-m.y.-old Lawlor Tuff (see locality 17, Sarna-Wojcicki, 1976, p. 17).

Andesite of Tulucay Creek and tuff breccia of Napa.--The andesite of Tulucay Creek overlies the rhyolite of Mount George at several places in the mountainous region east of Napa. The andesite has not been dated by radiometric methods. The unit, mostly covered with alluvial deposits, also underlies the semicircular basin flanking the low hills immediately east of Napa. The hills and the partially encircling basin are known locally as the Cup and Saucer. The hills themselves are underlain by a composite unit, the tuff breccia of Napa. This unit, also undated, is believed to be piled on top of the andesite, but no contacts were actually observed.

The tuff breccia of Napa consists of altered lapilli pumice breccia, obsidian-bearing (spatter?) breccia, and breccia containing abundant xenoliths of chert and fine-grained plutonic rock (unpublished data, E. C. Schwarzman and K. F. Fox, Jr., 1978). This material is capped by aphanitic rhyolite. The unit is thought to have formed as a resurgent volcano near the center of a caldera about 7 km in diameter whose outer rim is now partly defined by the steep semicircular wall of the Saucer.

Tuff of Petrified Forest.--The tuff of Petrified Forest is the most extensive unit within the upper member of the Sonoma Volcanics. The tuff of Petrified Forest unit is predominantly pyroclastic material comprised of ash-flow tuff, welded tuff, tuff breccia, and agglomerate, as well as several intercalated andesitic lava flows. Only one radiometric age is available--3.5 m.y. (sample KA1281R, table 3) from tuff at the very base of the unit at Petrified Forest. At this locality, the tuff rests unconformably on greenstone of the Franciscan Complex, but several kilometers to the west the tuff interfingers with the upper part of the Huichica Formation. The age of the Petrified Forest tuff is narrowly bracketed by the ages of the Huichica Formation below and the rhyolite of Calistoga above--3.7 to 4.1 m.y. and 2.6 to 3.0 m.y., respectively.

Rhyolite of Calistoga.--The rhyolite of Calistoga consists chiefly of several very light gray to white, platy to massive, vesicular rhyolite flows that locally grade to black glass at their basal contacts. At various places within the flows relic eutaxitic textures and shard structure are present (observed microscopically), which indicate a pyroclastic and welding phase in the evolution of certain parts of the rhyolite. The unit has been dated at three localities, yielding ages of 3.7±0.5 m.y. (sample SV-417B, table 1), 3.0±0.2 m.y. (sample S30, table 3), and 2.6±0.3 m.y. (sample SV-614M, table 1). At locality SV-614M, the rhyolite conformably overlies a thin blanket of tuff, distinguished from the subjacent tuff of Petrified Forest by the presence of scattered subangular pebble-size clasts of black obsidian. This unit, like the overlying rhyolite of Calistoga, unconformably overlies the tilted and truncated sequence of ash-flow tuffs, agglomerate, and andesite flows that compose the tuff of Petrified Forest unit. The age of the obsidian-bearing tuff is thus thought to be related more closely to that of the overlying rhyolite than to the age of the tuff of Petrified Forest. Because of these contact relations with the tuff of Petrified Forest, the age of sample SV-417B appears to be marginally too old.

Huichica Formation

The Huichica Formation was originally named by Weaver (1949) for exposures east of Sonoma near Huichica Creek. Near that locality the formation consists of tuffaceous sand and gravel and unconformably overlies volcanic rocks correlated with the andesite of Rodgers Creek. Unpublished drill hole data indicate that the Huichica Formation thickens markedly to the southwest. A thin tuff in the type section (Weaver, 1949, p. 50) was dated at 4.09±0.19 m.y. (sample 8-H-1, table 2).

A thick sequence of clay, shale, gravel, minor diatomite, and tuff near Bennett Valley, about 10-13 km southeast of Santa Rosa, was originally assigned to the Petaluma Formation by Weaver (1949) and was reassigned to the Huichica Formation by Fox (1983). This sequence overlies the andesite of Rodgers Creek and contains a thin lapilli tuff dated at 3.95±0.32 m.y. (sample BH-71-2, table 2). About 11 km northeast of Santa Rosa, a discontinuous layer of gravel and sand unconformably overlies the Franciscan Complex and Great Valley sequence and interfingers in its upper part with tuffaceous rocks of the tuff of Petrified Forest. A thick tuff in the upper part of the sand and gravel sequence was dated at 3.7±0.3 m.y. (sample SV-5M, table 1), hence these rocks are probably a northern outlier of the Huichica Formation.

The Huichica Formation is interpreted to have been a westward-thickening wedge of fresh-water fan, alluvial, and lake deposits that accumulated from about 4.1 to 3.7 m.y. ago on a topographically irregular surface cut across older strata. The unit thus forms a datum of widespread extent locally sandwiched between the lower and upper members of the Sonoma Volcanics. The pyroclastic deposits within the Huichica may have been erupted from volcanoes in the Mount George area (east of Napa), because the age of the rhyolite of Mount George is comparable to the age of the tuffs in the Huichica.

Sand and gravel of Cotati

The sand and gravel of Cotati, an undated unit of provenance similar to that of the Huichica, unconformably overlies the Wilson Grove and Petaluma Formations. It could be a western extension of the Huichica Formation, but the possibility that Cotati rocks are younger cannot be ruled out.

Tehama Formation

At the eastern edge of the map area, the Putah Tuff Member of the Tehama Formation, whose basal part was dated at 3.43 m.y. (sample KA 1933, table 3), appears to be contemporaneous with the lower part of the tuff of Petrified Forest. The Putah Tuff Member forms an interlayer in the lower part of the Tehama Formation, which within the map area is an eastward-thickening wedge of conglomerate, sand, and clay of fluviatile origin (Miller, 1966, p. 20-21). According to Miller (1966, p. 27-47), the tuff consists of multiple beds of variably reworked dacitic tuff derived from a source area to the west, and is 16 m thick at the type locality (at locality of sample KA 1933). Chemical fingerprinting indicates that the source was probably the Sonoma Volcanics (Sarna-Wojcicki, 1976). We do not know the age of the upper part of the Tehama.

Clear Lake Volcanics (lower part)

The rhyolite of Calistoga is overlain at several places by andesite believed to be erosional outliers of the basal lava flows of the Clear Lake Volcanics. Most outcrop areas are too small to show at the map scale. One outlier was dated at Table Mountain at 1.96±0.06 m.y. (sample 2986, table 3). Donnelly-Nolan and others (1981, p. 51) found that north of the map area, flows of comparable lithology gave ages of 1.34±0.29 m.y., 1.33±0.53 m.y., 1.45±0.12 m.y., and 1.66±0.10 m.y.

Glen Ellen Formation

The Glen Ellen Formation unconformably overlies the tuff of Petrified Forest as well as older rocks and has not been dated radiometrically. However, the obsidian pebbles that are the hallmark of the Glen Ellen gravels are similar in their minor-element chemistry to obsidian associated with the rhyolite of Calistoga and its basal obsidian-bearing tuff (M. B. Norman and K. F. Fox, Jr., unpublished data, 1978), hence the Glen Ellen probably includes detritus weathered from the rhyolite of Calistoga and is therefore younger than that unit. B. C. Hearn, Jr. (oral commun., 1977), found obsidian-bearing gravels below andesitic flows of the Clear Lake Volcanics at Hells Half Acre (located north of the map area). One andesite flow at that locality was dated at 1.45±0.12 m.y. (Donnelly-Nolan and others, 1981, p. 51) The Glen Ellen is thus younger than the rhyolite of Calistoga (2.6 to 3.0 m.y.) and at least part of the unit is probably older than 1.45 m.y.

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TABLE 1.--Fission-track ages of zircons from rocks in the study area

[C. E. Meyer, analyst, USGS Laboratory]

Sample number	Latitude (38° north)	Longitude (122° west)	Spontaneous tracks: ρ (density per cm²)	Spontaneous tracks: N_s (number)	Induced tracks: ρ (density per cm²)	Induced tracks: N_i (number)	Φ (neutrons per cm²) x 10^{14}	Age (in m.y.)	Map unit
SP-5	12.1'	32.2'	9.81×10^5	136	6.85×10^6	1830	8.06	6.9 ± 0.3	Petaluma Formation
SV-5M	31.8'	39.0'	8.21×10^5	169	1.13×10^7	1147	8.12	3.7 ± 0.3	Huichica Formation
SV-287B	17.7'	24.7'	8.75×10^5	23	6.01×10^6	79	8.20	7.5 ± 1.8	Rhyolite of Arrowhead Mountain
SV-417B	34.3'	35.1'	1.78×10^6	213	1.50×10^7	898	4.55	3.7 ± 0.5	Rhyolite of Calistoga
SV-500	18.3'	27.35'	2.39×10^6	148	8.76×10^6	271	4.55	7.9 ± 0.8	Andesite of Rodgers Creek
SV-614M	35.0'	38.45'	1.08×10^6	139	2.07×10^7	1340	8.35	2.6 ± 0.3	Rhyolite of Calistoga
SV-628	18.0'	12.1'	2.66×10^6	407	2.33×10^7	1734	4.55	3.4 ± 0.2	Andesite of Atlas Peak
SV-782	29' 18"	51'14"	1.51×10^6	459	8.05×10^6	1226	4.55	5.4 ± 0.3	Wilson Grove Formation

TABLE 2.--Potassium-argon ages from rocks in the study area.

[*, radiogenic]

Sample number	Latitude (38° north)	Longitude (122° west)	Material	Percent K_2O	Mol $^{40}Ar^*$/g (x 10^{-11})	Percent $^{40}Ar^*$	Age (m.y.)	Map unit	Source of data
GHC-170A	22.34'	12.16'	Plagioclase?	0.2820	0.1833	22.9	4.51 ± 0.48	Andesite of Atlas Peak	1
GHC-170A	do	do	Whole rock?	2.418	1.9140	40.6	5.50 ± 0.16	Andesite of Atlas Peak	1
GHC-172	24.0'	12.8'	Whole rock	2.081	1.5254	29.9	5.06 ± 0.15	Andesite of Atlas Peak	1
GHC-173	Do	Do	Plagioclase	0.4055	0.3124	21.1	5.35 ± 0.37	Andesite of Atlas Peak	1
GHC-176	21.44'	12.14'	Plagioclase	0.7114	0.3984	52.9	3.89 ± 0.01	Rhyolite of Mount George	1
GHC-178	11.2'	28.3'	Whole rock?	0.8962	1.3732	38.8	10.64 ± 0.27	Tolay Volcanics	1
GHC-179	11.0'	28.9'	Plagioclase	1.161	1.5985	63.8	9.56 ± 0.15	Tolay Volcanics	1
GHC-180A	13.5'	36.8'	Whole rock?	0.7243	1.2804	29.4	12.26 ± 0.38	Tolay Volcanics	1
GHC-180B	do	do	Whole rock?	0.6965	1.2531	29.7	12.47 ± 0.74	Tolay Volcanics	1
GHC-182	13.2'	40.6'	Whole rock	0.7658	1.2994	24.2	11.76 ± 0.44	Tolay Volcanics	1
GHC-183	17.6'	41.6'	Whole rock?	0.8474	1.6649	7.6	13.62 ± 2.39	Tolay Volcanics	1
GHC-185	19.3'	44.2'	Whole rock	0.7140	0.4379	21.1	4.26 ± 0.27	Andesite of Rodgers Creek	1
GHC-186	20.9'	38.0'	Plagioclase	0.0535	0.0448	3.2	5.82 ± 2.35	Andesite of Rodgers Creek	1
GHC-187	21.0'	38.2'	Plagioclase	0.0531	0.0366	2.8	4.78 ± 5.19	Andesite of Rodgers Creek	1
GHC-188B	24.4'	41.9'	K-Feldspar	6.611	7.5774	74.5	7.96 ± 0.14	Rhyolite of Arrowhead Mtn.	1
GHC-188B	do	do	Plagioclase	1.294	1.3408	60.8	7.20 ± 0.26	Rhyolite of Arrowhead Mtn.	1
GHC-611	11.3'	28.2'	Whole rock	1.464	1.9564	52.6	9.28 ± 0.16	Tolay Volcanics	1
GHC-616	11.3'	28.9'	Whole rock	0.5733	0.7032	58.8	8.52 ± 0.18	Tolay Volcanics	1
GHC-658	08.9'	27.2'	Plagioclase	1.415	1.1765	48.9	5.77 ± 0.12	Petaluma Formation	1
GHC-664	13.2'	29.1'	Whole rock	0.4306	0.4114	36.3	6.62 ± 0.20	Andesite of Rodgers Creek	1
GHC-675	11.8'	29.2'	Whole rock	0.8776	1.2485	14.0	9.85 ± 0.74	Tolay Volcanics	1
GHC-705	11.8'	27.1'	Glass	5.588	5.6052	45.1	6.95 ± 0.20	Andesite of Rodgers Creek	1
68-7-11A	19.0'	47.3'	Whole rock?	1.110	1.2494	29.5	7.83 ± 0.29	Andesite of Rodgers Creek	1
68-6-27A	19.8'	45.4'	Whole rock	0.4947	0.4499	10.4	6.32 ± 0.66	Andesite of Rodgers Creek	1
69-7-30C	11.8'	26.7'	Whole rock	4.249	2.3271	53.5	3.80 ± 0.01	Andesite of Rodgers Creek	1
676-SH-1	19.4'	12.4'	Plagioclase	0.5546	0.2977	13.5	3.73 ± 1.23	Rhyolite of Mount George	1
676-SH-5	17.7'	12.8'	Whole rock	1.095	0.7911	35.6	5.02 ± 0.22	Andesite of Atlas Peak	1
SV-34A-2	14.3'	30.3'	Plagioclase	0.826	0.8666	5.79	7.36 ± 2.24	Rhyolite of Arrowhead Mtn.	2
SV-35B	14.2'	30.65'	Plagioclase	0.451	0.4590	16.19	7.05 ± 1.10	Andesite of Rodgers Creek	2
SV-42A	14.6'	30.4'	Plagioclase	0.164	0.1599	17.70	6.75 ± 0.63	Andesite of Rodgers Creek	2
SV-43A	17.7'	31.65'	Plagioclase	0.677	1.107	20.25	11.33 ± 0.88	Petaluma Formation	2
SV-136B-2	22.0'	39.0'	Plagioclase	0.797	0.8179	29.42	7.12 ± 0.34	Andesite of Rodgers Creek	2
SV-150B	23.3'	35.6'	Plagioclase	0.856	0.6979	25.72	5.66 ± 0.33	Andesite of Rodgers Creek	2
BH-71-2	22.15'	37.35'	Plagioclase	0.7505	0.423	11.3	3.95 ± 0.32	Huichica Formation	3
BH-71-3	22.3'	38.3'	Plagioclase	0.9375	0.800	46.4	5.99 ± 0.18	Andesite of Rodgers Creek	3
8-H-1	14.9'	23.2'	Plagioclase	0.484	0.2820	30.8	4.09 ± 0.19	Huichica Formation	4
9-FS-1	15.2'	08.7'	Plagioclase	0.7565	0.4534	13.3	4.20 ± 0.41	Andesite of Atlas Peak	4
7-218-E-2	06.4'	06.15'	Plagioclase	0.726	0.3488	23.2	3.37 ± 0.23	Andesite of Atlas Peak	4

$=5.544 \times 10^{-10} yr^{-1}$; $= 4.963 \times 10^{-10}$; $=0.581 \times 10^{-10}$; mol ^{40}K/ mol K = 1.167×10^{-4}

1/ G. H. Curtis and R. J. Fleck, collectors and analysts

2/ K. F. Fox, Jr., and C. E. Meyer, collectors; F. K. Miller, analyst

3/ J. A. Bartow, written communication, 1981.

4/ A. Sarna-Wojcicki, written communication, 1981.

TABLE 3.--Recalculated and previously reported potassium-argon ages for rocks in the study area

Sample number	Material	Age (in m.y.) (as originally reported)	Age (in m.y.) (recalculated, using constants given in table 2)	Source of data	Map unit
KA1281R		3.4	3.5	Evernden and James, 1964, p. 971	Tuff of Petrified Forest
S1	Plagioclase	11.8 ± 0.8	12.1 ± 0.8	Mankinen, 1972, p. 2065	Tolay Volcanics
S2	Plagioclase	4.7 ± 0.2	4.8 ± 0.2	do.	Andesite of Atlas Peak
S5	Plagioclase	4.2 ± 0.1	4.3 ± 0.1	do.	Rhyolite of Mount George
S8	Whole rock	5.3 ± 0.2	5.4 ± 0.2	do.	Andesite of Atlas Peak
S14	Plagioclase	4.0 ± 1.2	4.1 ± 1.2	do.	Andesite of Atlas Peak
S17	Plagioclase	1.4 ± 0.8	1.4 ± 0.8	do.	Andesite of Atlas Peak
S20	Plagioclase	8.9 ± 4.5	9.1 ± 4.5	do.	Andesite of Rodgers Creek
S30	Plagioclase	2.9 ± 0.2	3.0 ± 0.2	do.	Rhyolite of Calistoga
KA2321	Plagioclase	5.68 ± 0.68	5.83 ± 0.68	Sarna-Wojcicki, 1976, p. 7 locality 37	Wilson Grove Formation
BH-11	Plagioclase	6.05 ± 0.1	6.21 ± 0.1	Bartow and others, 1973, and Sarna-Wojcicki, 1976, p. 15 and fig. 1, locality 40	Wilson Grove Formation
2986	Whole rock	1.96 ± 0.06	1.96 ± 0.06	Donnelly-Nolan and others, 1981, p. 50	Lower part of Clear Lake Volcanics
KA1983		3.34	3.43	G. H. Curtis, personal communication cited by Miller, 1966, p. 49	Putah Tuff Member

Table 4.--Comments on samples listed in tables 1 and 2

Sample	Comments
SP-5	Tuff intercalated in Petaluma Formation. Contains pumice lapilli to about 2 cm in diameter.
SV-5M	Massive tuff from the Huichica Formation. The sample represents a zone extending from about 0.26 m to 0.9 m above base of 3-m-thick tuff containing scattered lapilli and overlying gravel of the Huichica Formation. Near the top of the tuff unit is a red ferruginous zone that in turn is overlain by a 10-m-thick composite tuff unit. This tuff is overlain by more gravel and sand of the Huichica Formation.
SV-287B	Flow-banded amygdular rhyolite porphyry from the rhyolite of Arrowhead Mountain. Nearby, the rhyolite grades to perlitic glass which overlies thin-bedded pumicitic tuff.
SV-417B	Flow-banded and lineated lithoidal rhyolite from the rhyolite of Calistoga. The sample is from a road cut in Khortum Canyon about 110 m east of the western contact of the rhyolite. At the contact, the rhyolite grades to black obsidian that overlies massive pumiceous tuff.
SV-500	Massive lapilli tuff from the andesite of Rodgers Creek unit. The sample is from a 1.8-m-thick layer that overlies a 90-cm-thick layer of bedded pumiceous tuff that in turn overlies an andesite flow.
SV-614M	Massive lapilli tuff from the lowermost part of the rhyolite of Calistoga unit. The tuff contains scattered obsidian tears and unconformably overlies the sequence of ash flows and welded tuffs composing the tuff of Petrified Forest unit. The obsidian-bearing tuff is overlain by rhyolite southeast of sample locality SV-614M.
SV-628	Massive ash-flow tuff from the andesite of Atlas Peak unit. The tuff contains black, glassy, scoriaceous clasts up to 15 cm long. The sample is from the center of a 4.7-m-thick eutaxitic, partially welded zone. The ash flow overlies basalt flows to the west and is not overlain by other rocks near the sample locality.
SV-782	Massive lapilli tuff from the Wilson Grove Formation. Sample is from the lower 30 cm of a thick zone of tuff intercalated in this formation. Sample locality is the same as that from which sample BH-11 (table 3) was collected.
GHC-170A	Dark-gray to black porphyritic volcanic rock, probably andesite or dacite, from the andesite of Atlas Peak unit. Rock is generally altered, but some fresh material is present. Collected from road cut west of hill 964 (see Mount George 7 1/2' quadrangle, sec. 16, T. 6 N., R. 3 W.).
GHC-172	Dark-gray to black, porphyritic basaltic andesite, from the andesite of Atlas Peak unit. The sample was collected from stream bank cut into a sequence of andesitic flows whose stratigraphic base lies not more than 30 m below the sample locality.
GHC-173	Hypersthene andesite from the andesite of Atlas Peak unit, collected about 60 m southwest of GHC-172 in same stream-cut. Sample is megascopically similar to GHC-172, but redder in color.
GHC-176	Rhyolite from rhyolite of Mount George. The sample was collected from flow about 4 1/2 m below flow top. Locality is north of California Highway 37 near summit of hill 1498 (see Mount George 7 1/2' quadrangle, N1/2 NW1/4, sec. 21, T. 6 N., R. 3 W.).
GHC-178	Porphyritic basalt from the Tolay Volcanics. The sample has a fine grained groundmass and was collected from road cut at about 200-ft elevation, west of saddle on road and southeast of Wildcat Mountain on east side of Tolay Creek (see Sears Point 7 1/2' quadrangle). Bedding dips 39° SW.
GHC-179	Rhyolite or quartz latite from the Tolay Volcanics. The sample represents a flow that overlies calcareous shale and mudstone and other sedimentary rocks that locally contain fish scales. Collected about 25 m above bed of Tolay Creek, near the 185-ft elevation (see Sears Point 7 1/2' quadrangle T. 4 N., R. 5 W.,). This sample may be float.
GHC-180A and 180B	Dark-gray basalt from the Tolay Volcanics. The sample was and collected from dump at Hein Brothers quarry at Haystack Landing (see Petaluma River 7 1/2' quadrangle, NW1/4 NE1/4 sec. 3, T. 4 N., R. 7 W.).
GHC-182	Dark-gray-weathering basalt from the Tolay Volcanics. The sample was collected from road cut about 3 km southwest of Petaluma and about 0.3 km southwest of Marin School (see Petaluma 7 1/2' quadrangle, SW1/4 sec. 6, T. 4 N., R. 7 W.).
GHC-183	Basalt from the Tolay Volcanics. The sample is from the lower flow at this locality and the upper contact of that flow is marked by a red baked zone. The baked zone strikes east-west and dips 15° to 20° N. Collected at old quarry on southwest side of Meacham Hill at about the 250-ft elevation (see Cotati 7 1/2' quadrangle).
GHC-185	Basalt from the andesite of Rodgers Creek unit. The sample was taken from the top of a basalt flow, which is overlain by very fine grained fossiliferous sediments. Collected at quarry at Washoe Creek north of Stony Point (see Cotati 7 1/2' quadrangle).
GHC-186	Coarsely porphyritic basalt from the andesite of Rodgers Creek unit. The sample was collected from the outcrop that forms bank of Crane Creek. The locality is east of Cotati, (see Cotati 7 1/2 quadrangle, SE1/4 sec. 21, T. 6 N., R. 7 W.).
GHC-187	Coarsely porphyritic basalt from the andesite of Rodgers Creek, collected from outcrop at 520-ft elevation, about 50 m east of Roberts Road and north of Crane Creek. Locality is about 260 m west-northwest of GHC-186 and is probably stratigraphically higher than GHC-186.

GHC-188B Vitrophyric andesite or dacite from the rhyolite of Arrowhead Mountain unit, collected from quarry floor south of Santa Rosa (see Santa Rosa 15' quadrangle, SW 1/4 sec. 36, T. 7 N., R. 8 W.). Rocks not in place; presumably lowered from a horizon somewhere above the quarry floor.

GHC-611 Clast in tuff breccia from the Tolay Volcanics, and stratigraphically below GHC-178.

GHC-616 Basalt collected from Tolay Volcanics at the northeast bank of Tolay Creek. Basalt forms 2-m-thick flow interlayered with sedimentary rock of the Petaluma Formation.

GHC-658 Rhyolite tuff from the Petaluma Formation. The sample was collected along California Highway 37 about 0.8 km southwest of Sears Point. Tuff rests on rocks of the Franciscan Complex.

GHC-664 Andesite from the andesite of Rodgers Creek unit, collected from locality southeast of hill 857 in the northwestern part of the Sears Point 7 1/2' quadrangle, east of Lee Lake. Andesite overlies dacitic tuff.

GHC-675 Basaltic andesite from the Tolay Volcanics.

GHC-705 Perlitic glass from the andesite of Rodgers Creek unit, collected from an agglomeratic unit that underlies a basalt flow. Sample is a loose boulder weathered from the agglomerate. Age represents maximum age of formation of the agglomerate.

68-7-11A Olivine basalt with scoriaceous and oxidized upper part, from the andesite of Rodgers Creek unit. Collected from upper 6 m of basalt flow that underlies conglomeratic sediments. Sediments contain marine fossils 15 to 45 m stratigraphically above the basalt. Locality is in Two Rock 7 1/2' quadrangle, T. 6 N., R. 8 W.

68-6-27A Black, medium-grained, zeolite(?)-bearing basalt from the andesite of Rodgers Creek unit. The basalt forms an interlayer in sedimentary strata which at this locality dip 15° to the northeast. Locality is in Two Rock 7 1/2' quadrangle, sec. 33, T. 6 N., R. 8 W.

69-7-30C Sample from an area of interlayered andesite, dacite, and dacitic tuff mapped as part of the andesite of Rodger Creek.

676-SH-1 Sample from an area of rhyolite and quartz latite flows mapped as the rhyolite of Mount George.

676-SH-5 Sample from an area of interlayered andesite, dacite, and dacitic tuff mapped as part of the andesite of Atlas Peak.

SV-34A-2 Flow-banded porphyritic rhyolite from rhyolite of Arrowhead Mountain unit. Sample is from small quarry cut into rhyolite on north side of highway.

SV-35B Massive tuff from the andesite of Rodgers Creek unit. The tuff contains abundant grains (sand-size) of obsidian and scattered pumice lapilli. Sample from layer about 1.2 m thick exposed in road cut. The tuff is overlain by about 0.5 m of scoriaceous reddish-gray ash, which in turn is overlain by scoriaceous to vesicular black basalt.

SV-42A Amygdular basalt from the andesite of Rodgers Creek unit. Sample is from active quarry cut into sequence of basalt flows with thin interlayers of tuff. The layers strike about N. 42° W. and dip 80° NE. The flow from which the sample was taken shows well-defined pillow structures, with tops to the southwest, hence the sequence is overturned.

SV-43A Pumiceous (fine lapilli) tuff from the Petaluma Formation. Sample is from bed 40 to 45 cm thick intercalated in sequence of silt, sand, clay, pebbly sand, and diatomite exposed in cut along O'Brien Road.

SV-136B-2 Massive pumiceous ash-flow tuff from the andesite of Rodgers Creek unit. The ash-flow tuff strikes about N. 20° E. and dips about 65° SE. It is in contact with a basalt flow to the east, but the contact is concealed. To the west, the ash-flow tuff depositionally overlies crystal lithic tuff, which in turn overlies poorly lithified pebbly clay.

SV-150B Pumice lapilli tuff from the andesite of Rodgers Creek unit. Sample is from massive ash flow exposed in road cut. The ash flow is part of a thick sequence with ill-defined contacts discontinuously exposed in roadcuts from the Bennett Valley Road northward to the 1000-ft contour (see Kenwood 7 1/2' quadrangle) where it is overlain by a basalt flow. Bedding in the upper part of the tuff sequence strikes N. 50° W., and dips about 10° NE.

BH-71-2 Lapilli tuff from Huichica Formation. Road cut reveals sequence of thin lapilli tuff beds intercalated in diatomite. The sequence strikes about N. 75° E., and dips about 45° N. Six beds of tuff are exposed over a stratigraphic thickness of about 2.5 m. The lowermost bed is the thickest and is about 90 cm thick, but was not sampled because of penetrative ferruginous alteration. The age sample was taken from the third bed from the top. This bed ranges in thickness from 8 to 13 cm.

BH-71-3 Massive tuff from the andesite of Rodgers Creek unit. Sample is from thick sequence of massive tuff--probably ash flows--exposed in road cuts along the Crane Canyon Road (Sample collected from about the 700-ft elevation--see Cotati 7 1/2' quadrangle).

8-H-1 Tuff from Huichica Formation. The sample was taken from a tuff bed intercalated with gravel and sand exposed in an inactive quarry.

9-FS-1 Massive pumice lapilli ash-flow tuff from andesite of Atlas Peak unit.

7-218-E-2 Tuff from andesite of Atlas Peak unit.