UNITED STATE DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Potassium-argon age dates and the thermal history of the Tower Peak quadrangle Central Sierra Nevada, California

By

Brent D. Turrin

345 Middlefield Road
Menlo Park, California 94025

Open-File Report 84-151

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ABSTRACT

Age dates from the Tower Peak quadrangle and surrounding area demonstrate that there was a period of continuous thermal-plutonic activity from about 100 Ma to 82 Ma, during which time four large plutonic sequences were emplaced. This period began with the emplacement of the Avonelle Lake adamellite, approximately 100 Ma. The second plutonic event was the in emplacement of the Fremont Lake-Topaz Lake plutonic sequence, 87 Ma to 82 Ma. The third plutonic sequence, the Mt. Gibson-Lake Vernon plutonic sequence, was emplaced 94 Ma to 87 Ma. The emplacement of the Tuolumne Intrusive Suite, 87 Ma to 82 Ma, concluded this period of plutonic activity. The combined K-Ar, Rb-Sr, and U-Pb age dates from the Mt. Gibson-Vernon Lake plutonic sequence, Fremont Lake-Topaz Lake plutonic sequence, and the Tuolumne Intrusive Suite indicate that each of these large Late Cretaceous plutonic sequences was emplaced over a period of 3-5 m.y. and that the times of emplacement were partially overlapping. K-Ar age dates from older plutonic rocks within the Tower Peak quadrangle indicate that the thermal effects from the emplacement of these large plutons extend at least 3 km into the adjacent country rock. The disparity between hornblende and biotite K-Ar cooling ages indicates emplacement depths of 2-6 km for the northern portion of the Cathedral Peak unit of the Tuolumne Intrusive Suite and 6-8 km for the Mt. Gibson-Vernon Lake complex.

INTRODUCTION

This study was undertaken to determine the ages of plutonic rocks in the Tower Peak quadrangle, which is located 175 km southeast of Sacramento, California, in northern Yosemite National Park. The 25 Mesozoic intrusive bodies within the quadrangle are well exposed due to Pleistocene glaciation, making it relatively easy to determine intrusive relations. Potassium-argon age dates for hornblende and biotite mineral pairs have been used to determine the cooling ages of various granitic bodies within the Tower Peak quadrangle. This information was used to examine possible emplacement depths for these Late Cretaceous plutons, and to develop a regional cooling history for this portion of the Sierra Nevada. Additionally, K-Ar dates have been used to delineate episodes of plutonic activity within the Tower Peak quadrangle and adjacent areas.

The Sierra Nevada Batholith is part of a continuous belt of Mesozoic granitic plutons that extends from Baja California northward through the Sierra Nevada into the Klamath Mountains and forms an east-facing arc through northwestern Nevada, Idaho, and back through northeastern Washington to southeastern Alaska (Bateman et al., 1963; Schweickert, 1981). Individual plutons within the Sierra Nevada Batholith are dominantly tonalite to adamellite in composition, with relatively few small bodies of granite, alaskite, diorite, and gabbro

(Bateman et al., 1963). Intrusive bodies within the batholith vary in areal extent from less than 1 km^2 for small stocks to greater than 1000 km^2 for large composite bodies.

The Sierra Nevada Batholith intruded Precambrian, Paleozoic, and early Mesozoic rocks (Bateman and Wahrhaftig, 1966; Dibblee, 1980). Most of the plutons were passively emplaced. Xenoliths of wall rock showing all stages of assimilation are preserved within some of the plutons that compose the batholith, implying that stoping and crustal assimilation were the principle mechanisms of emplacement (Kistler, 1966; Kistler and Bateman, 1966; Kistler, Evernden, and Shaw, 1971).

The mountain range known as the Sierra Nevada is approximately 500 km long and 100 to 130 km wide and cuts obliquely across the Sierra Nevada Batholith. Structurally, the Sierra Nevada Range is a westward-tilted Cenozoic fault block of Paleozoic and Mesozoic granitic and metamorphic rocks unconformably overlain on its west flank by undeformed uppermost Cretaceous and Tertiary volcanic and sedimentary rocks (Curtis, Evernden, and Lipson, 1958; Bateman et al., 1963).

Isotopic age data obtained by Evernden and Kistler (1970), Stern et al., (1981), and Chen and Moore (1982) on plutons within the Sierra Nevada indicate the following:

1) Plutons range in age from Triassic to Late Cretaceous.

2) A N20W-trending belt of Cretaceous granitoids was emplaced across a belt of Jurassic granitoids.

3) The Cretaceous intrusive sequence becomes progressively younger eastward; the Jurassic series shows no such relation.

Based on K-Ar and Rb-Sr dating, Evernden and Kistler (1970) proposed that the Sierra Nevada Batholith was emplaced during five intrusive epochs, each lasting 10 to 20 m.y. and separated by intervals of approximately 30 m.y. U-Pb ages reported by Stern et al., (1981) and Chen and Moore (1982), however, provide only partial support for five cyclic intrusive epochs. The U-Pb data indicate that:

1) Plutonism was more or less continuous between 210 and 155 m.y. ago.

2) Intrusion of large-volume plutons occurred about 120 to 80 m.y. ago.

3) A hiatus of about 35 m.y. exists between the Triassic-Jurassic and the Cretaceous intrusive periods.

Chen and Moore (1982) suggest that this hiatus correlates with a change in the regional stress field that is recorded by the Nevadan orogeny and by the intrusion of the Independence dike swarm.

GENERAL GEOLOGY OF THE TOWER PEAK QUADRANGLE

The rocks within the Tower Peak quadrangle are principally granodiorite and adamellite but range in composition from gabbro to leucogranite. At least 25 Mesozoic intrusive events are represented by discrete bodies with sharp vertical to near-vertical contacts (Wahrhaftig, written comm., 1983). Tertiary volcanic and sedimentary rocks and Mesozoic metavolcanic and metasedimentary rocks outcrop locally.

In the Tower Peak quadrangle, an L-shaped body of older plutonic and metamorphic rock (JPmvr, JPmvb, JҔbs, JҔq, JҔms, KJdi, KJgd, Kal, Ktl, Kpm, Khl, Khla, Kdl, Lbp,Ka, Kult, Kgm, and Klc) forms a septum between younger Cretaceous composite plutons to the north, east, and southwest (Figure 1). This body of older rock, covering approximately 300 km^2, extends diagonally across the quadrangle, both northeast and southeast. Some of the plutonic rocks within this older L-shaped body show a metamorphic foliation and lineation. Zones of intense shearing are found locally within the Harriet Lake granodiorite (Khl), Dorothy Lake granite (Kdl), and Bond Pass granite (Kbp). The shearing, best developed in the Bond Pass granite, trends approximately N40W. The shear texture is cut in turn by the Cathedral Peak Granodiorite (Kcp) and Fremont Lake granodiorite (Kf), indicating that there was a period of tectonic activity that postdates intrusion of the Harriet Lake granodiorite, Dorothy Lake granite, and Bond Pass granite and predates intrusion of the Cathedral Peak Granodiorite and Fremont Lake granodiorite.

The oldest rocks in the Tower Peak quadrangle are metasedimentary and metavolcanic rocks that occur as roof pendants and septa. The metasedimentary rocks include white orthoquartzite, thick units of biotite-sillimanite-andalusite schist, crystalline marble, and calc-silicate hornfels (Wahrhaftig, written comm., 1982). The structure of the metasediments in the southwest corner of the quadrangle is an anticline with vertical limbs. The northern body of metasedimentary rocks show evidence of at least two periods of deformation; isoclinal folding followed by deformation into a flat-topped dome with vertical flanks along intrusive contacts (Wahrhaftig, written comm., 1982). These thick units of metasedimentary rocks are lithologically similar to and are tentatively correlated with the Kings sequence of Bateman and Clark (1974), and are, therefore, considered Late Triassic to Early Jurassic in age. If this correlation is correct, it extends the known occurrence of the Kings sequence another 40 km northwest.

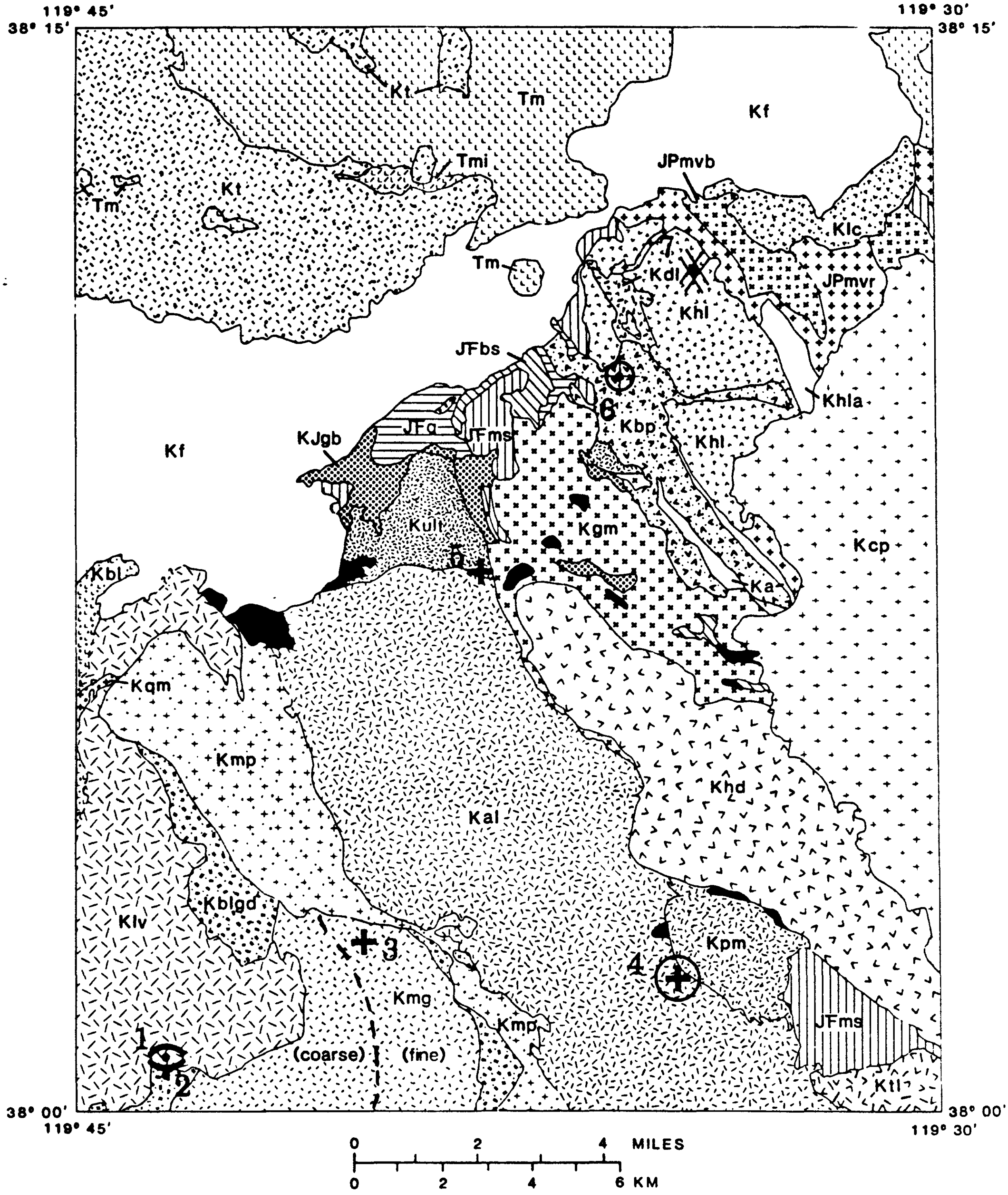

Figure 1. Generalized geologic map of the Tower Peak quadrangle, geology from Wahrhaftig (unpublished data). K-Ar sample locations are indicated. Δt_m = difference between hornblende and biotite K-Ar ages.

Δt_m < 1 m.y.

Δt_m = 1-3 m.y.

Δt_m = 3-5 m.y.

Δt_m = 5-7 m.y.

Δt_m = 7-9 m.y.

= biotite K-Ar age only.

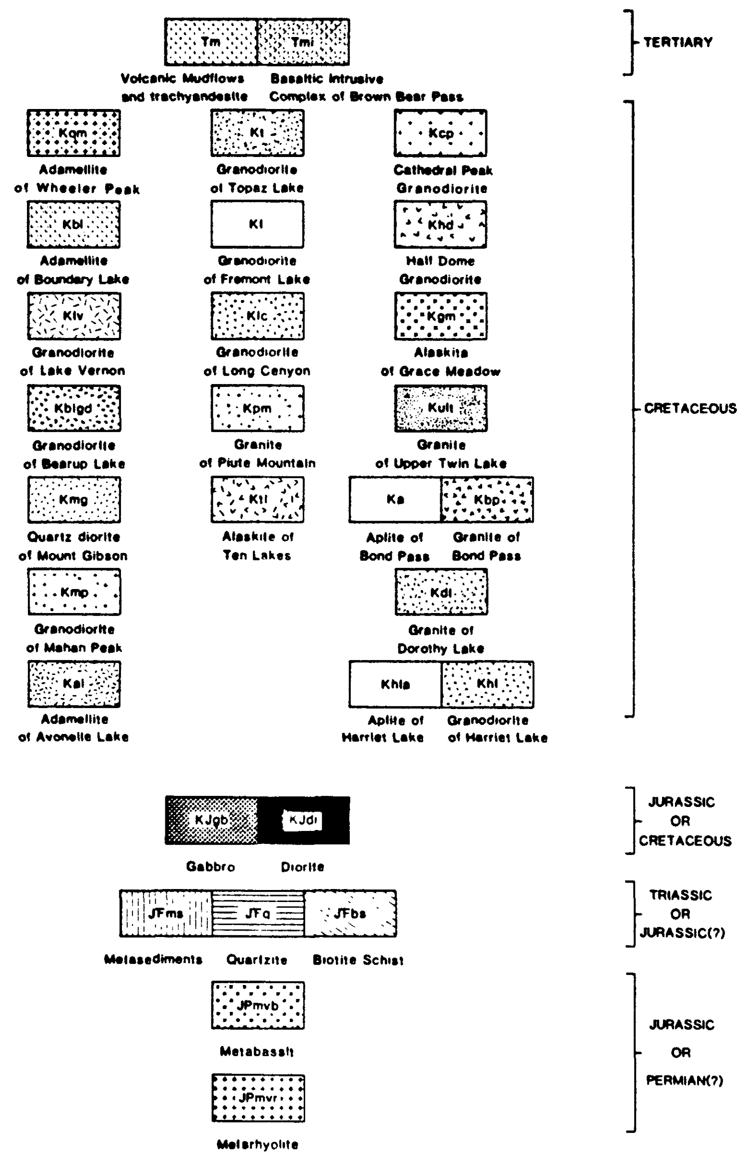

Figure 2. Map explanation.

Metavolcanic rocks outcrop in the northeast corner of the Tower Peak quadrangle near the West Fork of the West Walker River and in the West Walker River drainage. This volcanic sequence is composed of intermediate to felsic flows and tuffs. Fiamme can be seen on weathered outcrops of the metarhyolite, indicating an ignimbrite protolith (Wahrhaftig, written comm., 1982). The metavolcanic rocks within the Tower Peak quadrangle are lithologicaly similar to and are tentatively correlated with the lower Ritter Range sequence of Fiske and Tobisch (1978) and are, therefore, probably Permian to Middle Jurassic in age.

A complex of Tertiary volcanic and volcanoclastic rocks rests unconformably on Mesozoic granitic basement in the northern part of the Tower Peak quadrangle. The oldest Tertiary unit in the quadrangle is a rhyolite tuff of the Valley Springs Formation. Dalrymple (1963, 1964) dated a series of welded tuffs from the Valley Springs Formation northwest of the Tower Peak quadrangle in the Sonora Pass area of the Dardanelles Cone quadrangle, at 25.7 Ma. Other age dates from tuff units of the Valley Springs Formation range from 19.9 to 33.2 Ma (Slemmons, 1966). Overlying the Valley Springs rhyolite is a complex of andesitic flows, dikes, sills, and intrusive breccias of the Mehrten Formation. Dalrymple (1963, 1964) reported age dates of 8.8 Ma for a latite flow within the Mehrten Formation northwest of the Tower Peak quadrangle in the Dardanelles Cone quadrangle and 8.9 Ma for a latite flow south of the Tower Peak quadrangle in the Hetch Hetchy quadrangle.

METHODS

Samples were thin-sectioned and examined under a petrographic microscope to determine if the hornblende and/or biotite were unaltered and suitable for K-Ar age dating. Hornblende and biotite concentrates were obtained using standard mineral separation techniques (Appendix I). Mineral concentrates of greater than 99% purity were then split for potassium and argon analyses.

Potassium analyses were done by the flame photometry method using lithium for an internal standard (see Appendix II). Samples were put into solution by fusing the mineral with lithium metaborate and dissolving the resultant glass in nitric acid.

Argon extractions were done at Stanford University using an extraction system recently constructed by the author. Procedures used for the argon extractions are described by Dalrymple and Lanphere (1969). Argon analyses were done at the University of California, Berkeley, using a Reynolds-type gas source mass spectrometer in the laboratory of Garniss Curtis.

RESULTS AND DISCUSSION

Potassium-argon dates for plutons within Tower Peak quadrangle range from 82 to 94 Ma (Table 1). K-Ar ages from the older plutonic rocks within the quadrangle show evidence of having been reset by the emplacement of later, large plutonic bodies.

Field evidence indicates that the Harriet Lake granodiorite (Khl) is the oldest plutonic body within the quadrangle. K-Ar ages of 89.5 ± 1.2 Ma and 86.0 ± 1.4 Ma obtained from hornblende and biotite, respectively, are much younger than a Rb-Sr whole-rock isochron age of 133 ± 13 Ma determined by A. Robinson and R. Kistler (oral comm., 1982). If one assumes that the biotite age date was completely reset by the thermal event, the 86 m.y. date is the age for this event. If it is only partially reset, the biotite date would be older than the age of the thermal event.

The adamellite of Avonelle Lake (Kal) is the largest plutonic body of the older plutonic group. A hornblende and biotite mineral pair yielded discordant dates of 91.2 ± 2.6 Ma and 82.7 ± 1.4 Ma, respectively. Robinson and Kistler (oral comm., 1982) obtained a Rb-Sr whole-rock isochron age of 100 Ma for the Avonelle Lake adamellite and 98 Ma for the alaskite of Ten Lakes (Ktl). The Rb-Sr age dates for these plutons are in agreement with field relationships. From these data it would appear that the Avonelle Lake adamellite has lost radiogenic argon. If one assumes complete argon loss in the biotite, the age of this event would be 83 Ma.

K-Ar ages of hornblende and biotite from the Bond Pass granite (Kbp) give age dates of 82.8 ± 1.7 Ma and 82.5 ± 1.3 Ma, respectively. The Upper Twin Lakes granite (Kutl) gives a biotite K-Ar age of 82.8 ± 1.8 Ma. The three K-Ar ages from Bond Pass and Upper Twin Lakes granites are analytically indistinguishable. Field relationships indicate that the Bond Pass granite is bracketed in time by the intrusion of the Harriet Lake granodiorite (Khl) and the Fremont Lake granodiorite (Kf) and that the intrusion of the Upper Twin Lake granite predates intrusion of the Fremont Lake granodiorite (Figure 3). Robinson and Kistler (oral comm., 1983) obtained a Rb-Sr whole-rock isochron age for the Fremont Lake granodiorite of 87 Ma. Evernden and Kistler (1970) report six K-Ar ages from the Fremont Lake granodiorite that average 86.3 ± 1.0 Ma. Given the differences in composition, crystallography, and argon diffusion rates of hornblende and biotite, the concordant ages from the Bond Pass granite are highly unlikely unless both the hornblende and biotite were completely reset at 82 Ma. This evidence, along with age dates from other plutonic bodies, indicates that a thermal event occurred at 82 Ma. These data indicate that:

1) The Bond Pass Granite was intruded between 86 and 133 m.y. ago.

2) A period of deformation occurred during this interval as

TABLE 1. Potassium-Argon age data.

Sample #	Lab #	Location Longitude	Location Latitude	Unit Name	Mineral	$^{40}Ar^*$ moles/gm x 10^{-9}	%K	% Atmos. ^{40}Ar	Age ± 2 σ	Distance From Younger Pluton
1 ---	SKAR 12	119° 43' 30"	38° 00' 36"	Lk. Vernon	hornblende	0.1465	0.876	18.1	94.0 ± 1.9	5.8 km
	SKAR 13	119° 43' 30"	38° 00' 36"	Lk. Vernon	biotite	1.2020	7.621	16.8	88.8 ± 2.0	
2 ---	SKAR 18_R	119° 43' 30"	38° 00' 29"	Bearup Lk.	hornblende	0.1311	0.799	13.2	92.2 ± 1.3	0.2 km
	SKAR 11	119° 43' 30"	38° 00' 29"	Bearup Lk.	biotite	1.2170	7.660	12.1	89.4 ± 1.3	
3 ---	SKAR 27	119° 40' 01"	38° 02' 20"	Mt. Gibson	biotite	1.2160	7.305	5.7	93.5 ± 1.5	1.5 km
4 ---	SKAR 25_R	119° 34' 34"	38° 01' 55"	Avonelle Lk.	hornblende	0.2466	1.521	57.0	91.2 ± 2.6	2.3 km*
	SKAR 24	119° 34' 34"	38° 01' 55"	Avonelle Lk.	biotite	1.0060	6.860	2.2	82.7 ± 1.4	
5 ---	SKAR 30	119° 38' 01"	38° 07' 28"	Upper Twin Lk.	biotite	1.0210	6.950	5.3	82.8 ± 1.8	0.2 km
6 ---	SKAR 17	119° 35' 30"	38° 10' 10"	Bond Pass	hornblende	0.2585	1.759	13.8	82.8 ± 1.7	2.0 km
	SKAR 16	119° 35' 30"	38° 10' 10"	Bond Pass	biotite	1.0510	7.181	10.2	82.5 ± 1.3	
7 ---	SKAR 14	119° 34' 08"	38° 11' 37"	Harriet Lk.	hornblende	0.2563	1.612	9.2	89.5 ± 1.2	2.1 km
	SKAR 15	119° 34' 08"	38° 11' 37"	Harriet Lk.	biotite	0.9026	5.911	10.8	86.0 ± 1.4	

^{40}K decay constants: $\lambda_{\epsilon} + \lambda_{\epsilon'} = 0.581 \times 10^{-10} yr.^{-1}$; $\lambda_{\beta} = 4.962 \times 10^{-10} yr.^{-1}$; $^{40}K/K = 1.167 \times 10^{-4}$.

*Sample 4, the adamellite of Avonelle Lake (Kal) is approximately 0.2 km from the granite of Piute Mountain (Kpm). However, (Kal) and (Kpm) are nearly identical in age, 100 Ma and 98 Ma, respectively therefore the distance shown above is the distance to the nearest large Late Cretaceous pluton.

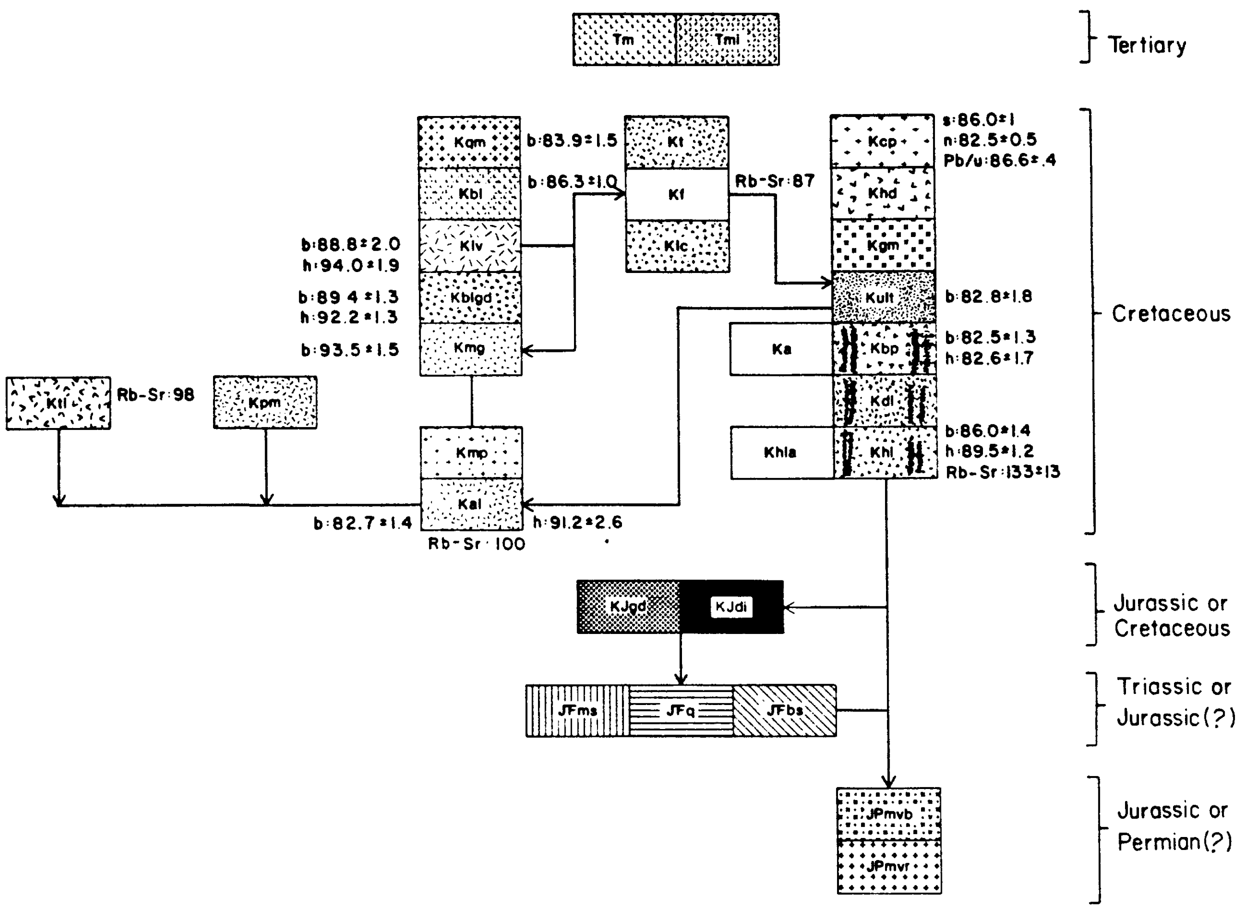

Figure 3. Unit correlation diagram showing intrusive relationships (Wahrhaftig, unpublished data). Plutonic units young upward within the columns. The arrows point from younger units to the older units that they intrude; b: K-Ar age from biotite; h: K-Ar age from hornblende; n: K-Ar age, northern end of pluton; s: K-Ar age, southern end of pluton; Rb-Sr: Rb-Sr whole rock isochron age; Pb/U: $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ age; ⁑: Indicates shear zones are present.

evidenced by local shear zones within the Dorothy Lake granite (Kdl), Harriet Lake granodiorite (Khl), and Bond Pass granite.

3) The K-Ar ages obtained in this report for the Bond Pass and Upper Twin Lakes granites have been reset by later thermal events, which occurred approximately 82 m.y. ago.

A plutonic complex of four large plutons is located in the southeast corner of the Tower Peak quadrangle. From oldest to youngest, this complex is composed of the Mt. Gibson quartz diorite (Kmg), Bearup Lake granodiorite (Kblgd), Lake Vernon granodiorite (Klv), and Boundary Lake adamellite (Kbl) (Wahrhaftig, written comm., 1982) (Figure 3). The color index of the Bearup Lake granodiorite grades from a value similar to that of the Mt. Gibson quartz diorite near their contact to a value near that of the Lake Vernon granodiorite, where the latter intrudes the Bearup Lake granodiorite (Wahrhaftig, written comm., 1982). This suggests that the three plutons are consanguineous. However, a diorite dike swarm that cuts the Mt. Gibson quartz diorite and the Bearup Lake granodiorite is truncated by the Lake Vernon granodiorite, indicating a time break and interval of cooling (Wahrhaftig, written comm., 1982). K-Ar age dates from this plutonic complex span a 5 m.y. period, from 88 Ma to 93 Ma.

The oldest unit of the series, a fine-grained facies of the Mt. Gibson quartz diorite (Kmg), yielded a biotite K-Ar cooling age of 93.5 ± 1.5 Ma. The fine-grained facies is intruded by a coarse-grained facies along a sharp, well-defined contact (Wahrhaftig, written comm., 1982). The Bearup Lake granodiorite (Kblgd) has hornblende and biotite cooling ages of 92.2 ± 1.3 Ma and 89.4 ± 1.3 Ma, respectively. The Lake Vernon granodiorite (Klv), which intrudes both the Mt. Gibson and Bearup Lake units, gives K-Ar cooling ages indistinguishable from these units: 94.0 ± 1.9 Ma on hornblende and 88.8 ± 2.0 Ma on biotite.

In the Hetch Hetchy quadrangle to the south, Kistler (1973, 1974) reported K-Ar ages of 83.8 Ma and 85.6 Ma for hornblende and biotite, respectively, from the Mt. Gibson quartz diorite (Kmg). Because Kistler (1973, 1974) did not distinguish coarse-grained and fine-grained facies within the Mt. Gibson quartz diorite or differentiate between the Mt. Gibson quartz diorite phase and the Bearup Lake granodiorite (Kblgd) phase of this intrusive complex, it is not possible to compare directly the results for the two studies.

The apparent age difference of 4.7 m.y. in the biotite K-Ar ages of the fine-grained Mt. Gibson quartz diorite (Kmg) (93.5 Ma) and Lake Vernon granodiorite (Klv) (88.8 Ma) is slightly greater than the 95% confidence level critical value. This suggests that there may be a hiatus between the Mt. Gibson unit and the Lake Vernon unit.

The Cathedral Peak Granodiorite (Kcp) unit of the Tuolumne

Intrusive Suite outcrops along the eastern edge of the quadrangle. Biotite K-Ar age dates from the southern end of the Cathedral Peak pluton average 86.0 ± 1 Ma, whereas biotite K-Ar age dates from the northern end range from 82 to 83 Ma (Evernden and Kistler 1970). Concordant U-Pb dates from the southern part of Cathedral Peak of 86.2 Ma ($^{206}Pb/^{238}U$) and 87.0 Ma ($^{207}Pb/^{235}U$) have been reported by Stern et. al. (1981). The concordant K-Ar and U-Pb ages suggest that the cooling age is within analytical error of the crystallization age for the southern part of the Cathedral Peak pluton. The spread in the K-Ar ages between samples from the northern and southern ends of the Cathedral Peak, although near the limits of resolution, indicate that the cooling age of the northern end is 2 to 3 m.y. younger than the southern end. One possible explanation for this result is that the southern part of the Cathedral Peak Granodiorite was emplaced at a higher level than the northern part and therefore cooled more quickly. Another possible explanation is that the root of the pluton is located within the northern part; as a result, the more massive northern portion would require more time to cool and would yield younger K-Ar ages.

The Topaz Lake granodiorite (Kt), near the northern boundary of the Tower Peak quadrangle, is similar in appearance to the Cathedral Peak Granodiorite (Kcp), but is separated from it by a 6 to 7 km septum of older plutonic and metamorphic rocks. The Topaz Lake granodiorite is bordered on the south by the Fremont Lake granodiorite (Kf), which appears to be an earlier, more mafic phase of the same magma pulse. Thus the Topaz Lake granodiorite is thought to bear the same relationship to the Fremont Lake granodiorite as the Cathedral Peak Granodiorite does to the Half Dome (Khd) granodiorite (Wahrhaftig, written comm., 1982).

Biotite K-Ar ages from the Topaz Lake granodiorite (Kt) yield an average age of 83.9 ± 1.5 Ma (Evernden and Kistler, 1970). The Rb-Sr and K-Ar age data from the Fremont Lake and Topaz Lake units indicate that this northern intrusive series was emplaced 87 to 84 m.y. ago, approximately the same time the Tuolumne Intrusive Suite was emplaced.

THERMAL HISTORY AND DEPTH OF EMPLACEMENT

Hart (1964), Westcott (1966), and Hansen and Gast (1967) examined the thermal effects that younger intrusive bodies have on K-Ar ages of surrounding country rock, and showed that biotite is more susceptible to argon loss than hornblende. Subsequent laboratory studies on argon diffusion have shown that, indeed, biotite has a lower argon closure temperature than hornblende (Berger and York, 1981; Harrison, 1981). Argon closure temperatures of 300-400°C for biotite and 500-700°C for hornblende have been reported by Dallmeyer (1978), Berger and York (1981), and Harrison (1981).

Westcott (1966) and Hanson and Gast (1967) studied argon loss from wallrocks caused by the intrusion of younger dikes. They found that hornblende and biotite show argon loss up to approximately 0.5 to 1.0 dike-width away from the contact. The areal dimensions of the Cathedral Peak Granodiorite unit of the Tuolumne Intrusive Suite are approximately 20 km by 40 km. The Topaz Lake granodiorite unit of the Topaz Lake-Fremont Lake intrusive complex covers approximately 25 km by 30 km. Within the Tower Peak quadrangle, the Vernon Lake intrusive complex covers about 80 km by 15 km. The empirical relation of Hanson and Gast (1967) and Westcott (1966) suggests that intrusion of the Cathedral Peak Granodiorite, Topaz Lake granodiorite, and Vernon Lake intrusive complex would have thermal effects on the surrounding country rock up to 10 to 20 km away from the contacts. Consequently, one would expect argon loss on the 4 to 6 km wide septum of older plutonic rocks that separates the Cathedral Peak, Topaz Lake, and Mt. Gibson-Vernon Lake plutonic sequences.

Potassium-argon age dates for hornblende and biotite mineral pairs from plutons within the L-shaped septum (Harriet Lake granodiorite, Avonelle Lake adamellite, Bond Pass granite, and Upper Twin Lakes granite) do show evidence of argon loss. Using median closure temperatures of 350°C and 600°C for biotite and hornblende, respectively, the K-Ar cooling ages from the Bond Pass granite and Harriet Lake granodiorite suggest that:

1) The septum of older plutonic rocks in the area of the Bond Pass granite and Harriet Lake granodiorite was heated to at least 600°C about 83 m.y. to 86 m.y. ago.

2) The portion of the Avonelle Lake adamellite that is about 2-3 km away from the contact with the Tuolumne Intrusive Suite was heated to approximately 350°C about 83 m.y. ago.

In summary, the intrusion of the Tuolumne Intrusive Suite, Fremont Lake-Topaz Lake and Mt. Gibson-Vernon Lake plutonic complexes had thermal effects on the surrounding country rock out to at least 3 km from the contacts.

If a pluton is emplaced at sufficiently shallow depths, it will cool quickly enough that no significant difference can be resolved between hornblende and biotite cooling dates. For more deeply emplaced plutons, differences in cooling ages for hornblende and biotite pairs can be used to calculate an approximate crystallization depth or the depth of burial of a reset sample. When calculating the crystallization depth, it is assumed that the K-Ar cooling age for hornblende is the same, within analytical error, as the crystallization age.

These depth calculations are only valid for samples that meet one of the following criteria:

1) Samples that have experienced no post-emplacement partial argon loss. For these, the calculated depth would be a depth of emplacement.

2) Samples that have been completely reset by a later thermal event. For this case, the result would be the depth of burial at the time of resetting.

The only plutonic bodies that meet either of these criteria are the Bond Pass granite, Harriet Lake granodiorite, Bearup Lake granodiorite, and the Lake Vernon granodiorite. The Bearup Lake granodiorite and the Lake Vernon granodiorite satisfy the first criterion. The Bond Pass granite and the Harriet Lake granodiorite meet the second criterion. Thus a depth calculation for the Bond Pass unit and the Harriet Lake unit would indicate the depth of burial of these units at the time they were reset by emplacement of the Cathedral Peak Granodiorite and Fremont Lake-Topaz Lake intrusive complex.

These calculations are based on a model involving cooling by conduction of the pluton and surrounding country rock through the hornblende and biotite argon closure temperatures. In Table 2, the temperatures at 1 km depth versus time were calculated from the following equation:

$$T_t = T_o * erf[d/2*(k*t)^{1/2}].$$

This function is a solution to Fick's second, law where T_t is the temperature at time (t); T_o is the inital temperature of the pluton (1000°C); d is depth (1 km); k (kappa) is the heat diffusivity of the earth's crust, for which the value 0.007 was used; t is time (m.y.); erf is the error function.

The error function, usually written as erf z, is defined as follows:

$$\mathrm{erf}\ z = 2/\pi^{1/2} \int_0^z \exp(-n^2)\ dn,$$

where $n = E/2(kt)^{1/2}$. It is a standard mathematical function, for which extensive tables are available. This function has the properties

$$\mathrm{erf}(-z) = -\mathrm{erf}\ z,$$

$$\mathrm{erf}(0) = 0,$$

$$\mathrm{erf}(\infty) = 1.$$

TABLE 2. Cooling of half-space at 1 km depth, for which $T_{initial}$ is 1000°C

Time (m.y.)	Temperature
0.001	1000
0.002	999
0.003	994
0.004	983
0.005	967
0.006	948
0.007	928
0.008	908
0.009	888
0.010	868
0.020	714
0.030	616
0.040	549
0.050	500
0.060	462
0.070	431
0.080	406
0.090	385
0.100	366
0.200	264
0.300	217
0.400	188
0.500	169
0.600	154
0.700	143
0.800	134
0.900	126
1.000	120
2.000	85
3.000	69
4.000	60
5.000	54
6.000	49
7.000	45
8.000	42
9.000	40
10.000	38

A detailed discussion of the mathematics of heat conduction is given by Carslaw and Jager (1959).

Emplacement depths were calculated using the equation:

$$[\Delta t_m \text{ (my)}/\Delta t_{1km} \text{ (my)}]^{1/2} = d \text{ (km)},$$

where Δt_m is the difference between the hornblende K-Ar age and the biotite K-Ar age and Δt_{1km} is the expected difference between the hornblende K-Ar age and the biotite K-Ar age at a 1 km depth (from Table 2).

Using median closure temperatures of 350°C and 600°C for biotite and hornblende, respectively, the extrapolated time (m.y.) from Table 2 is 0.032 at 600°C and 0.116 at 350°C. Thus the calculated age difference between hornblende and biotite at 1 km, Δt_{1km}, would be 0.084 m.y. If different biotite and hornblende closure temperatures are used, this value would change.

Using the K-Ar data from the Bearup Lake granodiorite, the hornblende cooling age is 92.2 m.y. and the biotite cooling age is 89.4 m.y.; thus, Δt_m equals 2.8 m.y. The calculated depth is 5.8 km.

$$5.8 = (2.8/0.084)^{-1/2}$$

Because the analytical errors of the individual dates are a significant fraction of the difference between the biotite and hornblende dates (Δt_m), these depth estimates have large uncertainties.

From the method presented above, calculated depths of emplacement for Late Cretaceous plutons within the Tower Peak quadrangle and surrounding area range from 2-8 km. The reset hornblende and biotite cooling ages from the Bond Pass granite and Harriet Lake granodiorite yield a calculated depth of 2-6 km. This is the calculated burial depth for the surrounding country rock near the northern portion of the Cathedral Peak unit of the Tuolumne Intrusive Suite and Topaz Lake-Fremont Lake plutonic sequence and is, therefore, a maximum emplacement depth for these plutons. Results from the Lake Vernon granodiorite and Bearup Lake granodiorite indicate emplacement depths of 6-8 km for these units.

It can be argued that the association of metamorphic roof pendants with the Cathedral Peak Granodiorite and Fremont Lake granodiorite within the area of the Bond Pass granite and Harriet Lake granodiorite indicates that only the upper portion of the Cathedral Peak and Fremont Lake plutons are exposed (Figure 1). The absence of metamorphic rocks in the area of the Bearup Lake and Vernon Lake granodiorite indicates that the upper levels of these plutons have been removed by erosion, exposing lower levels of these plutons. This argues for a period of erosion between the emplacement of the Mt. Gibson-Vernon Lake plutonic sequence and the emplacement of the Late Cretaceous plutons of the Topaz Lake-Fremont Lake plutonic sequence and the Tuolumne Intrusive Suite. An examination of a modern analogue of the Sierran paleotectonic setting supports this argument. It is thought that the Late Cretaceous Sierran plutons were emplaced along an Andean-type margin (Hamilton, 1969; Dickinson, 1981; Saleeby, 1981). K-Ar dates from Tertiary plutons in the central Chilean Andes, as young as 7 Ma have been reported by Drake (1974). This indicates that the time required to erode the volcanic cover and expose plutons in this type of tectonic setting is relatively short.

These calculations suggest that the Cretaceous Sierran plutons were emplaced at relatively shallow depths. There are several independent lines of evidence that support these conclusions:

1) Swanson (1978) reports a minimum crystallization pressure of 0.5-1.5 kb (2-6 km) for the Rocklin granodiorite, an Early Cretaceous pluton in the western foothills of the Sierra Nevada. This depth calculation is based on aplite dike compositions from the Rocklin pluton.

2) Curtis et al., (1958) report a K-Ar age of 137 Ma for the Shasta Bally granodiorite, which is unconformably overlain by marine sediments of the lower Valanginian stage (138-131 Ma) of the Lower Cretaceous. This indicates that the Shasta Bally granodiorite was emplaced, the overburden removed, and the Lower Cretaceous Valanginian sediments deposited within a short period of geological time. From this it can be argued that the Shasta Bally pluton must have been emplaced at a relatively shallow depth.

3) A Middle Cretaceous subvolcanic pluton and its associated volcanic rocks are found approximately 50 km southeast of the Tower Peak quadrangle, in the Mono Craters quadrangle (Kistler and Swanson, 1981). From aplite compositions, Kistler and Swanson (1981) calculate a minimum emplacement depth of 1-2 km (0.5 kb).

4) Concordant U-Pb and K-Ar ages and concordant hornblende and biotite K-Ar ages from many of the Cretaceous Sierran plutons imply that these plutons must have been emplaced at depths less than 12 km. If one assumes a 30°C per km geothermal gradient and closure temperatures of 350°C and 600°C for biotite and hornblende, respectively, the 350°C isotherm is at about 12 km and the 600° isotherm is at about 20 km. Plutons emplaced at depths greater than 12 km would have discordant hornblende and biotite K-Ar ages. A similar argument was applied by Evernden and Kistler (1970) to the Late Cretaceous

Cathedral-Peak-type plutons.

5) Evernden and Kistler (1970) used the change in K-Ar ages as a function of elevation in Cathedral-Peak-type plutons to determine depths of emplacement. Assuming a geothermal gradient within the range of 25-33°C per km, a blocking temperature of 325°C for biotite, and cooling of the plutonic bodies to the geothermal gradient by conduction, they concluded that the Late Cretaceous Sierran plutons were emplaced at depths of 5 km or less. The results that they obtained are in close agreement with the results of this report.

In summary, the depth calculations from this study and the evidence stated above suggest that the Cretaceous Sierran plutons were emplaced at depths of 2-8 km, and at least locally were subsequently unroofed in a relatively short period of geological time.

CONCLUSIONS

The principal conclusions of this study are:

1) Age dates from the Tower Peak quadrangle and surrounding area demonstrate that there was a period of continuous thermal-plutonic activity from approximately 100 Ma to 82 Ma.

2) Confirming earlier dating by Evernden and Kistler (1970), Stern et al., (1981), Chen and Moore (1982), and Robinson and Kistler and mapping by Wahrhaftig, four large plutonic sequences were found in the present study to have been emplaced during this period. Emplacement of the Avonelle Lake adamellite was followed by emplacement of the Fremont Lake-Topaz Lake plutonic sequence. This was closely followed by the third plutonic event, the emplacement of the Mt. Gibson-Lake Vernon plutonic sequence. The emplacement of the Tuolumne Intrusive Suite concluded this period of plutonic activity. However, the age data suggests that the emplacement of the Mt. Gibson-Lake Vernon plutonic sequence and the Fremont Lake-Topaz Lake plutonic sequence, and Tuolumne Intrusive Suite may have been partially contemporaneous.

3) The combined K-Ar, Rb-Sr, and U-Pb age dates from the Mt. Gibson-Vernon Lake plutonic sequence, Fremont Lake-Topaz Lake plutonic sequence, and the Tuolumne Intrusive Suite indicate that these large Late Cretaceous plutons were each emplaced over a period of about 3-5 m.y.

4) Thermal effects from emplacement of the Cathedral Peak Granodiorite of the Tuolumne Intrusive Suite, Fremont Lake-

Topaz Lake Intrusive Complex, and Mt. Gibson-Vernon Lake Intrusive Complex extend at least 3 km into the adjacent country rock. Reset K-Ar ages indicate that the surrounding country rocks were heated above the Ar closure temperatures of hornblende and biotite.

5) The disparity between hornblende and biotite cooling ages yield a calculated depth of emplacement of 6-8 km for the Mt. Gibson-Vernon Lake complex and a 2-6 km burial depth for the surrounding country rock near the northern portion of the Cathedral Peak unit of the Tuolumne Intrusive Suite. This indicates a maximum emplacement depth of about 2-6 km for the Cathedral Peak Granodiorite.

APPENDIX I

SAMPLE PREPARATION METHODS

Samples were thin sectioned and examined under a petrographic microscope to determine if the hornblende and/or biotite was unaltered and suitable for K-Ar dating. Suitable samples were crushed, sieved, and washed. Hornblende and biotite were separated using bromoform.

Biotite concentrates were further purified by ball-milling and resieving the concentrates. The resieved biotite concentrates were passed through a Franz isodynamic magnetic separator. Hornblende concentrates were purified by passing through a Franz isodynamic magnetic separator. Hand picking of biotite and hornblende samples to greater than 99% purity was done on the samples that required it.

The mineral separates were examined in immersion oils under a petrographic microscope in order to determine sample purity. Samples that were greater than 99% pure were then split for potassium and argon analysis. A mechanical splitter was used for splitting the hornblende separates. Biotite separates were split by the cone and quarter method.

APPENDIX II

METHOD OF K_2O ANALYSIS.

Potassium analyses were done by flame photometery using a lithium internal standard. Analyses were performed by USGS personnel. Samples were put into solution by fusing the mineral with lithium metaborate and dissolving the resultant glass in nitric acid. The procedure is listed below:

1) A 100 mg split of the sample is weighed and added to 700 mg of pure anhydrous $LiBO_2$.

2) The mixtures are then put into a graphite crucible and fused at 950°C for 15 minutes.

3) Samples are then put into solution by adding the molten mixture to 100 ml of 4 percent v/v HNO_3 and agitated for ten minutes.

4) The solution is then diluted 1:10 with distilled water.

5) Solutions are then aspirated through the flame photometer. The weight percents of K_2O in the unknowns are determined by linear interpolation between bracketing standards.

APPENDIX III

SAMPLE LOCALITY DESCRIPTIONS

Sample No.	Unit Name	Locality Description
1	Granodiorite of Lake Vernon	Sample site is 0.16 km south of Lake Vernon, approximately 0.13 km east of the Tilltill Valley-Lake Vernon trail at an elevation of 6700 ft.
2	Granodiorite of Bearup Lake	Sample location is 0.4 km south of Lake Vernon, 30 m west of the Tilltill Valley-Lake Vernon trail at 6880 ft.
3	Quartz diorite of Mt. Gibson	Collected at an elevation of approximately 7600 ft., from the south-southwest face of the ridge that lies northeast of Middle Branigan Lake, southwest of Upper Branigan Lake, and north of Tilltill Mountain.

4	Adamellite of .... Avonelle Lake	From the base of the prominent spire south of the outlet of the lake in Bear Valley, at an elevation of 9760 ft.
5	Granite of .... Upper Twin Lake	Collected approximately 0.35 km due east of Kendrick Peak at an elevation of 9760 ft.
6	Granite of .... Bond Pass	Sample site is located 0.15 km south of the second pond at the outlet of Dorthy Lake, in line with the northwest trending ridge from Forsyth Peak at an elevation of 9440 ft.
7	Granodiorite of........ Harriet Lake	Sampled from the first dynamited section of the Pacific Crest Trail, 0.13 km south of the bridge across Cascade Creek at 9060 ft. elevation.

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