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Ages of Coexisting Minerals from Heat-Flow Borehole Sites, Central Sierra Nevada Batholith[1]

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Fission track and potassium-argon ages have been determined on minerals in drill core from two heat-flow boreholes in the western central Sierra Nevada batholith. Biotite, apatite, and zircon ages from the ST site are concordant at 128 m.y. The apatite and biotite from the SJ site are also concordant and have an age of 105 m.y. These concordant ages suggest that granites were emplaced at a shallow depth.

A geothermal model of the Sierra Nevada, based on heat flow and heat production data for four boreholes in the Sierra Nevada batholith, has been proposed by *Lachenbruch* [1968]. Lachenbruch has kindly given us samples of core from the boreholes, and we have used them for geochronologic studies. Fission track ages of accessory minerals from plutonic rocks of the four boreholes, along with a number of other fission track ages from granitic rocks elsewhere in the central Sierra Nevada, have been reported by *Naeser and Dodge* [1969]. Additional fission track and K-Ar ages have been determined on minerals in cores from two of the borehole sites and are reported herein (Table 1).

According to *Lachenbruch* [1968, p. 6985], if the batholith had been generated by anatexis under present conditions of mantle heat flow, rocks at boreholes SJ and ST must have been emplaced at depths of 20 and 30 km, respectively. Erosion must then have occurred over a period of 75 m.y., bringing rock at the two sites to their present surface or near-surface levels approximately 65 to 75 m.y. ago.

The geochronologic data presented here do not support *Lachenbruch*'s proposed model. All mineral ages from the same site are concordant within limits of assigned errors. Earlier studies [e.g., *Evernden et al.*, 1960; *Fleischer et al.*, 1965; *Naeser and Faul*, 1969] have demonstrated that ages of biotites, apatites, and zircons will be differentially influenced at elevated temperatures. Thus, the concordance of ages indicates that rock from each of the borehole sites cooled through the interval of temperature in which the individual minerals could not retain argon or fission tracks in less time than the time represented by the spread of the individual mineral ages from each site. For borehole ST, the spread is 6 m.y., and for borehole SJ, the spread is 3 m.y., although only two different minerals were dated from SJ, whereas three were dated from ST.

Apatite will lose part of its fission tracks at 75°C in a million years and will lose all tracks at 150°C in that length of time [*Naeser and Faul*, 1969]. *Evernden and Kistler* [1970] discussed argon loss in biotite and concluded that argon will be lost at temperatures above 325°C. Extrapolation of data presented by *Fleischer et al.* [1965] suggests that zircon will lose part of its fission tracks from 350° to 450°C in a million years and that it will lose all tracks between 450° and 600°C in the same period of time. The rock at ST must have cooled from more than 450°C to less than 75°C in less than 6 m.y. approximately 130 m.y. ago; rock at SJ cooled from 325° to 75°C in an interval of 3 m.y. approximately 105 m.y. ago.

Using thermal gradients reported by *Lachenbruch* [1968] at the two borehole sites (6.3°C/km at ST and 8.9°C/km at SJ), an ambient temperature of 75°C would be reached at 12 and at 8.4 km below the present surface. Because of the temperature restraints imposed by the chronologic data, these depths can be considered

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TABLE 1. Ages of Minerals from Rock of Sierra Nevada Boreholes

Depth of sample, meters	Mineral	Fission-Track Data* ρs	ρi	ϕ	K-Ar Data† K_2O	Ar^{40}	Radiogenic Ar^{40}	Age, m.y.
		Borehole ST						
157	apatite	2.10×10^6	1.05×10^6	1.11×10^{15}				131 ± 10
485		2.03×10^6	1.10×10^6	1.11×10^{15}				125 ± 9
485	zircon	7.18×10^6	4.61×10^6	1.38×10^{15}				130 ± 12
		6.16×10^6	4.02×10^6	1.38×10^{15}				129 ± 16
485	biotite				9.26 9.13	177.24	97	126 ± 4
		Borehole SJ						
3	apatite	1.03×10^6	6.67×10^5	1.13×10^{15}				106 ± 5
459		1.58×10^6	1.03×10^6	1.13×10^{15}				106 ± 5
3	biotite				9.45 9.48	147.38	95	103 ± 3

* Fission track data were determined by C. W. Naeser. ρs is number of spontaneous tracks per cm^2; ρi is number of induced tracks per cm^2; and ϕ is thermal neutron dosage, in neutrons/cm^2.

† K_2O (in wt. %) was determined by L. B. Schlocker. Ar^{40} (in 10^{-11} moles/gm) and radiogenic Ar^{40} (in per cent of total Ar^{40}) were determined by R. W. Kistler.

maximum emplacement depths. Furthermore, a steeper thermal gradient, which likely existed at the time of emplacement, suggests even shallower depths of emplacement. From Lachenbruch's analysis, this, in turn, suggests either that the Sierra Nevada batholith was not formed by crustal anatexis or that the mantle heat flow was much greater in Mesozoic time than at present.

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