Crystallization, fractionation, and solidification of the Tuolumne Intrusive Series, Yosemite National Park, California

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ABSTRACT

Study of the Tuolumne Intrusive Series, a concentric texturally and compositionally zoned plutonic sequence in the eastern part of Yosemite National Park, was undertaken to develop and test a model for the origin of comagmatic plutonic sequences in the Sierra Nevada batholith. The granitoid units that make up the sequence are progressively younger and more felsic inward. The bulk of the rocks are granodiorite, but the outermost formation is quartz diorite, and the innermost one is granite porphyry. The compositional gradient changes both gradually within formations and abruptly between them. The change is greatest in the outer 1 km and lower toward the center of the sequence. Hornblende and biotite, abundant in the marginal rocks, decrease rapidly inward for 1 km as K-feldspar and quartz increase, but farther inward, they decrease slowly. The most conspicuous chemical changes are shown by the elements that are enriched in the mafic minerals.

The compositional zoning indicates that with decreasing temperature, the sequence solidified from the margins inward. Solidification was interrupted repeatedly by surges of fluid core magma. The magma eroded the adjacent solidifying rock, and it expanded the area of the magma chamber at the exposed level by crowding the wall and roof rocks outward and upward and by breaking through the solidifying carapace into the wall rocks. The compositional zonation resulted from crystal fractionation that could have involved (1) preferential accretion of crystalline material present in the magma to the margins of the magma chamber, thus displacing the melt phase progressively inward, and/or (2) downward settling of crystals, probably accompanied by upward movement of melt and volatiles; the residual magma solidifying to form the granitoids. Although either mechanism can explain the observed relations, they lead to very different interpretations of the composition of the magma when the first exposed granitoids solidified at the margins of the magma chamber and as the sequence solidified inward.

INTRODUCTION

Field mapping and accompanying routine petrologic and geochemical studies, together with radiometric age dating, are showing with increasing certainty that most of the large number of granitoid plutons in the central part of the Sierra Nevada batholith can be combined in a much smaller number of comagmatic sequences (Bateman and Dodge, 1970; Presnall and Bateman, 1973). The simplest comagmatic plutonic sequences are concentrically zoned plutons in which relatively mafic rock in the margins, composed of high-temperature mineral assemblages, passes inward without discontinuities to more felsic rock in the core, composed of lower temperature mineral assemblages. This compositional pattern indicates that these plutons solidified from their margins inward with falling temperature. In slightly more complex sequences, sharp contacts between concentrically arranged units indicate that inward solidification was interrupted by movements of the less-crystallized (fluid) core magma, which eroded, stoped, and probably assimilated some of the more completely solidified marginal rock. Still more complicated sequences, in which the consanguinity of the different rock units may be difficult to establish, result from the core magma breaking through the outer solidifying carapace and intruding the country rocks. Core magma repeatedly broke through the solidifying carapace of the Tuolumne Intrusive Series, but a concentric pattern is still obvious. In more extreme examples, all vestiges of concentric zonation may be lost.

These observations and interpretations provide the basis for a model for the origin of comagmatic plutonic sequences in the Sierra Nevada. Our objective in this report is to develop and test such a model. A simple concentrically zoned pluton without discontinuities would be the best kind of comagmatic sequence to study because all of the solid products would be present, and their relations to one another would be unequivocal. Although concentrically zoned plutons without discontinuities are present in the Sierra Nevada, most of them are small, represent only part of a comagmatic sequence, or are difficult of access. We selected the Tuolumne Intrusive Series for study because (1) it is readily accessible; (2) the work of Calkins (1930) has made it the best-known, firmly established comagmatic plutonic sequence in the Sierra Nevada; (3) traverses across the sequence can be located where negligible amounts of solidified rock has been removed at discontinuities; and (4) exposures are excellent.

Many other concentrically zoned plutons have been described and models proposed for their origin, although in none of these models is the zoned pluton viewed as a key to understanding the broader problem of how comagmatic plutonic sequences are formed. Some of the more thoughtful studies that have come to our attention are: the Bald Rock pluton in the northern Sierra Nevada (Compton, 1955); the White Creek batholith of British Columbia (Reesor, 1958); the Tunk Lake pluton, Maine (Karner, 1968); and the West Farrington pluton, North Carolina (Ragland and Butler, 1972). Compton (1955) and Reesor (1958) both postulate contamination as an explanation of the compositional zonation. They assume that the uncontaminated magma is represented by rock in the central part of the body, and that the magma has been contaminated by the surrounding wall rocks. Karner (1968) attributes the zonation in the alkaline Tunk Lake pluton to crystallization at the margins of the magma chamber, which was accompanied and followed by subsolidus replacement and late-stage recrystallization fluxed by hydrous fluids. He interprets a zone of medium-grained

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rock, present locally at the margins of the pluton, as having been chilled, and he believes it to represent the composition of the magma at the time of emplacement. Ragland and Butler (1972) also identify a chilled border in the West Farrington pluton, which is close to the average composition of the exposed rocks of the pluton, and they assume it to represent the composition of the magma at the time of emplacement. Their model involves solidification from the margins inward with minimal contamination, crystal settling or floating, or metasomatism. They consider the rocks to be mixtures of early crystallizing minerals (liquidus and near-liquidus phases) and crystallized interstitial melt; the proportion of entrapped pore liquid having increased inward in the pluton. In contrast, Robinson (1977) attributes the zonal pattern in the Tuolumne Intrusive Series to crystal setting during inward solidification without preferential marginal accretion of crystals.

The compositional zonation in the Tuolumne Intrusive Series can be explained very well by crystal fractionation, whereas the obvious alternative, contamination by wall rocks, is not acceptable because field evidence of contamination is minimal, and the compositions of the wall rocks are not appropriate for producing the compositional variations in the sequence. However, the exact mechanism of crystal fractionation is uncertain because either of two mechanisms seems capable of explaining the observed features. These are (1) preferential marginal accretion of crystalline material with which the magma was saturated and inward displacement of the melt phase, and (2) downward settling of crystalline material from the fluid core magma, probably accompanied by upward movement of melt and volatiles. Arguments can be made in support of both mechanisms, but the data in hand do not permit a clear choice. In our working model, we assume that both mechanisms operated.

In the following discussions, a distinction will be made between crystallization and solidification, even though the two processes overlap. Crystallization is the precipitation of minerals from the melt phase of the magma; whereas, solidification is the formation of solid rock.

SCOPE OF INVESTIGATION AND METHODS OF STUDY

This report deals chiefly with some of the results of a detailed petrologic and chemical study of the rocks along a traverse that runs eastward 21 km from a point about 1 km north of May Lake entirely across the Tuolumne Intrusive Series near its core to Tioga Pass (traverse A-B on Fig. 1). Most of traverse A-B follows California State Highway 120, but a 5-km segment at the west end runs cross country. A second traverse (traverse C-D on Fig. 1) follows the highway 8 km northeast from Olmstead point, past Tenaya Lake, to the point where traverse A-B joins the highway. Because traverse C-D runs diagonal to the internal contacts of the sequence and crosses only three units (two incompletely), C-D shows relatively little compositional variation; we discuss it only incidentally. Modal data for all the samples are given in Table 1, and chemical data for selected samples are given in Table 2. Both traverses are entirely within the Tuolumne Meadows 15-min quadrangle. Although the results of a program of mapping and sampling the Tuolumne Meadows 15-min quadrangle, in progress by geologists of the U.S. Geological Survey (including Bateman), are available to us for testing the validity of our inferences and conclusions, we do not report the results of the quadrangle studies here.

In all, 52 samples were collected along the two traverses: 34 along the May Lake–Tioga Pass traverse (A-B), and 18 along the Olmstead Point–Tenaya Lake traverse (C-D). Modes were determined by counting at least 2,000 equally spaced points on each of two slabs on which plagioclase was selectively stained red and K-feldspar was stained yellow (Norman, 1974). The area of all of the slabs, except those of the fine-grained Johnson Granite Porphyry, exceeds 150 cm^2. The relative proportions of biotite, hornblende, and accessory minerals, which cannot be distinguished on stained slabs, were determined from thin sections (at least two for each sample) and apportioned to the total mafic content measured on slabs. The percentages of K-feldspar megacrysts in the Cathedral Peak Granodiorite were determined on the outcrops from which the samples were collected by counting points on a transparent overlay sheet. Two thousand points, 2.54 mm (1 in.) apart on a square grid, were evaluated. Samples collected for chemical analysis ranged in size from ~5 kg for the fine-grained Johnson Granite Porphyry to 20 kg for the coarse-grained Cathedral Peak Granodiorite. Chemical analyses for major and minor elements were determined at the Australian National University, chiefly by X-ray spectrometry. The compositions of plagioclase, hornblende, biotite, and magnetite were determined with an electron microprobe. All of the plagioclase crystals are compositionally zoned, and 20 to 40 measurements were made on each sample to determine the range of the zoning.

GENERAL GEOLOGICAL RELATIONS

The Tuolumne Intrusive Series is known to underlie about 1,145 km^2 of the high Sierra Nevada in the eastern part of Yosemite National Park (Fig. 1), and it may underlie an additional 200 km^2 along California State Highway 120 west of the area shown in Figure 1. Rocks of the Tuolumne Intrusive Series are exposed in glaciated outcrops from upper Yosemite Valley eastward across Tuolumne Meadows to the Sierra divide. They can be readily inspected along Highway 120, where most of our traverses are located.

The term "Intrusive Series" is no longer acceptable under the American Stratigraphic Code, but it will be retained in this report because impending changes in the code will affect the approved term. As defined by Calkins (1930, p. 121), the Tuolumne Intrusive Series consists (from oldest to youngest) of: the Sentinel Granodiorite, the Half Dome Quartz Monzonite, the Cathedral Peak Granite, and the Johnson Granite Porphyry. When these formations were named, little compositional data were available, and our data require that two of these names be modified. Both the Cathedral Peak Granite and the Half Dome Quartz Monzonite are, in fact, predominantly granodiorite (Fig. 2). Accordingly, these names are changed in this report to Cathedral Peak Granodiorite and Half Dome Granodiorite. Studies in progress by D. L. Peck (1976, written commun.) in the Yosemite quadrangle show that the western part of Calkin's Sentinel Granodiorite, including the rock at Sentinel Rock, the type locality, does not belong to the Tuolumne Intrusive Series. In his field notes and maps, Peck designates the eastern part, which does belong to the Tuolumne Intrusive Series, as the tonalite of Glacier Point, and we have adopted this informal name for this report. Other areas of similar rock having similar relations to the younger members of the Tuolumne Intrusive Series but spatially separated from the tonalite of Glacier

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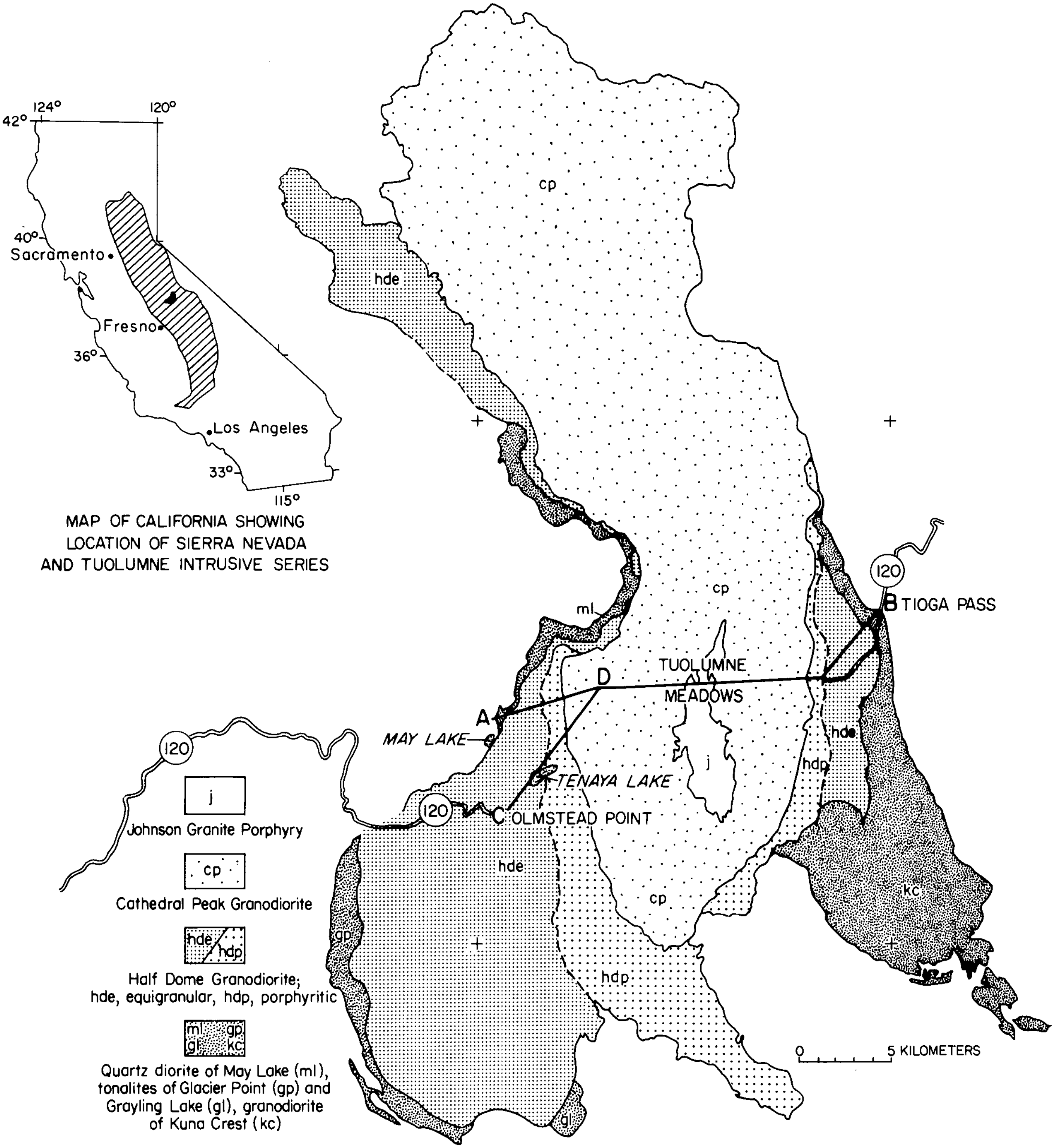

Figure 1. Tuolumne Intrusive Series showing distribution of formations. Sequence may extend west along California State Highway 120, but assignment of formations in that area is not settled.

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TABLE 1. MODAL ANALYSES, SPECIFIC GRAVITY, K-FELDSPAR PHENOCRYST ABUNDANCES, AND

									Traverse A-B (May
Rock unit sample no.	Quartz diorite north of May Lake				Half Dome Granodiorite Equigranular				
	0	1	2	3	4	5	6	7	8
Location (km)	0.00	0.00	0.19	0.44	0.46	0.62	0.81	1.24	1.44
Mode									
Quartz	3.4	12.7	12.2	18.4	20.4	22.5	24.2	24.3	25.4
K-feldspar	2.4	7.8	3.0	10.6	15.9	20.5	23.3	16.6	21.8
Plagioclase	59.5	49.7	54.9	48.4	43.2	42.5	39.6	44.9	42.7
Biotite	12.0	12.6	12.0	10.6	11.1	6.2	5.7	8.7	6.1
Hornblende	21.0	15.8	16.3	10.9	7.9	7.2	5.0	4.3	2.9
Magnetite	0.8	0.7	0.9	0.5	0.7	0.6	1.3	0.8	0.6
Sphene	0.6	0.2	0.2	0.4	0.6	0.4	0.7	0.2	0.3
Apatite	0.3	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2
Pyroxene	..	0.3	0.3	..	..	..	..	..	..
Color index	34.4	29.6	29.7	22.4	20.3	14.4	12.7	14.0	9.9
Sp. gravity	2.82	2.80	2.80	2.76	2.74	2.70	2.70	2.71	2.69
% K-feldspar phenocrysts	..	..	..	..	..	..	..	..	..
Plag. max. mol. % An	..	49	44	42	40	42	42	39	41
Plag. min. mol % An	33	35	32	29	31	23	23	23	19

Rock unit sample no.		Johnson Granite Porphyre			Cathedral Peak Grandiorite				
		20	21	22	23	24	25	26	27
Location (km)		10.31	10.77	10.77	11.96	12.46	12.66	15.14	16.46
Mode									
Quartz		28.5	27.6	32.7	29.6	24.7	26.6	25.9	26.1
K-feldspar		34.2	29.0	40.2	28.1	23.2	23.0	20.9	15.1
Plagioclase		35.0	41.1	26.1	40.5	46.8	45.2	47.5	51.9
Biotite		1.6	1.5	0.6	1.3	4.0	3.4	3.5	3.4
Hornblende		..	..	..	..	tr	0.3	0.8	1.6
Magnetite		0.3	0.3	0.3	0.3	0.7	0.6	0.6	1.1
Sphene		0.1	0.1	0.1	0.1	0.4	0.7	0.5	0.6
Apatite		tr	0.1	tr	0.1	0.2	0.2	0.3	0.2
Muscovite		0.3	0.3	tr	..	..	..	..	..
Color index		2.0	1.9	1.0	1.7	5.1	5.0	5.4	6.7
Sp. gravity		2.61	2.63	2.61	2.61	2.65	2.66	2.66	2.67
% K-feldspar-phenocrysts		<1.0	<1.0	..	<1.0	2.5	3.2	4.2	6.7
Plag. max. mol % An		21	21	24	24	25	24	31	30
Plag. min. mol % An		11	13	11	11	14	12	12	17

									Traverse C-D (Olstead
									Half Dome
Rock unit sample no.	Equigranular								
	35	36	37	38	39	40	41	42	43
Location (km)	0.00	0.26	0.53	1.00	1.46	2.06	2.46	2.94	3.56
Mode									
Quartz	27.1	25.0	23.5	26.0	22.2	23.4	20.3	27.5	24.9
K-feldspar	25.0	20.7	21.3	21.6	21.4	22.0	17.2	26.5	21.2
Plagioclase	41.4	43.4	44.2	42.8	44.7	44.8	49.2	39.3	44.8
Biotite	3.7	5.5	7.8	5.3	4.8	4.9	6.5	4.3	4.4
Hornblende	1.4	2.9	1.8	2.9	4.8	3.0	4.3	1.2	3.1
Magnetite	0.6	1.4	1.1	0.6	1.2	1.0	1.1	0.6	0.9
Sphene	0.7	0.8	0.2	0.6	0.7	0.6	1.2	0.5	0.5
Apatite	0.1	0.3	0.1	0.2	0.2	0.3	0.2	0.1	0.2
Color index	6.4	10.6	10.9	9.4	11.5	9.5	13.1	6.6	8.9
Sp. gravity	2.66	2.69	2.71	2.67	2.70	2.68	2.71	2.66	2.68
% K-feldspar phenocrysts	..	..	..	..	..	..	..	..	..
Plag. max. mol % An	..	37	37	35	38	37	42	34	37
Plag. min. mol % An	..	20	19	19	22	19	21	22	20

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PLAGIOCLASE COMPOSITIONS OF GRANITOIDS FROM TUOLUMNE INTRUSIVE SERIES

Lake = Tioga Pass)

		Porphyritic		Cathedral Peak Granodiorite						
9	10	11	12	13	14	15	16	17	18	19
1.44	2.42	3.01	3.66	4.47	5.98	6.84	7.97	8.59	9.02	10.02
26.0	25.3	22.6	24.8	26.2	24.4	23.1	26.9	25.9	26.1	28.0
24.2	23.4	24.5	21.9	20.9	20.1	22.5	24.0	20.8	17.6	23.9
39.7	43.5	44.1	44.7	46.6	48.8	48.0	44.1	47.7	50.7	43.8
6.0	3.7	5.5	4.8	3.1	3.6	4.0	3.3	3.8	4.4	3.1
2.5	2.3	1.6	2.4	1.6	1.4	1.0	0.4	0.4	0.1	tr
0.8	1.0	0.8	0.7	0.9	0.9	0.7	0.7	0.7	0.6	0.5
0.6	0.6	0.7	0.5	0.5	0.6	0.5	0.5	0.5	0.3	0.5
0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2
..	..	..	..	..	..	..	..	..		..
9.9	7.6	8.6	8.4	6.1	6.5	6.2	4.9	5.4	5.4	4.1
2.69	2.67	2.67	2.68	2.66	2.67	2.67	2.65	2.66	2.65	2.63
..	..	10.0	9.0	7.7	7.5	6.7	4.5	3.7	2.4	1.4
38	34	31	39	34	30	27	30	25	24	23
17	19	15	23	20	14	15	13	13	12	9

Half Dome Granodiorite			Granodiorite of Kuna Crest		
Porph.	Equigr.				
28	29	31	32	33	34
17.25	18.97	20.60	20.62	20.98	21.27
21.6	24.8	19.9	22.2	20.7	14.4
21.4	16.6	17.5	14.6	12.7	8.8
47.4	46.3	44.7	43.9	46.8	50.6
5.0	6.6	9.8	9.9	11.7	12.3
2.5	4.1	6.8	7.5	6.9	12.8
1.1	0.8	0.7	0.6	0.7	0.5
0.7	0.7	0.5	1.1	0.4	0.4
0.3	0.1	0.1	0.2	0.1	0.2
..	..	..	..	..	..
9.3	12.2	17.8	91.1	19.7	26.0
2.68	2.71	2.73	2.73	2.76	2.78
4.0	..	..	..	..	..
34	36	41	41	45	44
19	22	27	26	24	30

Point = Tenaya Lake)

Granodiorite

Porphyritic					Cathedral Peak Grandiorite			
44	45	46	47	48	49	50	51	52
3.83	4.11	4.64	5.12	5.38	5.74	5.98	6.51	7.85
24.2	23.5	23.7	23.4	23.4	24.5	23.8	24.7	23.9
20.9	23.4	24.2	16.4	22.1	21.5	21.2	22.8	21.2
45.2	45.0	44.5	51.6	46.7	46.9	47.3	46.3	47.9
4.6	5.6	4.6	5.2	3.5	3.6	4.2	4.0	4.5
3.4	1.1	1.6	1.5	2.2	2.0	1.6	1.0	1.2
1.0	0.7	0.7	0.9	1.2	0.8	1.0	0.6	0.8
0.5	0.6	0.5	0.7	0.7	0.5	0.6	0.4	0.4
0.2	0.1	0.2	0.3	0.2	0.2	0.3	0.2	0.1
9.5	8.0	7.4	8.3	7.6	6.9	7.4	6.0	6.9
2.70	2.66	2.67	2.70	2.65	2.67	2.66	2.67	2.67
1.1	3.1	3.8	3.5	3.7	11.4	9.0	8.5	7.8
36	32	31	30	33	31	32	30	27
18	17	20	18	21	18	17	17	15

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Point, are here informally called: the quartz diorite north of May Lake, the granodiorite of Kuna Crest (Kistler, 1966), and the granodiorite of Grayling Lake (Peck, 1964). All of these rocks vary in composition, and individual samples may fall in the quartz diorite, quartz monzodiorite, tonalite, or granodiorite fields. The compositional designations represent average compositions of the different bodies.

The Tuolumne Intrusive Series is of early Late Cretaceous age and includes the youngest granitoids in the region (Evernden and Kistler, 1970, p. 17). At all external contacts, its members intrude either metamorphic rocks or older granitoids. The adjacent metamorphic rocks are in the hornblende-hornfels facies of contact metamorphism. Absence of alteration zones characterized by hydrous minerals indicates that at the time the Tuolumne Intrusive Series was emplaced, the exposed rocks were below the zone of meteoric water — possibly at depths of 7 to 10 km (Bateman and Eaton, 1967, p. 1415).

Figure 1 shows the location of the Tuolumne Intrusive Series and the spatial distribution of its constituent rocks. In broad outline, they are nested one within the other. The oldest and most mafic

TABLE 2. MAJOR AND TRACE ELEMENT ANALYSES AND CIPW NORMS OF

sample No.	0	1	2	3	4	5	9	11	13	15
SiO_2	55.27	58.59	58.91	62.18	62.78	65.61	69.23	67.83	69.72	69.22
TiO_2	0.94	0.90	0.89	0.77	0.70	0.54	0.44	0.49	0.42	0.40
Al_2O_3	17.39	16.93	16.87	16.12	15.74	15.44	14.55	15.44	15.02	15.38
Fe_2O_3	2.84	2.26	2.31	1.78	2.07	1.76	1.67	1.55	1.39	1.36
FeO	4.48	4.31	4.25	3.65	3.22	2.38	1.53	1.44	1.18	1.00
MnO	0.14	0.11	0.11	0.09	0.09	0.08	0.08	0.06	0.06	0.05
MgO	3.80	3.26	3.19	2.65	2.50	1.80	1.22	1.03	0.81	0.77
CaO	7.13	6.25	6.22	5.21	4.80	4.10	3.00	3.22	2.90	2.73
Na_2O	3.59	3.53	3.62	3.45	3.25	3.62	3.51	4.02	4.03	4.31
K_2O	1.51	2.38	2.04	2.83	3.22	3.11	4.02	3.65	3.59	3.63
P_2O_5	0.24	0.22	0.21	0.18	0.17	0.16	0.14	0.17	0.15	0.14
H_2O	1.82	1.01	1.16	0.84	1.06	0.78	0.48	0.61	0.59	0.49
H_2O	0.33	0.14	0.13	0.11	0.25	0.14	0.11	0.10	0.08	0.14
CO_2	0.13	0.07	0.07	0.07	0.11	0.09	0.11	0.13	0.11	0.05
rest	0.22	0.25	0.22	0.23	0.24	0.19	0.18	0.25	0.21	0.24
total	99.83	100.21	100.20	100.16	100.20	99.80	100.27	99.99	100.26	99.91
									TRACE ELEMENTS	
Ba	440	720	475	660	745	515	565	905	670	860
Rb	88	108	102	140	134	138	153	129	135	134
Sr	616	574	551	507	478	451	397	658	582	663
Pb	15.5	12.5	12.0	14.5	13.5	16.5	21.5	18.5	18.0	18.5
Th	12.2	16.6	17.0	19.4	31.8	21.8	33.2	18.0	20.0	18.6
U	3.8	4.2	5.2	5.4	8.4	7.4	10.0	5.2	4.8	6.0
Zr	86.	126.	139.	132.	143	116	96	119	117	123
Nb	7	8	8	8	8	7	9	7	7	8
Y	18	18	17	17	26	9	10	8	6	7
La	19	21	23	19	24	23	30	25	23	31
Ce	48	47	47	39	50	38	49	44	37	50
Nd	19	18	18	15	22	11	15	13	10	16
Sc	19	16	16	14	13	8	6	4	4	4
V	172	157	158	126	117	81	52	46	39	36
Cr	24	17	23	12	13	9	2	6	3	6
Co	27	23	24	20	18	14	9	7	6	4
Ni	14	11	11	9	8	5	2	2	1	2
Cu	28	44	51	44	17	11	10	7	7	4
Zn	106	95	94	76	81	69	65	66	56	62
Ga	20.4	19.0	19.4	18.2	17.6	18.0	17.2	18.8	18.8	19.8
										CIPW
Q	7.69	10.43	11.63	15.71	17.32	21.15	25.55	22.47	25.51	23.66
c	..	..	..	..	..	..	..	..	..	..
or	8.92	14.06	12.05	16.72	19.03	18.38	23.76	21.57	21.21	21.45
ab	30.38	29.87	30.63	29.19	27.50	30.63	29.70	34.02	34.10	36.47
an	26.88	23.32	23.76	20.14	18.85	16.70	12.07	13.30	12.29	11.90
di	5.83	5.35	4.88	3.93	3.37	2.30	1.71	1.56	1.14	0.87
hy	11.23	10.28	10.20	8.81	7.81	5.54	3.08	2.49	1.91	1.65
mt	4.12	3.28	3.35	2.58	3.00	2.55	2.42	2.25	2.02	1.97
il	1.79	1.71	1.69	1.46	1.33	1.03	0.84	0.93	0.80	0.76
hm	..	..	..	..	..	..	..	..	..	..
ap	0.57	0.52	0.50	0.43	0.40	0.38	0.33	0.40	0.36	0.33
rest	2.28	1.22	1.36	1.02	1.42	1.01	0.70	0.84	0.78	0.68
total	99.69	100.05	100.05	99.99	100.02	99.67	100.16	99.83	100.12	99.74

Note: Ba and Sr are included in the calculations under CIPW norms.

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granitoids (the tonalite of Glacier Point, quartz diorite north of May Lake, and the granodiorites of Kuna Crest and Grayling Lake) lie along the west-central, southwest, southeast, and south-central margins. The next younger unit (the Half Dome Granodiorite) occupies much of the south part of the sequence, and, in places, it is the marginal rock of the sequence. The unit is in sharp contact with the older rocks of the sequence in most places, but it locally grades into the quartz diorite north of May Lake. The Half Dome Granodiorite has two facies: the outer one is equigranular, and the inner one is porphyritic, containing large crystals (megacrysts) of K-feldspar. In most places, the two facies of the Half Dome are completely gradational, but about 2 km north of Tenaya Lake, the porphyritic facies is in sharp contact with, and intrudes, the equigranular facies.

The Cathedral Peak Granodiorite occupies the central and northern part of the sequence. Contacts with the older members are generally sharp and clearly intrusive. However, along California State Highway 120, the contact is diffuse because of an intermixing of the Cathedral Peak with the porphyritic Half Dome. Along and south of Highway 120, the Cathedral Peak lies almost entirely

REPRESENTATIVE GRANITOIDS FROM TUOLUMNE INTRUSIVE SERIES

	17	19	21	23	26	31	33	43	44	47	49	51
	69.76	71.51	71.65	74.66	69.60	63.47	62.48	67.76	66.65	67.32	67.40	69.33
	0.37	0.28	0.24	0.13	0.38	0.72	0.74	0.46	0.53	0.55	0.53	0.45
	15.49	14.75	14.87	13.80	15.34	15.81	16.03	15.61	15.73	15.68	15.80	15.22
	1.24	0.78	0.84	0.56	1.30	2.14	2.39	1.64	1.93	1.69	1.77	1.40
	0.95	0.89	0.81	0.28	0.95	3.03	2.98	1.48	1.47	1.58	1.36	1.29
	0.05	0.05	0.04	0.02	0.06	0.09	0.09	0.07	0.07	0.06	0.06	0.06
	0.66	0.49	0.38	0.19	0.70	2.28	2.40	1.14	1.23	1.10	1.02	0.85
	2.52	2.07	1.87	1.52	2.68	4.72	4.98	3.51	3.62	3.59	3.45	3.12
	4.33	4.07	3.98	4.17	4.31	3.32	3.46	3.83	4.14	4.17	4.08	4.12
	3.72	4.19	4.19	3.80	3.64	3.22	2.89	3.66	3.27	3.22	3.63	3.40
	0.13	0.10	0.08	0.03	0.14	0.17	0.17	0.17	0.19	0.19	0.20	0.17
	0.45	0.50	0.58	0.38	0.58	0.88	0.90	0.32	0.66	0.42	0.35	0.30
	0.09	0.17	0.17	0.16	0.23	0.15	0.15	0.07	0.12	0.08	0.11	0.10
	0.05	0.07	0.13	0.06	0.08	0.03	0.06	0.09	0.09	0.04	0.03	0.10
	0.22	0.21	0.26	0.12	0.23	0.26	0.24	0.24	0.26	0.25	0.27	0.21
	100.03	100.13	100.09	99.88	100.22	100.29	99.96	100.05	99.96	99.94	100.06	100.12
(ppm)												
	740	760	1170	325	785	905	745	900	960	895	1015	615
	137	165	158	150	133	123	119	127	117	100	113	128
	621	525	484	369	648	515	482	572	633	709	715	618
	19.0	20.5	23.5	22.0	19.0	13.0	15.0	20.0	19.0	16.0	16.5	18.0
	18.4	16.8	16.8	19.4	19.6	31.4	38.4	25.4	16.6	12.8	15.4	20.0
	8.8	6.0	3.8	2.6	5.0	9.0	11.0	5.8	5.4	3.6	5.2	5.2
	126	112	138	59	125	174	130	105	126	121	127	116
	8	7	9	6	8	9	8	8	8	8	8	7
	7	6	8	3	7	17	16	9	9	8	8	7
	29	22	31	17	31	23	25	28	27	26	29	22
	49	35	58	25	51	44	48	42	49	46	49	38
	14	11	15	7	15	16	18	13	15	15	15	14
	3	2	2	2	3	12	14	5	5	5	5	4
	33	22	18	9	35	113	123	53	61	56	54	44
	1	<1	<1	2	2	9	16	8	4	7	1	5
	5	4	2	1	6	16	18	9	10	8	8	7
	2	1	2	1	1	7	8	3	4	2	2	2
	4	9	8	3	5	19	27	6	8	8	7	6
	60	54	54	23	63	78	78	60	72	69	69	62
	19.6	19.2	18.4	18.0	19.4	18.0	16.8	18.2	20.0	19.8	19.4	18.8
NORMS												
	24.11	26.57	27.73	32.33	24.19	18.24	17.19	22.69	21.19	21.97	21.58	24.84
	..	..	0.44	0.07	..	..	..	..	..	..	..	..
	21.98	24.76	24.76	22.46	21.51	19.03	17.08	21.63	19.32	19.03	21.45	20.09
	36.64	34.44	33.68	35.29	36.47	28.09	29.28	32.41	35.03	35.29	34.52	34.86
	11.84	9.60	9.15	7.53	11.76	18.73	19.67	14.59	14.68	14.56	14.08	12.99
	0.12	0.27	..	..	0.77	3.18	3.40	1.65	1.92	1.93	1.70	1.35
	1.79	1.71	1.42	0.47	1.54	6.92	6.79	2.79	2.52	2.53	2.01	2.05
	1.80	1.13	1.22	0.59	1.88	3.10	3.47	2.38	2.80	2.45	2.57	2.03
	0.70	0.53	0.46	0.25	0.72	1.37	1.41	0.87	1.01	1.04	1.01	0.85
	..	..	..	0.15	..	..	..	..	..	..	..	..
	0.31	0.24	0.19	0.07	0.33	0.40	0.40	0.40	0.45	0.45	0.47	0.40
	0.59	0.74	0.88	0.60	0.89	1.06	1.11	0.48	0.87	0.54	0.49	0.50
	99.88	99.99	99.93	99.81	100.06	100.12	99.79	99.89	99.79	99.79	99.88	99.96

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within the porphyritic facies of the Half Dome, but north of the highway, it truncates all of the older granitoids of the sequence and is the marginal rock of the sequence along the northeast side and at the north end (Chesterman, 1975; Wahrhaftig, 1977, written commun.).

The Johnson Granite Porphyry occupies an elongate area in the south-central part of the sequence. It is fine grained and is cut by many still finer-grained dikes of similar composition. The contacts of the Johnson with the Cathedral Peak are very sharp and extremely complex; dikes of Johnson Granite Porphyry intrude irregularly into the Cathedral Peak.

Figure 3 shows our interpretation of the magmatic movements that occurred during the emplacement and inward solidification of the Tuolumne Intrusive Series. Each surge of magma resulted in increased area at the present level of exposure.

STRUCTURAL AND TEXTURAL VARIATIONS

Progressive changes in the fabric and textures, as well as in the mineral content, take place inward from the margins of the sequence. Dark, generally fine-grained, well-foliated granitoids in the margins give way inward to progressively lighter colored, coarse-grained, poorly foliated granitoids. Mafic minerals, abundant in the marginal rocks, decrease inward as quartz and K-feldspar increase. The outermost rocks along traverse A-B, the quartz diorite north of May Lake and the granodiorite of Kuna Crest, are dark and strongly foliated parallel to their external contacts. The marginal part of the equigranular facies of the Half Dome Granodiorite is also strongly foliated, especially where it is the marginal rock of the sequence. The foliation reflects the preferred orientation of tabular and prismatic minerals, especially hornblende and biotite, and of disc-shaped mafic inclusions. The foliation and the disc-like shapes of the mafic inclusions are interpreted to be the result of stretching of the partly crystallized marginal parts of the body during emplacement and solidification (Bateman and others, 1963, p.

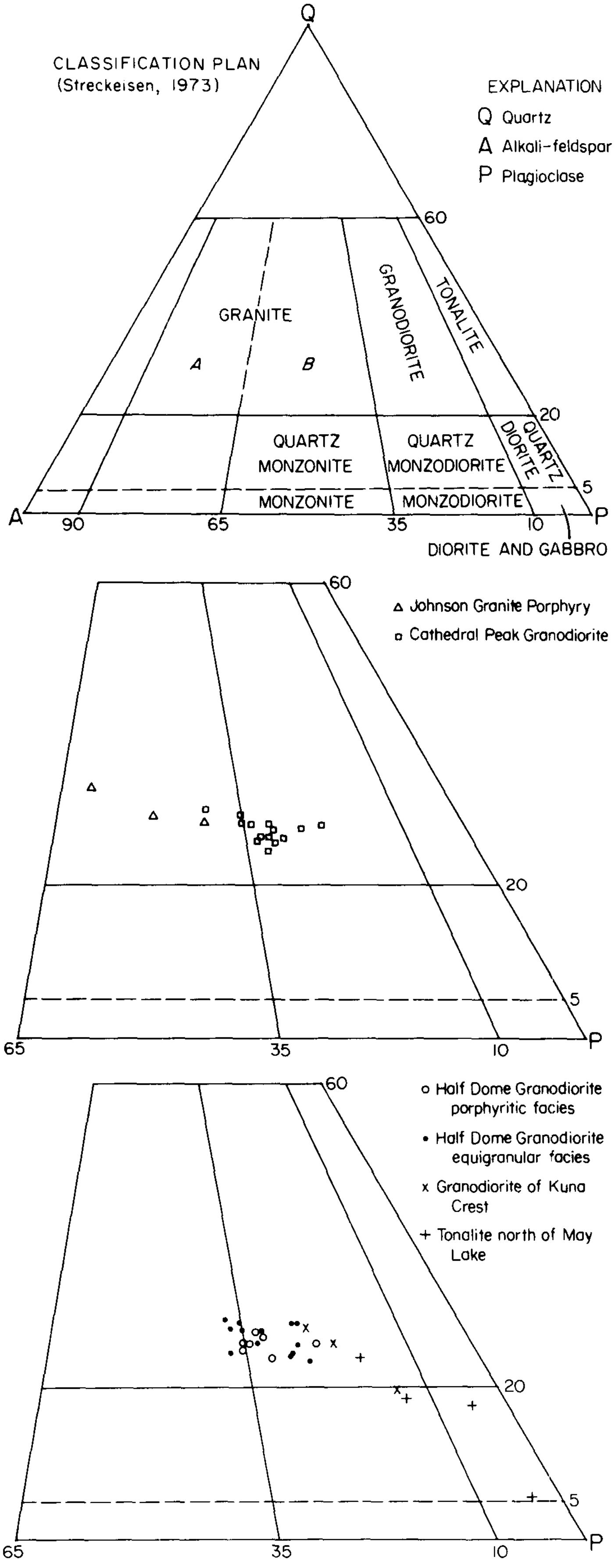

Figure 2. Plots of modes of samples along traverse A-B and C-D.

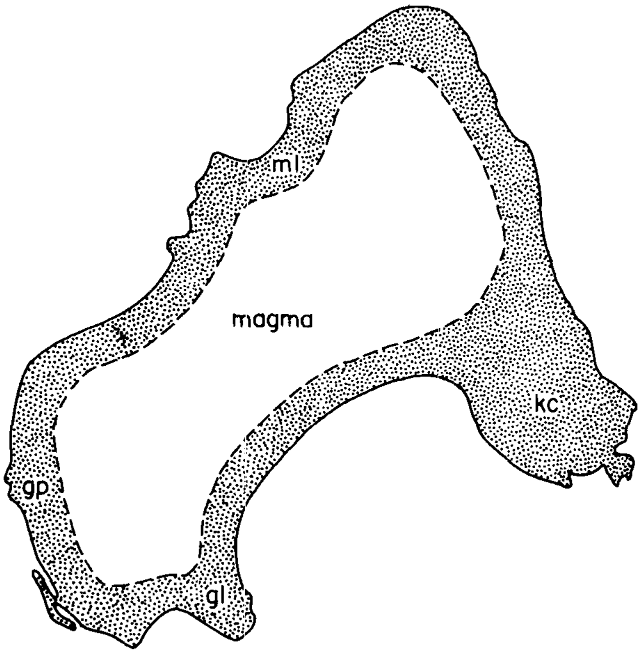

Figure 3A. Initial intrusion and solidification of marginal granitoids: ml, quartz diorite north of May Lake; gp, tonalite of Glacier Point; gl, tonalite of Grayling Lake; and kc, granodiorite of Kuna Crest.

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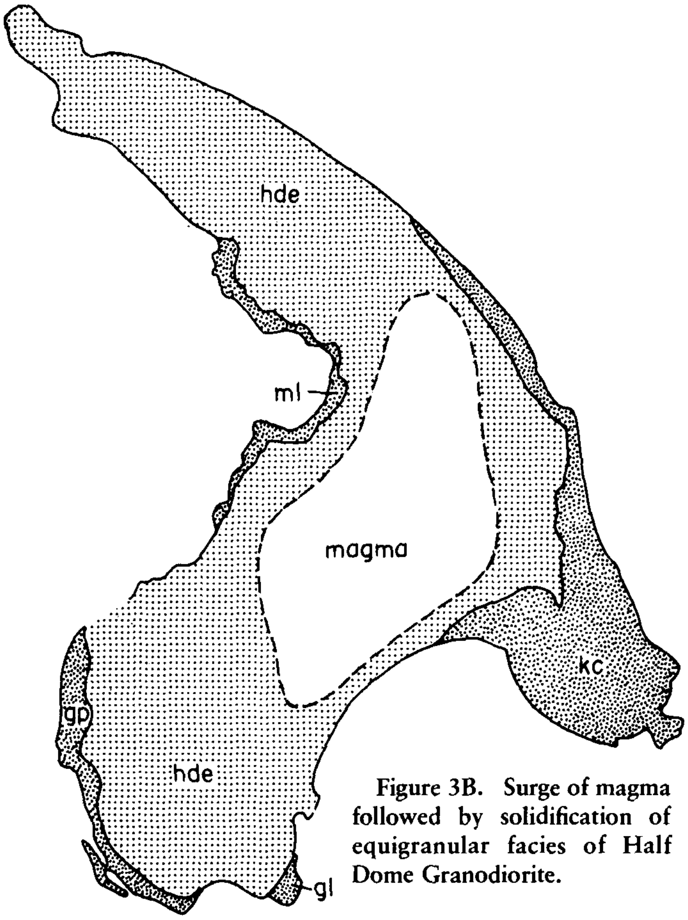

Figure 3B. Surge of magma followed by solidification of equigranular facies of Half Dome Granodiorite.

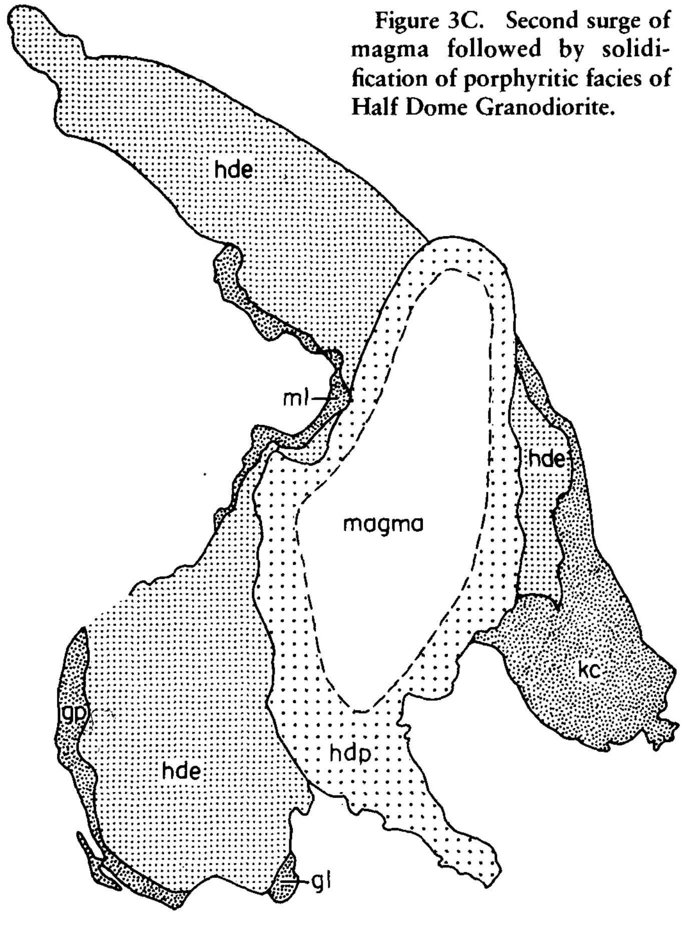

Figure 3C. Second surge of magma followed by solidification of porphyritic facies of Half Dome Granodiorite.

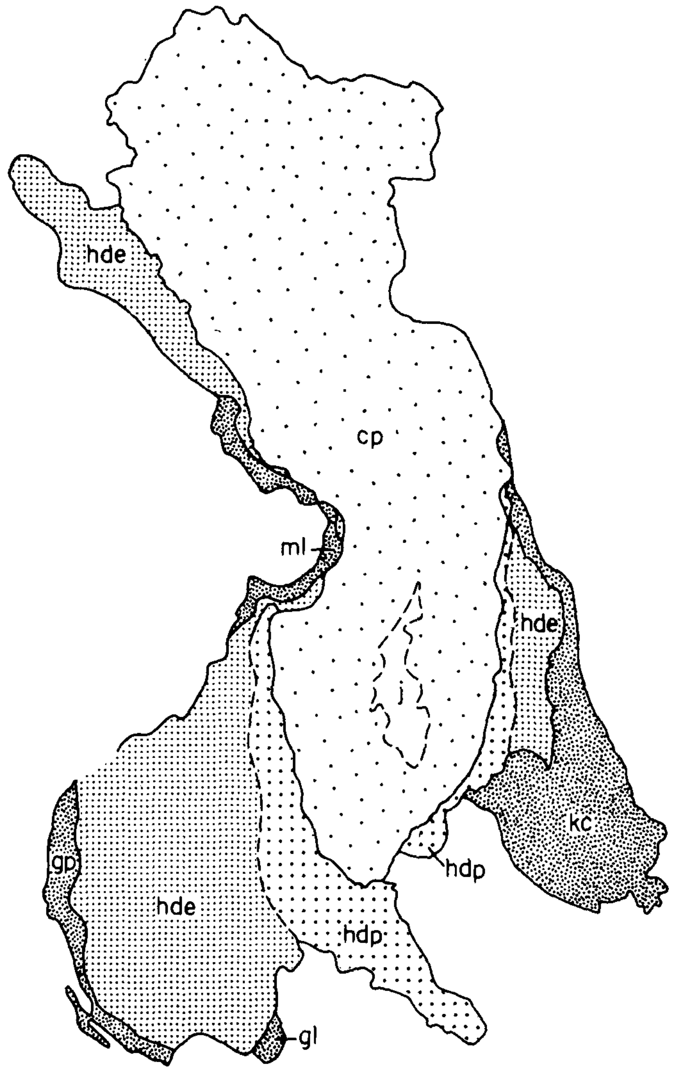

Figure 3D. Third surge of magma followed by solidification of Cathedral Peak Granodiorite. Eruption and solidification of Johnson Granite Porphyry was final stage of emplacement.

D19). The facts that the foliation approximately parallels the external contacts of the sequence and weakens inward support this view. In the Cathedral Peak Granodiorite, foliation is difficult to discern and, where visible, is steep or vertical, and it runs diagonally north of west across the sequence rather than parallel to the external contacts.

The marginal part of the quartz diorite north of May Lake is fine grained; individual grains of the principal minerals — plagioclase, hornblende, and biotite — do not exceed 3 mm in greatest dimension. Some hornblende crystals contain pyroxene cores. Magnetite and sphene are less than 0.3 mm across. Most of the minerals have irregular (anhedral) shapes, but apatite is in tiny (0.2 × 0.5 mm) prismatic crystals. Some magnetite is in equant crystals, and some sphene occurs as skeletal crystals. The size and perfection of crystal shape of most of these minerals increase inward in the sequence. Biotite, hornblende, and sphene occur as discrete well-formed crystals in the Half Dome. They reach their largest size in the inner half of the equigranular facies, where hornblende and biotite commonly range up to 5 mm in maximum dimension, and sphene, up to 3 mm. Some hornblende prisms are as long as 1.5 cm. Farther inward, in the porphyritic facies of the Half Dome and in the Cathedral Peak Granodiorite, crystals of hornblende, biotite, and sphene

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become smaller as they decrease in abundance. Plagioclase and magnetite increase inward slightly to 5 and 0.5 mm, respectively, in the porphyritic facies of the Half Dome and in the Cathedral Peak. Prismatic crystals of apatite increase into the inner part of the Cathedral Peak, reaching lengths of 0.5 mm. The occurrence of relatively large apatite crystals is a conspicuous feature of much of the Half Dome and Cathedral Peak.

Quartz and K-feldspar, sparse in the marginal rocks, increase in size and abundance inward well into the equigranular facies of the Half Dome Granodiorite. Within the Cathedral Peak Granodiorite and into the Johnson Granite Porphyry, the abundance of both minerals remains relatively constant. Quartz increases progressively in grain size and forms equidimensional crystals 1 cm across in the inner part of the Cathedral Peak Granodiorite. K-feldspar increases in grain size to the boundary between the equigranular and porphyritic facies of the Half Dome Granodiorite, where megacrysts appear. These megacrysts increase in size and abundance inward to the contact between the Half Dome and the Cathedral Peak. In the outer margins of the Cathedral Peak, K-feldspar megacrysts are 6 to 8 cm across; they decrease in size and abundance inward.

The texture of the Johnson Granite Porphyry is distinct from that of the other rocks of the Tuolumne Intrusive Series. A few large megacrysts of K-feldspar and smaller irregular-shaped fragments of quartz and plagioclase are contained in a fine-grained groundmass of quartz, K-feldspar, and plagioclase. In places, the Johnson is miarolitic. Biotite is altered to chlorite and locally is accompanied by epidote, secondary sphene, and sparse fluorite. Muscovite aggregates replace plagioclase cores; magnetite is altered; and primary sphene, though present, is rarely in well-formed crystals. Apatite occurs as long thin prisms containing fluid inclusions. Dark-brown pleochroic crystals of allanite, absent in the other units of the sequence, show little sign of metamictization, but small zircons, where enclosed in chlorite, have pleochroic haloes.

Finer-grained margins of plutonic rock bodies have traditionally been considered to result from chilling. We subscribe to that view, but we are wary of the usual concept that the finer-grained marginal rock is a representative sample of the entire magma body. If any preferential accretion of crystalline material occurred during inward solidification, the crystalline phases must be over-represented in the marginal rocks. The fine grain size results from loss of heat to the wall rocks which causes temperatures to fall more rapidly in the

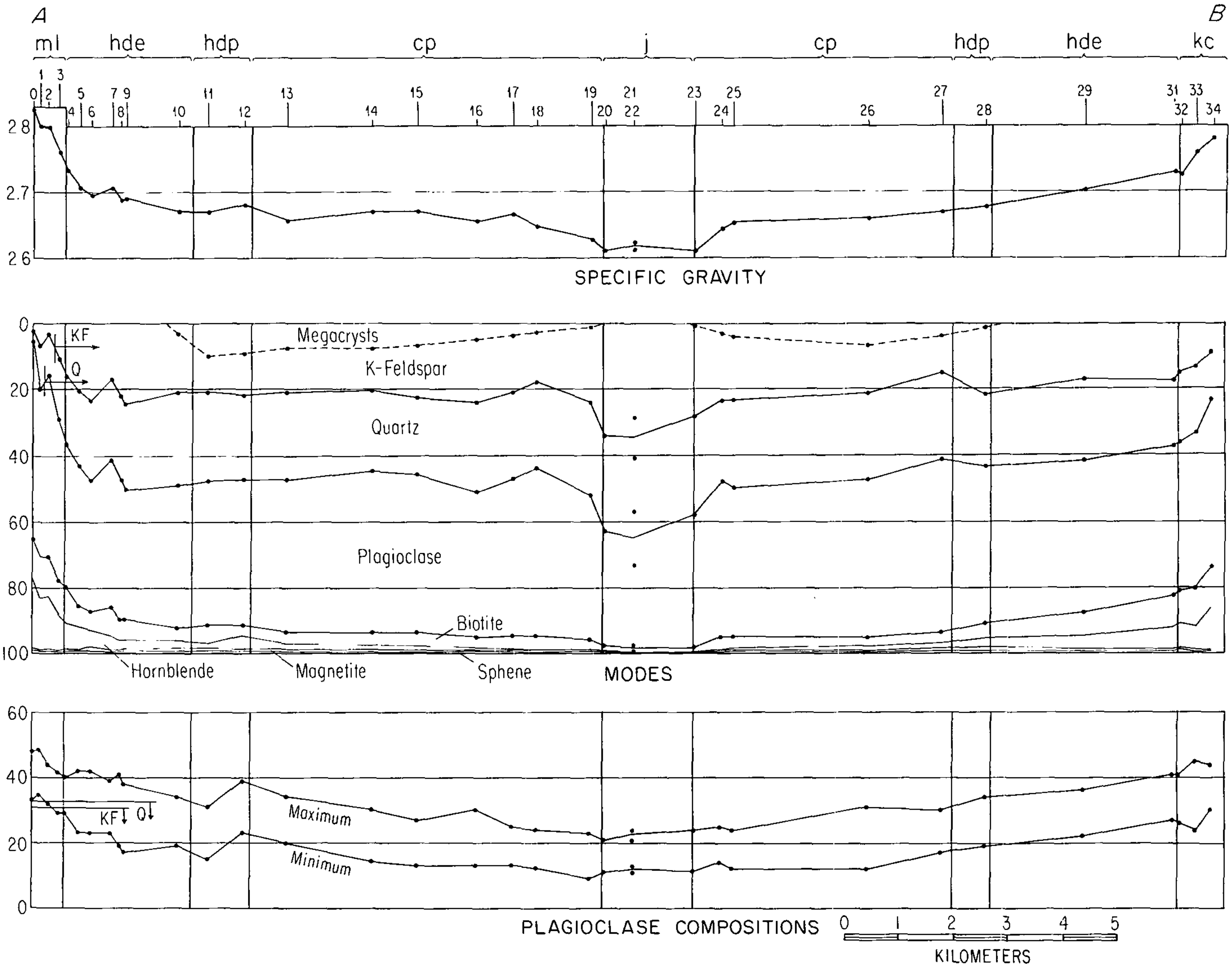

Figure 4. Specific gravity, modes, and plagioclase compositions along traverse A-B. Q and KF show beginning of crystallization of quartz and K-feldspar in terms of inward solidification of the sequence and composition of crystallizing plagioclase.

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marginal part of the magma than in the interior, promoting the formation of abundant new nuclei and shortening their growth time, and, consequently, their size before they solidify to form the marginal rocks. A contributing factor to the finer grain size of the marginal rocks is that the minerals in them — hornblende, biotite, and plagioclase — characteristically form smaller crystals than the minerals that predominate in the interior — quartz and K-feldspar.

Two notable characteristics of the Tuolumne Intrusive Series are a general dearth of mafic inclusions — except locally in marginal parts of the Half Dome Granodiorite, the granodiorite of Kuna Crest, and the quartz diorite north of May Lake — and characteristically discrete euhedral shapes of both hornblende and biotite — except in the marginal rocks. In many Sierran and eastern Australian granitoids, these minerals are chiefly in clots composed of anhedral hornblende and biotite; magnetite, apatite, and sphene, which range in size from conspicuous mafic inclusions 10 or more cm in longest dimension to tiny spots less than a centimetre across. Presnall and Bateman (1973, p. 3197) suggested that mafic clots of anhedral minerals represent residual, largely crystalline material that was carried and equilibrated with the magma from its place of origin and that euhedral hornblende and biotite crystallized in the magma from the melt phase. An observed inverse relationship between the abundance of mafic inclusions and euhedral crystals of hornblende and biotite in the granitoids of the western United States and eastern Australia supports this interpretation. The presence of widely scattered euhedral crystals within and adjacent to mafic inclusions suggests that the euhedral crystals may have been fed, at least in part, by constituents contained in the mafic inclusions.

SPECIFIC GRAVITIES AND MODES INWARD TO THE JOHNSON GRANITE PORPHYRY

Because better and more abundant exposures along the west half of traverse A-B (Fig. 1) permitted collecting samples at closer intervals than along the east half, especially close to the external contact of the sequence, the following discussion will be directed toward it. However, the east half approximates a mirror image of the west half.

Inspection of Figures 4 and 5 shows that along traverse A-B, the bulk specific gravity, biotite, hornblende, and the anorthite content of plagioclase decrease inward. The rate of decrease is greatest approximately a kilometre inward from the margins; beyond a kilometre, the rate of decrease is slight until the Johnson Granite Porphyry is reached, where the specific gravity and the plagioclase and biotite content drop abruptly. The relative smoothness of the decrease across the contacts (discontinuities) between the different formations (except the Johnson) indicates that movements of fluid core magma that produced the contacts eroded very little of the adjacent solidifying rock along traverse A-B.

The two most westerly samples, collected within a few metres of the external contact, contain equant crystals of plagioclase, hornblende, biotite, magnetite, and sphene, but only thin intergranular stringers of quartz and K-feldspar. We interpret these re-

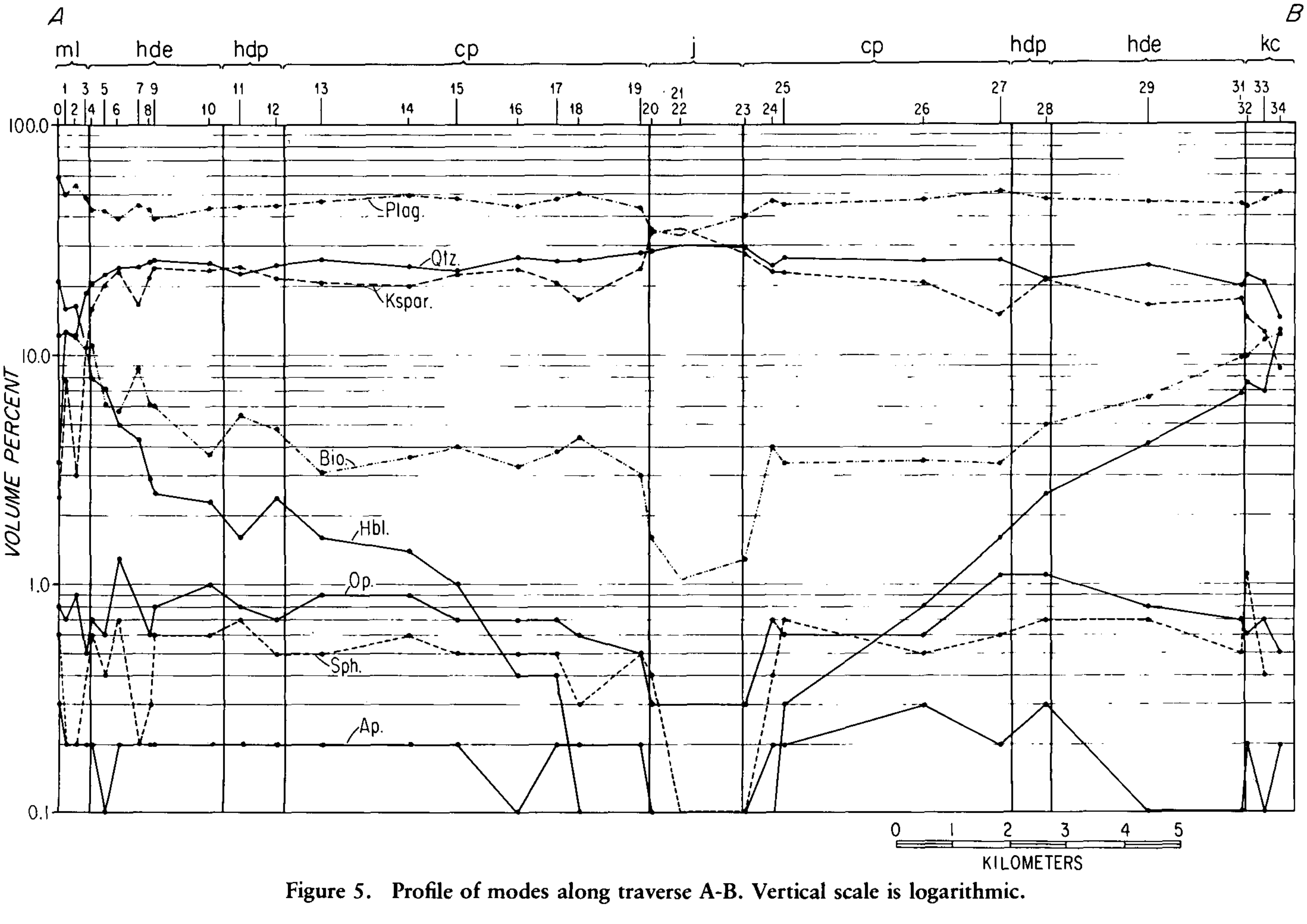

Figure 5. Profile of modes along traverse A-B. Vertical scale is logarithmic.

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lations to indicate that at the time these rocks began to solidify, the equant and subequant minerals were present in the magma as crystals, but that quartz and K-feldspar crystallized from interstitial melt. The principal compositional differences between the two samples is the greater abundance of quartz and K-feldspar in sample 1 than in sample 0. Sample 0 contains 3.4% quartz and 2.4% K-feldspar, whereas sample 1 contains 12.7% quartz and 7.8% K-feldspar. In both samples, the ratio of quartz to K-feldspar is about 3:2, representing the ratio of quartz-forming to K-feldspar-forming constituents in the interstitial melt. Apparently a larger amount of interstitial recrystallized melt is contained in sample 1. If the amount of albite-forming constituents in the interstitial melt was approximately equal to the K-feldspar-forming constituents, and if the amount of femic constituents was small, as is suggested by the compositions of the rocks in the interior of the Tuolumne Intrusive Series, sample 0 contains no more than 9% of recrystallized intergranular melt and sample 1 contains $\sim$28%.

Sample 2 and all samples inward from sample 2 contain equant or subequant grains of quartz, and sample 3 and samples inward from sample 3 contain subequant grains of K-feldspar. This indicates that quartz began to crystallize between the times when samples 1 and 2 solidified, and that K-feldspar began to crystallize between the times when samples 2 and 3 solidified.

Figure 6 shows the experimentally determined liquidus relations in the salic tetrahedron, which represents the system $KAlSi_3O_8$-$NaAlSi_3O_8$- $CaAl_2Si_2O_8$-SiO_2 (Or-Ab-An-Q), at moderate confining pressures. An unknown amount of H_2O is also assumed to have been present. The internal surfaces of the tetrahedron and their line of intersection shift positions with different total pressure and partial pressure of water, but these shifts are not important to the present qualitative considerations. The presence of plagioclase and the absence of discrete crystals of quartz and K-feldspar in samples 0 and 1 show that when the marginal rock began to solidify, the melt was in the plagioclase liquidus-phase volume. The appearance of subequant grains of quartz in sample 2 and of K-feldspar in sample 3 further show that the melt was close to the quartz saturation surface (the surface separating the quartz and plagioclase liquidus-phase volumes) and to the cotectic (the line of intersection of the quartz-saturation surface and the two feldspar surface). Crystallization of plagioclase while the rocks in samples 0 and 1 were forming caused the melt to move onto the quartz-saturation surface, in some such position as A in Figure 6, before sample 2 solidified, and onto the cotectic before sample 3 solidified. Crystallization of plagioclase, quartz, and K-feldspar with falling temperature then caused the melt to move along the cotectic toward the temperature minimum until all the melt was crystallized.

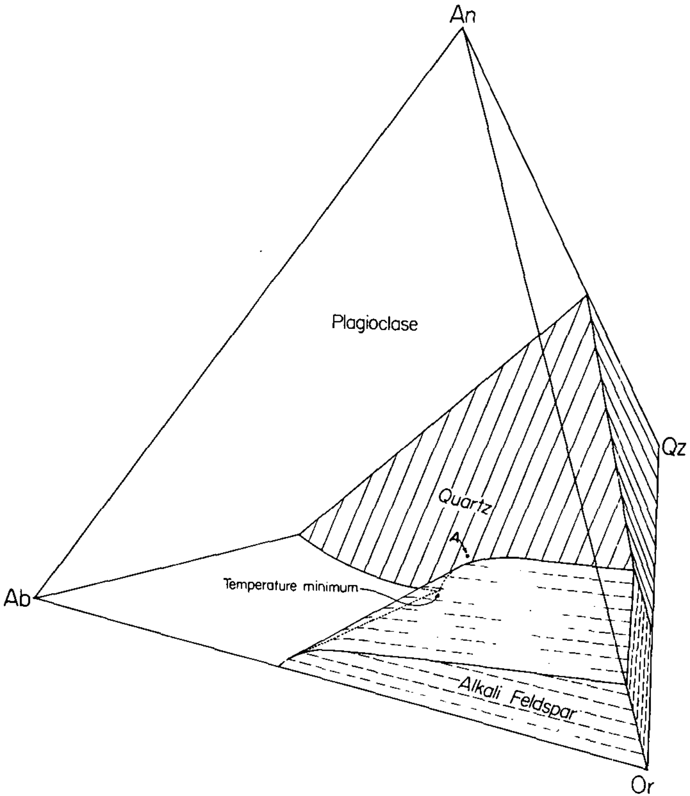

Figure 6. Salic tetrahedron showing liquidus-phase volumes.

The relations in Figure 5 indicate that when the quartz-saturation surface is first intersected, quartz will immediately begin to crystallize in about the same proportion to other crystallizing minerals as it will later on, and when the cotectic is intersected, K-feldspar will do likewise. However, this does not happen because the rates of both nucleation and crystal growth increase with undercooling to maxima that are not usually coincident (Swanson, 1977). They may then decrease. Thus, the appearance of subequant quartz grains in sample 2 and K-feldspar in sample 3 (Fig. 4 and Table 1) is visible evidence of the beginning of nucleation, and their increasing abundance inward to sample 6 marks their increasing rate of precipitation because of the increasing rates of nucleation and crystal growth with undercooling. Their approximately constant amounts in samples 6 to 19 indicate that the proportions of quartz and K-feldspar being precipitated where relatively constant. If crystals selectively accreted to the margins of the magma chamber, two other mechanisms may have contributed to the gradual increase of quartz and K-feldspar inward to sample 6. The first is that both minerals doubtless began to crystallize in the margins of the magma chamber where temperatures were lowest, and crystallization spread inward into large volumes of magma with cooling. The second mechanism is that when quartz and K-feldspar began to crystallize, no crystals of these minerals were present in the magma, and their proportion increased as new crystals precipitated and as crystals already present in the magma were subtracted.

Relatively constant amounts of plagioclase and magnetite in samples 1 through 19 indicate that when solidification began at this level of exposure, both minerals were crystallizing in the proportions in which they occur in the marginal rock and that those proportions changed little as the magma crystallized and solidified. The very small gradual decrease of biotite from samples 1 through 19 suggests a slow decrease in the proportion of biotite crystallizing.

Hornblende diminishes inward through samples 1 through 6 at a rapid rate, then more slowly to sample 17, suggesting that the proportion of hornblende crystallizing decreased rapidly between the time when samples 1 through 6 formed. After that, hornblende either decreased more slowly or stopped crystallizing entirely.

PLAGIOCLASE COMPOSITIONS

The data on plagioclase compositions of the Tuolumne Intrusive Series, given in Table 1, are the maximum and minimum values for the general range of compositions. The few high An values probably represent relict material from the source region of the magma, or early precipitated crystals, most of which were separated from the magma before the exposed marginal rocks began to solidify. Some of the more common low values probably represent plagio-

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clase that crystallized from interstitial melt; others of compositions that are extremely rich in albite along contacts between plagioclase and K-feldspar reflect subsolidus separation of albite from K-feldspar.

The plagioclase crystals are zoned generally through compositional ranges of about 15% anorthite (Table 1). The average composition and the maximum and minimum values decrease inward from the margins; the range at the margins is ~An_{48} to An_{33}, and in the inner part of the Cathedral Peak Granodiorite, An_{23} to An_{10}. The progressive change in the compositional range clearly indicates that differentiation in the sequence results from crystal fractionation and not from simple unmixing of near-liquidus minerals and melt. As generally understood, simple unmixing involves separating end members of fixed compositions from one another; the compositional variations reflect the proportions of end members. Crystal fractionation also involves unmixing but is more complicated; it involves separating crystalline material of changing bulk composition from melt of changing composition. Thus, the compositional variants resulting from crystal fractionation reflect the changing compositions of the crystals and interstitial melt, as well as the proportion of melt to crystals.

Minimum anorthite contents of plagioclase crystals must represent the plagioclase compositions that were precipitating from the melt phase of the magma at the time the plagioclase crystals were sealed off from the main body of magma. Thus, the last and most sodic plagioclase to crystallize in sample 0, An_{33}, must reflect the composition of the plagioclase that was precipitating in the outer marginal part of the magma when the rock in sample 0 solidified. By omitting from consideration sparsely represented compositions more sodic than the general range, we have minimized the possibility that this composition may be more sodic than that of crystals precipitating in the magma. The fact that plagioclase as calcic as An_{48} is present in sample 0 indicates that plagioclase, and doubtless other minerals as well, had been precipitating in the magma through a temperature decrease represented by the compositional change from An_{48} to An_{33} before the exposed marginal rock solidified. A few of the plagioclase crystals exhibit oscillatory zoning, which Chappell (1966) has interpreted as frequently indicating early growth of plagioclase in a matrix of residual solids. However, dearth of such crystals and of mottled calcic cores believed to be residual (Presnall and Bateman, 1973, p. 3197; Chappell, 1966; White and Chappell, 1977) indicates that most of the crystals in the exposed rocks have been precipitated from the melt phase of the magma and are not residual. This interpretation is in agreement with the interpretation made from the euhedral forms of biotite and hornblende. The early granitoids of most other plutonic sequences in the Sierra Nevada contain plagioclase with mottled cores and complex oscillatory zoning and also mafic clots of anhedral minerals. If such restite material were present in the parent magma of the Tuolumne Intrusive Series, as we believe it was, most of it was already separated from the magma, presumably by settling and marginal accretion, before the exposed rocks began to solidify.

The composition of the plagioclase that was crystallizing when quartz and K-feldspar began to precipitate from the melt phase of the magma can be estimated by observing the composition of the most sodic plagioclase in samples bracketing the first appearance of subequant crystals of these minerals. Plagioclase compositions of An_{35} (sample 1) and An_{32} (sample 2) bracket quartz, and An_{32} (sample 2) and An_{29} (sample 3) bracket K-feldspar. Plagioclase of An_{33} composition in sample 1 further limits the composition of the plagioclase crystallizing when quartz crystals began to precipitate to the span of An_{33} and An_{32}.

K-FELDSPAR MEGACRYSTS

A distinctive feature of the Tuolumne Intrusive Series is the presence of a wide zone characterized by K-feldspar megacrysts (Fig. 4). This zone covers the porphyritic facies of the Half Dome Granodiorite and the Cathedral Peak Granodiorite; scattered megacrysts also are present in the Johnson Granite Porphyry. Along the west part of traverse A-B, northeast of May Lake where the porphyritic facies of the Half Dome intrudes the equigranular facies, the change from equigranular to porphyritic is abrupt at an internal intrusive contact, but elsewhere, including along traverse C-D at Tenaya Lake, the transition is gradual. Sparse, small K-feldspar megacrysts appear at the facies change, and they can be seen to increase in size and abundance toward the Cathedral Peak. However, because the porphyritic facies of the Half Dome is seriate rather than porphyritic, reliable measurements of the changing size and abundance of megacrysts in the Half Dome could not be made in the field. In adjacent parts of the Cathedral Peak, megacrysts are commonly 6 to 8 cm long and make up about 10% of the rock. Most of the megacrysts are blocky and have well-formed but rough crystal faces, but some can be seen on stained slabs to interdigitate with bordering crystals. The megacrysts commonly contain abundant small crystals of plagioclase and biotite but rarely quartz. The included crystals are arranged in zones parallel with the crystal facies, showing stages in the growth of the megacrysts.

Both the size and abundance of the megacrysts decrease from the outer margin of the Cathedral Peak inward toward the Johnson Granite Porphyry and constitute less than 2% of the rock near the contact with the Johnson. Throughout these changes in the size and percent of K-feldspar megacrysts, the total amount of K-feldspar in both phenocrysts and in the groundmass remains relatively constant at ~20%.

This pattern of distribution of megacrysts in calc-alkaline granitoids is common. In many places, the earliest and most mafic rocks of a comagmatic granitoid sequence are equigranular, next younger rocks contain megacrysts, and the youngest and most felsic rocks are equigranular (see Reesor, 1958; Bateman and Wones, 1972). Lockwood (1975, p. C3-C18 and Fig. 10) has shown that the megacrysts in the quartz monzonite of Mono Recesses, a few miles southeast of the Tuolumne Intrusive Series, diminish in abundance inward. Wagener (1965, p. 56) has described a similar decrease in the East Farrington stock of North Carolina, and Chappell and White (1976, p. 9–11) report an inward decrease in the abundance of megacrysts in the alkaline Dromedary Complex of southeastern Australia.

Both magmatic and metasomatic origins have been proposed for K-feldspar megacrysts. Those in the Tuolumne Intrusive Series appear to be chiefly magmatic, for they have been carried into dikes, and in roadcuts at the east end of Tenaya Lake can be seen to have been involved in schlieren that originated through flow sorting of crystals (Bhattacharji and Smith, 1964). A few megacrysts have grown across boundary surfaces in the schlieren and within biotite-rich streaks, probably as porphyroblasts, but most of the megacrysts in the Tuolumne Intrusive Series could not have originated in this way. Kerrick (1969), who determined that the megacrysts have higher Ba contents and lower obliquities than groundmass K-feldspar, suggests that they crystallized earlier and at higher temperatures.

Any explanation for the origin of the megacrysts must account for their systematic change in size and abundance inward in the sequence with the absence of a significant change in the total amount of K-feldspar. Several temperature-dependent processes are prob-

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ably involved — the rate at which K-feldspar was being precipitated, the rate of nucleation, the rate of crystal growth, and the length of time the K-feldspar crystals had to grow in the magma before being sealed in solid rock. Swanson (1977) has shown experimentally that in magma of granodioritic composition, the growth rate of K-feldspar reaches a maximum at a temperature only slightly below the temperature at the beginning of nucleation. This occurs when the rate of nucleation is relatively low.

THE JOHNSON GRANITE PORPHYRY

The Johnson Granite Porphyry differs significantly from the other members of the Tuolumne Intrusive Series, in that it has a fine-grained groundmass, porphyritic texture, and miarolitic cavities. Typically, it contains a few scattered large K-feldspar megacrysts like those in the contiguous Cathedral Peak Granodiorite, many scattered angular fragments of plagioclase and quartz in the range of 2 to 4 cm across, and an extremely fine-grained groundmass of quartz, K-feldspar, and plagioclase. These features suggest that the porphyry was formed in an eruption. The fine-grained groundmass requires that magma with a moderately high percentage of melt has been quenched, the angular plagioclase and quartz fragments indicate comminution, and the miarolitic cavities indicate the presence of a separate fluid phase. Fluid inclusions are present in the apatite crystals of the Johnson but not in any other minerals. The most likely cause of quenching of the melt is release of pressure, which would diminish the solubility of water in the melt and raise the crystallization temperature.

Probably the eruption was caused by build-up of water in the magma, beyond the amount soluble in the melt phase, because of the crystallization of minerals that contain little or no water. Further crystallization after the melt was saturated with water would cause a separate aqueous phase to appear, which would quickly increase the volume of the system beyond the amount for

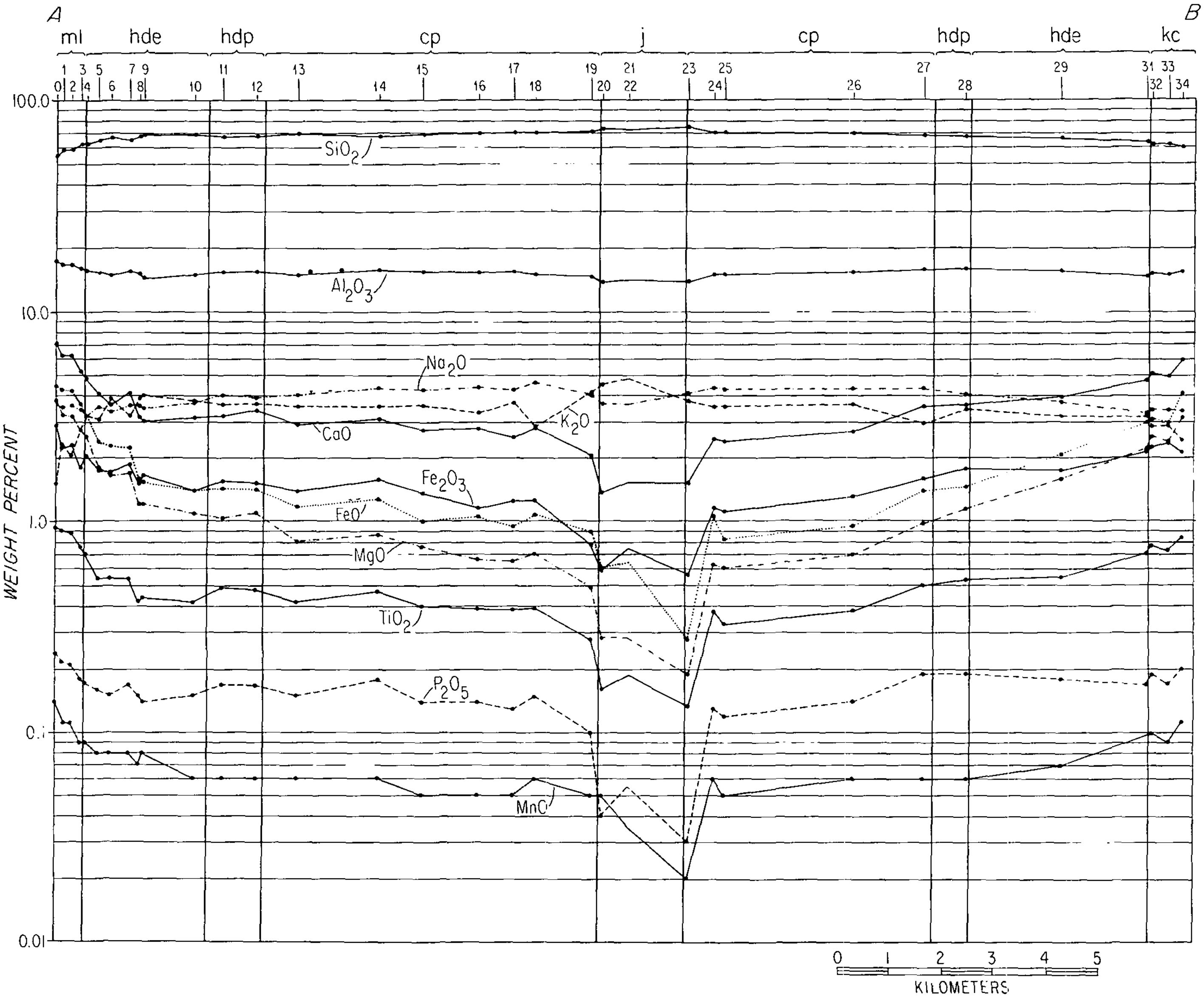

Figure 7. Profiles of oxides of major elements along traverse A-B. Vertical scale is logarithmic.

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which the wall and roof rocks could adjust without fracturing (Burnham, 1972).

Irregularity of modal and chemical data make it unlikely that the Johnson represents simply the end-stage melt resulting from crystal fractionation. The modes show that the Johnson generally contains much more K-feldspar and less plagioclase and mafic minerals than do any of the other rocks (Figs. 3 and 4; Table 1). Depletion of plagioclase and mafic minerals may have been accomplished by the expulsion of crystalline material during eruption and enrichment of K-feldspar by transport of potassium in an aqueous phase. The source of the potassium may have been the adjacent parts of the Cathedral Peak Granodiorite, which exhibits compositional variations that suggest it was affected by the eruption.

WHOLE-ROCK CHEMISTRY

Although major- and trace-element data for only 16 representative samples along traverse A-B are given in Table 2, all of the samples for which modal data are given in Table 1 have been analyzed chemically and were used in constructing Figures 7 and 8. The chemical data, like the modal data, show pronounced symmetry along traverse A-B. The compositions of the quartz diorite of May Lake and the granodiorite of Kuna Crest are similar, although the samples analyzed do not establish the exact identity of the two units, and the other formations are nearly symmetrical in their chemical patterns. Nevertheless, chemical gradients are better delineated on the west side, which has been more intensively sampled; the discussion that follows, like that of the modes, is directed toward that side.

Much of the total chemical variation occurs within 1 km of the outer contact of the sequence — in the quartz diorite north of May Lake and the outer Half Dome Granodiorite. The most conspicuous variations are progressive decreases inward of those elements that are removed by precipitation of the mafic minerals. No chemical discontinuities are apparent at any of the contacts between the mapped units except at the contact between the Cathedral Peak Granodiorite and the Johnson Granite Porphyry. Samples collected along traverse C-D (Fig. 1) show erratic variation in their chemistry, and regular zoning is evident only in that part of the equigranular facies of the Half Dome Granodiorite adjacent to the porphyritic facies.

Five principal patterns of behavior are evident among the major mineral-forming and associated trace elements:

1. With increasing distance from the western contact of the sequence, SiO_2 rises rapidly from 55 to 68% in the first 1,500 m, then more slowly to 70% in the innermost Cathedral Peak Granodiorite (see Fig. 7). It is highest (74 to 75%) within the innermost and most felsic part of the Cathedral Peak Granodiorite (sample 23) and in two samples from the Johnson Granite Porphyry.

2. Al_2O_3 is high (close to 17%) in the marginal rocks, in which the plagioclase is most Al-rich, but falls to 15% 600 m from the contact. This level is then maintained until the most felsic parts of the Cathedral Peak Granodiorite and the Johnson Granite Porphyry are reached, where values fall to 13.5%. Ga decreases with Al in the outer marginal rocks (from 20 to 16 ppm), but unlike Al, it rises through the Cathedral Peak and Half Dome to reach levels close to 20 ppm in the innermost part of the Cathedral Peak; then values fall significantly in the Johnson Granite Porphyry.

3. Na_2O rises progressively from the external contact of the sequence inward to the inner part of the Cathedral Peak, then it drops abruptly in the Johnson Granite Porphyry (Fig. 7).

4. K_2O rises rapidly with increasing K-feldspar in the first 800 m from the outer contact of the sequence, from ~1.5 to 3.9%. It remains fairly constant through most of the central part of the sequence but rises sharply near and within the Johnson Granite Porphyry (Fig. 7). Rb and Pb both follow K_2O.

The K:Rb ratio increases from a minimum value of 142 in the quartz diorite of May Lake to an average value of 236 in the analyzed samples from the Half Dome Granodiorite, falling slightly to 217 in the Cathedral Peak Granodiorite and to 213 in the Johnson Granite Porphyry. The early increase in this ratio is due to the crystallization and removal of biotite (low K:Rb) from the melt in the early stages of solidification. Subsequent extraction of these elements from the more felsic derivative melt was dominated by K-feldspar (high K:Rb), leading to lower ratios near and at the center of the sequence. Ba, which is relatively abundant in the Tuolumne Intrusive Series (500 to 1,000 ppm), and which was expected to follow K as a component of both biotite and K-feldspar, is unexpectedly erratic in its behavior, and no pattern is apparent.

5. TiO_2, total FeO, MgO, and CaO fall rapidly in the first 1,600 m inward from the outer contact to approximately one-third the initial level of MgO and to one-half the initial level of the other elements (Fig. 7). These continue to fall slowly toward the inner contact of the Cathedral Peak Granodiorite, and they all drop abruptly in the Johnson Granite Porphyry. This behavior is clearly related to the presence of large amounts of Ca-rich plagioclase and mafic minerals in the marginal rock, and to the decreasing proportions of these minerals toward the center of the sequence. As expected, the transition-metal trace elements follow these major oxides. Of this group, all are extracted in the mafic silicates, and V and Cr also are removed in magnetite. In order of decreasing chemical gradient (or rate of removal), these elements are: Ni, Cr, V, Sc, Co, Mn, and Zn (for V variation, see Fig. 8). The mechanism of Cu removal from the melt is uncertain; this element drops to one-fifth of its maximum value in the first 600 m from the external contact, and then it continues to decrease very slowly inward in the sequence but rises again in the Johnson.

Sr shows well defined but relatively complex variations (Fig. 8). It falls from 620 to 400 ppm in the first kilometre inward from the outer contact as the plagioclase content falls. When abundant K-feldspar appears at that point, Sr is incorporated in that mineral, and its abundance rises to 700 ppm near the boundary between the Half Dome and Cathedral Peak Granodiorites; it then falls to about 500 ppm in the inner part of the Cathedral Peak. Three of the samples of Johnson Granite Porphyry contain less Sr, one only 230 ppm.

Th increases sharply from 12 to 35 ppm in the first 800 m from the outer contact (Fig. 8). This higher level is maintained through the equigranular facies of the Half Dome Granodiorite; it then falls rapidly to a level of 16 to 20 ppm which is maintained inward to the center of the sequence. U follows Th closely; the Th:U ratios generally fall within the range 3.5 to 4.5. These radioactive elements probably are largely contained in sphene; their rapid increase in abundance within a short distance of the outer contact is coincident with the increase in the abundance of sphene.

Zr rises sharply for a short span in the inner parts of the tonalite of May Lake and in the outermost Half Dome, and then it falls to a remarkably constant level of 110 to 140 ppm across the remainder

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of the sequence, showing no tendency to increase in the more felsic rocks. P falls slightly from the outer margin of the sequence through the May Lake, and then it remains relatively constant before dropping abruptly in the most felsic Cathedral Peak Granodiorite and the Johnson Granite Porphyry.

The light rare earth elements (La, Ce, and Nd) and the heavy rare earth-like element Y probably are contained in sphene, hornblende, and apatite, in that order of relative importance. La is present in distinctly higher amounts (30 ppm) in the porphyritic facies of the Half Dome Granodiorite, in the Cathedral Peak Granodiorite, and in the Johnson Granite Porphyry than in the mafic marginal rocks (20 ppm). Ce is slightly higher in the center, but Nd decreases inward through the May Lake and outer part of the equigranular facies of the Half Dome, and it remains unchanged farther inward. Y falls rapidly from 18 to 10 ppm inward, 1,500 m from the outer contact and is relatively constant (6 to 8 ppm) across the interior of the sequence (Fig. 8). These limited data point to a preferential removal of the heavier rare earth elements in the early stages of crystallization.

MINERAL COMPOSITIONS

In addition to the plagioclase analyses, preliminary microprobe determinations have been made on hornblende, biotite, and

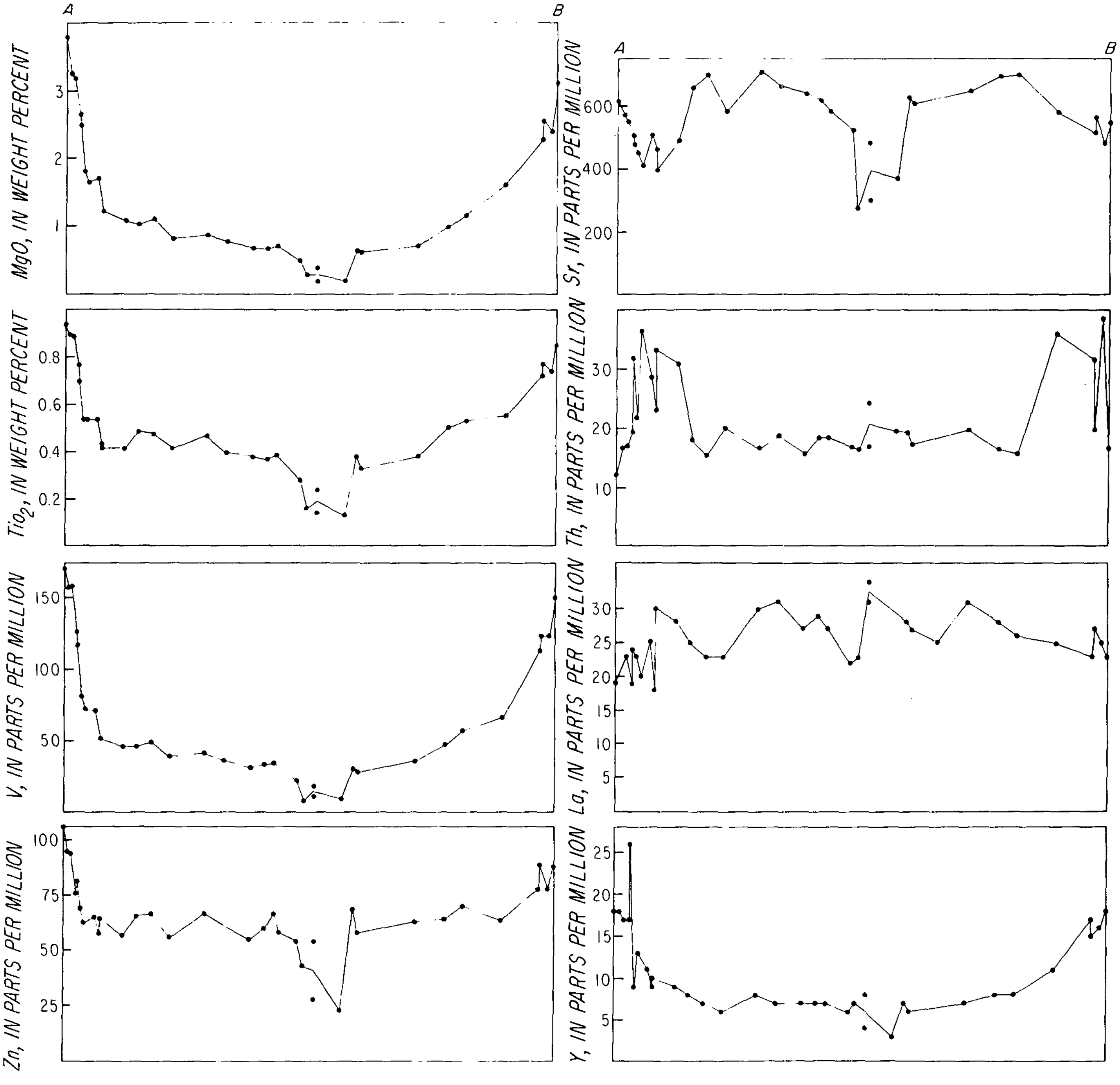

Figure 8. Profiles of representative oxides and minor elements along traverse A-B.

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magnetite. Hornblende compositions conform closely to those reported by Dodge and others (1968), and biotite compositions to ones reported by Dodge and others (1969). Both minerals also are in agreement with older determinations by Turner (1899) on hornblende and biotite from a single sample of Half Dome Granodiorite.

Hornblende and biotite show limited ranges of Mg:Fe ratios; for both minerals, this ratio is highest in the more felsic rocks. No data are available for the tonalite north of May Lake, but samples collected from the granodiorite of Kuna Crest and westward into the inner, more felsic part of the Cathedral Peak Granodiorite show an increase in Mg:Fe (atoms) from 1.2 to 2.0 for hornblende and from 1.1 to 1.5 for biotite. The most significant chemical changes were observed in Mn, F, and Cl. Mn undergoes a threefold increase in coexisting hornblende and biotite from the mafic to the felsic rocks, and it is still higher (MnO = 1.6%) in biotite from a hornblende-free sample (no. 23) from the Cathedral Peak Granodiorite. Cl decreases and F increases in amount going from mafic to felsic rocks. For hornblende, the ratio F:Cl (atomic) increases from 1 to 50, and for biotite, from 4 to 300.

The magnetites are nearly pure Fe_3O_4 ($FeO + Fe_2O_3$ are in excess of 99%). Mn in magnetite increases in amount from ~500 ppm in the more mafic rocks to 1,500 ppm in the more felsic rocks, but the data in hand do not show this variation to be systematic. Cr is low and decreases from 500 ppm in magnetite from mafic rocks to 100 ppm in magnetite from felsic rocks. V decreases systematically in the magnetites from 2,000 ppm in the granodiorite of Kuna Crest to 1,100 ppm in the inner parts of the Cathedral Peak Granodiorite.

SUMMARY OF MODEL AND INFERENCES

The model that was developed in this study begins with the intrusion of magma composed of melt and crystalline material. The sequence solidified from the margins inward, and relatively mafic high-temperature assemblages in the margins gave way inward to lower temperature felsic assemblages because of crystal fractionation with falling temperature and increasing H_2O in the melt phase of the magma. During solidification, the more fluid core magma moved episodically upward, eroding the adjacent solidifying rock and expanding the area of the magma chamber at the exposed level by crowding the wall and roof rocks outward and upward and by breaking through the solidifying carapace into the country rocks. When the first granitoids began to solidify, the magma was saturated with plagioclase, biotite, hornblende, magnetite, and sphene, but not quartz and K-feldspar. The absence of equant or subequant crystals of quartz and K-feldspar in the marginal rocks indicates that these minerals did not begin to crystallize until after the marginal granitoids were largely solidified. Plagioclase does not change significantly in abundance inward, but both the maximum and minimum content of anorthite decrease inward. The first appearance of subequant crystals indicates that quartz began to crystallize a little earlier than K-feldspar. Hornblende and biotite, abundant in the marginal rocks, decrease inward as quartz and K-feldspar increase. Elements contained in the mafic minerals decrease inward and show the greatest range in abundance. When solidification began, the amount of H_2O dissolved in the melt phase of the magma was probably small but sufficient for hornblende and biotite to occur as stable phases. Pyroxene cores in the hornblende crystals of marginal rocks indicate that at an earlier stage the temperature of the magma was higher and/or the H_2O content was lower. Crystallization of anhydrous and nearly anhydrous minerals during inward solidification doubtless caused the amount of H_2O in the melt to increase. When the melt became saturated with H_2O, a separate aqueous fluid phase formed, and further crystallization caused a volume increase that resulted in an eruption, loss of volatiles, and a pressure quench that produced the Johnson Granite Porphyry.

Regular progressive zoning in most of the plagioclase and generally euhedral form of much of the hornblende and biotite suggest that most of the crystals in the exposed rocks precipitated from the melt phase of the magma. Because the earliest members of most Sierran granitoid sequences contain abundant mafic inclusions and mottled cores in plagioclase, which are thought to represent crystalline material carried in the magma from its source, their sparsity in the marginal rocks of the Tuolumne Intrusive Series suggests that crystalline material in substantial amounts was separated from the magma before the exposed granitoids began to solidify. This speculation is supported by the relatively low range of anorthite content in the plagioclase of the marginal rocks as compared with other Sierran granitoid sequences, which also suggests that temperatures had fallen and that plagioclase, and presumably other minerals, had precipitated and were separated from the magma before the exposed rocks began to solidfy.

Except for the Johnson Granite Porphyry, none of the rocks exhibit textures that indicate eruption. Nevertheless, earlier eruptions could have occurred, and probably did. An eruption such as that indicated by the textures in the Johnson would be recorded in the rocks only if the amount of magma was small and completely quenched. If the volume were large, as during earlier stages of solidification of the sequence, only a small part would be involved in the eruption, and any rocks formed as a result of quenching because of loss of volatiles would soon be destroyed and reincorporated in the magma.

Lack of information as to the relative importance of preferential marginal accretion of crystals and of crystal settling during crystal fractionation results in some important uncertainties in interpretation. Our data do not indicate whether one mechanism was more important than the other, or whether one operated to the exclusion of the other. The variations we see are essentially horizontal, and we have no evidence of variations that can be related to elevation. At magmatic temperatures, crystals may be somewhat sticky and tend to adhere to the walls of the magma chamber. Nevertheless, it also seems likely that at least the early crystallizing heavy mafic minerals would have settled downward (Shaw, 1965, p. 124–128). Seismic data indicate increasing density with depth throughout the Sierra Nevada batholith (Bateman and Eaton, 1967), and Oliver (1977, p. 453) has interpreted gravity data to indicate increasing density downward in the Tuolumne Intrusive Series. Although these studies indicate that the density of the rocks increases downward, they do not indicate that plutons necessarily bottom at shallow depths. Emplacement of a comagmatic plutonic sequence, such as the Tuolumne Intrusive Series, probably involves massive vertical redistribution of material, early formed heavy mafic crystals and possibly some plagioclase settling downward, and the melt phase and volatiles moving upward. If both crystal settling and marginal accretion of crystals occurred, the modal changes in depth would not exactly duplicate the lateral changes because the settling rates would be different for each mineral. In a section across the Tuolumne Intrusive Series, isopleths on specific gravity (or on biotite or hornblende) very likely would have the form of parabolas that open upward because of the combined effects of crystal settling and marginal accretion.

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The mechanism of crystal fractionation is important because it determines the relation of the composition of the exposed granitoids to the composition of the magma from which they solidified. If crystal settling was the sole mechanism of crystal fractionation, the granitoids would have the same compositions as the magma from which they solidified. Thus, the composition of the most marginal granitoids would be representative of the composition of the magma when the sequence began to solidify at the exposed level, and successively inward granitoids would represent the changing composition of the magma as the sequence solidified. However, if selective marginal accretion of crystals occurred, with or without concurrent crystal settling, none of the granitoids is a good representative of the magma from which it solidified, although the inner part of the Cathedral Peak Granodiorite may approximate a late stage of the magma. If only selective marginal accretion occurred, without downward settling or upward movement of melt and volatiles, the average composition of the sequence would represent the bulk composition of the magma when the sequence began to solidify.

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