[AMERICAN JOURNAL OF SCIENCE, VOL. 272, MARCH, 1972, P. 217-233]

POTASSIUM-ARGON DATING OF FRANCISCAN METAMORPHIC ROCKS

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ABSTRACT. Fifty-two new K–Ar dates on Franciscan metamorphic rocks are reported for localities spread over a distance of 1750 km from Cedros Island, offshore of central Baja California, to northern California.

Under favorable conditions, K–Ar dates for minerals and whole rocks from the low-temperature, high-pressure Franciscan metamorphic belt may approximate closely the times of metamorphic crystallization. Many samples, however, apparently remained open to Ar loss following original crystallization. The resistance to Ar loss is observed to be:

$$\text{White mica} \cong \text{hornblende} \geqq \text{blue amphibole} \geqq \text{whole rock}$$

In addition, at least some pyroxenes are low in the sequence. Whole rock dates on low-grade metamorphic rocks have a large range (20-30 m.y.) within single structural units and reflect in a general way the time of closing for an entire region composed of various units. No evidence for excess radiogenic Ar was found.

The K–Ar dates span approximately the same time range as that defined by Franciscan fossils (150-70 m.y.), suggesting that for much of Franciscan time some rocks were undergoing metamorphism at depth while others were being deposited on the sea floor. Furthermore, this time span is identical to the period of extensive magmatism in the batholith belt, an observation that provides support to the concept of paired basement belts. The dates, in combination with other geologic data, require that all these rocks have been displaced by very large amounts relative to their surroundings since metamorphism, an important constraint for some theories of Franciscan metamorphism.

INTRODUCTION

The Late Jurassic and Cretaceous basement rocks of California, Baja California, and southwestern Oregon (fig. 1) quite naturally divide themselves into two parallel, contrasting belts (albeit somewhat disturbed by large Tertiary displacements along the San Andreas fault system (Hill and Dibblee, 1953; Suppe, 1970b)): (1) the *Franciscan belt* characterized by high-pressure, low-temperature, blueschist metamorphism, minor mafic volcanic rocks, and serpentinites, and (2) the *batholith belt* characterized by low-pressure, high-temperature, Abukuma-type metamorphism, and abundant intermediate plutonic rocks and their extrusive equivalents (Reed and Hollister, 1936; King, 1959; Smith, 1906, p. 185; Miyashiro, 1961). Paired basement belts such as these exist as well in other parts of the Pacific margin, and because of various petrologic and geophysical correspondences with modern volcanic arcs and their environs, they are almost certainly the eroded remains of ancient ocean floors, trenches, and andesitic volcanic chains and are the sites of ancient subduction (Benioff) zones (Matsuda, 1964; Takeuchi and Uyeda, 1965; Miyashiro, 1967; Dickinson, 1970). For this reason, the study of Franciscan tectonics should eventually yield considerable insight into the internal workings and history of one such subduction zone; toward this end we present a number of K–Ar isotopic dates from a diversity of Franciscan metamorphic rocks.

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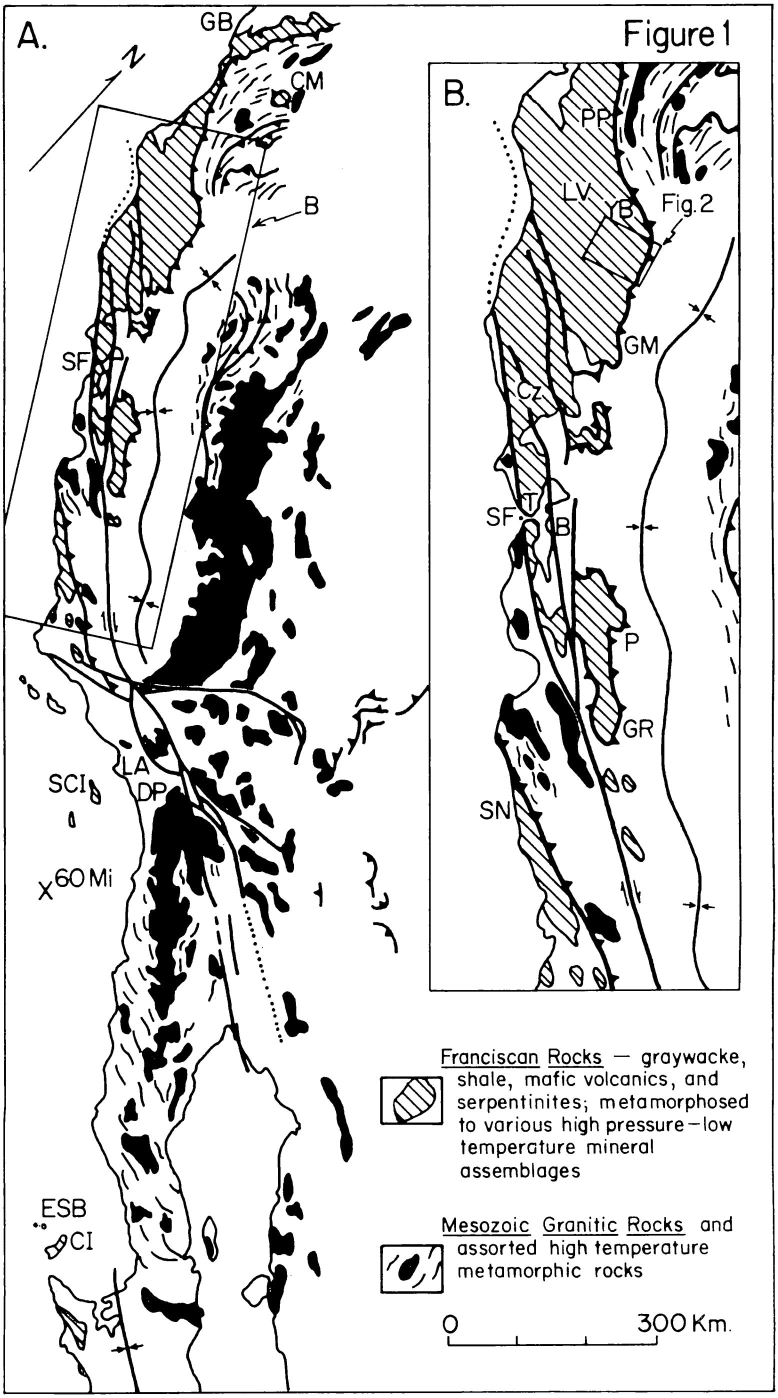
Figure 1
A.
GB
CM
N
B
SF
P
LA
DP
SCI
60 Mi
ESB
CI
B.
PP
LV
YB
Fig. 2
GM
Cz
T
SF
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P
GR
SN
Franciscan Rocks — graywacke, shale, mafic volcanics, and serpentinites; metamorphosed to various high pressure—low temperature mineral assemblages
Mesozoic Granitic Rocks and assorted high temperature metamorphic rocks
0
300 Km.

K–Ar and Rb–Sr mineral dates from high-temperature metamorphic terrains indicate the approximate time of post-metamorphic cooling below a temperature of 200° to 300°C (Armstrong, 1966; Jäger, Niggli, and Wenk, 1967) and thus yield information concerning the uplift and denudation or cooling history of a region (Hadley, 1964; Clark and Jäger, 1969). Such dates place a younger limit on the time of metamorphic recrystallization. In contrast with this, the Franciscan terrain presents special problems and possibilities for isotopic dating by virtue of its low temperatures of metamorphism (generally below 300° or 350°C (Taylor and Coleman, 1968; Ernst, 1965)). Franciscan metamorphism took place at temperatures close or identical to those at which diffusion of Ar in and out of crystal lattices effectively ceases. Hunziker (1969, 1970) demonstrated that phengitic muscovites from Alpine rocks of the low-temperature, high-pressure facies series in western Switzerland became closed systems virtually at the same time as the culmination of the last phase of metamorphism. A similar possibility of closely dating Franciscan metamorphism exists, but the interpretation of the dates is not without hazard.

Franciscan rocks span the range from diagenetically altered sediments to coarse-grained schists. It is relatively easy to prepare pure mineral separates for dating the coarse schists, but whole-rock dating must be resorted to with the fine-grained, although recrystallized, samples. For whole-rock dating it is important to exclude all samples containing relict detrital minerals with significant quantities of K or Ar. This condition is satisfied by all the samples studied. All the K, and presumably Ar, is apparently in a single metamorphic white mica phase or in blue amphibole. Quartz, metamorphic albite (K-free), lawsonite, chlorite, and jadeite act only as dilutants. In addition, it will be seen that there are no data suggesting important excess Ar for any of the dated metamorphic rocks. Thus all the dates seem to place minima on the times of metamorphism. Since the Franciscan is a polymetamorphic terrain (Suppe, 1969a) and not all materials have the same argon retention properties, some dates may be very close to the time of metamorphic crystallization while others are clearly much younger.

The dates reported in this paper (table 1) were obtained by the authors in the Yale K–Ar laboratory. Some dates on Franciscan metamorphic rocks were reported previously (particularly, Lee and others, 1964; Suppe, 1969a) and will be reviewed in the course of this discussion.

Fig. 1. Locations of dated Franciscan metamorphic rocks and place names referred to in the text. The generalized geologic base map showing the distribution of Mesozoic basement rocks is modified from the Tectonic Map of North America (King, 1969). Abbreviations from north to south: GB = Gold Beach, Oreg.; CM = Condrey Mountain, Calif.; PP = Pickett Peak; LV = Laytonville; YB = Yolla Bolly Mountains; GM = Goat Mountain; Cz = Cazadero; T = Tiburon Peninsula; SF = San Francisco; B = Berkeley Hills; P = Pacheco Pass; GR = Glaucophane Ridge; SN = Sur-Nacimiento area; LA = Los Angeles; DP = Dana Point; SCI = Santa Catalina Island; 60 Mi. = Sixty-Mile Bank; ESB = East San Benito Island; CI = Cedros Island. Location of figure 2 is shown (Leech Lake Mountain-Ball Mountain region).

TABLE 1*

General Locality	Sample Number	Dated†† Material	Weight Percent K	Radiogenic ^{40}Ar 10^{-6}cc STP (percent air corr.)	Date, Error m.y.(σ)
Condrey Mtn.	CMSV(6)	R	2.05, 2.03	13.15(18)	155 ± 3
Pickett Peak	PP2**	R	0.672, 0.669	3.77(40)	136 ± 3
Laytonville Quarry	969cM	M	7.75, 7.71	46.35(15)	145 ± 3
Leech Lake Mtn. Region	198**	M	6.00, 5.97	37.05(12)	151 ± 3
	199	G	1.405	6.79(40), 6.65(48)	116 ± 3
	199**	M	8.42, 8.47	51.7(8), 52.4(11), 52.6 (15)	150 ± 3
	197	R	1.05	4.51(50)	105 ± 2
	914	R	1.490	5.69(24)	93 ± 2
	401**	R	1.46, 1.48	6.26(42)	104 ± 2
	420**	R	1.48, 1.49, 1.51	6.65(38)	108 ± 2
	653**	R	1.35, 1.37	6.11(48)	109 ± 2
	1160	R	1.43, 1.43	6.68(28)	113.5 ± 2
Ball Mtn. Region	1816	R	0.981, 0.991	4.25(40)	105 ± 2
	1858	R	1.14, 1.14	5.22(34)	111.5 ± 2
	1844	R	1.21, 1.21	5.75(28)	115 ± 2
	1886	R	0.52, 0.50	2.86(55)	136 ± 3
	1875	R	1.04, 1.03	5.36(27), 5.26(33)	124 ± 2
	1915	R	0.91, 0.91	4.54(53)	121 ± 2
	1895	R	1.31, 1.31	6.14(20)	114 ± 2
	1925	R	0.93, 0.93	4.60(47), 4.52(45)	119 ± 2
	1944	R	1.85, 1.86	11.03(21)	143 ± 3
	2035	R	1.03, 1.02	4.50(46), 4.27(71)	104 ± 2
	2057	R	0.82, 0.84	4.18(27)	122 ± 2
Black Butte Region	Fr6**	R	1.27, 1.25	6.50(50)	125 ± 3
	9**	R	1.21, 1.21	6.24(52)	127 ± 3
	Fr101**	R	1.08, 1.08	5.39(39)	123 ± 3
Goat Mtn.	G19M	M	6.76, 7.00	42.28(6)	148 ± 3
Tiburon Peninsula	GRS-1M	M	8.34, 8.47, 8.39***	51.45 (9)	147 ± 3
Berkeley Hills	563M	M	7.88, 7.45, 7.85	45.75(9)	143 ± 3
	563G	G	0.229, 0.227	1.379(75), 1.334(72)	143 ± 3
Pacheco Pass	AR-1	R	1.18, 1.22, 1.20	3.99(44)	83 ± 2
	X-111G	G	0.169, 0.170	0.853(64)	122 ± 3
	X111M	M	5.40, 5.80, 5.61	27.12(60), 26.13(36)	115 ± 3
	DR 185	R	1.35, 1.30	5.70(29), 6.30(31)	110 ± 2
	DR 202B	R	1.30, 1.28	5.54(48), 6.23(31)	111 ± 2
	DR 203A	R	2.10, 2.08	6.23(28), 6.88(37), 6.40(32)	76 ± 2

	DR 7	R	1.67, 1.63	6.47(38), 6.16(28)	93 ± 2
	DR 8	R	1.84, 1.85	6.33(32), 7.20(20)	90 ± 2
	DR 79	R	1.48, 1.47	5.16(68), 5.34(44), 5.70(28)	90 ± 3
	DR 249	R	1.90, 1.92	6.91(50), 6.89(29)	88 ± 2
	DR 55	R	1.81, 1.79	7.78(39), 7.87(81)	106 ± 2
	DR 291	R	0.933, 0.914	4.28(23), 4.52(33)	116 ± 2
Glaucophane Ridge	GR-1M	M	7.99, 7.98	47.34(23), 46.90(13)	142 ± 3
	175a-Ms	M	8.04, 8.06, 8.14†	47.12(19)	141 ± 3
Sur-Nacimiento	W-69-22	R	1.24, 1.24	3.73(60)	73.8 ± 2
	W-69-59	R	1.23, 1.25	4.44(31)	87.7 ± 2
	W-69-226	R	1.46, 1.44	4.15(28)	70.4 ± 1.4
Santa Catalina Island	5a	H	0.265, 0.263	1.176(65), 1.182 (73)	109 ± 3
	509	R	0.750, 0.750	3.24(38)	105 ± 2
	69-147M	M	5.81, 5.80	25.46(15), 25.47(17)	107 ± 2
	69-147G	G	0.265, 0.264, 0.260	0.979(64), 1.069(39), 1.027(57)	95.1 ± 2.5
Dana Point (San Onofre Breccia)	4-10R	R	0.132, 0.129	0.548(88)	102 ± 9
	4-12R	R	0.350, 0.350, 0.339	1.280(51), 1.297(44)	91.0 ± 1.8
Sixty-Mile Bank	SC-69-6	R	1.94, 1.93	8.58(12)	108 ± 2
East San Benito Island	ESB59	H	0.278, 0.287	1.695(55), 1.767(91), 1.746(72)	148 ± 5
	ESB72M	M	6.95, 6.90, 6.80	42.17(13)	148 ± 3
	ESB72G	G	0.727, 0.717	0.704(88), 0.672(79)	104 ± 2
Cedros Island	PN1G	G	0.178, 0.178	0.704(88), 0.672(79)	94.4 ± 4
	PN2H	H	0.268, 0.266, 0.272	1.584(89), 1.655(74)	145 ± 6
	CG1M1	M	5.21, 5.15, 5.08	23.28(22)	110 ± 2
	CG1M2	M	6.81, 6.78	30.51(15), 30.24(18)	109 ± 2

* Potassium determinations on purified mineral separates and whole-rock samples were done using a Perkin-Elmer atomic absorption spectrophotometer. Argon analyses were done by isotope dilution using conventional gas preparation and mass spectrometric techniques (Armstrong, 1970). The precision of both potassium and argon analyses is 1 percent (σ), and the potassium and argon values obtained for standard micas indicate that the calibrations are accurate within 2 percent. All data are calculated using the constants $K\lambda_\beta = 4.72 \times 10^{-10}y^{-1}$, $K\lambda_\epsilon = 0.584 \times 10^{-10}y^{-1}$, $^{40}K/K = 0.0119$ atomic percent.

** Reported in Suppe, 1969a

*** Analysis by Ernst and others (1970), table 12

† Analysis by Ernst and others (1970), table 14

†† R = whole rock, M = white mica, G = blue amphibole, H = hornblende

Comments on the geologic interpretation of specific samples are included with the sample descriptions in the appendix.

LEECH LAKE MOUNTAIN-BALL MOUNTAIN REGION

This region within the northeastern Franciscan belt (see figs. 1 and 2) is *relatively* well studied in contrast with the Franciscan in general (Ghent, 1963, 1964, 1965; Suppe, 1969a, b, 1970a, ms); therefore isotopic dates from this region provide some basis for interpreting dates from Franciscan metamorphic rocks in general.

The Leech Lake Mountain-Ball Mountain region is composed of five structural units or sheets separated from each other by thrust faults (fig. 2). The uppermost sheet is the latest Jurassic and Cretaceous Great Valley sequence, 12 km thick, which lies on Jurassic oceanic crust ("ultramafic and related rocks" of fig. 2; see also Bailey, Blake, and Jones, 1970) and onlaps diverse Mesozoic continental crust to the east and north. Relative to the underlying coeval Franciscan, this sequence is little deformed and has experienced only a low-grade zeolitic metamorphism near its base (Dickinson, Ojakangas, and Stewart, 1969). All the structural units below the Great Valley sequence and its oceanic basement are referred to the Franciscan and have low-temperature, high-pressure blueschist mineral assemblages (aragonite–lawsonite–albite–quartz ± pumpellyite ± jadeite ± blue amphibole). The Taliaferro Metamorphic Complex[1] and the South Fork Mountain Schist are obviously metamorphic in the field while the sparsely fossiliferous unnamed Franciscan metasediments above and below the Taliaferro sheet appear to be only very well indurated sediments, lacking obvious metamorphic fabrics except locally where phyllitic. Nevertheless, in thin section they exhibit extensive or complete mineralogic reconstitution.

The phyllitic bedding-plane foliation in the unnamed Franciscan metasediments is developed near the thrust faults (Suppe, 1969b, p. 69-72; 1971); fabric and mineralogy indicate that the juxtaposition of these various Franciscan structural units took place at depth (5 to 7 kb, ~ 250°C) and that the faulting is synmetamorphic. In the case of the lower contact of the South Fork Mountain Schist, this increased foliation has been the source of some controversy concerning the nature of the contact; some workers have argued that the contact is grada-

[1]The name, *Taliaferro Metamorphic Complex,* is hereby designated for the metamorphosed thin-bedded cherts and mudstones as well as minor graywacke and basalt that are exposed along Bear Creek in the Buck Rock, California, 7½′ quadrangle between the elevations 1256 and 1548 m. Much of the Taliaferro Complex is metamorphosed to jadeite + quartz ± albite + aragonite metagraywacke and lawsonite-blue amphibole-aragonite metabasalt. The Complex exists as a folded and faulted sheet (fig. 2) bounded above and below along thrust faults by unnamed Tithonian through Valanginian Franciscan metasediments, which are younger than the minimum antiquity of the Taliaferro Complex (151 ± 3 m.y., see discussion of the dates). The Complex is named for Taliaferro Ridge which runs from near Leech Lake Mountain northeast for 7 km to the Middle Fork of the Eel River (Leech Lake Mountain, California, 7½′ quadrangle); the lower half of this ridge is supported by rocks of the Taliaferro Complex. The ridge itself is named for Professor N. L. Taliaferro (1890-1961), long a student of Franciscan geology (Taliaferro, 1943, is a summary of his work and ideas).

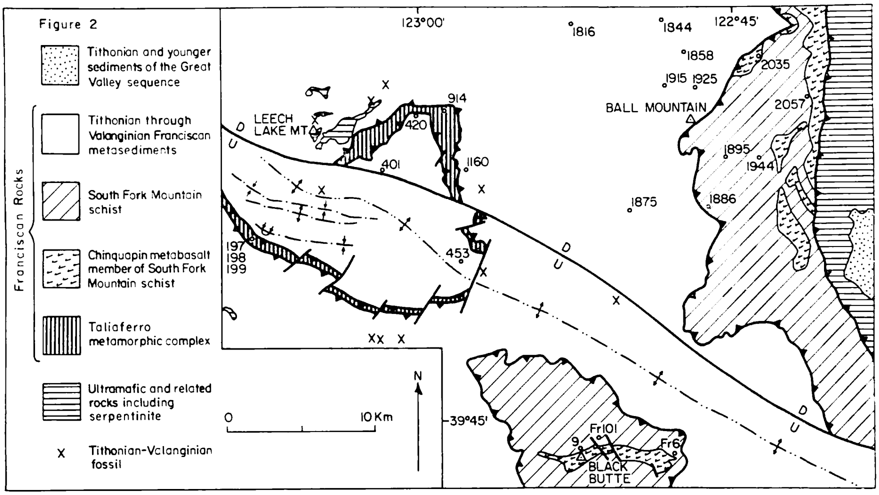

Fig. 2. Generalized geologic map of the Leech Lake Mountain-Ball Mountain region, northern California, showing the areal distribution of the five major structural units or sheets and the locations of the dated samples and fossil localities (adapted from Suppe, 1969b, 1971; and Ghent, 1964). See figure 1 for the location of this region in northern California.

tional (notably Blake, Irwin, and Coleman, 1967; 1969, p. 241), and indeed with respect to the strength of the foliation it is in many areas. At least in the Ball Mountain Region, however, there exists a sharp break in pre-metamorphic lithology: dominately metagraywacke below and dominately metamorphosed mudstones and extensive metabasalt in the South Fork Mountain Schist above (Suppe, ms). It is this sharp break that is shown as a thrust fault in figure 2. At the contacts of the Taliaferro Complex there is a marked change in mineral assemblage, the Taliaferro Complex being notably higher grade (~ 9 kb, 300°C) than the adjacent sheets of metasediment above and below (5-7 kb, ~ 250°C); further, a thin strip of serpentinite lies along the upper contact in some places (Suppe, 1969a, 1970a). The Taliaferro Complex has undergone some retrograde metamorphism to the assemblages of the surrounding metasediments (jadeite + quartz → albite), possibly at the general time of their juxtaposition.

With this essential geologic framework in mind, we may now consider the isotopic dates from these various Franciscan metamorphic rocks (see fig. 3 and table 1). The oldest dates from the region are 150 and 151 m.y. for two coarse-grained white micas from Taliaferro metabasalt; these dates are older than the fossils in the adjacent sheets of lower grade metasediments (Suppe, 1969a, b). Coexisting Taliaferro jadeitic metagraywacke and blue amphibole samples gave dates of 93, 105, and 116 m.y. which are younger than the fossils and roughly the same as the dates from the immediately adjacent lower grade metasediments (104, 108, 109, and 113 m.y.). At a higher structural level, not far below the South Fork Mountain Schist near Ball Mountain, the unnamed Franciscan metasediments yield a somewhat older range of whole-rock dates (105, 111, 115, 119, 121, and 124 m.y.), all still younger than the fossils found farther to the west in the same structural unit (fig. 2). The South Fork Mountain Schist yields a similarly broad range of dates (104, 114, 122, 123, 125, 127, 136, and 143 m.y.), and the age range overlaps that of the fossils below it. A similar overlap of dates and fossil age in underlying rocks is observed for other parts of the South Fork Mountain Schist (figs. 1 and 3): Pickett Peak (Suppe, 1969a, Blake, 1965, p. 45; Jones and Irwin, 1971, p. 821) and Gold Beach Oregon (Dott, 1965; Koch, 1966; Coleman *in* Medaris and Dott, 1970, fig. 1).

The most remarkable aspect of these results is that the coarse Taliaferro white micas have remained closed systems from 150 m.y. ago through the entire subsequent history of the region, including the time of juxtaposition of the Taliaferro Complex with the younger metasediments and the possibly contemporaneous partial retrograde recrystallization. In addition, it has been argued elsewhere on predomi-

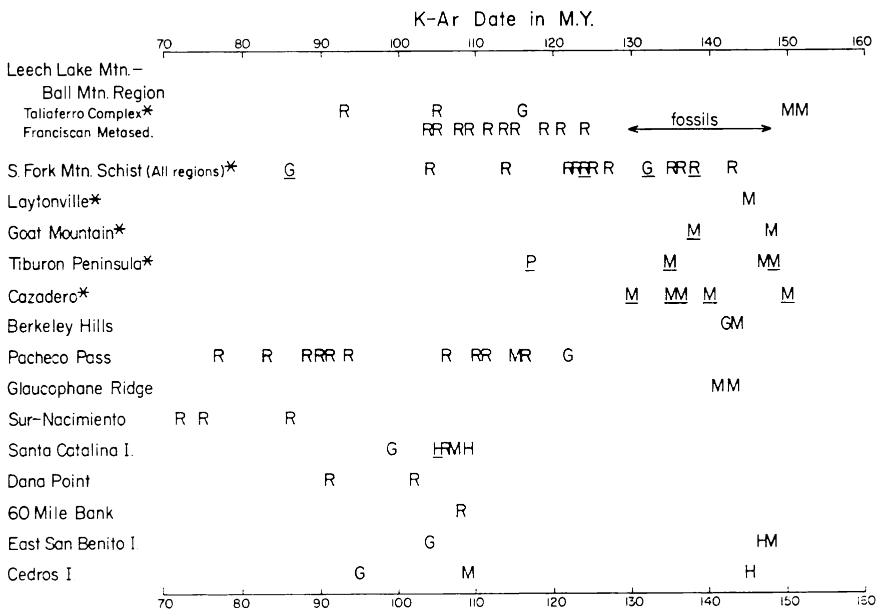

Fig. 3. Timeline showing K–Ar dates from Franciscan metamorphic rocks for the localities given in figure 1. R = whole rock, M = white mica, G = blue amphibole, H = hornblende, P = pyroxene. South Fork Mountain Schist dates include the following localities: Ball Mountain, Yolla Bolly Mountain, Pickett Peak, and Gold Beach area. Dates by other workers are underlined (Lee and others, 1964; Dott, 1964; Ernst and others, 1970, p. 220; Forman, 1970, p. 42; Blake, 1965, p. 45). Other isotopic dates on Franciscan rocks which are not shown are reported by Keith and Coleman (1968), Evernden and others (1964, p. 155), and Peterman and others (1967). Asterisks indicate that the dated rocks are in close proximity to fossiliferous, less metamorphosed Franciscan rocks; in all cases there are fossils younger than the minimum antiquity of metamorphism as suggested by the isotopic dates.

nately structural grounds that the Taliaferro Complex quite possibly was stored in its place of metamorphism from at least 150 m.y. until the time of this juxtaposition (Suppe, 1970a). It thus seems possible that these and perhaps other Franciscan, coarse white micas were closed from the time of their initial crystallization. On the other hand, the Taliaferro blue amphibole and whole rock metagraywacke samples have not remained closed; they apparently closed at the same time as the adjacent younger metasediments. Groups of such whole-rock dates have a large range (20-30 m.y.) within a single structural unit and reflect more the general range for the region than the specific structural unit from which they came, as shown by the dates from the Leech Lake Mountain, Ball Mountain, and Pacheco Pass regions. Still, the K-Ar evidence of the greater antiquity of the South Fork Mountain Schist has not been entirely obliterated in some whole-rock samples.

All these results suggest the range of geologic meanings K–Ar isotopic dates may have for various Franciscan metamorphic rocks.

K-AR DATING PROPERTIES OF FRANCISCAN MINERALS AND ROCKS

The general results obtained for the Taliaferro Complex were also found for East San Benito and Santa Catalina Islands; the white micas (and hornblendes) gave dates older than coexisting blue amphiboles. For the Berkeley Hills the results were concordant, and for the one case in which the blue amphibole gave an older date (Pacheco Pass, X-111) there is textural evidence that it grew first. Thus there is reason to suspect that in some situations hornblende and blue amphibole as well as white mica may be closed from the time of metamorphic crystallization, but in many cases the blue amphibole is not. A general sequence of resistance to Ar loss may be given for the minerals of Franciscan metamorphic rocks:

$$\text{White mica} \cong \text{hornblende} \geqslant \text{blue amphibole} \geqslant \text{whole rock}$$

In addition, at least some pyroxenes are low in the sequence (Keith and Coleman, 1968; Forman, 1970).

Excess radiogenic Ar in minerals has been observed where crystalline rocks have undergone a second period of metamorphism after considerable quantities of radiogenic argon had been generated *in situ* (Brewer, 1969; Lambert, 1970; Wanless, Stevens, and Loveridge, 1970). Remetamorphism thus occurred under conditions favoring relatively high partial pressures of radiogenic Ar resulting in its inclusion in silicate lattices. Such a situation is probably not a problem during Franciscan metamorphism. The sediment undergoing reconstitution was derived predominantly from young, almost coeval, volcanic and plutonic rocks of the batholith belt and thus was not particularly enriched in radiogenic Ar. The partial pressure of Ar during metamorphism was probably vanishingly small.

The observed dates provide no evidence that excess Ar is present; mineral dates from the Taliaferro Complex, Glaucophane Ridge, Pacheco Pass, Santa Catalina Island, East San Benito Island, and the

Berkeley Hills are roughly concordant for at least some samples of different K content or mineralogy. Further, the existence of a well defined upper limit of about 150 m.y. for dates throughout the Franciscan places a limitation on possible amounts of excess Ar in all samples. The observation that whole-rock samples give younger dates than coexisting K-rich minerals (Taliaferro Complex, Pacheco Pass, and the southern Franciscan region) and that whole rock dates of fossiliferous metasediments in the Leech Lake Mountain region are all younger than the fossils is evidence that excess Ar is not present in whole-rock samples. Thus at present there are no data suggesting important excess Ar for any of the dated Franciscan metamorphic rocks.

GENERAL IMPLICATIONS OF K-AR DATES FOR FRANCISCAN TECTONICS

The isotopic dates from Franciscan metamorphic rocks, in combination with other data, place important constraints on the possible ways in which these rocks were metamorphosed and emplaced in their present structural positions.

1. The dates, from samples taken over a distance of 2000 km, suggest that Franciscan rocks were under low-grade metamorphic conditions at a variety of times between about 150 and 70 m.y. ago. This is approximately the age range defined by Franciscan fossils: Late Jurassic (Tithonian) to Late Cretaceous (Turonian or possibly Campanian) (Bailey, Irwin, and Jones, 1964, p. 115-122). The oldest metamorphic rocks are probably slightly older than the oldest fossils yet found in the Franciscan; however, there is moderate uncertainty in that part of the timescale (Suppe, 1969a). We may conclude that through much of Franciscan time some rocks were being deposited on the sea floor while other rocks were buried and undergoing metamorphism at depths of as much as 20 to 30 km (5 to 10 kb); the end product of this tectonism is the juxtaposition of these rocks of diverse histories at the Earth's erosion surface today. The general implications for megatectonics are obvious and have been recognized and developed by Hamilton (1969, p. 2415-6) and Ernst (1970), among others.

2. In a number of regions the dated schistose rocks are in close proximity to fossiliferous, less metamorphosed Franciscan rocks: Leech Lake Mountain (Suppe, 1969a, b), Gold Beach (Dott, 1965; Koch, 1966; Coleman *in* Medaris and Dott, 1970, fig. 1), South Fork Mountain-Pickett Peak (Suppe, 1969a; Blake, 1965, p. 45; Jones and Irwin, 1971; Rowland, ms, p. 81-82), Ball Mountain (Suppe, ms), Black Butte (Ghent, 1963; Suppe, 1969a), Laytonville (Thalmann, 1943), Goat Mountain (Brown, 1964; Ernst and others, 1970, p. 19-20), Cazadero (Lee and others, 1964; Bailey, Irwin, and Jones, 1964, p. 115-122), and Tiburon Peninsula (Dudley, 1967, p. 21-22). In all cases fossils exist that are *younger* than the minimum antiquity of metamorphism of adjacent higher grade rocks. Where field relationships are known, these rocks are juxtaposed along faults, or tectonic blocks of higher grade rocks are enclosed in a matrix of deformed lower grade rocks, with the possible

controversial exception of the South Fork Mountain Schist (as discussed in an earlier section); unconformable relationships are so far unknown within the Franciscan.

Furthermore, at Ball Mountain (fig. 2), Pacheco Pass (Ernst and others, 1970; Cowan, 1971), Glaucophane Ridge, and possibly Goat Mountain (see Ernst and others, 1970, p. 19-20) high-pressure Franciscan metamorphic rocks directly underlie the so-called "Coast Range thrust" which places the broadly coeval Great Valley sequence over the Franciscan. The K–Ar dates indicate that the high-pressure metamorphism took place before much of the Great Valley sequence was deposited; thus, the hanging wall could have provided *no more* than 1 kb of the 5 to 10 kb required for metamorphism of the foot-wall rocks, and a 4 to 9 kb pressure discontinuity exists across this fault. In the cases of Ball Mountain, Pacheco Pass (Cowan, 1971; Ernst, 1971a), Goat Mountain, and probably Glaucophane Ridge (Alfors, 1959; Ernst, 1971), the dated, metamorphosed rocks are structurally underlain by lower grade Franciscan metasediments, which in the cases of Ball Mountain and Goat Mountain are known to be younger than the higher grade rocks.

Blake and others (1967, 1969) have suggested that the higher grade rocks were formed as a result of "a zone of anomalously high water pressure" just below the sole of the "Coast Range thrust". This carries the assumption (Suppe, 1970a) that these rocks have not been displaced significantly since metamorphism or that they were never any deeper structurally; the above results would require excess fluid pressures of 4 to 9 kb at a depth of a few kilometers, which is impossible (see also Ernst, 1971b). A plausible general structural solution to the problem has been proposed by one of us elsewhere (Suppe, 1970a): it is suggested that the higher grade rocks were emplaced as great slabs and tectonic blocks *up* existing thrust faults from their place of metamorphism. This is a new general class of structures not unique to the Franciscan. Thus, the Taliaferro Complex and the South Fork Mountain Schist in the Leech Lake Mountain-Ball Mountain region (fig. 2) and the sheet of jadeite + quartz metagraywacke in the Pacheco Pass area (Cowan, 1971) would have been emplaced ("intruded") as sheets up into their present structural positions where they are bounded by lower grade rocks along low-angle "thrust" faults above and below. Kinematically analogous would be the emplacement of smaller tectonic blocks upward along imbricate fault systems to form some types of mélange (see Hsü, 1968, for a description of tectonic mélange in the Franciscan). A mechanical explanation for this process remains to be discovered, but the structural relations observed in the field and the age relationships appear to be indisputable.

3. The minimum age of many, but not all, coarse-grained blueschist samples through the entire length of the Franciscan terrain is Late Jurassic, suggesting the possibility that an episode of extensive blue-

schist metamorphism affected coastal North America from Oregon to Mexico near the end of the Jurassic. This would correspond in time to the "Nevadan" orogenesis recognized in the Klamath and Sierra regions of the batholith belt (Irwin, 1966; Bateman and Wahrhaftig, 1966). The first and most widespread culmination of Mesozoic granitic pluton emplacement occurs at almost the exact same time (150 m.y.) in the western United States south of 42°N latitude (Armstrong and Suppe, 1972) and is certainly closely related to this episode of blueschist metamorphism. Only a few fragments of apparently earlier Mesozoic blueschist rocks are known in the western United States (for example, Davis, 1968; Misch, 1966). The widespread 90 to 110 m.y. dates in the southern Franciscan region correspond closely in time to a major episode of magmatism in the adjacent, parallel Peninsular Range batholith (Armstrong and Suppe, 1972). The youngest dates on Franciscan metamorphic rocks (~ 70 m.y.) correspond to the youngest dates in the batholith belt (Armstrong and Suppe, 1972; Evernden and Kistler, 1970). The coeval time span of extensive magmatism in the batholith belt and metamorphism in the Franciscan provides striking support for the concept of paired basement belts as outlined in the introduction.

ACKNOWLEDGMENTS

We thank the following persons who contributed to this project by supplying samples for dating: W. G. Ernst, University of California at Los Angeles; Frank Kilmer, Humboldt State College; Darrel Cowan and Wyatt Gilbert, Stanford University; E. L. Winterer, University of California at San Diego; John Forman, Mobil Oil Company; and A. O. Woodford and D. McIntyre, Pomona College. Field work on Santa Catalina Island was facilitated through the efforts and hospitality of O. Bandy, University of Southern California; R. B. Tibby and R. L. Zimmer, Santa Catalina Marine Biological Laboratory; and M. J. Renton, Santa Catalina Island Company. The Rev. Paul Taylor aided in all stages of sample preparation and analytical work.

We thank R. Cliff, D. Cowan, K. Crawford, W. G. Ernst, and M. Lanphere for their editorial criticism and comments.

Initial field work was supported through grants from the Geological Society of America (Penrose Bequest) and the D. F. Hewett Fund. Most of the field work and the dating laboratory were supported by the National Science Foundation through the following grants: GA-1670 (Yale), GA-1694 (Yale), and GA-11488 (UCLA). The mass spectrometer was a gift of the Research Corporation and the Sheffield Scientific School of Yale University. This work was completed while Suppe was a National Science Foundation Postdoctoral Fellow; the hospitality of the University of California at Los Angeles as extended by the members of the Geology Department during the tenure of this fellowship is gratefully acknowledged.

APPENDIX

Sample localities, descriptions, and comments

Condrey Mountain. Sample CMSV (6) (122°57′44″W, 41°50′58″N) is a quartz–muscovite–chlorite–albite schist. The schists of Condrey Mountain with their associated glaucophane–epidote metabasalts are reminiscent of the South Fork Mountain Schist, although somewhat coarser grained. Inasmuch as they occupy a window below more typical Klamath Mountains basement (Hotz, 1967), they are in a structural position somewhat analogous to the South Fork Mountain Schist. If these two units are correlated, then Franciscan rocks may underlie much of the Klamath Mountains. Still, the date of 155 m.y. is slightly older than any available Franciscan dates; another date reported from Condrey Mountain is 141 m.y. on muscovite (Lanphere, Irwin, and Hotz, 1968, p. 1037).

Laytonville Quarry (123°37′6″W, 39°27′42″N) is noted as the type locality for the minerals deerite, howieite, and zussmanite. See Chesterman (1966) for a description of the locality. Sample 969c is a glaucophane–actinolite–white mica–garnet metabasalt.

Leech Lake Mountain-Ball Mountain (fig. 2). Samples 198 (123°7′43″W, 39°51′46″N) and 199 (123°7′47″W, 39°51′43″N) are white mica–lawsonite–blue amphibole metabasalts from the Taliaferro Complex. Samples 197 (123°7′44″W, 39°51′44″N) and 914 (122°58′54″W, 39°56′17″N) are jadeite + quartz-bearing metagraywacke from the Taliaferro Complex. Samples 401 (123°1′6″W, 39°54′0″N), 420 (123° 0′3″W,39°56′12″N), 653 (122°57′6″W, 39°5′47″N), 1160 (122°57′40″W, 39°54′10″N), 1816 (122°52′47″W, 39°59′29″N), 1844 (122°48′24″W, 39°59′37″N), 1858 (122°47′ 24″W, 39°58′24″N), 1875 (122°49′55″W, 39°52′31″N), 1886 (122°46′22″W, 39°52′ 52″N), 1895 (122°45′26″W, 39°54′37″N), 1915 (122°48′16″W, 39°57′7″N), 1925 (122°46′56″W, 39°57′7″N), 1944 (122°43′46″W, 39°54′34″N), 2035 (122°43′5″W, 39°58′17″N), and 2057 (122°41′31″W, 39°56′53″N) are quartz–albite–white mica–chlorite ± lawsonite ± pumpellyite ± aragonite metagraywacke. See also Suppe, 1969a, b and ms.

Goat Mountain. Sample G19 (122°42′57″W, 39°15′23″N) is a garnet–white mica–quartz–blue amphibole schist collected by W. G. Ernst (see also Ernst and others, 1970, pl. 1, for sample locality; also Seki, Ernst, and Onuki, 1969, p. 13).

Tiburon Peninsula. Sample GRS-1 is a actinolite–blue amphibole–white mica–aragonite–chlorite schist collected near Reed Station (122°29.9′W, 37°54.3′N) by W. G. Ernst (see Ernst and others, 1970, p. 59, 61, 67, and Seki, Ernst, and Onuki, 1969, p. 31). The geology of this region is reported on by Dudley (1967).

Berkeley Hills. Sample 563, from Yale Petrographic Collection labeled "glaucophane schist 1 mi. north of North Berkeley", a small area (122°17.3′W, 37°53.3′N) of Franciscan schist mapped on the San Francisco 15′ quadrangle corresponds to this locality description (Lawson, 1914). Brothers (1954) reports on glaucophane schists from the Berkeley Hills.

Pacheco Pass. A broad terrain of jadeite + quartz-bearing metagraywacke directly below the Great Valley sequence has been studied by Ernst and others (1970) and is apparently (see Ernst, 1971a) continuous with the thin jadeite + quartz unit mapped by Cowan (1971). Directly below this unit are two other tectonic units: (A) a mélange containing blocks of a variety of metamorphic grades and more- or less-coherent slabs of albite-metagraywacke, and then (B) a thin- to thick-bedded albite–pumpellyite metagraywacke unit (Cowan, 1971).

Sample AR-1 (121°12′35″W, 37°4′37″N), jadeite + quartz metagraywacke collected by J. Suppe along new State Highway 152 just east of Pacheco Pass (halfway between loc. 182 and 183 of Ernst and others, 1970, pl. 3). Sample X-111 (121°9′55″W, 37°5′6″N) is a lawsonite–white mica–quartz–blue amphibole schist associated with the lower chert–metabasalt unit, collected by W. G. Ernst (see also Ernst and others, 1970, pl. 3 for loc.; also Seki, Ernst, and Onuki, 1969, p. 27).

All the DR series samples and petrographic descriptions were provided by Darrel S. Cowan of Stanford University. Samples DR-185 (121°15′6″W, 37°13′24″N), DR-202B (121°15′48″W, 37°14′12″N), and DR-203A (121°15′45″W, 37°14′6″N) are all from the structurally highest unit of semischistose metagraywacke, and each has a well developed planar fabric. All contain quartz + albite + jadeitic pyroxene + lawsonite + white mica. Samples DR-202B and DR-203A both contain glaucophane.

Samples DR-55 (121°19′6″W, 37°12′30″N) and DR-291 (121°21′18″ W, 37°13′ 6″N) are tectonic blocks from a structurally intermediate mélange unit. These are exotic metaclastic rocks with quartz + lawsonite + white mica ± chlorite assemblages and schistose textures. The dates on these tectonic blocks are comparable to the dates from the jadeite + quartz terrain.

Samples DR-7 (121°21′48″W, 37°13′18″N), DR-8 (121°21′48″W, 37°13′00″N), DR-79 (121°20′24″W, 37°14′6″N), and DR-249 (121°21′54″W, 37°15′18″N) are from the structurally lowest unit of coherent thin- to thick-bedded metagraywacke. All contain the assemblage quartz + albite + pumpellyite + white mica + chlorite. All except DR-79 contain rare lawsonite growing in white mica. Sample DR-249 contains calcite and a few grains of metamorphic glaucophane.

As in the Leech Lake Mountain-Ball Mountain region there is a general overlap of whole-rock dates between tectonic units with older dates at the higher structural levels. The jadeite + quartz terrain has given no evidence of antiquity greater than about 120 m.y., and these rocks apparently closed at the same general time as the unnamed Franciscan metasediments of the Leech Lake Mountain-Ball Mountain region and many of the southern Franciscan rocks.

Glaucophane Ridge (Little Panoche Pass, 120°53′W, 36°40′N). Sample 175a is a garnet–epidote–white mica–blue amphibole schist collected by W. G. Ernst (Ernst and others, 1970, p. 59, 61, 69; and Seki, Ernst, and Onuki, 1969, p. 31); GR-1, very coarse vug phengite from tectonic block from Cooney Collection, UCLA (no. 10, table 1, of Ernst, 1963).

Sur-Nacimiento Area. Samples W-69-22 (121°23′10″W, 35°57′15″N), W-69-59 (121°24′ 55″W, 35°58′10″N), and W-69-266 (121°28′0″W, 35°59′25″N) are lawsonite–pumpellyite–aragonite metagraywacke samples from just west and on the footwall of the Sur-Nacimiento thrust fault (collected by W. Gilbert). The dates of 70 to 88 m.y. are similar to dates on the adjacent Salinian granitic complex of the hanging wall (Evernden and Kistler, 1970). The granitic dates record the denudation and related cooling of that terrain in the Late Cretaceous which is unconformably overlain by Upper Cretaceous and possibly Paleocene sediments which are cut by later movement on this fault (Page, 1970, p. 680-681). The Salinian and Franciscan basement types are incompatible; however, they may have been juxtaposed by Late Cretaceous when their K/Ar systems both closed.

Santa Catalina Island. Sample 5a is a garnet–hornblende schist block from Ripper's Cove collected by J. Forman (118°26.0′W 35°25.6′N). Sample 509 is a blue-amphibole bearing metachert collected by J. Rodgers at stop no. 4 of Bailey (1954) (118°28′ 21″W, 39°22′36″N). Sample 69-147 is an *in situ* lawsonite–white mica–quartz–blue amphibole schist collected by J. Suppe (118°28′4″W, 39°23′29″N). See Woodford (1924) for a discussion of the Catalina schists.

Dana Point. Samples 4-10 and 4-12 are schistose Franciscan glaucophane metabasalt blocks from the Miocene San Onofre Breccia approximately 1 km north of Dana Point (117°43′5″W, 33°28′23″N). See Woodford (1925) for a description of the breccia.

Sixty-Mile Bank (118°14′W, 32°10′N). Sample SC-69-6 is a blue amphibole–white mica–quartz phyllite dredged from a submarine basement outcrop in the vicinity of this bank in the continental borderland off southern California (collected by E. L. Winterer). See Emery (1960) for a review of the submarine basement outcrops of this region.

East San Benito Island (115°32.0′W, 28°18.9′N). Samples ESB59, a hornblende schist with secondary blue amphibole, and ESB72, a quartz–white mica–blue amphibole schist with relict hornblende, were collected on a Pomona College expedition to Cedros and San Benito Islands in the late 1950's. Samples were provided by D. McIntyre and A. O. Woodford. Cohen and others (1963) report on the geology of this small island.

Cedros Island is being studied by F. Kilmer of Humboldt State College who provided the dated samples. Sample PNIG (115°9.0′W, 28°10.7′N) is a quartz–calcite–blue amphibole schist. Samples CG1M1 and CG1M2 are white mica–blue amphibole–bearing metacherts (float) from Gran Cañon (115°10.1′W, 28°12.7′N). Sample PN2H (115°12.8′W, 28°21.8′N) is an altered fine-grained hornblende quartz diorite (float). This last sample is not Franciscan but part of a volcanic-plutonic complex, possibly the basement of the "Great Valley sequence", that appears to structurally overlie the Franciscan rocks.

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