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Rb-Sr, K-Ar, and Fission-Track Geochronological Studies of Samples from LASL Drill Holes GT-1, GT-2, and EE-1

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Rb-Sr, K-Ar, AND FISSION-TRACK GEOCHRONOLOGICAL STUDIES OF SAMPLES FROM LASL DRILL HOLES GT-1, GT-2, AND EE-1

by

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ABSTRACT

Geochronological investigations using the Rb-Sr, K-Ar, and fission-track methods have been completed on core samples from the three LASL deep drill holes, GT-1, GT-2,and EE-1. This work indicates a complex history for these Precambrian rocks beginning with a metamorphic event at 1.66 b.y. which generated the gneisses and schists from older sedimentary and igneous rocks. The metamorphic complex was intruded by at least two different magmas at 1.3 - 1.4 b.y. producing thin felsic dikes and a major biotite granodiorite pluton. This igneous activity caused pervasive argon loss to occur, lowering the K-Ar ages to about 1.4 b.y. Plio-Pleistocene igneous activity related to formation of the Valles Caldera increased the local geothermal gradient to 50 - 60°C/km and produced fission track annealing in apatite and again argon loss from the biotite in deeper samples.

I. INTRODUCTION

The Los Alamos Scientific Laboratory (LASL) recently drilled three holes into Precambrian basement rocks of north-central New Mexico as part of its Hot Dry Rock Geothermal Energy Development Program. For scientific as well as project-related reasons it was important to characterize these Precambrian rocks which are expected to serve as the thermal reservoir. To accomplish the characterization, cores, cuttings, and geophysical logs were obtained from these holes.

Many physical, chemical, and geochronological studies on these core samples are complete or nearing completion. In this report we summarize the results of geochronological studies of the Precambrian rocks using the Rb-Sr, K-Ar, and fission track methods. Individual reports on each method are being published elsewhere.

II. GEOLOGIC SETTING

The three LASL deep-drill holes, GT-1, GT-2, and EE-1, are located on the Jemez Plateau outside the west rim of the Valles Caldera in north-central New Mexico (Figure 1). The Caldera itself lies on the western margin of the Rio Grande rift, part of the Basin and Range Province. The sites are thus approximately located on the boundary between the Colorado Plateau and Basin and Range Provinces.

The region around the sites is one of high heat flow[1,2,3]. Reiter et al.,[2] showed that the entire length of the western boundary of the Rio Grande rift is marked by heat flow values in excess of 2.5 HFU. Superimposed on this high are the local effects produced by formation of the Caldera. Potter[1] and Reiter et al.,[3] recognized a higher heat flow on the west side of the Caldera, decreasing with radial distance from the Caldera.

The Precambrian basement rocks at both sites are overlain by approximately 700 m of Paleozoic sedimentary and Cenozoic volcanic rocks.

III. SAMPLE HANDLING PROCEDURES

All cores were washed in distilled water at the drill site and transported in plastic tubing back to the laboratory for lithologic logging. Cores from GT-2 and EE-1 were photographed in color, rotating the core 120° between photographs to insure complete surface coverage. Each different lithology in each core was sampled for petrographic and whole-rock major and trace-element analysis. Splits of the same samples were also used for the whole-rock Rb-Sr analyses. Selected samples from different depths and lithologies were used to obtain mineral separates for K-Ar and fission-track dating. The same separates were then used for mineral Rb-Sr analyses. A summary of procedures is illustrated in Fig. 2.

IV. SUMMARY OF PETROGRAPHY AND GEOCHEMISTRY OF CORE SAMPLES

Core samples from GT-1 were studied by Perkins[4] who found that the upper 28.7 m of Precambrian rocks cored in this hole were gneissic granites and granodiorites. The lower 18.6 m were biotite amphibolite with veins of tonalite-aplite. Large variations in composition were observed within the gneissic rocks, due mainly to variations in the microcline content of the samples.

The petrography and geochemistry of cores from the Precambrian rocks from GT-2 and EE-1 have been examined by Laughlin and Eddy.[5,6] A generalized lithologic log of the Precambrian section is shown in Figure 3. As is shown in this figure, the bulk of the Precambrian section consists of a metamorphic complex of gneiss and minor mafic schist. Spectral-gamma logging[7] indicates that the schist makes up about 8% of the Precambrian section. The gneissic rocks are variable in composition (Table 1) ranging from syenogranitic to tonalitic. These compositional changes are often abrupt, occurring within a few centimeters.

Laughlin and Eddy[6] show that most of the Fenton Hill gneisses are corundum normative suggesting that the precursor rocks were sedimentary and aluminous. A sedimentary origin was also suggested by Heimlich,[8] on the basis of the morphology of zircon crystals.

Rocks equivalent to the amphibolites observed in GT-1 were not intersected by GT-2 or EE-1. The first mafic rocks seen in these two holes were encountered at a depth of 1690 m, considerably deeper than in GT-1. These mafic rocks from GT-2 are of a lower metamorphic grade than the amphibolites from GT-1 and most commonly are schistose rather than granoblastic. As may be seen in Table 1, the schists closely resemble a basaltic andesite in composition. Only one contact, a fault, was observed between the gneiss and schist, so relations between the two rocks are uncertain.

Intrusive into the metamorphic terrane are two distinctly different igneous rocks. The most important of these is a biotite granodiorite which extends from a depth of 2588 m to near the bottom of the GT-2 (∿2929 m). Megascopically, petrographically, and chemically, this rock is very homogeneous. Mineralogically, it is characterized by high sphene and apatite contents. Chemically, it is rich in TiO_2, K_2O, and P_2O_5 (Table 1). In three cores obtained from this unit it is typically unfoliated to poorly foliated. An additional short (0.5-m) core at the bottom of GT-2 shows prominent vertical foliation. We are not certain that this core represents the same biotite granodiorite.

The second igneous rock unit is a leucocratic monzogranite encountered in core #10 from GT-2 and from the Spectralog, we have determined that this rock extends from a depth of 1295 m to 1311 m. This unit was also encountered in EE-1 at about the same depth and we interpret it as a subhorizontal dike cutting across the foliation. This monzogranite is light pink in color, medium grained, and equigranular. Chemically it is similar to some of the monzogranitic gneisses (Table 1). A similar dike which was not cored was recognized on the Spectralog in the interval 2454 to 2469 m in GT-2.

All of the core samples of the gneisses and schists show abundant fractures which are generally sealed with calcite. Some samples record a complex history of repeated fracturing, sealing, and wallrock alterations. Alteration of plagioclase and biotite, which is moderate in all of the core samples, is generally more intense along the fractures. This is particularly obvious in the mafic schists where bleached zones up to 0.75 cm in thickness border some of the fractures.

V. GEOTHERMAL GRADIENTS IN LASL DRILL HOLES

In order to interpret the results of the geochronological studies, it is essential to know the temperature at the depths where samples were collected. Temperature measurements were made in all three drill holes and detailed plots of the geothermal gradients in GT-1 and GT-2 are shown in Figures 4 and 5, respectively. The gradients are not constant in either hole, varying with both lithology and the movement of meteoric water. The correlation between perturbations in the gradient and permeable zones indicates that the latter factor is dominant, except perhaps at the Precambrian unconformity.

Rock temperatures are sufficiently high in both GT-2 and EE-1 to perturb the K-Ar and fission-track systems used in these studies. In GT-2, the bottom-hole temperature was 197°C at 2929 m (Ref. 9) and in EE-1 it was 205.5°C at 3062 m. The shallower hole, GT-1, had a bottom-hole temperature of 100°C at 785 m.

VI. Rb-Sr STUDIES

Precambrian samples from the three drill holes have been used for two different types of studies. The first consisted of standard Rb-Sr age determinations using both whole-rock samples and mineral separates. In the second, ^{87}Sr was used as an isotopic tracer to investigate the origin of the ubiquitous calcite fracture fillings in the core. Both studies will be summarized here.

The analytical techniques used in these studies are reported in Brookins and Laughlin.[10] The results of these analyses are presented in Tables 2 and 3 and in Figs. 6-12.

Nine samples from GT-1 yield a preliminary isochron age of 1.95 ± 0.12 b.y. and an initial ratio (R_0) of 0.701 ± 0.001. These samples do not fulfill whole-rock criteria however, and the "age" is presumed to be excessively old.

Twenty-seven samples from the metamorphic complex encountered by GT-2 and EE-1 have been analyzed and yield a whole-rock isochron age of 1.66 ± 0.5 b.y. and a R_0 of 0.707 ± 0.003. These samples fulfill all requirements of whole-rock samples and the reported age is in agreement with ages of magmatic rocks from north-central New Mexico.

The igneous rocks intrusive into the metamorphic complex yield distinctly younger ages. Four samples of the leucocratic monzogranite sill or dike from the 1295-1311 m (4250-4300 ft) interval yield a 1.4 ± 0.2 b.y. age while the extensive biotite granodiorite, first encountered at a depth of 2588 m in GT-2, has an isochron age of 1.29 ± 0.03 b.y. and a R_0 of 0.7069 ± 0.0011. Sixteen samples were used for this isochron.

Mineral separates prepared for K-Ar and fission-track dating were also used for Rb-Sr analysis and for the construction of mineral isochrons. The mineral isochrons from GT-2 (Figure 10) yield a range of ages from 1.1 to 1.5 b.y. with variable $^{87}Sr/^{86}Sr$ ratios. Those closer to 1.1 b.y. are usually anchored at the high $^{87}Rb/^{86}Sr$ end of the isochron by altered biotites, thus the 1.1 b.y. ages may be too low. Mineral separates from the biotite granodiorite from the bottom of GT-2 yield a mineral isochron "age" of 1.10 ± 0.02 b.y. and because the rocks from this interval are relatively fresh and unaltered, the apparent "age" may reflect a local metamorphic event.

As has been discussed above, large numbers of calcite-filled fractures are present within the core samples. Because impermeable reservoir rocks are a prerequisite for the LASL method of energy extraction, it was considered important to determine if these fracture systems were continuous into the overlying limestone (Madera limestone). It seemed likely that if the fractures were connected, then the calcite in fractures would have been derived from the limestone. An alternative source for the calcite would be from the observed alteration of plagioclase in the granitic rocks.[5,6] Local derivation of the calcite would imply non-continuous fractures. To distinguish between these alternatives, $^{87}Sr/^{86}Sr$ ratios were determined in the calcites and these values compared with those from the limestone and granitic rocks.[10,11]

Ratios in the calcite (Table 3) ranged from 0.724 to 0.734. Makhopadhyay[12] measured $^{87}Sr/^{86}Sr$ ratios in the Madera Limestone of 0.7066 to 0.7111 with a mean for 11 samples of 0.7088. It is clear that the calcites are enriched in ^{87}Sr relative to the Madera limestone. We thus conclude that most of the calcite was locally derived from the 1.66 b.y. old basement rocks and that fractures probably are not connected between basement rocks and overlying sedimentary rocks.

VII. K-Ar STUDIES

Analytical procedures in use at the University of Alaska for ^{40}K-^{40}Ar dating are summarized in Turner and others.[13] Analytical data for LASL samples are presented in Table 4. Variations of these apparent ages with depth are presented graphically in Figure 13.

A total of 14 separate Precambrian rock samples were analyzed. These included a surface sample of biotite amphibolite from Guadalupe Box, about 21 km southwest of GT-1, two samples from GT-1, and 11 from GT-2. Five samples contained dateable biotite-amphibole pairs. Muscovite was dated at the 1.67-km (5487-ft) depth of GT-2. Each argon analysis was done in duplicate, with a total of 43 individual ^{40}K-^{40}Ar ages being determined.

Biotite and muscovite K-Ar ages are easily perturbed by relatively low-temperature thermal events, with temperatures of approximately 200-300°C being sufficient to cause significant argon loss. Such a "resetting of the clock" is shown by all of the analyzed mica samples. Mica ages from the surface sample, the GT-1 samples, and all GT-2 samples from 2.17 km and less average 1.37 ± 0.03 (1σ) b.y. This average age is shown by a dashed line through the data in Figure 13. This age is concordant with Brookins and Laughlin's[10] whole-rock Rb-Sr isochron age of 1.4 ± 0.2 b.y. for the leucocratic monzogranite dikes, leading to the conclusion that the magmatic event producing the dikes also produced a thermal event of sufficiently high temperature to reset the K-Ar mica ages.

The 146°C temperature measured at a depth of 2.04 km, and presumably resulting from volcanism associated with the Valles Caldera, was not sufficiently high to lower the 1.37 b.y. ages. At depths of 2.67 and 2.90 km, however, temperatures were high enough at some time in the geologic past to cause additional argon loss, reducing the 1.37 b.y. age to 1.32 and 1.26 b.y., respectively. This effect is shown graphically in Figure 13.

We find no evidence in the K-Ar data to support the 1.1 b.y. Rb-Sr mineral isochron age discussed in Section VI. As discussed above, the ^{40}K-^{40}Ar mineral ages are all significantly older than this value, suggesting that the 1.1 b.y. age is anomalously low.

Amphiboles are generally considered to be more resistant to thermal resetting by loss of argon than biotite or muscovite. This observation is borne out by the 1.41 b.y. hornblende versus 1.35 b.y. biotite age from Guadalupe Box and by the 1.44 b.y. hornblende versus 1.35 b.y. biotite age from the 0.77-km depth in GT-1. In GT-2, hornblende and biotite ages are essentially concordant at the 1.72-km and 2.17-km depths.

The amphibole-biotite pair from the 1.59-km depth in GT-2, however, gives a rather surprising result. The hornblende age is anomalously low at 1.21 b.y. (2 replicate analyses), while the biotite age is "normal" at 1.33 b.y. A significant kink occurs in the measured geothermal gradient in GT-2 at this depth which may indicate hydrothermal activity.

In this regard, Kulp and Engles[14] have shown that ^{40}K-^{40}Ar ages are unaffected by the removal of up to 50% of the potassium in biotites by base exchange in laboratory experiments. Comparable experiments have not been done for amphiboles, however. It seems possible that this discordance may be due to hydrothermal resetting of the hornblende age, with no accompanying effect on the biotite. This speculation is supported by the fact that the fission-track apatite age is also partially reset at this depth, as discussed in the following section on fission-track studies.

VIII. FISSION-TRACK STUDIES

Mineral separation of the Precambrian samples from the LASL samples has yielded two minerals, apatite and sphene, amenable to fission-track dating. Epidote, which is common as a fracture filling and alteration product has proved to be too fine grained or filled with flaws to be useful.

Apatite is a particularly intriguing mineral for geochronological studies of geothermal systems because of its relatively low annealing temperatures. Naeser and Faul[15] have suggested that temperatures of about 150°C are sufficient to totally anneal apatite if they persist over about 10^6 years. Fortunately, sufficient apatite was available to provide mineral separates from 10 of the LASL samples. Apatite from the amphibolite from Guadalupe Box gave an apparent "age" of 242 ± 48 m.y. This sample is assumed to be comparable in age to the metamorphic complex encountered in GT-2 (1.66 b.y.). In this case the 242 m.y. apparent "age" probably reflects the time when this sample last passed through the 100°C isotherm, and thus related to time of uplift and not any specific thermal event. If geothermal gradients were normal at that time (∿30°C/km) the sample was probably at a depth of about 3 km, 242 m.y. ago.

Apparent "ages" of apatite from GT-2 show a roughly linear decrease with depth in the hole (Figure 14). All samples except that that from a depth of 1.59 km fall on a straight line. The results from the 1.59-km sample are particularly interesting because the continuous temperature log of GT-2 shows a positive disturbance at approximately that depth. The additional perturbation necessary to pull this point off the straight line apparently results from a fracture or fracture zone along which hot water is or has been moving.

IX. GEOTHERMAL IMPLICATIONS

Certain aspects of the geochronological data bear directly on the evaluation of Fenton Hill as a hot dry rock geothermal site.

First, the multiple periods of igneous and metamorphic activity reflected by all of the geochronological methods is probably the cause of the low permeability generally measured within the reservoir rock. Fluid activity accompanying these thermal events has apparently sealed or increased the rate of healing within the tectonically induced fractures. Although at the present time we have not been able to "date" any of the specific fracture fillings, it seems likely that they would have more than one age, reflecting the multiple events.

As has been discussed above, the $^{87}Sr/^{86}Sr$ ratios in the calcite from fracture fillings suggest that it was largely derived locally from alteration of plagioclase and not from the overlying Madera limestone. Thus, it is not likely that fractures within the Precambrian basement rocks are continuous with those in the sedimentary cover and fluid leakoff from the reservoir would not be expected.

Apparent ages determined by the K-Ar method on samples from depths less than 2.17 km average 1.37 $\pm$ 0.03 b.y., concordant with the Rb-Sr whole-rock isochron age of the monzogranite dike. Clearly, dike emplacement heated the host gneisses sufficiently so that pervasive argon loss occurred. At greater depths, additional argon loss is not occurring in response to the present high-temperature gradient. The fact that total Ar loss has not taken place, even at a temperature of 200°C, suggests that the present gradient is the highest felt by these rocks in the last 1.37 b.y. This implies that the Fenton Hill site is still undergoing rising temperatures from the thermal pulse related to Valles Caldera formation. The results of apatite fission track dating support this conclusion.

The relative sensitivity of apatite to thermal annealing of fission tracks offers distinct possibilities for geothermal exploration. This possibility is currently under investigation by Naeser, Forbes, and Turner.

X. SUMMARY AND DISCUSSION

Application of a variety of radiometric dating techniques to the Precambrian samples from Fenton Hill has revealed a long and complex history for these rocks. The recorded history begins at 1.66 b.y. when the metamorphic complex of gneiss, schist, and amphibolite was formed. Ancillary evidence from the petrography, whole-rock chemistry,[5,6] and zircon morphology[8] suggests that the precursor rocks for the gneisses may have been sedimentary. Chemical evidence indicates that the mafic schists and amphibolite may be metamorphosed basaltic andesites or similar igneous rocks.

The next recorded event was emplacement of at least two leucocratic monzogranite dikes at ∿1.4 b.y. As evidenced by the large number of 1.4 b.y. K-Ar biotite apparent ages from the gneisses, this magmatic event caused degassing of the biotite resetting the K-Ar clock. Rubidium and Sr were also mobile within individual minerals at this time, mineral-ages varying from 1.1 to 1.5 b.y.

Although several uplifts of the Precambrian rocks may have occurred in the past, the last is reflected in the 242 m.y. apatite age from the amphibolite from Guadalupe Box. Assumption of normal geothermal gradient permits an estimate of the depth of the amphibolite of about 3 km at that time.

Formation of the Jemez Mountains beginning about 9 m.y. ago again established a higher geothermal gradient and perturbed the K-Ar ages on deeper samples and all of the apatite ages from GT-2. Apatite ages vary linearly with depth and temperature except where locally hydrologically perturbed.

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TABLE 1

CHEMICAL COMPOSITIONS OF TYPICAL PRECAMBRIAN ROCKS FROM GT-2 (wt%)

	(1)	(2)	(3)	(4)	(5)
SiO_2	63.86	72.08	55.10	65.05	77.43
TiO_2	0.97	0.19	1.44	0.56	0.11
Al_2O_3	14.57	14.20	15.54	16.00	11.98
Fe_2O_3	3.10	0.67	1.87	1.13	0.34
FeO	3.02	1.37	7.14	2.89	0.38
MgO	1.41	0.45	4.67	1.46	0.03
CaO	3.24	1.12	5.14	3.15	0.69
MnO	0.092	0.050	0.140	0.079	0.015
SrO	0.045	0.017	0.023	0.043	0.004
Na_2O	3.30	3.33	2.87	4.50	3.43
K_2O	4.18	4.73	3.31	2.89	4.68
$H_2O^{(-)}$	0.07	0.14	0.11	0.12	0.07
$H_2O^{(+)}$	0.98	1.06	1.28	1.22	0.54
CO_2	0.23	0.10	0.48	0.69	<0.01
P_2O_5	0.59	0.05	0.51	0.18	<0.01

(1) Biotite granodiorite (average of 5 samples, from bottom of GT-2).

(2) Leucocratic monzogranite dike (average of 3 samples).

(3) Ferrohastingsite - biotite schist (average of 2 samples).

(4) Biotite granodioritic gneiss [depth 960 m (3151 ft)].

(5) Leucocratic monzogranitic gneiss [depth 1056 m (3464 ft)].

TABLE 2.

Rb-Sr Data: GT-1 and GT-2

Sample	$^{87}Sr/^{86}Sr$	Rb(ppm)	Sr(ppm)	$^{87}Rb/^{86}Sr$
A. GT-1: Whole Rocks				
PD2-1	0.7737	143.1	158.0	2.64
PD2-3	0.7478	172.0	267.1	1.87
PD2-4	0.7445	124.6	257.6	1.40
PD2-6	0.7279	86.5	288.2	0.87
PD2-7	0.7333	144.1	330.2	1.27
PD2-8	0.7280	119.5	369.7	0.94
PD2-15	0.7173	58.3	295.1	0.57
PD2-16B	0.7197	81.0	322.4	0.79

TABLE 2 (Cont'd.)

Rb-Sr Data: GT-1 and GT-2

Sample	$^{87}Sr/^{86}Sr$	Rb(ppm)	Sr(ppm)	$^{87}Rb/^{86}Sr$
B. GT-2: Whole Rocks (from depths less than 2588 m)				
2603	0.7793	147.1	125.5	3.41
2855-2	1.0045	172.4	40.5	12.69
3464-1b	0.9977	152.9	38.4	11.88
3464-10	0.8070	111.6	72.1	4.53
3694-1.1	0.8101	131.6	83.7	4.59
3696-1.1	0.8448	184.4	91.3	5.92
3696-2.1	0.8340	164.5	86.4	5.58
3699-2.1	0.8050	140.1	94.0	4.35
3703-2.1	0.7588	116.1	140.9	2.40
4895-2	0.7694	156.4	142.4	3.20
4917-2	0.7688	121.2	133.1	2.65
4919-5	0.7762	136.4	128.6	3.09
4920-3-p	0.7631	117.6	137.4	2.49
4920-3-g	0.7761	166.2	149.9	3.23
5234-10	0.7479	79.7	138.2	1.68
5234-11	0.7584	98.2	125.8	2.27
5487-M1	0.9616	139.1	36.9	11.18
5487-M2	0.9760	137.8	35.7	11.46
5487-M4	0.9780	121.8	30.9	11.72
6155-2b	0.7421	88.6	182.5	1.41
6160-4	0.7475	118.9	206.3	1.67
7103-1a	0.7668	153.9	149.5	3.00
7103-5e	0.7474	102.2	171.2	1.74
7103-8h	0.7501	103.6	164.9	1.83
7918-1b	0.7356	86.7	181.2	1.39

TABLE 2 (Cont'd.)

Rb-Sr Data: GT-1 and GT-2

Sample	$^{87}Sr/^{86}Sr$	Rb(ppm)	Sr(ppm)	$^{87}Rb/^{86}Sr$
C. GT-2: Whole Rocks (from depths greater than 2588 m)				
8573-4A	0.7314	228.3	480.6	1.38
8573-4B	0.7216	124.9	413.5	0.88
8578-M	0.7249	136.4	441.5	0.90
8583-1A	0.7331	162.9	388.6	1.22
8583-1B	0.7212	142.2	447.4	0.92
9519-1	0.7216	144.2	462.9	0.90
9520-3	0.7256	124.8	450.3	0.80
9521	1.0310	287.6	47.5	18.09
9522-5A	0.7276	182.2	379.5	1.39
9522-5B	0.7276	143.2	424.3	0.90
9529-2	0.7215	124.1	454.9	0.79
9530-2	0.7309	222.9	344.6	1.88
9607-M2-2	0.7231	90.1	349.3	0.75
9607-M2-B	0.7202	98.4	327.6	0.87
9607-M7	0.7244	98.8	332.8	0.86
9607-2B	0.7278	103.6	310.4	0.97
D. GT-2: Whole Rocks from Dike				
4279-2	0.7911	218.0	147.9	4.30
4280	0.7835	206.7	157.8	3.80
4281-4M	0.7889	210.1	146.1	4.19
4282-4M	0.7699	193.8	175.2	3.22

TABLE 2 (Cont'd.)

Rb-Sr Data: GT-1 and GT-2

Sample	$^{87}Sr/^{86}Sr$	Rb(ppm)	Sr(ppm)	$^{87}Rb/^{86}Sr$
E. GT-2: Whole Rock and Mineral-Dominated Systems: 1295-1311 m				
4893-1a	0.7613	67.7	132.8	1.48
4893-1b	0.7776	122.6	110.3	3.25
4893-1c	0.7549	93.1	128.2	2.11
4895-2	0.7764	156.4	142.4	3.20
4898-2	0.7694	70.8	129.6	1.59
F. GT-2: Mineral Isochron: 9529				
9529(B)	3.5699	673.8	13.3	187.95
9529(H)	0.7162	107.3	1120.0	0.28
9529(L)	0.7149	83.1	504.6	0.48
9529(R)	0.7215	124.1	454.9	1.34
G. GT-2: Mineral Isochron: 5654				
5654(L)	0.7124	30.2	433.7	0.20
5654(B)	4.8160	484.1	6.9	286.25
5654(H)	0.7212	7.6	40.2	0.55
5654(R-2b-c)	0.7484	196.0	236.7	2.41
5654(R-1)	0.7401	168.0	228.5	2.13

TABLE 2 (Cont'd.)

Rb-Sr Data: GT-1 and GT-2

Sample	$^{87}Sr/^{86}Sr$	Rb(ppm)	Sr(ppm)	$^{87}Rb/^{86}Sr$
H. GT-2: Mineral Isochron: 5234 feet				
5234(H)	0.7527	13.2	21.7	1.77
5234(L)	0.7508	98.7	147.4	1.95
5234(R-10)	0.7479	79.7	138.2	1.68
5234(R-11)	0.7584	98.2	125.8	2.27
I. GT-2: Mineral Isochron: 5487 feet				
5487(B,C)	0.7523	73.0	208.3	1.02
5487(L)	0.9777	106.9	29.9	11.88
5487(R-M2)	0.9760	137.8	35.7	11.46
5487(R-M4)	0.9780	121.8	30.9	11.72
5487(R-M1)	0.9616	139.1	36.9	11.18

TABLE 2 (Cont'd.)

Rb-Sr Data: GT-1 and GT-2

J. GT-2: Miscellaneous Data for Altered Samples

6344/6350	1.0580	188.6	34.4	16.49
3151-5a	0.7238	40.3	429.3	0.26
6152-3	0.7708	46.8	133.4	1.02
6155-2B	0.7421	88.6	182.5	1.41
6160-4a	0.7400	48.5	207.7	0.68
5985-1.2-RE.	0.7460	138.0	166.2	2.41
5985-1.2-LE.	0.7258	70.9	378.1	0.54
6154-B	15.1468	586.3	2.7	1531.8
5654-2b,c	0.7484	196.0	236.7	2.41
2580	0.7681	49.6	112.0	1.29
4898	0.7764	70.8	129.6	1.59

K. EE-1: Whole Rock Data

6875-2	0.7767	156.6	35.1	3.47
9877-2b	1.0105	205.0	172.4	13.31

TABLE 3*

Sr Geochemistry of Some GT-2 Core Samples

Sample (Depth in feet)	Rb(ppm)	Sr(ppm)	$^{87}Sr/^{86}Sr$	Remarks
A. Samples for Whole Rock Rb-Sr				
4896-2	22.2	129.6	0.7764	Altered leucocratic monzogranitic gneiss
4917-2	121.2	133.1	0.7688	Leucocratic monzo-granitic gneiss
5487-M1	139.1	36.9	0.9616	Leucocratic monzo-granitic gneiss
B. Calcites from Core Samples				
4896-2.1a-C	n.d.	n.a.	0.7331	Leach from calcite covered fracture
4896-2.1b-C	n.d.	n.a.	0.7237	Hand-picked calcite
4917-2-C	n.d.	n.a.	0.7268	Hand-picked calcite
5487-M1-C	n.d.	(200)	0.7336	Hand-picked calcite
5985-1.1-C	n.d.	n.a.	0.7258	Hand-picked calcite
C. Whole Rock for Leaching Experiment (Hornblende-biotite schist)				
5985-2.1a	138.0	166.2	0.7460	Insoluble Residue
5985-2.1b	70.9	378.1	0.7336	Leach from 5985-2.1a

*Notes:

(1) All samples are fractures; of those studied for Rb-Sr whole-rock analysis only 4896-2 contained significant alteration products along fracture fillings.

(2) Notation: n.d. = not detected (<10 ppm) by atomic absorption spectrometry; n.a. = not analyzed; parentheses () = indicates analysis by atomic absorption spectrometry, all other values by isotope dilution.

(3) Leaching experiments conducted by use of vycor distilled 2N HCl on rock surface (4896-2.1a-C) or on crushed whole rock (5985-2.1).

TABLE 4

APPARENT MINERAL AGES OF LASL SURFACE AND CORE SAMPLES

				Apparent Age				
				Fission Track		K-Ar		Downhole
				Apatite 10^6yr	Sphene 10^6yr	Mica 10^6yr	Amphibole 10^6yr	Temperature °C
Surface Guadalupe Box	0	0	Amphibolite	242 ± 48	N.D.	1350 ± 40(B)	1410 ± 40	Ambient
GT-1	2439	0.74	Monzogranitic Gneiss	54.3 ± 10.8	1304 ± 163(Z)	1320 ± 40(B)	N.D.	98
GT-1	2540	0.77	Amphibolite	N.D.	N.D.	1350 ± 40(B)	1440 ± 40	100
GT-2	2580	0.79	Monzogranitic Gneiss	68.6 ± 7.0	N.D.	1390 ± 40(B)	N.D.	100
GT-2	3696	1.13	Monzogranitic Gneiss	N.D.	N.D.	1370 ± 40(B)	N.D.	110
GT-2	3697	1.13	Monzogranitic Gneiss	55.1 ± 6.0	N.D.	1380 ± 40(B)	N.D.	110
GT-2	4279	1.30	Monzogranite	38.2 ± 4.0	N.D.	1370 ± 40	N.D.	113
GT-2	5234	1.59	Granodioritic Gneiss	13.2 ± 1.3	N.D.	1330 ± 40(B)	1210 ± 40	125
GT-2	5487	1.67	Muscovite Vein	N.D.	N.D.	1400 ± 40(M)	N.D.	127
GT-2	5487	1.67	Granodioritic Gneiss	N.D.	N.D.	1360 ± 40(M)	N.D.	127
GT-2	5654	1.74	Amphibole-Biotite Schist	17.4 ± 1.7	1381 ± 171(S)	1370 ± 40(B)	1320 ± 40	128
GT-2	6154	1.88	Biotite Granodiorite	0.0	1343 ± 170(S)	1420 ± 40(B)	N.D.	135
GT-2	7103	2.17	Granodioritic Gneiss	0.0	N.D.	1370 ± 40(B)	1380 ± 40	151
GT-2	8581	2.61	Biotite Granodiorite	0.0	1371 ± 134(S)	1320 ± 40(B)	N.D.	177
GT-2	9529	2.90	Biotite Granodiorite	0.0	1050 ± 150(S)	1260 ± 40(B)	N.D.	197

(B) - Biotite
(M) - Muscovite
(S) - Sphene
(Z) - Zircon

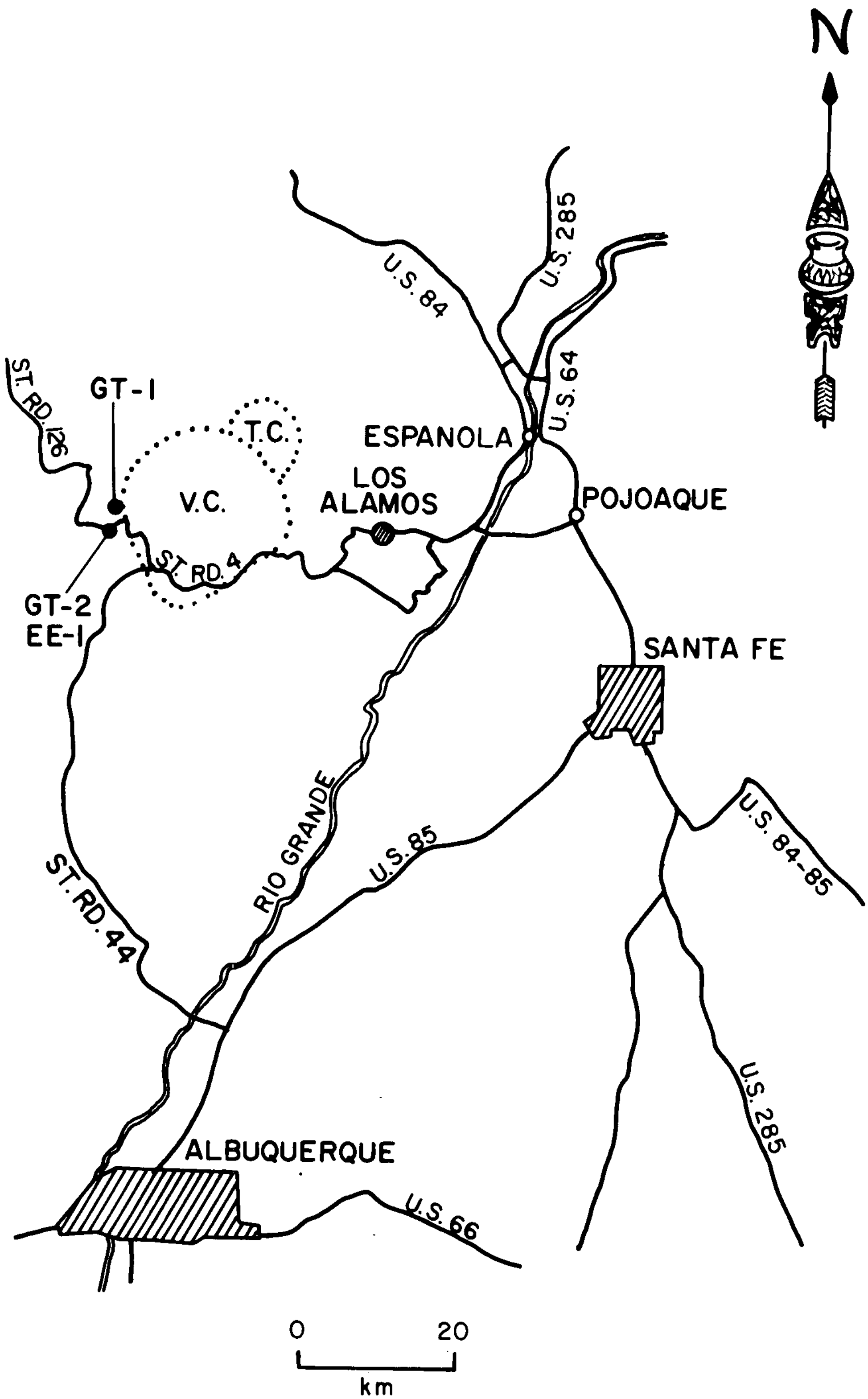


Fig. 1. Index map showing the location of the Barley Canyon (GT-1) and Fenton Hill (GT-2, EE-1) drill sites. The Valles and Toledo Calderas are indicated by the symbols V.C. and T.C., respectively.

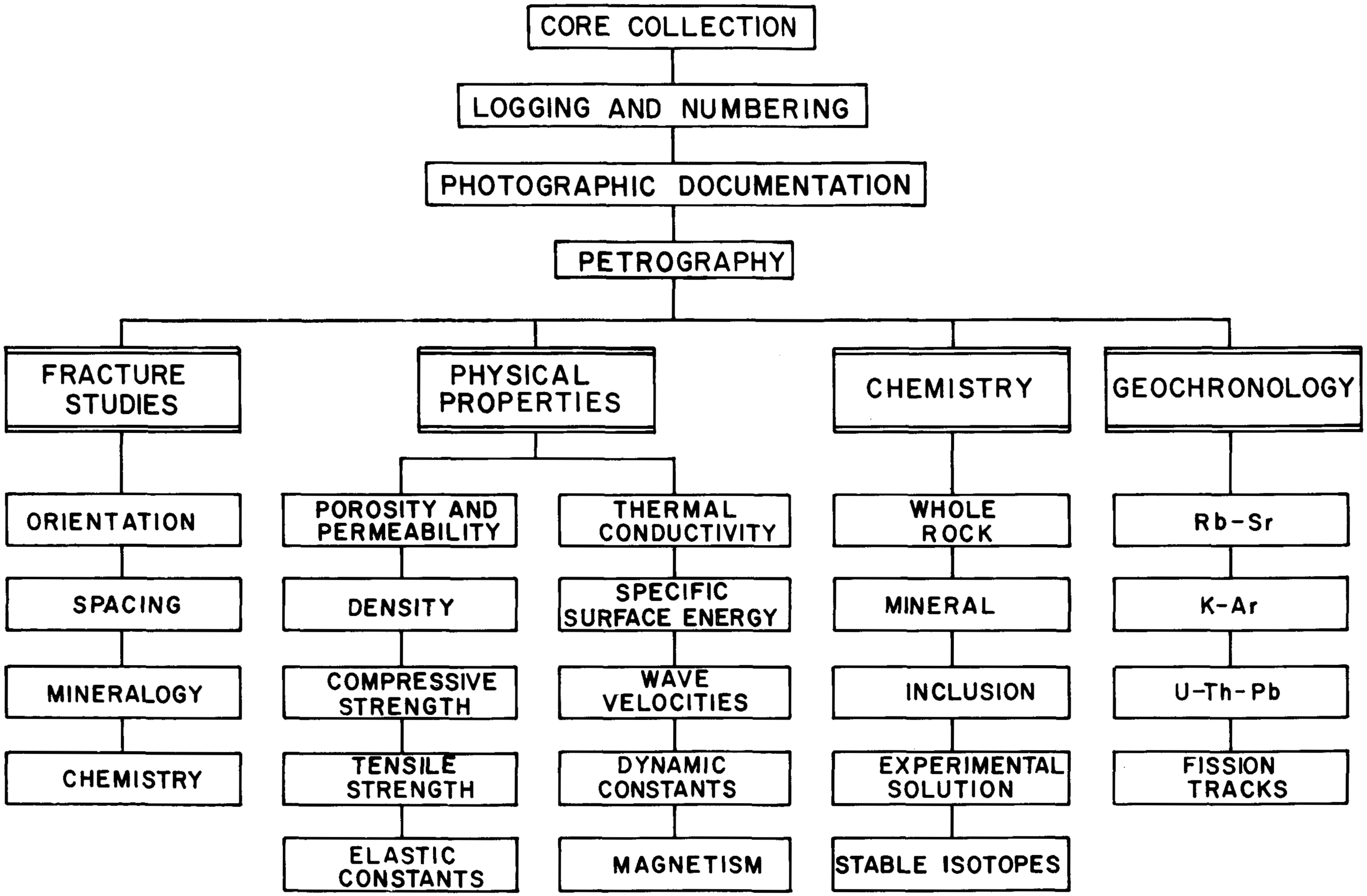


Fig. 2. Flow chart of core handling procedures and investigations in progress or completed.

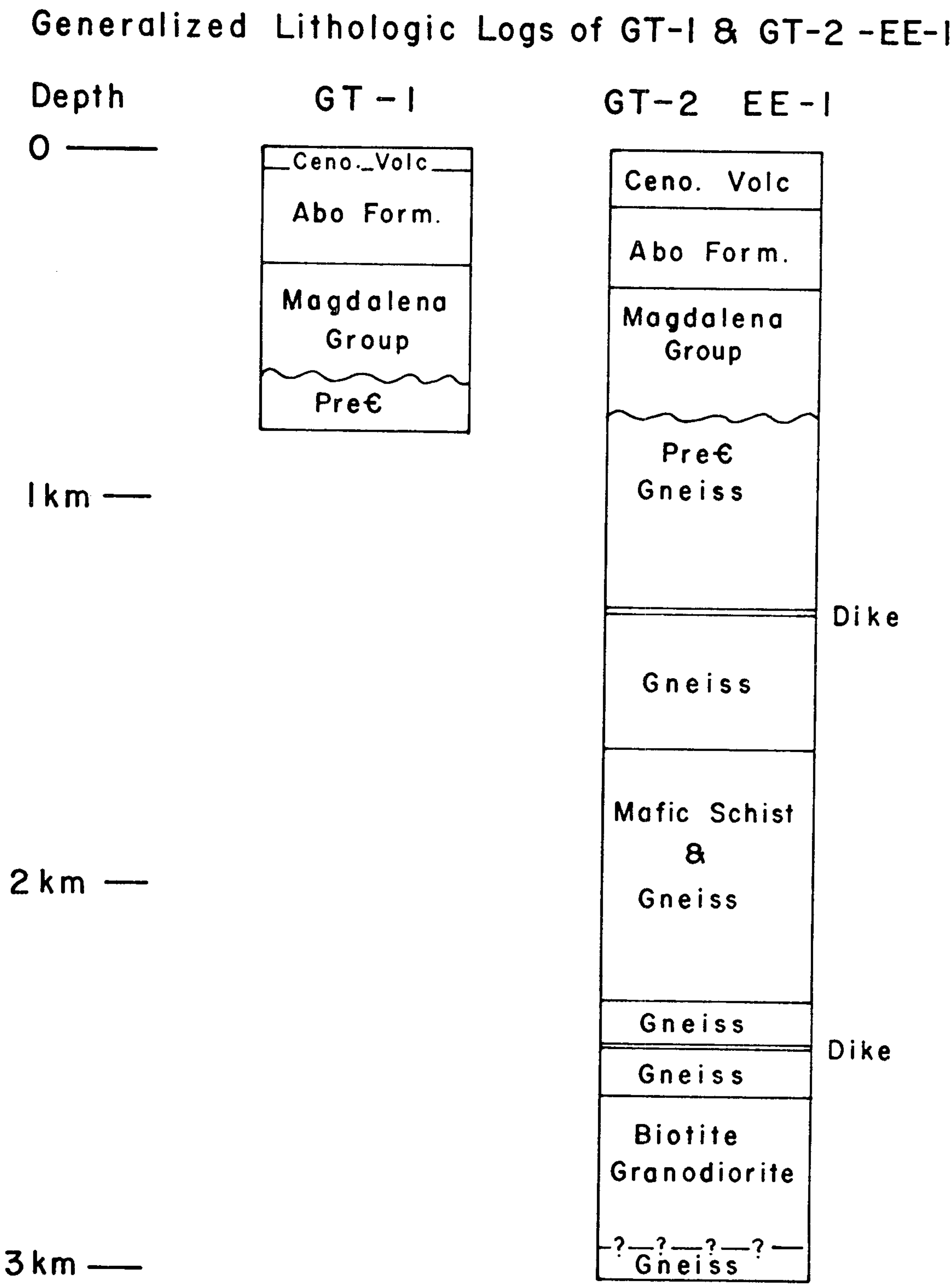


Fig. 3. Generalized lithologic log for GT-1 and the combined log for GT-2 and EE-1.

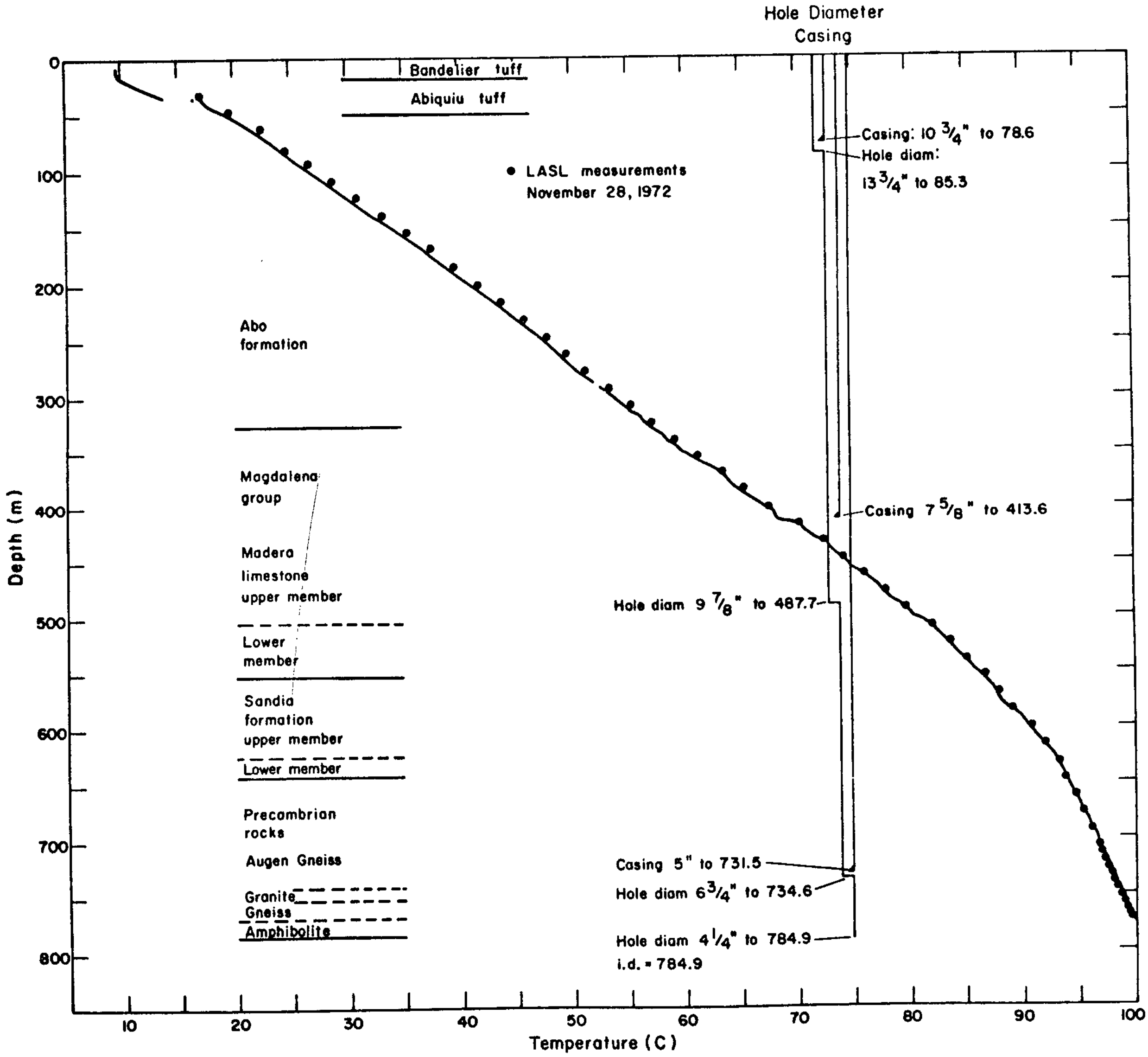


Fig. 4. Geothermal gradient for GT-1.

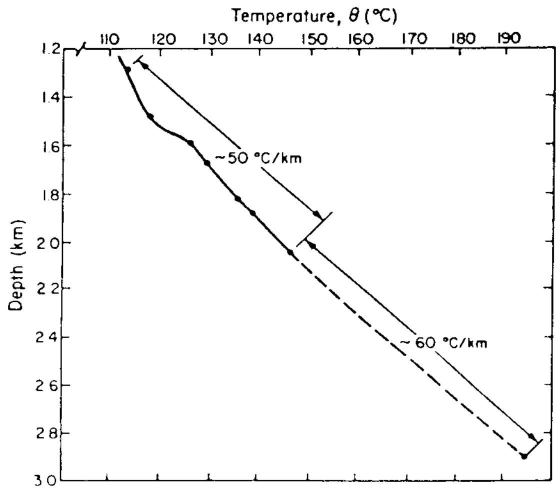


Fig. 5. Geothermal gradient for GT-2.

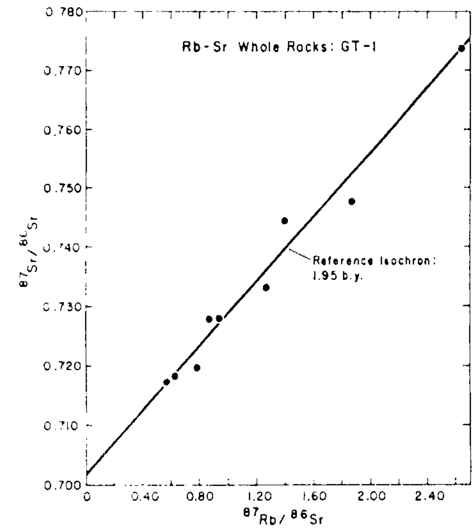


Fig. 6. Rb-Sr isochron plot from GT-1. These samples did not meet whole-rock criteria for Rb-Sr analysis.

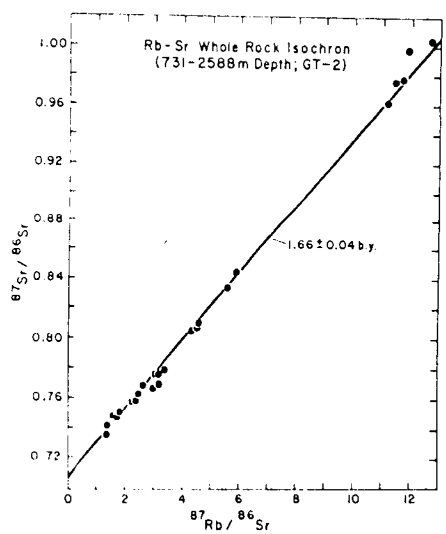


Fig. 7. Rb-Sr isochron plot for samples from the interval 731 to 2588 m in GT-2.

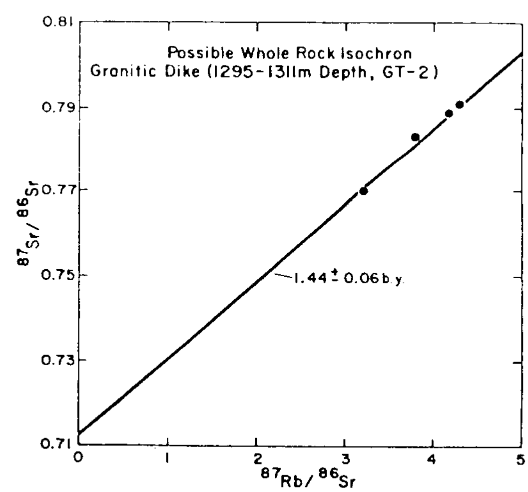
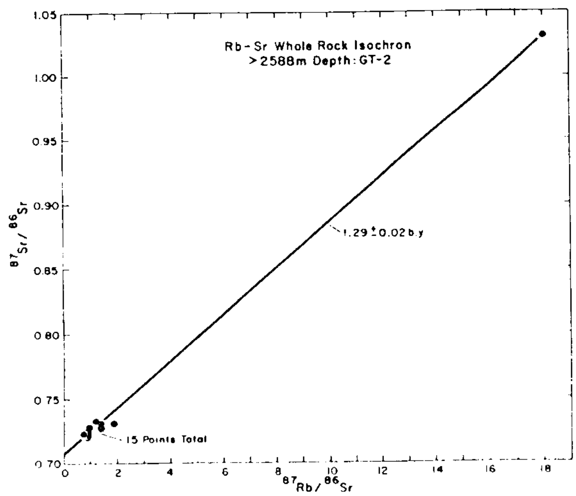


Fig. 8. Rb-Sr isochron plot for samples from leucocratic monzogranite dike in GT-2.



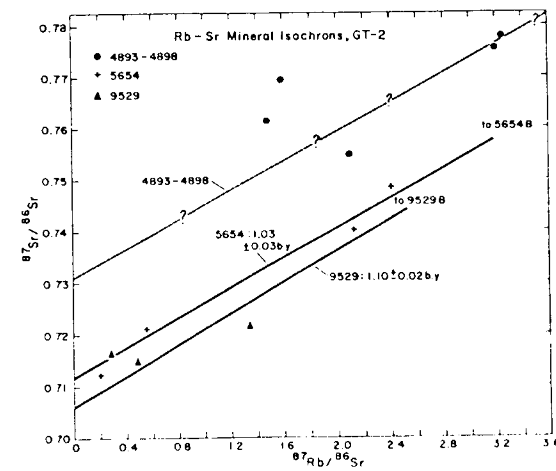
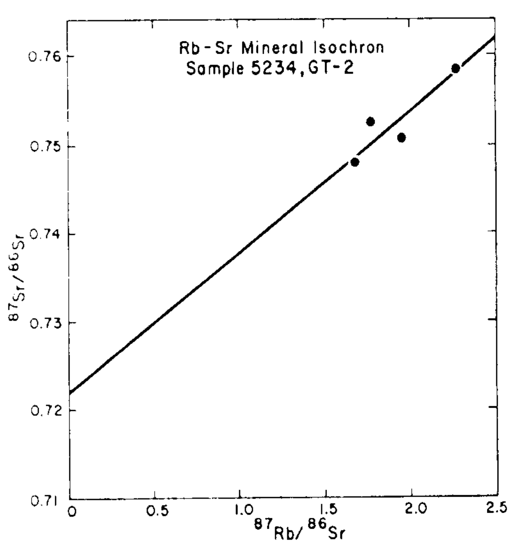


Fig. 9. Rb-Sr isochron plot for samples of biotite granodiorite at depths greater than 2588 m in GT-2.

Fig. 10. Rb-Sr mineral isochrons for samples from GT-2.



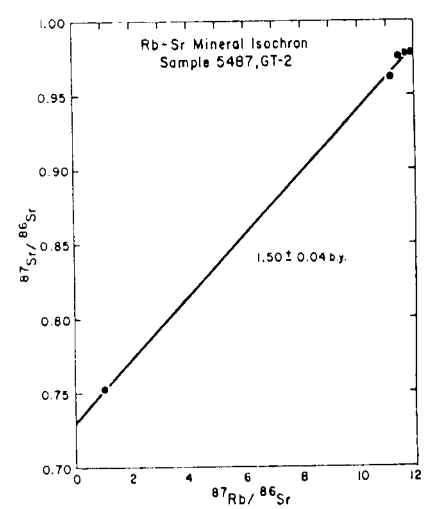


Fig. 11. Rb-Sr mineral isochron for sample 5234 from GT-2.

Fig. 12. Rb-Sr mineral isochron for sample 5487 from GT-2.

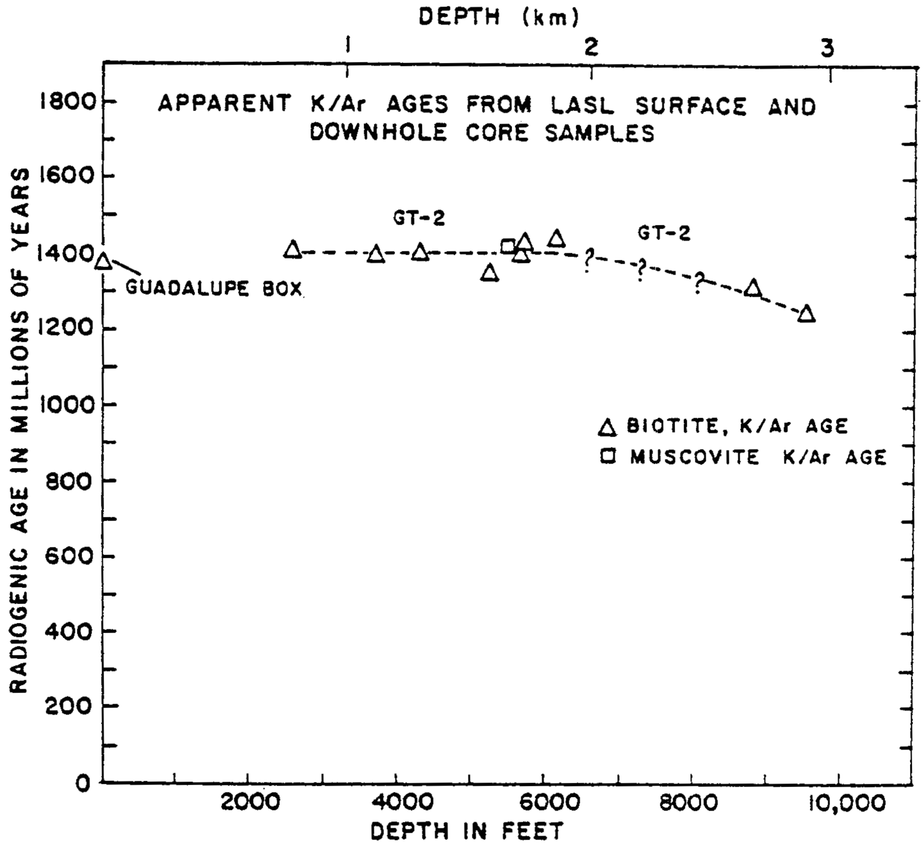


Fig. 13. K-Ar apparent ages for surface and core samples from LASL drill sites.

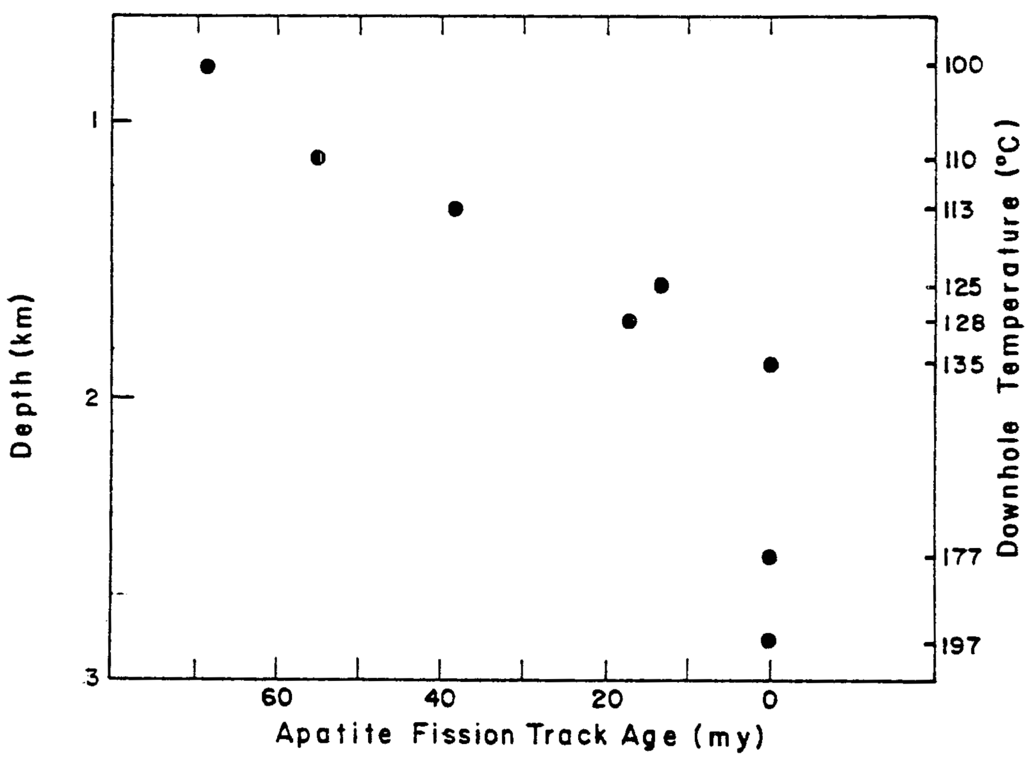


Fig. 14. Variation of apatite fission track ages with depth in GT-2.

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