JOURNAL OF GEOPHYSICAL RESEARCH VOLUME 67, No. 10 SEPTEMBER 1962

A Study of the Ages of the Precambrian of Texas

G. J. WASSERBURG

California Institute of Technology, Pasadena

G. W. WETHERILL

Institute of Geophysics and Department of Geology
University of California at Los Angeles

L. T. SILVER

California Institute of Technology, Pasadena

P. T. FLAWN

Bureau of Economic Geology, University of Texas

Abstract. Age determinations using the Sr^{87}-Rb^{87}, Ar^{40}-K^{40}, and Pb-U methods were made on samples of muscovite, biotite, amphibole, microcline, and zircon from igneous and metamorphic rocks from the Franklin Mountains, Hueco Mountains, Pump Station Hills, and Carrizo and Van Horn Mountains. In addition ages were determined on a number of basement cores from Texas and New Mexico. The results show that a belt of rocks of varied lithology extending from El Paso to east of the Llano uplift are all of the same age. The general age by the strontium and argon methods is 1000 to 1090 m.y.; and by the lead-uranium method on zircons it is 1150 to 1200 m.y. This event is in the same time band as the 'Grenville' orogeny in Canada and the northeastern United States and possibly should be considered part of the general 'Grenville' episode. All the data now available indicate that the orogenic event at about 1000 to 1200 m.y. is the most widespread and pervasive episode of Precambrian orogeny on the North American continent for which adequate evidence has been presented. At least one and probably two older periods of igneous activity and metamorphism occurring at 1250 and 1400 m.y. are found in the northern regions of the Texas Precambrian basement. No evidence was found for any igneous event between the early Paleozoic and the 1000-m.y. episode.

INTRODUCTION

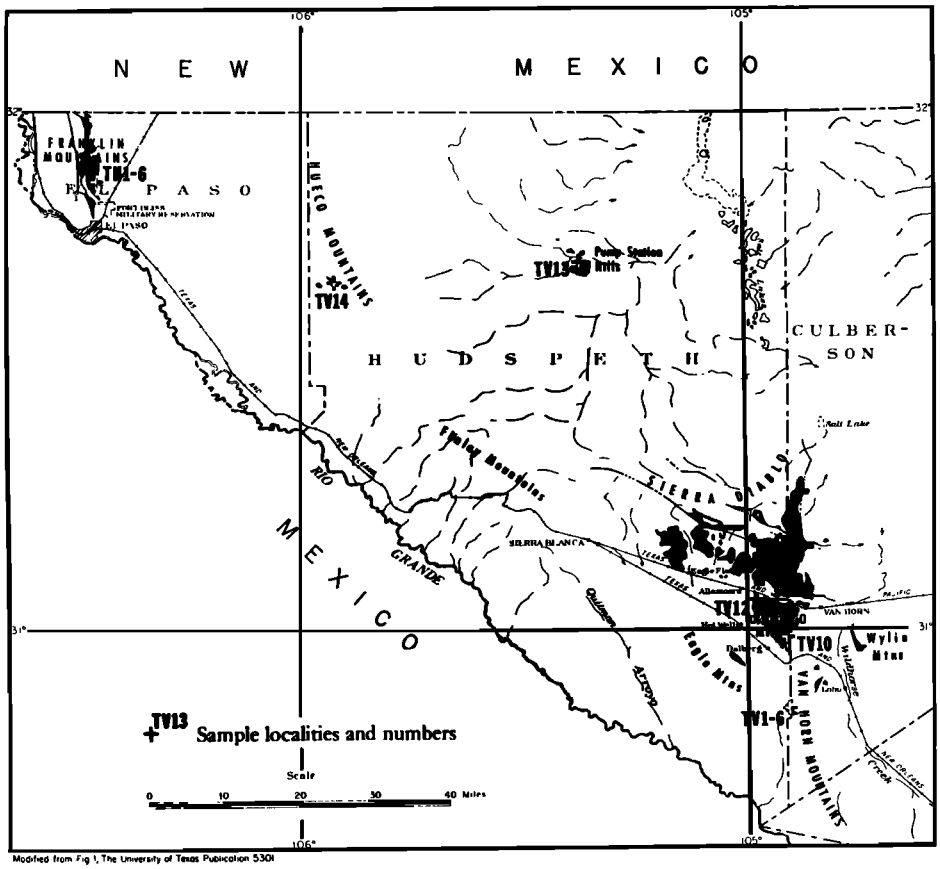
The purpose of this study is to attempt to use mineral ages to correlate igneous and metamorphic rocks of Precambrian age in Texas.

Precambrian rocks in Texas crop out in the Llano uplift area of central Texas and in a number of separated mountain uplifts in Trans-Pecos Texas (Figure 1). Stratigraphic evidence as to the age of these rocks is as follows:

1. Central Texas granites which intrude metasedimentary rocks are overlain by Upper Cambrian strata (Hickory sandstone member of the Riley formation [*Cloud, Barnes, and Bridge,* 1945]).

2. In Trans-Pecos Texas stratigraphic relations differ in the separate mountain ranges. (*a*) In the Franklin mountains, granite, volcanic rocks, and metamorphic rocks lie beneath the Cambro-Ordovician Bliss formation [*Harbour,* 1960]. (*b*) In the Hueco Mountains the granite is either surrounded by unconsolidated alluvial deposits or in fault contact with younger beds; general regional evidence, however, suggests that it is pre-Bliss (Cambro-Ordovician) in age. (*c*) Rhyolite in the Pump Station Hills is surrounded by unconsolidated alluvial deposits, and there is no convincing stratigraphic evidence pertaining to its age. On the basis of regional geology earlier investigators suggested that the rocks are Precambrian [*King and Flawn,* 1953; *Masson,* 1956]. (*d*) Metamorphic rocks and pegmatites in the Carrizo and Van Horn Mountains are overlain by Permian (Wolfcamp) beds, but regional stratigraphic evidence suggests that the rocks are pre-Van Horn sandstone (Precambrian?), which is pre-Bliss (Cambro-Ordovician) in age.

A number of chemical lead-uranium and lead-



Modified from Fig 1, The University of Texas Publication 5301

Fig. 1. Map showing the exposures of Precambrian rocks in Trans-Pecos Texas and the sample localities.

thorium ages up to 1100 million years have been determined on the rare-earth minerals from the Barringer Hill pegmatite in the Llano region [*Barrell,* 1917; *Holmes,* 1931]. More recently age estimates have been made on zircons from the Llano region and from well cores in west Texas by the 'Pb-α' technique [*Jaffe, Gottfried, Waring, and Worthington,* 1959]. Owing to the many difficulties both technical and inherent in this nonisotopic method, the results will not be considered in detail.

Modern age determinations using Ar^{40}-K^{40}, Sr^{87}-Rb^{87}, Pb^{206}-U^{238}, and Pb^{207}-U^{235} methods have been made by several workers on minerals in the granitic rocks and associated pegmatites in the Llano area [*Aldrich, Wetherill, Davis, and Tilton,* 1958; *Goldich, Nier, Baadsgaard, Hoffman, and Krueger,* 1961; *Zartman,* 1962, 1963].

The data obtained by Aldrich et al., in the Llano region are summarized in Table 1. They clearly show the existence of plutonic igneous activity at about 1100 m.y. in the south-central United States. The correlation of this occurrence with 1000-m.y. plutonic activity in eastern North America some 1200 miles distant was not specifically made by these workers.

In the present study samples for age determination were obtained both from the exposed Precambrian and from basement cores. Samples were collected from the various localities with the previous geologic studies as a guide, and basement cores were selected with the study by *Flawn* [1956] as a guide, the purpose being to establish time correlations and compare the various geochronometric methods.

Results

The results for the exposed rocks are presented by area, after which the basement core data are given. Thin sections of the rocks and

TABLE 1. Age Determinations from the Llano Region

Locality	Mineral	Ar^{40}/K^{40}	Sr^{87}/Rb^{87}	Pb^{206}/U^{238}	Pb^{207}/U^{235}	Pb^{207}/Pb^{206}
Petrick Quarry (granite)	Biotite*	1060	1100	...	...	...
	Zircon*	...	...	950	990	1070
(pegmatite)	Biotite†	1060	1110	...	...	...
Lone Grove Pluton (granite)	Biotite, feldspar‡	1060		...	...	...

* After *Aldrich, Wetherill, Davis, and Tilton* [1958].
† After *Goldich, Nier, Baadsgaard, Hoffman, and Krueger* [1961].
‡ After *Zartman* [1962*a*]. Average of several determinations by both methods. All ages have been recalculated for the decay constants used in this paper.

the mineral separates are described in the appendix.

Franklin Mountains

Precambrian rocks are exposed in North Franklin Mountain in the vicinity of El Paso (see Figure 2). These have been described in a recent publication by *Harbour* [1960]. He has presented a sedimentary sequence in this area comprised of the following units in order of decreasing age: (1) The Castner limestone, possibly equivalent to the Allamore limestone of the Van Horn area. Several diabase sills are included in the Castner. (2) The Mundy breccia, which rests unconformably on the Castner. (3) The Lanoria quartzite. On top of this unit is (4) a rhyolite extrusive. (5) The youngest rock in the area underlying the Bliss sandstone is a massive granite, which is seen to surround and engulf large blocks of the sedimentary section. This granite shows a variety of phases, the larger exposures being a pink-white biotite granite, which is typically rather friable. One phase is a gray-white biotite granite, which locally contains numerous reacted inclusions and shows a jointing structure with the fractures spaced at approximately 30 to 60 cm. These fractures all show iron oxide stains and a pale green discoloration even in a fresh quarry face. We infer this alteration to be a deuteric effect. A sample of this phase, TH-1, was taken from the interior of a boulder of about 120-cm diameter (see Figure 2). Samples of a third phase, a granophyric biotite-hornblende granite, TH-5, were collected in Fusselman Canyon. This rock has a spotted appearance produced by the isolation of dark gray microcline crystals by an interstitial white micrographic intergrowth. This rock also shows distinct iron oxide stains on the freshest material.

A sample of feldspar, TH-6, was taken from a microcline-perthite-quartz pegmatite which was seen to cut the granophyric granite. This dike has a thickness of about a meter. No fresh mica was found in this pegmatite.

In addition to these materials a sample of a friable tourmaline-biotite-plagioclase schist, TH-2, was collected. This material was not found in the measured section reported by Harbour for a traverse further west (see Figure 2). The unit is about 3 meters thick and lies between a thick section of Castner limestone on the west and a diabase sill to the east. The Castner shows beautifully developed stromatolite structures and mud cracks at this locality. The top of the limestone here shows distinct contact metamorphic effects from the granite. The diabase sill contains abundant biotite near the granite contact. The origin of the schist layer is not understood.

The ages for the Sb^{87}-Rb^{87} and Ar^{40}-K^{40} methods on various mineral separates are presented in Table 2; the ages for the zircons, in Table 3. An estimated maximum error is given for each of the ages. This estimate is based solely on the analytical data without considering possible errors in the decay constants. A more detailed discussion of errors is presented in the appendix under analytical procedures.

The biotite and microcline separated from granite TH-1 gave the following results: the strontium age of the biotite is considerably less than the argon age, and both are less than the strontium age of the coexisting microcline. The 6

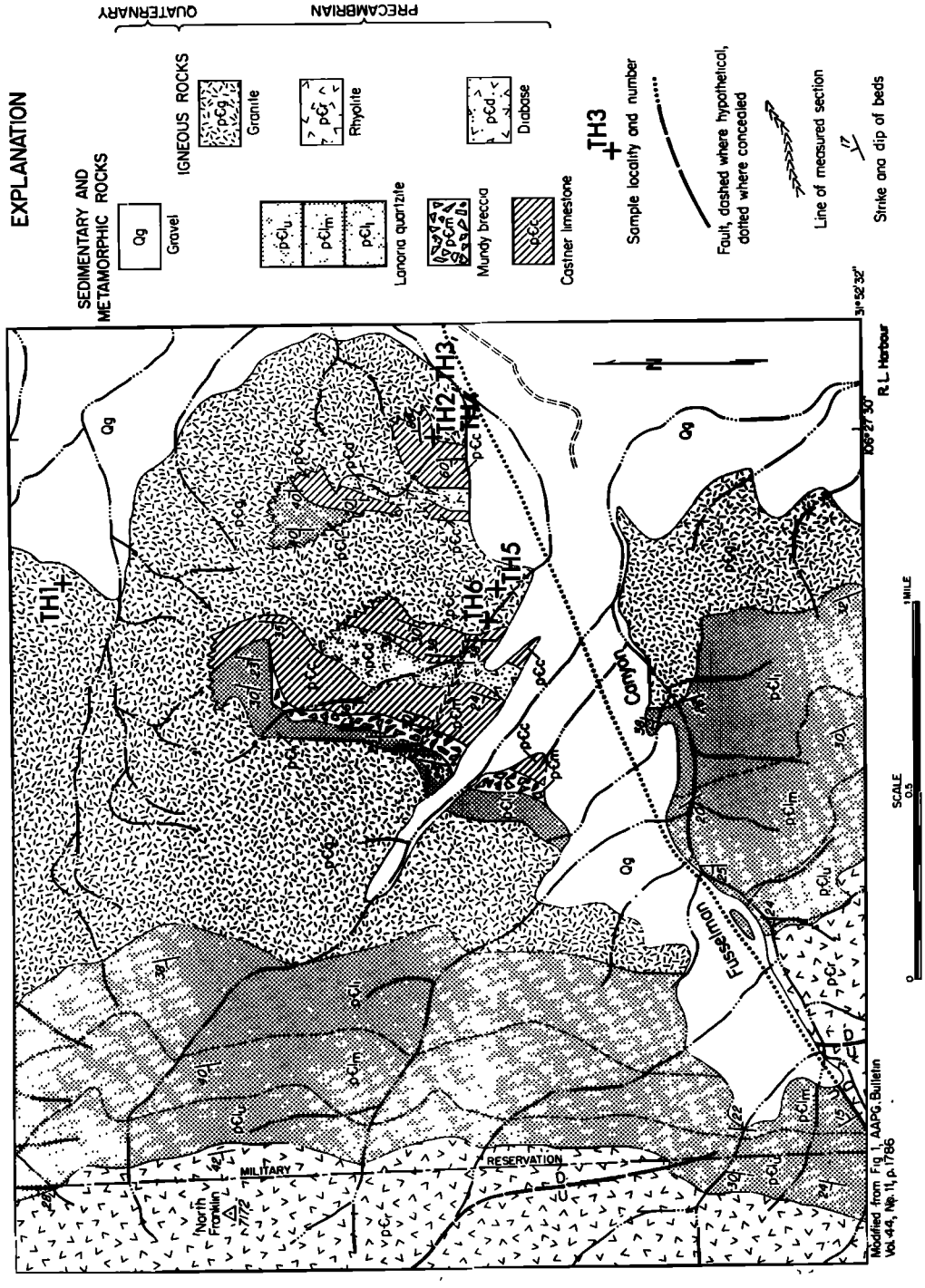


Fig. 2. Geologic map of the North Franklin Mountains (after Harbour), showing the sample localities.

TABLE 2. Age Determinations from the Franklin Mountains near El Paso, Texas

No.	Rock	Mineral	Age, m.y. K-Ar	Age, m.y. Rb-Sr
TH-1	Granite	Biotite	980 ± 20	930 ± 20
		Feldspar		1040 ± 30
TH-2	Biotite schist	Biotite	860 ± 20	710 ± 50
TH-5	Granite	Hornblende	1000 ± 20	
		Feldspar		970 ± 50
TH-6	Pegmatite	Feldspar		1090 ± 20

per cent difference between the feldspar and the biotite is well beyond analytical error. This age pattern is rather typical of almost all the data.

A biotite separated from the friable schist TH-2 gave discordant ages, the argon age being considerably less than that obtained on the biotite from TH-1. In both cases it was apparent in the field that the rocks were not 'fresh.' Nonetheless no characteristics were observed in thin sections of the rocks, or in the grain mounts of the separated minerals, which might indicate that the biotite was unsuitable for age determination.

Samples of hornblende and microcline were separated from the granophyric granite TH-5 and a microcline from a crosscutting pegmatite TH-6. Strontium ages were determined on the feldspars, and an argon age was determined on hornblende [*Hart*, 1961].

The younger pegmatite gives a strontium age of 1087 m.y., which is greater than the results on the other feldspars. The difference between the feldspars from TH-6 and TH-5 is well outside of experimental error. The difference between TH-6 and TH-1 feldspars is just at the limits of error. While this disagreement is not large, it is certainly real and is yet another example of the 'pegmatite-country rock' discrepancy reported by previous workers [*Wasserburg, Wetherill, and Wright*, 1959; *Wetherill, Davis, and Tilton*, 1960; *Gerling and Polkanov*, 1958].

Two zircon concentrates of differing uranium content were extracted from the granophyric granite TH-5 for Pb-U analysis. The techniques followed are described by *Silver, McKinney, Deutsch, and Bolinger* [1962]. The analytical results are given in Table 3, and the parent daughter ratios are plotted in Figure 3 in a concordia diagram [*Wetherill*, 1956]. A straight line drawn through these points intersects the concordia curve at about 1200 m.y. It has been shown by *Silver and Deutsch* [1961] that discordant U-Pb systems in cogenetic zircons may generate linear patterns on a concordia diagram.

TABLE 3. West Texas and Llano Zircons

Sample	Apparent Ages, m. y. Pb^{206}/U^{238}	Pb^{207}/U^{235}	Pb^{207}/Pb^{206}
West Texas Samples			
Micrographic granite (TH-5), Franklin Mts., El Paso Co.			
Fraction A	880 ± 20	950 ± 20	1095 ± 20
Fraction B	770 ± 20	860 ± 20	1080 ± 20
Rhyolite porphyry (TV-13), Pump Station Hills, Hudspeth Co.			
Fraction A	1065 ± 20	1105 ± 20	1175 ± 25
Fraction B	1005 ± 25	1050 ± 25	1140 ± 20
Granite well core, Phillips Puckett #1c, Pecos Co.	925 ± 20	970 ± 20	1065 ± 20
Muscovite-oligoclase-quartz schist (TV-1), Van Horn Mts., Hudspeth Co., fine fraction	745 ± 20	875 ± 25	1220 ± 40
Llano Samples			
Town Mt. granite, Petrick quarry [*Tilton et al.*, 1957]	950 ± 25	990 ± 15	1070 ± 25
Town Mt. granite, Granite Mt. quarry, [Silver et al., in preparation]	970 ± 20	1020 ± 20	1120 ± 20

Constants: $\lambda_{238} = 1.537 \times 10^{-10}$; $\lambda_{235} = 9.72 \times 10^{-10}$; (atoms U^{235})/(atoms U^{238}) = 1/137.8.

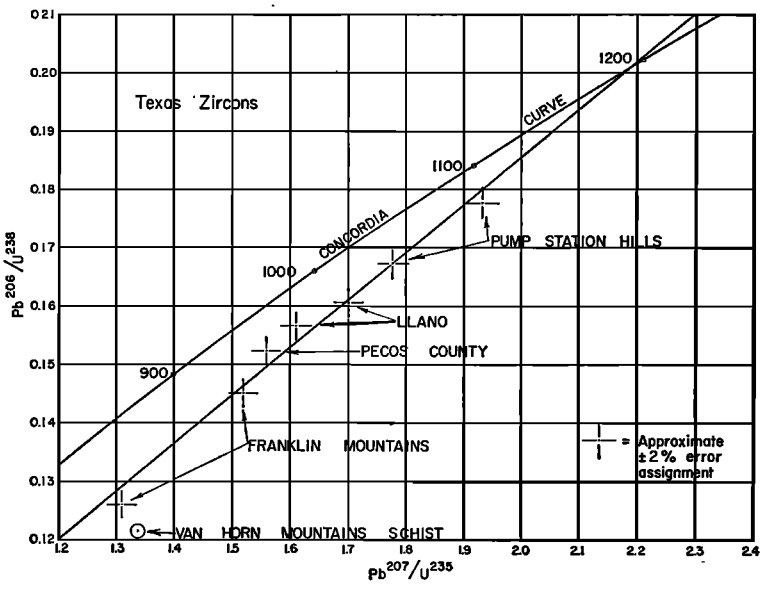


Fig. 3. The Pb^{206}/U^{238} and Pb^{207}/U^{235} ratios for samples of zircons from the Precambrian of Texas.

Throughout this paper the linear pattern of the accumulated zircon data is used as an argument for contemporaneity. The intersection of the pattern with the concordia curve is interpreted as an original age of crystallization for the zircons. A more complete discussion of this intersection is given in a later section. The Pb^{207}-Pb^{206} age must be taken as minimal assuming any (nonfractionating) form of lead loss.

The results obtained in this area by the various methods indicate an event at about 1100 m.y. However, they scatter far outside of experimental error. The only visible evidence for a postemplacement metamorphism is the alteration and recent weathering previously described. The block faulting in this area does not appear to have caused more general metamorphic effects, but post-Paleozoic intrusive activity is evident in the region and its local effects cannot be estimated.

Hueco Mountains

A sample was collected from a low-lying knob of red porphyritic hornblende granite from the foothills of the Hueco Mountains. No fresh pegmatites containing mica were found in this locality. The granite shows a tendency to granular disintegration, presumably due to weathering. The granite could be described as 'inelastic.' In thin section the microcline shows only slight clouding and in general appears unaltered. A strontium age of 1045 m.y. was determined on a sample (TV-14) (Table 4).

Pump Station Hills

A sample of a granophyric rhyolite porphyry was collected from this locality. This rock is extremely tough and resistant but in thin section shows considerable alteration. Samples of the other phases that have been reported within the Pump Station Hills area [*Masson*, 1956] were not collected. A 2.5-cm cube of rhyolite, TV-13, was crushed to pass 80 mesh, and a split was taken for whole-rock strontium analysis. Another strontium age was determined on a sample of microcline separated from another specimen. The results, given in Table 4, are in good agree-

TABLE 4. Age Determinations from the Hueco Mountains and Pump Station Hills

No.	Locality	Rock	Mineral	Age, m.y., Rb-Sr
TV-14	Hueco Mts.	Granite	Feldspar	1050 ± 60
TV-13	Pump Station Hills	Rhyolite	Feldspar	1060 ± 40
			Whole rock	1020 ± 60

ment and indicate a strontium age of 1060 m.y.

Two zircon separates of differing uranium content were obtained from a hand specimen of this porphyry. The results are given in Table 3 and Figure 3. The two fractions give Pb^{207}-Pb^{206} ages of 1175 and 1140 m.y. and lie close to the same line as the Franklin Mountain samples (Figure 3). These results clearly indicate the Precambrian age of the rocks in the Pump Station Hills.

Carrizo Mountains

This area is known to be structurally more complex than any of the others investigated in this work. It is bounded to the north by the Hillside fault and is possibly involved in the Streeruwitz overthrust in this region. Flawn [*King and Flawn*, 1953] has described the Carrizo Mountain group as a series of steeply tilted metasedimentary and metaigneous rocks. The sedimentary rocks were intruded by rhyolites and basic dikes, and the section was subsequently deformed. The rhyolites, markedly deformed and sheared, are described as metarhyolites. Toward the northwest of the map area (Figure 4) the metarhyolite is converted into a mylonite. The metasedimentary rocks are a relatively low-grade metamorphic assemblage, although there is distinct evidence for a polymetamorphic history.

Samples of metarhyolite TV-12-c and an amphibolite schist TV-12-b were collected from the northwestern part of the area, where the rhyolite shows profound evidence of cataclasis and has a strong planar structure and lineation. The schist is only locally present and presumably is a metaigneous rock. A 2.5-cm cube of the metarhyolite was crushed to pass 80 mesh, and a fraction was taken for a total-rock strontium age determination. A biotite separate was obtained from the schist. The results, given in Table 5, indicate an age in the neighborhood of 1070 m.y.

In addition to these materials, samples of a fine-grained hornblende-biotite-garnet schist TV-10a and a hornblende-epidote schist TV-10b were collected from the southern part of the area, farther from the locus of the overthrust. TV-10b occurs in a small dike-like body about 13 cm thick. Biotite was extracted from TV-10a, and hornblende from TV-10b. The results shown in Table 5 indicate an argon age of 900 m.y. for the hornblende and a distinctly younger result on the biotite. The strontium age on the biotite is much less than the argon age.

TABLE 5. Age Determinations from the Carrizo Mountains

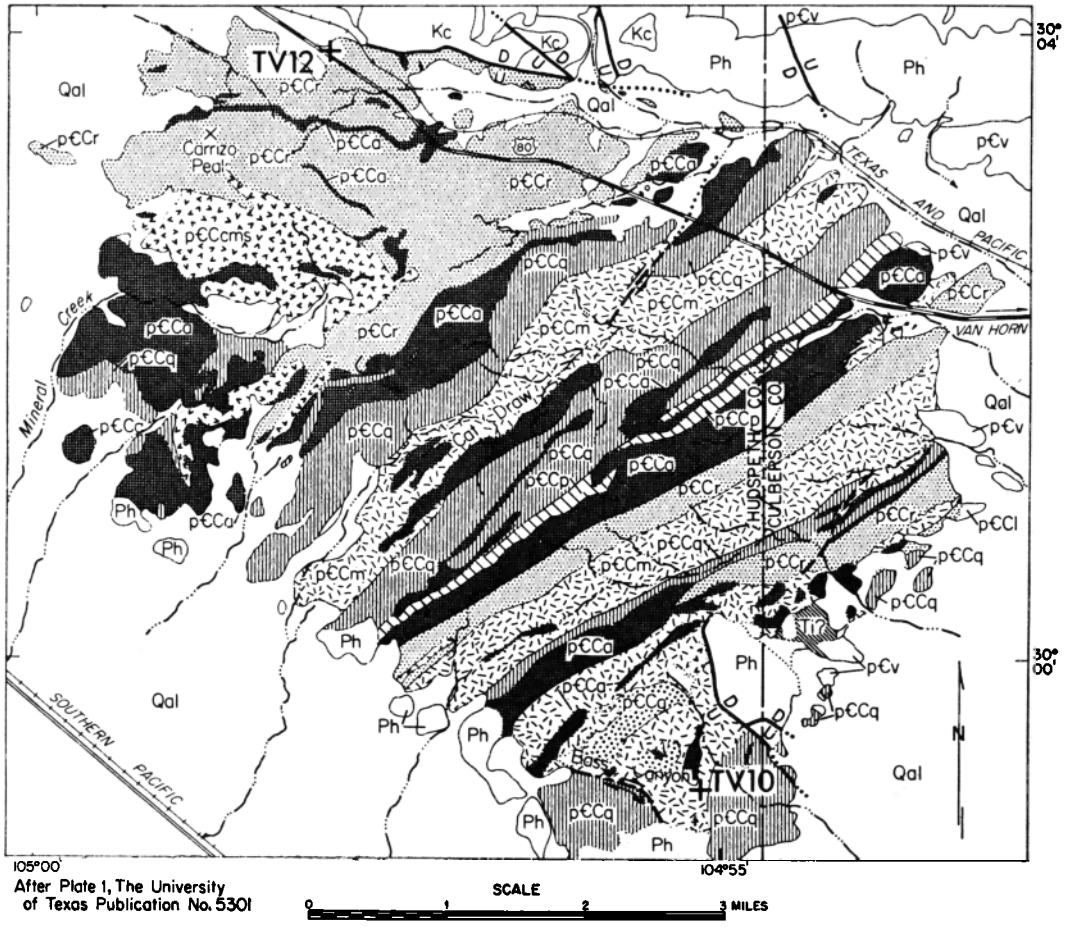
No.	Rock	Mineral	Age, m.y. K-Ar	Age, m.y. Rb-Sr
TV-10-a	Schist	Biotite	780 ± 20	580 ± 20
TV-10-b	Amphibolite	Hornblende	900 ± 20	
TV-12-b	Schist	Biotite		960 ± 60
TV-12-c	Metarhyolite	Whole rock		1070 ± 70

These measurements have a pattern quite similar to that obtained in the Franklin Mountains, but because of the polymetamorphic history in the Carrizo Mountain area it is rather difficult to make any simple statements, and the conclusions must be regarded as tentative. It is evident that these rocks are at least 1000 m.y. old. The apparent age may reflect the effects of recrystallization during shearing, and the true age may be considerably higher. It is also impossible to draw any conclusions about the time of thrusting from these data. If the biotite from TV-12-b lost its radiogenic strontium at the time of shearing, the time of shearing would be greater than 960 m.y., but whether complete loss would occur under these conditions is not known. Furthermore, the shearing need not have been concurrent with the thrusting. Although experience with deformed rocks of this type is very limited, we tentatively suggest that the whole-rock strontium age on the rhyolite is the most reliable estimate of the age of the rhyolite.

Van Horn Mountains

A thick section of middle-grade metamorphic rocks intruded by pegmatites is exposed in the Mica Mine area of the Van Horn Mountains, an area described by *Flawn* [1951, 1956]. These rocks are unconformably overlain by Permian (Wolfcamp) rocks. The metamorphic sequence is comprised of a feldspathic quartzite, a feldspathic muscovite schist, and biotite schist and amphibolite. The pegmatites occur in bodies of varied shape that conform to and cut across the foliation of the host rock.

A detailed comparison of the various mineral



After Plate 1, The University of Texas Publication No. 5301

EXPLANATION

Qal — Alluvial deposits	Ph — Hueco limestone	p€Cr — Metarhyolite	p€Cq — Quartzo-feldspathic rocks
Ti(?) — Intrusive igneous rocks	p€v — Van Horn sandstone	p€Cl — Limestone	p€Ccms — Chlorite-mica schist
Kc — Cox sandstone and Campogrande limestone	p€Cg — Granodiorite	p€Cp — Phyllite	+ TV12 — Sample locality and number
p€Ca — Amphibolite		p€Cm — Mixed units	

Fig. 4. Geologic map of the Carrizo Mountains (after Flawn), showing the sample localities.

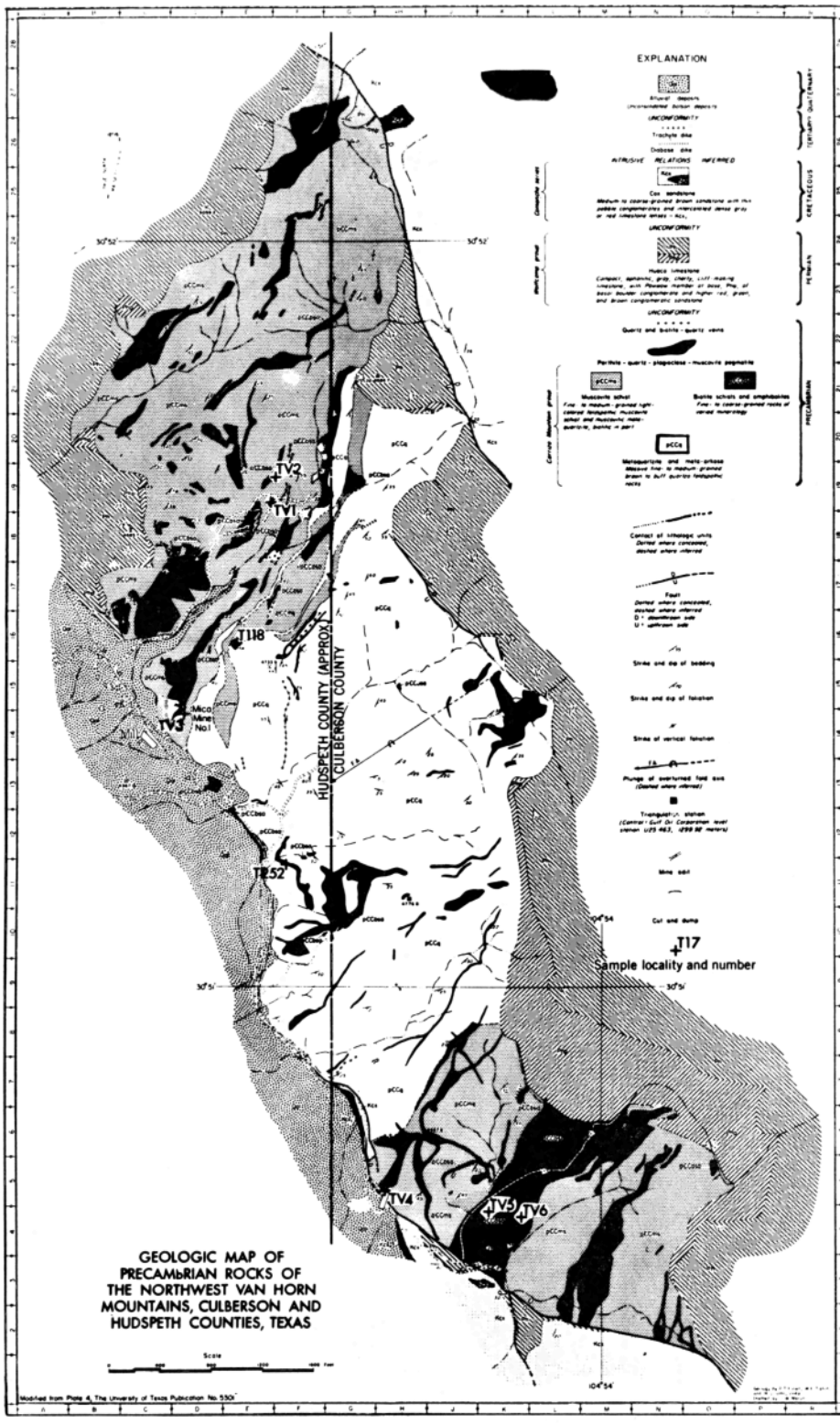


Fig. 5. Geologic map of Mica Mine area in northwest Van Horn Mountains (after Flawn), showing sample localities.

ages was undertaken at this locality because of the wide variety of minerals in the various lithologies and the relative freshness of the rocks. The locality provides an excellent opportunity to compare the ages of several cogenetic metamorphic minerals and a presumably late-stage pegmatite. The sample localities are shown in Figure 5.

A sample (TV-1) of the biotitic muscovite-albite-oligoclase schist was collected. This rock is quite friable, presumably because of the high mica content. Mineral separates of muscovite, biotite, and zircon were made, and in addition a total-rock sample was obtained from a 4-cm cube. Argon and strontium ages were determined on the mineral separates, and a strontium age was determined on the total-rock sample. The zircons are variable in form and color and show markedly irregular forms due to corrosion. The general suite has the appearance of detrital origin modified by reaction in the metamorphic environment.

Hornblende samples were obtained from two amphibolites, TV-2 and TV-6. These samples are of very high purity, and the argon ages are unaffected by any biotite or K-feldspar impurities.

A sample of a coarse-grained biotite schist TV-5 was collected, and the biotite separate was analyzed. The results of these analyses (TV-1, TV-2, TV-5, TV-6) on the metamorphic rocks are presented in Table 6. Except for the TV-1 biotite sample, all the ages are in excellent agreement, the spread being just larger than the analytical error. The TV-1 biotite has a rather low argon age and a distinctly low strontium age.

The maximum age obtained on these metamorphic rocks was 1030 m.y. by the strontium-rubidium method on a muscovite from TV-1.

The total rock age on TV-1 was somewhat low compared with the muscovite result. The zircon concentrate yielded a very discordant set of ages (see Table 3), the Pb^{207}/Pb^{206} age being the highest observed among the zircons studied. The age pattern for the zircon strongly suggests that they retained at least part of their original predetrital daughter products. The great discordance indicates that at least some of the zircons originated considerably more than 1220 m.y. ago. This is reflected in the location of the point representing the TV-1 zircons in the concordia diagram in Figure 3. If the detrital sources of the other minerals in TV-1 were not significantly different from those of the zircons, we must conclude from the whole-rock strontium age of 970 m.y. that the strontium of this system was mixed with a common strontium reservoir at the time of metamorphism.

Samples of four pegmatites were collected: TV-3, TV-4, TV-118, TV-252. TV-3 muscovite was obtained from a single crystal of 17-cm diameter. A cleavage fragment of microcline was taken from the same outcrop. A fraction was ground to pass 40 mesh (total F); the remainder was ground, and the −28 +40 mesh fraction was taken for analysis. The strontium and rubidium contents of these two feldspar fractions are slightly different. The resulting ages are in good agreement. The argon age of the coexist-

TABLE 6. Age Determinations from the Mica Mine Locality near Van Horn, Texas

No.	Rock	Mineral	Age, m.y. K-Ar	Age, m.y. Rb-Sr
TV-1	Muscovite schist	Muscovite	980 ± 20	1030 ± 30
		Biotite	940 ± 20	890 ± 30
		Whole rock		970 ± 50
TV-2	Amphibolite	Hornblende	1000 ± 20	
TV-5	Biotite schist	Biotite	1020 ± 20	990 ± 30
TV-6	Amphibolite	Hornblende	990 ± 20	
TV-3	Pegmatite	Muscovite	1020 ± 20	1090 ± 20
		Feldspar (sized)		1050 ± 30
		Feldspar (total)		1040 ± 30
TV-4	Pegmatite	Muscovite		1060 ± 20
TV-118	Pegmatite	Muscovite	1090 ± 20	1090 ± 20
TV-252	Pegmatite	Biotite	1010 ± 20	970 ± 20

ing mica agrees with the strontium ages of the feldspars but is significantly less than the strontium age of the mica. The feldspar ages and the muscovite strontium age agree just within experimental error. The agreement of the two feldspar ages indicates that there is no significant fractionation of parent or daughter on the scale of the sampling.

Muscovite (TV-4) was obtained from crystals of 2-cm diameter from a graphic granite phase of a pegmatite. TV-118 was collected during previous field work by Flawn. The argon age was first determined, and since it gave a result significantly higher than previous samples the strontium age was also measured. It also yielded a high value of 1090 m.y., which is not different from that obtained on the other pegmatitic muscovites.

In one locality (TV-252) pegmatitic biotite crystals were found. They have a diameter of about 3 cm and occur in a coarse microcline pegmatite as thin (0.1 to 0.2 cm) plates along fractures crosscutting the quartz and feldspar. The biotite is a late-stage phenomenon and shows some iron stains around the borders of the crystals. Fresh elastic material was carefully selected for analysis. The argon age is in good agreement with the other argon results, but the strontium age is distinctly low, by 7 per cent.

From these results on the pegmatitic materials we conclude that the minimum and most probable age of emplacement of the pegmatites is 1090 m.y. These pegmatite results are definitely greater than the ages of the geologically older metasedimentary rocks (970 to 1030 m.y.). Although the discrepancy is not large, it appears to be distinctly greater than the analytical error. This is an additional example of the 'pegmatite-country rock' discrepancy. Assuming diffusion to be the cause of relative daughter loss this would suggest that pegmatitic materials other than biotite have a characteristically smaller D/a^2 value, possibly reflecting larger units in the mosaic structure. The biotites in both the schists and the pegmatites tend on occasion to give low results, particularly by the Sr-Rb method. The preceding data show that during middle-grade metamorphism all the Sr^{87}-Rb^{87} and Ar^{40}-K^{40} clocks in the parent minerals were completely reset during recrystallization, and no evidence of the premetamorphic history appears to be preserved in the micas and amphiboles.

Basement Cores

The minerals dated on the exposed Precambrian rocks of the Trans-Pecos region indicate that all these minerals were formed or recrystallized at about 1100 m.y. This result was obtained on a variety of lithologies representing a wide spectrum of metamorphic and igneous activity. These events appear to be contemporaneous with the metamorphism and plutonism of the Llano area some 500 miles distant. To delineate the occurrence of this activity further it was necessary to use samples of basement cores. Samples were chosen from wells lying between the Van Horn Mountains and the Llano uplift and adjacent regions to test the continuity of the 1100-m.y. event.

For this purpose cores of granite were obtained from Pecos, Schleicher, Williamson, and Coleman counties. Their petrography has been described by *Flawn* [1956]. The well locations and data are given in Figure 6 and Table 7.

Enough of the Pecos County core was available to permit a zircon analysis. However, feldspar separates made from this sample had unfavorable Rb-Sr ratios, and so no other analyses were possible. The Pb^{207}-Pb^{206} age obtained on the zircons was 1070 m.y. The data plot in the concordia diagram close to the same line as the previous samples.

The feldspar separates obtained from the other cores had favorable Rb-Sr ratios and were used for age determination. The cores show considerable fracturing and some alteration, but in the samples presented here the microcline appears fresh and only slightly clouded by alteration. The feldspar in the Schleicher County core shows more staining and clouding than that in the other samples. The biotite in some of the cores was typically altered and shredded and did not appear suitable for dating purposes.

The ages obtained for these samples range from 960 to 1050 m.y. This spread is beyond experimental error and is comparable to the dispersion exhibited by the feldspars from the Franklin Mountains.

Two core fragments from the Coleman County well represented a coarse-grained leucogranite and a fine-grained or aplitic phase. The results are in excellent agreement.

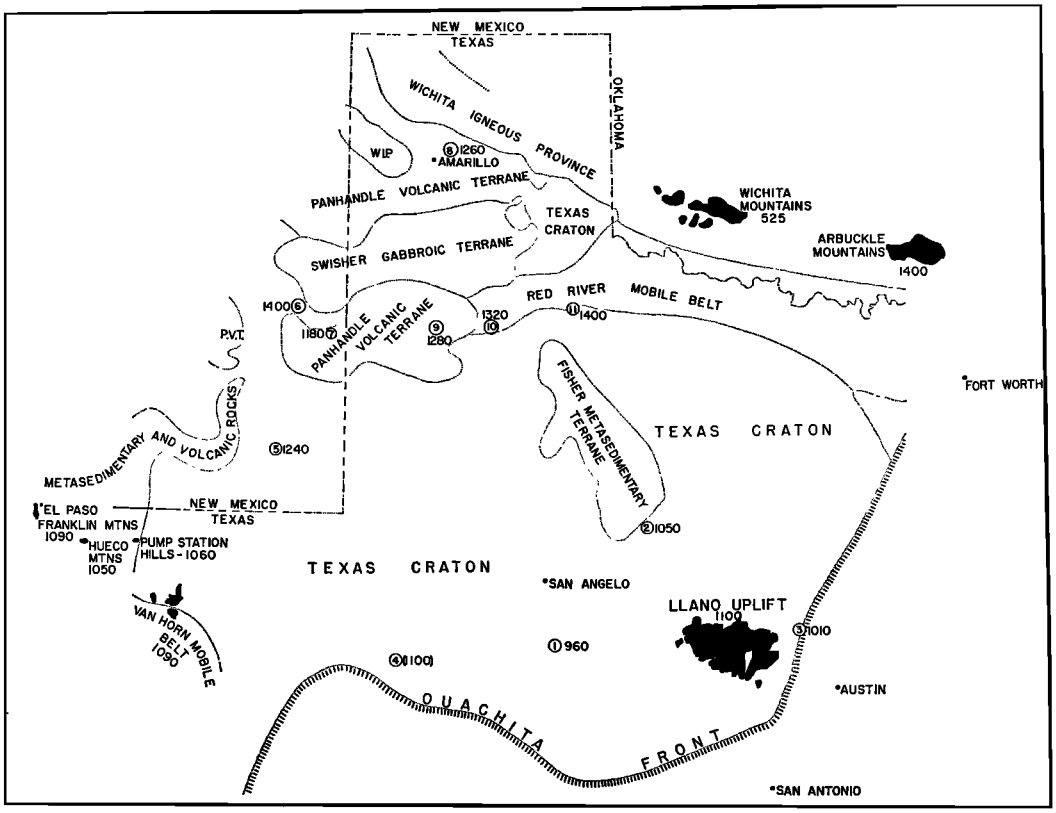


Fig. 6. Map of part of Texas, showing the sample locations and the various terranes as designated by *Flawn* [1956]. Well cores are numbered as in Table 7. The best age estimate for each locality is given.

TABLE 7. Age Determinations on Drill Core Samples

Locality	Rock	Terrane	Mineral	Age, m.y. K-Ar	Age, m.y. Rb-Sr
1. Schleicher Co., Texas	Alkaline granite	Texas craton	Feldspar		960 ± 30
2. Coleman Co., Texas	A. Aplite dike	Texas craton	Feldspar		1050 ± 30
	B. Granite	Texas craton	Feldspar		1040 ± 40
3. Williamson Co., Texas	Granite Gneiss	Texas craton	Feldspar		1010 ± 70
5. Eddy Co., N. M.	Granite	Texas craton	Feldspar		1240 ± 60
6. Roosevelt Co., N. M.	Hornblende Biotite gneiss	Texas craton	Biotite		1400 ± 40
			Hornblende	1390 ± 30	
7. Roosevelt Co., N. M.	Rhyolite	Panhandle volcanic	Feldspar		1180 ± 70
8. Potter Co., Texas	Granite	Panhandle volcanic	Feldspar		1260 ± 40
			Whole rock		1190 ± 70
9. Lubbock Co., Texas	Rhyolite	Panhandle volcanic	Feldspar		1235 ± 120
10. Crosby Co., Texas	Amphibolite	Red River mobile belt? Texas craton?	Hornblende	1320 ± 30	
11. Cottle Co., Texas	Biotite-amphibole Gneiss	Red River mobile belt	Biotite		1400 ± 40
12. Giles Co., Tenn.	Granite	...	Feldspar		1120 ± 30

In addition to these samples several cores were obtained from other areas to gain information on the ages in other parts of the basement as described by *Flawn* [1956].

Flawn outlined a number of structural and lithologic divisions of the Texas and southeast New Mexico basement on the basis of petrographic study of the available basement well cores and samples. He distinguished the following units: Texas craton, Van Horn mobile belt, Red River mobile belt, Panhandle volcanic terrane, Fisher metasedimentary terrane, Swisher gabbroic terrane, and Wichita igneous province. He also attempted to relate these divisions to one another in time by means of lithologic characteristics, structural behavior, and the available age determinations, and he presented a tentative correlation of these subdivisions.

From the limited number of cores available for this study a number of favorable samples were selected for investigation. These samples, described below, are grouped according to Flawn's divisions:

Texas craton. In addition to the granite samples from Pecos, Williamson, Schleicher, and Coleman counties previously described, cores from Eddy and Roosevelt counties, New Mexico, were run. The micrographic granite from Eddy County yielded microcline suitable for strontium analysis. Whereas the biotite in this rock is severely altered, all the feldspars appear rather fresh. The age obtained was 1240 m.y.

The sample from Roosevelt County is described by Flawn as a quartz diorite gneiss. This rock lies beneath a brecciated granite found at a shallower depth in the same well. The rock is quite fresh and contains both biotite and hornblende. An argon age was determined on the hornblende, and a strontium age on the biotite. The results are in very good agreement at 1400 m.y.

Panhandle volcanic terrane. Cores from Roosevelt County, New Mexico, and Potter and Lubbock counties, Texas, were obtained from this terrane.

The samples from Roosevelt and Lubbock counties are rhyolite porphyries. All the feldspars in these rocks show characteristic discoloration and clouding. The Lubbock County sample exhibits distinct flow structure. The alteration of the feldspars is somewhat less than in the previous sample. Feldspar separates were obtained from the rhyolite porphyries, and the strontium ages were measured. The results are 1180 and 1235 m.y.

The Potter County sample is a micrographic granite having some fine-grained phases. The feldspars are partly sericitized and clouded, the degree of alteration being similar to that of the Roosevelt County sample. The strontium age was determined on a total-rock sample taken from a 3-cm cube. The result was 1190 m.y. For a felspar separate from this rock a strontium age of 1260 m.y. was obtained.

Red River mobile belt. Cores were obtained from Crosby and Cottle counties, Texas. Flawn indicated that the assignment of the Crosby County sample is uncertain and that it may belong to the Texas craton. Both cores are quite fresh. Some sericitization of the plagioclase occurs, but it is confined to occasional fractures. Hornblende was obtained from the Crosby County core and biotite from the Cottle County core. Biotite, mostly chloritized, is present in the Crosby County sample. The ages for the two samples are 1320 and 1400 m.y., respectively.

Discussion of Sr^{87}-Rb^{87} and Ar^{40}-K^{40} Results

Comparison of the results obtained on the outcrop materials, where there is more control than in the well cores, indicates several regularities. The pegmatitic muscovites, although showing some scatter, have the highest strontium and argon age in a locality. The strontium ages on microcline are usually in agreement with those on muscovite in the one locality where there are comparisons. The argon ages on amphiboles appear somewhat low; relative to the highest strontium ages they indicate a retentivity of about 90 per cent. Biotites, particularly fine-grained material ($\leq$0.5 mm), yield rather low argon ages and even more disturbed strontium ages.

Conversely, data of other workers [*Aldrich, Wetherill, Davis, and Tilton*, 1958; *Tilton, Wetherill, Davis, and Bass*, 1960] have shown that it is also common for the strontium age of biotite to be greater than the argon age. From the present observations we conclude that no regular relationship is to be expected between the two ages in this mineral, in contrast to potassium feldspar where the argon age is invariably less than (or equal to) the strontium age.

The strontium and argon ages from all the

outcrop samples are illustrated in the histograms of Figure 7. These results show a wide dispersion over a range of about 350 m.y. The maximum age is 1090 m.y., and 77 per cent of the results are above 950 m.y. The maximum age in each of the five outcrop localities lies between 1050 and 1090 m.y. All but one of the ages significantly less than 1000 m.y. are from biotites showing obviously discordant ages.

As previous experience in this field indicates, pegmatitic feldspar and muscovite apparently give the best measure of the absolute age by the strontium and the strontium and argon methods, respectively. The scatter in the ages is due to time resetting mechanisms in which the daughter-parent ratio is diminished in a mineral.

The nature of the resetting mechanisms is somewhat different for each mineral species in response to the particular decay scheme and the physical-chemical characteristics of the species. The mechanisms are poorly understood, and there are few a priori criteria for choosing materials for dating. The general effects, however, are apparent in all the mineral species and are manifest on a very local scale (hand specimen, outcrop, and locality) as well as on a regional scale for rocks that are the product of synchronous primary events. The very local manifestations of age dispersion of one mineral species must be partly due to differential weathering and to differences in the nature of the crystal mosaic and in the particular geometric location of the crystal. The dispersion on a regional scale of a synchronous event is a result of both the local effects and the grosser differences in geologic history. The superposition of several episodes of metamorphism (in the general sense) at different times and intensities at different localities on a primary regional event produces dispersion. This may involve the local 'quenching' of a particular site or mineral early in a regional episode of considerable duration, in which case the dispersion should give information about the time scale for a single-episode regional metamorphism, or it may involve one or more completely independent later events. Several examples of two events clearly separated in time have been found [*Tilton, Davis, Wetherill, and Aldrich,* 1958; *Compston, Jeffery, and Riley,* 1960; *Wetherill, Kuovo, Tilton, and Gast,* 1962]. These results are well known and were elucidated by comparing the Pb-U ages of zircons with the Sr^{87}-Rb^{87} and Ar^{40}-K^{40} ages of the other minerals and by studying the Sr^{87}-Rb^{87} ages in whole-rock samples and in the mineral components. In the present discussion we wish to emphasize the situation where the 'events' are not so disparate in time.

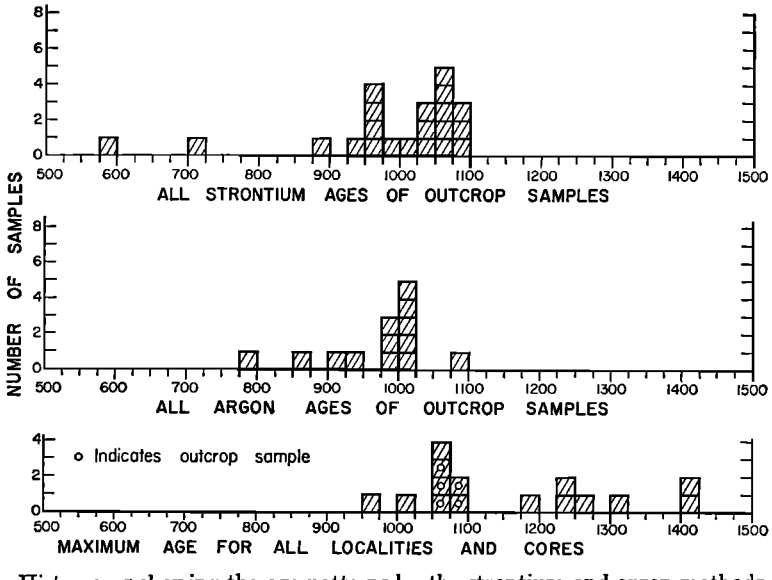


Fig. 7. Histograms showing the age patterns by the strontium and argon methods on all the outcrop materials studied. The lowest diagram shows the maximum ages obtained at each locality by either method.

As a consequence of these resetting processes, for regional-scale phenomena we may expect to obtain a time band with the age distribution dependent on the details and time scale of the processes, as has been discussed in more detail by *Wasserburg* [1961]. The fact that the maximum ages by the strontium and argon methods at all the outcrop localities lie between 1050 and 1090 m.y. strongly suggests that all the rocks are of the same age and that the dispersion observed to be common to them, despite the diversity of their occurrence, is dominantly the product of local phenomena, although some of the other effects may be present. These age measurements are indistinguishable from the results obtained by previous workers on the Llano granites [*Aldrich, Wetherill, Davis, and Tilton,* 1958; *Goldich et al.,* 1961; *Zartman,* 1962, 1963].

Uranium-Lead Ages on Zircons

The Pb^{207}/Pb^{206} ages on the zircons are equal to or greater than the maximum ages obtained by the strontium and argon methods. The zircon isotope ratios from the Trans-Pecos and the Llano localities lie close to a well-defined common line in the concordia diagram (Figure 3), suggesting approximate, if not precise, contemporaneity. It is probable that the zircon data represent a distinct spread in ages among the various areas but in a comparatively small time interval. Both the episodic and continuous diffusion models of lead loss would give a primary age of 1150 to 1200 m.y. for both the Pump Station Hills and the Franklin Mountains, which is greater by about 10 per cent than the maximum age obtained by the other methods. This effect is manifest in some other suites of data comparing zircon-uranium ages with the strontium and argon ages. The reason for this discrepancy is not understood.

Regional Considerations

From the comparison of the results by the various dating methods we conclude that the Franklin Mountains granite, Hueco Mountains granite, Pump Station Hills rhyolite, Carrizo and Van Horn metamorphic rocks and pegmatites, and the Llano granites originated nearly contemporaneously, possibly within a period of 100 m.y. The different lithologies and modes of occurrence, therefore, represent a wide variety of geologic environments in which there has been magmatic activity ranging from shallow intrusion and vulcanism to deep-seated plutonic emplacement and middle-rank metamorphism. These contemporaneous events represent the manifestations of a single diversified orogenic period.

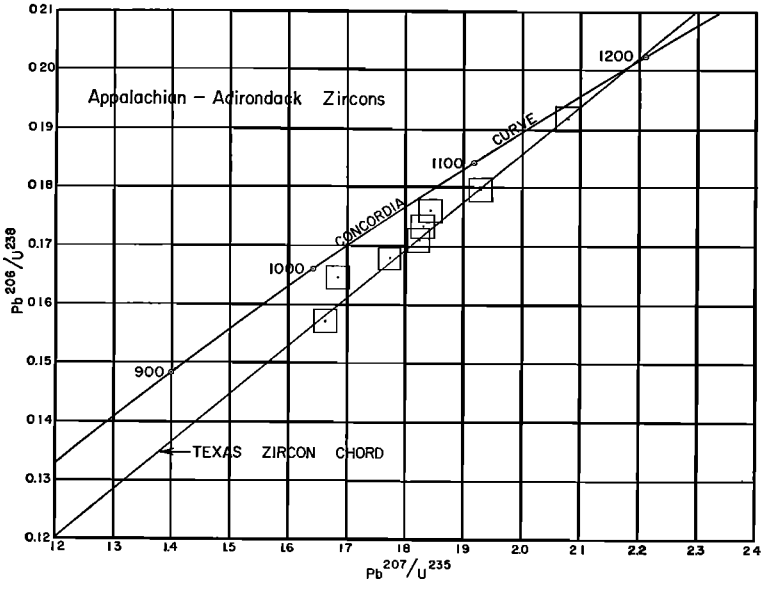


Fig. 8. Concordia diagram illustrating the location of some Appalachian Grenville zircons. The best-fit straight line for the Texas zircons is shown for reference.

Various workers, including *Flawn* [1956] and *Bass* [1960], have used lithologic character and distinctions in lithologic character to map the concealed basement and to make time-tectonic correlations. The results presented above clearly indicate the difficulties inherent in using lithologic character as the principal basis of classification in time-tectonic problems.

The zircon ages determined on the granite core from Pecos County and the strontium ages on cores from Schleicher, Williamson, and Coleman counties indicate that these rocks originated contemporaneously with all the outcrops studied. This finding is highly suggestive of an almost continuous belt of magmatic and orogenic activity extending from El Paso to beyond the Llano-Burnet region—more than 500 miles. The time of this orogeny was about 1090 m.y. by the Sr^{87}-Rb^{87} and Ar^{40}-K^{40} methods and between 1150 and 1200 m.y. by the Pb-U method on zircons. These ages are very similar to those obtained by previous workers on the Grenville orogenic belt in the northeastern United States and Canada [see *Tilton, Wetherill, Davis, and Bass,* 1960]. Some of the ages in this region are complicated by a Paleozoic metamorphism, but where satisfactory comparisons are available by the strontium and argon methods the results are directly comparable with the data presented for Texas. Since the zircon ages are less affected by the younger metamorphism we have plotted the available zircon data for 'Grenville' samples from the northeastern United States and the best-fit chord from the zircon results from Texas on a concordia diagram (Figure 8). Uranium-lead systems in Ontario and Quebec are generally similar but contribute a somewhat broader dispersion to the data. All the results lie essentially on a common line with a rather good fit. The assembled age data from these geographically widespread regions indicate that the Grenville orogeny and the episode of intrusion, extrusion, and metamorphism found in Texas lie in the same time band. Detailed discussion of the dispersion of U-Pb system data for the type Grenville of Ontario and the Adirondack-Appalachians will be discussed by Silver (in preparation). It is our opinion that the orogeny found in Texas should be considered part of the general 'Grenville' orogenic episode. The question of the continuity of this orogeny in the buried basement between Williamson County, Texas, and eastern Tennessee remains open. No basement cores are available from this intervening region. Through the generous cooperation of Manuel Bass one sample of cuttings from a well which penetrated granophyric granite was obtained from south central Tennessee (see Figure 9). A strontium age determination on a feldspar separate gave a result of 1120 m.y. (see Table 7). This result is in agreement with an earlier independent determination by Bass (personal communication).

There is a scarcity of basement cores containing minerals suitable for dating in the intervening region. The availability of such cores in the future will be of great value in clarifying this matter.

The widespread occurrence of the 'Grenville' event (about 1000 to 1100 by Sr-Rb) in northeastern North America has been recently discussed by *Tilton, Wetherill, Davis, and Bass* [1960]. *Silver* [1961], has pointed out that evidence for 1150 to 1200-m.y. magmatic activity appears intermittently from California to Greenland. To illustrate the geographical distribution of these ages we have compiled the available data, including our results, those of *Tilton et al.* [1960], and some recent ages from eastern Canada, southwest Greenland (Illimaussaq), western United States, and the Lake Superior region by other workers [compilation by *Lowdon,* 1961; *Moorbath, Webster, and Morgan,* 1960; *Silver,* 1960, 1961; *Silver et al.,* 1962; *Goldich et al.,* 1961; *Fairbairn, Bullwinkel, Pinson, and Hurley,* 1959]. These data are shown in Figure 9, together with some data indicating older terranes, to delineate the boundary of the Grenville event. These do not represent complete coverage of the older rocks, and none of the Phanerozoic orogenies are represented. The available data suggest that the Grenville orogenic event is the most widespread and pervasive episode of Precambrian orogeny and magmatic activity on the North American continent for which recognizable evidence is preserved.

The Discrepancy between Methods

Some uncertainty remains about the time of the Grenville orogeny, in particular about the age of the orogeny in Texas. It is manifested in part by the dispersion of the strontium and argon ages and by the difference between them and

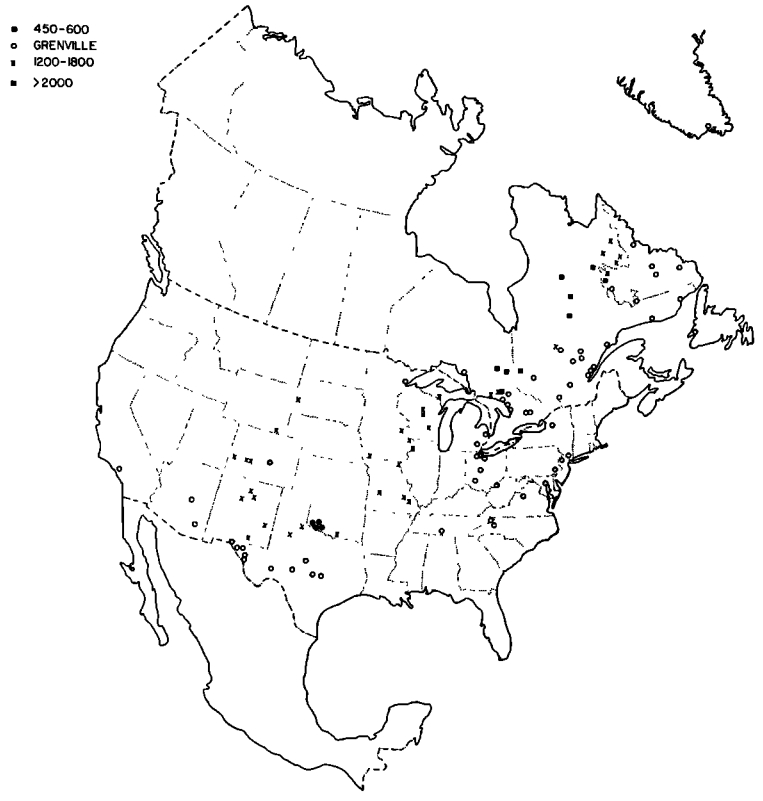


Fig. 9. The occurrence of 1000- to 1200-m.y. events in North America. Open circles represent 1000- to 1200-m.y. events; crosses, events between 1200 and 2000 m.y.; squares, events greater than 2000 m.y. The solid circles represent the 525-m.y. ages found in the Wichita Mountains.

the Pb-U age as determined from the concordia construction. As was seen from the data shown earlier, all the Pb-U ages on the zircons from Texas show varying degrees of discordance. Nevertheless, all these results lie near a single straight line on the concordia diagram with an upper intercept of 1150 to 1200 m.y. and an approximate lower intercept of 200 to 400 m.y. From the point of view of episodic loss [*Wetherill*, 1956] this implies that these zircons represent systems with a primary age of 1150 to 1200 m.y. which were subject to a reduction in their Pb/U ratio 200 to 400 m.y. ago. The continuous diffusion loss model [*Tilton*, 1960] for a 1150- to 1200-m.y. primary age generates an almost identical line over the range for which the data are shown with no inferred second episodic event, and therefore the data do not distinguish between these mechanisms of discordance. The age 1150 to 1200 m.y. is significantly greater than the maximum strontium and argon ages of 1090 m.y. Up to this point we have used the common linear relationship exhibited by the zircons and the characteristic age pattern given by the strontium and argon methods to argue for contemporaneity. However, the precise specification of the age must remain in question because of the differences between the methods. This effect is present in a similar comparison of the different methods in the 'Grenville' of the eastern United States and Canada, where the intercept on the concordia plot (see Figure 8) is again 1150 to 1200 m.y., whereas the oldest strontium and argon ages on associated minerals in this area are about 1070 m.y.

Possible explanations of this discrepancy are an error in the U^{235} half-life superimposed on the 'normal' pattern of lead loss, a loss of intermediate daughter (possibly Rn^{222}) from the U^{238} chain superimposed on the 'normal' pattern of

lead loss, on a differential response of the various minerals to loss of daughter products.

The effect of increasing the decay constant for U^{235} would be to generate a concordia curve displaced to the right of the curve characterized by the original choice of $\lambda_{U^{235}}$ and $\lambda_{U^{238}}$. For small changes the shape of the curve will not be drastically altered. It can be seen that the constant fractional loss of an intermediate daughter product in the U^{238} chain would give a decreased Pb^{206}/U^{238} ratio for a given age. Such changes will decrease the age determined by the intersection of a line with the concordia curve. This is illustrated in Figure 10 for a 2.2 per cent increase in $\lambda_{U^{235}}$. The best-fit line for the Texas zircon data is also shown on the graph. It is evident that the intercept on concordia is widely shifted by this change, the 1200-m.y. intercept on curve *A* changing to a 1100-m.y. intercept on curve *B*. This is due to the small angle of intersection of the episodic loss line and the concordia curve. It is difficult to evaluate the possibility of a constant fractional loss of intermediate daughter, but it seems reasonable to expect such losses to be dependent on the detailed history of each sample and hence to be rather irregular. The regular loss required for the samples reported here would be surprising.

The experimental uncertainty in the decay constant of U^{235} has been discussed by *Aldrich and Wetherill* [1958], who have emphasized that the best determination of this decay constant is the experiment by *Fleming, Ghiorso, and Cunningham* [1952]. The experimental error quoted by these workers is 2.2 per cent. Aldrich and Wetherill concluded that the uncertainty in $\lambda_{U^{235}}$ is at least 2 per cent. An increase of the decay constant by this uncertainty factor would essentially eliminate the discrepancy between the zircon and the strontium and argon ages as presented in this work. There is no independent evidence, however, to justify such a change. A consideration of the changes in the Rb^{87} and K^{40} decay constants necessary to account for the difference in the ages indicates that these are unlikely.

In this paper we have chosen to use the geologically determined decay constant for Rb^{87} [*Aldrich, Wetherill, Tilton, and Davis,* 1956]. There are several recent determinations of this decay constant by counting methods [*Flynn and Glendenin,* 1959; *McNair and Wilson,* 1961; *Egelkraut and Leutz,* 1961; *Beard and Kelly,* 1962]. They show a wide range of values, and it is not possible to choose one of them as definitive. As a matter of convenience we have continued to use the value $\lambda = 1.39 \times 10^{-11}$ yr^{-1} for presenting the age data. When a definitive determi-

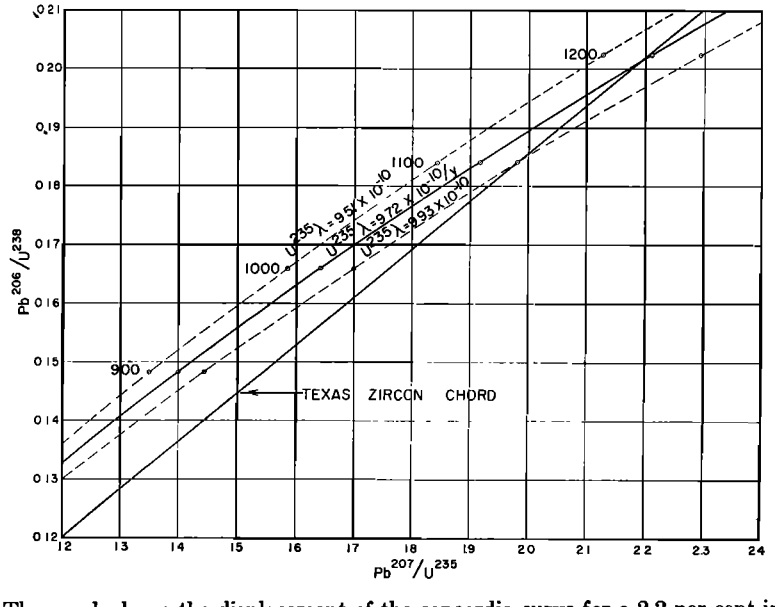


Fig. 10. The graph shows the displacement of the concordia curve for a 2.2 per cent increase in $\lambda_{U^{235}}$. The straight line represents the best fit to the Texas zircon data.

nation of this constant becomes available, all the strontium ages calculated using this value will have to be slightly revised by the same factor.

If the decay constant is significantly decreased below the value used here, the strontium and lead ages reported in this paper will be brought closer to concordance. This would in turn imply a lower argon retentivity in the micas. Such a change is not suggested by our evaluation of present counting results. If the decay constant is increased by as much as 6 per cent [*Flynn and Glendenin*, 1959], the age measurements would indicate that radiogenic strontium is preferentially lost in both feldspars and micas in comparison with argon in micas.

Although zircons very commonly display discordant ages, they are also more likely to preserve evidence of their original age during some metamorphic processes because of the peculiarities of the two uranium decay schemes. It is therefore possible that the difference in ages reported by the strontium and argon methods and by the zircon lead-uranium method is due to the fact that the zircons form partially closed systems under higher temperature (or metamorphic) conditions than the feldspars, micas, and hornblendes. Thus, for example, in deep-seated rocks the zircons could possibly begin registering time before other minerals during a cooling period. This could possibly account for the observations. There is some difficulty in applying this argument to such shallow intrusions as occur in the Franklin Mountains and Pump Station Hills. It is possible that strontium and argon losses under normal near-surface conditions are responsible for this effect or that a more recent undetected thermal event caused the losses.

The available data do not permit any conclusions about the cause of this discrepancy between the methods. It must be resolved by future studies.

Regional Geological Implications

The relationship of the measured ages to the basement provinces of *Flawn* [1956] is complicated. Flawn's fundamental basement element is the Texas craton, which was defined both on a lithologic basis as consisting largely of granitic plutonic rocks and structurally on the basis of its apparent behavior as a stable element after the extensive granitic intrustion [*Flawn*, 1956, p. 68]. The metamorphic rocks of the Carrizo Mountains and Van Horn Mountains which Flawn assigned to the Van Horn Mobile belt were interpreted as younger than the Texas craton because they appeared to have been deformed against a stable mass to the north. The new data developed in this study indicate that the metamorphic rocks of Flawn's Van Horn mobile belt are the same age as some of the rocks assigned to the Texas craton, namely about 1100 m.y. Moreover, rocks in the Pump Station Hills, Hueco Mountains, and Franklin Mountains west of Flawn's Texas craton are of this same age.

In the following discussion the comparative ages in the various terranes are evaluated by restricting consideration to the data obtained by the Rb-Sr method, which provides the most complete locality coverage.

The micrographic granite from Eddy County, New Mexico, was assigned to the Texas craton, but the measured strontium age of 1240 m.y. is distinctly older than that obtained on the previous samples. This result is particularly interesting, since on lithologic grounds the material is almost identical with many of the granites of the craton. The metadiorite from Roosevelt County, New Mexico, comes from a rather complex area that was assigned to the Texas craton. The age obtained for this material, 1400 m.y., is the oldest found in our study.

Similar older ages of 1320 and 1400 m.y. are found in metamorphic rocks in cores from Crosby and Cottle counties, respectively. These localities have been assigned by Flawn to the Red River mobile belt. Previous work by *Tilton, Wetherill, and Davis* [1962] on rocks from the Arbuckle Mountains also gives ages of 1400 m.y. by the strontium, argon, and lead methods.

Samples of rhyolites from the Panhandle volcanic terrane in Roosevelt County, New Mexico, and Lubbock County, Texas, and a granite from Potter County, Texas, give ages of 1180, 1235, and 1260 m.y., respectively. All these ages are greater than the 1090 m.y. that appears so commonly farther south across the Texas craton.

No evidence of the younger igneous event of 500 m.y. found in the Wichita Mountains, Oklahoma [*Tilton, Wetherill, and Davis*, 1962], has been found in Texas. *Roth* [1960] has reported a whole-rock Ar^{40}-K^{40} age of 650 m.y. on a rhyolite core from Deaf Smith County, Texas. The

result reported by Roth is at best a minimum age, since it is well known that argon is lost from feldspars. The age he reported was unsubstantiated as to analytical accuracy and is an isolated result of questionable quality. Such a measurement cannot be seriously considered evidence of a younger event.

The rhyolites in the Panhandle volcanic terrane pose a very puzzling problem. They include extrusive rocks which Flawn interpreted as extruded on rocks of the Texas craton and therefore younger than the 1100-m.y. granite rocks. The new data presented here indicate that they are older. Petrographically they are similar to the younger 500-m.y. suite in the Wichita Mountains, but they are also petrographically similar to the older Precambrian rhyolites in Missouri. The samples from the Panhandle volcanic terrain suggest that this terrain may be a true time unit. Since it is made up almost exclusively of extrusive rocks, it must rest on an older (earlier than 1250-m.y.) basement.

All the results are illustrated in the histogram of Figure 7. There is little doubt that the ages of 1090 and 1400 m.y. are well resolved. The ages ranging from 1180 to 1260 m.y. are significantly greater than the 1090-m.y. results. It is not clear whether these 1090-m.y. results represent a single event or a degraded or dispersed older event. The older ages (1100 to 1200 m.y.) obtained on zircons from the so-called 1090-m.y. rocks also suggest the possibility that the true age of these rocks is about 1200 m.y. If so, the distinction between the 1090- and the 1180- to 1260-m.y. ages becomes uncertain. It may be noted that all the 1180- to 1260-m.y. ages are the same to within analytical error. From consideration of earlier discussions we tentatively conclude that the 1180- to 1260-m.y. results represent a single event at about 1250 m.y. and that this is distinct from the 1090-m.y and the 1400-m.y. events. The 1320-m.y. age is from a hornblende. The comparisons presented earlier indicate that this result may be low by several per cent. We thus assign the 1320- to 1400-m.y. samples to a single episode at about 1400 m.y. The rocks of this age may represent an orogenic belt extending to the Arbuckle Mountains. It now appears that Flawn's Texas craton is composed of older rocks, 1250 to 1400 m.y., to the north, and a younger 1090-m.y terrane to the south. These rocks are part of the larger cratonic structure comprising all the buried basement studied, the southern part of this province being a dominantly granitic terrane that appears to be a southwestern extension of the Grenville belt. To the north this larger cratonic structure contains older rocks of 1250- and 1400-m.y. age. The southern boundaries are undefined. The preceding assignments are partly arbitrary, and they must be looked on as tentative until more materials have been studied and the dating methods better understood.

In the oversimplified picture presented above, we may appear to have assumed that the orogenic events must actually be associated with very sharply defined times. The problem of the dispersion of ages and the existence of time bands makes such a simplified interpretation doubtful. More data on adequate samples may clarify the question of the width of the time bands. Our knowledge of the episodes of igneous and metamorphic activity in the Phanerozoic shows clearly that in certain regions there were long intervals of time that were almost densely populated with orogenies. Certain events may have been more widespread and indicate a greater intensity of activity, but they were not always widely separated in time. If we consider the age distribution in the Phanerozoic translated back in time by 1000 m.y., we would see that the events which are resolved stratigraphically and sometimes geochronologically in the Phanerozoic may (within the experimental error and natural dispersion) merge in the translated assemblage, and from this point of view could appear more as a continuous distribution. Our understanding of Phanerozoic history indicates that we need not always expect to find sharply defined, widely spaced orogenic episodes in the Precambrian. The only evidence suggesting a change in orogenic phenomena between the Phanerozoic and the Precambrian is the fact that in North America where many age measurements have been made there is no evidence for an orogeny that occurs between the early Cambrian (about 500 to 550 m.y.) and the Grenvillian at about 1100 m.y. The present study again fails to indicate any event in this wide (some 500-m.y.) time gap. Less complete data on other continents indicate a gap of at least between 650 and 1000 m.y. The existence

of this period of orogenic quiescence is a most remarkable fact deserving considerable attention.

The outcrop and well core data for all the samples studied indicate some relationships different from those based on the regional lithologic-structural interpretation of the basement as presented by *Flawn* [1956]. It is evident that a classification based solely on lithologic and structural criteria in the absence of a reliable stratigraphy may yield equivocal results in interpreting geologic history. Flawn emphasized this earlier and pointed out that, in the absence of age data, many of the time-tectonic conclusions are decidedly tentative and conjectural. Several difficulties are inherent in such an approach. One is the fact that most rock types occur throughout the geologic column, and, consequently, a lithologic type is not necessarily a time type. This includes much finer correlations such as those based on accessory minerals and mode of occurrence, which sometimes appear to be more exclusive criteria.

Perhaps the greatest difficulty with all our studies is that a fundamental understanding of orogenic processes and driving forces is very incomplete, and our ability to make consequential predictions in this field is singularly lacking. We in no way imply that age measurements will provide the critical answers, but in favorable circumstances they may permit a clearer interpretation of simultaneity (of crystallization) and possibly add more knowledge to the morphology of orogenesis, so that some more fundamental insight may provide a basis for understanding.

Appendix

Analytical Procedures

The analytical procedures were essentially those reported in previous papers. Argon was extracted from the minerals by fusion in molybdenum crucibles with a radio-frequency heater. All the samples were heated to a temperature of 1400°C, producing a fluid melt. One sample of biotite was heated to produce a sintered mat, and a split of the same material was heated to 1400°C. The argon yields were the same. The gases produced during heating were frozen out continuously on charcoal at liquid nitrogen temperature. After the fusion was completed, the charcoal traps were warmed and the sample was mixed with Ar^{38} tracer which had been introduced previously. The gases were then purified over hot CuO and passed through a cold trap into a titanium furnace. After purification the argon residue was transferred to the mass spectrometer using a charcoal sample tube. The samples were run on a 60° sector mass spectrometer with a 6-inch radius of curvature. This instrument has two collectors, one of which is a normal Faraday cup and the other an electron multiplier. Ar^{40}/Ar^{38} data were taken on the simple collector, Ar^{36}/Ar^{38} data on the multiplier.

Discrimination was monitored by running normal argon samples. Samples TV-3M, TV-5Bi, and TV-6Hbd were each run in duplicate for argon; the maximum difference observed was 2 per cent. The Ar^{38} tracers were made by a pipetting technique following P. Hurley and J. Zähringer (personal communication). The particular spike line used in this laboratory was designed and tested by Dr. M. Lanphere, R. E. Zartman, and G. J. Wasserburg. This apparatus consists of a 2-liter reservoir and a double pipette isolated by two stopcocks and two mercury cutoff reservoirs (Figure 11). The pipette

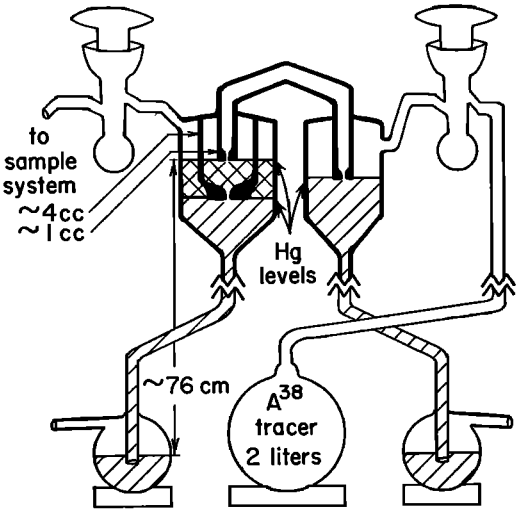


Fig. 11. Argon spike pipette. Drawing not to scale. An aliquot of the spike is taken by raising the left-hand column to one of the two cutoff positions. The right-hand column is lowered below the cutoff and the gas is equilibrated. The aliquot is then isolated by raising the right-hand column. The fractional depletion per release is about 2×10^{-3}.

TABLE 8. Analytical Data for Rb-Sr and K-Ar Ages

Sample	K, %	Ar^{40*}, 10^{-8} mole/g	Ar^{40*}/Ar^{40}	Rb, ppm	Sr^{87*}, ppm	Sr^{87*}/Sr^{87}
TH-1 (Bi)	6.19	1.416	0.97	2274	8.35	0.90
TH-1 (F)	...	...	...	304.9	1.253	0.36
TH-2 (Bi)	6.06	1.168	0.96	243.5	0.684	0.095
TH-5 (Hb)	0.937	0.2195	0.90	...	...	...
TH-5 (F)	...	...	...	282.9	1.089	0.14
TH-6 (F)	...	...	...	3483	15.02	0.95
TV-1 (M)	8.54	1.947	0.98	244.2	1.001	0.50
TV-1 (Bi)	7.14	1.540	0.96	442.0	1.557	0.61
TV-1 (Rk)	...	...	...	85.42	0.3274	0.14
TV-2 (Hb)	0.176	0.04114	0.52	...	...	...
TV-3 (M)	8.58	2.071	0.96	1070	4.608	0.93
TV-3 (F)	...	...	...	427.0	1.781	0.46
TV-3 (total F)	...	...	...	422.8	1.736	0.49
TV-4 (M)	...	...	...	663.0	2.791	0.84
TV-5 (Bi)	7.69	1.845	0.99	336.4	1.326	0.65
TV-6 (Hb)	0.253	0.05841	0.79	...	...	...
TV-10a (Bi)	5.92	1.014	0.94	651.5	1.505	0.47
TV-10b (Hb)	0.268	0.0548	0.80	...	...	...
TV-12b (Bi)	...	...	...	187.3	0.710	0.11
TV-12c (Rk)	...	...	...	103.6	0.441	0.097
TV-13 (F)	...	...	...	374.5	1.576	0.26
TV-13 (Rk)	...	...	...	180.2	0.724	0.13
TV-14 (F)	...	...	...	184.8	0.760	0.11
TV-118 (M)	8.58	2.256	0.96	875.9	3.796	0.93
TV-252 (Bi)	7.60	1.805	0.98	937.8	3.60	0.76
Drill Cores						
1. Schleicher Co., Texas (F)	...	...	...	471.1	1.782	0.33
2A. Coleman Co., Texas (F)	...	...	...	676.7	2.807	0.57
2B. Coleman Co., Texas (F)	...	...	...	736.8	3.026	0.26
3. Williamson Co., Texas (F)	...	...	...	346.9	1.382	0.093
5. Eddy Co., N. M. (F)	...	...	...	256.7	1.265	0.15
6. Roosevelt Co., N. M. (Hb)	1.19	0.433	0.95	...	...	...
(Bi)	...	...	...	318.2	1.769	0.43
7. Roosevelt Co., N. M. (F)	...	...	...	291.8	1.359	0.11
8. Potter Co., Texas (F)	...	...	...	532.8	2.669	0.26
(Rk)	...	...	...	280.6	1.322	0.12
9. Lubbock Co., Texas (F)	...	...	...	234.6	1.150	0.077
10. Crosby Co., Texas (Hb)	0.869	0.295	0.87	...	...	...
11. Cottle Co., Texas (Bi)	...	...	...	314.1	1.745	0.36
12. Giles Co., Tenn. (F)	...	...	...	182.3	0.810	0.41

has a sufficiently large volume to overcome the problems associated with capillary tubes. The double pipette permits the removal of two different spike aliquots, depending on the sample size. The ends of the pipette are tapered to a 2-mm bore and are ground flat. Aliquots of the spike are transferred by expanding into the sample system and freezing on charcoal. The whole apparatus is built in a portable frame and can be conveniently moved after cutting the connection to the sample line.

Potassium analyses were done on a Perkin-Elmer flame photometer using a lithium internal standard. In addition, all the hornblende analyses were done by isotope dilution. The results by the two methods agreed to within experimental error. The estimated maximum error in the Ar^{40}/K^{40} ratio is taken to be 2.5 per cent.

The atomic abundance of K^{40} was taken to be 1.19×10^{-4}, and the decay constants used are $\lambda_e = 0.585 \times 10^{-10}\ yr^{-1}$, $\lambda_\beta = 4.72 \times 10^{-10}\ yr^{-1}$.

The isotope dilution procedures for the strontium and rubidium analyses are essentially those developed at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. We should particularly like to thank the members of that group for aiding us in setting up the procedures.

Samples were run by a surface ionization technique on a 60° sector mass spectrometer with a 12-inch radius of curvature, with an electron multiplier as the collector. Discrimination was monitored by running normal rubidium and strontium.

The rubidium and strontium tracer solutions were calibrated by mixing with known normal rubidium and strontium solutions. The normal rubidium solutions were made with spectroscopically pure RbCl purchased from Johnson and Matthey and Co., Ltd., and with RbCl purified from C.P. grade salt by the $RbICl_2$ procedure as described by *Archibald* [1932]. Both salts were analyzed by a conventional optical spectrographic method for cationic impurities and were found to contain less than 0.01 per cent for the maximum impurity. Rubidium and

TABLE 9. West Texas Zircon Analyses

	Observed Lead Isotope Ratios			Radiogenic Lead Isotopic Composition, atom %			Concentrations, ppm	
	Pb^{206}/Pb^{204}	Pb^{206}/Pb^{207}	Pb^{206}/Pb^{208}	Pb^{206}	Pb^{207}	Pb^{208}	Pb^{rad}	U
Micrographic granite (TH-5), Franklin Mts., El Paso Co.								
Fraction A	905.7	11.141	5.459	81.80	6.16	12.05	50.4	330
Fraction B	711.5	10.544	4.277	79.38	5.93	14.49	71.8	527
Rhyolite porphyry (TV-13), Pump Station Hills, Hudspeth Co.								
Fraction A	351.4	8.413	3.268	77.71	6.09	16.20	61.6	313
Fraction B	528.4	9.616	3.654	77.77	5.99	16.24	54.1	299
Granite well core, Phillips Puckett # 1c, Pecos Co.								
Total zircon	459.5	9.482	4.852	82.98	6.16	10.86	32.4	205
Muscovite-oligoclase-quartz schist (TV-1), Van Horn Mts., Hudspeth Co.								
Zircon fraction, pass 200 mesh	177.5	6.244	2.894	81.50	6.53	11.97	42.0	329
Common Pb correction	206/204 17.9	207/204 15.65	208/204 38.0					

chlorine were determined in duplicate on the Johnson and Matthey material. Rubidium was determined as the perchlorate after a butyl alcohol–ethyl acetate extraction. The chloride was determined by precipitating AgCl from a $AgNO_3$ solution. The RbCl was found to be stoichiometric to within better than 0.1 per cent.

The normal strontium solutions were made with spectroscopically pure $SrCO_3$ (Johnson and Matthey and Co., Ltd.) and reagent grade $SrCO_3$ (Merck). The cationic impurities of both salts were negligible. The salts were analyzed in duplicate by the following procedures. Strontium was precipitated as the sulfate from acid solution containing 50 per cent by volume C_2H_5OH (denatured), washed in 95 per cent C_2H_5OH, and filtered; the precipitate was dried to constant weight at 700°C. The salts were also converted directly to the sulfate. The results showed that the $SrCO_3$ was stoichiometric to within 0.1 per cent.

The interlaboratory standards M1A-Std microcline and B-3203 biotite were analyzed. The results obtained on M1A-Std are 6.78 ppm Sr^{87*} and 1004 ppm Rb. The results obtained previously by L. T. Aldrich (personal communication) are 6.90 ppm Sr^{87*} and 1010 ppm Rb. The results obtained on B-3203 Bi are 1.701 ppm Sr^{87*} and 440.6 ppm Rb. G. W. Wetherill (personal communication) had previously obtained 1.707 ppm Sr^{87*} and 439 ppm Rb. Our values are in good agreement with the data reported by these workers. The data on B-3203 Bi are somewhat different from the results by P. Hurley (personal communication).

The Carnegie Institution rubidium tracer concentration was determined by us. Our results agreed to within 0.5 per cent of the value measured previously by Wetherill et al. (personal communication).

Duplicate analyses were done on several samples, including the following. Eddy County, New Mexico, feldspar: 256.6 ppm Rb, 1.274 ppm Sr^{87*}. TH-1 biotite: 2278 ppm Rb, 8.269 ppm Sr^{87*}. TV-1 biotite: 438.5 ppm Rb, 1.574 ppm Sr^{87*}. These results are in good agreement with the first measurements reported in Table 8.

The estimated maximum error in the Sr^{87*}/Rb^{87} ratio is taken as 2 per cent for highly radiogenic samples. For samples only slightly enriched in radiogenic strontium the errors are considerably amplified, owing to changes in discrimination of the mass spectrometer. For a 10 per cent enrichment the maximum error is estimated as 6 per cent. A more complete discussion of analytical errors is given by *Zartman* [1963].

The decay constant used for calculating the strontium ages is $\lambda = 1.39 \times 10^{-11}$ yr^{-1}. The isotopic ratios for normal strontium used in this work are $Sr^{86}/Sr^{88} = 0.1194$, $Sr^{87}/Sr^{88} = 0.0843$. The ratio Sr^{87*}/Sr^{87} given in the last column of Table 8 is the ratio of radiogenic Sr^{87} to total Sr^{87} in the experiment.

Description of Thin Sections of Rocks and Mineral Separates

Van Horn Mountains

TV 1. Quartz and albite-oligoclase (79%), muscovite (15%), potassium feldspar (5%), biotite (1%), apatite (tr.), zircon (tr.). Parallel oriented plates of muscovite and pale-brown biotite occur in a quartz-feldspar mosaic. Grain size: 0.1–0.3 mm. Fabric: crystalloblastic. Rock: *biotitic muscovite albite-oligoclase schist.* Muscovite separate (−40 +80 mesh): 98.5% musc., 15% qtz., bio, plag. Biotite separate (−40 +80 mesh): 89% bio, 6% musc., 1% partly chloritized biotite, 4% opaques, feldspar, quartz.

TV 2. Plagioclase (56%), hornblende (40%), magnetite-ilmenite (4%), apatite (tr.). Blue-green hornblende in sheaves and small prismatic grains, locally poikiloblastic, forms a mosaic with plagioclase (oligoclase-andesine). Grain size: 0.2–0.3 mm, hornblende up to 2 mm. Fabric: crystalloblastic. Rock: *amphibolite.* Hornblende separate (−80 +100 mesh): 97% hbd. 0.2% musc., 0.8% opaques, 2% plagioclase and unidentified inclusions.

TV 3. Pegmatitic perthite containing shreds of muscovite, small grains of quartz, and a trace of apatite. Feldspar quite fresh. Some slight discoloration.

TV 5. Quartz (48%), plagioclase (25%), biotite (25%), muscovite (2%), garnet (tr.), hematite (tr.), apatite (tr.), zircon (tr.). Dark green biotite and poikiloblastic sodic (?) plagioclase occurs in a mosaic of strained quartz. Plagioclase is partly to completely altered to sericite. Grain size: 0.2–3 mm. Fabric: crystalloblastic. Rock: *biotite schist.* Biotite separate (−40 +80 mesh): 96% bio., 1% musc., 1% opaques, 2% plag. and qtz.

TV 6. Plagioclase (51%), hornblende (45%), magnetite-ilmenite (4%), biotite (tr.), apatite (tr.). Prismatic to large poikiloblastic blue-green hornblende grains occur in an aggregate with incipiently sericitized plagioclase (oligoclase-andesine). Grain size: 0.2–0.5, hornblende up to 2 mm. Fabric: crystalloblastic. Rock: *amphibolite.* Hornblende separate (−40 +80 mesh): 96% hbd., 3.6% opaques, 0.4% apatite.

TV 12B. Plagioclase (45%), biotite (30%), hornblende (10%), epidote (7%), microcline (2%),

sphene (2%), magnetite-ilmenite (2%), quartz ? (1%), apatite (1%). Plagioclase, partly altered to epidote, occurs as broken twinned subhedra and mosaic fragments. Green biotite forms a foliated mass and includes hornblende prisms and grains of epidote. Sphene occurs as abundant clusters of small grains. A few large grains of microcline are present, and quartz (?) occurs as a granular aggregate around some feldspar grains. Grain size: average 0.1–0.5 mm, larger grains up to 2 mm. Fabric: relict hypidiomorphic granular-crystalloblastic. Rock: *hornblende-epidote-biotite schist* derived from alteration of an igneous rock, probably a diorite. Biotite separate (−100 +150): 73% bio., 2% hbd., 7% chlor., 2% qtz. and feldspar, 12% opaques, 4% epidote.

TV 12-C. Plagioclase and microcline (10%), quartz (5%), groundmass (85%), calcite (tr.), sericite-muscovite (tr.), sphene (tr.), zircon (tr.). Large grains of microcline and plagioclase subhedra (phenocrysts) together with fragments of quartz mosaic occur in a crushed and sheared groundmass of alkali feldspar and quartz containing sericite fibers. Quartz mosaic fragments may be fragments of broken quartz veins. Other quartz veins occur parallel to the flow structure or foliation in the groundmass. Grain size: groundmass 0.01–0.10 mm, phenocrysts up to 2 mm. Fabric: relict prophyritic-cataclastic. Rock: sheared *rhyolite porphyry* or *metarhyolite.*

Carrizo Mountains

TV 10A. Quartz and albite-oligoclase (74%), biotite (14%) partly altered to chlorite (20%), muscovite (7%), garnet (2%), apatite (tr.), zircon (tr.), iron oxides (1%), tourmaline (tr.). Thinly laminated schist with alternate coarser-grained quartz-rich laminas and finer-grained mica-rich laminas. Orientation of both micas is transverse to lamination and does not show good orientation. Grain size: 0.1–0.5 mm. Fabric: crystalloblastic laminated. Rock: *garnet-biotite schist.* Biotite separate (−100 +150): 76% bio., 16% chlor., 3% qtz. and plag., 1% hbd., 1% musc., 3% opaques.

TV 10B. Hornblende (34%), plagioclase and quartz (57%), epidote (6%), opaques (2%), sphene and apatite (1%), biotite (tr.). Blades of hornblende randomly oriented in a finer-grained mosaic of plagioclase and epidote. Separate clots of epidote and of hornblende occur irregularly through the rock. Magnetite in irregular coarse aggregates. Grain size: 0.1–2 mm. Fabric: Rock: *amphibolite.* Hornblende separate: 88% hbd., 10% iron stained hbd., 2% opaques.

Hueco Pump Station and Pump Station Hills

TV 13. Feldspar phenocrysts (15–20%), largely altered to clay (?) and rounded and corroded quartz phenocrysts (75–80%) occur in a granophyric groundmass. The groundmass contains sericite, chlorite, and biotite (?) as well as finely intergrown quartz and alkali feldspar. Biotite (?) occurs as tiny plates. Zircon (tr.) is present. Grain size: phenocrysts up to 3–5 mm, groundmass intergrowth 0.2–0.4 mm. Fabric: porphyritic. Rock: *rhyolite porphyry.*

TV. 14. Microcline microperthite (80%), plagioclase and quartz (15%), amphibole (5%), epidote (tr.), magnetite-ilmenite (tr.), zircon (tr.). Microcline microperthite occurs as large grains and as smaller grains in an intergranular aggregate with sodic plagioclase and quartz. Quartz occurs as round grains in feldspar and in amphibole. The amphibole is a deeply colored green to brown hornblende that occurs in large skeletal grains. Grain size: perthite 1 cm ±, smaller grains 0.1–5 mm. Fabric: panallotriomorphic granular. Rock: *hornblende granite.*

Franklin Mountains

TH 1. Microcline microperthite (70%), sodic plagioclase (10%), quartz (10%), biotite (8%), sericite (1%), fluorite (1%), magnetite-ilmenite (tr.), zircon (tr.). Microcline microperthite occurs in large grains; plagioclase, as twinned subhedra. Deeply colored brown biotite forms large irregular skeletal grains and also occurs in small plates. It is partly altered to a fibrous mass that may be a mixture of bleached biotite, chlorite, and sericite. Fluorite is in large grains connected by thin veinlets. Zircon is abundant. Grain size: 0.5–5.0 mm. Fabric: hypidiomorphic granular. Rock: medium- to coarse-grained *biotite granite.* Biotite separate (−20 +40 mesh): 82% bio., 4% hbd., 9% opaques, 5% qtz., plag., microc.

TH 2. Plagioclase (60%), biotite (26%), tourmaline (8%), sphene (2%), ilmenite (2%), semi-opaque titanium (?) mineral (2%), microcline (tr.), pyrite (tr.), apatite (tr.). Plagioclase (oligoclase?) and biotite occur in a poikiloblastic mosaic. Foliation is well developed. Plagioclase is partly altered to sericite. Large poikiloblasts of plagioclase and pink-brown tourmaline enclose other rock constituents. The semiopaque mineral may be mixed sphene and leucoxene. Grain size: poikiloblasts 1.0–2.0 mm., groundmass 0.05–0.20 mm. Fabric: crystalloblastic-poikiloblastic. Rock: *tourmaline-biotite-plagioclase schist.* This is an interesting rock which shows disequilibrium relations. Growth of poikiloblasts may be a reflection of near-by granitic intrusion. Biotite separate (−40 +80 mesh): 75% bio., 24% bio. with opaque inclusions, 1% qtz. and feld. No chlorite observed.

TH 5. Microcline microperthite (75%), myrmekite (10%), biotite and amphibole (8%), quartz (7%), magnetite-ilmenite (tr.), apatite (tr.), zircon (tr.). Microcline microperthite occurs as large grains. Micrographic intergrowths are rare. Ferromagnesian minerals occur as intergranular 'nests.' Grain size: microperthite up to 1 cm, interstitial grains 0.2–1.0 mm. Fabric: granophyric. Rock: *biotitic hornblende granite.* Hornblende separate (−60 +200): 69% hbd., 14% bio., 1.5% microcl., 2% qtz., 8% zircon, 5.5% opaques.

Basement Cores

The majority of cores are described by *Flawn*

[1956]. The page reference to the core description is given by the number (FXXX).

1. Schleicher Co., Texas. Humble No. 1 Spencer 6909–10 feet (F-196).

2. Coleman Co., Texas. Naylor No. 1 Stone 5335–38 feet (F-140).

3. Williamson Co., Texas. Shell and Sinclair No 1 Purcell 9474–79 feet (F-202).

4. Pecos Co., Texas. Phillips No. 1-C Puckett 14924-30 feet (F-189).

5. Eddy Co., New Mexico. Richardson and Bass No. 1 Cobb-Federal 16459 feet (F-216).

6. Roosevelt Co., New Mexico. Spartan No. 1–36 State 7240–42 feet (F-232). Biotite separate (—40 +80 mesh): 91% bio., 8% hbd., 1% opaques, feldspar, sphene.

7. Roosevelt Co., New Mexico. Shell Saunders No. 1 8650 feet (F-231). 86% hbd., 6.5% bio., 2.7% alkaline feldspar, 2% quartz, 2.8% opaques, plagioclase, apatite, zircon.

8. Potter Co., Texas. Shell Bivins Ranch No. 1–207 located 1000 feet from west line and 660 feet from north line, section 207, block 2, AB and M Survey, micrographic granite.

9. Lubbock Co., Texas. Farris No. 1—11 778–83 feet (F-175).

10. Crosby Co., Texas. Humble No. 1 Irvin 9947 feet (F-147). Hornblende separate (—80 +100 mesh): 98% hbd., 0.2% feldspar, 1.8% opaques, epidote, sphene, and zircon.

11. Cottle Co., Texas. General Crude No. 13–1 Swenson 5719–20 feet (F-144). Hornblende separate (—80 +150 mesh): 95% hbd., 3% biotite, 1.6% feldspar, 1.4% apatite, opaques.

12. Giles Co., Tennessee. California Company No. 1 E. W. Beeler NE, NE, section 4-15S-29E ⅓ mile SW of Campbellsville 5620–5750. Cuttings. Massive granophyric porphyry. Microcline phenocrysts. Contains a blue sodium amphibole (0.5%) plagioclase (tr.), the remainder being quartz and microcline.

Acknowledgments. We should like to acknowledge the help of Robert L. Harbour of the U. S. Geological Survey, who generously aided us in our collecting trip to the Franklin Mountain area. Some of the core samples were made available to us through the kindness of Dr. R. G. Swanson of the Shell Oil Company, Dr. Milton Williams of the Humble Oil and Refining Company, and Dr. James F. Johnson of the Sinclair Oil Company.

We should particularly like to thank Professor Manuel Bass, whose enthusiastic interest encouraged this work and who gave freely of his time and knowledge in discussing the problems.

This work was supported by the National Science Foundation grants NSF-G19084 and NSF-G15945, and the Atomic Energy Commission contract AT(11-1)-208.

References

Aldrich, L. T., and G. W. Wetherill, Geochronology by radioactive decay, *Ann. Rev. Nuclear Sci., 8,* 257–298, 1958.

Aldrich, L. T., G. W. Wetherill, G. L. Davis, and G. R. Tilton, Radioactive ages of micas from granitic rocks by Rb-Sr and K-A methods, *Trans. Am. Geophys. Union, 39,* 1124–1134, 1958.

Aldrich, L. T., G. W. Wetherill, G. R. Tilton, and G. L. Davis, Half life of Rb^{87}, *Phys. Rev., 103,* 1045–1047, 1956.

Archibald, E. H., *The Preparation of Pure Inorganic Substances,* John Wiley & Sons, New York, 1932.

Barrell, J., Rhythms and the measurements of geologic time, *Bull. Geol. Soc. Am., 28,* 858–871, 1917.

Bass, M. N., Grenville boundary in Ohio, *J. Geol., 68*(6), 673–677, 1960.

Beard, G. B., and W. H. Kelly, *Nuclear Phys.,* in press, 1962.

Cloud, P. E., V. E. Barnes, and J. Bridge, Stratigraphy of the Ellenburger group in central Texas —a progress report, *Univ. Texas Publ. 4301.* 133–161, 1943, 1945.

Compston, W., P. M. Jeffery, and G. H. Riley, Age of emplacement of granites, *Nature, 186,* 702–703, 1960.

Egelkraut, K., and H. Leutz, *Z. Physik, 161,* 13–19, 1961.

Fairbairn, H. W., H. J. Bullwinkel, W. H. Pinson, and P. M. Hurley, Age investigations of syenites from Coldwell Ontario (abstract), *Bull. Geol. Soc. Am., 69*(12), p. 1543, 1959.

Flawn, P. T., Pegmatites of the Van Horn Mountains, Texas, *Econ. Geol., 46*(2), 163–192, 1951.

Flawn, P. T., Basement rocks of Texas and southeast New Mexico, *Univ. Texas Publ. 5605,* 1956.

Fleming, E. H., Jr., A. Ghiorso, and B. B. Cunningham, The half life of U^{235}, *Phys. Rev., 88,* 642, 1952.

Flynn, K. F., and L. E. Glendenin, *Phys. Rev., 116,* 744–748, 1959.

Gerling, E. K., and A. A. Polkanov, Problems of absolute ages of the Precambrian of the Baltic shield, *Geokhimiya, 8,* 695, 1958.

Giletti, B. J., S. Moorbath, and R. St. J. Lambert, A geochronological study of the metamorphic complexes of the Scottish Highlands, *Quart. J. Geol. Soc. London, 117,* 233–272, 1961.

Goldich, S. S., A. O. Nier, H. Baadsgaard, J. H. Hoffman, and H. W. Krueger, The Precambrian geology and geochronology of Minnesota, *Minn. Geol. Survey Bull. 41,* 1961.

Harbour, R. L., Precambrian rocks at north Franklin Mountain, Texas, *Bull. Am. Assoc. Petrol. Geologists, 44*(11), 1785–1792, 1960.

Hart, S. R., The use of hornblendes and pyroxenes for K-Ar dating, *J. Geophys. Research, 66*(9), 2995–3001, 1961.

Holmes, A., *Bull. Natl. Research Council, 80,* 330–334, 1931.

Jaffe, H. W., D. Gottfried, C. C. Waring, and H. W. Worthington, Lead-alpha age determina-

tions of accessory minerals of igneous rocks, *U. S. Geol. Survey Bull. 1097B*, 131–133, 1959.

King, P. B., and P. T. Flawn, Geology and mineral deposits of Precambrian rocks of the Van Horn area, Texas, *Univ. Texas Publ. 5301*, 1953.

Lowdon, J. A., Age determinations by the Geological Survey of Canada, *Geol. Survey Can. Paper 61–17*, 127 pp., 1961.

Masson, P. H., Age of igneous rocks at Pump Station Hills, Hudspeth Co., Texas, *Bull. Am. Assoc. Petrol. Geologists, 40*(3), 501–518, 1956.

McNair, A., and H. W. Wilson, *Phil. Mag., 6*, 563–573, 1961.

Moorbath, S., R. K. Webster, and J. W. Morgan, Absolute age determination in southwest Greenland, *Medd. Grønland, 162*(9), 5–14, 1960.

Roth, R., Swisher gabbroic terrane of the Texas Panhandle, *Bull. Am. Assoc. Petrol. Geologists, 44*(11), 1775–1784, 1960.

Silver, L. T., Age determinations on Precambrian diabase differentiates in the Sierra Ancha, Gila County, Arizona (abstract), *Bull. Geol. Soc. Am., 71* (12), 1973, 1960.

Silver, L. T., Major gabbroic magmatic events and geochronology, *J. Geophys. Research, 66*(8), 2560, 1961.

Silver, L. T., and S. Deutsch, Uranium-lead method on zircons, *Ann. N. Y. Acad. Sci., 91*, 279–283, 1961.

Silver, L. T., C. R. McKinney, S. Deutsch, and J. Bolinger, Precambrian age determinations in the western San Gabriel Mountains, California, *J. Geol.*, in press, 1962.

Tilton, G. R., Volume diffusion as a mechanism for discordant lead ages, *J. Geophys. Research, 65*, 2933–2945, 1960.

Tilton, G. R., G. L. Davis, G. W. Wetherill, and L. T. Aldrich, Isotopic ages of zircon from granites and pegmatites, *Trans. Am. Geophys. Union, 38*, 360–371, 1957.

Tilton, G. R., G. W. Wetherill, and G. L. Davis, Mineral ages from the Wichita and Arbuckle Mountains, Oklahoma, and the St. Francis Mountains, Missouri, *J. Geophys. Research, 67*(10), 1962.

Tilton, G. R., G. W. Wetherill, G. L. Davis, and M. N. Bass, 1000-m.y.-old minerals from the eastern United States and Canada, *J. Geophys. Research, 65*(12), 4173–4179, 1960.

Tilton, G. R., G. W. Wetherill, G. L. Davis, and C. A. Hopson, Ages of minerals from the Baltimore gneiss, *Bull. Geol. Soc. of America, 67*, 1469–1474, 1958.

Wanless, R. K., J. A. Lowdon, R. D. Stevens, R. J. Traill, J. Y. H. Rimsaite, and S. Abbey, Age determinations by the Geological Survey of Canada, *Geol. Survey Can. Paper 61–17*, 127 pp., 1961.

Wasserburg, G. J., Crustal history and the Precambrian time scale, *Ann. N. Y. Acad. Sci., 91*, 583–594, 1961.

Wasserburg, G. J., G. W. Wetherill, and L. A. Wright, Ages in the Precambrian terrane of Death Valley, California, *J. Geol., 67*(6), 1959.

Wetherill, G. W., Discordant uranium lead ages, *Trans. Am. Geophys. Union, 37*, 320–326, 1956.

Wetherill, G. W., G. L. Davis, G. R. Tilton, Age measurements on minerals from the Cutler batholith, Cutler, Ontario, *J. Geophys. Research, 65*, 2461–2466, 1960.

Wetherill, G. W., O. Kouvo, G. R. Tilton, and P. W. Gast, Age measurements on rocks from the Finnish Precambrian, *J. Geol., 70*, 74–88, 1962.

Zartman, R. E., Thesis, California Institute of Technology, 1963.

Zartman, R. E., and G. J. Wasserburg, A geochronologic study of a granitic pluton from the Llano uplift, Texas (abstract), *J. Geophys. Research, 67*, 1664, 1962.

(Manuscript received May 7, 1962;
revised June 19, 1962.)