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GEOLOGIC TIME SCALE

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ABSTRACT

Evidence is gradually accumulating that the presently accepted (Holmes-Marble) geologic time scale should be lengthened, and that this extension should be greatest in the Paleozoic era. Age determinations on glauconites, however, contradict this evidence and generally support the present scale. A review of available data indicates many uncertainties. It still seems doubtful to attempt the construction of a new time scale until the key points can be established firmly enough to be useful.

Numerical values of time can be attached to points in the stratigraphic time scale whenever a rock satisfies three rather stringent requirements: (1) the rock must contain at least one mineral that is a closed system to both parent and daughter isotopes; (2) the mineral must have crystallized at a time that can be geologically related to the deposition of fossiliferous sediments, and (3) the rock must not have been subjected to subsequent metamorphism severe enough to alter parent/daughter ratios. The first requirement is, of course, the basic premise tacitly assumed whenever one calculates an age by radioactive decay.

Geochronologically Useful Minerals

Zircon, monazite, xenotime, uraninite, thorianite, coffinite, biotite, muscovite, lepidolite, K feldspar, and glauconite all have been used in age determination. Tilton and his coworkers (1957) have shown that zircon often gives concordant ages by the three uranium-lead methods. The thorium-lead age is usually low, and the reason for this discrepancy remains obscure. Uraninite also often gives concordant ages, but the rarity of this mineral curtails its usefulness. On the other hand, zircon and the uranium minerals may give discordant ages by the uranium and lead methods. The usual pattern is $U^{238}/Pb^{206} < U^{235}/Pb^{207} < Pb^{207}/Pb^{206}$. There are ways of adjusting such ages into concordance (Wickman, 1942; Stieff and Stern, 1956; Wetherill, 1956a; 1956b), and unique solutions are obtained for some groups of data (Wetherill, 1956a; 1956b; Gerling, 1958); but as a rule the calculations have little meaning for rocks younger than about 500 million years, and that includes all rocks related to fossiliferous sediments. One way of explaining the difficulty is to point out that the Concordia curve (Wetherill, 1956a; 1956b) does not have much curvature over the span of less than 500 m.y., and most analytical data are not sufficiently accurate to permit precise numerical calculations here. The original-lead correction is often the root of the difficulty. We may generalize that discordant lead ages provide some insight into the past history of a rock but are of little use in the establishment of a time scale for Paleozoic and younger rocks.

In this light we must consider the results of the Larsen (Pb/α) method on zircon (Jaffe *et al.*, 1959; Gottfried *et al.*, 1959). The method offers simplicity and speed, but no means of recognizing a discordant age. The Pb/α ratio reflects primarily the Pb^{206}/U^{238} ratio in normal zircons so that, if the zircon is concordant, the Pb/α age will be very nearly correct; when the zircon is discordant, however, the Pb/α age may be seriously in error.

Aldrich *et al.* (1958) have shown that muscovite and biotite usually give concordant ages by the K/Ar and Rb/Sr methods. Wherever the K/Ar and Rb/Sr ages clearly disagree, most workers prefer to accept the Rb/Sr ages as more nearly correct. In some pegmatites (Wasserburg *et al.*, 1959; Polkanov and Gerling, 1958) the Rb/Sr age of the muscovite is greater than other measured ages, for unknown reasons, but in granites the muscovite and biotite Rb/Sr ages generally agree.

K/Ar measurements on old feldspar give ages that are almost always too low, for feldspar does not retain all its radiogenic argon. The argon loss is variable and may be as high as 40 per cent (Wetherill *et al.*, 1955; Wasserburg *et al.*, 1956; Goldich *et al.*, 1957). Age measurements on feldspathic whole rocks, therefore, can be expected to give erroneously low values if much of the potassium in the rock is present in feldspar (Gentner and Kley, 1958; Mehnert, 1958).

Rb/Sr measurements can serve as a basis for accurate ages only when the ratio of radiogenic strontium^{87} to common strontium^{87} in the mineral is large enough to permit a meaningful calculation. In practice that means a value of at least 0.1. Confidence is greater when the ratio is larger. Many feldspars and glauconites do not meet this requirement. To a certain degree, a favorable radiogenic/common Sr ratio is a matter of clean mineral separation, but even with the greatest care it is often impossible to calculate a meaningful Rb/Sr age.

Glauconite, like feldspar, also loses radiogenic argon in varying proportion, largely as a function of temperature (Evernden *et al.*, 1959; Amirkhanov *et al.*, 1957). Consequently, K/Ar ages measured on glauconite can be expected to be lower than the real age of the rock.

Stratigraphic Correlation

Most of the geochronologically useful minerals occur in igneous rocks, and it is usually difficult to establish sufficiently narrow stratigraphic limits of the time when an igneous rock crystallized. Good exposures are necessary to reveal the contacts, but stratigraphic correlation is usually complicated by contact metamorphism which tends to obscure the fossils and stratigraphic relations in the rock that determines the lower stratigraphic limit. The upper contact also must be seen well enough to prove that it is unconformable.

Plutons without overlying sediments nevertheless can be useful in giving a minimum age for sediments they intrude. Tectonic evidence may indicate that intrusion probably followed soon after deposition of the sediments that now make up the hornfels rim. This is the case in Jackman, Maine (Hurley, Boucot, *et al.*, 1959), Katahdin, Maine (Boucot, 1954), and in the Oslo region (Faul *et al.*, 1959), where age measurements give minimum values compatible with other measurements on more closely bracketed plutons.

The stratigraphic age of most pegmatites is particularly difficult to determine. Of the five points used by Holmes (1947) to establish his famous time scale, two are pegmatites with excellent concordant lead age measurements (Nier *et al.*, 1941) but with only a nebulous stratigraphic correlation. The Pala point listed below is suspect for similar reasons.

Some volcanic ash falls contain biotite and K feldspar. The stratigraphic position of bentonites is rarely to be questioned, and it is petrologically reasonable to assume that the biotite in these rocks crystallized (or was hot enough to lose its argon) shortly before the ejection and deposition of the material. The effect of this process on the Rb/Sr ratio in mica or feldspar is incompletely known.

Glauconite is fairly common in sedimentary rocks and would be extremely useful if it were not for the problems of the time of its crystallization, argon loss, and excessive common strontium contamination, discussed above.

Metamorphism

Finally, one must consider all possibilities of metamorphism which could have caused even partial recrystallization of the minerals. The effects of metamorphism on different age ratios and different minerals are widely different. Zircon can survive fairly drastic metamorphism, and feldspar may retain its Rb/Sr ratio under similar conditions (Tilton *et al.*, 1958). Argon is lost fairly quickly at elevated temperatures (Reynolds, 1957; Evernden *et al.*, 1959). The resistance of micas to metamorphic processes is not well known. The pegmatite ages already mentioned (Wasserburg *et al.*, 1959) may indicate that muscovite retains its radiogenic strontium even when biotite loses it and when all micas lose argon.

Points in the Time Scale

In the light of these considerations, we may now review the available age determinations on rocks that fulfill at least some of the stated requirements, recomputed, where necessary, with the decay constants reported by Aldrich and Wetherill (1958; Aldrich *et al.*, 1958). For the Rb half-life we use the new value of 4.7 × 10^{10} years (K. F. Flynn and L. E. Glendenin, preliminary report, 1959).

Middle or late EOCENE

Carbonatite with large (10 cm) biotite crystals occurs in the composite Rocky Boy stock in western Hill County, Bearpaw Mountains, Montana. The stock is correlated with intrusives that cut sediments of Wasatch (early Eocene) age. Associated volcanic rocks are interbedded with sedimentary layers bearing fossil plants of middle and late Eocene age (Pecora, 1957).

K/Ar (Rocky Boy prospect biotite, Faul, Table 2) 52 ± 2 m.y.

LARAMIDE Mineralization (Post-Late Cretaceous)

This is one of the five tie points of the time scale of Holmes (1947, Gilpin County, Colorado). The ages are U^{238}/Pb^{206} on uraninite from veins near Central City, Colorado, that cut bostonite dikes petrologically correlated with other dikes that in turn intrude the Pierre shale of Late Cretaceous age near the southwestern end of the porphyry belt. The complex relationship is summarized by Lovering and Goddard (1938, 1950, p. 44–47).

U^{238}/Pb^{208}	
(Nier *et al.*, 1941, average of 2 samples)	58 m.y.
(U. S. Geological Survey, *see* Faul, 1954, p. 263, average of 4 samples)	63 ± 6 m.y.
(Wood mine, Kulp, 1955)	56 ± 5 m.y.

Probably Early LATE CRETACEOUS

The lepidolite-bearing pegmatite at Pala (40 miles north of San Diego, California) lies in the San Marcos gabbro which is part of the Southern California batholith. By extrapolation to rocks in Baja California, the batholith is tentatively dated as Early Late Cretaceous (Larsen *et al.*, 1958, p. 48).

Rb/Sr	
(lepidolite, Webster *et al.*, 1957, recomputed)	96 m.y.
(lepidolite, Aldrich *et al.*, 1958, recomputed)	100 m.y.
(lepidolite, Herzog *et al.*, 1956, recomputed)	114 m.y.
K/Ar	
(lepidolite Aldrich *et al.*, 1958b)	89 m.y.
(lepidolite, Reynolds, 1957)	87 m.y.
(K feldspar, same)	88 m.y.
(lepidolite, Baadsgaard *et al.*, 1957)	96 m.y.

Early LATE CRETACEOUS (Post-Albian, pre-Maestrichtian)

In northwestern Baja California, intrusive rocks of mostly dioritic composition invaded and metamorphosed fossiliferous limestones and volcanic sediments of Albian age. A fossiliferous sedimentary sequence of Maestrichtian age nonconformably overlies the plutons as well as the rocks they have metamorphosed (Silver *et al.*, 1956, and preliminary report, 1956).

U/Pb (La Grulla granodiorite, concordant age on monazite, Silver *et al.*, preliminary report)	115 m.y.

Probably post-JURASSIC and pre-EARLY CRETACEOUS (Valanginian)

The Shasta Bally batholith in the Klamath Mountains, California, intrudes Mississippian sedimentary rocks. Structural evidence suggests that it was emplaced in early Late Jurassic time, or later. It is overlain by essentially untransported debris correlated with fossiliferous Valanginian (Early Cretaceous) sedimentary rocks (Curtis *et al.*, 1958; F. G. Wells private note).

K/Ar (biotite, chlorite present, Curtis *et al.*, 1958)	127 m.y.

LATE JURASSIC (Oxfordian-Kimmeridgian) or later

In central California, the Guadalupe Mountain quartz monzonite intrudes the Mariposa formation (Oxfordian-Kimmeridgian) and older volcanic rocks. About 100 miles northwestward, the Horseshoe Bar quartz diorite is surrounded by the Rocklin granodiorite, which probably also intrudes rocks correlated with the Mariposa (Curtis *et al.*, 1958).

K/Ar	
(biotite, Guadalupe Mtn.)	136 m.y.
(biotite, Horseshoe Bar)	136 m.y.
(biotite, Rocklin)	125 m.y.
(muscovite, Rocklin)	124 m.y.

EARLY PERMIAN or later

Granite and nordmarkite intrude the Oslo rhomb-porphyry lavas which are interbedded with fossiliferous lake sediments of early Permian age that are correlative with the German *Rotliegendes.*

K/Ar	
(biotite from the Drammen granite, Faul *et al.*, 1959)	259 m.y.
U^{238}/Pb^{206}	
(zircon from the Oslo nordmarkite, Faul *et al.*, 1959)	260 m.y.

LATE PENNSYLVANIAN or later

Pennsylvanian rocks of the Narragansett Basin, Rhode Island, are intruded and metamorphosed. The metamorphism may have followed soon after the end of deposition (Hurley *et al.*, in press).

Rb/Sr	
(biotite from granite, recomputed)	244 ± 13 m.y.
K/Ar	
(biotite from granite, average of 2 samples)	234 ± 11 m.y.
(biotite from schist)	250 ± 12 m.y.
(whole slate, average of 3 samples)	248 ± 13 m.y.

LATE CARBONIFEROUS (post-Westphalian) or later

The Dartmoor and Land's End granites in Cornwall intrude Lower Westphalian (Lower Pennsylvanian) sedimentary rocks (Brammall, 1926), but their upper limit is uncertain. "No rocks occurring in the [Permian] breccias can be ascribed with certainty to the Dartmoor granite. . . ." (Dewey, 1948, p. 40), but detrital minerals probably of Dartmoor origin are identified in Weald (Lower Jurassic) sediments (Groves, 1931).

Dartmoor:	
K/Ar	
(biotite from granite; Mayne *et al.*, 1959, recomputed)	295 m.y.
(biotite sample furnished by K. I. Mayne; Faul, Table 2)	290 m.y.
Land's End:	
K/Ar	
(biotite from granite, Mayne *et al.*, 1959, recomputed)	330 m.y.

EARLY CARBONIFEROUS (Dinantian, pre-Visean)

In northeastern France, the Vosges granites intruded and metamorphosed Tournaisian sedimentary rocks. Overlying fossiliferous rocks of early Visean age were not affected (Jung, 1928, p. 34).

Rb/Sr (biotite, average of 3 samples; Carnegie Institution, 1957, recomputed)	322 m.y.
K/Ar (biotite, average of 4 samples; Faul, Table 2)	315 m.y.

LATE DEVONIAN

A biotite-bearing layer of bentonite, about 1 inch thick, is found in the upper part of the Dowelltown member of the Chattanooga shale of Late Devonian age in Tennessee. The layer is recognized as clearly volcanic in origin (Hass, 1948).

Rb/Sr (biotite, Adams *et al.*, 1958, recomputed) 385 ± 40 m.y.
K/Ar (biotite, Faul and Thomas, 1959) 340 ± 7 m.y.

MIDDLE DEVONIAN or later (post-Oriskany)

The Hog Island quartz monzonite near Jackman, Maine, intruded and contact-metamorphosed fossiliferous sedimentary rocks of Oriskany age to a cordierite hornfels (Hurley, Boucot, *et al.*, 1959).

Rb/Sr(biotite, recomputed) 362 m.y.
K/Ar
(biotite, average of 4 samples) 360 m.y.
(whole slate and hornfels, average of 4 samples) 365 m.y

EARLY or MIDDLE DEVONIAN

Late Silurian (middle Ludlow to lower Gedinne) fossiliferous slates near Calais, Maine, are intruded and metamorphosed. The intruding granites were unroofed and eroded, and one of them is now unconformably overlain by sandstone of Late Devonian age (D. H. Amos, 1959, Ph.D. thesis, Univ. Ill.; A. J. Boucot, private letter, 1959).

K/Ar (biotite, average of 4 samples, Faul, 1959, and Table 2) 404 ± 8 m.y.

LATE SILURIAN or later

The Cairnsmore of Fleet granodiorite (Kirkcudbrightshire, Scotland) intrudes Llandovery sediments, and the related Criffell-Dalbeattie pluton intrudes both Llandovery and Wenlock graywackes and shales (Phillips, 1956). Both plutons were unroofed in Late Devonian or Early Carboniferous time, judging by fragments in the sedimentary rocks of that age.

K/Ar (biotite, Cairnsmore, Mayne *et al.*, 1959, recalculated) (460) m.y.

MIDDLE ORDOVICIAN

A layer of volcanic ash occurs near the top of the Carters limestone, Stones River group, in the Middle Ordovician of Albama. It is exposed in mines and borings, and there it contains fresh euhedral biotite, sanidine, and some zircon (Faul and Thomas, 1959).

Rb/Sr
(biotite, Adams *et al.*, 1958, recomputed) 466 ± 50 m.y.
(biotite, Wenonah No. 8 mine, Tilton, private note) 447 ± 40 m.y.
K/Ar
(biotite, average of 2 samples, Pyne mine and Wenonah No. 8, Faul and Thomas, 1959) 419 ± 5 m.y.
(same, Curtis and Evernden, private note) 421 ± 5 m.y.
U^{238}/Pb^{206} (zircon, Tilton, private note) 445 ± 10 m.y.
U^{235}/Pb^{207} (Tilton, private note) (455 ± 10 m.y.)
Pb^{207}/Pb^{206} (Tilton, private note) (545 ± 45 m.y.)

Another similar tuff is found in the Eggleston limestone, Middle Ordovician, of Tennessee.

Rb/Sr (biotite, average of 2 samples, Adams *et al.*, 1958, recomputed) 437 ± 50 m.y.

The same ash bed extends far to the north. Zircon concentrates were prepared from bentonite samples taken at Alexandria, Dowelltown, and Nashville, Tennessee, and analyzed by Edwards and coworkers (1959) by the isotopic lead-uranium method.

U^{238}/Pb^{206}
(zircon, Alexandria) 452 m.y.
(zircon, Dowelltown) 446 m.y.
(zircon, Nashville) 438 m.y.

A sample of another bentonite was collected near Vonore (southwest of Knoxville), Tennessee, from the Middle Ordovician Bays formation (Edwards *et al.*, 1959).

U^{237}/Pb^{206} (zircon, Edwards *et al.*, 1959) 453 m.y.

LATE CAMBRIAN

Glauconite occurs in the Franconia sandstone of Late Cambrian age at Readstown and Sparta, Wisconsin, and in Goodhue County, Minnesota.

Rb/Sr (Readstown, Wisconsin, Herzog *et al.*, 1958, recomputed) 414 m.y.
K/Ar (Sparta, Wisconsin, Wasserburg *et al.*, 1956) 442 m.y.
(Goodhue County, Minnesota, Goldich *et al.*, 1959, average of 2 samples) 439 m.y.

Discussion

Some of these highly selected numbers satisfy our stated conditions reasonably well, but most of them fall short on one count or more.

Of the five points on which Holmes based his time scale, only one (Laramide) can be included now. The stratigraphically unimpeachable "Swedish Kolm" from the alum shale does not present a closed system, and all attempts to establish an age for it have failed. The stratigraphic limits on Holmes' remaining three points are too vague to make them useful.

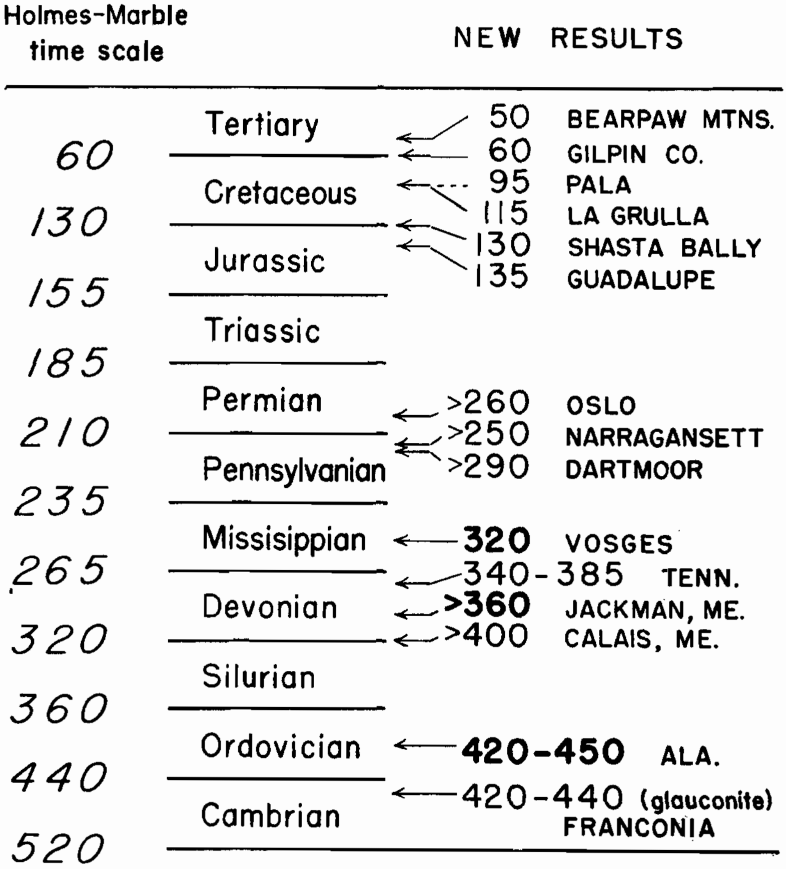
Some of the other points quoted here are based on determinations by just one method in one laboratory. On biotites, one would naturally prefer to have both the Rb/Sr and the K/Ar ages, be they concordant or not. K feldspar also should be helpful where the radiogenic/common Sr ratio is favorable. If the rock contains sufficient zircon, then isotopic U/Pb analysis is a necessity, for it will either confirm the mica ages or give a glimpse of the past metamorphic history of the rock.

Reasonably complete analyses are available for only four of the new tie points (Jackman, Vosges, Alabama-Tennessee bentonite, and Franconia glauconite). Of these points, the Jackman age is only a minimum, and the Franconia age suffers from all the uncertainties inherent in glauconite ages.

The discordance in the ages of the Alabama tuffs is small but probably significant. The low argon ages could be explained by partial loss of argon and/or addition of potassium as a result

TABLE 1.—HOLMES-MARBLE TIME SCALE AND SUMMARY OF NEW RESULTS

All in millions of years. Bold type indicates points based on better-than-average evidence, both geologic and experimental. Minimum ages are marked >.



of slight early alteration of the mica. The discordance in the U^{238}/Pb^{206}–Pb^{207}/Pb^{206} ages may indicate the presence of some relic zircon from older rocks. The true age of the zircon may be obtainable from a systematic mathematical analysis of all the zircon data. For the moment one can say only that the Alabama bentonite was deposited not later than 420 million years ago and probably not earlier than about 450 million years ago.

The reported K/Ar age of the Cairnsmore of Fleet pluton is too great to fit even the broad scheme. Only additional analyses can clarify this apparent discrepancy.

In the Calais (Maine) area the granite body intruding the Silurian slates is petrographically slightly different from the body overlain by the Devonian sandstone. Contacts between the two granites are not exposed, but the K/Ar age of most of the granites in the area is the same, and we assume that the different granitic rocks are merely facies of the same igneous body. There is some evidence of possible metamorphism to the west, however, which may complicate the picture.

The upper stratigraphic limits of the Dartmoor and Land's End granites are still uncertain, in spite of extensive geologic work in that area.

The field relation of the Horseshoe Bar and Rocklin plutons is not clear. However, the measured age of the Horseshoe Bar sample supports the value for the Guadalupe Mountain quartz monzonite which clearly intrudes the Mariposa formation. The stratigraphic limits on the Pala pegmatite are uncertain, and the point is of limited use in the time scale.

The K/A–Rb/Sr ages of the glauconite from

TABLE 2.—NEW K/AR AGES AND ANALYTICAL DATA

All analyses are on pure biotite fractions. Brackets indicate replicate determinations.

	Age (m.y.)	K (per cent)*	Radiogenic Ar^{40} (ppm)†	Radiogenic Ar^{40} / Total Ar^{40}
Rocky Boy stock, Bearpaw Mtns.	52	7.76	.0292	0.57
			.0290	0.35
Dartmoor granite, Cornwall	290	7.05	.159	0.51
			.157	0.86
Vosges, France:				
Andlau	298	6.29	.146	0.70
		6.41		
Lac Blanc	314	7.44	.180	0.84
		7.45	.180	0.88
		7.34		
Natzviller	324	6.24	.157	0.88
Grosse Pierre	318	6.82	.170	0.92
		6.89	.165	0.85
		6.80		
		6.76		
		7.01	.173	0.78
Chattanooga shale bentonite layer (Late Devonian)	340	5.98	.157	0.73
			.164	0.67
			.155	0.82
Calais, Maine, granites:				
Red Beach	403	4.83	.158	0.88
			.156	0.51
			.153	0.89
			.153	0.79
Keene Lake	407	5.66	.183	0.76
Charlotte	406	5.79	.187	0.89
Meddybemps	404	5.20	.167	0.92
Bessemer, Alabama, bentonite (Middle Ordovician):				
Pyne mine	420	6.94	.232	0.81
			.233	0.90
Wenonah No. 8 mine	419	6.23	.209	0.77
			.207	0.85

* Perkin-Elmer flame photometer analyses by W. W. Brannock and P. L. D. Elmore. $K^{40} = 1.22 \times 10^{-4}$ g/gK

† Isotope-dilution analyses by H. Faul and H. H. Thomas

the Franconia sandstone, are concordant, yet clearly low as compared to the other data in Table 1, and we are faced with the question whether or not glauconite is a suitable mineral for this purpose. Argon and strontium loss must be considered, but the possibility of later overgrowths on glauconite (or some other means of introducing more potassium and rubidium long after the sediment was laid down) seems more likely. Independent evidence for such a process is lacking. Addition of potassium and rubidium in proportion to the amounts already present would produce erroneously low but almost concordant ages.

At the same time we should consider the possibility that the glauconite age is right, and all the "hard-rock" ages are too high because of inherited old radiogenic isotopes (Holmes, private letter, 1958). Inherited daughter products in the minerals from hard rocks would make these minerals seem older than they are, but again it seems improbable that such old radiogenic lead, argon, and strontium could be absorbed in different growing crystals in the proportion that would give concordant ages when now measured. The absence of argon from Paleozoic margarite (Damon and Kulp, 1957) and the concordant Rb/Sr–K/Ar ages measured on very young micas (Jäger and Faul, 1959) would indicate that micas, at any rate, do not usually absorb significant amounts of old radiogenic isotopes when they crystallize.

Construction of a Time Scale

When we now attempt to construct a time scale by reasonable interpolation between these points (Table 1), it becomes obvious that the available data are still too few, too poor, and internally inconsistent. A rough time scale could be constructed on the igneous and metamorphic rocks alone (Mayne *et al.*, 1959; Faul, 1959; Kulp, 1959), and this time scale would be about a third longer than the Holmes-Marble scale (Committee on Measurement of Geologic Time, 1950). Another time scale could be interpolated between the glauconites, and that scale would roughly agree with Holmes-Marble (Hurley, Pinson, *et al.*, 1959; Amirkhanov *et al.*, 1958; Herzog *et al.*, 1958; Lipson, 1956; 1958; Wasserburg *et al.*, 1956). The few data on volcanic tuffs seem to support the hard-rock scale, but the agreement is far from perfect.

Until these difficulties are resolved, any new time scale constructed either on glauconites or on tuffs or on granitic rocks alone is questionable. Extensive research on the subject is in progress. A new time scale will gradually evolve, based on sound geologic ground work, interlaboratory analysis, and broad co-operation among the many interested workers.

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