14 April 1961, Volume 133, Number 3459 SCIENCE

Geologic Time Scale

Isotopic age determinations on rocks of known stratigraphic age define an absolute time scale for earth history.

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The concept that earth history has encompassed millions of years became established with the development of the geological sciences. Since the time dimension is central to geology, quantitative measurement of time is necessary if earth processes are to be fully understood. Such measurement became theoretically possible with the discovery of radioactivity, but it is only with the developments of the past decade in theory and technique that it has become possible to make reasonably accurate determinations.

The term *geological time scale* generally refers to the absolute calendar to which the progressive development of animals and plants may be related. The interval of earth history involved is from the Cambrian period to the present. The Cambrian is the earliest period for which detailed faunas can be described. Isotopic age measurements have been widely used to determine the time of formation of igneous and metamorphic rocks in the seven-eighths of geologic history that occurred before the Cambrian, but utilization of such measurements to determine the absolute age of fossil-bearing sedimentary rocks has been slow to develop, because of problems of measurement and of suitability of materials or geologic settings.

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In Table 1, the earlier estimates of the geological time scale from potential age measurement based on radioactive decay are compared with the new data at several key points. Holmes's 1933 and 1947 estimates (*1*, *2*) came to be used by all earth scientists. The agreement between these and the current estimates is surprising and obscures the fact that the new scale is far more accurate than the earlier ones. When Barrell (*3*) compiled his time scale it was not even recognized that thorium as well as uranium produces radiogenic lead. In the 1933 scale of Holmes there was still no correction for the presence of common lead in uranium minerals. Holmes's 1947 scale was based on complete isotopic determinations of five samples carefully analyzed by A. O. C. Nier, but at that time the effects of geochemical alteration on these isotopic ages were not adequately appreciated. Unfortunately, it was subsequently shown that two of these points carried incorrect stratigraphic assignments (Bedford, N.Y., and Middletown, Conn.) and that two others yielded incorrect ages because of geochemical alteration (Swedish kolm and Joachimsthal pitchblende). In retrospect, it seems largely fortuitous that these early estimates of the time scale were fair approximations of the actual scale.

No significant improvement in the construction of the geologic time scale could be made until the new isotopic geochronometers based on the radioactive decay of rubidium-87 and potassium-40 were discovered and until improved analytical techniques for all methods were developed. It is only within the past few years that suitable measurements based on these methods have been reported. Thus, a reconsideration of calendars of geologic events was warranted.

Recent preliminary revisions of the time scale, based in large part on data available in early 1959, have been published by Kulp (*4*) and by Holmes (*5*). A large body of critical data has become available since these reports were written, however, and the causes of geochemical alteration are now more fully understood, so that it is possible to examine the time scale in much greater detail. In 1959 Mayne *et al.* (*6*) proposed a greatly extended time scale based essentially on two new experimental points—Hercynian and Caledonian granites from Britain—but these measurements and the supporting arguments have been shown to be incorrect (*7–9*). Evernden *et al.* (*10*) have suggested a time scale back to the Jurassic, based on their extensive and excellent measurements of ash beds and flows, made largely on continental rocks from the western United States.

Folinsbee and his co-workers (*11*) have contributed some very important measurements, particularly for the Cretaceous, and suggest that the Holmes 1947 time scale must be lengthened. This is also the conclusion of Hurley *et al.* (*12*) on the basis of measurements in New England and Nova Scotia on rocks of Devonian and Carboniferous-Permian age. Faul (*13*) considered the time-scale problem and concluded that not enough information was available to merit a serious revision. Some of the anomalies which led him to this conclusion, however, were due to uncertain stratigraphic definition, the inclusion of a number of Cambrian glauconites which surely have lost argon, and the measurements of Mayne *et al.* (*6*). Many new measurements, together with clarification of some of the problems raised by Faul (*13*), make it possible to estimate the time boundaries

Table 1. Comparison of earlier and current estimates of certain points in the geological time scale.

Geologic period	Date of beginning of period ($\times 10^6$ yr)			
	Barrell, 1917 (*3*)	Holmes, 1933 (*1*)	Holmes, 1947 (*2*)	This study
Tertiary	55–65	60	58–68	63 ± 2
Jurassic	155–195	158	152–167	181 ± 5
Carboniferous	300–370	285	255–275	345 ± 6
Ordovician	480–590	440	430	500 ± 20

for most of the geologic periods, and in some cases the epochs, within relatively narrow limits. It is the purpose of this article (*14*) to evaluate the available pertinent measurements and from these data to construct the most probable geological time scale.

Methods

The isotopic chronometers that are applicable to this problem are listed in Table 2. The decay constants are known to within at least 5 percent, and in the case of uranium-238, uranium-235, and rubidium-87 the error is probably less than 3 percent. Any small change will, of course, shift all ages from one chronometer relative to another. At present, different mineral phases from the same rock, regardless of age, may give isotopic ages based on the decay schemes of uranium, rubidium, and potassium that agree within the limits of analytical error; hence, no major change in the decay constants is expected.

For each measurement there are three areas of uncertainty: (i) the analysis, (ii) the degree to which the mineral sample has remained a closed chemical system, and (iii) the stratigraphic definition of the sample. By using isotope dilution techniques, virtually all of these isotopic ratios can be determined to within 3 percent. Standard errors as low as 1 percent can be obtained. For example, five laboratories in the United States analyzed a biotite standard supplied by the department of geophysics of Massachusetts Institute of Technology. The reported values for the radiogenic argon-40 concentration were all within 1 percent of the mean. For a critical sample, replicate analyses are made routinely. Intercalibrations on at least one sample have been made by all of the laboratories whose results are discussed below, so it appears that there are no major systematic errors.

The mineral phases that have proved most useful for these investigations are, (i) for the potassium-argon method: muscovite, biotite, phlogopite, sanidine, and glauconite; (ii) for the potassium-calcium method: sylvite; (iii) for the rubidium-strontium method: biotite, muscovite, microcline, and glauconite; and (iv) for the uranium-lead method: zircon, uraninite, pitchblende, and black shale. All of these mineral phases appear to be capable of remaining as closed chemical systems under specified conditions. The most sensitive, and therefore least useful, systems are potassium-calcium dating of sylvite and uranium-lead dating of black shales; in both these materials the criterion of a closed system is difficult to attain. The Pb^{207}–Pb^{206} age of zircon appears least susceptible to alteration. The common potassium micas and sanidine, if well crystallized, appear to retain their radiogenic products quantitatively if not heated to above 125° to 150°C. Microcline may retain its rubidium and strontium quantitatively at higher temperatures but leaks about 30 percent of its argon at room temperature. If well crystallized, glauconite may retain almost 100 percent of its argon for at least 100 million years, if maintained essentially at room temperature, but it loses its argon readily at elevated temperatures (*10*). Sylvite, when recrystallized, readily loses its radiogenic products.

There are specific geologic situations where each type of isotopic chronometer may be applied to the dating of sedimentary rocks. Volcanic ash beds intercalated with fossiliferous strata make possible precise stratigraphic definition. These ash beds, if uncontaminated by other sedimentary material, may carry zircon, biotite, and sanidine. If this material has not been seriously weathered or deeply buried, the potassium-argon ages determined with mica and sanidine and the uranium-lead ages determined with zircon should be accurate and concordant. Lavas which carry mica or zircon may be used similarly.

Table 2. Methods for determining the geochronometry of rock systems.

Isotopes	Minerals	Decay constants (yr^{-1})
U^{238}–Pb^{206}	Uraninite, pitchblende, zircon	1.54×10^{-10}
U^{235}–Pb^{207}	Uraninite, pitchblende, zircon	9.72×10^{-10}
Th^{232}–Pb^{208}	Uraninite, pitchblende, zircon	0.499×10^{-10}
Rb^{87}–Sr^{87}	Micas, potassium feldspars	1.47×10^{-11}
K^{40}–Ar^{40}	Micas, sanidine, glauconite	$\lambda_\beta = 4.72 \times 10^{-10}$
K^{40}–Ca^{40}	Sylvite	$\lambda_e = 0.584 \times 10^{-10}$

Igneous intrusives, such as granites, which cut one fossiliferous horizon and are unconformably overlain by another stratigraphically defined sedimentary rock may be dated by their micas (potassium-argon, rubidium-strontium), feldspar (rubidium-strontium), or zircon and uraninite (uranium-lead). Pitchblende veins may be used in the same way but are very sensitive to alteration and must be studied in some detail.

Glauconite is found in many sedimentary rocks and thus is an ideal chronometer from the viewpoint of stratigraphic definition. In any case, so long as it is well crystallized and carefully purified it will yield a reliable minimum age by the potassium-argon or rubidium-strontium methods (*15*). Likewise, many extrusive rocks as a whole retain 80 to 95 percent of their radiogenic argon, so that they also may be used to define minimum ages.

Sylvite is found in evaporite deposits of known stratigraphic level and may yield a valid K^{40}–Ca^{40} age determination under ideal conditions (*16*).

Cobb and I (*17*) have shown that, under ground-water conditions, lead loss is the common alteration pattern for the uranium mineral in black shales. Thus, these shales may yield valid minimum ages under certain conditions.

The problem of stratigraphic definition is twofold. For those cases where the chronometer is not formed at the time of formation of the fossiliferous unit, the geologic setting must define the total time interval. Even where the fossil association is immediate, the time uncertainty in intercontinental correlations may be larger than the analytical error in the age. Thus, although the age of a Tertiary ash fall might be determined to within 0.5 million years, the world-wide correlation of that particular faunal assemblage might be much less certain. Therefore, quantitative geochronometry has developed to the point where the isotopic ages may assist the paleontologist in determining absolute rates of evolution, ecological change, and world-wide migration of organisms. The uncertainty in the isotopic ages, in years, increases from the Cenozoic to the Cambrian, but then so does the uncertainty in paleontological definition; hence, correlation of the new isotopic ages with the accepted intercontinental paleontological correlation should be valuable for all of Phanerozoic (post-Precambrian) time. For example, at the present time it is questionable whether synchronous fauna can be defined on a world-wide basis even for a 5- to 10-million-year interval such as Trenton time. Thus, the uncertainty in intercontinental correlation must be defined by the age measurement of the strata involved.

Critical Samples

Those samples that appear to be most definitive for the geological time scale are listed in Table 3 and described briefly in the appendix. For convenience they are divided by era. The precise geological data are essential in the use of these points. The errors listed in Table 3 are estimated analytical errors only, although it is believed that these samples represent closed chemical systems except where noted. From these data and certain supporting information from glauconites and effusive rocks, discussed below, it is possible to construct the geological time scale shown in Fig. 1.

1960 Geological Time Scale

Cenozoic. The first important division in the geological time scale is the boundary between the Recent and the Pleistocene. This is most logically placed at 11,000 years ago—a time marked by an abrupt change in sea level, sudden warming of the surface layer of the oceans, and rapid retreat of the continental glaciers (*18, 19*). It should be noted that some outstanding students of the Pleistocene, such as Flint (*20*), believe that inclusion of the Recent epoch is superfluous. The beginning of the last major period of continental glaciation occurred about 70,000 years ago (*19*), and the substages of

Table 3. Critical points for the geological time scale.

Stratigraphic position	Locality	Rock	Mineral	Method	Age ($\times 10^6$ yr)	Reference
		I. Cenozoic Era				
Pleistocene-Pliocene boundary	Sierra Nevada, Calif.	Tuff	Biotite	K–Ar	1.0 ± 0.5	(*21*)
		Pliocene				
Latest Pliocene	Sutter Buttes, Calif.	Rhyolite	Biotite	K–Ar	1.7 ± 0.4	(*21*)
Upper Pliocene	Mendocino Co., Calif.	Sandstone	Glauconite	K–Ar	3.5 ± 0.5	(*15*)
Middle Pliocene	Kruisschens, Belgium	Sandstone	Glauconite	K–Ar	7 ± 1	(*22*)
Lower Hemphillian	Nevada	Tuff	Biotite	K–Ar	9.1 ± 0.5	(*31*)
Clarendonian	West Walker Canyon, Calif.	Welded tuff	Biotite	K–Ar	10.6 ± 0.5	(*31*)
Clarendonian	Nevada	Tuff	Biotite	K–Ar	11.1 ± 0.5	(*31*)
Clarendonian	Nevada	Tuff	Biotite	K–Ar	11.8 ± 0.5	(*31*)
Pliocene-Miocene boundary	Coal Valley, Nev.	Rhyolite tuff	Biotite	K–Ar	12.0 ± 0.5	(*31*)
		Miocene				
Barstovian	Barstow, Calif.	Dacite tuff	Biotite	K–Ar	15.2 ± 0.5	(*15*)
Barstovian	San Guillermo Quad., Calif.	Vitric tuff	Biotite	K–Ar	15.2 ± 0.5	(*15*)
Mid-Miocene	N. Cascades, Wash.	Snoqualmie granite	Biotite	K–Ar	17.0 ± 0.5	(*11*)
Hemingfordian	California	Tuff	Biotite	K–Ar	17.3 ± 0.6	(*31*)
Arikarean	Nebraska	Tuff	Biotite	K–Ar	21.6 ± 0.7	(*31*)
Lower Zemorrian	Cymric well No. 1, Calif.	Sandstone	Glauconite	K–Ar	23 ± 1	(*15*)
Burdigalian	Bad Hall, Austria	Sandstone	Glauconite	K–Ar	25 ± 1	(*15*)
		Oligocene				
Whitneyan	Oregon	Tuff	Biotite	K–Ar	25.7 ± 0.8	(*31*)
Chadronian	Texas	Tuff	Biotite	K–Ar	33.1 ± 1.0	(*31*)
		Eocene				
Upper Eocene	Vakis-Jvary, U.S.S.R.	Granite	Biotite	K–Ar	38 ± 4	(*27*)
Basal Kreyenhagen	Hernandez Valley, Calif.	Sandstone	Glauconite	K–Ar	43 ± 2	(*15*)
Lutetian	Fosse, Paris Basin	Sandstone	Glauconite	K–Ar	47 ± 2	(*15*)
Alpine	Kressenberg, Austria	Sandstone	Glauconite	K–Ar	51 ± 2	(*15*)
Upper Wilcox	Gulf Coast, Tex.	Sandstone	Glauconite	K–Ar	52 ± 2	(*15*)
Post early Eocene	Bearpaw Mt., Mont.	Carbonatite	Biotite	K–Ar	52 ± 2	(*13*)
Claiborne Group	Smithville, Tex.	Sandstone	Glauconite	K–Ar	54 ± 2	(*22*)
Lowermost Eocene	Clayton, N.J.	Sandstone	Glauconite	K–Ar;	62 ± 2	(*22*)
				Rb–Sr	55 ± 6	
		Paleocene				
Pre-Eocene	Fakhralo, U.S.S.R.	Dacite	Biotite	K–Ar	57 ± 8	(*27*)
Top Paleocene	Gen. Petroleum Co. well, Calif.	Sandstone	Glauconite	K–Ar	59 ± 3	(*15*)
Upper Paleocene	Central City, Colo.	Ore	Pitchblende	U–Pb	59 ± 2	(*32*)
Mid-Paleocene	Oldhaven Group, England	Sandstone	Glauconite	K–Ar	57 ± 2	(*15*)
Paleocene	Standard Oil Co. well, Calif.	Sandstone	Biotite	K–Ar	59 ± 3	(*15*)
		II. Mesozoic Era				
		Cretaceous				
Uppermost Maestrichtian	Whitecourt, Alberta	Coal seam	Biotite	K–Ar	63 ± 2	(*11*)
			Sanidine	K–Ar	64 ± 2	
Maestrichtian	Strawberry Creek, Alberta	Tuff	Biotite	K–Ar	65 ± 2	(*11*)
			Sanidine	K–Ar	67 ± 2	
Maestrichtian	Gulf Coast	Sandstone	Glauconite	K–Ar	69 ± 2	(*15*)
Upper Campanian	Lethbridge, Alberta	Bentonite	Biotite	K–Ar	75 ± 2	(*11*)
			Sanidine	K–Ar	76 ± 2	
Lower Campanian	Hannover, Germany	Sandstone	Glauconite	K–Ar	81 ± 2	(*15*)

Stratigraphic position	Locality	Rock	Mineral	Method	Age (× 10^6 yr)	Reference
Post Coniacian	Western Montana	Granite	Biotite	K–Ar	72–78	Appendix
Lower Santonian	Salzgitter, Germany	Sandstone	Glauconite	K–Ar	83 ± 3	*(15)*
Middle Turonian	Herne, Germany	Sandstone	Glauconite	K–Ar	83 ± 3	*(15)*
Lower Turonian	Dortmund, Germany	Sandstone	Glauconite	K–Ar	85 ± 3	*(15)*
Coniacian	Hannover, Germany	Sandstone	Glauconite	K–Ar	87 ± 3	*(15)*
Cenomanian	Coleman, Alberta	Agglomerate	Sanidine	K–Ar	93 ± 2	*(11)*
Cenomanian	Mill Creek, Alberta	Bentonite	Biotite	K–Ar	96 ± 3	*(11)*
			Sanidine	K–Ar	96 ± 3	
Turonian-Cenomanian	Coast Range, Calif.	Granites	Biotite	K–Ar	84–95	*(34)*
Upper Albian-Lower Cenomanian	Cache Creek, Calif.	Bentonite	Biotite	K–Ar	92 ± 3	*(15)*
Upper Albian	Lyme Regis, England	Sandstone	Glauconite	K–Ar	96 ± 3	*(15)*
Albian	Salzgitter, Germany	Sandstone	Glauconite	K–Ar	97 ± 3	*(15)*
Albian-Aptian	Salzgitter, Germany	Sandstone	Glauconite	K–Ar	102 ± 3	*(15)*
Upper Albian	Predkavkaz'e, U.S.S.R.	Sandstone	Glauconite	K–Ar	117 ± 12	*(23)*
Post Albian	So. Calif. batholith	Granite	Monazite	U, Th–Pb	116 ± 5	*(35)*
Middle Albian	Hudson Hope, B.C.	Tuff	Biotite	K–Ar	116 ± 3	*(11)*
Aptian	Gundelen, U.S.S.R.	Silt	Glauconite	K–Ar	118 ± 12	*(23)*
		Jurassic				
Post-Kimmeridgian–pre-Valanginian	Ono, Calif.	Granite	Biotite	K–Ar	127 ± 4	*(15)*
Portlandian	Moscow area, U.S.S.R.	Clayey sandstone	Glauconite	K–Ar	134 ± 13	*(23)*
Post-Kimmeridgian	Loomis, Calif.	Quartz diorite	Biotite	K–Ar	136 ± 4	*(15)*
Oxfordian	Oberpfalz, Germany	Sandstone	Glauconite	K–Ar	135 ± 4	*(15)*
Portlandian	Hannover, Germany	Sandstone	Glauconite	K–Ar	138 ± 4	*(15)*
Callovian	Oberpfalz, Germany	Shale	Glauconite	K–Ar	139 ± 4	*(15)*
Bathonian	Kelasury, Georgia	Granite	Biotite	K–Ar	165 ± 3	*(27)*
Lower Jurassic	Alaska	Granite	Biotite	K–Ar	169 ± 5	*(36)*
Post Triassic	Billiton, Indonesia	Granite	Biotite	K–Ar	180 ± 5	*(22)*
Triassic-Jurassic boundary	Ashcroft, B.C.	Granite	Biotite	K–Ar	181 ± 5	*(38)*
		Triassic				
Upper Triassic	Fort Lee, N.J.	Diabase	Biotite	K–Ar	195 ± 5	*(33)*
		III. Paleozoic Era				
		Permian				
Middle Permian	Solikamsk, U.S.S.R.	Evaporite	Sylvite	K–Ca	241 ± 8	*(16)*
Post mid-Autunian	Oslo, Norway	Granite	Biotite	K–Ar	259 ± 7	*(13)*
		Nordmarkite	Zircon	U–Pb	260 ± 5	
Carboniferous-Permian boundary	Dartmoor, England	Granite	Biotite	K–Ar, Rb–Sr	280 ± 5	*(8)*
			Uraninite	U–Pb	288 ± 5	*(40)*
		Carboniferous				
Uppermost Carboniferous	New South Wales, Australia	Toscanite	Biotite	K–Ar	287 ± 9	*(15)*
Tournaisian-Visean boundary	Vosges Mts., France	Granite	Biotite	K–Ar	315 ± 5	*(13)*
				Rb–Sr	322 ± 5	
Pre-Stephanian–post Visean	Harzburg, Harz	Gabbro	Biotite	K–Ar	325 ± 10	*(15)*
Post Lowermost Carboniferous	Magnitogorsk, U.S.S.R.	Granite	Biotite	K–Ar	340 ± 10	*(41)*
Devonian-Carboniferous boundary	Snobs Creek, Australia	Rhyolite	Biotite	K–Ar	344 ± 10	*(15)*
Devonian-Carboniferous boundary	Chattanooga fm., Tenn.	Bentonite;	Biotite	K–Ar	340 ± 7	*(13)*
		Black shale		U–Pb	350 ± 15	*(17)*
		Devonian				
Post Lower Devonian	Jackman, Maine	Granite	Biotite	K–Ar, Rb–Sr	360 ± 5	*(12)*
Lower-Middle Devonian boundary	Eastern Greenland	Granite	Biotite	K–Ar	393 ± 10	*(44)*
Post-Silurian–pre-Upper Devonian	Eastern Maine	Granite	Biotite	K–Ar	404 ± 8	*(13)*
Lower Devonian	Shap, England	Granite	Biotite	K–Ar, Rb–Sr	395 ± 5	*(8)*
		Silurian				
Lower Silurian	Brassfield, Ohio	Sandstone	Glauconite	K–Ar	410 ± 15	*(22)*
		Ordovician				
Trenton	Bessemer, Ala.	Bentonite	Zircon	U^{238}–Pb^{206}	445 ± 10	*(13)*
Trenton	Eastern Tennessee	Bentonite	Zircon	U^{238}–Pb^{206}	447 ± 5	*(42)*
Upper Carodocian	Kinnekulle, Sweden	Bentonite	Sanidine	K–Ar	452	*(38)*
			Biotite	Rb–Sr	447	
Post Cambrian	Boisdale Hills, Nova Scotia	Granite	Biotite	K–Ar, Rb–Sr	490 ± 10	*(29)*
		Cambrian				
Post mid-Upper Cambrian	Shovde, Sweden	Black shale	Kolm	U–Pb	500 min.	*(17)*
Pre-basal Upper Cambrian	Wichita Mts., Okla.	Granite	Zircon	U–Pb	550 max.	*(28)*
Middle Cambrian	U.S.S.R.	Rhyolite	Whole rock	K–Ar	533 ± 50	*(43)*
Lower Cambrian	Kupa Station, U.S.S.R.		Glauconite	K–Ar	556 ± 56	*(23)*
Lower Cambrian	Lipyagi Village, U.S.S.R.		Glauconite	K–Ar	577 ± 58	*(23)*
Lower Cambrian	Serdobsk, U.S.S.R.		Glauconite	K–Ar	610 ± 61	*(23)*

this period are being defined in detail by radiocarbon dating. From the end of the Pliocene to 50,000 years ago, where the radiocarbon method becomes effective, there are very few data; but since Evernden (*21*) has reported the extension of the potassium-argon method down into the Pleistocene, it appears that in the next few years the subdivisions of the Pleistocene can be dated.

The date of the Pleistocene-Pliocene boundary is probably the most poorly known of the dates for boundaries between geologic periods, at least if expressed as the percentage of the correct age. From rather crude extrapolations of the rates of deep-sea sedimentation or of soil leaching and erosion over the past 70,000 years, the beginning of the Pleistocene can be placed at an estimated 500,000 to 2 million years before the present. Evernden (*21*) has reported dates on formations that are supposed to lie either at the Pliocene-Pleistocene boundary or in the late Pliocene which suggest an age of about 1 million years (Table 3), but the analytical error on these determinations was about 50 percent. Future work will undoubtedly permit close definition of the age of such rocks. The definition of synchronous faunas around the world within a time interval of only 100,000 years is so difficult that it may be best to use the beginning of the first continental glaciation, a global event, to define this boundary rather than try to define it by faunal assemblages, as is being done at present (*20*). With the existing data it appears best to assume a date of 1.0 million years before the present for the Pliocene-Pleistocene boundary, with the understanding that this figure is subject to considerable revision.

Great advances have been made in dating the Cenozoic epochs, largely as a result of the work of Curtis and Evernden at the University of California (*10, 15*). They have collected apparently uncontaminated volcanic ash beds, welded tuffs, and lava flows that are intercalated with continental vertebrate faunas of the western United States. The analyses of biotite from these rocks by the potassium-argon method should give highly reliable results, since the mica was not buried deeply or significantly heated subsequent to its formation. The only cause for uncertainty with such samples is the possibility that older detrital material was introduced, particularly in the case of the tuffs. Petrographic examination and multiple analyses on a given horizon should ultimately reduce this uncertainty to a very low value. These results are summarized in Table 3.

It also appears (*15, 22*) that glauconite can give a reliable age if it is found in a pure form, if it has been close to the surface throughout its history, and if it is less than 200 million years old. The small dimension of the crystal and the weakness of the bonding along the *c* axis make possible loss of argon under mild conditions. Evernden *et al.* (*15*), for example, found that at the relatively shallow depth of 8000 feet the well-formed glauconite from the Kreyenhagen formation of Upper Eocene age began to lose detectable amounts of argon. The potassium-argon age for glauconite is, therefore, always a minimum age, but under favorable circumstances glauconite may give the true age. Careful determinations of the potassium-argon age of glauconite, taken throughout the geological column, have been made by Kazakov and Polevaya (*23*), Hurley *et al.* (*22*), and Evernden *et al.* (*15*). Where any of these glauconite determinations are useful in setting a minimum date for an epoch or stage, they have been included in Table 3. It appears that quite a number of post-Triassic glauconites have retained most, if not all, of their argon and therefore give isotopic ages in agreement with those obtained on other, more stable minerals. Before the Mesozoic, however, the glauconite ages are always lower than the probable age. Hurley *et al.* (*22*) suggest this may be due to the gradual addition of potassium to the glauconite structure. An alternative view is that the surface temperature is adequate to cause detectable loss of argon by diffusion. For example, if the average of the highest glauconite ages for each epoch is taken, the data are roughly consistent with an argon loss of 2 to 3 percent per 100 million years. In any event, the glauconite data provide useful minimum dates.

There are eight well-defined points in the Pliocene, suggesting that the Hemphillian stage began about 10 million years ago and that the base of the Pliocene should probably be taken as 13 ± 1 million years.

In the Miocene, dates are available for the Barstovian, Hemingfordian, Arikarean, and Burdigalian stages. Age determinations for biotite from the Snoqualmie granite and for glauconite from California and Austria fit consistently with determinations for ash-bed samples. From the data on the Whitneyan (uppermost continental stage of the Oligocene), the Miocene-Oligocene boundary is dated at 25 ± 1 million years. Evernden *et al.* (*15*), using only their data, suggest 26 million years for this boundary.

Only two dates are available in the Oligocene, but from ages determined for the Upper Eocene granite from Vakis-Jvary, U.S.S.R. (38 ± 4 million years) and for the Kreyenhagen glauconite (43 ± 2 million years) (basal Upper Eocene), the Oligocene-Eocene boundary is dated at 36 ± 2 million years.

In the Eocene it is noteworthy that the Upper Wilcox glauconite provides a minimum date of 52 ± 2 million years for the top of the Lower Eocene, and that 52 ± 2 million years is also obtained for the age of the biotite from the Bearpaw Mountain carbonatite, which must have been intruded *after* the Wasatch stage of the early Eocene (*13, 24*). The Upper-Middle boundary of the Eocene is tentatively dated at 45 ± 2 million years, and the Middle-Lower Eocene boundary, at 52 ± 2 million years.

A number of samples bear on the date of the Eocene-Paleocene boundary. The Central City pitchblende, which is post-Fort Union (*25*), and the glauconite from a General Petroleum Company well in California both give ages of 59 million years and represent uppermost Paleocene. The Lower Eocene glauconites give average ages of 54 and 59 million years, with errors of about ± 2 million years. It appears that the Eocene-Paleocene boundary dates back 58 ± 2 million years.

Mesozoic. The excellent determinations by Folinsbee and his co-workers (*11*) of the age of the uppermost Maestrichtian, made by concordant potassium-argon age determinations on biotite and sanidine, fix the end of the Cretaceous at 63 ± 2 million years before the present. This date indicates that the Danian stage is Paleocene, but the analytical error is probably greater than the stratigraphic uncertainty. The date of 70 million years taken by Evernden *et al.* (*15*) for the Danian-Maestrichtian boundary appears too early in view of these new data.

The concordant dates given by two minerals from various Cretaceous ash beds in determinations by Folinsbee and his co-workers (*11*) produce the most precisely dated interval in the time scale. In addition, there are a number of useful glauconite dates for the Cretaceous. Collectively these data suggest the following boundary dates, in millions of years before the present: Maestrichtian-Campanian, 72 ± 3; Campanian-Santonian, 81 ± 3; Santonian-Coniacian, 84 ± 3; Coniacian-Turonian, 88 ± 3; Turonian-Cenomanian, 90 ± 2; Cenomanian-Albian, 110 ± 3; and Albian-Aptian, 120 ± 4. The Crowsnest volcanics (Coleman, Alberta, sample) are underlain by strata containing late Albian flora. They are interbedded with strata containing late Albian or early Cenomanian plants, which are in turn overlain by marine shales of upper Cenomanian age. According to Folinsbee (*26*), 100 feet above the Crowsnest zone the worldwide *Inoceramus labiatus* zone occurs (Lower Turonian).

There are too few data to permit a subdivision of the Cretaceous below the Albian-Aptian boundary.

The Cretaceous-Jurassic boundary must be defined from the minimum glauconite date of the Portlandian (Upper Jurassic) sample from Hannover, Germany, and from the Ono, California, granite, which must have been intruded between the end of the Kimmeridgian (Upper Jurassic) and the beginning of the Valanginian (Lower Cretaceous). Hence, the Valanginian probably dates back less than 127 ± 4 million years, and the Portlandian, probably at least 138 ± 4 million years. The Loomis, California, sample shows that the top of the Kimmeridgian must be at least 136 ± 4 million years old. The glauconite sample from the Portlandian of the Moscow area will be more useful when the experimental error is reduced. Consideration of all these data leads to the suggestion of 135 ± 5 million years before the present as the date of the Cretaceous-Jurassic boundary.

The Bathonian is well dated at 165 ± 2 million years, both by Rubinstein (*27*) and by workers at this laboratory. The date of the Jurassic-Triassic boundary appears to be 181 ± 5 million years, to judge from three biotite ages of well-defined granites which lie very close to this boundary. The biotite age on the Palisades diabase of the Newark series of the Upper Triassic suggests that the date of the Middle-Upper Triassic boundary is probably about 200 ± 10 million years. There are no data by which to date, in years, the other subdivisions of the Triassic. By linear interpolation the Triassic-Permian boundary is set at about 230 million years, but the uncertainty is probably at least ± 10 million years.

Paleozoic. The sylvite dated as 241 ± 8 million years by Polevaya *et al.* (*16*) by the potassium-calcium method is known to be Kungurian (Middle Permian). The experimental error is that given by the analysts and is dominated by the correction for common calcium in the sample. Since sylvite can recrystallize easily, this should probably be regarded as a minimum date, though Polevaya *et al.* (*16*) claim the sample was not recrystallized.

Since the Oslo igneous series was dated by Faul (*13*) as probably late Lower Permian, a date of 260 ± 10 million years for the Middle-Lower Permian boundary seems reasonable. The Dartmoor granite and associated veins have been dated by potassium-argon, rubidium-strontium, and uranium-lead determinations on various minerals by various laboratories. The average ages given by these methods are quite similar, suggesting a time of intrusion of 280 ± 5 million years before the present. The most recent evaluation of the stratigraphic relationships (*9*) suggests that the granites are certainly post-Lower Stephanian and pre-Middle Permian. In view of the toscanite in New South Wales, which is interlayered in uppermost Carboniferous rocks, the Carboniferous-Permian boundary is tentatively set at 280 ± 10 million years.

The intensive study by Faul (*13*) on the micas from the Vosges granites, which were intruded near the Tournaisian-Visean boundary, gives concordant ages, by the rubidium-strontium and potassium-argon methods, of 320 ± 5 million years. The single determination on the biotite from the gabbro of the Harz Mountains in Germany is not inconsistent with this, if the fairly large analytical error is considered. No further subdivision of the Carboniferous is currently possible.

The Carboniferous-Devonian boundary, however, appears to be rather well defined, in part due to the occurrence of both a uranium-rich black shale and a volcanic ash bed in the Chattanooga formation of Tennessee, which is thought to lie astride the boundary that separates these two periods. There is some debate among stratigraphers as to whether this formation should be placed wholly in the uppermost Devonian or partly in the basal Carboniferous, but this question is probably trivial insofar as the age is concerned, in view of the present degree of analytical precision. In addition, this boundary is bracketed by the Magnitogorsk granite, which cuts lowermost Carboniferous beds, and the Snobs Creek rhyolite, which is either uppermost Devonian or at the Devonian-Carboniferous boundary. When all of these data are taken into account, the best date for the Devonian-Carboniferous boundary would appear to be 345 ± 10 million years.

The highly consistent results on intrusives and contact metamorphic rocks from the Jackman, Maine, area obtained by Hurley *et al.* (*12*) provide an analytically accurate date of 360 ± 5 million years. Unfortunately, the stratigraphic relations only permit this material to be identified as post-Oriskany (that is, post-Lower Devonian). Thus, although the material appears to be Upper Devonian, it does not provide a close definition. The other three Devonian rocks do provide dates that rather closely define the Lower Devonian-Middle Devonian boundary. The sample from eastern Greenland lies either at the Lower-Middle Devonian boundary or slightly up into the Middle Devonian. The granites from eastern Maine are post-Silurian and probably post-lowest Devonian. Although it is only certain that they are pre-Upper Devonian, it is probable that they were formed immediately after the post-Silurian folding. The Shap granite has been dated by the Oxford, Harwell, and Lamont laboratories from determinations on multiple samples, which give an average age of 395 ± 5 million years. This granite, too, must lie somewhere up in the Lower Devonian. The Lower-Middle Devonian boundary, therefore, would seem to be dated about 390 ± 5 million years ago. The date 405 ± 10 million years has therefore been chosen rather arbitrarily for the base of the Devonian.

Dates in the next group are all from Ordovician rocks of the Trentonian in North America (Alabama and Tennessee) and the upper Carodocian in Sweden. From determinations on biotite and zircon from ash beds, the age appears to be close to 445 million years. If this date is accepted for Trenton, then the Ordovician-Silurian boundary would be at about 425 ± 10 million years. There is currently no information to permit subdivision of the other stages of the Ordovician.

The date for the Upper Cambrian-Ordovician boundary and the duration of the Upper Cambrian can be roughly inferred from the results of three sepa-

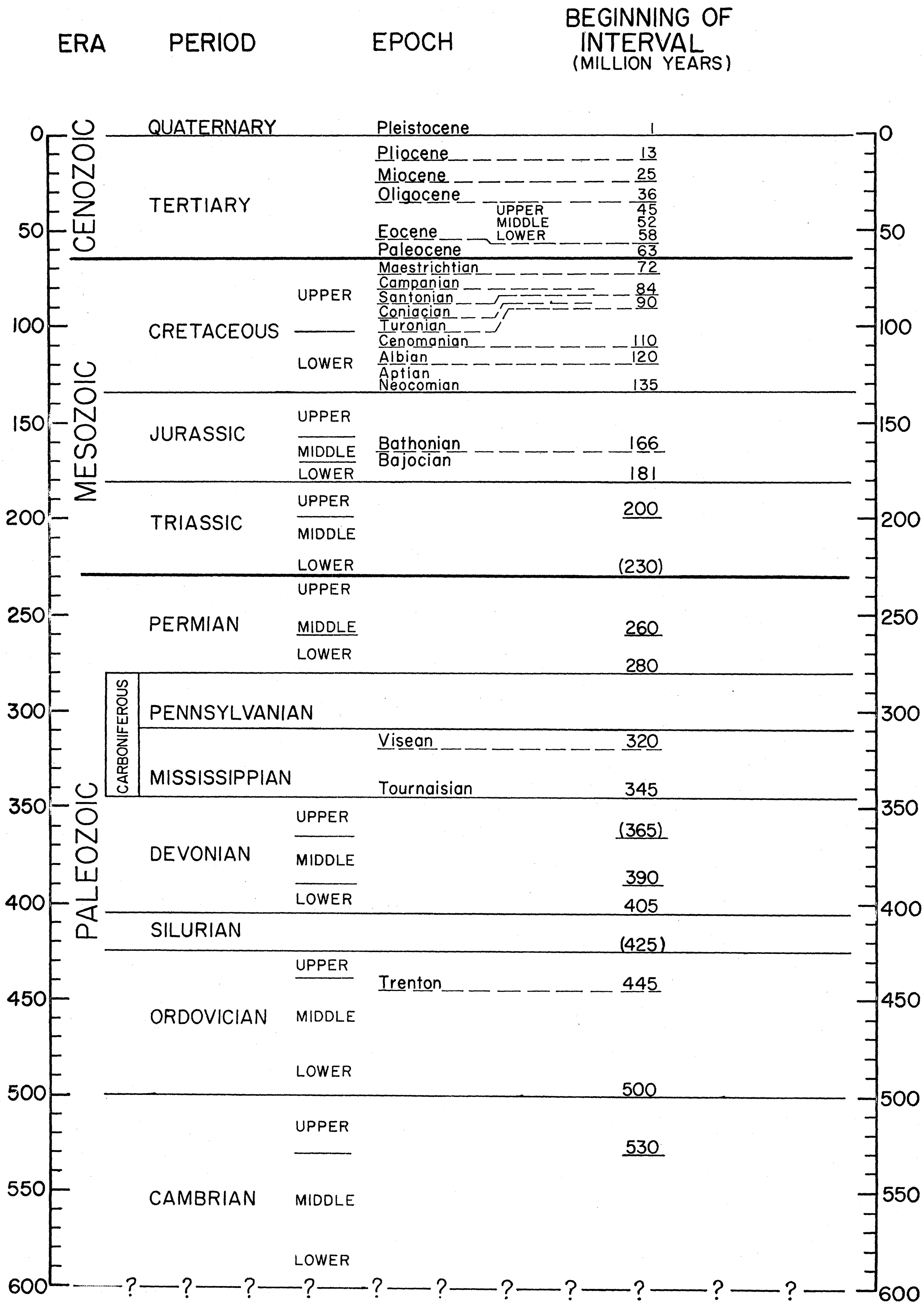

Fig. 1. Geologic time scale.

rate investigations. Cobb and I (*17*) have studied the geochemistry of uranium and lead in the Swedish kolm of the Peltura zone (middle Upper Cambrian). This study showed that the alteration process has consisted of lead loss, including preferential loss of lead-206, so that the highest age obtained from U^{235}–Pb^{207} determinations is a reliable minimum for this material. It is concluded that 500 million years is a minimum age for this formation and that it probably is not as old as 550 million years.

On the other hand, Aldrich *et al.* (*28*) have analyzed zircon from the igneous complex in the Wichita Mountains of Oklahoma, which is unconformably overlain by the Reagan sandstone of the basal Upper Cambrian. The nearly concordant results gave an age, from Pb^{207}–Pb^{206} determinations, of 550 million years. This should represent a reliable maximum for the bottom of the Upper Cambrian.

Fairbairn and his co-workers (*29*) have determined the age of the Boisdale Hills granite in Nova Scotia, which cuts uppermost Cambrian and possibly cuts lowermost Ordovician. The average age, as determined by the rubidium-strontium and potassium-argon methods, is about 485 million years, but the deviation among the measurements is large.

These three groups of data suggest that the Cambro-Ordovician boundary should be placed at 500 ± 10 million years and that the Middle-Upper Cambrian boundary may be placed at about 530 ± 15 million years.

For the Middle and Lower Cambrian, the only available dates are on whole extrusive rocks and glauconite. The analytical errors are large, and the exact relationship to *Olenellus* of the rocks designated Lower Cambrian is not known. If it is assumed, however, that the Lower Cambrian beds are correlative with beds containing *Olenellus,* these data would suggest that the Lower Cambrian is at least 580 ± 20 million years old.

An important feature of the determinations on glauconite on the Russian platform (*30*) is that more or less continuous ages, from about 600 million years to 1300 million years, have been found for glauconite lying directly on the 1450-million-year-old basement. The stratigraphic identification of the rocks from which these glauconite samples were taken ranges from Lower Cambrian to Sinian. Thus, if it is assumed that argon loss averaged only about 10 percent, the date for the base of the *Olenellus* zone would lie in the range 600 to 650 million years. On the other hand, further experimental work is required on these materials before accurate values are available. If the Cambrian lasted as long as the usual major geologic period, as the depth to the base of *Olenellus*-bearing strata would indicate, then *Olenellus* almost surely entered the scene later than 600 million years ago. In order, therefore, to set a reasonably accurate date for the base of the Cambrian, more measurements on better materials are needed. If it is decided that the first appearance of *Olenellus* marks the base of the Cambrian, the question of date may not be settled for decades, while all parts of the world are being examined to determine where and when *Olenellus* first appeared. If it should be definitely shown that *Olenellus* appeared more recently than 600 million years ago, it might then be best simply to adopt this round number for the base of the Cambrian.

New Time Scale

The new geological time scale developed from the critical determinations described above is shown in Fig. 1. The linear time scale is given at the left. The boundaries between periods and epochs are indicated where data permit. Parentheses are used if considerable interpolation was required.

It may be seen that the Cenozoic and Cretaceous are now much better defined than any other part of the time scale. Much remains to be done in defining the Pleistocene. No data exist for the Silurian, and only a few quantitative points are available for the Cambrian, Ordovician, and Triassic. It is clear that the Eocene is the longest epoch (18 million years) and the Paleocene the shortest (4 million years) in the Tertiary. Likewise, in the Cretaceous, the Cenomanian is the longest stage, occupying nearly one-third of the period, whereas the Danian, Santonian, Coniacian, Turonian, Barremian, Hauterivian, and Valanginian must be quite short, on the order of a few million years each (the last three are included in the Neocomian of Fig. 1).

The length of the major periods averages about 60 million years, with surprising uniformity. The longest period, except for the Cambrian, about which there is uncertainty, appears to be the Ordovician. The shortest period is the Silurian. The division of the periods into Upper (late), Middle, and Lower (early), clearly does not, on the basis of biostratigraphic considerations, represent equal or even similar time intervals.

The geological time scale has developed to the place where it can be used for correlation problems in paleontology, orogeny, and mineralization. Although much remains to be done, particularly in the lower Paleozoic, enough has been accomplished to demonstrate the potential accuracy that may ultimately be attained and the new objectivity that has been introduced in the time dimension in geology.

Appendix

Description of critical samples used in constructing the time scale for the Cenozoic.

1. Bishop tuff, Sierra Nevada, California. This tuff lies beneath a widely distributed moraine system but still overlies glacial till of unknown affinity. K–Ar, biotite age, (1.0 ± 0.5) 10^6 yr (*21*).
2. Sutter Buttes, California. Biotite from rhyolite and andesite from the latest Pliocene volcanic unit gave K–Ar, (1.5 ± 0.5) 10^6 and (1.8 ± 0.5) 10^6 yr, respectively (*21*).
3. Mendocino County, California. Surface glauconite in sandstone. Unweathered material. Upper Pliocene. K–Ar, (3.5 ± 0.5) 10^6 yr (*15*).
4. Kruisschens, Belgium. Glauconite from Scaldisien formation in the Pliocene. K–Ar, (7 ± 1) 10^6 yr (*15*).
5. Lower Hemphillian, Nevada. Biotite from tuff. K–Ar, (9.1 ± 0.5) 10^6 yr (*31*).
6. West Walker River Canyon, California. Biotite from latite welded tuff that is Clarendonian in age. K–Ar, (10.6 ± 0.5) 10^6 yr (*31*).
7. Clarendonian, Nevada. Biotite from tuff. K–Ar, (11.1 ± 0.5) 10^6 yr (*31*).
8. Clarendonian, Nevada. Biotite from tuff. K–Ar, (11.8 ± 0.5) 10^6 yr (*31*).
9. Coal Valley, Nevada. Biotite from rhyolite tuff. Lower Clarendonian very near Miocene-Pliocene boundary. K–Ar, (12.0 ± 0.5) 10^6 yr (*15*).
10. Barstow, California. Biotite from dacite tuff, Barstovian. K–Ar, (15.2 ± 0.5) 10^6 yr (*15*).
11. San Guillermo Quadrangle, California. Biotite from crystal vitric tuff, Barstovian. K–Ar, (15.2 ± 0.5) 10^6 yr (*15*).
12. Snoqualmie batholith intrudes late Oligocene (John Day vertebrate fauna) and is generally accepted as mid-Miocene. K–Ar, (17.0 ± 0.5) 10^6 yr (*11*).
13. Hemingfordian, California. Biotite from tuff. K–Ar, (17.3 ± 0.6) 10^6 yr (*31*).
14. Arikarean, Nebraska. Biotite from tuff. K–Ar, (21.6 ± 0.7) 10^6 yr (*31*).

15. 22S-21E Hub Petroleum cymric well No. 1, California. Glauconite of Lower Miocene (Lower Zemorrian); (23 ± 1) 10^6 yr (*15*).

16. Bad Hall, Austria. Glauconite from Lower Miocene (Burdigalian). K–Ar, (25 ± 1) 10^6 yr (*15*).

17. Whitneyan, Oregon. Biotite in tuff. K–Ar, (25.7 ± 0.8) 10^6 yr (*31*).

18. Chadronian, Texas. Biotite in tuff. K–Ar, (33.1 ± 1.0) 10^6 yr (*31*).

19. Biotite from a granite at Vakis-Jvary, Georgia, U.S.S.R., which cuts fossiliferous Middle Eocene but which is overlain by fossiliferous Lower Oligocene. Geologists believe the intrusion took place in the lower part of the Upper Eocene. K–Ar, (38 ± 4) 10^6 yr (*27*).

20. Hernandez Valley, California. Excellent surface glauconite from Basal Kreyenhagen (base of Upper Eocene). K–Ar, (45 ± 2) 10^6 yr (*15*).

21. Fosse, Paris Basin. Excellent glauconite from surface outcrop, Lutetian stage of Middle Eocene. K–Ar, (47 ± 2) 10^6 yr (*15*).

22. Kressenberg, Austria. Glauconite from Lower Eocene. K–Ar, (51 ± 2) 10^6 yr (*15*).

23. Gulf Coast. Glauconite from upper Lower Eocene (Upper Wilcox). K–Ar, (52 ± 2) 10^6 yr (*15*).

24. Biotite from carbonatite in Bearpaw Mountains, Montana. Post-early Eocene. K–Ar, (52 ± 2) 10^6 yr (*13*).

25. Smithville, Texas. Glauconite from Viesca, Weches formation in Eocene. K–Ar, (54 ± 2) 10^6 yr (*22*).

26. Clayton, N.J. Glauconite from Hornerstown formation in Lower Eocene. K–Ar, (62 ± 2) 10^6 yr; Rb–Sr, (55 ± 6) 10^6 yr (*22*).

27. Fakhralo, U.S.S.R. Biotite in dacites of post-Turonian but pre-Eocene age. K–Ar, (57 ± 8) 10^6 yr (*27*).

28. Kodor River, Abkhaziya, U.S.S.R. Glauconite from limestone with *Protocardium Edwardsi Desh.* var. *orientalis, Spondylus* sp., *area* sp., *Dentalium* sp., and so on. Upper Paleocene. K–Ar, (58 ± 6) 10^6 yr (*23*).

29. General Petroleum Espe Road 75–33, California. Glauconite from top of Paleocene. K–Ar, (61 ± 2) 10^6 yr (*15*).

30. Pitchblende from Central City, Colorado. Stratigraphic age is post-Fort Union (Upper Paleocene) but pre-Eocene (*25*); (59 ± 3) 10^6 yr, based on the average of several U^{238}–Pb^{206} ages (*32*).

31. Standard Oil Co., well No. 62-13C, California. Biotite of volcanic origin from glauconitic sandstone, Paleocene in age. K–Ar, (59 ± 3) 10^6 yr (*15*).

Description of critical samples used in constructing the time scale for the Mesozoic.

32. Pembina coal seam, Whitecourt, Alberta, 54°05′N, 115°31′W. Biotite (63 × 10^6 yr) and sanidine (K–Ar, 64 × 10^6 yr) from uppermost Maestrichtian (*11*).

33. Strawberry Creek, Alberta, 53°16′N, 114°07′W. Sanidine [(67 ± 2) 10^6 yr, three samples] and biotite [(65 ± 2) 10^6 yr, two samples] from Maestrichtian. K–Ar, (66 ± 1) 10^6 yr (average) (*11*).

34. Gulf Coast. Glauconite from sandstone outcrop from the Ripley formation, Maestrichtian stage. K–Ar, 68.5 × 10^6 yr, 69.5 × 10^6 yr (*15*).

35. Lethbridge, Alberta, 49°42′N, 114°31′W. Biotite [(75 ± 2) 10^6 yr] and sanidine [(76 ± 2) 10^6 yr] from bentonite No. 1 in Bearpaw shale (Upper Campanian). K–Ar, (75 ± 2) 10^6 yr (*11*).

36. Western Montana, Boulder batholith. Various phases have been dated by K–Ar on biotite. Folinsbee reported 74 × 10^6 yr, Curtis 74 × 10^6 yr, and Kulp 72 × 10^6 yr at the New York Academy of Sciences Conference (see *11, 31, 33*).

37. Hannover, Germany. Core from 500 meters in glauconitic sandstone of Lower Campanian stage. K–Ar, (81 ± 2) 10^6 yr (*15*).

38. Salzgitter, Germany. Glauconite from sandstone of Lower Santonian age. K–Ar, (83 ± 3) 10^6 yr (*15*).

39. Herne, Germany. Glauconite from sandstone in Bochumer Greensand of the Middle Turonian stage of the Upper Cretaceous. K–Ar, (83 ± 3) 10^6 yr (*15*).

40. Dortmund, Germany. Core from well. Glauconitic sandstone of Lower Turonian age. K–Ar, (85 ± 3) 10^6 yr (*15*).

41. Hannover, Germany. Core from 711 meters in glauconitic sandstone of Coniacian stage. K–Ar, (87 ± 3) 10^6 yr (*15*).

42. Coleman, Alberta, 49° 39′N, 114° 31′W. Sanidine from Crowsnest volcanic agglomerate. Cenomanian. K–Ar, (93 ± 2) 10^6 yr (*11*).

43. Mill Creek, Alberta, 49°25′N, 114° 09′W. Biotite and sanidine from bentonite. Cenomanian. K–Ar, (94 ± 2) 10^6 yr (*11*).

44. Coast Range granites and granodiorites of California. Turonian-Cenomanian. K–Ar, 84 × 10^6 to 95 × 10^6 yr (*34*).

45. Cache Creek, California. Biotite from bentonite in top of Antelope Shale (Upper Albian or Lower Cenomanian). K–Ar, (92 ± 3) 10^6 yr (*15*).

46. Lyme Regis, England. Glauconite from outcrop of Upper Greensand of Dorset Coast. K–Ar, (101 ± 3) 10^6 yr (*15*).

47. Salzgitter, Germany. Core of glauconitic sandstone from 430 meters, Albian stage. K–Ar, (97 ± 3) 10^6 yr (*15*).

48. Salzgitter, Germany. Core of glauconitic sandstone from 613 meters, Albian-Aptian boundary. K–Ar, (102 ± 3) 10^6 yr (*15*).

49. Predkavkaz'e, U.S.S.R. Glauconite from clayey sandstones in the Vyselki orientation borehole (Upper Albian). K–Ar, (117 ± 12) 10^6 yr (*23*).

50. Southern California batholith. Monazite from granite which invades and metamorphoses fossiliferous limestones and volcanic sediments of Albian age. The whole sequence is overlain by sedimentary rocks of Maestrichtian age. Th, U–Pb, (115 ± 5) 10^6 yr (*35*).

51. Baksan River, Gundelen, Caucasus, U.S.S.R. Glauconite from silts of Aptian age. K–Ar, (118 ± 12) 10^6 yr (*23*).

52. Hudson Hope, British Columbia. Biotite from tuff in Harmon shale (Middle Albian). K–Ar, (116 ± 3) 10^6 yr (*11*).

53. Ono, Shasta County, California. Biotite from quartz diorite of the Shasta Valley batholith. By association with other intrusives this has been designated post-Kimmeridgian and pre-Valanginian. Evernden *et al.* (*15*) consider this to be close to the Jurassic-Cretaceous boundary. K–Ar, (127 ± 4) 10^6 yr (*15*).

54. Moscow area, U.S.S.R. Egorevskoe deposit. Horizon under the phosphorites: *Oxynoticeras fulgens* fauna. Glauconite in clayey sands. Upper Jurassic (Volga stage, Portlandian). K–Ar, (134 ± 13) 10^6 yr (*23*).

55. Loomis, California. Biotite from quartz diorite from quarry near Horseshoe Bar on the American River 3 miles northeast of Loomis. K–Ar, (136 ± 4) 10^6 yr (*15*).

56. Oberpfalz, Germany. Core from 29.4 meters in glauconitic sandstone. Oxfordian stage (Plicatilis Schichten). K–Ar, (135 ± 4) 10^6 yr (*15*).

57. Hannover, Germany. Core from 24 meters in glauconitic sandstone. Upper Portland stage (Munder Mergel). K–Ar, (138 ± 4) 10^6 yr (*15*).

58. Oberpfalz, Germany. Core from 33 meters in shale containing glauconite pellets representing Callovian stage of Upper Jurassic (Ornatentone). K–Ar, (139 ± 4) 10^6 yr (*15*).

59. Kelasury, Georgia, U.S.S.R. Biotite in intrusive that cuts Bajocian is pre-Lower Cretaceous and probably Bathonian. K–Ar, (165 ± 3) 10^6 yr (*27*).

60. Alaska. Pre-Pliensbachian but Lower Jurassic. K–Ar, (169 ± 5) 10^6 yr (*36*).

61. Billiton, Indonesia. Tin granite. Latest Triassic or early Lower-Jurassic biotite. K–Ar, (180 ± 5) 10^6 yr (*37*).

62. Ashcroft, British Columbia. Biotite from granite in the Guichon batholith. Post-Carnian, pre-Bajocian. K–Ar, 181 × 10^6 yr (*38*).

63. Fort Lee, N.J. Biotite from the Palisades sill. Associated with lavas in the Newark series of the Upper Triassic. Probably early or middle Upper Triassic; (193 ± 3) 10^6 yr (*33*).

Description of critical samples used in constructing the time scale for the Paleozoic.

64. Solikamsk, U.S.S.R. Bed "B" of the Verkhnekamerisk formation (Mt. Berezniki), Solikamsk. This lies in the Kungar (Middle Permian) stage. Polevaya *et al.* (*16*) believe this sample of coarse crystals of milky white sylvite was not recrystallized. The K^{40}–Ca^{40} age is (241 ± 8) 10^6 yr, whereas the K^{40}–Ar^{40} age is lower [(224 ± 10) 10^6 yr], indicating some argon loss. The K–Ca age is adopted.

65. Oslo, Norway. Granite and nordmarkite intrude Oslo porphyry lavas which are interbedded with fossiliferous lake sediments of early Permian age correlative with the German *Rotliegendes.* O. A. Hoeg believes that the lake sediments probably date from about the middle of the Lower Permian. [Work done by Faul *et al.* in 1959 (*39*).] Biotite from the Drammen granite; K–Ar, 259 × 10^6 yr. Zircon from the Oslo nordmarkite; U^{238}–Pb^{206}, (259 ± 5) 10^6 yr.

66. Dartmoor, England. Granite which cuts folded Westphalian, where folds are aligned with those that involve Lower

Stephanian strata. Overlain by Middle Permian gravels but probably near Permian-Carboniferous boundary. Many K–Ar and Rb–Sr measurements on a variety of samples give an average value of (280 ± 5) 10^6 yr (*8*).

67. Cornwall, England. Uraninite from Geevor Mine, which is probably associated with Dartmoor type granite. U^{238}–Pb^{206}, 288 × 10^6 yr; U^{235}–Pb^{207}, 288 × 10^6 yr; Pb^{207}/Pb^{206}, (307 ± 25) 10^6 yr; Th^{232}/Pb^{208}, (300 ± 15) 10^6 yr (*40*).

68. Lower Hunter Valley, South Wales, Australia. Biotite from toscanite in the Kuttung Series. K–Ar, (287 ± 9) 10^6 yr (*15*). These beds were deposited before the Permian glacial period and are directly overlain by lower Permian marine beds.

69. Vosges Mountains, northeast Europe. Here granites have intruded and metamorphosed Tournaisian sedimentary rocks, and they are overlain by fossiliferous strata of early Visean, so this formation closely marks the Visean-Tournaisian boundary. Three samples of biotite analyzed by the Rb–Sr method gave an average isotopic age of (322 ± 5) 10^6 yr. Four samples of biotite analyzed by the K–Ar method gave an average isotopic age of (315 ± 5) 10^6 yr (*13*).

70. Harzburg, Harz, Germany. Biotite separated from the Harzburger gabbro, which is pre-Stephanian but post-Kulm-graywacke (probably Visean). K–Ar, (325 ± 10) 10^6 yr (*15*).

71. Magnitogorsk, U.S.S.R. Biotite from granite which cuts a thin unit of lowermost Carboniferous. Presumably this cut occurred shortly after deposition. K–Ar, (340 ± 10) 10^6 yr (*41*).

72. Snobs Creek, Warburton, Victoria, Australia. Biotite from rhyolite sampled 2 miles east of the Rubicon power station. Essentially at the top of the Devonian. K–Ar, (341 ± 10) 10^6 yr (*15*).

73. Smithville, Tennessee. Biotite from bentonite layer in Dowelltown, member of the Chattanooga shale taken at Sligo Bridge. K–Ar, (340 ± 10) 10^6 yr (*13*).

74. Youngs Bend area, Tennessee. Whole-rock analyses by the U^{238}–Pb^{206} method gave (350 ± 15) 10^6 yr; this is theoretically the minimum age, but in this case of relatively uniform uranium distribution it may be close to the true age (*17*).

75. Jackman, Maine. Hog Island quartz monzonite intrudes and has metamorphosed fossiliferous rock of Oriskany age; hence the intrusion is post-Lower Devonian. Rubidium-strontium dating on biotite from monzonite gave 362 × 10^6 yr; four samples from granite dated by K–Ar gave 360 × 10^6 yr. Four other samples, from whole slate and hornfels, gave 365 × 10^6 yr (*12*).

76. Eastern Greenland geosyncline. Granite which intrudes Lower Devonian and is overlain by Middle Devonian. K–Ar, (393 ± 10) 10^6 yr (*14*).

77. Shap, Westmorland, England. Granites that were intruded after the Silurian folding and probably after the moderate folding of lowest Devonian. Considered Downtownian, which is the continental equivalent of Maine Lower Devonian (*9*). Four separate determinations of K–Ar ages at the Lamont laboratory gave (391 ± 7) 10^6 yr. Four separate Rb–Sr determinations at Oxford gave (397 ± 11) 10^6 yr. Four Rb-Sr determinations at Harwell gave (372 ± 20) 10^6 yr (*8*).

78. Brassfield, Ohio. Glauconite from sandstone in Lower Silurian. K–Ar, (410 ± 15) 10^6 yr (*22*).

79. Bessemer, Alabama. Zircon from bentonite of the Carters limestone analyzed by G. R. Tilton. U^{238}–Pb^{206}, (445 ± 10) 10^6 yr (*13*).

80. Eastern Tennessee and Alabama. Zircon from the Ordovician bentonites of Trenton age (the Stones River group in Tennessee and the Bays group in Alabama) gave (447 ± 10) 10^6 yr for the U^{238}–Pb^{206} age. Rubidium-strontium ages on biotite from these horizons are reported to be consistent with the U^{238}–Pb^{206} age (*41*).

81. Kinnekulle, Sweden. Sanidine and biotite from the upper Caradocian horizon. Three determinations on biotite gave 447 × 10^6 yr, and two on sanidine gave 452 × 10^6 yr, by the K–Ar method (*26*).

82. Boisdale Hills, Nova Scotia. Biotite from granite which clearly cuts uppermost Cambrian and possibly some Lower Ordovician. Both K–Ar and Rb–Sr analyses gave about 485 × 10^6 yr (*29*).

83. Shovde, Sweden. In a study of the geochemistry of uranium and lead in the kolm of this locality it was shown that the age of 500 × 10^6 yr for this formation is a reliable minimum (*17*).

84. Wichita Mountains, Oklahoma. Zircon from granite. According to the geologists who have studied the area (W. Hamilton and W. H. Ham and their associates), the rock from which the zircon was taken is clearly part of the igneous complex which is uncomformably overlain by the basal Upper Cambrian Reagan sandstone. The ages were as follows: U^{238}–Pb^{206}, 520 × 10^6 yr; U^{235}–Pb^{207}, 525 × 10^6 yr; and Pb^{207}–Pb^{206}, 550 × 10^6 yr. Thus, the Reagan is probably younger than 550 × 10^6 yr.

85. U.S.S.R. Whole-rock analysis on felsite intercalated in Middle Cambrian rocks. K–Ar, (533 ± 50) 10^6 yr (*43*).

86. Kupa Station, Belorussia, U.S.S.R. Borehole R-2, 252 to 257 meters deep. Glauconite from Lower Cambrian limestone. K–Ar, (556 ± 56) 10^6 yr (*23*).

87. Lipyagi Village, U.S.S.R. Glauconite from standstone from borehole R-1, 1430 meters deep. Lower Cambrian, Valdai Complex, Lyaminarite Suite. K–Ar, (577 ± 58) 10^6 yr (*23*).

88. Serdobsk Orientation, U.S.S.R. Glauconite from Lower Cambrian sandstone with relicts of pollen (*Paleopirosaceus atavus* Naum, *Paleopirosaceus poroscus* Naum, *Phosphosphaera laminarita* Naum). K–Ar, (610 ± 61) 10^6 yr (*23*).

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14. This research was supported by the Atomic Energy Commission. I wish to acknowledge the helpful discussions with J. A. S. Adams, G. H. Curtis, Henry Faul, R. E. Folinsbee, Arthur Holmes, P. M. Hurley, Marshall Kay, and M. M. Rubenstein. The measurements made at the Lamont Geological Observatory were performed largely by L. E. Long, G. Erickson, and R. Kologrivov. J. Brokaw, M. Rippey, and J. Sonderburg aided in the preparation of the manuscript. This article is Lamont Geological Observatory contribution No. 486.

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