glacial substages, therefore, may be due to a shift of the geographic distributions toward the equator during the cooler glacial substages.

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Sphene: Uranium-Lead Ages

Abstract. *Uranium-lead ages were measured on 14 samples of sphene from rocks aged from 1000 to 2750 × 10^6 years. All samples gave concordant or nearly concordant ages, the maximum difference between the Pb^{206}-U^{238} and Pb^{207}-Pb^{206} ages being 10 percent. Sphene has more concordant ages than has the coexisting zircon in each of seven rocks in which they were compared. Sphene sometimes has greater ages than does coexisting biotite, although in two metamorphic rocks, in which metamorphism was sufficiently intense to cause redistribution of radiogenic strontium-87 between various mineral phases, sphene dates the time of metamorphism rather than of original crystallization of the rocks.*

Determinations of ages of minerals by the uranium-lead method are uniquely valuable because two isotopes of uranium, U^{238} and U^{235}, decay at different rates into two isotopes of lead, Pb^{206} and Pb^{207}, giving two age values from the isotopic ratios of uranium and lead. In addition, the ratio of radiogenic Pb^{207} to radiogenic Pb^{206} defines a third age value, although just two of the three values are independent. When the three age values agree, the ages are said to be concordant.

Concordant ages are strong evidence that no isotopic disturbance has occurred and that the calculated age reflects the true time of crystallization of the mineral. In practice, the isotopic-lead ages rarely agree within the limits set by analytical errors (± 1 to 2 percent). One of the most favorable minerals is uraninite, which commonly exhibits a discordance of 10 percent or less (*1*). Since uraninite is too rare to serve generally for study of geologic problems, most uranium-lead ages are determined for the mineral zircon, a common accessory mineral in various rocks. Generally the ages of zircons are discordant. In only a few instances have the differences between the Pb^{206}-U^{238} and Pb^{207}-Pb^{206} ages been less than 10 percent; usually they amount to 20 to 30 percent and may exceed even 50 percent.

Experimental studies (*2*) as well as investigations of many zircon suites (*3–6*) show that loss of lead is probably the most important cause of discordance, but much disagreement persists as to the nature of the processes causing the loss. The amount of lead lost from zircon can sometimes be related to the uranium content of the sample: that is to say, the Pb/U ratios decrease as the concentration of uranium increases (*3–5*). Because the crystal structure of zircon is slowly destroyed by α-particle and recoil-nucleus bombardment, leading to the metamict state, it is conceivable that radiation damage may cause loss of lead.

Several factors indicate the potential utility of sphene, another widely distributed accessory mineral. Sphene occurs with zircon in many rocks, providing a second independent uranium system for measurement of age; it contains 5 to 10 times less uranium than does zircon, so that the rate of radiation damage is proportionately lower. Finally, the stability of sphene toward metamorphic processes should differ from that of zircon.

The existing determinations of age for sphene mostly agree within 10 percent and can be considered nearly concordant (*7*). Nearly concordant ages for sphene are reported by Oosthyzen and Burger (*7*) from a rock whose zircon ages are quite discordant. To test further the suitability of sphene for dating purposes we selected samples from rocks on which results of isotopic studies were available, including in most instances age data for zircons.

Great care was taken in purification of mineral separates. In addition to the usual separations based on density and magnetic susceptibilities, all samples were hand-picked to reduce impurities to abundances of 0.1 percent. All separates were cleaned in warm (50°C) 8*M* nitric acid for 30 minutes before analysis. The uranium and lead concentrations (Table 1) were determined by stable-isotope dilution techniques closely following those described (*8*). The concentrations are believed to be accurate within 1 percent; the isotopic ratios for lead are known within 1 percent (*9*). Thus the uranium-lead and the Pb^{207}-Pb^{206} ages are known within about 1.5 percent.

Two different size fractions of sample NM-5 (granite from Sandia Mountains, New Mexico), +50 mesh [NM-5(a)] and −100 +150 mesh [NM-5(b)], were analyzed separately. The uranium concentrations of the two fractions are identical within analytical errors; so are the nearly concordant ages. The results date the sphene accurately at about 1480 × 10^6 years, a value in close agreement with Pb^{207}-Pb^{206} ages of discordant zircons from the same rock sample (*10*). The two zircon results (Table 2) represent the extremes in their data; the uranium concentrations are 418 parts per million (ppm) for the most concordant sample and 652 ppm for the most discordant. The sphene age of 1480 × 10^6 years coincides on the concordia curve with the upper intercept of the best-fit linear array defined by the zircon data; the result is compatible with the model of episodic loss of lead for the zircons.

It is interesting that the sphene from this rock contains strontium having an anomalous isotopic-Sr composition (*11*). Since the ages of the sphene samples are concordant and agree with the extrapolated age for the zircons, we believe that the sphene results give the time of crystallization. Possibly the sphene crystallized with anomalous Sr. Alternatively, radiogenic Sr may have been added to the mineral during an episode of metamorphism under conditions such that radiogenic lead was retained.

Further work is needed to clarify this observation and lead to better understanding of the difference between the U-Pb ages of sphene and zircon and the 1400 × 10^6-year Rb-Sr age for the whole rock (*11*).

Sample A-26 originated from another locality within the same granite pluton as NM-5. The sphene ages are concordant within the estimated analytical errors and agree with the reported (*12*) Pb^{207}-Pb^{206} age of zircon. Once again the ages of sphene are much more concordant than those of zircon and are greater than the Rb-Sr age of coexisting biotite. The K-Ar age of the biotite is 1300 × 10^6 years (*12*).

The ages of sphene in sample MG-17, granite from Manitouwadge, Ontario, are concordant within analytical errors; the indicated age of 2710 × 10^6 years is in close agreement with the Pb^{207}-Pb^{206} age of nearly concordant zircon separates and with the Rb-Sr age of the whole rock (*13*). The two zircon samples from this rock were separated on the basis of magnetic susceptibilities and differ greatly in their uranium contents—257 and 701 ppm of uranium for the nonmagnetic and magnetic fractions, respectively. Unlike the NM-5 data, here the large difference in uranium concentration makes very little difference in the degree of discordance of the zircon ages. The Rb-Sr age of biotite is less than that of the whole rock, but many data show that biotite can be affected by very mild conditions of metamorphism that do not seriously affect other minerals (*14*).

Two samples, CC-29 of syenite from Rainy Lakes, Ontario, and CC-43 of granite from Saganaga Lake, Minnesota, are from a suite of rocks used in a study of zircon ages in the Rainy Lake district (*15*). Sphene-zircon comparisons were made on them because they include the most concordant (CC-29) as well as one of the most discordant zircon samples (CC-43) within the suite investigated (*15*). In both instances the sphene gives much more concordant ages than does zircon; sample CC-29 is concordant within analytical errors.

Sample 66-93 of granite-gneiss from French River, Ontario (*16*), comes from the Grenville province of high-grade metamorphism about 55 km from the boundary of the Grenville and Superior provinces; it was studied by Krogh (*16*) in a search for ages greater than 1000 to 1100 × 10^6 years within the Grenville province. Krogh established a Rb-Sr age of 1730 ± 75 × 10^6 years on the basis of five whole-rock samples of this granite. Individual minerals such as biotite however give Rb-Sr ages of about 1000 × 10^6 years. The granite appears to be 1730 × 10^6 years old, but to have been subjected to metamorphism 1000 × 10^6 years ago that was sufficiently intense to cause redistribution of radiogenic Sr^{87} within it.

The sphene and the zircon samples are from the same pluton, collected in the same locality but not from the hand specimen used for Rb-Sr determinations of age. Dark [66-93(a)] and light-colored [66-93(b)] sphene fractions, concentrated on the basis of magnetic susceptibilities, were analyzed separately. The fractions contained substantially different concentrations of uranium, but yielded nearly concordant ages that date the time of the Grenville metamor-

Table 1. Analytical data for sphene. Assumed isotopic composition for common Pb—Pb^{206}/Pb^{204}, Pb^{207}/Pb^{204}, and Pb^{208}/Pb^{204}, respectively: samples MG-17, CC-29, CC-43, A-50, CL-11, WYWR-4, and RN-1—13.35, 14.52, and 33.57; samples CO-55, NM-5, and A-26—16.25, 15.51, and 35.73; samples 66-93(a), 66-93(b), and 65-142—16.87, 15.51, and 36.52. For identities of samples see text.

Sample (No.)	Concentrations		Isotopic abundances relative to Pb^{206}			
	U	Pb^{206} (radiogenic)	Pb^{204}	Pb^{206}	Pb^{207}	Pb^{208}
NM-5(a)	148.9	31.93	0.386	100	14.18	109.2
NM-5(b)	148.8	31.67	.285	100	13.16	90.0
A-26	161.2	36.55	.288	100	13.10	112.1
MG-17	73.5	31.89	.0662	100	18.89	8.20
CC-29	70.9	31.56	.306	100	22.08	29.32
CC-43	33.95	15.34	.269	100	21.68	125.2
66-93(a)	145.1	20.46	.618	100	16.34	60.06
66-93(b)	90.2	12.83	.360	100	12.54	42.66
65-142	65.6	9.92	.647	100	16.97	62.01
CO-55	48.7	9.75	.297	100	13.48	110.6
A-50	76.4	35.68	.944	100	30.19	122.4
CL-11	60.1	24.84	.345	100	23.05	64.60
WYWR-4	126.6	54.17	1.164	100	32.34	105.7
RN-1	63.6	27.47	0.1333	100	20.02	45.84

Table 2. Mineral ages; references in italics. Decay constants: U^{238}, 1.54 × 10^{-10}/year; U^{235}, 9.72 × 10^{-10}/year; Rb^{87}, 1.39 × 10^{-11}/year. For identities of samples, see text.

Sample (No.)	Mineral	Apparent ages (× 10^6 yr)			
		Pb^{206}-U^{238}	Pb^{207}-U^{235}	Pb^{207}-Pb^{206}	Sr^{87}-Rb^{87}
NM-5	Sphene (+50 mesh)	1450	1465	1480	
	Sphene (−100 +150 mesh)	1440	1460	1490	
	Zircon (β-1) (*10*)	1290	1360	1470	
	Zircon (β-2) (*10*)	935	1105	1460	
	Whole rock (*11*)				1400
A-26	Sphene	1460	1462	1470	
	Zircon (*12*)	1120	1250	1475	
	Biotite (*12*)				1340
MG-17	Sphene	2660	2685	2710	
	Zircon, light (*13*)	2500	2610	2700	
	Zircon, dark (*13*)	2420	2560	2670	
	Whole rock (*13*)				2700
	Biotite (*13*)				2630
CC-29	Sphene	2720	2725	2730	
	Zircon (*15*)	2450	2600	2730	
CC-43	Sphene	2620	2680	2730	
	Zircon (*15*)	1540	2020	2550	
66-93	Sphene, dark	989	1024	1100	
	Sphene, light	998	1018	1060	
	Zircon (*26*)	1220	1315	1470	
	Whole rock (*16*)				1725
65-142	Sphene	1055	1090	1160	
	Whole rock (*16*)				1330
CO-55	Sphene	1360	1425	1520	
	Whole rock (*17*)				1640
A-50	Sphene	2820	2795	2770	
	Zircon (*18*)	2360	2575	2750	
	Biotite (*18*)				1750
CL-11	Sphene	2560	2680	2775	
	Biotite (*21*)				2750
	Zircon (*4*)	770	1400	2580	
WYWR-4	Sphene	2630	2680	2720	
RN-1	Sphene	2650	2695	2730	
	Biotite (*23*)				2545*

* Potassium-argon age.

phism. Sphene may have crystallized as a result of the metamorphism. However, we cannot exclude the possibility that sphene was present in the rock before Grenville time, but that the age record was completely erased by metamorphism 1000 $\times$ 10^6 years ago. Although the U-Pb ages of the zircon give pre-Grenville dates, they are less than the Rb-Sr age of the whole rock.

Sample 65-142, granite-gneiss from North Bay, Ontario, also comes from the Grenville province, about 100 km from the boundary with the Superior province. Krogh (*16*) reported a Rb-Sr age of 1330 $\pm$ 70 $\times$ 10^6 years for the whole rock. No zircon data are yet available. Again the U-Pb ages of sphene appear to date the Grenville metamorphism and to give no indication of premetamorphic history of the mineral.

Regarding sample CO-55, granodiorite from Monarch Crest, Colorado, Wetherill and Bickford (*17*) have measured Rb-Sr ages on whole-rock samples of granitic and granodioritic rocks from the Precambrian basement complex of central and western Colorado; 13 rocks defined an isochron for an age of 1640 $\pm$ 35 $\times$ 10^6 years, but Rb-Sr measurements on separate minerals from four of the rocks indicated that radiogenic Sr^{87} was reequilibrated between the various mineral phases about 1350 $\times$ 10^6 years ago.

We separated sphene from the CO-55 granodiorite reported in (*17*). Zircon data are not available for sample CO-55, but zircon from a granite of the same suite, sample A-38 from 25 km west of CO-55 (*8*), has Pb^{206}-U^{238} and Pb^{207}-Pb^{206} ages of 925 and 1700 $\times$ 10^6 years, respectively (*8*). The sphene appears to record neither of the two Rb-Sr ages perfectly. In particular, the Pb^{207}-Pb^{206} age of sphene is less than 1640 $\times$ 10^6 years but greater than 1350 $\times$ 10^6 years. Here as at French River the zircon gives discordant ages but records the premetamorphic age better than does sphene.

Sample A-50, granite from Ilomantsi, Finland, is one of six rocks studied (*18*) from the pre-Karelian basement complex in eastern Finland. Zircon from the granite has an age of 2750 $\times$ 10^6 years, while biotite has a Rb-Sr age of 1750 $\times$ 10^6 years—the age found for nearly all biotites in eastern Finland (*19*). The biotite age apparently reflects the effects of metamorphism during the Karelian orogeny. As we have mentioned, relatively mild metamorphism suffices to lower Rb-Sr ages of biotite. Like zircon, the sphene gives an age of 2750 $\times$ 10^6 years and shows little if any effect of the Karelian metamorphism; it is the only sphene in Table 2 having a Pb^{206}-U^{238} age greater than the Pb^{207}-Pb^{206} age, although the discrepancy is within analytical error.

Sample CL-11, amphibolite from Beartooth Mountains, Wyoming, was collected along U.S. Highway 212 near Beartooth Pass; Z-5 on Harris's map (*20*). Only sphene data are known for it, but a Rb-Sr age of 2750 $\times$ 10^6 years is reported (*21*) for biotite from another amphibolite that was collected 1.3 km southwest of CL-11. Catanzaro and Kulp (*4*) have published isotopic ages for zircon from a granite-gneiss (GL) from Gardiner Lake, 1.5 km east of CL-11. The zircon ages (Table 2) are very discordant and contrast strongly with the sphene ages.

Regarding sample WYWR-4, granite from Louis Lake, Wyoming, and sample RN-1, granodiorite from Abitibi Lake, Noranda, Quebec, the sphenes give nearly concordant isotopic ages of about 2750 $\times$ 10^6 years for both. The Pb^{207}-Pb^{206} age of coexisting zircon from WYWR-4 agrees closely with that of the sphene (*22*). A K-Ar age of 2545 $\times$ 10^6 years has been reported for biotite from RN-1 (*23*).

The U-Pb ages from sphene samples that we report are all concordant or nearly concordant; the total spread in age values is usually less than 5 percent. Although the agreement between ages is within analytical error for about half the samples, the Pb^{206}-U^{238} age is the lesser in all instances but one. We therefore believe that most of these samples have lost several percent of their lead, despite the agreement in the ages. Sphene ages are considerably more concordant than zircon ages in all comparisons made by us.

The few results from metamorphic rocks suggest that sphene is not strongly influenced by relatively mild metamorphic processes that are nevertheless sufficiently strong to lower Rb-Sr ages of biotite; examples are the data from samples A-26, NM-5, and A-50. In the case of high-grade metamorphism, sphene may record through concordant ages the time of metamorphism, as for samples 66-93 and 65-142. Isotope studies may ultimately help to distinguish between sphenes of primary and metamorphic origins; if so, these results have broad petrologic implications.

The contrast between sphene and zircon ages is consistent with radiation-damage mechanisms for loss of lead from zircon, but our observations by no means prove such a hypothesis. One must still evaluate chemical factors such as the possible role of water in promotion of loss of lead from zircon, as was suggested by observations of zircons in natural environments (*5*, *24*) and in the laboratory (*2*, *25*). Comparable data for sphene are still unknown. Moreover, knowledge of the distribution of uranium within individual crystals is critical to mechanisms involving damage by radiation. If the radioactive elements are heterogeneously distributed, only local areas may experience extensive radiation damage, and the model meets serious complications (*5*, *10*). Observations of more-radioactive varieties of sphene, such as keilhauite, will also contribute toward better understanding of the problem. Whatever the mechanism or mechanisms for loss of lead, sphene shows a pattern of isotopic ages, quite different from that of coexisting zircon, that can provide an independent check of zircon data. Sphene should be useful for extending the U-Pb method of dating igneous and metamorphic rocks that lack zircon (*25*).

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Globorotalia truncatulinoides as a Paleo-oceanographic Index

Abstract. *In Recent surface sediments of the ocean floor* Globorotalia truncatulinoides *(d'Orbigny) grades from highly conical forms in tropical areas to rather compressed forms in cold-water areas. An interdependence exists between temperature of the surface water and form ratios as defined by mean ratio of width to height and mean ratio of width to the height from keel to ventral extremity. Values of these ratios serve to identify various water masses and thus constitute a potentially useful method in determining paleo-temperatures in Quaternary marine sediments. Subpolar populations, as end members of the cline, are found only in the Southern Hemisphere.*

Distributions of planktonic foraminiferal tests in marine sediments generally reflect their living patterns within given water masses. As a result of this, the distribution of planktonic tests in fossil marine sediments are being used increasingly for paleo-oceanographic reconstructions.

In addition to exhibiting changes in relative abundance with latitude, a number of planktonic species have been found to undergo morphological changes with latitude, apparently constituting clines (*1*, *2*). The value of these clines in establishing greater precision in the interpretation of past climates is well demonstrated by the stratigraphic application of changes in coiling direction in *Globigerina pachyderma* (*1*, *3*).

Examination of *Globorotalia truncatulinoides* populations in 50 surface sediment samples from all the major oceanic areas revealed that distinctly different morphological types occur in polar and tropical areas. [The presence of different forms has been reported only briefly before by Blair (*4*) and by Boltovskoy (*5*).] Furthermore, a complete gradation in morphology occurs with latitude between the respective end members. I found that northward from Antarctic waters in the Southern Hemisphere there is a gradual increase in mean test height and decrease in convexity of the dorsal side until it becomes flattened or concave in tropical–northern subtropical waters.

Samples examined are mostly calcareous oozes containing abundant specimens of *G. truncatulinoides* and were mainly from the upper 3 cm of cores obtained from depths between 1000 and 4000 m, with an average depth of about 2000 m. Samples in the Northern Hemisphere are located between 43° and 16°N and those in the Southern Hemisphere between 59° and 21°S. The following specific areas were studied: south Pacific, Drake Passage, Peru-Chile Trench, Mozambique Channel, off Hong Kong, Gulf of Mexico and Caribbean, western Mediterranean, and the Atlantic Ocean near France and Florida.

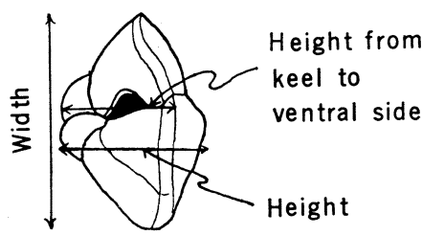

Fig. 1. Side view of a specimen of *Globorotalia truncatulinoides* (d'Orbigny) showing the parameters that were measured. This is a biconvex, relatively compressed form typical of subantarctic areas.

In order to quantify the change in test height, the samples of *G. truncatulinoides* were analyzed in terms of mean ratio of width to height (ratio A) and mean ratio of width to the height from keel to ventral extremity (ratio B) (Fig. 1). Fifty specimens from each sample were measured with an ocular micrometer, except for seven samples in which there were fewer numbers available for measurements. Only mature specimens with a maximum diameter of more than 450 μ were measured. Multivariate analyses have been conducted on these and other parameters, including coiling direction, and a detailed account will be presented elsewhere.

Bé (*6*) has shown from studies of planktonic tow samples that *G. truncatulinoides* deviates from the usual bipolar nature of planktonic species distributions. He showed that in the Northern Hemisphere it does not extend north of subtropical waters (surface temperatures less than 14°C), but in the Southern Hemisphere it flourishes in subantarctic waters (surface waters as low as 4°C). Thus a discussion of its latitudinal changes relates mainly to the Southern Hemisphere, but it is important to note that reciprocal morphological changes occur in tropical-subtropical populations of both hemispheres.

An interdependence between surface water temperatures and the calculated average ratios is evident from Figs. 2 and 3. A general and somewhat gradational decrease in average ratio of width to height (Fig. 2) from northernmost Antarctic to tropical areas reflects a change from rather compressed forms in cold water to highly conical forms in tropical waters. Ranges of these ratios within certain areas in the Southern Hemisphere in turn serve to identify the following water masses: tropical–northern subtropical (1.30 to 1.38), southern subtropical–northern subantarctic (1.40 to 1.52), and southern subantarctic–northernmost Antarctic (1.48 to 1.55).

Likewise, the average ratios of width to the height from keel to ventral side (ratio B, Fig. 3) show a gradational decrease from the northernmost Antarctic to tropical areas. This ratio, al-