Colorado. In both these sequences the rocks show mixed polarities and overlie a thick sequence of rocks that are reversely magnetized (Fig. 2). On the basis of the Australian data and sparse data from Europe (6), the beginning of the Kiaman interval is placed at the base of the Upper Pennsylvanian. On the western slope, the lower reversal is located in rocks of this approximate age. In places, the Fountain formation contains fossils as old as Lower Pennsylvanian, but it is probable that formation was initiated during Upper Pennsylvanian in the area sampled; thinning of the formation in this area supports this interpretation.

It is important to establish the time at which the magnetic moment was acquired by these rocks. Unlike igneous rocks (which have thermoremanent magnetization) or varved clays (which have detrital remanent magnetization), the mechanism, and therefore the time, of magnetization of red beds is poorly understood.

In the western interior of the United States the good correlation between the established stratigraphic relations and the top of the Kiaman division, as determined from available paleomagnetic data, suggests that the magnetization of the beds was acquired near the time of deposition. Further supporting this interpretation is the observation that in the red beds of the western interior of the United States there is a steadily reversed zone which, on the basis of fossil evidence (4), is the approximate age-equivalent of the Kiaman division defined by Australian paleomagnetic data.

Thus we may conclude that the evidence to date suggests that the pattern of polar reversals occurs on three time scales: approximately 10^4 or 10^5, 10^6, and 50×10^6 years. An effort to check the validity of the Kiaman magnetic interval as a worldwide event has demonstrated good correlation between the western interior of the United States and observations based primarily upon Australian paleomagnetic data. Because the Australian data came from igneous rocks dated by radio isotopes, and the data from the western interior of the United States were obtained from red beds dated by fossils, the evidence favors the interpretation that the red beds were magnetized early in the history of the deposits. Finally, the correspondence between paleomagnetic data and classical geological correlations within the western interior suggests that paleomagnetic information may eventually aid stratigraphic correlation.

BEVERLY E. MCMAHON*
Department of Geological Sciences, University of Colorado, Boulder
DAVID W. STRANGWAY
Department of Geology and Geophysics, Massachusetts Institute of Technology, Cambridge 02139

References and Notes

1. R. R. Doell, G. B. Dalrymple, A. Cox, *J. Geophys. Res.* **71**, 531 (1966).
2. N. Opdyke, before Amer. Geophys. Union Meeting, Washington, D.C., April 1966.
3. F. Irving and L. G. Parry, *Geophys. J.* **7**, 395 (1963).
4. N. W. Bass and S. A. Northrup, *Amer. Assoc. Petrol. Geologists Bull.* **34**, 1540 (1950); E. T. Peterson, *Paleozic Rocks in Southeastern Colorado in Stratigraphic Cross Section of Paleozoic Rocks, Colorado to New York*, W. L. Adkison, Ed. (Amer. Assoc. Petrol. Geologists, New York, 1966), pp. 1–5. O. Tweto, *Colorado Sci. Soc. Proc.* **15**, 149 (1949).
5. M. D. Picard, *Amer. Assoc. Petrol. Geologists Bull.* **48**, 269 (1964).
6. A. E. M. Nairn, *J. Geol.* **68**, 285 (1960).
7. For aid we thank the Univ. of Colorado Council on Research and Creative Work and NSF (grant GP-5341).
* Present address: Massachusetts Institute of Technology, Cambridge 02139.

13 December 1966

Composition of the Ancient North American Crust

Abstract. *Geochemical studies of Wyoming Precambrian graywackes derived from continental crust older than 3.2×10^9 years indicate that their source area was at least as highly differentiated as most younger Precambrian crust. The composition of this early crust (approximately that of calcium-rich granite) is not unlike that of the 2.5 to 3.2×10^9 year old North American crust. Limited geochemical data suggest that the composition of North America may not have changed significantly during the last 3.0 to 3.5×10^9 years.*

Whether or not continents have changed appreciably in composition as a function of geologic time is a major problem in the study of continental evolution. Although geologic and geochemical data indicate that K:Na, Fe^{3+}:Fe^{2+}, and Ca:Mg ratios of sediments (which in turn reflect continent composition) have increased in the last 0.6 to 1×10^9 years (1), the evidence for secular compositional changes prior to this period is less certain.

It appears that the oldest orogenic granite-forming event preserved in the continental crust is about 3.4 to 3.6×10^9 years old (2). Although exposures of such ancient crust have been reported only in northern Europe and southern Africa (2), zircons that may be of this age have been found in younger Precambrian terranes of North America (3, 4). Such relict zircon ages suggest that a 3.4 to 3.6×10^9 year old crust also once existed in North America. Although detailed results of geochemical studies of the European and African terranes are not available, geologic studies indicate that they are composed predominantly of granite, gneiss, and migmatite, with lesser amounts of mafic igneous and metamorphic rock and only minor amounts of sedimentary rock (2); their gross lithology is not unlike that of younger Precambrian shields.

Graywackes that occur as large pendants engulfed in 2.5 to 3.2×10^9 year old granitic batholiths in North America represent rapidly eroded mineral and rock-clast assemblages derived from a source, partially or entirely, older than 3.2×10^9 years. The existence of zircons that may be 3.5×10^9 years in age (4) in the Wyoming-Montana portion of the 2.5 to 3.2×10^9 year old North American crust (Superior Province) suggests the possibility that such graywackes in this area may have been derived from crust as old as 3.5×10^9 years.

Graywackes from a large pendant in the Precambrian core of the southern Wind River Range in Wyoming have been sampled in order to estimate the composition of this ancient crust in this area. Although the graywackes have undergone low-grade metamorphism, as evidenced by their constituent mineral assemblages, it is unlikely that their original composition has been appreciably affected. Especially suggestive of approximately isochemical metamorphism is the fact that the enclosed rock fragments indicate a source-area composition similar to that indicated by the bulk chemical composition of the graywackes (5); the fragments indicate a dominant granitic igneous and metamorphic component in the source area.

Twenty-three graywacke samples have been analyzed for eight major and five trace elements by nondestructive x-ray fluorescence and neutron activation (5). The mean values for each oxide and trace element are accompanied (Table 1) by an estimate of

Table 1. Compositions of, and elemental ratios in, ancient North American graywackes and common igneous rocks. Total Fe as Fe_2O_3. Rocks: A, calcium-poor granitic (*6*); B, calcium-rich granitic (*7*); C, continental basaltic (*6*); D, oceanic tholeiitic basalt (*8, 15*); E, average 2.5 to 3.2 $\times$ 10^9 year old North American sediments (*1*); F, average 2.5 to 3.2 $\times$ 10^9 year old Wyoming graywacke.

Item	Rock					
	A	B	C	D	E	F
			Oxides (percentage by weight)			
SiO_2	74.22	67.17	49.20	49.30	66.0	64.43
TiO_2	0.20	0.57	2.30	1.49		0.62
Al_2O_3	13.61	15.50	14.74	17.04	14.5	15.48
Fe_2O_3	2.03	4.23	12.37	9.57	5.7	6.54
MgO	0.27	1.56	7.63	7.19	2.2	?3.12
CaO	.71	3.54	10.64	11.72	2.8	2.22
Na_2O	3.48	3.83	2.43	2.73	3.0	3.74
K_2O	5.06	3.04	1.00	0.16	1.4	2.44
			Trace elements (ppm)			
Mn	390	540	1500	1300		529
Ni	4.5	15	130	97		91
Rb	170	110	30	1.2		88
Sr	100	440	465	120		424
Zr	175	140	140	95		196
			Ratios			
Rb:Sr	1.7	0.25	0.65	0.01		0.27
K:Rb	246	229	277	1400		230
Na:K	0.6	1.1	2.2	16	1.9	1.4
Ca:Sr	59	44	153	640		37

the composition of 2.5 to 3.2 $\times$ 10^9 year old sediments (*1*) and average values of common igneous rocks. The gross similarity in composition of the Wyoming graywackes to calcium-rich granites (*6*) suggests that they were derived from a source area of this composition. The fact that the graywackes contain somewhat less Si and Ca and more Mg, Fe, and Ni than granodiorites and most quartz diorites (*7*) indicates, however, some contribution from more mafic igneous rocks. It is clear, however, from the geochemical data (Table 1) that rocks of basaltic composition were not major components of the source area. The typical continental values of the K:Rb and Ca:Sr ratios in the Wyoming graywackes seem to indicate that oceanic basalts similar to those found on the ocean bottoms today (*8*) were negligible in or absent from the ancient source area.

With the exception of perhaps K and Mg, the composition of 2.5 to 3.2 $\times$ 10^9 year old North American sediments (chiefly graywackes), estimated by Engel and Engel (Table 1; *1*), is grossly similar to that of the Wyoming graywackes. Such data suggest that the North American crust older than 3.2 $\times$ 10^9 years was chiefly of a calcium-rich granite composition. The overall compositional similarity of these ancient clastic sediments to younger Precambrian terranes (Table 2) poses the possibility that the sediments were derived from an ancient crust of similar composition. The fact that in lithologic composition preserved 3.4 to 3.6 $\times$ 10^9 year old crust in Africa and Europe is not unlike later Precambrian crust adds support to this possibility. At any rate the conclusion seems justified that the earliest continental crust in North America of which we still have record was at least as highly differentiated as most later Precambrian crust.

In an attempt to estimate the composition of the Wyoming portion of the 2.5 to 3.2 $\times$ 10^9 year old Superior Province, about 300 samples were collected from major rock types in the Wyoming Precambrian crust and analyzed for Si, Al, Ti, Fe, Mg, Ca, K, Na, and Mn by x-ray fluorescence and neutron activation. By combining these data with other published results of analyses (*9*) and by weighting each rock type according to its approximate abundance, an average composition was calculated. The results are accompanied (Table 2) by other estimates of compositions of the Precambrian shield. This estimate closely agrees with two recent compositional estimates for the Superior Province in Ontario (*10*) and Quebec (*11*), and with a compositional estimate for 1.8 to 2.5 $\times$ 10^9 year old sediments (*1*) that were probably derived chiefly from 2.5 to 3.2 $\times$ 10^9 year old terranes. The mean value of these four estimates (Table 2, column E) may serve as a best approximation of the composition of the 2.5 to 3.2 $\times$ 10^9 year old North American crust at the present time. It is noteworthy that in composition this crust appears to closely resemble the crust older than 3.2 $\times$ 10^9 years as inferred from the graywackes.

Because sampling in the Superior Province has included terranes representing metamorphic grades as high as the granulite facies, one probably may infer that the compositional estimates of Table 2 apply to depths in the crust of at least 10 to 20 km. The fact that seismic data imply that the upper one-third to two-thirds of the continental crust is of similar overall composition supports this inference.

Also shown in Table 2 are estimates of the average composition of the Ca-

Table 2. Compositions of the 2.5 to 3.2 $\times$ 10^9 year old Superior Province. Included are two estimates of Precambrian-shield compositions. Total Fe as Fe_2O_3. Key: A, average composition of Superior Province in New Quebec (*11*); B, average composition of Superior Province in northwestern Ontario (*10*); C, average composition of Superior Province in Wyoming (this report); D, average composition of 1.8 to 2.5 $\times$ 10^9 year old North American sediments (*1*); E, average of estimates A–D; F, average composition of Canadian Shield (*12*); G, average composition of Finnish Shield (*13*).

Item	Composition, average						
	A	B	C	D	E	F	G
			Oxides (percentage by weight)				
SiO_2	64.5	66.3	65.3	65.2	65.3	63.1	67.5
TiO_2	0.48	0.47	0.50		0.48	0.8	0.4
Al_2O_3	16.1	15.4	16.5	14.1	15.5	16.8	14.6
Fe_2O_3	4.7	4.4	4.3	4.9	4.6	5.6	4.8
MgO	2.3	2.1	2.6	2.3	2.3	1.8	1.7
CaO	3.3	4.0	3.5	3.1	3.5	4.1	3.4
Na_2O	4.0	3.9	3.6	2.8	3.6	3.6	3.1
K_2O	2.8	2.3	2.5	2.6	2.6	3.1	3.6
			Manganese (ppm)				
Mn	600	500	400		500	200	300
			Ratio				
Na:K	1.3	1.5	1.3	1.0	1.3	1.0	0.8

nadian Shield (*12*) (including terranes varying in age from about 1 to 3 $\times 10^9$ years) and of the Finnish Shield (*13*) (including terranes varying in age from 1.7 to 3 $\times 10^9$ years). Because of the fewer samples available, errors in early silicate analytical methods, and the limited amount of data related to lithologic abundances when these studies were made, these estimates should not be regarded as being as accurate as the other estimates in Table 2. It is notable, however, that with the exception of their lower Mg, Mn, and Na:K values, which may or may not be real, both the Canadian and Finnish shields are of approximately the same composition as the Superior Province. If the 2.5 to 3.2 $\times 10^9$ year old graywackes in North America reflect the approximate composition of the North American crust older than 3.2 $\times 10^9$ years, it appears unwarranted to propose major compositional changes in the North American continent during the period between about 1.0 and 3.5 $\times 10^9$ years ago. Furthermore, even though sedimentary rocks younger than 1 $\times 10^9$ years show some secular compositional changes (*1*), the fact that they occupy a very small part of the North American continent seems to indicate that North America has not changed appreciably in composition during the last 3 to 3.5 $\times 10^9$ years.

There are now two popular theories regarding rates of continental growth: (i) one proposes that continents have grown at a rather uniform rate throughout geologic time (*1*), and (ii) the other advocates rapid growth during the early stages of continental evolution, with little subsequent growth (*14*). The conclusion that the North American continent may not have changed appreciably in composition during the last 3.0 to 3.5 $\times 10^9$ years appears to be compatible with either theory. If one assumes that the first is correct, it appears that the composition of new material being added to the continents from the mantle has had approximately the same composition for the last 3.0 to 3.5 $\times 10^9$ years. The second theory makes it appear as though the uniformity of composition was maintained primarily by recycling of crustal material.

In summary, the results of this investigation suggest that: (i) at least part of the ancient North American crust older than 3.2 $\times 10^9$ years was as highly differentiated as most younger North American Precambrian crust, and (ii) the North American crust may not have changed appreciably in composition during the last 3.0 to 3.5 $\times 10^9$ years.

KENT C. CONDIE

Department of Earth Sciences, Washington University, St. Louis, Missouri 63130

References and Notes

1. A. E. J. Engel and C. G. Engel, in *Advancing Frontiers in Geology and Geophysics*, A. P. Subramaniam and S. Balakrishna, Eds. (Osmania Univ. Press, Hyderabad, India, 1964), p. 17.
2. W. L. Donn, B. D. Donn, W. G. Valentine, *Geol. Soc. Amer. Bull.* **76**, 287 (1965).
3. E. Catanzaro, *J. Geophys. Res.* **68**, 2045 (1963).
4. ——— and J. L. Kulp, *Geochim. Cosmochim. Acta* **28**, 87 (1964); R. S. Cannon, Jr., R. W. Bayley, T. W. Stern, A. P. Pierce, in Rocky Mtn. Sect. Geol. Soc. Amer. program (1965), p. 27.
5. Detailed geochemical and mineralogic results on the graywackes are in preparation.
6. K. K. Turekian and K. H. Wedepohl, *Geol. Soc. Amer. Bull.* **72**, 175 (1961).
7. S. R. Nockolds, *ibid.* **65**, 1007 (1954).
8. A. E. J. Engel, C. G. Engel, R. G. Havens, *ibid.* **76**, 719 (1965).
9. Compiled from about 15 published papers.
10. G. A. Reilly, thesis, McMaster Univ., 1965.
11. K. E. Eade, W. F. Fahrig, J. A. Maxwell, *Nature* **211**, 1245 (1966).
12. F. F. Grout, *J. Geol.* **46**, 486 (1938).
13. J. J. Sederholm, *Bull. Comm. Geol. Finlande No. 70* (1925).
14. C. Patterson and M. Tatsumoto, *Geochim. Cosmochim. Acta* **28**, 1 (1964).
15. M. Tatsumoto, C. E. Hedge, A. E. J. Engel, *Science* **150**, 886 (1965).
16. Research sponsored by Washington University's NASA multidisciplinary research grant NaG-581. I thank A. M. Stueber for assistance with neutron-activation analysis, and W. D. Johns and W. J. Hannon for reading the manuscript and making suggestions.

7 December 1966

Gravity Increase at the South Pole

Abstract. *Measurements made between December 1957 and January 1966 of the gravity difference between the McMurdo Sound pendulum station, which is on bedrock, and the South Pole station, which is on the Antarctic ice sheet, show a gravity increase at the South Pole of 0.11 milligals per year. The most likely hypothesis for the increase is that it was caused by ice flowing downslope across a gravity gradient and by the sinking of the South Pole station as a result of accumulation of ice. An alternate hypothesis that the gravity increase was caused by a decrease in ice thickness, of about 40 centimeters per year, is theoretically possible but is not supported by direct evidence.*

The Antarctic ice sheet is the largest ice sheet in the world, and any vertical or horizontal movement that can be detected on it has significant glaciological implications. Changes in gravity on the ice sheet at the South Pole are indicated by repeated measurements of the difference in gravity between the South Pole station and McMurdo station from December 1957 (*1*) to January 1966. As McMurdo station is on bedrock, the change presumably occurred at the South Pole.

Recent improvements of gravimeters in sensitivity, calibration, and stability have increased the possibilities of detecting changes in elevation of the earth surface, and measurable changes have been reported (*2*). All measurements, or gravity ties, presented here were made by direct aircraft flight between stations with La Coste Romberg geodetic gravimeters calibrated on the North American calibration range (*3*), with the exception of gravimeter G91, for which the calibration provided by the manufacturer was used. These gravity ties are believed to include all of those made with thermostated gravimeters. Several ties made with Worden gravimeters (*1, 4*) were not included, as the drift closures were too great and there were uncertainties in the calibration due to temperature effects. The original data were recomputed to the nearest 0.01 mgal, earth tide corrections were made, and the values were all adjusted to the Gulf pendulum station at McMurdo station (*5*).

At McMurdo, Sparkman used the pendulum station base (*5*), which is now relatively inaccessible; Behrendt and Rambo used an auxiliary base at the Biological Laboratory, and Den Hartog, Robinson, and Jiracek used an auxiliary base in the U.S. Antarctic Research Program warehouse. At the South Pole (*6*) all observers used the same base. The data are presented in Table 1 and Fig. 1.

Figure 1 shows an apparent decrease in the differences in gravity between McMurdo station and the South Pole station of 0.11 mgal/year, determined by a least-squares fit to the data. As the standard deviation of the data from the line is only about 13 percent of the total change, I believe that the change shown is real. Since the gravity is greater at McMurdo, the net result is an increase in gravity at the South Pole station.