Reports

Early Miocene Subglacial Basalts, the East Antarctic Ice Sheet, and Uplift of the Transantarctic Mountains

Abstract. *Subglacially erupted volcanic rocks from Mount Early and Sheridan Bluff, Antarctica, yield whole-rock potassium-argon dates and argon-40/argon-39 release spectra of Early Miocene age. Field associations suggest the existence of the East Antarctic ice sheet and significant uplift of the Transantarctic Mountains by that time.*

Remnants of two subglacially erupted volcanoes at the head of Scott Glacier, Antarctica (Fig. 1), suggest the presence of the East Antarctic ice sheet and uplift of the Transantarctic Mountains by Early Miocene time. At Sheridan Bluff (*1*), volcanic rocks rest directly on a glacially striated surface of granodiorite, part of the late Precambrian–early Paleozoic Ross Orogen. Throughout the Transantarctic Mountains, rocks of the Ross Orogen are unconformably overlain by gently dipping strata of the Devonian-Triassic Beacon supergroup, which attains a maximum thickness of 3500 m in the Beardmore Glacier area, 400 km northwest of upper Scott Glacier (*2*). The prevolcanic erosion surface at Sheridan Bluff is irregular and gains elevation toward the north from a minimum exposed altitude of approximately 2070 m. Mount Saltonstall (altitude 2973 m) indicates a minimum relief of 900 m in the area prior to the eruption of the volcanic rocks. The Beacon supergroup in the Scott Glacier area is no younger than Permian, with a maximum thickness of 680 m preserved at Mount Weaver (*3*). Even greater prevolcanic erosion has occurred if Triassic rocks, like those found to the northwest, were present in the area and have been stripped away. However, their absence may also indicate nondeposition in the Scott Glacier area during the Triassic. Regardless, the 900 m of prevolcanic relief suggests considerable uplift and erosion of the Transantarctic Mountains in this region prior to eruption.

The volcanic sequence at Sheridan Bluff has a maximum thickness of about 200 m. The glacial pavement is overlain by a unit of pillow breccia 10 m thick which passes upward into hyaloclastite breccia, composed of a yellow palagonite matrix with angular pillow fragments, many of which still preserve original glassy, chilled portions of their margins. The hyaloclastite has a maximum thickness of 85 m and pinches out to the north against the rising surface of granodiorite. The section continues upward with a lava flow, followed by a hyaloclastite unit 5 to 10 m thick, and nine subaerially erupted lava flows, which comprise a sequence of alternating olivine tholeiite and mildly alkaline basalt 110 m thick. The eruptive vent for these rocks is not exposed.

Mount Early stands in isolation, 20 km to the south, 475 m above the surrounding ice; the base is not exposed. This deeply dissected peak displays a stratigraphy similar to that documented on numerous subglacially erupted volcanoes in Iceland (*4*). The core is a shield-shaped pile of pillow lavas, composed of alkali-olivine basalt. These are mantled by pillow breccias that grade upward into fine-grained palagonite breccia. The palagonite breccia is massive in its lower portion but becomes bedded higher in the section. Observations from a distance of about 200 m suggest that the summit, which would not be reached on foot, is capped by lavas. The proximity of hyaloclastites on the glacial pavement at Sheridan Bluff and the great distance from a body of standing water strongly argue that Mount Early also was erupted subglacially rather than subaqueously.

We have dated whole-rock samples from four lava flows at Sheridan Bluff and one whole-rock sample from a flow at Mount Early by conventional K-Ar techniques (Table 1) (*5*, *6*). On the basis of the critical value test of Dalrymple and Lanphere (*6*, p. 120), all dates from the flows at Sheridan Bluff can be interpreted as being the same. However, since samples 24, 27, and 30 have similar K concentrations and $^{40}Ar_{rad}$ yields, we have chosen to average those three to obtain an estimate of the age of volcanism at Sheridan Bluff, $18.32 \pm 0.35 \times 10^6$ years. Sample 22, from the lowest flow unit dated at Sheridan Bluff, has an apparent age of $19.21 \pm 0.39 \times 10^6$ years. Duplicate analyses of the Mount Early sample (34) yielded an average date of $15.86 \pm 0.30 \times 10^6$ years, which represents our best estimate for the minimum age of volcanism there. Since it is possible for rocks of this type to contain "excess" ^{40}Ar or to have lost ^{40}Ar, we analyzed two samples (22 and 27) by the $^{40}Ar/^{39}Ar$ age spectrum technique (*7*) to check for disturbance of the K-Ar system (Table 1). The age spectrum of each sample was concordant, indicating no disturbance of the K-Ar system, and argues rather strongly against either excess ^{40}Ar or a loss of ^{40}Ar. Thus the conventional K-Ar ages should be close approximations to the true age of the basalts. All ages, from both localities, fall within the Early Miocene (*8*), with important implications for the histories of both the uplift of the Transantarctic Mountains and the glaciation of Antarctica.

Uplift of the Transantarctic Mountains has been called the Victoria Orogeny (*9*). This is thought to have occurred along a major boundary fault adjacent to the

Table 1. Data on K-Ar and $^{40}Ar/^{39}Ar$ from whole-rock basalt samples, Mount Early and Sheridan Bluff, Antarctica.

Sample	Locality	K (%)		$^{40}Ar_{rad}$ (mole/g $\times 10^{-11}$)	$^{40}Ar_{rad}$ (%)	Apparent age ($\times 10^6$ years)
		K-Ar data				
34	Mount Early	1.652 1.652	1.652	4.444 4.680	82.8 82.9	15.45 ± 0.19 16.27 ± 0.23
30	Sheridan Bluff	1.351 1.352	1.352	4.366	83.3	18.54 ± 0.37
27	Sheridan Bluff	1.314 1.321	1.318	4.126	81.7	17.98 ± 0.24
24	Sheridan Bluff	1.280 1.289	1.284	4.122	80.4	18.43 ± 0.23
22	Sheridan Bluff	0.5310 0.5287	0.5298	1.773	28.6	19.21 ± 0.39
		$^{40}Ar/^{39}Ar$ data				
27	Weight-average plateau age (88.13% of $^{39}Ar_K$)					19.43 ± 0.65
22	Weight-average plateau age (87.6% of $^{39}Ar_K$)					19.75 ± 1.57

0036-8075/80/0215-0757$00.50/0

Ross Ice Shelf and a series of fault blocks which descend beneath the present-day East Antarctic ice sheet (*10*). Numerous faults, both longitudinal and transverse, also occur throughout the Transantarctic Mountains (*11*). The mountains had been considerably uplifted, and deep valleys had been carved by the outflow of glaciers from the East Antarctic ice sheet by the Late Miocene. This observation is based on foraminiferal data from a drill core taken at the mouth of Taylor Valley, in marine sediments deposited under fjord conditions (*12*). Deep Sea Drilling Project (DSDP) site 270 indicates littoral conditions in the Ross Sea area during the Late Oligocene. By the Early Miocene rapid downwarping had created bathyal conditions there (*13*). Webb has suggested that corresponding uplift occurred in the Transantarctic Mountains (*14*). The prevolcanic erosion surface at Sheridan Bluff indicates that uplift had indeed begun by the Early Miocene and that it was extensive enough for erosion to have cut a minimum of 900 m of relief by that time.

Ice sheet conditions existed probably as early as the Middle Oligocene in Marie Byrd Land, as indicated by subglacially erupted volcanic rocks (*15*). The oldest record of glacial activity from the Ross Sea area is ice-rafted pebbles in Late Oligocene sediments from DSDP site 270 (*16*). Drilling at site J-9 of the Ross Ice Shelf Project penetrated sediment containing ice-rafted detritus as old as the Middle Miocene (*17*). Both cores indicate only that glaciation had reached sea level in the Ross Sea area, and not whether ice sheet conditions existed in East Antarctica at the time.

On the basis of oxygen and carbon isotope data from DSDP cores southwest of New Zealand, Shackleton and Kennett have postulated that the East Antarctic ice sheet accumulated rapidly between the early Middle Miocene and the early Late Miocene (*18*). The carving of Taylor Valley by the Late Miocene, by outlet glaciers from the East Antarctic ice sheet, is consistent with this interpretation.

It has been suggested that the East Antarctic ice sheet formed by the outflow and coalescence of valley glaciers from the Transantarctic Mountains (*19*). Bedrock clearly was emergent through the ice adjacent to Sheridan Bluff at the time of eruption there. But the setting does not permit one to distinguish between ice that was confined by valley walls or ice that was ponded against the Transantarctic Mountains. Mount Early, on the other hand, strongly suggests eruption through an extant ice sheet. If it were erupted through a valley glacier, surely the bedrock of the valley walls would have been as resistant to erosion as the friable palagonite that mantles Mount Early. In fact, Mount Early stands more than 5 km from the nearest exposed bedrock and rises approximately 475 m above the present-day ice sheet.

The difference in elevations of subaerial lava flows (approximately 2180 m versus 2720 m) at Sheridan Bluff and Mount Early does not permit a unique interpretation of the glacial record. If no vertical movement has occurred between the two localities since their eruption, then an increase in ice level, perhaps a shift from valley glacier to ice sheet conditions, is plausible. However, differences in glacial topography, due to outflow through the ancestral Scott Glacier (analogous to the situation today), could account for the elevation differences. In addition, it is possible that displacement along a transverse fault, many of which exist in the Scott Glacier area, caused the differences in elevation if not the location of the volcanoes themselves (*11*).

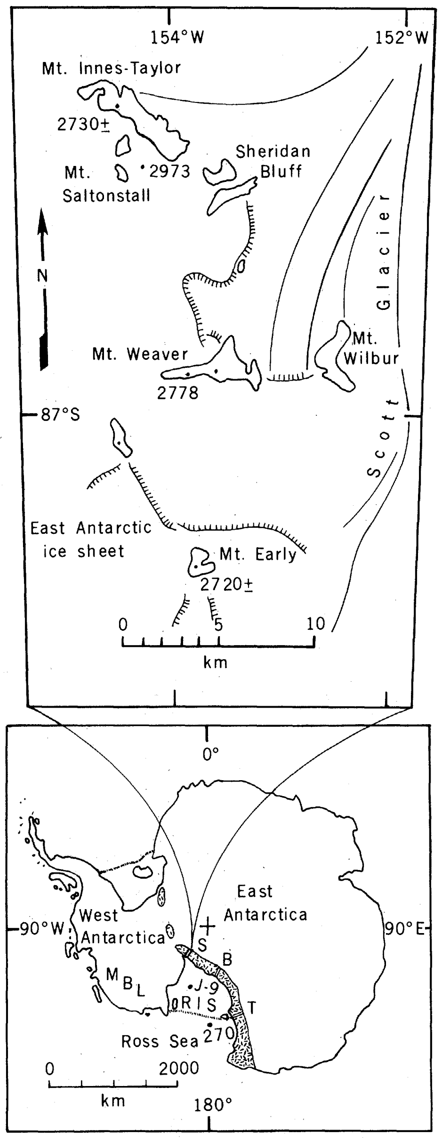

Fig. 1. Location maps of the upper Scott Glacier area (top) (elevations in meters) and the Antarctic continent (bottom) (*S*, Scott Glacier; *B*, Beardmore Glacier; *T*, Taylor Valley; *RIS*, Ross Ice Shelf; *MBL*, Marie Byrd Land; *J-9*, Ross Ice Shelf Project site J-9; *270*, Deep Sea Drilling Project site 270; stippled area, Transantarctic Mountains).

Tills of the Sirius Formation record the oldest and highest glaciation in the Scott Glacier area. They are interpreted to have been deposited beneath an ice sheet, whose projected, maximum elevation limits bracket the summit of Mount Early (*20*). The data from upper Scott Glacier suggest the presence of the East Antarctic ice sheet in that area since Early Miocene time.

EDMUND STUMP
MICHAEL F. SHERIDAN
SCOTT G. BORG
Department of Geology, Arizona State University, Tempe 85281
JOHN F. SUTTER
Department of Geology and Mineralogy and Institute of Polar Studies, Ohio State University, Columbus 43210

References and Notes

1. Name pending approval of the U.S. Board of Geographic Names. Initial reports on volcanic rocks from the head of Scott Glacier were written by G. A. Doumani and V. H. Minshew [*Antarct. Res. Ser.* **6**, 127 (1965)] and S. B. Treves [*JARE (Jpn. Antarct. Res. Exped.) Sci. Rep. Spec. Issue* **1**, 136 (1967)].
2. P. J. Barrett, G. W. Grindley, P. N. Webb, in *Antarctic Geology and Geophysics*, R. J. Adie, Ed. (Universitetsforlaget, Oslo, Norway, 1972), p. 319.
3. V. H. Minshew, Jr., thesis, Ohio State University (1967).
4. G. E. Sigvaldason, *Contrib. Mineral. Petrol.* **18**, 1 (1968).
5. The K-Ar dates reported here were measured in the K/Ar Laboratory at Ohio State University. Whole-rock samples of basalt were ground to −80, +100 mesh and then washed with 10 percent HCl, acetone, alcohol, and triple distilled water. After drying, an aliquant was removed and ground to −100 mesh and analyzed for K content by chemical separation of alkalies [J. A. Cooper, *Geochim. Cosmochim. Acta* **27**, 525 (1963)] and single-channel flame photometry with a flame photometer (Zeiss PF-5). The pooled coefficient of variation for the laboratory's last 50 whole-rock duplicate K analyses is 0.55 percent. We measured the Ar isotopic compositions and concentrations on the −80, +100 size fraction, using extraction techniques described by G. B. Dalrymple and M. A. Lanphere (*6*), bulk-type ^{38}Ar tracers, and a mass spectrometer (Nuclide Corporation model SGA 6-60) operated in the static mode. Argon analyses of both intra- and interlaboratory standards demonstrate an analytical precision of less than 1 percent. Constants used in the age calculations are as follows: $\lambda^{40}_{K_{\beta^-}} = 4.962 \times 10^{-10}$; $\lambda^{40}_{K_e} + \lambda'^{40}_{K_e} = 0.581 \times 10^{-10}$ per year; ^{40}K/K $= 1.67 \times 10^{-4}$ atom per atom [R. H. Steiger and E. Jager, in *Contributions to the Geologic Time Scale, Studies in Geology No. 6* (American Association of Petroleum Geologists, Tulsa, Okla., 1978), p. 67]. Error estimates for the calculated dates reflect analytical precision only and were calculated in the manner described by A. Cox and G. B. Dalrymple [*J. Geophys. Res.* **72**, 2603 (1967)]. Samples 22, 24, 27, and 30 were from lava flows numbered 2, 4, 7, and 10, respectively, at Sheridan Bluff, lava flow 2 being lowermost.
6. G. B. Dalrymple and M. A. Lanphere, *Potas-*

sium-Argon Dating (Freeman, San Francisco, 1969).
7. ——, *Earth Planet. Sci. Lett.* **12**, 300 (1971).
8. The Neogene time scale is after T. Thayer and S. R. Hammond [*ibid.* **22**, 307 (1974)].
9. B. M. Gunn and G. Warren, *N.Z. Geol. Surv. Bull.* **71** (1962).
10. P. J. Barrett, *N.Z. J. Geol Geophys.* **8**, 344 (1965); D. J. Drewry, in *Antarctic Geology and Geophysics*, R. J. Adie, Ed. (Universitetsforlaget, Oslo, Norway, 1972), p. 693.
11. H. R. Katz, in *Antarctic Geoscience*, C. Craddock, Ed. (Univ. of Wisconsin Press, Madison, in press).
12. P. N. Webb and J. H. Wrenn, in *ibid.*; *Antarct. J. U.S.* **7**, 227 (1972); C. G. Vucetich and W. W. Topping, *N.Z. J. Geol. Geophys.* **15**, 227 (1972).
13. D. E. Hayes and L. A. Frakes, *Init. Rep. Deep Sea Drill. Proj.* **28**, 919 (1975).
14. P. W. Webb, in *3rd Dry Valley Drilling Conference* (Tokyo, in press), part 8, p. 124; *Earth Sci.*, in press.
15. W. E. LeMasurier and D. C. Rex, in *Antarctic Geoscience*, C. Craddock, Ed. (Univ. of Wisconsin Press, Madison, in press); W. E. LeMasurier, W. C. McIntosh, D. A. Tewksbury, *Antarct. J. U.S.* **13**, 31 (1978); W. Karlen and O. Melander, *ibid.*, p. 46.
16. P. J. Barrett, *Init. Rep. Deep Sea Drill. Proj.* **28**, 757 (1975).
17. P. N. Webb, T. E. Ronan, Jr., J. H. Lipps, T. E. DeLaca, *Science* **203**, 435 (1979); H. Brady and H. Martin, *ibid.*, p. 437.
18. N. J. Shackleton and J. P. Kennett, *Init. Rep. Deep Sea Drill. Proj.* **29**, 743 (1975).
19. D. J. Drewry, *J. Geol. Soc. London* **131**, 255 (1975).
20. P. A. Mayewski, *Ohio State Univ. Inst. Polar Stud. Rep. 56* (1975).
21. This work was supported by NSF grant DPP76-82040. Contribution No. 383, Institute of Polar Studies.

29 October 1979

Migrations of California Gray Whales Tracked by Oxygen-18 Variations in Their Epizoic Barnacles

Abstract. *Barnacles attached to the California gray whale have oxygen isotope compositions that serve as a record of changing ocean temperatures as the whale migrates between arctic and subtropical waters. The isotopic values for the barnacles can be used to track whale migrations and to reconstruct the recent movements of beached whales. The method may be useful for tracing the movements of other animals, living or fossil, and for reconstructing the voyages of ancient ships.*

Each year the California gray whale *Eschrichtius robustus* performs the longest migration of any mammal—a round trip of between 16,000 and 22,000 km (*1*, *2*). During the warm months of the Northern Hemisphere (late May through October), gray whales generally feed on the benthos in shallow waters of the Bering Sea, the Chukchi Sea, and the western Beaufort Sea as far north as the southern edge of the close pack ice. During the cold months, many of the whales are found in the warm lagoons and bays of Baja California, Mexico. The southward migration generally lasts from October through January. The whales swim south, roughly following the coastline until they reach Baja California. A few travel even farther south, and they winter in protected waters along the Gulf of California.

Deeply embedded in the skin of virtually all gray whales is the host-specific sessile barnacle *Cryptolepas rhachianecti*. This barnacle is closely related to the genus *Coronula* (*3*), which is frequently found on humpback whales (*2*, *4*). Although stable isotope studies of mollusk shells have been used to ascertain the range and succession of seasonal changes in temperature and physical processes (*5*), and to relate progressive changes in oxygen and carbon stable isotopes of benthopelagic fish otoliths to changes in their depth habitats (*6*), no detailed isotopic analyses have been performed on crustacean shells such as those of barnacles (Cirrepedia). I show here how temperature-related changes in $^{18}O/^{16}O$ ratios of the shell of *C. rhachianecti* can be employed as a tracking device to trace the migrations of the host animal.

The first specimen of *C. rhachianecti* that I analyzed was collected from the San Ignacio Lagoon, Baja California, where gray whales mate and calve. The shell (determined by x-ray diffraction to be pure calcite) was ultrasonically cleaned and treated with sodium hypochlorite. It was then broken in two across its diameter, and small samples were removed from the sequential growth lamellae of the sheath with a dental drill (0.5-mm diameter). Each sample (about 0.5 mg) was heated in a vacuum for 30 minutes at 250°C and then analyzed isotopically (*7*); the analytical precision was 0.07 per mil. Two other specimens of *C. rhachianecti* were treated and analyzed in a similar way. These had been removed from a small gray whale that had beached itself in October 1976 on Mission Beach, San Diego (*8*, *9*). Figure 1 gives a magnified view of one of these shells.

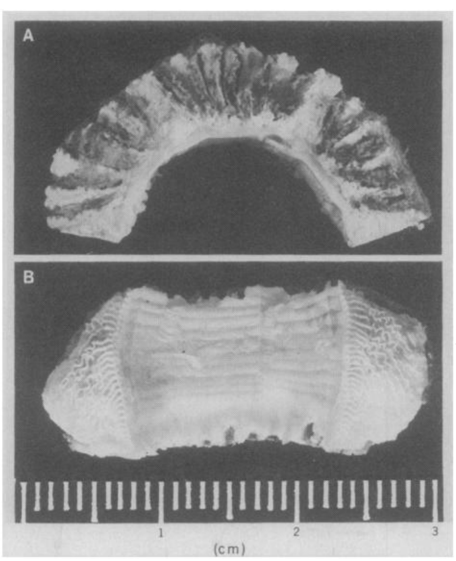

Fig. 1. Plan (A) and inside (B) views of half of the 28-mm barnacle from the beached whale. The inside view shows the sequential growth lamellae with the oldest (partly broken) sections at the top and the most recent growth (irregular toothlike protrusions) at the base.

Figure 2 shows the $\delta^{18}O$ (*10*) results for samples from the San Ignacio barnacle plotted against distance from the base of the shell (the terminal edge). There is a progressive decrease in $\delta^{18}O$ in the direction of shell growth, reflecting movement of the host animal from cold to warm waters. The $\delta^{18}O$ values can be used to calculate the temperature of the water from which the calcite precipitated by using a paleotemperature equation (*11*) that gives temperature as a function of the isotopic composition of the precipitated calcite and the isotopic composition of the water from which precipitation occurred. Conversely, expected calcite $\delta^{18}O$ values can be obtained if temperature and water $\delta^{18}O$ values are available. Estimates of the isotopic composition of the water can be made if the salinity is known (*12*).

From reported average values of salinity for the Arctic Ocean and the northeastern Pacific (*13*), I estimated ocean water $\delta^{18}O$ values and then used the paleoequation to calculate expected calcite $\delta^{18}O$ values for selected temperatures. Temperatures were estimated (*14*) at six points for a model in which a gray whale travels from Point Hope, Alaska (starting 15 October) to San Ignacio Lagoon (arriving 23 January, or 100 days later). Sequential points A to F (Fig. 2) are separated by 20-day intervals and correspond to expected locations during the migration (*1*).

Figure 2 shows the calculated $\delta^{18}O$ values and corresponding temperatures. The model migration agrees well with an actual migration as interpreted from the isotopic values for the barnacle. The average vertical growth rate of the *C. rhachianecti* shell during the migration south is indicated as 0.12 mm per day, and since the whale travels nearly 100 miles per day toward the end of its voyage south (where there is the greatest change of temperature with latitude), individual samples removed for analysis probably represent several days' growth.

0036-8075/80/0215-0759$00.50/0