a necessary constituent (5). The presence of some amount of a highly polymerized hydrocarbon, like the bitumen present in tar sands, may be needed to modify the clay spectrum in the region from 0.8 to 1.4 μm. A few percent of bitumen can be present and not exhibit distinct absorption bands. Finally, a material spectrally similar to the coal tar extract is needed, which can effectively mask the negative slope of the clays between 2.2 and 2.6 μm, reduce the reflectance rise at longer wavelengths, and suppress clay-organic bands at 2.2 to 2.6 μm.

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1. The tar sand samples used in this study are from the Athabasca deposit in northeastern Alberta and consist of viscous organic matter embedded in clastic sediments of the Cretaceous McMurray and Clearwater formations [B. Nagy and G. C. Gagnon, *Geochim. Cosmochim. Acta* **23**, 155 (1961)]. They were obtained from the Alberta Oil Sands Technology and Research Authority [(AOSTRA), Edmonton, Alberta] Oil Sands Sample Bank, along with some analytical data. The reflectance spectra were acquired at the U.S. Geological Survey spectrometer facility in Denver, CO, and the National Aeronautics and Space Administration Reflectance Experiment Laboratory (RELAB) spectrometer facility at Brown University in Providence, RI. Comprehensive descriptions of the instruments and data-processing procedures are available in the following references: R. N. Clark, *Publ. Astron. Soc. Pac.* **92**, 221 (1980); C. M. Pieters, *J. Geophys. Res.* **88**, 9534 (1983); T. V. V. King and W. I. Ridley, *ibid.* **92**, 11457 (1987). The homogeneity of the tar sand samples could only be assessed visually. The samples were gently chopped and mixed until a visually uniform mixture resulted. They were then placed in sample holders and lightly compressed to provide a flat surface for spectral measurement. All samples were measured relative to Halon. The tar sand spectra were acquired with the use of an integrating sphere arrangement at the U.S. Geological Survey facility. The glauconite was spectrally characterized in a bidirectional reflectance mode at the NASA RELAB facility, using an incidence angle of 0° and an emission angle of 15°. A duplicate tar sand spectrum, acquired to check for reproducibility, was within the error limits of the data. The error bars in the spectral data represent 1 SD of the mean. Band depth (D_b), used extensively in spectral analysis, is here defined as

$$D_b = 1 - R_b/R_c$$

where R_c is the reflectance of a straight-line continuum at the wavelength position of a reflectance minimum and R_b is the minimum reflectance at the same wavelength. The continuum was constructed as a straight line tangent to the spectrum on either side of the absorption feature of interest. The continuum for the region from 2.3 to 2.6 μm was taken as a horizontal line tangent to the reflectance maximum near 2.2 μm.
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Temperature Measurements in Carbonatite Lava Lakes and Flows from Oldoinyo Lengai, Tanzania

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The petrogenesis of carbonatites has important implications for mantle processes and for the magmatic evolution of mantle melts rich in carbon dioxide. Oldoinyo Lengai, Tanzania, is the only active carbonatite volcano on Earth. Its highly alkalic, sodium-rich lava, although different in composition from the more common calcium-rich carbonatites, provides the opportunity for observations of the physical characteristics of carbonatite melts. Temperature measurements on active carbonatitic lava flows and from carbonatitic lava lakes were carried out during a period of effusive activity in June 1988. Temperatures ranged from 491° to 519°C. The highest temperature, measured from a carbonatitic lava lake, was 544°C. These temperatures are several hundred degrees lower than measurements from any silicate lava. At the observed temperatures, the carbonatite melt had lower viscosities than the most fluid basaltic lavas. The unusually low magmatic temperatures were confirmed with 1-atmosphere melting experiments on natural samples.

CARBONATITES ARE IGNEOUS ROCKS rich in primary carbonates, dominantly calcite and dolomite. Although rare compared with silicate rocks, carbonatites provide important constraints on partial melting processes, volatile content, and chemical composition in the earth's mantle.

Oldoinyo Lengai, Tanzania, the only active carbonatite volcano on Earth, is famous for its unusual alkali-rich magma, termed natrocarbonatite. The volcano, a

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steep cone about 2900 m high, is 16 km south of Lake Natron in the Tanzanian part of the Gregory Rift Valley. There have been about ten eruptions since early explorers reached the area around the year 1880 (1, 2). Most eruptions were dominantly explosive, but accounts of lava flows date back to 1913 and 1917 (1). However, until the 1960 lava eruption, the carbonatitic composition of its lava was not recognized (3, 4). Since then, Oldoinyo Lengai has attracted a great deal of scientific interest because its activity provides direct evidence for the physical nature, chemical composition, and crystallization history of carbonatite magmas (5–8). As natrocarbonatites have not been found elsewhere, several workers have suggested that the more common calcite-rich carbonatites originally crystallized from a sodium-rich magma and were subsequently altered to calciocarbonatites (8).

In spite of the petrological importance of Oldoinyo Lengai, no systematic observations of active flows were possible since the 1960 eruption mainly because of discontinuous activity and the difficult access to the volcano. A large eruption in 1966 was explosive (9), and since then there was no reported activity until 1983 (10). After the explosive eruption of January 1983, sporadic visitors to the summit reported the renewal of effusive activity in the north crater (10). It also appeared from these reports that the deep explosion pit resulting from the 1966 explosive events (9) had been filled by subsequent lavas.

During a 1-week investigation of the active summit crater in June 1988, we studied the eruptive phenomena during a period of continuous lava-lake and lava-flow activity in the north crater. We were also able to carry out systematic temperature measurements on flowing carbonatite lava and in active lava lakes and to collect fresh lava samples.

The activity during June 1988 was purely effusive. In the crater, which has a diameter of about 250 m (Fig. 1), three open vents were filled with pools of molten lava. One of these lava lakes, with a diameter of 10 m, showed a steady-state vigorous boiling during the period of observation. Periodically the level of the lake rose 1 to 2 m and overflowed. This activity resulted in lava flows 100 to 200 m long, which flooded the flat crater floor (Fig. 1). The lava flows were rarely thicker than 0.5 m and were extremely fluid with flow velocities of 1 to 5 m/s. The flows near the vent were generally of "pahoehoe" type, but the distal part of some flows had an "aa"-like appearance. Lava flows originated not only from the overflowing lava lakes, but also from parasitic vents on the crater floor where small spatter

Table 1. Temperature measurements from carbonatitic lava, Oldoinyo Lengai, 24 to 27 June 1988 (14).

Volcanic feature	Temperature (°C)
Lava lake	Maximum 544
Adventive vent	Maximum 527
Fast-moving flow in lava tube	516, 519
Fast moving flows	502, 505, 506
Distal front of lava flows	491, 494, 495, 503
Residual melt pressed out from cracks in solidified crusts	498, 499, 500, 503

cones formed. A distinct feature of the lava flow activity was the leaking out and squeezing out of fluid, crystal-poor melt from fissures and cracks in the solidified crust of the flows, forming driblets and small secondary flows.

A rather low temperature of Oldoinyo Lengai natrocarbonatite lava had been suspected by several authors. Dawson (2) reported that flows of the 1960 eruption showed no incandescence, and even at night no glow was observed in the vents. Even though he did not make temperature measurements, Dawson estimated that the tem-
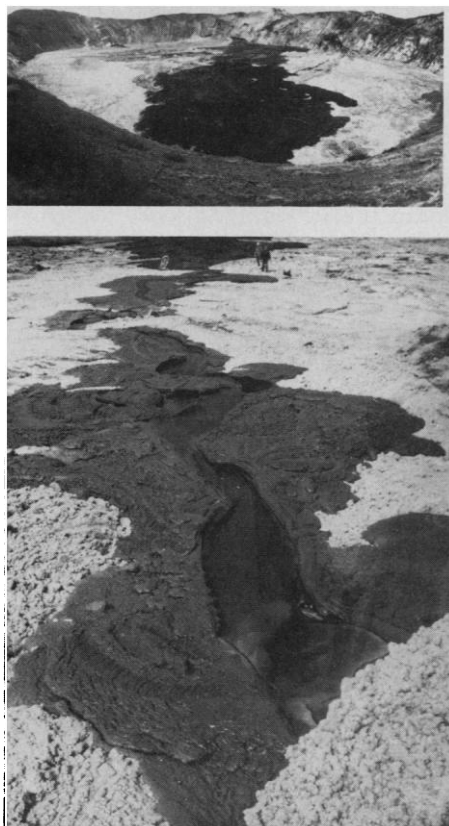

Fig. 1. Active natrocarbonatitic lava flows, Oldoinyo Lengai (Tanzania), June 1988. (**Top**) Summit crater viewed from south on 25 June 1988; crater diameter is ~250 m. (**Bottom**) Lava flow of 27 June 1988 in the summit crater. Length of flow is ~100 m.

perature was most likely not greater than about 500°C (2). In contrast, Richard (11) and Guest (12) reported that a "red glow" was observed during the 1940–1941 and 1954 eruptions.

Cooper et al. (13) determined experimentally that the anhydrous liquidus of the 1960 lava was 655°C at 1 kbar and estimated that the liquidus temperature at 1 atm would be about 20°C lower. This natural anhydrous liquidus is lower than the solidus temperature in the synthetic Na_2CO_3-K_2CO_3-$CaCO_3$ system (13). The K_2CO_3-rich part of the system has a cotectic minimum at 665°C, but this composition is significantly different from that of the natural lava. Liquidus temperatures for the part of the system that resembles the composition of the natural natrocarbonatite are above 700°C (13).

During our visit to Oldoinyo Lengai, the lava lakes and the more proximal parts of the flows showed a dull, red incandescence at night. Upwelling of hot magma to the lake surface was observed on several occasions, and as a result of this upwelling, the lava lake and the flows that originated from the overflowing lake had a distinct orange incandescence.

Temperature measurements were carried out with NiCr-NiAl thermocouples (14). The maximum temperature measured was 544°C. This measurement was obtained during one of the episodes of upwelling of hot magma in the lava lake (Table 1). Similar temperatures (527°C) were measured in a parasitic vent that opened on the crater floor within 20 m of a complex lava lake with a central spatter cone. The parasitic vent was clearly related to this lava lake.

Temperatures in the moving flows were consistently between 491° and 506°C. A fluid melt was being pressed out from fissures and cracks in the crust of partially solidified flows. This melt represents a residual liquid that separated from the crystal mesh of nyerereite and gregoryite phenocrysts because of its low viscosity and low density (15). This phenocryst-poor lava had temperatures from 498° to 503°C, similar to those measured from the fast-moving flows (Table 1). In all, the temperature measurements ranged from 544° to 491°C. Variation in temperature is large for the narrow range of compositions observed (16).

Temperatures of fumaroles emanating from fissures on the crater rim ranged from 78° to 143°C. These values overlap with some of the earlier measurements by Guest (12) and Dawson (2), which were slightly lower, 50° to 80°C.

The chemical composition of the 1988 lavas is similar to that of the known products of the 1960 eruption: CaO + BaO + SrO ≈16 to 17% (weight percent), Na_2O ≈31

to 32%, K_2O ≈8 to 9%, and CO_2 ≈27 to 32% (3–5, 15). Analyses of fresh samples, which were sealed before complete cooling, indicate that the 1988 lavas were almost water-free. The volatile contents of F (2.5 to 4.5%), Cl (3.5 to 5%), and SO_3 (4 to 5.5%) are higher than reported previously for the 1960 lavas (15). Such high volatile concentrations no doubt contributed to the lower solidus temperature of the lava of Oldoinyo Lengai compared with that of the synthetic system studied by Cooper et al. (13).

The temperature measurements on natural lava flows are in good agreement with experimental melting-temperature determinations carried out on samples from the same flows. The rock powder of the natural lava melted easily at temperatures of 500° to 550°C. The melting temperature at 1 atm was determined by differential thermal analysis (DTA) and differential thermal gravimetry (DTG). A pronounced DTA endotherm, representing the onset of melting, began at 490°C (±5°) and had its maximum at 510° to 520°C. This range (490° to 520°C) is similar to the range of the temperature measurements of the lava flows. Dissociation of CO_2 from the carbonate melt began at 660°C.

The observed temperatures are several hundred degrees lower than the lowest 1-atm temperatures of silicate lavas. Significant cooling must have occurred from temperatures of possible partial melting in the mantle (6). Concomitant crystallization can account for the distinctly fractionated composition of natrocarbonatites (5, 6, 15).

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Magnification of Secondary Production by Kelp Detritus in Coastal Marine Ecosystems

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Kelps are highly productive seaweeds found along most temperate latitude coastlines, but the fate and importance of kelp production to nearshore ecosystems are largely unknown. The trophic role of kelp-derived carbon in a wide range of marine organisms was assessed by a natural experiment. Growth rates of benthic suspension feeders were greatly increased in the presence of organic detritus (particulate and dissolved) originating from large benthic seaweeds (kelps). Stable carbon isotope analysis confirmed that kelp-derived carbon is found throughout the nearshore food web.

ALTHOUGH PHYTOPLANKTON IS UNdoubtedly the primary source of organic carbon in much of the world's oceans, benthic plants are thought to be important contributors to food webs in estuarine and coral reef habitats (1). In the early 1970s, Mann and others (2–4) showed exceptionally high productivity in benthic macrophytes belonging to the order Laminariales (kelps) and inferred that kelp-derived organic carbon could play a significant role in temperate coastal (nearshore) secondary production. We assessed the significance of kelp-derived organic carbon to secondary production by a natural experiment involving islands in the Aleutian archipelago (Alaska) with and without sea otters, and thus with and without extensive kelp forests (5). We show that growth rates of benthic suspension feeders are two to five times as high at kelp-dominated islands as at those without kelp beds. Stable carbon isotope ($\delta^{13}C$) analyses show that kelp-derived carbon contributes significantly to the carbon assimilated by secondary consumers at these islands.

Kelps are a dominant feature of many exposed and semiexposed temperate coastlines, where they frequently form dense stands from the low intertidal zone to depths approaching 40 m. Individual kelps can achieve large biomass and rapid growth even at high density, thus forming one of the world's most productive habitats (3, 6). Benthic marine herbivores such as sea urchins (Echinoidea) can retard the growth of kelp populations and occasionally decimate extant populations, but most kelp biomass is not consumed directly (7). This has led to speculation that kelp biomass enters the nearshore food web through indirect (detrital) routes. By releasing particulate as well as dissolved organic matter (POM and DOM, respectively) as they grow and senesce, kelps could provide a significant organic carbon source for the diverse and abundant assemblages of nearshore suspension feeders, pelagic as well as benthic. Even the considerable quantity of kelp biomass deposited on beaches adjacent to kelp stands ultimately may reenter the nearshore food web as POM and DOM after decomposition.

The reestablishment of sea otters in the Aleutians after their near extinction in the 19th century and the subsequent resurgence of otter predation upon sea urchins allow us to compare secondary production between areas that differ greatly in kelp biomass but are otherwise similar. Oceanographic data indicate that the pervasive influence of the westward-flowing Alaskan Stream accounts for relatively uniform physical conditions among the central and western Aleutian Islands (8). Neither the few prior studies nor our surveys provide evidence for significant differences in species composition (including phytoplankton) along this segment of the archipelago (9).

The mid- and low-intertidal zones throughout the Aleutian Islands are dominated by kelps belonging to the genera

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