earlier are relationships which depend on the influence of temperature on the isotopic composition of precipitation rather than any direct temperature effect. Our model relates only to those changes in oxygen isotope composition that occur in and immediately around the tree leaf.

The $\delta^{18}O$ values calculated from Eq. 3 agree rather closely with measured values (Table 1; r^2 = .96). The model-calculated $\delta^{18}O$ value for the tree from Manashtash Ridge is much closer to the measured value than the value from the simple model mentioned above. This difference is thought to be related to the large (~30 percent) difference in humidity between coastal sites and Manashtash Ridge.

If, instead of substituting temperature and humidity, we substitute temperature and the measured cellulose $\delta^{18}O$ values, Eq. 3 can then be used to calculate relative humidity (*21*). The calculated values (Table 1) are all within 1 standard deviation of the average measured daytime relative humidity values for the growing season (*22*).

Valuable information on past changes in humidity can be obtained from measured cellulose $\delta^{18}O$ values and our model, if D/H or other isotope ratios can provide source water $\delta^{18}O$ values (δ_I). A 1 per mil change in δ_I represents approximately a 1 per mil shift in cellulose $\delta^{18}O$ values.

We have used Eq. 3 to calculate humidity values and could make a similar calculation for temperature since α and ϵ^* in the model are a function of temperature. The change with respect to temperature, however, is approximately 0.2 per mil per degree Celsius, which is a small effect compared to changes in relative humidity (1 percent change in relative humidity $\simeq$0.3 per mil change in cellulose $\delta^{18}O$).

Epstein *et al.* (*4*) have shown that α^* (*23*) between aquatic plants and their surrounding water is 1.027. The calculated α^* for the samples in Table 1, with 100 percent relative humidity to approximate the conditions under which aquatic plants grow, is either 1.027 or 1.026. This result suggests that the model can be used for aquatic plants as well as terrestrial plants. However, for aquatic plants ϵ^* no longer maintains its physical significance and must be treated as a constant.

We have shown that the oxygen isotope content of cellulose from trees can be used as a temperature indicator in specific West Coast areas where humidity values are fairly constant. An empirical model is derived which incorporates the currently known factors which determine $\delta^{18}O$ values in cellulose. Model results suggest that source water $\delta^{18}O$, humidity, leaf boundary-layer dynamics, and the $\delta^{18}O$ composition of atmospheric water vapor are factors that must be considered when evaluating oxygen isotope data in tree rings.

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References and Notes

1. Oxygen isotope ratios are calculated from

$$\delta^{18}O = \left(\frac{R_{sample}}{R_{standard}} - 1\right) \times 1000 \text{ (per mil)},$$

where R = $^{18}O/^{16}O$ (atom ratio). The standard is standard mean ocean water (SMOW).
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$$\bar{\delta}_w = \frac{\sum_{i=1}^{n} P_i\delta_i}{\sum_{i=1}^{n} P_i}$$

where P_i and δ_i represent, respectively, the monthly precipitation and its δ value.
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15. It is assumed that δ_{AV} is in equilibrium with the average $\delta^{18}O$ of precipitation: $\epsilon^* = 2.644 - 3.206(10^3/T) + 1.534\ (10^6/T^2)$ where T is in degrees Kelvin [Y. Bottinga and H. Craig, *Earth Planet. Sci. Lett.* **5**, 285 (1969)]. Only daytime humidity values are used. Temperatures used are daily averages since daytime-only values were not usually available.
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$$\alpha = \frac{(5.112 - 0.214t + 0.00041t^2 + 1000)1.04075}{1000}$$

where t is in degrees Celsius [Y. Bottinga and H. Craig, *Earth Planet. Sci. Lett.* **5**, 285 (1969)].
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21. Relative humidity is given by

$$h = \frac{\delta^{18}O_{cellulose} + 1016 + \alpha(-10^3 - \delta_1 - \epsilon^* - \epsilon_K)}{\alpha(\delta_{AV} - \epsilon_K - \delta_1)}$$

and

$$K = -16 \text{ (see text)}$$

22. The growing season used for Fairbanks was June, July, and August; for Ketchikan, May through August; and for the sites in Washington and California, May through September. Water $\delta^{18}O$ values (δ_I) used in the model are from an interpolation of IAEA values (see Fig. 1C) or from our direct measurements on lakewater (Fairbanks) or precipitation (Tyee).
23. $$\alpha^* = \frac{1 + \delta^{18}O_{cellulose}/1000}{1 + \delta^{18}O_{precipitation}/1000}$$
24. This research was supported by Department of Energy contract DE-AT06-79 EV10206 and NSF grant EAR-7904523, Geochemistry Program. We appreciate the assistance of P. Grootes, J. McCracken, P. Quay, P. Reimer, J. White, P. Wilkenson, and A. Yang.

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Volcanic Origin of the Eruptive Plumes on Io

Abstract. *A quadruple long exposure of Io in eclipse exhibits faint auroral emission from the eruptive plumes. No luminous spots in the vents, predicted by Gold, were observed. Heat from the interior of Io appears to be the predominant source of energy in the plumes.*

Gold (*1*) has recently expanded upon the idea that the large potential across Io generated by its interaction with the Jovian magnetosphere must drive electric currents (*2*). He proposed that these currents concentrate through the observed volcanic vents (*3–5*) and then pass through Io's interior. He calculated that these currents can be strong enough to account for the observed volcanic activity and that they are responsible for the eruptive plumes. He also predicted that luminous spots might be seen at night at the vents, a phenomenon not to be expected in the volcanic model based on sulfur dioxide as the driving gas and molten sulfur as the hot contact surface from which it proceeds (*5, 6*). This continues to be true for the models corresponding to observed temperatures (*7*) higher than those originally believed plausible. In these models (*8*) both sulfur vapor and SO_2 are present, the former predominating as driver.

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Fortunately, there is a wide-angle unfiltered ("clear") frame of the dark side of Io available from Voyager 1 [for a brief description of the cameras and filters, see Smith *et al.* (*3*)]. It consists of four superimposed images of Io exposed for 38 seconds each (FDS 16395.39, PICNO 0376J1 + 000), the camera having been slewed between these exposures (Fig. 1). The multiple images of several stars have been identified (Fig. 2). A gyro turn was executed during the last 6 seconds of the third exposure. Io was only 7° from the sun and had just entered eclipse (that is, was in Jupiter's shadow). The images were obtained while the sun was eclipsed by Jupiter as seen from the spacecraft.

Contrary to Gold's (*1*) prediction, no trails of bright luminous spots appear. Instead, very faint diffuse luminous glows are seen. Figure 2 shows the locations of the glows seen on Io's surface or at its limb. Plume 1 accounts for one of the glows at the limb. The other glow extending south within the limb along longitude 225° from the north pole to latitude +50° also appears to reach above the limb. No plume has been seen in this area, but the area has not been mapped. There is also a feeble glow near the south pole. No plume has been seen near the south pole, and the relevant area has not been mapped. The remaining glows come from areas well on Io's disk and evidently are due to electric glow discharges through the SO_2 vapor in the plumes. We shall henceforth refer to these as auroras. We estimate our detection threshold at 3000 S_{10} units or, for our 2000-Å-wide passband, at 30 kilorayleighs. The emissions seen have intensities comparable to those of the terrestrial auroras of medium brightness. The auroral activity at both poles correlates suggestively with the large numbers of small vents seen at high latitudes (*4*, *9*), mainly at the bases of scarps.

The view in Fig. 1 is at high elevation angles into plumes 3 and 4. Neither in these cases nor at plumes 5, 6, and 7, observed at low elevation angles, do we see any sharp concentration of light at the base of a plume. If gases exist at the solar photospheric temperatures (~6000 K) calculated by Gold for the acceleration of SO_2 to 1 km sec^{-1}, then at our limiting magnitude of detection (~ +9.0) bright spots as small as 6 cm in diameter could have been seen. Inasmuch as plume 3 lies about 12° from the subspacecraft point, the vent walls would have to be steeper than 78° to conceal the luminous gas. Such steep walls are not precluded for small vents, but the walls of large gaseous eruption vents on Earth (>1 km in diameter) typically flare at slopes of 45° or less at the orifice (*10*). Even if luminous gas at 6000 K were hidden at the base of steep-walled vents, it would illuminate the central parts of the plumes above them. The illuminated part of a plume would then have been visible, as a result of scattering, and would have appeared as a starlike streak in our frame if a collimated beam of light as much as a few tens of meters in diameter is present. We conclude that the very hot gases suggested by Gold as the sources of the plumes probably are not present. Their absence removes the primary argument used by Gold for the suggested electrical origin of the plumes.

We must consider several points in Gold's (*1*) discussion in order to clarify the situation. First, it is generally recognized that SO_2 vapor is present on Io (*11*) and is a prominent gas in the plumes (*5*, *6*, *8*). It has also been shown by Smith *et al.* (*5*) and Kumar (*12*) that SO_2 should have survived on Io although more volatile gases did not.

Second, with reference to the plumes, Gold stated (*1*) that only in very special circumstances is it possible for solid particles to gain speeds in excess of the speed of sound in the propelling gas. The inference here is that the velocity of the gas itself cannot exceed the speed of sound in the gas prior to expansion. However, the limiting flow velocity of a perfect gas for steady isentropic, one-dimensional expansion into a vacuum (that is, down a smooth-walled tube) is given by the well-known formula (*13*)

$$u = c_0 \left(\frac{2}{\gamma - 1} \right)^{1/2} \tag{1}$$

where u is the limiting flow velocity, c_0 is the sound speed for the initial unexpanded state, and γ is the ratio of specific heats, which is constant for a perfect gas. As γ commonly is near 1.3 for polyatomic gases such as SO_2, the limiting flow velocities indicated by Eq. 1 are typically about 2.5 c_0. A literal application of Eq. 1 to SO_2 gas, with expansion started at an initial temperature of 393 K and an adopted value of γ measured at room temperature, would yield a limiting expansion velocity of ~600 m sec^{-1}. Although this velocity is in the range required to explain all the observed plumes on Io except plume 1 (*5*), the application of Eq. 1 does not provide the true limiting expansion velocity for SO_2. Depending upon the initial entropy, phase changes intervene long before the SO_2 gas can approach the limiting velocity indicated. Moreover, for real gases, including SO_2, γ is a function of pressure

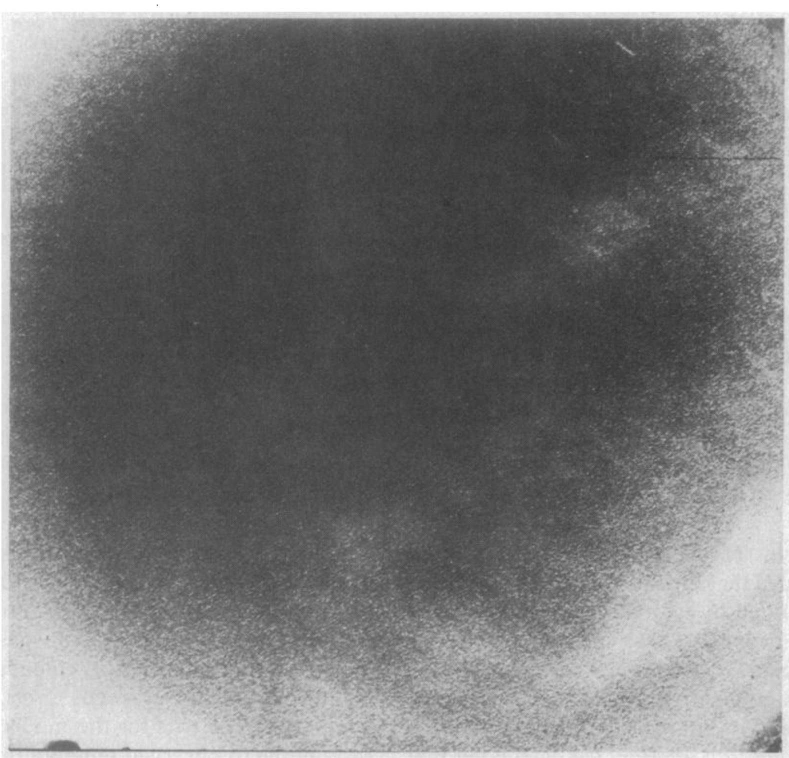

Fig. 1. Quadruple exposure (FDS 16395.39, PICNO 0376J1 + 000) of Io obtained through the wide-angle camera with the clear filter. Exposure began at 1979 March 4^d 17^h 1^m 32^s ephemeris time at the spacecraft; total exposure 3^m 2^s at 38^s in each position with 10^s slews in between and a 6^s gyro turn at the end of the third exposure. The camera drifted during the exposure, whence the stars and Io are trailed.

and temperature; if solid or liquid phases are present, the effective γ for the multiphase system is generally much less than for the gas phase alone.

In the expansion of a real multiphase system, the energy carried in the entrained liquid and solid phases and the latent heats of melting and vaporization must be considered. For this reason, Smith *et al.* used a modified form of the Bernoulli equation to obtain one-dimensional flow velocities at various steps of steady isentropic expansion (*5*). The Bernoulli equation relates increments of specific kinetic energy of the system to decrements of specific enthalpy. On the basis of extensive thermodynamic data available for SO_2, limiting expansion velocities of 1030 and 1224 m sec^{-1} were found for an initial temperature of 393 K and two different entropies, one corresponding to the liquid boundary of the liquid plus vapor field and the other to the vapor boundary. The expanding systems considered are multiphase at all times after the start of expansion. The initial state for the low-entropy case is entirely liquid, whereas the initial state for the high-entropy case is entirely gas. Still higher velocities can readily be attained by expansion of a SO_2 multiphase system if, at a given entropy, expansion is started at a higher temperature than 393 K (the temperature of sulfur at its liquidus at 40 bars). In this case the onset of droplet formation leads to the formation of weak shock fronts and dissipation in the supersonic flow (*14*). Inasmuch as temperatures near 600 K have been observed (*7*), there is quite enough energy to spare to explain the observed heights of the plumes. Thus temperatures in the thousands of kelvins are simply not required to explain the plumes on Io.

Third, it has been shown by Matson *et al.* (*15*) that the constituents on Io's surface have a low enough thermal conductivity that heat escape may be largely through active hot spots (presumptively identified with the calderas) and not through conduction to and radiation from the remainder of the surface. The evidence for this is the ease of fitting the infrared observations of Io during eclipses by the combination of rapid cooling of the general surface to a very low temperature at the cessation of insolation and steady radiation from local hot spots. Indeed, such a low conductivity is to be expected in a loosely compacted surface essentially in vacuo (*16*).

Peale *et al.* (*17*) originally proposed that tidal heating and runaway melting would produce a solid crust so thin that volcanic activity might be driven through it. According to their model, without any internal circulation there would be a concentration of volcanic activity toward the great circle along the two meridians perpendicular to the mean direction of Jupiter (longitudes 90° and 270°), a point made by Gold (*1*). The observed concentration to the equator does not invalidate their entire model, as suggested by Gold, but rather appears to require a significant redistribution of tidal energy by an internal circulation within the molten interior. Furthermore, Matson *et al.* (*15*) found, from the ground-based infrared data, that the hot spots emit a total flux of $(2 \pm 1) \times 10^3$ erg cm^{-2} sec^{-1}, averaged over Io's surface, whereas Gold (*1*) estimated for heating by electric currents about 50 erg cm^{-2} sec^{-1} averaged over Io's surface; this falls short by a factor of ~40. Matson *et al.* (*15*) also showed that reasonable values of the Love number for the contribution to the potential of the second degree and for the tidal dissipation factor (0.26 and 23, respectively) will yield the observed heat flux from tidal dissipation alone by the mechanism of Peale *et al.* (*17*). This fit requires that

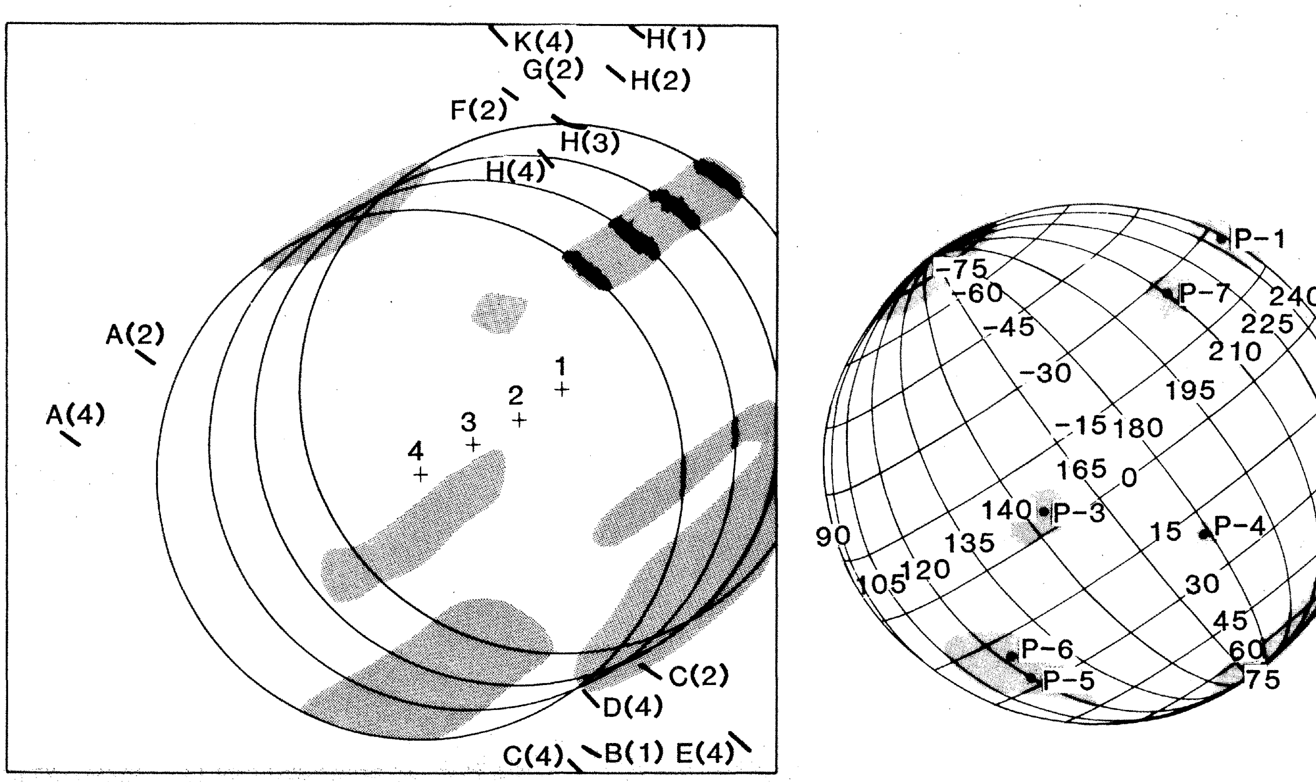

Fig. 2. Diagram of the positions of Io, star trails, and glows (auroras), and a consolidated plot of the positions of the auroras. The trailed stars are lettered with image numbers in parentheses. Their BD (*20*) and Smithsonian Astrophysical Observatory (*21*) numbers are as follows: A (−14° 5861, 163918); B (−11° 5434, 163918); C (−11° 5447, 163940); D (−12° 5854, 163953); E (−11° 5456, 163966); F (−13° 5807, 164025); G (−13° 5810, 164036); H (−13° 5813, 164046); and K (−14° 5908, 164064). The plumes are identified by numbers with the prefix P. Their coordinates are given by Smith *et al.* (*22*). Their names are Pele (P-1), Prometheus (P-3), Volund (P-4), Amirani (P-5), Maui (P-6), and Marduk (P-7).

an extensive volume of Io's interior be molten.

The electric currents discussed by Gold (*1*) apparently do not provide more than a small part of the observed heat flow. Furthermore, there is no evidence that they produce the very-high-temperature gases that he suggested. Temporary local concentrations of current through volcanoes cannot play a role in the impulsive acceleration of material in the plumes, for example, by sputtering, to velocities of the order of 5 km sec^{-1} that appear to be required to explain the observed clouds of neutral sodium and potassium about Io (*18*). Herbert and Lichtenstein (*19*) concluded that charge storage falls far short of being adequate to support such temporary concentrations of current (lightning).

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Reworked Neritic Fossils in Upper Mesozoic and Cenozoic Central Pacific Deep-Sea Sediments Monitor Sea-Level Changes

Abstract. *Upper Mesozoic and Cenozoic pelagic sediments in the central Pacific Ocean contain occasional horizons with reworked and displaced fossils produced by organisms that once lived in neritic shallow-water environments. The flux of neritic fossils was restricted to eight intervals of low eustatic sea level during Late Mesozoic and Cenozoic times. They were eroded from shoals along the flanks of volcanic highs which often supported tropical islands and which since then have subsided.*

Displaced neritic fossils that are found in pelagic sediments are easily recognized regardless of whether the material is contemporaneous with or older than the host sediment. These fossils can tell us much about the nature and presence of former neritic depositional environments (shoals or coastal regions of small and large oceanic islands) which may not exist anymore because of the subsidence of the oceanic crust with time. They allow us to determine the date of existence and subsidence of these environments and to describe the mode of transport and in some instances the morphology of the transport path. Recently a search has been carried out in the reports of deep-sea drilling sites (*1*) in the tropical and subtropical Pacific Ocean (Fig. 1) to establish temporal (*2*) and spatial patterns in the distribution of reworked and displaced contemporaneous as well as noncoeval neritic fossils. The sediments that have been described as containing reworked fossils (Fig. 1) in the central Pacific Ocean span a wide time (from late Jurassic–early Cretaceous to Quaternary) and depth range (1.5 to 6 km). Because of the poor coring record of the sites drilled during the early phases of the Deep Sea Drilling Project (DSDP) and the long-lasting hiatuses that have been encountered, the deep-sea basin sites from the central Pacific Ocean are underrepresented as compared with the elevated areas. The sites are spread over the entire western subtropical and tropical Pacific Ocean (Fig. 1) where the sea floor is predominantly of Jurassic, Cretaceous, and early Tertiary age and which, because of the slow northward movement of the Pacific plate, has remained in the tropical and subtropical Pacific Ocean (*3*). Because of the distribution of the drilling site locations over such a wide area, a bias toward one single deep-sea basin or toward one very specialized, depositional environment can be excluded.

The occurrence, frequency, and age distribution of displaced fossils derived from shallow-water environments (Fig. 2) in many of the western central Pacific deep-sea drilling sites was surprising as these sites are presently located at a distance from extensive land areas. However, it has been known for some time that many of the submarine rises and platforms observed in the western central Pacific once reached close to or above the sea surface. The shallow-water carbonate rocks that have been dredged from the flanks of these features (*4, 5*) at several hundred to several thousand meters of water depth (*6*) indicate possible source localities for the displaced material. Evidence for the displacement of shallow-water carbonate fossils from their neritic depositional environment into the adjacent deep sea is widespread, both with respect to space and time. Most of the occurrences reveal the displacement of sediments of approximately the same age as the host sediment, whereas evidence for erosional events cutting into sections considerably older than the time of displacement have been found in only very few locations. These sites are situated in the vicinity of the Tuamotu Islands (site 76), the Line Islands (site 165), the Emperor Seamounts (site 309), and at site 462 in the Nauru Basin (*7*). These are areas where extensive reworking of shallow-water sediments has been recorded in deep-sea drilling sites (Fig. 2). The occurrence of noncoeval neritic fossils is also restricted to Cenozoic sediments. The maximum difference between the age of the reworked material and the time of displacement is 50×10^6 years in the late Oligocene deposits of site 462 (*8*).

Occurrences of displaced contempora-