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18. Once the gas phase has been exsolved from the melt, the O_2 and H_2 pressures are no longer buffered. Any process selectively removing H_2 will induce a degree of disequilibrium, which will be followed by the dissociation of H_2O vapor. (This will restore the H_2 to approximately its previous pressure but will greatly increase the O_2 pressure.) Two possible processes are the introduction of small amounts of atmospheric O_2 and the diffusion of H_2 through solid lava crusts, the latter having been postulated by Sato and Wright (*17*) to explain the oxidation of solidified basaltic lava.
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Ground-Based Thermal Infrared Surveys as an Aid in Predicting Volcanic Eruptions in the Cascade Range

Abstract. *Detailed, ground-based thermal surveys of selected slopes of Mt. Rainier and Mt. Lassen have provided quantitative data for the construction of thermal contour maps of portions of the flanks of these volcanoes. Preliminary surveys substantiate the existence of one suspected thermal anomaly on Mt. Rainier.*

Recent eruptions of supposedly extinct volcanoes such as Mt. Arenal in Costa Rica in 1968 and the recognition of large, geologically recent, lahars (mudflows from a volcano) in volcanic areas have led to an increase in the monitoring of potentially hazardous volcanoes. Volcanic eruptions often produce destructive quantities of lava and ash. However, lahars may pose even greater destructive threats because of their possible speed and size. Lahars covering tens of square miles have been found, for example, in many of the valleys adjacent to Mt. Rainier, Washington (*1*). It is possible that many of these lahars formed as a result of volcanic warming of portions of the ice- and debris-covered volcano and were not necessarily related to simultaneous outpourings of volcanic materials.

A variety of techniques are now being used on Cascade Range volcanoes in the western United States to predict volcanic eruptions. These include seismic monitoring, intermittent periodic aerial thermal infrared imagery, tiltmeter studies, geodetic surveys, and ground-based quantitative thermal scanning.

We report here preliminary results of one of the field-monitoring techniques, namely, ground-based quantitative thermal scanning of the slopes of some of the most potentially dangerous Cascade Range volcanoes. This particular thermal technique was first used by Birnie (*2*) on certain Central American volcanoes. Radiometry was also used by Tazieff and Jatteau to determine the temperatures of gases emitted at Mt. Etna, Sicily (*3*).

In our thermal technique we utilize a PRT-5 precision radiation thermometer (Barnes Engineering Company) (*4*). The radiation thermometer measures the radiant exitance between 9.5 and 11.5 μm of any target within its 0.14° (2.44 milliradians) field of view. This particular band pass substantially reduces errors normally induced by atmospheric absorption. The 0.14° field of view of the instrument makes it possible to integrate the radiant exitance of a circular area 1.0 m in diameter at a distance of 401 m from the sensor. The PRT-5 yields precise readings of apparent surface temperatures ranging from −20° to +75°C. The precision of the instrument is 0.1°C.

The radiation thermometer is set up on prominent view sites around each volcano. The PRT-5 optical scanning head is mounted on a goniometer-equipped tripod capable of reproducible vertical and horizontal movements as small as 15′. Readings are taken in the very early morning before the first rays of the sun strike the mountainside, thus minimizing the differential solar heating of the surface material from the preceding day. The slope is scanned horizontally from the top down, and the temperatures are recorded at 20-minute intervals. No corrections are made for the emissivity of the surface material, the atmospheric absorption of the infrared radiation, or the temperature change due to the adiabatic cooling rate with increasing elevation. The vegetation-free volcanic surfaces are approximately constant in composition; therefore, the emissivity is approximately constant but not equal to unity.

The thermal data were collected on clear mornings in August and September 1972, the season of minimum mountain snow cover. Recorded temperatures were rounded off to the nearest degree Celsius and then they were plotted on photographs of the mountain slopes taken from the monitoring sites, and the isotherm contours were

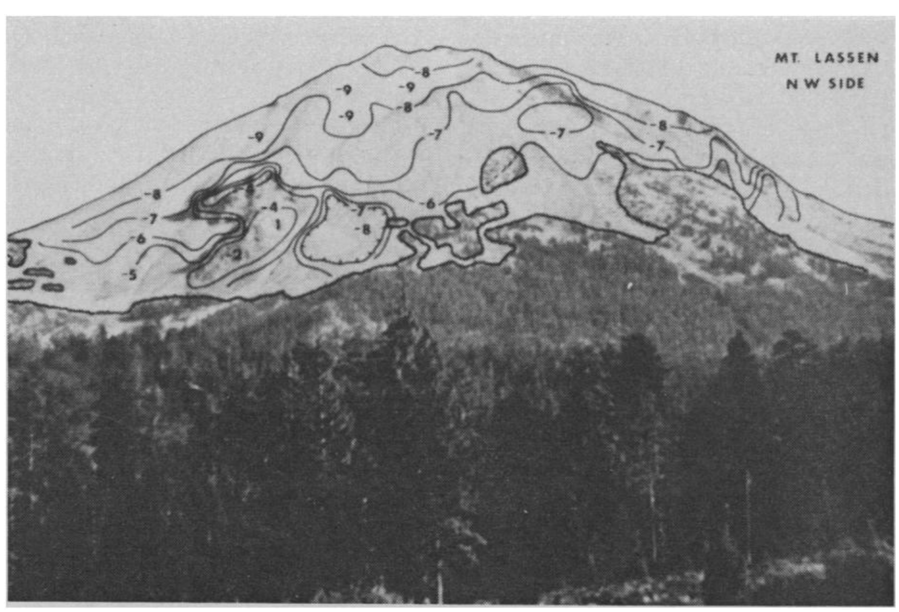

Fig. 1. Northwest side of Mt. Lassen (elevation, 3189 m), California, scanned 24 September 1972, from the north shore of Manzanita Lake (elevation, 1784 m). The distance between the station and the summit is approximately 8.1 km.

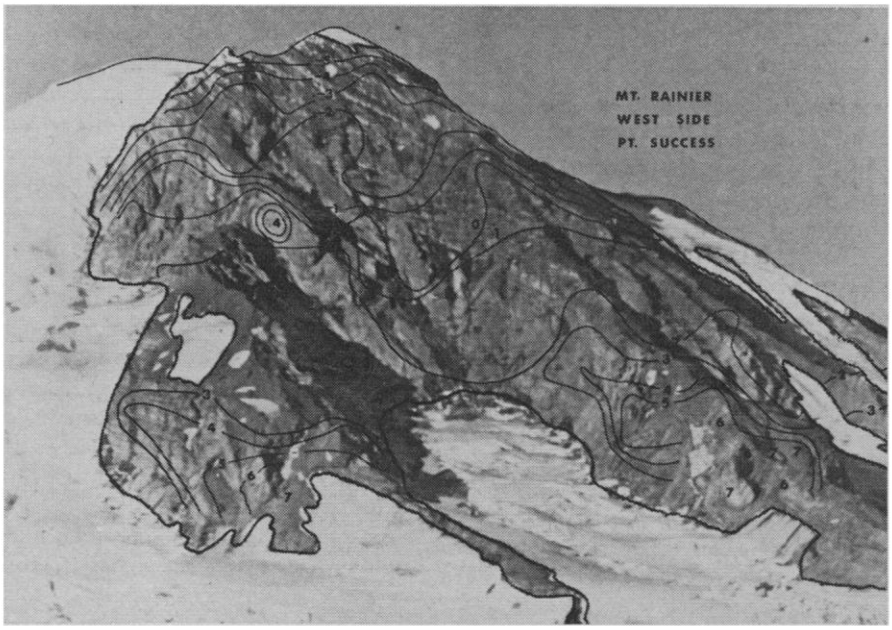

Fig. 2. West face below Pt. Success (elevation, 4316 m) of Mt. Rainier, Washington, scanned 28 August 1972, from Gobbler's Knob (elevation, 1647 m). The distance from the station to Pt. Success is approximately 12.5 km.

then drawn. The results of some of the many thermal scans are shown in Figs. 1 and 2.

The thermal scan of Mt. Lassen, California (Fig. 1), shows a "warm" outcrop-associated area (1°C) which has been known for a number of years (*5*). The cool depression to the right of the thermal anomaly is associated with a snow field. In addition, the −8°C contour near the summit is the reverse of the normal and expected adiabatic cooling with elevation and thus appears to be the result of post-eruptive heat leaving the 1914–1917 summit craters.

Figure 2 is a thermal picture of an area below Pt. Success on the west side of Mt. Rainier. An interesting thermal anomaly was noticed on the slope and is represented by a +4°C reading. This area, we later discovered, was the site of "steam" clouds observed during 23 and 24 September 1967 (*1*). It was also the locus of a debris slide which may be seen in a photograph taken on 8 October 1967 (*1*).

Preliminary results of the thermal mapping, summarized in Figs. 1 and 2, indicate the advantages as well as some of the disadvantages associated with the ground-based thermal scanning technique. Obvious advantages include the fact that quantitative results can be obtained remotely and rapidly. The quantitative results derived from this technique constitute a distinct advantage over many other available remote thermal-sensing techniques which generally yield only the relative differences between the thermal intensities of the anomalies.

The thermal measurements can be repeated at frequent intervals and can also be correlated with other thermal data if the proper absorption and atmospheric temperature corrections are made (*2*). Other advantages include the simplicity, yet great precision and accuracy, of the system in addition to its portability. Known and suspected thermal areas can be observed and thermally mapped at closer distances when necessary. Finally, steep slopes which defy accurate high-altitude airborne infrared surveillance except by "side-looking infrared" are easily scanned from the ground.

Another instrument also suitable for volcanic thermal studies is the "thermovision" type nutational scanner. It can be used both from the ground and from hovering aircraft. Data can be presented in the form of isotherms at intervals selected by the operator.

Problems inherent in the technique include the following: (i) the difficulty of finding ideal monitoring locations (we have not found it difficult to locate good monitoring sites, but it might prove to be a problem during detailed close-distance work on a volcano as massive as Mt. Shasta, California); (ii) snow and ice cover (the scans are carried out in late summer when snow cover is at a minimum; however, the perennially snow-covered surfaces of Mt. Rainier and Mt. Baker in Washington preclude thermal surveys); (iii) vegetation (slopes covered with vegetation cannot be surveyed, although infrared photography clearly and simply delineates such areas and vegetation is generally restricted to the lowermost slopes of these volcanoes); (iv) the necessity of favorable weather (scanning must be done in clear weather); (v) nocturnal ponding of cold air on some surfaces (surfaces of abnormally low temperature not related to snow or ice fields are probably most often due to the nocturnal ponding of cold air; one can generally substantiate whether this phenomenon has occurred by observing the particular surface configuration seen on aerial photographs and topographic maps); and (vi) the inability to scan the summits of the volcanoes (thermal surveys of summit areas cannot be done except from the air). Although each of these problems exists to some extent on each volcano, none of them has as yet proved to be particularly bothersome except for the inability to survey the summit regions.

The thermal readings are apparent surface temperatures and, as previously mentioned, were not corrected for the emissivity of the material, atmospheric absorption, and the adiabatic lapse rate. Corrections would change the temperatures slightly but not the thermal patterns, their anomalies, or their locations. The reader is referred to Birnie's (*2*) discussion of these corrections and their significance. Obviously, corrections will be necessary when one is comparing readings taken at different times and under different atmospheric conditions from the same location.

All the thermal anomalies discovered thus far appear to occur on rock outcrops. This is not to say that thermally warmer areas do not exist under talus- and debris-covered slopes. However, heat transfer by conduction through solid rock and especially by convection through fissure systems in the rock is considerably more effective than heat transfer through deposits of rock debris. Therefore, the likelihood of discovering a thermal anomaly on a debris-covered slope is probably small except perhaps immediately before an actual eruption at that site or if the rock debris is very thin.

Finally, because atmospheric conditions vary on the volcanoes from year to year and month to month, the detection of surface thermal changes which actually signify changes in volcanic heat from year to year require critical examination of past temperature and precipitation records. For example, temperatures colder than normal or snowfall in above-average amounts, or both, during the previous winter can depress ground temperatures over anomalous areas even though volcanic heat discharge through the site remains constant.

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Chondrites: Initial Strontium-87/Strontium-86 Ratios and the Early History of the Solar System

Abstract. *A sodium-poor, calcium-rich inclusion in the carbonaceous chondrite Allende had a* $^{87}Sr/^{86}Sr$ *ratio at the time of its formation of 0.69880, as low a value as that found in any other meteorite. The higher* $^{87}Sr/^{86}Sr$ *ratios found in ordinary chondrites indicate that their formation or isotopic equilibration occurred tens of millions of years later.*

During the past 20 years, radioactive dating methods have increasingly been applied to the problems of establishing the chronology of the earth, moon, and solar system. Many of these methods involve a fixed percentage error, which makes it impossible to resolve events occurring within $\sim 100 \times 10^6$ years of one another early in the history of the solar system.

Two methods have been developed for the resolution of the fine structure in the time scale for the formation of the solar system. One of these is based on the xenon daughter products of the extinct radioactive isotopes ^{129}I (half-life $t_{1/2} = 17 \times 10^6$ years) (*1*) and ^{244}Pu ($t_{1/2} = 80 \times 10^6$ years) (*2*), and the other depends on the initial isotopic abundance of radiogenic ^{87}Sr, the daughter of ^{87}Rb ($t_{1/2} = 50 \times 10^9$ years).

This latter method is based on the assumption that at the time of its formation the solar nebula had a uniform $^{87}Sr/^{86}Sr$ ratio (about 0.698). If the solar nebula had a $^{87}Rb/^{86}Sr$ ratio typical of chondrites (0.75), the $^{87}Sr/^{86}Sr$ ratio of the solar nebula will increase at the rate of 0.0001 per 9×10^6 years. If the $^{87}Rb/^{86}Sr$ ratio of the solar nebula were that of the sun (1.9), the $^{87}Sr/^{86}Sr$ ratio of the solar nebula will increase at the rate of 0.0001 per 4×10^6 years (*3*). At the time of formation of the planetary bodies or of the parent bodies of meteorites or at the time of mineral separation of the constituents of these bodies, the preexisting $^{87}Rb/^{86}Sr$ ratio was changed (fractionated). If the resulting $^{87}Rb/^{86}Sr$ ratio was sufficiently low, and if the time since the ratio changed is known, then it is possible to calculate the $^{87}Sr/^{86}Sr$ ratio which prevailed at the time of fractionation. The differences between these initial ratios for various objects can then be interpreted as time intervals in the formation of the solar system.

Using this method, Papanastassiou and Wasserburg (*4*) have shown that, if the parent bodies of the differentiated basaltic achondrites were fractionated from material of chondritic composition, the fractionations took place over a time span of about 4×10^6 years or less, as indicated by their having nearly the same $^{87}Sr/^{86}Sr$ ratio (0.69899 ± 0.00004) at the time of this fractionation. The pyroxene achondrite Angra dos Reis had an even lower initial $^{87}Sr/^{86}Sr$ ratio (0.69884 ± 0.00003), thus suggesting that the corresponding fractionation of this material occurred about 10×10^6 years earlier.

The chondritic meteorites have long been considered to be among the most primitive objects in the solar system, both because of their age ($\sim 4.6 \times 10^9$ years) (*5*) and because of their lack of extensive chemical differentiation (*6*). Therefore it was somewhat surprising to find that the chondrite Guareña [H6 in the Wood–Van Schmus classification

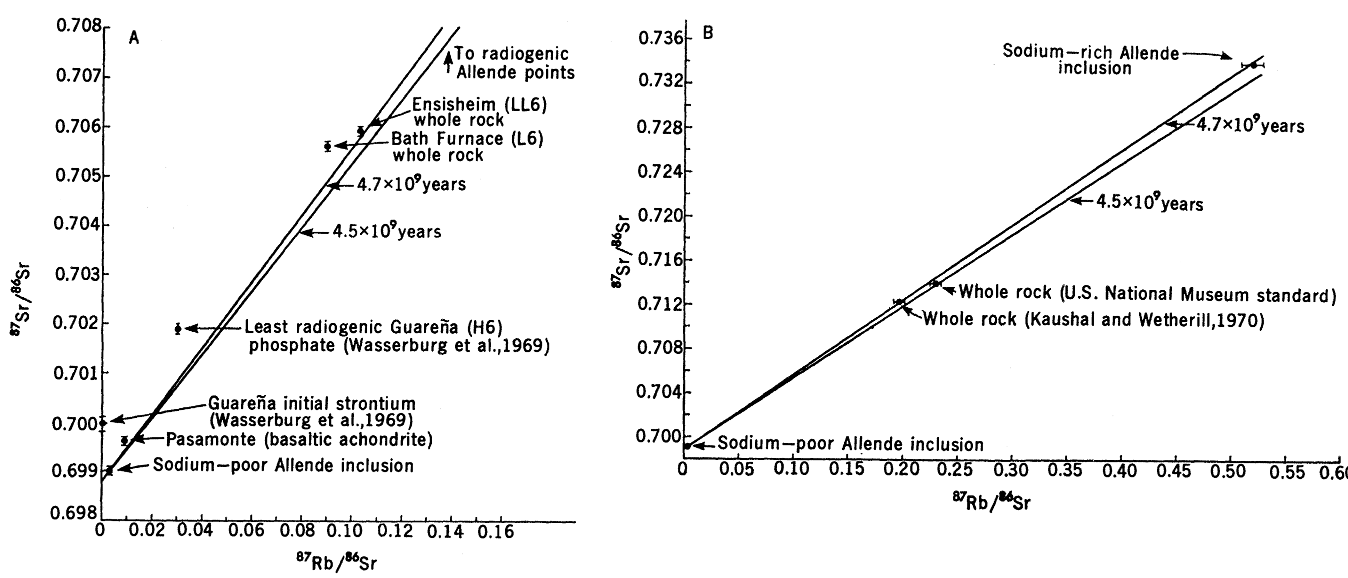

Fig. 1. Strontium evolution diagrams. (A) Less radiogenic samples. The extrapolation of the sodium-poor Allende inclusion point to the $^{87}Sr/^{86}Sr$ axis gives an initial ratio of 0.6988, lower than the initial ratio for the Pasamonte basaltic achondrite. The other chondrites shown have higher initial ratios. (B) Allende samples including more radiogenic data. All of the points lie between the lines corresponding to ages of 4.5×10^9 and 4.7×10^9 years. The initial ratio for the sodium-poor Allende inclusion is insensitive to whichever of these ages is used.