era did survive (*26*), even though the K-T impact, at 10^{30} ergs, far exceeded the total explosive power of 3×10^{26} ergs assumed for nuclear winter. Evidently the geologic record can provide data not only on an ancient cataclysm but also on similar disasters, manmade or natural, that threaten the earth in the future.

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27. This report is dedicated to the memory of Serge Regnier, principal organizer of the Bordeaux meeting of the Meteoritical Society that provided much of the impetus for the work reported here. We gratefully acknowledge the donors of the samples: H. J. Hansen, R. R. Brooks, and R. Ganapathy. We are also indebted to E. D. Goldberg for valuable advice and a manuscript copy of his book and to O. Eugster and J. Geiss for unpublished data on an early search for noble gases in material from the Danish K-T boundary. A. M. Davis, A. Hashimoto, and T. K. Mayeda kindly provided advice and assistance in the identification of minerals. J. P. Bradley of Walter C. McCrone Associates provided Fig. 1D. Supported in part by NSF grant EAR 8212355 and NASA grant NAG 9-52.

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Halite Particles Injected into the Stratosphere by the 1982 El Chichón Eruption

Abstract. *Halite particles about 2 micrometers in size were collected by a quartz crystal microbalance cascade impactor from the El Chichón eruption cloud in the lower stratosphere during April and May 1982. These particles are probably derived from the erupted chloride-rich, alkalic magma. Enrichments of hydrogen chloride and increases in optical depolarization in the eruption cloud observed by lidar measurements may reflect the influence of the halite particles. There is evidence that the halite particles reacted with sulfuric acid after about 1 month, releasing gaseous hydrogen chloride, which can influence the catalytic destruction of ozone in the stratosphere.*

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The El Chichón volcano in southern Mexico (17.3°N, 93.2°W) injected large amounts of gases and particles into the stratosphere during eruptions between 28 March and 4 April 1982. Mass and size distributions of the aerosol were measured in situ in a layer of eruption material in the lower stratosphere (altitude, 18 to 21 km) by a quartz crystal microbalance (QCM) cascade impactor (*1*) on a U-2 aircraft. Size-fractionated aerosol particles were collected by the QCM and were analyzed after the flight. The general character of the aerosol particles was similar to that in other volcanic clouds in most respects (*2, 3*), but scanning electron microscopy (SEM) and x-ray energy spectroscopy (XES) revealed the presence of NaCl particles (halites), which are rarely if ever seen at these altitudes. These halite particles are a natural source of chloride that, in addition to anthropogenic sources (such as chlorofluoromethanes), could have a major impact on the stratosphere through the catalytic destruction of ozone (*4*). The particles may have also caused the enhanced optical depolarization in the El Chichón cloud observed by lidar measurements (*5*).

Table 1. U-2 aircraft sampling flights from Moffett Field, California (~37°N, 122°W).

Date (1982)	Destination	
15 April	23°N	111°W
4 May	23°N	111°W
20 July	23°N	111°W
23 July	23°N	111°W
4 November	32°N	106°W
5 November	41°N	106°W
15 December	23°N	111°W
17 December	40°N	105°W

The monodisperse nature of the halite aerosol was evident because almost all the particles appeared on impactor stage 5 [corresponding to a geometric mean diameter (GMD) of 2 μm], except for a few that appeared on stage 4 (GMD, 4.5 μm). On the basis of the SEM data from impactor stage 5 and the mass-loading rate inferred from the QCM data, we estimate that the halites accounted for 7 percent of the total aerosol mass (or about 0.5 $\mu g\ m^{-3}$) in the most dense part of the plume on 5 May 1982. Halites represented much less than 1 percent of the total aerosol mass in the samples collected on 15 April.

Additional sampling flights were conducted in July, November, and December 1982 (Table 1), but no halite particles were found in any samples collected after 5 May 1982. It is likely that their disappearance was due to chemical processes involving the NaCl particles and the H_2SO_4 droplets that were a major constituent of the eruption cloud (*6*). We suggest the following reaction

$$2\ NaCl + H_2SO_4 \rightarrow Na_2SO_4 + 2\ HCl \qquad (1)$$

on the basis of results we obtained with laboratory samples. The 15 April and 5 May samples were analyzed during the first week of May 1982, a little more than 1 month after they were injected into the stratosphere. NaCl particles were identified by SEM and XES in the presence of liquid H_2SO_4 in both samples (Fig. 1, A and B). The 15 April and 5 May samples were reexamined in November 1982, about 8 months after the eruptions; at this time the original NaCl particles had converted to Na_2SO_4 and had also changed in their physical appearance (Fig. 2).

In subsequent experiments with an aerosol mixture of NaCl and H_2SO_4 generated from a solution and collected on an impaction plate in the laboratory, we found that the reaction given by Eq. 1 does indeed occur. SEM and XES analyses performed at different times after collection indicated that the NaCl particles started converting to Na_2SO_4 after about 1 month. This is reasonably consistent with the airborne measurements, which indicated that the NaCl particles in the eruption cloud converted after 5 May 1982 (1 month after the eruption) but before 20 July 1982 (more than 3 months after the eruption). Since no airborne measurements were made between 5 May and 20 July 1982, our best estimate of the time for conversion of the halite particles in the eruption cloud is between 1 and 3 months. We rarely found Na_2SO_4 particles during the later sampling flights.

One important consequence of Eq. 1 is that gaseous HCl can be released to the stratosphere and can take part in the catalytic destruction of O_3. A 40 percent increase in the total column amount of HCl above 12 km was observed in the region of the cloud by airborne spectroscopic measurements between July and October 1982 (*7*). Our results indicate that HCl would have been released by conversion of halites by this time. Increases in HCl in the eruption cloud from filter data collected in situ were also observed (*8*). Although much of the observed increase in HCl in the eruption cloud may have been the result of direct injection, the timing of the increase suggests that the conversion of halites may also have contributed.

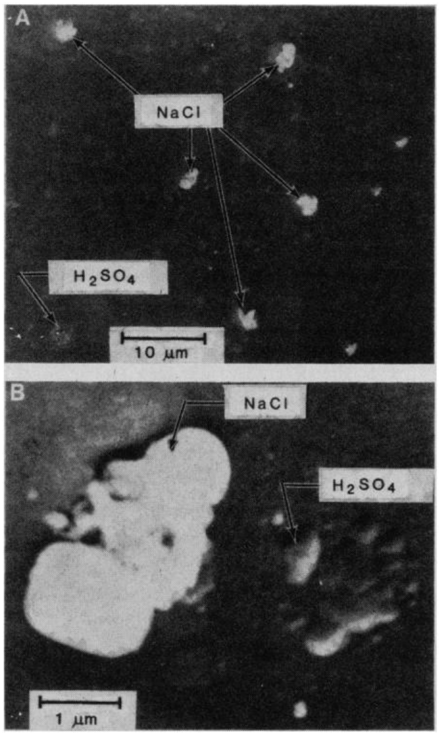

Fig. 1. Halite particles collected in the El Chichón eruption cloud on 5 May 1982 (altitude ~21 km). (A) A small fraction of the impaction area. The entire impaction area was uniformly populated by similar particles. (B) A higher magnification, showing the particle in the center of (A). X-ray energy spectroscopic analyses indicated that the nearly cube-shaped solid particles are NaCl. The liquid-like material near the particle consists of sulfur and is presumed to be hydrated H_2SO_4.

In addition to the release of HCl to the stratosphere, it is likely that the NaCl particles influenced results from optical measurements on the cloud. Because halites are nonspherical particles, their optical properties are different from those of H_2SO_4 droplets, which are often used in scattering calculations. Lidar observations made by Hayashida and coworkers (*5*) in Japan (35°N, 137°E) between May and September 1982 revealed depolarization ratios greater than 10 percent at 20 km, with a maximum value of 20 percent in early May 1982 compared to background values of less than 5 percent. These investigators have suggested that the high depolarization ratios were caused by nonspherical silicate particles in the cloud. Our samples contained large amounts (by mass) of silicate particles (*2*), but it is possible that the crystalline NaCl particles in the cloud also contributed to the depolarization and may have been responsible for the extremely high values (20 percent) observed in May 1982. Halites accounted

Table 2. Concentrations (in parts per million) of sulfur and chloride before and after eruption in magmas from some recently erupted volcanoes.

Component	Fuego (1974) (*16*)		Mount St. Helens (1980) (*17, 18*)		El Chichón (1982) (*12, 19*)	
	Before eruption	After eruption	Before eruption	After eruption	Before eruption	After eruption
Sulfur	2,800	75	300	20	11,000	5,100
Chloride	800	220	1,100	400	1,800	1,300

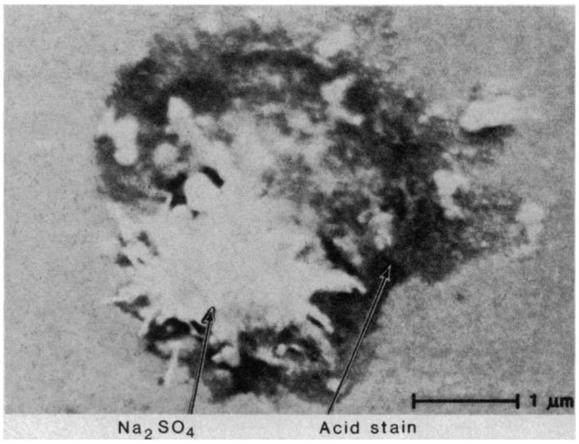

Fig. 2. The remains of a halite particle collected on 5 May 1982 as observed by scanning electron microscopy in November 1982. The x-ray energy spectroscopic spectrum indicated Na_2SO_4 by comparison with a reference sample. The dark area surrounding the particle is presumably a stain left by the acid.

for roughly 7 percent of the total aerosol mass in the cloud layer on 5 May 1982. The depolarization ratios calculated by Hayashida and coworkers start to drop from the maximum of 20 percent before about mid-May 1982, which is roughly in agreement with the time expected for the NaCl particles to start converting and disappearing from the atmosphere.

It is not clear how widespread the occurrence of halite may be in eruption clouds, but our data suggest that it may be specifically favored in alkalic volcanoes. The mildly alkalic El Chichón magma contains higher amounts of chloride (as well as sulfur) compared to other eruptions (Table 2), so that it is reasonable to expect a more prominent role for chloride components. The El Chichón magma volatilizes gaseous NaCl and probably other elements (*9*), and in the eruption cloud the NaCl forms halite aerosols (*10*). NaCl is also a common fumarolic incrustation at volcanoes (*11*). Analysis of materials absorbed on the ash of El Chichón (*12*) indicates an average of 355 parts per million (ppm) of sodium and 780 ppm of chloride, which is consistent with the presence of halite in the eruption cloud. The earlier idea that the unusual volatile signature of El Chichón's magma was caused by interaction with underlying evaporites (*13*) has been apparently ruled out by isotopic studies (*14*), and the high content of chloride and sulfur of the magma is thought to have a deeper origin. We have also found halite particles in volcanic plumes from Mount Erebus, Antarctica (*15*). Thus, although it has not been widely reported, halite probably forms in many eruption clouds but is most noticeable in the eruption of alkalic magmas.

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Oroclinal Bending of the Southern Sierra Nevada Batholith

Abstract. *Structural, magmatic, and isotopic features of the southern Sierra Nevada batholith are deflected clockwise with respect to its central and northern parts. Directions of magnetization at three localities in the southern Sierra Nevada are progressively deflected; this is consistent with the hypothesis that the region was tectonically rotated in an orocline. No paleomagnetic deflection was observed northwest of the White Wolf–Kern Canyon fault system. Oroclinal bending of a block bounded by the San Andreas, Garlock, and White Wolf–Kern Canyon faults may have occurred before about 16 × 10^6 years ago. The deformation may have been a response to shear at the western boundary of the North American plate caused by oblique subduction.*

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Structural, magmatic, and isotopic patterns of the northern and central Sierra Nevada batholith of California have nominal northwest-southeast trends, but to the south these features are systematically deflected clockwise (*1–4*). The deflection approaches 90° at the southernmost end of the batholith, where structures of the Tehachapi and San Emigdio Mountains have an east-west trend (Fig. 1). This observation has led to suggestions that the magmatic and isotopic patterns in the south were once approximately parallel to those of the northern and central Sierra Nevada but were subsequently deflected during post-Cretaceous tectonic activity (*4–6*).

Paleomagnetic data (*7*) suggest that part of the Bear Valley Springs pluton (age, 80×10^6 to 86×10^6 years) (locality 3 in Fig. 1) has rotated clockwise 45° ± 14°; this is consistent with the inferred tectonic flexure. Miocene strata that overlie the pluton show no rotation, constraining the time of deformation to later than 80×10^6 years ago but earlier than 16×10^6 years ago (*8*).

One key question is whether the observed deflection of paleomagnetic vectors was caused by oroclinal bending or by another process. The aberrant magnetizations could reflect movement of an independent block that was tilted or rotated, rather than flexure of the entire southern Sierra Nevada Batholith (*9*).

To discover whether oroclinal bending was the cause, we made paleomagnetic measurements at three points in the southern Sierra Nevada (localities 1, 2, and 4 in Fig. 1). If the orocline hypothesis is correct, a systematic increase in paleomagnetic deflection with distance should be observed along the trend of the southern Sierra Nevada. If the observed 45° deflection resulted from movement of an isolated block, a systematic trend in the deflection of paleomagnetic directions would be absent.

At locality 1 (Fig. 1) we collected biotite granodiorite samples from the Claraville pluton. At locality 2 we collected samples of hornblende-biotite tonalite from the Bear Valley Springs pluton. Both plutons are of late Cretaceous age. Biotite K:Ar ages for the Bear Valley Springs pluton range from 81×10^6 to 86×10^6 years, and biotite K:Ar ages from the Claraville pluton are 75×10^6 and 79×10^6 years (*4*). Localities 2 and 3 sample the same pluton but lie on opposite sides of the White Wolf–Kern Canyon (WWKC) fault.

At localities 1 and 2, no clear ancient horizontal reference is available because there are no younger strata in contact with basement rocks nearby from which to obtain estimates of the total amount of post-Cretaceous tectonic tilt. At locality 3, estimates of post-Miocene tectonic tilt were obtained from attitudes of nearby Miocene strata (*7*). At locality 4, the basement rocks are overlaid by Paleocene to Miocene strata, which provide an $(18 \pm 2) \times 10^6$ year (*10*) horizontal reference. Here, we sampled garnet-bearing tonalite, amphibolite, and gneiss, for which biotite K:Ar ages range from 77×10^6 to 87×10^6 years.

At each locality, samples were collected at a number of sites representing an outcrop area of about 10 m^2. Five individually oriented cores were drilled at nearly every site and oriented with solar compass and clinometer (accuracy, ±2°). One specimen cut from each sample was subjected to stepwise alternating field (AF) demagnetization in peak fields up to 75 mT. Representative specimens