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16. Rotational stresses are $\sim \rho r^2\omega^2$, tidal stresses are $\sim \rho r^2\Omega^2$, where ω is rotation rate and Ω is orbital frequency; hence, tidal stresses dominate for rotation slower than synchronous.
17. If the "avalanche" involves a substantial fraction of the particle's mass, its own gravitational potential allows easier escape than for the case of a single small particle (*4*).
18. R. Greenberg, J. Wacker, W. Hartmann, C. R. Chapman, *Icarus* **35**, 1 (1978); D. R. Davis, C. R. Chapman, R. Greenberg, S. Weidenschilling, A. Harris, in *Asteroids*, T. Gehrels, Ed. (Univ. of Arizona Press, Tucson, 1979), p. 528.
19. F. Bridges, A. Hatzes, and D. Lin (in preparation) have measured coefficients of restitution of 0.5 to 0.6 for smooth-surfaced ice spheres at the relevant impact speeds of 0.1 cm/sec. Ring particles are unlikely to have such idealized properties; experimental impact studies show that rebound is much slower for slightly irregular or unconsolidated surfaces [W. K. Hartmann, *Icarus* **33**, 50 (1978)]. Even for values of the coefficients of restitution as high as reported by Bridges *et al.*, accretion would occur within Saturn's rings, although at a slower rate than for lower values of the coefficient. Our basic conclusions would be unaffected. Moreover, once some accretion had occurred, the now-unconsolidated surfaces would have low coefficients of restitution.
20. The size distributions of the small and large particles are derived by different methods (*7*). The existence of an excess in the size range from 3 to 5 m is model-dependent; a more recent interpretation by H. Zebker, G. L. Tyler, and E. A. Marouf [*Icarus* **56**, 209 (1983)] suggests that the deviations from a power law are smaller. Nevertheless, most of the mass in the observed size range is in bodies 3 to 5 m in radius. The details of the size distribution do not affect our conclusions.
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Holocene Eruptive Activity of El Chichón Volcano, Chiapas, Mexico

Abstract. *Geologic and radiometric-age data indicate that El Chichón was frequently and violently active during the Holocene, including eruptive episodes about 600, 1250, and 1700 years ago and several undated, older eruptions. These episodes, involving explosive eruptions of sulfur-rich magma and associated dome-growth processes, were apparently separated by intervals of approximately 350 to 650 years. Some of El Chichón's eruptions may correlate with unusual atmospheric phenomena around A.D. 1300 and possibly A.D. 623.*

El Chichón (Fig. 1) erupted violently three times between 28 March and 4 April 1982, causing the worst volcanic disaster in Mexico's recorded history (*1, 2*). As many as 2000 human lives were lost. Although the recent eruption of El Chichón and that of Mount St. Helens on 18 May 1980 produced roughly equivalent volumes of silicate tephra, El Chichón injected two orders of magnitude more aerosols (10×10^6 to 20×10^6 metric tons) into the lower stratosphere (*3*). The resulting dense volcanic cloud, the atmospheric effects of which are still measurable and being monitored, may affect the weather of the Northern Hemisphere for several years (*3*).

Before the 1982 outburst, El Chichón was an obscure volcano that received little scientific notice since Mullerreid (*4*), in 1928, suggested that its last eruptive activity was in the late Pliocene or early Pleistocene. Several decades later, K-Ar dating (*5*) showed El Chichón to be at least as young as late Pleistocene. Still, with no documentation of historic or late prehistoric eruptions, potential volcanic hazards associated with El Chichón were largely ignored. However, between late 1980 and early 1981, geologists R. Canul and V. Rocha, doing fieldwork in the summit area, frequently heard loud noises and felt earthquakes. In a report (*6*) completed September 1981, they interpreted these phenomena to be related to "subsurface magmatic activity and/or tectonic movements" and warned that "a high volcanic risk" existed at El Chichón. Seven months later the volcano erupted. We describe data showing that the Holocene eruptive history of El Chichón was more eventful than had been supposed. Whether having such information before 1982 might have lent greater urgency to the warning of Canul and Rocha will never be known. Nonetheless, the El Chichón experience underscores the need to document the nature and frequency of a volcano's past eruptions in order to assess the potential for future activity.

Radiometric-age data for El Chichón (Table 1) can be considered in terms of a composite stratigraphic column (Fig. 2). Preliminary studies indicate that all magmatic products are similar in mineralogy and chemistry (*7*). In the interpretation of the radiocarbon ages, we conservatively estimate the overall laboratory variability for a simple measurement to be two or three times the 1 standard deviation (S.D.) counting error (*8*).

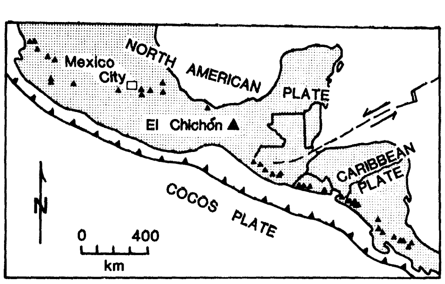

Fig. 1. Index map showing location of El Chichón and generalized tectonic setting of the region. Triangles represent volcanoes.

The oldest rocks (unit F, Fig. 2) are trachyandesites that make up a 250-m high central dome complex and smaller domes on or near the somma rim (*2*, figure 5). Two samples of dome rock from the eastern somma rim give whole-rock K-Ar ages of 209,000 and 276,000 years before present (B.P.) (Table 1). The rocks of the central dome, destroyed during the 1982 eruptions, have not been dated, but geologic considerations indicate that they are almost certainly younger than the dome rocks dated and probably similar in age to deposits of the pyroclastic unit B (Fig. 2).

The oldest studied pyroclastic deposits (unit E, Fig. 2) are thick debris flows, which rest on domal breccias in the summit area and on Tertiary sedimentary strata elsewhere. They represent block-and-ash flows and other deposits, perhaps generated by (gravitational?) dome collapse, which might be associated with several episodes of dome growth and related explosive activity. Deposits of unit E form the major foundation of the volcano's flanks; no charcoal has yet been found in them.

Next higher in stratigraphic succession is unit D, which rests on a well-developed soil and includes two major pyroclastic flows and associated surge and debris flows. Inasmuch as no major unconformities or soil horizons have been found in unit D, the deposits of this unit were probably emplaced during a single volcanic episode or a series of events in rapid succession. The radiocarbon ages for the upper and middle pyroclastic surge deposits, 1580 and 1600 years B.P., respectively, are consistent with this interpretation.

A duplicate sample from the same horizon as the 1600-year-old sample gave an age of 1870 years B.P.; however, given our estimate of overall laboratory variability (two to three times the 1-S.D. counting error), the difference between these two ages would not be statistically significant. Also, the 1600-year age determination required sample dilution and resulted in the largest error of any of the samples dated (Table 1). A "modern" age for the charcoal collected from the surface of the lower pyroclastic flow of unit D indicates that it most probably represents charred modern roots carbonized by the 1982 flows.

Unit C consists of a Plinian fall deposit, overlain by pyroclastic surge and flow deposits. Charcoal recovered from the upper part of unit C gave an age of 1250 years B.P. Because no soil has been observed between units C and D, the boundary between them is tentative. Immediately overlying a soil developed on unit C and underlying the modern soil are widespread Plinian air-fall and pyroclastic flow deposits of unit B (Fig. 2). Pottery shards and artifacts were found in the soil under the Plinian pumice fall at two sites. Archeologists (*9*) have determined the pottery shards to be of Mayan age (Late Classic or Early Postclassic), in the general time period A.D. 800 to 1200, possibly as late as A.D. 1400. The six radiocarbon ages available for unit B range from 550 to 700 years B.P., the period of the last major eruptive activity before that in March and April 1982. Thus the archeological evidence and radiocarbon ages are consistent.

Elderly residents of the El Chichón region remember stories of an eruption of air-fall debris described by their grandparents as sufficiently powerful to drive people from homes 10 km distant from the volcano. Canul and Rocha (*6*) equated this reported eruption with a fall deposit immediately below the modern soils; they estimated that the eruption took place about 130 years ago because of the generations spanned by the people involved in the storytelling. The radiometric-age and stratigraphic data now available, however, show that the presumed 130-year-old tephra is the same as the uppermost air-fall layer of unit B, which was deposited between 550 and 700 years ago. This finding, however, does not preclude the possibility that a small-volume eruption may have occurred about 130 years ago, the deposits of which might have been eroded by heavy rainfall prevalent in the region or intermixed with materials of the uppermost air-fall layer of unit B.

Table 1. Radiometric dates (± S.D.) for prehistoric pyroclastic and dome rocks of El Chichón grouped according to position in a composite stratigraphic column (Fig. 2). Prefixes of laboratory numbers denote the following: W, USGS Radiocarbon Laboratory, Reston, Virginia; UAKA, Laboratory of Isotope Geochemistry, University of Arizona, Tucson; and M, USGS Geochronology Laboratory, Menlo Park, California.

Sample number: Laboratory	Sample number: Field	Radiometric age* (years B.P.)
	Unit B	
W-5240	EC-220	550 ± 60
W-5244	EC-184	550 ± 60
W-5242	EC-201	570 ± 60
W-5252	EC-218	600 ± 70
W-5258	CHAR-1	650 ± 100
W-5256	EC-222	700 ± 70
	Unit C	
W-5089	DT-10	1,250 ± 70 (*2*)
	Unit D	
W-5248	EC-189	1,580 ± 70
W-5254	EC-199	1,600 ± 200†
W-5250	EC-198	1,870 ± 70†
W-5046	EC-209	Modern‡
	Unit F	
UAKA-74-26	12 WR	209,000 ± 19,000 (*4*)
M-151	DT-9	276,000 ± 6,000 (*2*)

*The radiocarbon dates, not adjusted for tree-ring corrections, are based on the Libby half-life (5568 ± 30 years) and referenced to the year A.D. 1950; laboratory precision is the 1-S.D. statistical counting error. †Samples collected 1 m apart from the same horizon. ‡Contains carbon-14 produced by atomic bomb explosions.

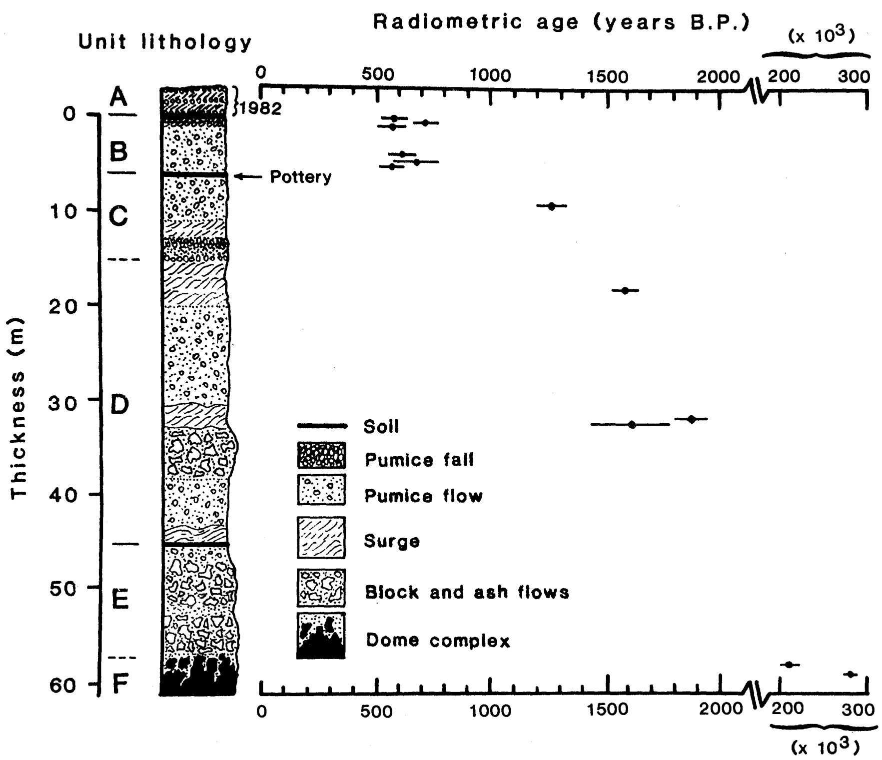

Fig. 2. Ages of dated rocks and their relative position in the composite stratigraphic column for El Chichón. Pottery shards found in soil between units B and C are Mayan in age. The error bars shown give 1-S.D. statistical counting error (see Table 1). Information on field locations of dated samples and outcrops used to construct the composite stratigraphic column is available from the authors upon request.

The results of our studies suggest four conclusions: (i) El Chichón's Holocene eruptive history was characterized by frequent and vigorous activity, involving explosive emission of pyroclastic ejecta interspersed with and possibly accompanied by dome growth. No evidence of the production of lava flows has yet been discovered. Stratigraphic and radiometric evidence indicates at least five eruptive episodes within the past few thousand years, at intervals ranging from about 350 to 650 years. (ii) If the radiocarbon ages for units B and D (Table 1) are averaged, a crude recurrence interval of 600 (±200) years is suggested for El Chichón explosive activity during the past 2000 years. (iii) Evidence of eruptive activity about 130 years ago (*6*) was not found, suggesting that, if such activity did take place, the eruptive products have been obscured by erosion and reworking. (iv) Two K-Ar age determinations on the dome rocks in the summit area give considerably older ages than the radiocarbon ages on the pyroclastic deposits. Field evidence reveals at least one major unconformity in the dome complex; the radiocarbon-dated deposits overlie the K-Ar–dated rocks, which probably represent eroded dome remnants from the earliest stages of El Chichón activity.

Data suggest that the pre-1982 eruptions also involved sulfur-rich magma (*7*), but good estimates of the volumes of ejecta cannot yet be made. Nonetheless, consideration of the thicknesses of the preserved pyroclastic deposits alone suggests that some of the pre-1982 eruptions must have produced ejecta volumes at least several times greater than the total volume of the 1982 eruptions (0.3 to 0.4 km^3). If the comparatively small eruptions of 1982 can produce significant and measurable atmospheric effects, then the major eruptive episode of

El Chichón about 600 years ago could have caused, or contributed to, the global cool period around A.D. 1300 (*10*). Compilation of data (*11*) correlating Greenland ice-core acidity peaks (*12*) with historic eruptions and unusual atmospheric phenomena in Europe includes two inadequately explained acidity peaks at A.D. 1258 (±1 year) and A.D. 623 (±3 years). We speculate that these peaks may reflect prehistoric explosive activity of El Chichón. Similarly, poorly explained "frost events" dated at A.D. 628, 687, 1171, and 1200 by La-Marche and Hirschboeck (*13*), who argue that frost damage in tree rings can record "climatically effective" eruptions, may be crudely correlated with the last two major eruptive episodes of El Chichón.

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Single-Crystal Elastic Properties of the Modified Spinel (Beta) Phase of Magnesium Orthosilicate

Abstract. *The single-crystal elastic moduli of the modified spinel structure (beta phase) of magnesium orthosilicate (Mg_2SiO_4) have been measured by Brillouin spectroscopy under ambient conditions. Single crystals with dimensions up to 500 micrometers were grown at 22 gigapascals and 2000°C over a period of 1 hour. Growth of crystals larger than 100 micrometers was achieved only when the pressure was within 5 percent of the pressure of the phase boundary separating the beta- and gamma-phase stability fields. A comparison of the elastic properties of the modified spinel phase with those of the olivine phase suggests that the 400-kilometer seismic discontinuity in the earth's mantle can be described by a mantle with 40 percent olivine. These results confirm that the 400-kilometer discontinuity can be due to the transition from olivine to modified spinel. The amount of olivine that must be present is less than that in a pyrolite model, although the results do not exclude pyrolite as a possible mantle model.*

Earth scientists have recognized for over half a century that the earth's mantle must have some vertical layering, which results from either chemical heterogeneities or phase transformations (*1*). The exact nature and location of this heterogeneity have implications concerning the origin and history of the earth and the current mode of evolution.

Thirty years ago, Francis Birch (*2*) demonstrated that the change in seismic velocities in the transition zone (at a depth of 400 to 800 km) required that phase transformations were present in this region. Laboratory high-pressure, high-temperature capabilities have continued to expand as the seismic resolution has improved. The transition zone is now recognized as consisting of at least two sharp velocity increases, one at a depth of 400 km and the other at 670 km (*3*). Laboratory studies have demonstrated that olivine and pyroxene undergo a number of phase transformations at pressures associated with these depths in the earth (*4*). A notable transformation is the change from olivine to a modified spinel structure (beta phase) and at higher pressures to a spinel structure (gamma phase). The first of these transformations has become associated with the 400-km seismic discontinuity in the mantle since the pressure-temperature regime of the transformation is appropriate to that depth. Further assessments of this discontinuity in the earth require laboratory measurements of the acoustic velocities of the high-pressure phase for comparison with the in situ seismic observations.

We present here the results of a laboratory determination of the single-crystal elastic properties of the modified spinel structure of Mg_2SiO_4. These properties define the acoustic velocities in polycrystalline samples as well as in single crystals and are thus appropriate to compare with the seismically determined velocities within the earth's transition zone.

It is now possible to make these measurements because of recent developments in two experimental programs over the past 10 years. One program is the development of large-volume, high-pressure equipment capable of 24 GPa and 2400°C. At Nagoya University these conditions were generated with the use of a multianvil pressure apparatus driven by a pair of guide blocks in a uniaxial press that can provide a ram load of 15,000 tons. In order to grow single crystals larger than 100 μm, we must generate such high pressures and temperatures with fluctuations of no more than a few percent on sufficiently large volumes. The high temperatures are achieved by electrical furnaces consisting of concentric cylindrical sleeves of graphite and $LaCrO_3$. During the early stages of the heating cycle, the graphite supplies most of the heat. However, $LaCrO_3$ is a semiconductor, and above a few hundred degrees it will contribute to the heating. At about 1000°C, graphite transforms to diamond and the $LaCrO_3$