



Fig. 3. Zeolite-enriched layers and their stratigraphic correlation in north-eastern Mexico.

(Fig. 3). These zeolite occurrences are of detrital origin and mainly present in the size fraction 2–16  $\mu\text{m}$ . Zeolites, as well as Mg-smectites, are generally considered an alteration product of volcanic terranes and become abundant from Campanian to Eocene times [4]. In the southeastern sections of El Mimbral, significant enrichment in zeolites is also observed in the boundary clay, the spherule-rich layer of unit 1, as well as in the underlying marls of the Mendez Formation [1,2]. These additional layers, enriched in zeolites compared to the northwestern sections, imply an increase of volcanoclastic influx toward the south-southeast, prior to and across the KT boundary.

Illite-smectite mixed layers characterized by low contents of smectite (<30%), are present in all lithologies in the La Sierrita, El Peñon, and El Mulato sections; however, they increase in the Mendez Formation, Velasco Formation, and in the silt-marl intervals of unit 3. Random chlorite-smectite mixed layers, characterized by higher contents in smectite layers (>40%), are common in the spherule-rich unit 1 and in the silt-marl intervals of unit 3; similar layers with lower values are present in unit 2. The increase of mixed layers in units 1 and 3 is similar to mixed layers in the Mendez and Velasco Formations and reflect periods of normal pelagic sedimentation. Chlorite and mica increase in the massive sandstone of unit 2, relative to units 1 and 2, indicating an increase in detrital influx and probably more rapid deposition. Chlorite and mica contents are variable in unit 3, but also increase in the sandstone layers. As already implied by the mixed-layer distribution, unit 3 represents a depositional environment that alternates between increased detrital influx and rapid deposition (silt-sandstone layers) and hemipelagic deposition (shale-marl layers). Based on these observations we conclude

1. Mineralogically and lithologically distinct units, which are correlatable over 300 km and represent variable detrital influx, alternating with normal hemipelagic sedimentation, are incompatible with a Chicxulub impact-generated tsunami deposit.

2. The presence of distinct and correlatable layers enriched in zeolites in the channel-fill clastic deposits as well as the Mendez

Formation and Velasco Formation indicates significant volcanoclastic influx during these times.

3. Dominant mixed/layer chlorite-mica assemblages, which derive from direct and mechanical erosion of bedrock, reflect tectonic instability and/or a sea-level lowstand that increased active erosion of local bedrock.

4. There is no important change in clay-mineral compositions across the KT boundary in the northeastern Mexico sections. Kaolinite, which is abundant in the Mendez Formation (but absent in the KT boundary deposits) suggests a change during the middle to Late Maastrichtian or active erosion due to tectonic instability preventing the development of soils enriched in kaolinite.

**References:** [1] Stinnesbeck W. et al. (1993) *Geology*, 21, 797–800. [2] Stinnesbeck W. et al., this volume. [3] Kubler B. (1987) *Cahiers Inst. Geol. Neuchatel, Suisse Série AX*, 13. [4] Robert C. (1982) Ph.D. Thesis, Fac. Science, Univ. Marseille, France, 136.

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**TRAJECTORIES OF BALLISTIC IMPACT EJECTA ON A ROTATING EARTH.** W. Alvarez, Department of Geology and Geophysics, University of California, Berkeley CA 94720, USA.

On an airless, slowly rotating planetary body like the Moon, ejecta particles from an impact follow simple ballistic trajectories. If we ignore gaseous interactions in the fireball, ejecta particles follow elliptical orbits with the center of the planetary body at one focus until they encounter the surface at the point of reimpact. The partial elliptical orbit of the ejecta particle lies in a plane in inertial (galactic) coordinates. Because of the slow rotation rate (for example,  $360^\circ/28$  days for the Moon), the intersection of the orbital plane and the surface remains nearly a great circle during the flight time of the ejecta. For this reason, lunar rays, representing concentrations of ejecta with the same azimuth but different velocities and/or ejection angles, lie essentially along great circles.

Ejecta from airless but more rapidly rotating bodies will follow more complicated, curving trajectories when plotted in the coordinate frame of the rotating planet or viewed as rays on the planetary surface. The curvature of trajectories of ejecta particles can be treated as a manifestation of the Coriolis effect, with the particles being accelerated by Coriolis pseudoforces. However, it is more straightforward to calculate the elliptical orbit in inertial space and then determine how far the planet rotates beneath the orbiting ejecta particle before reimpact.

The Earth's eastward rotation affects ballistic ejecta in two ways: (1) the eastward velocity component increases the velocity of eastbound ejecta and reduces the velocity of westbound ejecta; and (2) the Earth turns underneath inflight ejecta, so that although the latitude of reimpact is not changed, the longitude is displaced westward, with the displacement increasing as a function of the time the ejecta remains aloft.

Low-velocity ejecta reimpacts so quickly that the second effect is small. However, at ejection velocities above about 9 km/s and approaching escape velocity (11.2 km/s), the semimajor axis and the related height of apogee increase rapidly, and the time aloft may be measured in hours. In such cases, effect (2) becomes important. For example, ejecta particles sent eastward at an elevation angle of 45° from an equatorial impact at a velocity of about 10 km/s reach an apogee of >6 Earth radii and stay aloft for about 8 hr, during which time the Earth turns far enough for the ejecta to reimpact close to the site from which they were launched. Under similar conditions, but at a velocity of 10.5 km/s, the ejecta reach an apogee of 16 Earth radii and stay aloft for 34 hr. During that time the ejecta, seen from the Earth, make a complete rotation around the Earth, backward! At still higher velocities (but below escape velocity), the ejecta make multiple retrograde rotations.

Calculations still in progress suggest that because of this effect there may be a forbidden zone beyond about 90° east of the impact site, which cannot be directly reached by eastbound ejecta. If so, this will make a prediction that can be tested by mapping the size and column density of ejecta (spherules and shocked quartz) in the KT boundary layer.

Interactions between the atmospheric density gradient and the expanding fireball of a large impact can accelerate ejecta to velocities approaching and probably exceeding escape velocity. Thus the effects described above are relevant. The time-aloft difference between low- and high-velocity ejecta may explain the double KT layer in the western interior U.S. (a layer of altered melt ejecta overlain by a layer of shocked quartz, both of which appear to derive from Chicxulub). However, there are serious problems in explaining the failure of the shocked quartz (1) to melt and (2) to disperse, if it is interpreted as fast, high-trajectory ejecta.

The Earth's atmosphere complicates the calculation of ejecta trajectories in at least four ways: (1) At early stages in the evolution of the fireball, temperatures are sufficient to form a plasma, and electromagnetic interactions within the plasma distort the simple inertial trajectories that ejecta would otherwise follow. (2) Even after expansion of the fireball cools it to below plasma temperatures, thermal encounters in the fireball gases continue to distort the ballistic trajectories. (3) Low-velocity portions of the fireball may fall back close to the impact site, forming a base surge that expands radially on top of the normal atmosphere. (4) As ejecta particles settle through the atmosphere they will be carried laterally by winds for distances inversely related to the particle size.

The calculation of ballistic trajectories is an essential step in understanding ejecta distributions, but must be augmented by a fuller understanding of fireball-atmosphere dynamics under conditions that are difficult to calculate and have not been observed. The observational limitation may be partially overcome when the fragments of Comet Shoemaker-Levy impact Jupiter in July 1994.

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**DEVELOPMENTS IN THE KT IMPACT THEORY SINCE SNOWBIRD II.** W. Alvarez<sup>1</sup>, F. Asaro<sup>2</sup>, P. Claeys<sup>1</sup>, J. M. Grajales-N.<sup>3</sup>, A. Montanari<sup>4</sup>, and J. Smit<sup>5</sup>, <sup>1</sup>Department of Geology and Geophysics, University of California, Berkeley CA 94720, USA, <sup>2</sup>Lawrence Berkeley Laboratory, University of California, Berkeley CA 94720, USA, <sup>3</sup>Instituto Mexicano del Petroleo, Apartado Postal 14-805, 07730 DF, Mexico, <sup>4</sup>Osservatorio Geologico di Coldigioco, 62020 Frontale di Apiro (MC), Italy, <sup>5</sup>Institute of Earth Sciences, Vrije Universiteit, de Boelelaan 1085, 1081 HV Amsterdam, The Netherlands.

At the second Snowbird conference, entitled "Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality," held in October 1988, much of the discussion focused on criteria for choosing between the competing explanations—impact or volcanism—to account for the KT boundary mass extinction. Other participants argued that the paleontological record does not support a rapid mass extinction, and that neither impact nor volcanism was needed to explain the biostratigraphic observations.

At Snowbird II, the proponents of volcanism struggled to explain the physical characteristics of the KT boundary stratum (shocked quartz, spherules, anomalous Ir), but pointed with confidence to the Deccan Traps as the volcanic center responsible for the extinction. In contrast, the proponents of impact could reasonably explain the physical features, but had no candidate crater of anywhere near sufficient size.

As members of the proimpact group, we present the following account of our perception of developments since Snowbird II, well aware that supporters of volcanism will see the matter differently.

Back at the time of the first Snowbird conference, Signor and Lipps [1] showed that an abrupt extinction studied with insufficient sampling of the fossils would appear gradual. Two major animal groups previously said to have died out gradually have recently been studied with heavy sampling and careful statistics (ammonites [2] and dinosaurs [3]) and their disappearances at the KT boundary are now seen to be indistinguishable from a sudden extinction. These cases are clear examples of the Signor-Lipps effect, and weaken the case for a gradual KT extinction.

The strongest improvement in the volcanist position has come from isotopic dating of the Deccan Traps, which yielded an age of  $64.96 \pm 0.11$  Ma [4]. However, this date comes from a late intrusion cross-cutting the lavas, and earlier ages of  $68.53 \pm 0.16$  Ma and  $68.57 \pm 0.08$  Ma were measured on early volcanic alkalic complexes. Although the main pulse of volcanism may have occurred close to the KT boundary at 65 Ma, the Deccan Traps seem to have begun erupting well before the extinction, making a causal relationship less likely. Nevertheless, the near coincidence in timing is striking, keeping alive the possibility of some connection between the Deccan volcanism and the KT boundary event.