



Fig. 2.

found in fine intensely bioturbated silty chalk about 6–10 cm below an irregular 10 ± 5 -cm-thick micritic limestone layer. The upper tail of the Ir peak extends into the micritic limestone (Fig. 1). There are other considerably smaller Ir peaks extending as high as 7 m and possibly 8 m above the main peak and 0.2 m and possibly 0.9 m below. Generally, the more distant the subsidiary peaks are from the main peak, the smaller are their abundances. The Ir abundance in a thin sandstone layer below the main peak, however, was found to be lower than those in underlying and overlying silt layers. If ratios are taken of Ir abundances to those of Fe or Cs, anomalously high ratios are found where the Ir abundance is anomalously high.

The element abundance patterns, which are similar to those found in other marine KT sections in Haiti, Mexico, and Texas, are consistent with a fining-up debris deposited from a tsunami triggered by a bolide impact on the Yucatan Peninsula. Our preliminary study of the Bochil section indicates the Ir began depositing (or redepositing) immediately before the first appearance of the lowermost Tertiary microfossils. The 38-m breccia unit may have resulted from breakage of reefal sediments triggered by the Chicxulub impact, but other explanations are possible.

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EXTRATERRESTRIAL ACCRETION AND GLACIAL CYCLES. R. A. Muller, Department of Physics and Lawrence Berkeley Laboratory, University of California, Berkeley CA 94720, USA.

We propose that the ≈ 100 -k.y. cycle seen in terrestrial glaciation is due to changes in meteor flux that come from changes in the Earth's orbit. This model can explain a 70-k.y. "anomalous" period in climate data and the apparent discrepancy between present extraterrestrial fluxes and those in oceanic sediments. It can be tested by measuring Ir densities in sediments and ice during glacials and interglacials.

Milankovitch [1] attributed the changes in the Earth's ice coverage to perturbations in the motion of the Earth and the resulting changes in insolation in the northern hemisphere. The strongest effects were expected to come from changes in the Earth's obliquity (the tilt of the Earth's axis with respect to its ecliptic) and from a precessional term that accounts for the delay between solstice and perihelion. The success of this mechanism has been argued by Imbrie et al. [2]. The most compelling evidence is the presence of Earth orbital frequencies in Fourier analysis of proxy climate measurements such as CO_2 and $\delta^{18}\text{O}$. In a recent review and reanalysis of available data, MacDonald [3] showed that inclination, obliquity, and precession frequencies account for eight of nine statistically significant $\delta^{18}\text{O}$ frequencies in an eastern Pacific core. The "only anomalous line" in the data with no theoretical counterpart was a $\delta^{18}\text{O}$ peak at $0.014 \pm 0.001/\text{k.y.}$

However the insolation mechanism proposed by Milankovitch has difficulty accounting for the magnitudes and phases of the climate cycles. The spectrum is dominated by a 100-k.y. period, usually attributed to the oscillation of eccentricity e . However, yearly average insolation varies as $(1/2)e^2$, giving changes in insolation of only 10^{-3} . MacDonald [3] calculated the solar insolation at 60°N at the primary frequencies for (obliquity, precession, eccentricity) to be in the ratio (1, 5, 0.1); in sharp disagreement with the $\delta^{18}\text{O}$ data, which show the climate variations to be in the ratios (1, 0.4, 4.4).

Milankovitch explained the strong eccentricity dependence by arguing that the insolation effect of obliquity and precession are biggest when the eccentricity is greatest and that the effect is nonlinear. Other suggestions to solve the puzzle postulate resonances and time constants in the geologic system to enhance ice coverage at periods near 100 k.y. and to cause delays without enhancing the 20-k.y. and 40-k.y. periods. However, recent $\delta^{18}\text{O}$ measurements with precise dates show that the warming associated with several glacial terminations begins well before the start of above-average insolation, and this has been interpreted as disproving Milankovitch's mechanism [4,5].

The correspondence of observed climate frequencies with those of the Earth's orbit argue strongly for a causal connection, but the failure to predict the correct amplitudes and phases suggest that the insolation mechanism of Milankovitch may be incorrect, at least for the 100-k.y. period. We suggest that this cycle might be due to a different mechanism: extraterrestrial accretion. This mechanism yields the correct frequencies, can account for the "anomalous line" of MacDonald, gives a new interpretation to recent accretion measurements, and makes predictions that can be tested in the near future. Accretion does not account for the periods near 20 k.y. and 40 k.y., and we assume that the Milankovitch solar insolation mechanism correctly accounts for these.

Mechanism of Extraterrestrial Accretion: As the orbit of the Earth changes, it passes through different parts of the Sun's zodiacal ring, and should encounter different meteor streams. Changes in meteor flux can affect the density of dust and aerosols in the upper atmosphere. The fact that high-altitude dust can affect global climate is generally accepted. The eruption of Krakatoa has been estimated to cause global cooling $>1^{\circ}\text{C}$, and climate changes have been attributed to El Chichon and other eruptions that injected megatons of material into the stratosphere. Measurements of Ir in oceanic sediments [6] show that long-term global average flux from extraterrestrial materials is 60–120 kt/yr [6], comparable over 10–100 yr to that from a large volcanic eruption. The meteors may not come in at a steady rate but in bursts as we cross the meteor streams (with peaks much higher than the 60–120 kt/yr average) and in cycles as the Earth's orbit oscillates. The shortest variation detectable (the Nyquist period) in the best sediment records [6] ≈ 600 k.y., so a 100-k.y. oscillation would have been missed. Clube [7] analyzed the possibility of large unobserved meteor streams and argued that the zodiacal ring of the Sun is largely meteoroid in composition rather than dust. He concluded that large unobserved streams exist, and suggested that encounters with them could cause climate excursions and extinction events; however, he did not propose a relationship with the known climate cycles.

A single meteor stream can contain the mass of one comet $\approx 10^5$ Mt. The Earth can capture about 10^{-4} of the stream with each passage ≈ 10 Mt ≈ 1 large volcano equivalent/yr, as long as the orbits intersect. The cumulative effect would be very much larger than Krakatoa.

We do not propose that the climate effects are due to a single meteor stream, rather that the solar ring has many, in nearly circular orbits with semimajor axis ≈ 1 AU, so that their own orbital perturbation frequencies (but not necessarily their phases) closely match those of the Earth. We do not explain how such rings were formed, but for our model to work, they must have been present for the last million years.

Another orbital parameter expected to have little effect on climate, because of its negligible effect on insolation, has been the inclination of the Earth's orbital plane. Changes in inclination also cause the Earth to probe different regions of interplanetary debris, so we predict correlations between inclination and climate. The long-term variation of the inclination was calculated by Berger [8], who showed that the behavior is quasiperiodic with a period of 70 k.y., and a fundamental frequency of 0.0144/k.y. Note that this frequency is, within errors, equal to the one unexplained peak in the $\delta^{18}\text{O}$ data [3]; thus we explain the one "anomalous" frequency.

We can gain more insight into this effect, and possibly understand the relative intensities of the spectral lines, if we chose coordinates based on the invariable plane of the solar system, perpendicular to the total angular momentum vector of the planets, approximately the plane of Jupiter's orbit. In these coordinates the oscillations of inclination are nearly sinusoidal with peak-to-peak amplitude reduced by two, and period changed to 100 k.y. rather than 70 k.y. (The change simplifies the behavior because the primary perturber, Jupiter, has a nearly stationary orbit in this system.) In this frame the precession of the inclination vector, Ω , now shows a virtually steady advance of one cycle every 70 k.y. In the invariable frame, the inclination i oscillates with a 100 k.y. period, nearly identical to that of the eccentricity e . Changes in i and e both cause the Earth to sweep out new material with a frequency 0.01/k.y., identical to that of the strongest line seen in the climate data. The

"anomalous" line [3] at 70 k.y. period is Ω , the frequency of precession of the inclination vector (the advance of the line of nodes) measured in the invariable plane.

Accretion Measurements: Our proposed mechanism predicts a substantial reduction in the flux of meteoritic material in the present era compared to the long term average. In fact, just such a reduction is known. In a recent review, Rochia et al. [9] found six of seven published determinations of recent influx measured ≈ 10 kt/yr, yet the long-term flux [6] was 60–120 kt/yr. They speculate that the recent low flux is a fluctuation, due to few large meteoroid impacts recently. Yet the most straightforward measurement, that of Ir in Antarctic snow, gave 10 kt/yr despite the presence of the Tunguska event of 1908 ≈ 0.1 –1 Mt.

We offer a different interpretation, that the discrepancy is not from the absence of large impacts, but is due to the fact that interglacials (including the present one) are periods of low extraterrestrial meteoroid flux.

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A KT BOUNDARY SECTION FROM NORTHERN BELIZE. A. C. Ocampo¹ and K. O. Pope², ¹Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109, USA, ²Geo Eco Arc Research, 2222 Foothill Boulevard, La Canada CA 91011, USA.

A KT boundary section recently discovered in northern Belize provides new insights into cratering processes near the rim of the Chicxulub KT crater in northwestern Yucatan. The section is located in a quarry on Albion Island near the Mexican border, which is only 2–3 crater radii (≈ 350 km) from the center of Chicxulub. This is the most proximal exposed KT section yet studied from the Chicxulub Crater, excluding material from deep drilling within the crater and on the rim. The Albion Island section provides an example of deposits intermediate between the crater rim and more distal, possible impact-tsunami deposits in the region [1–3].

Quarrying activity on Albion Island has exposed a 45-m-thick section in a region where deep weathering and dense vegetation has obscured most bedrock exposures. The regional stratigraphy has been established in two exploratory wells drilled at near by Orange Walk and San Pablo [4]. The Orange Walk 1 well records place the KT boundary between dolomites of the Sand Hill Formation and undifferentiated Tertiary limestones at a depth of ≈ 1500 m. The KT boundary rises to a depth of ≈ 150 m in the San Pablo 1 well located 11 km north of Orange Walk 1. The Albion Island quarry is located 15 km northwest of Orange Walk, near the crest of an anticlinal fold and possible uplifted fault block that has further elevated the KT boundary. A major erosional unconformity separates the hard crystalline Cretaceous dolomites and a chaotic, poorly sorted breccia at a depth of ≈ 15 m in the quarry. We propose that this unconformity marks the KT boundary.