

fresh terrestrial impacts greater than ~30–40-km diameter should have interior rings. In the tabulation of large terrestrial impacts in, or dominantly in, crystalline rocks [5], the majority above 40 km diameter have central depressions, offset peaks, or rings, despite the interpretational difficulties posed by erosion. We also expect that terrestrial craters ≥ 150 km diameter have the potential to be true multiringed basins. The formation of outer, asymmetric-in-profile rings in the megaterrace/ring tectonic model depends on subsurface rheology, which is determined by composition and especially by temperature. Large asteroids striking present-day oceanic lithosphere could create rings by this mechanism, but probably would not within continental cratons because of the low heat flows there [7]. There the peak-ring form should persist to much higher diameters. As an example, we address one of the largest and most significant structures in the terrestrial record, Chicxulub.

Suspected from magnetic data, corroborated by gravity, and finally confirmed as an impact by petrology [8, cf. 9], Chicxulub is probably the KT crater (or the major one). Chicxulub is definitely in the size class to be multiringed. The gravity and magnetic anomalies define a bull's-eye pattern ~180 km across [8]. Unfortunately it is buried by younger carbonate platform rocks, so structural information on the crater itself is lacking. Reprocessed gravity data over the northern Yucatan by Sharpton and others [10] clearly show a main rim with a diameter of 199 ± 12 km and a central ring with a diameter of 105 ± 10 km. The gravity signature hints at an additional ring between the two others, but it is not nearly as prominent, if it exists. Chicxulub may thus be a very large peak-ring crater. On the other hand, Chicxulub apparently formed within a few hundred kilometers of several active plate margins [8], albeit excavating into early Paleozoic crystalline basement [10], so it is not inconceivable that the heat flow was high enough to, for example, define a crustal asthenosphere during transient crater collapse, leading to outer ring formation and thus to three (or four) rings. We are not claiming that Chicxulub is a true multiringed basin, only that it is a possibility.

The case for Chicxulub being a multiringed basin in the structural sense meant here would be enhanced if it were larger, implying greater driving stresses during collapse and lower deep crustal viscosities. A fourth, outer ring of 278 ± 22 km diameter is advocated in [10] on the basis of some very-low-amplitude, discontinuous gravity highs. It is also apparent that the argument for this ring and the intermediate one mentioned above is enhanced in [10] by belief in an invariant $\sqrt{2}$ spacing for impact rings [4]. Our results for Venus [2,3], as well as those of the Magellan team [1], demonstrate that ring spacing is not invariant and alone is an imperfect guide for understanding impact mechanics. Clearly, direct structural information must take precedence (this is partly why the relatively pristine craters on Venus are so valuable). Thus it is interesting that a less than conspicuous feature of the venusian multiringed structures, the inner "peak ring," should be so prominent in the gravity maps interpreted in [10], while a major structural feature, the outer down-faulted rim, hardly shows up in the Chicxulub gravity field (i.e., the outer ring in [10]). Volcanic burial of venusian peak rings and erosion of the original Chicxulub rim can be invoked, but erosion won't erase the offsets of subsurface layers caused by the outer ring fault. Greater attention to this last point, as well as additional gravity and seismic data, should confirm or deny the existence of the 280-km ring of Chicxulub. Modeling Magellan gravity to constrain the subsurface structure beneath the large

venusian craters, and well as theoretical models of their formation, will also be important.

Any discussion of Chicxulub naturally brings up the question of the KT mass extinction. It is sobering to contemplate a map of the venusian surface with its impact craters clearly marked (for example, Plate 2 in [11]). Over the same time period (~500 m.y., or the length of the Phanerozoic) the Earth has accumulated an even greater number of impacts because of the relative thinness of the terrestrial atmospheric shield, but the number of large craters (including those that are ringed) should be very similar. The formation of an Isabella or a Mead on the Earth would surely be a catastrophe for a large portion of our planet.

References: [1] Schaber G. G. et al. (1992) *JGR*, 97, 13257–13301. [2] Alexopoulos J. S. and McKinnon W. B. (1992) *Icarus*, 100, 347–363; Erratum: *Icarus*, 103, 161. [3] Alexopoulos J. S. and McKinnon W. B. (1994) *GSA Spec. Paper*, in press. [4] Pike R. J. and Spudis P. D. (1987) *Earth, Moon, and Planets*, 39, 129–194. [5] Grieve R. A. F. and Cintala M. J. (1992) *Meteoritics*, 27, 526–538. [6] Melosh H. J. and McKinnon W. B. (1978) *GRL*, 5, 985–988. [7] McKinnon W. B. (1981) *Proc. LPS 12A*, 259–273. [8] Hildebrand A. R. et al. (1991) *Geology*, 19, 867–871. [9] McKinnon W. B. (1982) *GSA Spec. Paper 190*, 129–142. [10] Sharpton V. L. et al. (1993) *Science*, 261, 1564–1567. [11] Phillips R. T. et al. (1992) *JGR*, 97, 15923–15948.

N94-28307

208823 p. 2
PROPOSED LAW OF NATURE LINKING IMPACTS, PLUME VOLCANISM, AND MILANKOVITCH CYCLES TO TERRESTRIAL VERTEBRATE MASS EXTINCTIONS VIA GREENHOUSE-EMBRYO DEATH COUPLING. D. M. McLean, Department of Geological Sciences, Virginia Polytechnic Institute, Blacksburg VA 24061, USA.

A greenhouse-physiological coupling killing mechanism active among mammals, birds, and reptiles has been identified. Operating via environmental thermal effects upon maternal core-skin blood flow critical to survival and development of embryos, it reduces the flow of blood to the uterine tract. Today, during hot summers, this phenomena kills embryos on a vast, global scale. Because of sensitivity of many mammals to modern heat, a major modern greenhouse could reduce population numbers on a global scale, and potentially trigger population collapses in the more vulnerable parts of the world. In the geological past, the killing mechanism has likely been triggered into action by greenhouse warming via impact events, plume volcanism, and Earth orbital variations (Milankovitch cycles).

Earth's biosphere is maintained and molded by the flow of energy from the solar energy source to Earth, and on to the space energy sink (SES) [1]. This SES energy flow maintains Earth's biosphere and its living components, as open, intermediate, dissipative, nonequilibrium systems whose states are dependent upon the rate of energy flowing through them. Greenhouse gases such as CO₂ in the atmosphere influence the SES energy flow rate. Steady-state flow is necessary for global ecological stability (autopoiesis).

Natural fluctuations of the C cycle such as rapid releases of CO₂ from the mantle, or oceans, disrupt steady-state SES flow. These fluctuations constantly challenge the biosphere; slowdown of SES energy flow drives it toward thermodynamical equilibrium and stagnation. Fluctuations induced by impact events, mantle plume

volcanism, and Milankovitch cycles can grow into structure-breaking waves, triggering major perturbations of Earth's C cycle, and mass extinctions.

A major C cycle perturbation involves readjustment of the outer physiochemical spheres of the Earth: the atmosphere, hydrosphere, and lithosphere, and by necessity, the biosphere. A greenhouse, one manifestation of a major C cycle perturbation, is the most dangerous natural phenomenon that life of Earth can experience. Greenhouse conditions existed during the KT mass extinctions of 65 m.y. ago [2], and the Pleistocene-Holocene (P-H) mammalian extinctions of 10,000–12,000 yr ago. Coupling climatology to reproductive physiology via effects of ambient air temperature upon uterine blood flow to developing embryos accounts for the extinctions via established physiological principles.

The KT extinctions seem a function of both Late Cretaceous climatic cooling and KT greenhouse warming that began at or about the KT boundary. A negative $\delta^{13}\text{C}$ excursion indicates a major C perturbation, and a synchronous negative $\delta^{18}\text{O}$ excursion, climatic warming. The greenhouse lasted 200–300 k.y. into the Early Tertiary.

Two natural phenomena are candidates for the KT boundary greenhouse: the Deccan Traps mantle plume volcanism in India, and the Chicxulub structure on Yucatan, which has been attributed to extraterrestrial impact event. Ninety percent of the Deccan Traps' vast volume of tholeiitic lavas erupted 65 m.y. ago [3]. The Chicxulub structure has been dated at about the same age [4]. Massive KT CO_2 release via Deccan Traps eruptions [5], or impact [6], or impact-induced water vapor release [7] would have disrupted SES energy flow, triggering change of state of the biosphere manifested in the KT transition extinctions.

Other sources of KT transition CO_2 -induced greenhouse conditions were failures of the Williams-Riley marine "pump" that removes CO_2 from the atmosphere-marine mixed layer and stores it in the deep oceans, and a KT transition marine transgression starting just below the KT boundary and extending through early Paleocene (130-m rise) [8] that flooded highly productive terrestrial plant ecosystems with low productive marine ecosystems [9]. The KT record contains no definitive evidences of an "impact winter" global blackout and refrigeration [10].

A key point in linking climate to embryo survival is that embryo damage and death can occur at environmental temperatures that pose little danger to adults. During hot conditions, adults shunt blood to the skin to transport body heat to the environment. This action reduces blood flow to the core and to the uterine tract. Blood flow to the uterine tract carries damaging metabolic heat away from developing embryos [11], and supplies critical O , H_2O , nutrients, and hormones [12]. Reduced uterine blood flow causes the uterine tract to overheat, damaging and killing fertilized eggs during the critical first cleavage. During later stages of development, reduced uterine blood flow can produce dwarfing and skeletal abnormalities. For modern pregnant, lactating European-type cattle, air temperature in the range of 70°–81°F (21°–27°C) causes the core temperature to rise. A rise in uterine temperature of 1.8°–2.7°F (1.0°–1.5°C) will kill most embryos. Study of air temperature vs. conception rates of 12,000 Florida cattle via artificial inseminations showed that on days when the air temperature following insemination exceeds 86°F (30°C), conception rates fall from 52% to 32%, and then stay low during the hot summer months [13].

Vertebrate adaptation to climate involves adjusting size and S/V ratios, body shape, insulation, and metabolism. Of the five, size

is slowest to change in response to sudden climatic warming. Large Pleistocene mammals adapted to a cold ice age climate would have had difficulty getting rid of body heat during rapid warming. The main pulse of the P-H mammalian extinctions coincided with the abrupt warming about 11,700 yr ago that ended the last ice age (indicated in Greenland ice cores). Those extinctions eliminated primarily large "big game" mammals, and produced dwarfing and skeletal abnormalities, reflecting the "signature" of climatic heat effects upon uterine blood flow to developing embryos [14]. Milankovitch cycles drive the Cenozoic ice age cycles and also seem to influence mammalian bioevolution and extinctions.

Among birds, uterine blood flow is reduced by high environmental temperatures. Studies of modern chickens indicate that hyperthermia diminishes blood flow to the ovarian follicles by 40–50%, decreasing shell weight and quality, and reducing egg production [15]. During the P-H climatic warming at the end of the last ice age, large birds experienced more extinctions than any other group except large mammals [16]. In the face of rapid warming, cold-adapted large birds would have experienced hyperthermia. Hyperthermia-induced reduction of uterine blood flow to the follicles would have reduced fertility and egg production, triggering collapse of populations.

For moderate to large reptiles (including the dinosaurs), "gigantothermy," a thermoregulatory strategy based on use of large body size, low metabolic rate, peripheral tissues as insulation, and control of blood flow between core and skin [17], allows successful response to diurnal and seasonal climatic changes. Via such strategy, the modern leatherback turtle, the largest marine turtle (1000 kg), maintains body temperature of 86°F (30°C) in Arctic waters of 50°F (10°C), or less; it has a problem dumping heat in a warm terrestrial environment [17]. Dinosaurs that were adapting to Late Cretaceous climatic cooling would have, in the face of KT boundary greenhouse warming, experienced thermal stress, and likely uterine blood flow-induced reproductive problems. Hot summers rather than cold winters likely caused the disappearance of the dinosaurs [18].

Proposed law of nature: Climate control of uterine blood supply to the fertilized egg during first cleavage and later embryo development influence population dynamics, bioevolution, and extinction.

References: [1] Morowitz H. J. (1979) *Energy Flow In Biology*, Ox Bow Press. [2] McLean D. M. (1978) *Science*, 201, 401–406. [3] Basu A. R. et al. (1993) *Science*, 261, 902–906. [4] Sharpton V. L. et al. (1992) *Nature*, 359, 819–821. [5] McLean D. M. (1985) *Cretaceous Research*, 6, 235–259. [6] O'Keefe J. D. and Ahrens T. J. (1988) *LPS XIV*, 885–886. [7] Emiliani C. et al. (1981) *EPSL*, 55, 317–334. [8] Keller G. et al. (1993) *GSA Bull.*, 105, 979–997. [9] McLean D. M. (1978) *Science*, 200, 1060–1062. [10] McLean D. M. (1991) in *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*, 493–503, MIT. [11] Gwazdauskas F. C. et al. (1974) *J. Anim. Sci.*, 39, 87–92. [12] Senger et al. (1967) *J. Exp. Zool.*, 165, 337–344. [13] Badinga L. et al. (1985) *J. Dairy Sci.*, 68, 78–85. [14] McLean D. M. (1981) *Am. J. Sci.*, 281, 1144–1152; (1991) in *Energy and Environment*, 93–100, ASHRAE. [15] Wolfenson D. et al. (1979) *Br. Poultry Sci.*, 20, 167–174. [16] Steadman D. W. and Martin P. S. (1984) in *Quaternary Extinctions*, 466–477, Univ. Arizona. [17] Spotila J. R. et al. (1993) *Mod. Geol.*, 16, 203–227. [18] Cloudsley-Thompson J. L. and Butt D. K. (1977) *Br. J. Herpet.*, 5, 641–647.