Interactions of the Earth With Very Large Meteorites *

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It is the experience of but a few to witness one of the very numerous meteorite strikes inexorably stitching the earth into the fabric of the universe. More may thrill to a first hand account of a meteorite strike given by a friend as he recalls, when a boy, the "cinder-like" piece which missed his foot by inches, or to another account of the thundering course of a meteor over Port Hope, Ontario, in the early 1940's spanning the landscape with a broad luminous band from one horizon to the other in a S.E. to N.W. direction. Many more marvel at the widely publicized account in 1954 of the meteorite which blasted through a house roof in Sylacauga, Alabama, glanced off a piece of furniture and then struck the housewife. These things can be believed; they are minor occurrences and they have been witnessed.

What witness is there to such occurrences which are not so minor? The moon, for one, displays on its always visible face about 30,000-35,000 circular scars accepted by most authorities to be the result of meteor collisions. These scars range in size from 500 meters to 600-1200 kilometers in diameter, with depths, in relation to the diameters, approaching 6,000 meters. This mute witness is almost 400,000 kilometers from the earth, but this distance is as nothing in the scale of the solar system. The moon and earth are essentially one object sampling a volume of space, so that the testimony of the moon leads to a very direct estimate that the earth should have a proportionate number of scars. However, estimates taking into account the greater gravitation of the earth increase the number by about 30 percent to a round million. This very number would seem to discredit the witness, for certainly this many could not have escaped notice. The most obvious explanations of the great discrepancy between the estimate and actual observation have to do with the severe weathering and the very effective concealment by the mantles of water, ice and sediments on the earth.

Weathering proceeds at different rates in different climatic, structural and compositional environments. If the problem involved only the weathering of known scars over the earth in the last

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10,000 to 1,000,000 years it might be possible to detail the rate of breakdown in specific areas. The time actually involved is closer to five billion years, the approximate age of the earth-moon system during which, it is assumed here as a working hypothesis, a continuous bombardment took place. At best the weathering rates can be only estimates of order of magnitude for broad application to meteorite scars in all possible locations. Weathering rates estimated for continental masses and great mountains are about 80 meters per million years, and for land masses in tropical regions 225 meters per million years. Circular ridges of less than 750 meters relief could be broken down enough in 5 million years, to be unrecognizable, and much more easily subject to being covered by wind, tide and vegetative actions. Therefore, it might be expected that only 1,000-1,200 out of the million remain fairly intact and ready for *identification.**

Of this "1,000," the water-ice mantle effectively conceals 75 percent by submerging the small ones and perhaps camouflaging the larger ones as sporadic island arcs or arcuate coast lines. What can the earth now say with regard to the "250" remaining? It can say that in the last few years a staccato tally of meteorite scar finds or recognitions (Table I) has raised the total to 42-50 at this writing. This is in marked contrast to the inventory of structures which were compared with the "giant" meteorite crater in Arizona, for decades not universally recognized for what it is, and with the tremendous knockdown of forests in the 1908 Siberian fall (Fig. 1).

The increase in identifications of meteorite scars is closely connected to the interplay of pure and applied research directed to the synthesis of high pressure materials and astute geological field work. The synthesis in 1953, by L. Coes, Jr., of a dense form of silica, coesite,[1] found to require pressures of at least 20 kilobars at 500°C,[2] remained an interesting and challenging fact for six years,

* Using other criteria, Paul D. Krynine, Professor of Petrology and Sedimentary Mineralogy (Pennsylvania State University), arrives at a survival number up to 10 times greater than the present author, as indicated in his letter:

"Without making any estimate as to the number of meteorite impacts that may have left scars upon the earth's surface, it seems to me that the number of scars potentially visible at the present time depends upon the following factors:

(1) All scars under the oceans are invisible.

(2) Scars on the continental surfaces have been reduced in number by two main processes of disappearance.

(a) Disappearance of scars through *covering-up* by later sediments ranging from early Pre-Cambrian to Recent, including glaciers. I estimate that not less than 90% of the original scars on the continents have disappeared through this process.

(b) *Erasure* of scars through process of tectonic uplift and erosion. I estimate as a rough approximation that at least 90% of the scars that survived (or escaped) covering-up have disappeared in this fashion.

This would leave as a potential maximum of visible scars perhaps 1% of the original scars on the continents, or probably considerably less."

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TABLE I*

METEORITE CRATERS

Accepted	*Year Identified*	*Approximate Diameter*
Meteor Crater, Arizona	1903	1.2 km
Odessa, Texas	1926	.16
Campo del Cielo, Argentina	1926	<.1
Kaalijaro, Estonia	1928	<.1
Ashanti, Ghana ("doubtful" in 1931)	1931	10.
Henbury, Australia	1931	.16
Wabar, Arabia	1932	<.1
Haviland, Kansas	1933	<.1
Henbury, Australia	1937	.16
Dalgaranga, Australia (5a)	1938	.07
Wolf Creek, Australia	1947	.9
Sikhote-Alin, Siberia	1948	<.1
Chubb, Quebec	1950	3.4
Aouelloul, Algeria	1951	.23
Talemzane, Algeria	1952	1.7
Brent, Ontario	1956	3.0
Holleford, Ontario	1957	3.0
Wetherbee, Labrador	1957	.16
Deep Bay, Saskatchewan	1957	11.0
Podkamennaya-Tunguska, Siberia	1957	3.
Ashanti, Ghana (doubtful, 1931)	1958–1962	10.
Steinheim, Bavaria	"	3.
Ries Kessel, Bavaria	"	30.
Clearwater (A), Quebec	"	32.
Clearwater (B), Quebec	"	22.
Hudson Bay Arc, Canada	"	440.
Gulf of St. Lawrence, Canada	"	320.
Vredefort, South Africa ("Inner Ring")	"	70.
Vredefort, South Africa ("Outer Ring")	"	200. (?)

"CRYPTO-VOLCANIC STRUCTURES"**

Highly Probable	"1962"***	
Jeptha Knob, Kentucky	——	(3) km
Sergent Mound, Ohio	——	6.7
Flynn Creek, Tennessee	——	3.2
Wells Creek Basin, Tennessee	——	13.
Decaturville Structure, Mississippi	——	(3)
Kentland Structure, Indiana	——	(3)
Magnet Cove, Arkansas	——	4.5
Upheaval Dome, Utah (?)	——	(3)
Estonia (L. J. Spencer)	——	4.5
Sierra Madera, Texas	——	4.5

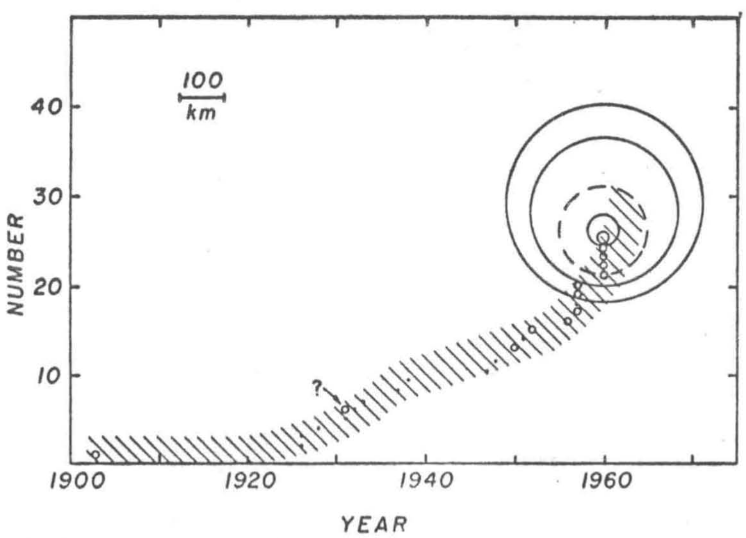

FIGURE 1.—Trend of the acceptance of structures as being of meteoritic origin. Aerial photography after World War II contributed several new finds. Small dots refer to craters less than 1 km diameter, open dots to those between 1 and 30 km, and the large circles are to the scale shown. A few are multiple, but are not so plotted.

contributing to many aspects of crystal chemistry. Interest was further enhanced by coesite never having been found in nature, and by its conditions of formation corresponding to inaccessible depths in the earth. However, when it was *looked for and found*[3] for the first time in the sandstone of the Arizona meteor crater an entirely new *attitude* was created by the possession of a new diagnostic tool. Additional impetus was given by the more recent but parallel synthesis of stishovite,[4] a rutile form of silica even denser than coesite, at pressures of about 110 kilobars at 1,200°C.[4a] This material, too, was found associated with coesite in the Arizona Crater, and in the much larger Ries Kessel in Germany.[4b] These finds justified the early predictions of H. H. Nininger[5] that such minerals would be found in impact craters.

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* The dated portion of the table to 1957 is adapted principally from D. M. Barringer.[21]

** Other supporting data are in the location plots of R. S. Dietz,[6] the summary of Canadian locations and work by C. S. Beals, *et al.*,[8] and discussions of crypto-volcanic structures by Eardley[22] and by Boon and Albritton,[23,24] who take W. H. Bucher as a first source.

*** Acceptance dates too indefinite. Actually, the structures have been known for decades.

Note added in proof.—Geophysical methods have located a 240 km diameter basin structure under the Antarctic ice near Long. 140°E, Lat. 70°S. If this is a crater and source area of the australites (see Virgil Barnes; Tektites, *Scientific American*, November, 1961) it would be of recent date, 5-10,000 years.

The significance of these finds is more impressive when correlated with the exhaustive work on shatter cones by R. S. Dietz, who much earlier showed their relation to high energy impact processes. Shatter cones and the new high pressure silica minerals found in the 1.2 km Arizona crater and in the 30 km Ries Kessel give substantial support to the proposal by Dietz that the inner Vredefort ring (64 km) in South Africa, where properly oriented shatter cones have been found, was formed by a meteorite.[6]

The encouragement inherent in these finds and proposals no doubt contributed greatly to an all-out effort by Canadian workers who earlier had been alerted by the find of the Chubb crater (3.5 km) described by V. B. Meen.[7] Lately, reports[8] have it that the Nastapoka arc in Hudson Bay (Fig. 2), representing part of a 440

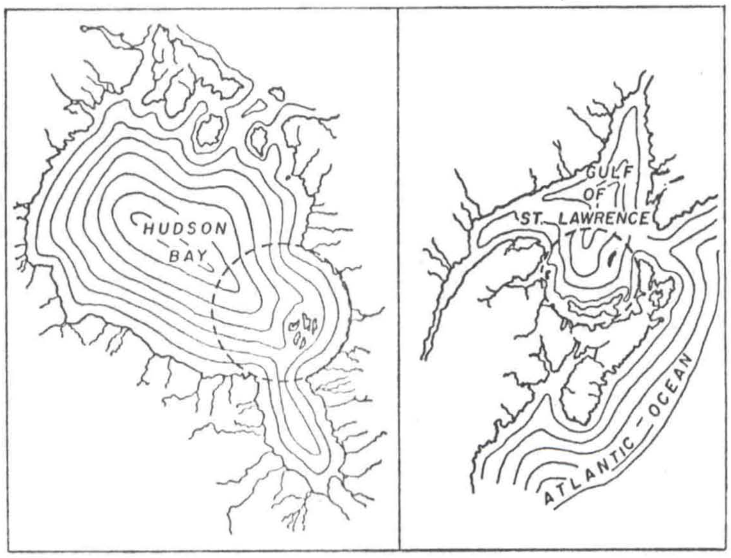


FIGURE 2.—Location of the Hudson Bay and Gulf of St. Lawrence arcs of ancient meteor craters.

km diameter circle, is a portion of a meteorite scar, as first pointed out by Kelly and Dachille[9] in 1953. More recently the Canadian workers believe they have positive evidence that the Gulf of St. Lawrence is essentially the site of a meteor crater approximately 320 km in diameter (Fig. 2).

The facts are not in to show whether these large craters show all the characteristics of impact phenomena. The overlap of the shatter cone and high pressure mineral criteria stands by as a potential check on other lines of evidence, some of which have been worked out for the Ries Kessel in a doctoral thesis,[10] supervised by Professor R. Brinkmann of Bonn. Dislocation of joint systems in the country rock, gradation of damage to rock from complete pulverization at the rim to largely loosened blocks farther out, the degree of disturbance showing radial symmetry, identification of literally hills of rocks as ejecta many kilometers outside the crater rim, and the radially oriented slickensides produced by these masses as they skidded to a halt are indicative of the approaches used and available. Gravity and seismic surveys have also been used to determine basin symmetries and to estimate the depth of shatter beneath the visible structures. Magnetic surveys generally yield negative results if the expectation is to find a consolidated mass or even high concentrations of an "iron" meteorite of large size. Drilling to depth for sampling and for obtaining profiles of the true crater anatomy is an expensive and difficult method, borne out by the experience in the Arizona Crater. Drilling also has been done in the Hudson Bay and in the Gulf of St. Lawrence, the Ries and other sites. (Professor E. Preuss of Munich informed the writer, during a field trip in the Ries, that another but more extensive drilling program is planned to study the Ries in detail. Such "dissection" should contribute greatly to the phenomenology of impact craters).

The point of all this is that the list of craters definitely and probably of impact origin shown in Table I makes a good start toward the "250" expected to have survived normal geological processes. Research of the next ten years should add significantly to the present list and perhaps add to the range of sizes beyond the 440 km Hudson Bay Crater to include those as large as the maria on the moon. It may be found, for example, that arcuate coastlines[9] or great continental plains surrounded by mountain ranges (Hungarian plain–Carpathian mountain complex[11]) are in fact remnants of old collisions.

POTENTIALITIES OF COLLISIONS

How big were the meteorites causing the larger accepted craters, the earth-equivalent now-hypothetical maria? How frequently do they fall? What happens to them? Aside from the formation of craters what else do they bring about? All these questions may find some answers in a consideration of collisions of very large meteorites.

An appropriate perspective for results of large collisions may be gained from the data of Table II, where values of high energy phenomena are listed. This is an aid to think big! That the earth has been struck by large meteorites is clear from the data already accumulated. It is believed most students should be convinced of this force of nature, a veritable *primum mobile*, even before the list grows to the estimated "250."

The most obvious results of collisions are quite simple. A hole is formed, ridges are thrown up and rays of ejecta are thrown out.

TABLE II

MISCELLANEOUS HIGH ENERGY PROCESSES

Process	*Energy*
Golfball off tee	10^{9} ergs
Thimbleful of TNT	10^{11}
Half ton of TNT	10^{16}
Atom bomb—20 kilotons	10^{21}
Total airborne explosives, World War II	10^{23}
H-bomb—100 megaton	10^{25}
Earthquake, San Francisco (1906), Chile (1960)	10^{24}
Annual total for earthquakes	10^{25}
Heat flow from Earth	8×10^{27}
Mountain range (1,600 × 480 × 1 km) raised 1 km	10^{29}
Arizona Meteor Crater—dig out	10^{22}
Ries Kessel—dig out	10^{27}
Hudson Bay Crater, 440 km—dig out	10^{31}
Spheroid, of density 3.5 gm/cc and speed 72 km/sec, with diameter of:	
0.032 km	1.5×10^{24}
0.32	1.5×10^{27}
3.2	1.5×10^{30}
32.	1.5×10^{33}
320.	1.5×10^{36}
640.	1.2×10^{37}
Rotational energy—Moon	3×10^{30}
Rotational energy—Earth	2×10^{36}
Energy—Moon about Earth	4×10^{35}
Energy—Moon about Sun	3×10^{38}
Energy—Earth about Sun	2×10^{40}

The larger the impact the greater the scars, but other effects become increasingly important. A partial list is given:

(1) Earth encircling tidal waves set off by shock on land masses and by direct hits in oceans.

(2) Triggering of volcanic or earthquake activity in unstable portions of the earth's crust, in addition to the creation of new local heat sinks and mechanical stress areas.

(3) Firestorms of great extent by collisions in densely forested areas, contributing vast quantities of organic debris in various stages of thermal decomposition to subsequent sedimentary accumulations. The Siberian fall of 1908, a small one, knocked down and "toasted" a forest 30 km across and knocked down a broader ring beyond this.

(4) Atmospheric disturbances related to the gases, vapors and dusts of the collision explosions (the volcanic explosion of Krakatoa, 1883, can only begin to illustrate this aspect of large meteorite collisions). Vladimir Vand[12] suggests that the rapid expansion and cooling of water vapor forced into the upper atmosphere by collision would contribute significantly to the growth of the polar ice caps, setting off a new cycle of glaciation.

(5) Contributions to sedimentary processes. It has been estimated that 2-10 $\times$ 10^6 kg of meteoritic dust are accumulated each year. This is equivalent to a single stony meteorite 17 meters in diameter. Larger meteorites would streak through the atmosphere with little loss in velocity. Consequently, bodies colliding at 10-72 km per second would actually explode, since only 1 percent of the energy at the lower velocity (10 km/sec.) is capable of vaporizing them completely. A portion of this matter no doubt is trapped in the focus and debris of the collision in the visible crater, but the balance would be broadcast widely unless the explosion were great enough to blast back through the atmosphere, carrying with it debris into accidental orbits about the sun or the earth. In effect, this operation creates *secondary* meteorites to be "harvested" by the earth at some later time. In this category might fit the carbonaceous chondrites and the tektites. (How valuable a find would be a well observed fall of a dinosaur skull encased in a huge block of siltstone, or an Egyptian style obelisk!)

(6) Disruption of the "equilibrium" composition of the atmosphere might be expected above a threshold size of meteorite. Wide dispersion of an evaporated "iron" 84 km in diameter (unlikely lump, but mentioned for order of magnitude) creates a virulent potential for decreasing the oxygen content of the air to negligible amounts. Certainly such interferences with organic and inorganic surface processes would be important *stagger* or *halt* points in the history of the earth.

All these are but an indication of the kinds of results which are possible, but it is not intended here to attempt a detailed history of large collisions. Rather, it is intended to describe possible collision effects in relation to (1) the tectonic activity of the earth and (2) the determination of the type of climate by the nature of changes in the rotation of the earth.

Returning to Table II, it is seen that the destructive horror of World War II pales into insignificance against the energy available in a few 100 megaton nuclear "devices," to use the jargon of the age. These are comparable to the energy released in the San Francisco earthquake or that estimated for the formation of the Arizona Crater. The energy required simply to "dig" the 440 km basin in Hudson Bay, in an industrious but normally inefficient manner (10 percent efficiency?), is up in even higher magnitudes.

The energies embodied by stony spheroids of various sizes at a relative velocity of 72 km/sec. are seen to overlap these high energy phenomena and fall within the rotational and translational energies of the earth and moon.

The justifications for the velocity chosen in the examples are simple: The distribution of velocities for meteorites in the solar system is between 13 and 72 km/sec., averaging 42 km/sec. (The probability of collision is increased for the faster ones, increasing the average). The earth-moon system has a velocity about the sun close to 30 km/sec. and, therefore, even more energy is available in the event of rarer, but nevertheless possible, head-on collisions.

The following observations are pertinent, based on the values of Table II. (1) The orbital motion of the earth, or moon, about the sun could be affected, but only to a small degree. The moon, because of its smaller mass, naturally would be subject to greater changes. (2) The orbit of the moon about the earth, on the other hand, can be affected significantly by collisions with spheroids of 50-100 km diameter. Secondary effects on the earth by lunar disturbances would be changes in body and superficial tides and in the precession of the axis. (3) Rotation of the moon about its own axis and the actual change of axis are within the capacity of collisions with bodies 1-10 km in diameter. Certainly the scarred face of the moon suggests many collisions of this order. It cannot be taken too patly that the moon's present rotation is of aeon-long duration. (4) The above are real, but with the earth as a protagonist a review of the mechanics of collision will offer more to savor. As a first approximation the earth is considered to behave as a rigid sphere in the short time of impact. The large spheroid, conversely, may behave as an inelastic body—that is, it may give all its in-flight momentum to the earth. However, because of the truly explosive nature of the collision the generation of a *reverse directed jet* of the blast material would approximate an elastic collision. The net momentum contribution to the earth could be between one and two times that of the spheroid. (If the collision were to set off a nuclear fusion process in the center of the collision zone the effective momentum in the jet could raise the net change to values greater than two. Theory does not countenance this possibility although pressures of 200-300 megabars and temperatures of 1½ million degrees may be available.)

The direction of the collision, for the present purpose, is taken as effectively tangential to the longitudinal or equatorial circles of the earth, and in their planes. The center of percussion is taken at the center of the earth. This combination tends to compensate one with the other in that the more probable collision angle is 45° and the center of percussion affords a lever arm 40 percent longer than the radius of the earth.

For the above conditions the angular momentum of the earth and the moment of momentum of the spheroid may be added vectorially to give the magnitude if not the precise displacement between the old and new axes and also the approximate changes in the angular velocity. In Table III are summarized calculated results for collisions of various magnitudes.

TABLE III

CALCULATED RESULTS FOR COLLISIONS OF VARIOUS MAGNITUDES

Angular momentum, Moon 2.3×10^{36} gm cm^2 sec^{-1}
Angular momentum, Earth 5.89×10^{40} gm cm^2 sec^{-1}

SPHEROIDS	EARTH		
	2 MVR *gm cm^2 sec^{-1}*	*Maximum axis change*	*Maximum rotational velocity change*
0.032 km	5.5×10^{26}		
0.32	6.5×10^{29}		
3.2	5.5×10^{32}		
32.	5.5×10^{35}	0°0′2″	.001%
320.	5.5×10^{38}	0°32′	.9%
640.	4.4×10^{39}	4°15′	7.5%
	MOON		
3.2	1.5×10^{31}	0°2′	.0006%
32.	1.5×10^{34}	0°22′	.65%
320.	1.5×10^{37}	81°20′	650.%

What do these figures mean? With regard to changes in velocity they say that at the outset a relative velocity will exist between the lithosphere and the air-water ocean which can amount to a sustained difference at the equator of 2-120 km/hr. This differential will cause inundations of vast coastal areas, the withdrawal of tides from others, the reworking of all sorts of sediments and other unconsolidated deposits and the scattering of the ice caps.

A closer look at the effects of a tangential collision in the equatorial plane, increasing the angular velocity of the earth by 5 percent (80 km per hour at the equator), will help illustrate the sequence of changes to be expected. (1) The shock, sound and fury of wind, water and ground. (2) The rotation of the lithosphere at the new, faster rate. (3) Inertial maintenance of the original rate by the air-ocean masses so that they run westward overcoming the eastern shores of continents and islands. The basic rise to be expected due to this velocity change is not small—25 meters—but the rise can be very much greater in special configurations of coast lines which funnel the water-air masses and set up hydraulic hammer conditions. (4) The lithosphere conforms easily in the limit of its elastic response to the new velocity so that relative to the hydrosphere (rotating essentially at the original velocity) the equatorial coastlines emerge a small amount but in the higher latitudes, submerge. (5) Frictional forces finally bring the air-ocean masses to the new velocity, and in doing so a reversal in trend of the coastline emersion-submersion takes place because the fluid shell can conform easily to the centrifugal forces whereas the friction in the lithosphere retards the assumption of the new figure. (6) This adjustment, however, eventually does take place, so that again equatorial coastlines emerge relative to the submergence of those at higher latitudes.

Assignment of time intervals can only be *guessed* at and these *guesses* shall be made for their heuristic value. Phases 1 and 2, one day to one week; phase 3, two to six months; phase 4, elastic response concurrent with 2 but coastline changes related to 3; phase 5, one to two years; phase 6, one hundred to ten thousand years.

Adjustments of the lithosphere to the rotation figure imposed by a new angular velocity are on a truly significant scale which may be evaluated by interpretations of Fig. 3. The diagram shows a

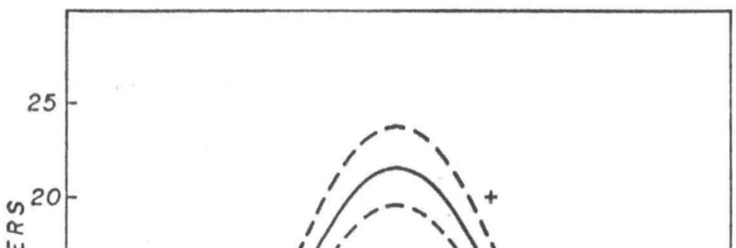


FIGURE 3.—Excess of radii over polar radii plotted as a function of latitude. The full line is for present rotation, the dashed lines are for ±5% change in velocity.

plot of the difference between the polar and other radii as a function of latitude. This designates a tangible profile of the equatorial "bulge" having a maximum difference at zero degrees latitude of 21.6 km. A collision sufficient to increase or decrease the rotation of the earth by 5 percent (see Table III) would change the profile as indicated in Fig. 3. Hence, at 45° latitude the change in radius is 1.1 km, at 20°, 2 km, and at the equator 2.1 with increased or decreased rotation. If these changes were to be realized immediately by both the lithosphere and hydrosphere, the relative shoreline motions would not be great—perhaps only 1/100 of these amounts. However, since the lithosphere most likely would respond slowly due to friction over appreciable periods of time, whereas the hydrosphere would conform to the new rotation figure in a short time, great changes in shorelines are to be expected. Here the term shorelines is used more in the sense of establishing a sea level, and the changes may therefore be considered as changes in elevations with the corollary changes in local climate, erosion and drainage patterns, drowning of coastlines or incisive action of great river systems.

The changes are by no means all such bland ones. For example, in the zone between 15° N and 15° S latitude the change in volume of the "bulge" is about 8 percent, requiring 2×10^8 cubic km of rock to change position by all mechanisms available. Earthquakes and faulting are brought about by forces which form mountains, and according to C. F. Richter[18] the nature and cause of mountain building is the central, outstanding problem of historical geology. As shown in Table II all the earthquake energy of the earth over 1,000 years would amount only to 10^{30} ergs. Adding to this the energy to raise five tolerably large mountain ranges each an additional 300 meters still would not alter the 10^{30} erg magnitude. All this activity is less than one millionth the mechanical energy of the rotation change (in fact, it could be matched by the collision energy of a 3.2 km diameter spheroid but when noticeable axis or velocity changes cannot occur the disturbance should be more localized). If it is assumed that most of the readjustment takes place in the crust above the Mohorovicic discontinuity, the percentage of this larger volume is still appreciable—3 to 5 percent. The net volume change remains the same but the intensity of shearing is decreased and spread deeper. The change in a linear element on the surface in the same region amounts to 0.3 meters out of each kilometer, enough to set up high compressive or tensile stresses in the surface of the same order as those which might arise from a change of temperature of the entire earth by 30°C (assuming an average thermal expansion coefficient of about 10^{-6}). The stresses due to temperature changes by cooling or radioactive heating, however, would accumulate ever so slowly because the change in the heat content of the earth is high: 2×10^{36} ergs.

A collision producing a change in the axis of rotation will bring about results of the same type and magnitude, with the modification necessarily related to the change in poles and equatorial planes. In Fig. 4 is shown a 5° shift of the bulge profile in the

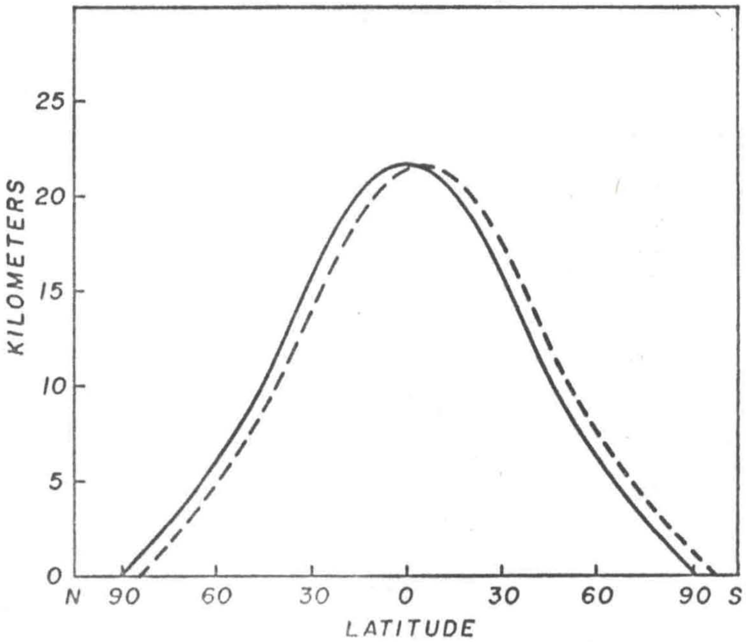


FIGURE 4.—Excess of radii over polar radii plotted as a function of latitude. The dashed curve is for a 5° displacement of a new axis of rotation.

plane containing the original and post-collision axes. The angular displacement of axis is taken as the arc whose tangent is the ratio of the moment of momentum of the spheroid to the angular momentum of the earth, as a first approximation. Pertinent values are shown in Table III and more discussion is to be found in reference 9. The point to be made is that the bulge contours are so displaced that in going about the great circle submergence-emergence-submergence and emergence of elements on the surface will take place. These effects taper off with a 90° change of longitude from the plane containing the two axes and will be at a minimum where the original and new equators intersect. The changes in elevation with reference to a newly stabilized hydrosphere provide a very important mechanism for the submergence and emergence of continental-sized areas simultaneously all over the earth. The reverse movement, due to the "relaxation" of the lithosphere to the new equilibrium figure, will then take place over long periods. It is suggested that the erosional and sedimentary history of continental-sized areas may be correlatable with a mechanism of this type.

A change of rotation of a "rigid" earth about an axis through the center of mass would be a "comfortable" one compared with a rotation about an impact axis not symmetrically placed. Also, the very small axis changes might be as nothing compared with geographical displacements of the old poles if, on impact, the core and mantle of the earth were to turn relative to each other. In fact, such reaction is inevitable in view of the interpretation that the outer core may be "liquid" and that marked changes in density, composition and rigidity occur at the core boundary. Further, if the earth were a homogeneous solid the moment of inertia of the core, and hence the angular momentum, would be about 1/20 that of the whole; but because of the high core density (10-17 gm/cm^3) the value is slightly less than ⅛. In effect, the core has "more a mind of its own" to maintain its original rotation and thereby increases the tendency to shear at the core boundary. Under any specific impulsive torque the mantle (plus the crust) can be displaced by a greater amount roughly proportional to this factor ⅛. The core (just as the oceans and atmosphere on the surface) can churn and bump away in the liquid lining about the original axis while the mantle strives to attain rotation about some other axis. The energy of this fractious fetus's activity is appreciable (8×10^{31} ergs) for only one minute of arc (rotational energy of core $\times$ tan 0°1′), an amount equal to 10,000 years' heat flow at the earth's present rate.

Temperatures produced by such frictional processes depend on many factors. It will suffice to note that a shell at the core boundary 5 km thick could have 3,600 cal/gm pumped into it, sufficient to melt it and cause fractionation into metallic and oxide phases. The question must be asked: Is it possible that the "metallic" core owes its very existence to a long history of large scale bombardments?

Climatic Change

Papers by specialists collated in *Climatic Change*[11] may guide a reader to conclude that (1) the evidences of climatic change on a planet-wide scale are good and acceptable; (2) geological causes to bring about these changes are plainly insufficient; (3) astronomical causes (solar variation, perturbation of earth's orbit, etc.) are likewise insufficient; (4) the highly important influence of an axis change is recognized but is considered as untenable because *great external forces* would be necessary.

In the foregoing discussion the "mechanical sufficiency" of large meteorite collisions has been described in quantitative approximations. Given large enough or frequent enough collisions appreciable axis changes are to be expected, with highly important changes of insolation of the north and south hemispheres. In effect, the two hemispheres are alternately hot and cold sinks which in time with the revolution of the earth in its orbit set up the atmospheric and oceanic circulation patterns, storms, local seasonal changes, determine the growth and recession of ice caps and so on. If one sets up "end members" as in Fig. 5, the control of planetary climate by the axis position relative to the orbital plane becomes obvious. In addition to the tilt of the axis, the collision mechanism provides that the poles in the earth also are changed in a geographical sense, as unquestionably they have been in the past.

Climate is merely another physical system until it is looked at in a manner similar to that of Harlow Shapley, who says, "Next to the genes and chromosomes,—climate is the major factor in organic evolution."[14] Major forms of life may well have been consolidated by the onset and duration of certain types of planetary climate. For example, Type I might have been the most favorable for the amphibian and reptilian forms whereas Type IV (if not completely hostile to the maintenance of life if of long duration) might have "crystallized" the optimum development of birds and other creatures capable of rapid migration or of efficient hibernation and estivation. Type II fits man reasonably well although the distribution of dense populations and the vacation preferences of people suggest that a change of about 5° toward Type I would suit him better, complete with fig leaves! Type III would have retarded and cowed man while serving favorably the giant mammals. Interwoven with the influence of type of climate is the very important factor of the *accidental survival* of sufficient but not large numbers of any one species to establish a new ecological balance after major collisions. The survival of a necessary *minimum number* of any species greatly favors the chances of concentrating inheritable characteristics *accidentally* best fitted to the new conditions and hence to evolutionary change. If these characteristics should already be found in variants forming minute proportions of pre-collision populations, the accidental concentration of these variants among the survivors will increase their chances of becoming established. In the aftermaths of collision nature certainly could have the two most important factors working together—chromosomes and climate.

FIGURE 5.—The probable conditions of the ice caps for different inclinations are shown as dark areas in the four panels. The climate of Type I would be even and relatively free of storms; the severity of storms would increase with the increase in tilt of axis, as the air masses raced from cold areas to hot areas. Day and night would be uniform all through the year in Type I but approaching Type 4, continuous, unbroken night would persist for months in the winter season; in summer, a "noonday" sun would stare down on the exposed polar areas for months without interruption. Only the tempering effects of the large oceans (the cradle of all early and persistent forms of life) and the atmosphere would keep the earth from developing the extremes of temperature that occur on the surface of the moon. (From A. O. Kelly and F. Dachille, *Target: Earth*[9])

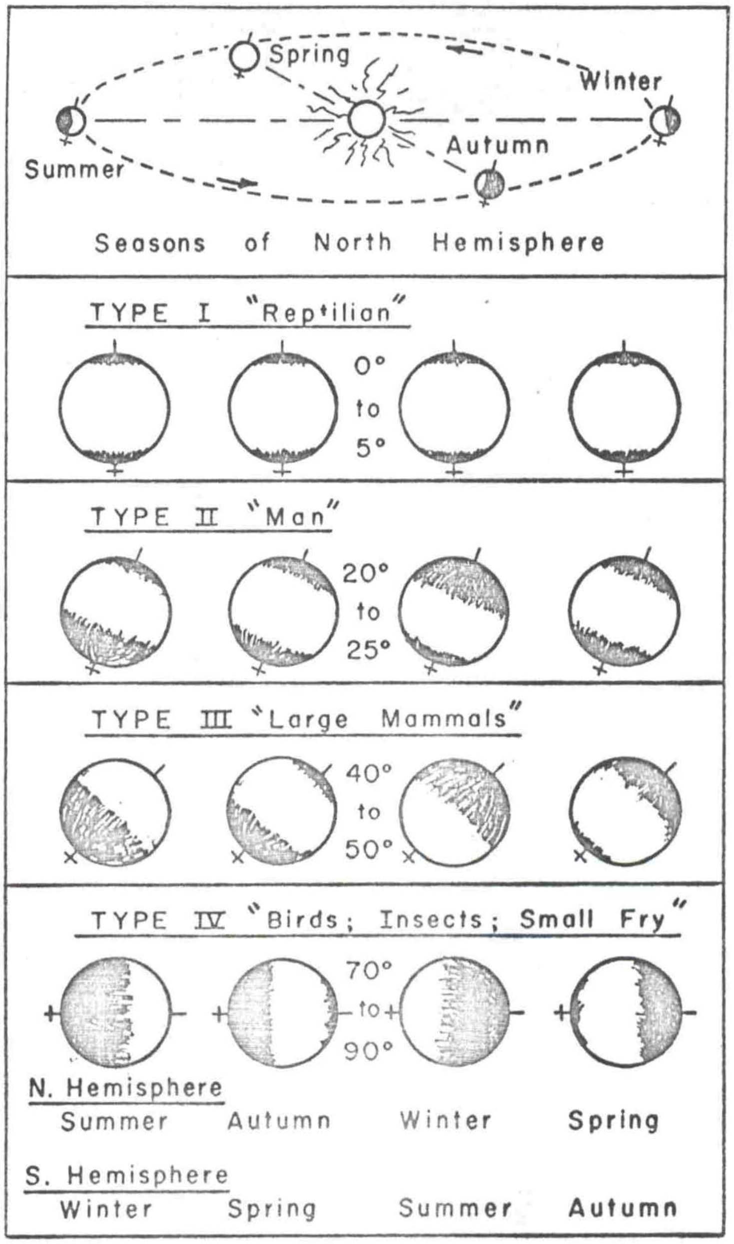
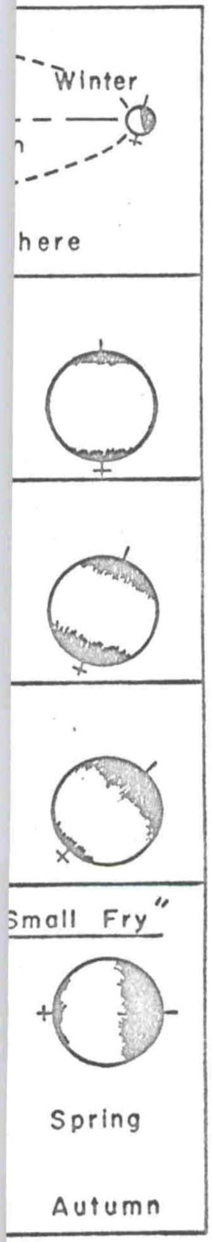

Spring
Winter
Autumn
Summer
Seasons of North Hemisphere
TYPE I "Reptilian"
0° to 5°
TYPE II "Man"
20° to 25°
TYPE III "Large Mammals"
40° to 50°
TYPE IV "Birds; Insects; Small Fry"
70° to 90°
N. Hemisphere
Summer Autumn Winter Spring
S. Hemisphere
Winter Spring Summer Autumn

FIGURE 5



"It Cannot Happen Here" or Has It?

A certain amount of comfort can be derived from the knowledge that the solar system is believed free of spheroids 200-600 km in diameter cruising about in random orbits, although the asteroid belt certainly could supply them if disturbed. An extrapolation of H. Brown's data (see later) from 10^4-10^7 gm meteorites to those of 10^{20} gm reduces the frequency of large ones to only a few in the age of the earth. Besides, experiments and observations of crater forming processes have provided convenient factors for estimating dimensions. One is that crater diameter is proportional to the ⅓ exponent of energy and another is that the diameter of the colliding body (for moderate meteor velocities) will be about 1/20 (or 1/30) that of the crater formed. The latter brushes away the annoying Hudson Bay Crater as insignificant because the meteor would have had to be in the order of 20 km, too small for changing things. It also kills suggestions that 600 km spheroids have scarred the earth—simple 12,000-18,000 km craters are hard to accept, and harder to recognize.

The comfort, however, should not be bone deep. The ballistics experiments were of low total energy and at speeds considerably lower than those of *slow* meteorites. The explosion experiments have been in the 10^{13-16} erg range until the recently reported[16] cratering experiments with 1.2 kiloton nuclear explosions. Even so, these involved but 10^{20} ergs and were by no means the equivalent of impacts. Pertinent findings were that maximum craters were formed by explosions at a critical depth but they *decreased sharply* for shallow and surface explosions (see also Ref. 16). The ⅓ exponent was found to hold for charges up to about 10^{16} ergs (1,000 pounds of TNT), but in the larger explosions 1/3.4-1/3.6 gave better fit to predictions. In fact, exponents down to 1/4.1 were found to fit in certain studies.[17] Smaller exponents might be expected in higher energy explosions.

What this leads to is quite interesting. The simple "dig-out" energy for the Hudson Bay Crater would be 10^{30}-10^{31} ergs—just to dig and cart away. The rule of thumb estimate of projectile size would be 1/20-1/30 of 440 km, say 18 km, which from the data of Table II would correspond to 2.5×10^{32} ergs. This does not appear sufficient to balance the mechanical energy of the recoil jet and the motions of the earth one might expect of such high order collisions. Scaling with $(\text{Energy})^{1/4.1}$, using the Arizona Crater as a reference model, it is found that the energy required to form a Hudson Bay Crater is about 2.7×10^{34} ergs, corresponding to a meteorite 87 km in diameter. The diameter of the crater is only 5 times this value. The potential for axis change is about 6′ of arc at least in the simple model set up. In the formation of this size of crater the earth starts to move.

That the exponent for scaling is about 1/4.1 is suggested in an unexpected area. The distribution of meteorite falls by size and number was found by H. Brown[18] to follow a relation Δ log mass/Δ log frequency = 0.77 through the range of 32 kg to 1,024 kg. He also pointed out the "striking resemblance" of the frequency distribution curve as a function of magnitude for asteroids (see Kuiper, *et al.*, Ref. 19) to the curves for meteorites, the congruent slope being 0.76. A study by Opik[20] of the size distribution of 812 craters on Mare Imbrium when plotted in the same manner, except that a fixed 20/1 ratio of crater to meteor diameters is used, gives a slope between 0.45-0.50. However, applying the energy exponent ¼ instead, the slope is 0.72-0.75. All this may be fortuitous, but it does represent different kinds of sampling of large numbers of the same kind of things in the space around the earth.

The frequency, in fact the very existence, of *random* bodies in the 300-600 km range may well be zero, and in the present inventory of astronomers, the number is zero. However, the presence of large maria on the moon is disturbing in this regard. It may be that in our time lunar explorations will clear up the dating and mechanism of formation of maria, but until then it should be useful as well as instructive at least to consider the possible effects of *large collisions*.

Penultimate disasters have not been missed by far in time or distance. The "mythologies" of ancient peoples include descriptions of very close passes. In 1960 an unknown object of an estimated 8 cubic km passed close to our orbit, 8 million km from the earth. The asteroid Hermes slid to within 320,000-640,000 km of the earth in 1937, and near the turn of the century, Eros, later Amor, came within 20 and 16 million km. Estimated kinetic energies represented by these bodies are in the order of 10^{30}, 10^{20}, 10^{31} and 10^{32} ergs. Visitations by these would have been no myths.

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