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Global Hydrocarbon Potential of Impact Structures

David B. Buthman
Unocal
Sugar Land, Texas

ABSTRACT.—Astroblemes, or ancient weathered impact craters, have produced hydrocarbons in North America at Red Wing Creek field, North Dakota; Viewfield field, Saskatchewan; Barrow gas field in the Avak structure, Alaska, Calvin-28 field, Michigan; and, discovered in 1991, the Ames astrobleme, Oklahoma, with estimated recoverable reserves approaching 50 million barrels of oil (MMBO) plus gas. Numerous oil and gas fields throughout North America produce from reservoirs and traps of astrobleme origin, and it is hypothesized that dozens more, if not hundreds, of already productive structures have yet to be recognized as having an astrobleme origin. Cumulative production from astroblemes is estimated to have already exceeded 1 billion barrels of oil.

Impact craters in the universe range from planet- or moon-annihilating monsters, to Copernican-scale basins, to craters a few miles to several dozen miles in diameter that may be prospected for hydrocarbons. Copernican-scale craters comprise the basins filled with flood basalt on the Moon, whereas on the Earth, such craters are filled with sedimentary deposits and evolve into what are recognized as sedimentary basins—features that may contain oil and gas deposits.

A contrarian theory is presented that challenges the prevailing paradigm that meteorite impacts are random, unpredictable events in time and space. A plot of the ages and locations of the meteorite-impact craters in North America shows that the majority of those discovered thus far lie within a northeast-trending belt extending from west Texas to Quebec. Plotting these impact craters and contouring their ages result in an isotime contour map that illustrates this trend. This impact-crater trend started forming in the Ordovician, about 450 Ma, and culminated about 300 Ma ago, during the Early Pennsylvanian. The plate-tectonics reconstruction of the contour map illustrates how the Pennsylvanian paleoequator once paralleled this meteorite-impact belt. One possible explanation for the existence of this meteorite-impact belt is that between the Ordovician and the Pennsylvanian Periods, a loosely indurated asteroid, comet, or primordial moon, in a decaying orbital trajectory around Earth, lofted fragmented masses toward the Earth over a time span of 150 m.y., leaving a swath of impact craters below. Hundreds, perhaps thousands, of significant impact craters will be found within this belt. A modern analogue to this Pennsylvanian meteorite-impact belt was the 1994 breakup of the Shoemaker-Levy 9 comet and the subsequent impact belt that formed across the face of the planet Jupiter.

It is hypothesized that other meteorite-impact belts, in addition to the Pennsylvanian trend, occur along different orbital trajectories during different ages of geologic history. For example, during the Cretaceous, a comet with an orbit antithetic to the galaxy's ecliptic lofted fragments toward the Earth in an orbit extending from the Gulf of Mexico to Barrow, Alaska, to offshore Japan. Undoubtedly, more meteorite belts will be found on Earth, many of which will have economic potential for their discoverers.

INTRODUCTION

The most common geologic structures in the solar system are craters formed by the hypervelocity impact of meteorites. The Moon, Mercury, Venus, Mars, the millions of asteroids, Encelades, Phobos, Deimos, Ariel, Uranus, Neptune, even Pluto—all exhibit abundant impact cratering. Through binoculars or a telescope one could, with enough perseverance, count 10,000 impact craters. After the landing on the Moon in 1969, it became evident that the Moon hosts hundreds of millions, perhaps billions, of impact craters.

David B. Buthman, Spirit Energy 76, 14141 SW Freeway, Sugar Land, TX 77478.

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primary craters themselves, whereas farther away, the fragments become progressively smaller. When the crater floors were excavated, mixed breccias, sheared and compressed target materials, overturned synclines beneath the downtrajectory rims, and, depending upon the velocity at impact, fragmented, powdered, even partly fused missile fragments were found.

In short, results of the White Sands missile experiments indicate that bilaterally symmetrical craters result from hypervelocity impact; simply put: Craters are circular.

THE MOST COMMON GEOLOGIC PHENOMENON IN THE UNIVERSE

The most common crustal structures on the terrestrial planets, asteroids, moons, and outer planets are impact craters. With the bare eye, one can see thousands of craters on the Moon. With binoculars or telescopes, one can see tens of thousands.

Impact craters are more common than plate tectonics, more common than volcanoes, more common than faults and salt diapirs and cratons and deserts and water. The Moon and Mercury are covered (Gault and others, 1975). Mars is covered. Millions of asteroids, Venus, and Pluto—the most striking, simple, and abundant geologic features on all their surfaces are impact craters.

This observation is so simple and obvious that it is perplexing that it was not obvious before.

Because human beings are not currently commuting to Mars or Pluto, it cannot be proved with utmost scientific rigor whether the circular, craterlike features observed on these planets are truly meteorite-impact craters. Elusive are the "smoking gun" evidences that define, irrefutably, an impact origin, such as the characteristic metamorphic minerals coesite and stishovite, diaplectic glass, fused feldspars, kinked micas, Widmanstätten and Neumann bands (herringbone and twinning structures, respectively, in iron meteorites), or cataclysmically disrupted strata. Breccias. Tektites. Concussion axes. Shatter cones. These things cannot be sampled on Pluto or Mars (not yet).

Today, it seems obvious that the craters on the Moon were formed by meteoritic impact. This is accepted as scientific truth. However, not long ago, eminent scientists and scholars argued with great vehemence about the origin of the craters on the Moon. One school argued that the craters were the result of lava extruding from continuously subsiding volcanic fissures in the lunar crust. The lava subsequently ponded and formed the maria of the Moon.

When the Apollo astronauts landed on the Moon in the late 1960s, the data they collected proved to everyone's satisfaction that indeed the craters, even the large Copernican-scale ones, were the result of hypervelocity impact events. Simply put, small meteorite impacts formed small craters, and big meteorite impacts formed very large craters.

On Earth, most impact craters on the continents and their shelves will eventually be buried under thousands of feet of sedimentary rock. Finding a shatter cone, a glass shard, or coesite or stishovite thousands of feet underground will, in most cases, prove prohibitively expensive. Drilling into a suspected astrobleme for economic reasons, however, in the search for oil and gas for example, is tolerable, even encouraged. Millions of barrels of crude oil and gas have been produced from deeply buried astroblemes. But drilling wells to prove irrefutably the origin of a circular structure, to spend millions of dollars to locate mineralogical and kinematic smoking-gun evidence, is in most cases, impractical unless economically rewarded.

For purposes of this study—specifically impact craters on Earth but also including analogue impact craters within the solar system—Pareto's 80/20 rule will be employed. Pareto's 80/20 rule states that roughly 20% of tasks account for 80% of the desired results. Pareto's rule suggests that most time is spent on low-payout projects, and very little is spent on big payout projects. It is typical to become bogged down in details, distracted by noise, and crippled in the processes of criticism and then to forget what it is that truly needs to be accomplished.

If a geologic structure is bilaterally symmetrical, with morphologic elements that mimic those of all other meteorite-impact craters, then for this study, unless other conflicting data exists, it has been considered an impact crater. Evidence such as impact metamorphism may be lacking. Petrophysical evidence may be lacking. In fact, the sole evidence in many cases for such a structure's being an impact crater has been its geometry: It looks like an impact crater, therefore it is an impact crater. Pareto's rule says that 20% of the time it may not be an impact crater, but why waste the remaining 80% of the time bogged down on the details that might yield only 20% of the desired results?

IMPACT-CRATER SIZE DISTRIBUTIONS

The largest impact "craters" in the universe result from impacts that catastrophically rifted or annihilated the target object (Fig. 2). The next generation of sizes are Copernican-scale craters—those measuring hundreds of miles in diameter (Fig. 3). On the Moon, these Copernican-scale craters have been filled with flood basalts, whereas on Earth, as well as on Mars, similar-scale impact craters have imposed the architecture for subsequent development of the major, and minor, basins of deposition.

The last size class of impact craters are those with the most economic potential. They range in size from tens of feet to tens of miles in diameter.

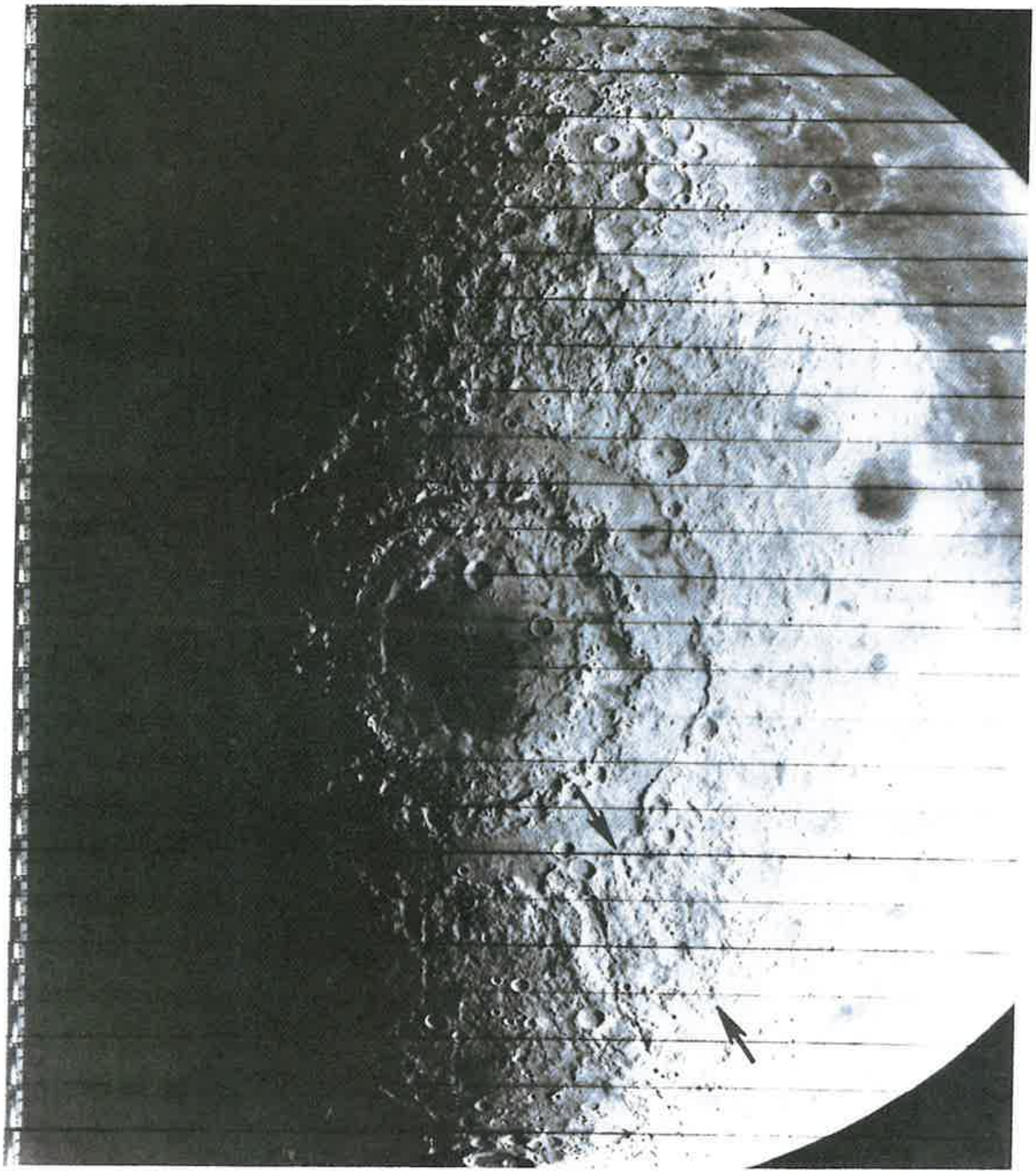

Figure 3. Copernican-scale craters, such as the 600-mi-wide Orientale Basin on the near side of the Moon, have been infilled with mare basalts and exhibit secondary-crater trains (arrows). On Earth, similar size classes of impact craters probably initiated the formation of large sedimentary basins. (Photograph L-67-4825, courtesy of NASA, 1967.)

On the Earth, then, there should be 5,797 to 144,925 impact craters, with 15,096 impact craters as the mean expected number (Table 4). But since two-thirds of the Earth is water, the majority of the impacts would have occurred in water, resulting in hydrobleme formation on the sea floor. The land surface of the Earth, then, is expected to have suffered between 5,797 and 144,925 crater-forming events, with 15,096 as the mean expected number. Conversely, the sea would have suffered

TABLE 2.—AVERAGE DENSITY OF LARGE CRATERS

Location	Large crater density
Oklahoma	1 crater per 703 mi^2
Fennoscandia	1 crater per 7,472 mi^2
Mars (max.)	1 crater per 1,800 mi^2
Mars (min.)	1 crater per 14,400 mi^2
Mars (mean)	1 crater per 4,000 mi^2
Moon	1 crater per 278 mi^2

TABLE 3.—AREA PER SIGNIFICANT CRATER

In our solar system probability*	Area per significant crater
P10	400 mi^2
P90	10,000 mi^2
Mean	3,840 mi^2

*Probability is expressed thus: P90 means 90% of the data is smaller than or equal to the value (area per significant crater); P10 means 10% of the data is smaller or equal to the given value.

TABLE 4.—EXPECTED NUMBER OF CRATERS

Probability*	Expected no. of craters
Earth Total	
P10	494,378
P90	19,775
Mean	51,498
Earth/Land	
P10	144,925
P90	5,797
Mean	15,096
Earth Hydroblemes	
P10	349,378
P90	13,978
Mean	36,401

*See Table 3 for explanation.

hydroblemes with minimum diameters of 5 to 6 mi.

At the White Sands Missile Range, missiles that impacted water-saturated sediments resulted in craters that were five to ten times wider than the craters formed when missiles with equivalent energies impacted dry sediments (Moore, 1976). Thus, in order to identify true hydroblemes on the ocean floor, the search must look for subdued, low-relief, and unusually wide, shallow crater-form structures. Hydroblemes will not mimic the morphology of their continental counterparts.

What would the formation of a hydrobleme look like from the surface? Don't get too close. But the sequence of events would involve an initial high-velocity central spout formation. The spout would persist, and a bubblelike lid would extend from the rim wave over the cavity. On the sea surface, the encircling rim of water bubbles, a gauntlet of steam spouts into the atmosphere, the central rebound peak eventually collapses, and then a series of globe-threatening tsunamis—horrible tidal waves rolls toward land.

Foremost evidence for past impacts of meteorites in the oceans are chondritic ablation debris, extinction of planktonic foraminifera (little sea critters), the enrichment of sea-floor clays with the rare element iridium, and the widespread microtektite layers called strewnfields. Microtektites are small, melted shards of black glass shaped like drops, twisted projectiles, or bullets. Presumably when the meteorite struck, the intense heat generated melted part of the Earth's crust, and the force of the impact lofted the melt as fused glass particles and deposited them thousands of miles away. The largest tektite strewnfields are the North American strewnfield, which extends westward into the Pacific Ocean from Cuba and the northern coast of South America, the Ivory Coast strewnfield, linked irrefutably to the Bosumtwi crater in Ghana, the Czechoslovakian strewnfield, and the largest on Earth, the Australasian strewnfield, which encompasses all of Australia, Southeast Asia, and parts of India, Madagascar, and southeast Africa (Alvarez and others, 1982). Some have even postulated that the Australasian strewnfield (Schneider and others, 1992) may be the scar from which the Moon was born.

Circular sea-floor features that are likely candidates for being hydroblemes include the Tagus Abyssal Plain, west of Portugal, and near Bombay, India, a paleohydrobleme is thought responsible for the origin of the Deccan basalts (Alvarez and others, 1982). Other candidates include the Massachusetts Bay—an arc along the eastern seaboard between Providence, Rhode Island, and Portland, Maine; the Lesser Antilles, Caribbean Sea; the Southern Ocean late Pliocene asteroid impact (off the southwest tip of South America); the circular area associated with the Australasian strewnfield (related to the Brunhes-Matuyama geomagnetic polarity reversal and coeval climate change); the Sea of Japan—a circular sea-floor anomaly surrounded by North Korea, South Korea, Japan, and Vladivostok; the Wrangel Abyssal Plain in the Arctic Ocean; the Sohm Abyssal Plain in the Atlantic Ocean; and the Pernambuco Abyssal Plain in the Atlantic Ocean off Brazil.

forth, the operator of the field suspects that a given reservoir is related to an astrobleme, then the first step to fully develop the production potential is to determine how the oil wells are situated on the astrobleme. If they are all on the encircling rim anticline, either on the upbasin or downbasin side, then the field may be extended along that structure. If the rim anticline has been developed satisfactorily, then the risks of there being a prospective central peak must be considered.

On Mercury, Venus, and the Moon, nearly all the impact craters larger than 2.5 to 3.1 mi have rim anticlines, some completely encircling, some broken into arcuate segments. On Mars, whose impact craters are thought to have formed under conditions very similar to those on the Earth, only about 50% of the impact craters larger than 2.5 to 3.1 mi have measurable encircling rim anticlines.

Throughout the solar system, central peaks associated with impact craters are much less common than encircling rim anticlines. Of the impact craters on Mercury, 62% have central peaks; 57% of the impact craters on the Moon have central peaks; 25% on Venus have peaks; and on Mars, only 11% of the impact craters exhibit measurable central rebound peaks. Earth's conditions place it between those of Venus and Mars.

The operator of a Midcontinent astrobleme-related oil field would predict the risk of drilling the center of the astrobleme thus: an astrobleme on Earth has an 11 to 25% chance of having a central peak. The worldwide odds of a wildcat well striking oil or gas, however, are no better than 10%. Of that 10%, only 1 or 2% of the strikes turn out to be a significant discovery. Compared to these odds, drilling the suspected central peak of any already oil-productive astrobleme seems like pretty good odds.

Warren Astrobleme

During the late 1920s to the late 1940s, Mt. Pleasant, Michigan, and surrounding towns, endured a major oil boom. Wells flowed as much as 10,000 barrels of oil per day from the Devonian Dundee Limestone above depths of 4,000 ft. Thousands of people flooded the area, thousands of wells were sunk, millions of barrels of oil were produced. The development of the Mt. Pleasant and Porter oil fields was not without problems. At first, geologists thought the Mt. Pleasant and Porter fields were one large connected anticlinal trap. Subsequent drilling proved this not to be the case. Near Oil City and eastward, drillers then found a surprise: the east flank of the Mt. Pleasant oil field was not structurally controlled; it was stratigraphically controlled. And because the rocks, not the subsurface structure, controlled production beyond Oil City, the field expanded.

As the years rolled by, the Mt. Pleasant field mapped out as an arcuate, part structure, part stratigraphic, oil pool. Then, in the early 1980s, the Rosebush field was discovered to the northwest (Fig. 5). This field proved to be a north-trending structure—very unlike the surrounding structural grain.

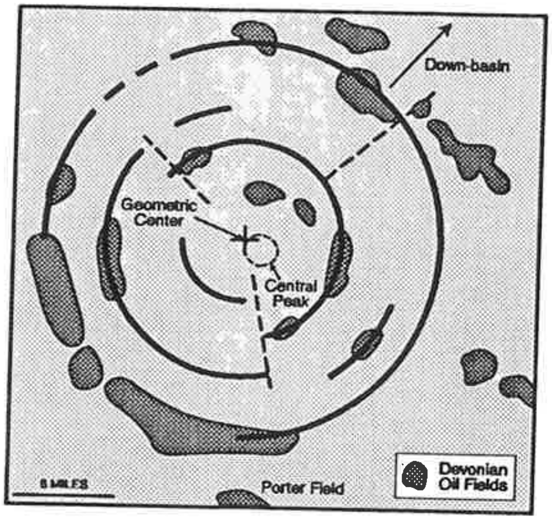

Figure 5. Proposed Warren astrobleme, central Michigan basin. Arcuate oil field to the northwest of Porter field is the Mt. Pleasant–Greendale field complex, and northwest of Mt. Pleasant is the north-trending Rosebush field.

In the middle 1980s, Union Oil Company mapped a dome, based on seismic and well data, located 14 mi to the northeast of the town of Mt. Pleasant. The dome covered approximately 2½ mi^2, had 80 ft of structural closure on top of the Ordovician, had a seismic velocity anomaly associated with it, and shallow wells with oil shows had already been drilled on top.

Today, though there is no longer any evidence of the oil fields between Oil City and Mt. Pleasant, nor any evidence of the once prosperous boom days and associated excesses, about 14 mi northeast of Mt. Pleasant there does still exist an oil and gas prospect, one that in all likelihood represents the central rebound peak of a 395 Ma astrobleme. The Warren astrobleme measures 24 mi in diameter, is a complex, highly eroded astrobleme, and its location in the center of an unusually circular Michigan basin begs the correlation to be made: did the Warren impact somehow effect the subsidence and subsequent deposition of sediments within the Michigan basin? Is the formation of the Michigan basin the result of asteroidal impact?

In today's dollars, it will take $3 million to find out, for that is what it will cost to drill to the depth of a possible central uplift.

Lima Field, Indiana and Ohio

The largest oil field east of the Mississippi River and north of Dixie is the Lima field, Indiana

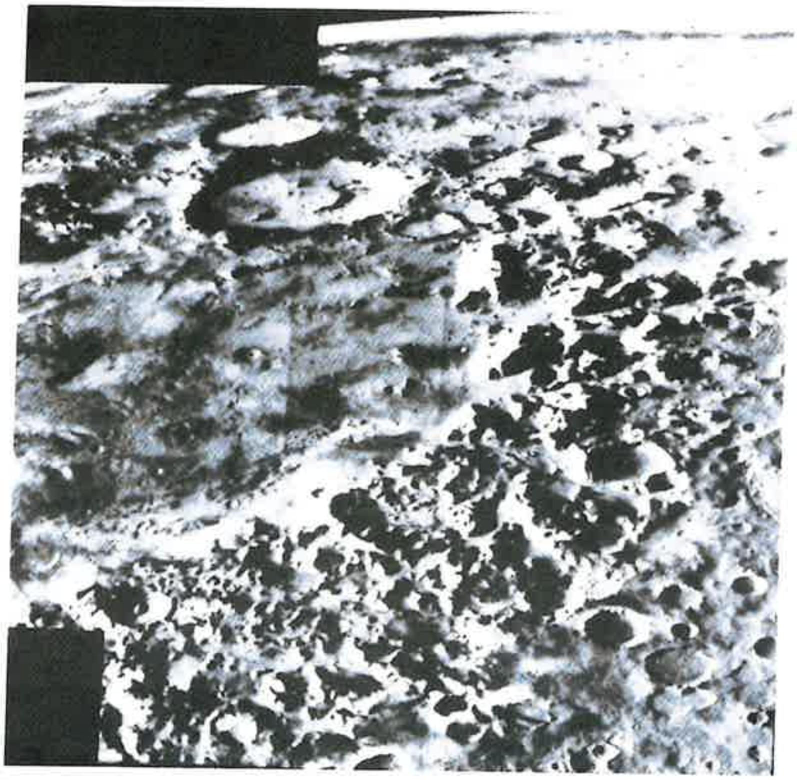

Figure 8. Oblique view of the 560-mi-diameter Argyre Basin on Mars—analogue for the Anadarko basin, Oklahoma. (Courtesy of NASA, Viking mosaic P17022.)

drilled, the drillers stopped drilling. As a consequence, >90% of all wells stop short of the Ordovician. Now data from these "shallow" wells are pointing drillers at other, deeper-target formations. Many fields in the Anadarko basin already produce from the Ordovician Viola and/or Arbuckle limestones. Most of these fields have semicircular geometry, and their production is concentrated on the upbasin side of the interpreted astrobleme. Many fields also produce from a central peak (Fig. 7).

The amount of oil and gas produced, or enhanced, by astrobleme structure in the Anadarko basin measures in the hundreds of millions of barrels. The problem is that a large number of oil fields that have been produced for decades may be producing from astrobleme-enhanced reservoirs and the operators do not even realize it. Furthermore, the complex erosional history probably sculpted the paleolandscape into a terrain like the Martian Argyre Basin (Fig. 8).

Ames, Oklahoma

Only one astrobleme-related oil field in Oklahoma has been so identified in publication: the Ames astrobleme in Major County, Oklahoma. A crater in the subsurface measuring 8 mi in diameter was first discovered during oil and gas drilling. The Ames astrobleme has two annular, concentric mountain ranges, annular valleys, and a 1,600-ft-tall central rebound peak. The high-velocity meteor impact blasted away nearly a 2,000 ft thickness of carbonate sediment in a nearshore-shelf setting; the 1,600 ft thickness of granite basement rock, 2 mi across at the center, rebounded; then the sea overran the structure and charged subsequently deposited sedimentary infill with hydrocarbons. During the summer of 1991, DLB Oil Company discovered oil above the circular rim mountain ranges, at a well called the DLB Oil #1-20 Gregory, which averaged 425 barrels of oil per day, flowing, during its first four months of production. Since then, dozens more successful producers have been added to the area, many of them as good or better than the Gregory well.

Calvin-28 Impact Crater, Cass County, Michigan

The Calvin-28 structure lies in Cass County, Michigan, in T. 7 S., R. 14 W. The village of Calvin Center lies within the annular depression surrounding the central uplift (Fig. 9). The crater is 4.5 mi in diameter, with an encircling depression and an encircling anticlinal ring. Over 100 wells have been drilled into this structure since 1982, when oil and gas were discovered in the central peak and also along the anticlinal rims. The original new field discovery and several subsequent associated oil fields have, or will ultimately, produce 600,000 barrels of oil from an average reservoir depth of 763 ft.

The age of the meteorite-impact event is thought to be Early Silurian, when the Michigan basin hosted warm shallow seas and, on the north and southern perimeters, contained hundreds of carbonate islands protecting the back-reef areas from primordial waves. The meteorite struck a shallow carbonate ramp in southwest Michigan. The massive heat generated, and the horrendous tsunamis radiated from the point of impact would have pounded any carbonate islands standing at the time, crushing many of them, destroying others.

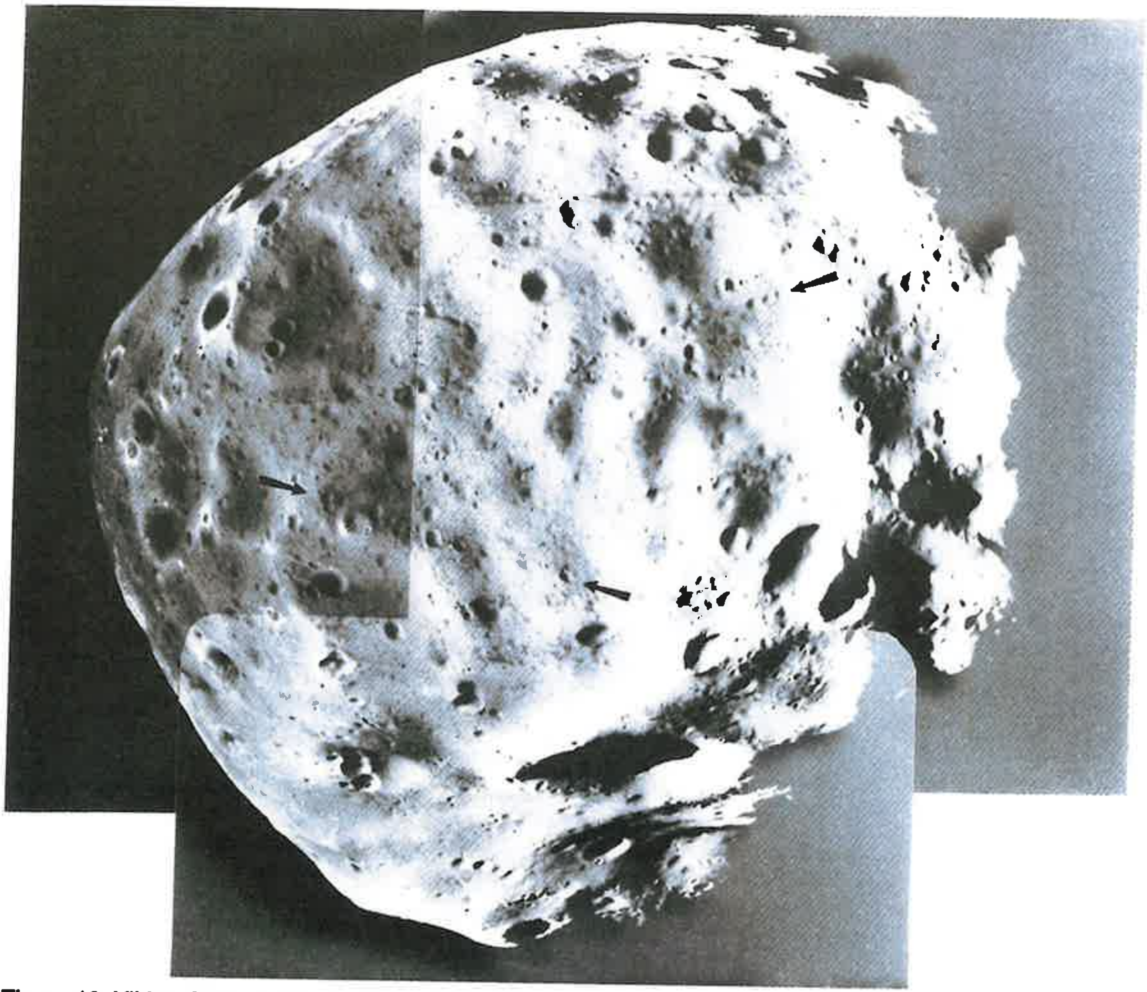

Figure 10. Viking Orbiter 300-mi-altitude flyby of Phobos, the inner satellite of Mars, showing chains of secondary-impact craters. In this image, Phobos measures approximately 13 mi × 11.8 mi. (Photograph 77-H-97, courtesy of NASA, released February 22, 1977.)

Five Cretaceous/Tertiary impact sites have been reported in recent literature. These are the Manson crater, Iowa (74 Ma); the Avak crater, Alaska (estimated to date at 65 Ma); the Marquez crater (58 Ma, Wong and others, 1997), the Chicxulub crater, Yucatan Peninsula, Mexico (65 Ma), and offshore Japan (Stein, 1993). These sites define an orbital trajectory antithetic to the Earth's equator, similar to what occurred on Jupiter in 1993–1994 (Figs. 11,12). If, over a period of 16 m.y., this orbit were to decay, craters would form beneath the orbital trajectory. Just such a case may have occurred during the Late Cretaceous—a dangerous time for any creatures of Earth that were not able to burrow safely into the ground and hide from the Armageddon.

I plotted meteorite-impact sites on a map of North America, coded the approximate ages of the impact events, and then reconfigured the continents into their relative plate-tectonic positions during various time slices. Then I constructed an impact isotime contour map that revealed a peculiar trend within the 300 Ma contour: The vast majority of the impact craters in North America (as well as those in Fennoscandia, i.e., the Siljan Ring region) lie within a northeast-trending belt. This Early Pennsylvanian meteorite belt is coincident with the Early Pennsylvanian paleoequator as determined from paleomagnetic data (Fig. 13).

Model Involving Two Moons During the Paleozoic

Starting during the Ordovician, 450 m.y. ago, and ending in the Early Pennsylvanian, 300 m.y. ago, the orbit around Earth of a large, loosely in-

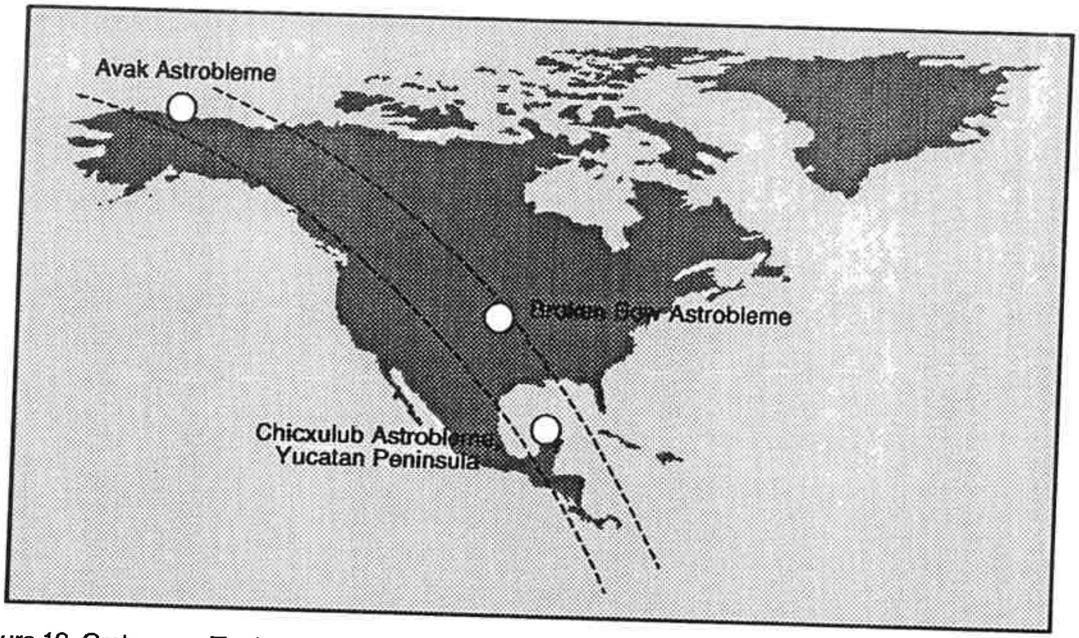

Figure 12. Cretaceous/Tertiary impact craters in North America. Random geographically? Or within a belt?

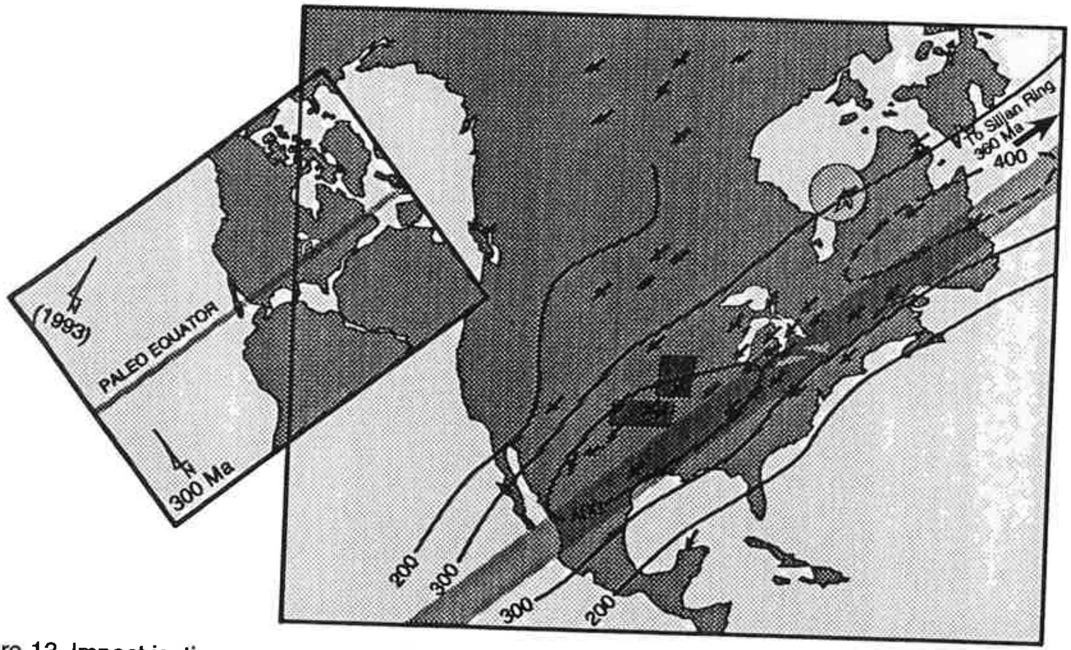

Figure 13. Impact isotime contour map of North America and plate-tectonic reconstruction at 300 Ma (left inset). Does the equatorial impact belt track the orbit of Earth's primordial second moon?

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