# GIANT METEOR IMPACT

*J. E. Enever*

The Federation Warning Post at Grimaldi perches on the rim of the crater. It was built with the five other Lunar posts, when power plays by member nations were still conceivable. Their radars have been kept abreast of discovery, and, though they have never tracked a hostile, are still the most sensitive in existence.

At this moment, Grimaldi is "out" for installation of an improved transmitter module. The Post Commander's desk is, therefore, adorned by his large boots in addition to the usual house phone and the hot radiophone link to Earth.

The house phone rings: Control console calling. The Commander reflects that Smittie must have balanced in the new circuit. We're operational again.

"Lo, Smittie, got it working?"

"Yes—but listen, Chiefie, I turned up an echo on my trial sweep. Unbelievably big . . ."

The Commander is very definitely interested. No interplanetary research fights are currently scheduled, and there can be no reason for normal traffic to wander out of the Lunar Commercial lanes into Grimaldi's sector.

"A ship, Smittie?"

"Not unless someone has built a ship with a square mile surface, Chief. It can't be anything except a big, big meteor—moving in the ecliptic, already across the moon's orbit. Even from our angle—it's something like 110° round from us—it's dopplering in like hell."

Chiefie has removed his boots from the desk and is hustling up to the control room.

Smith proves to be right. It can be nothing but a meteor;

the size is asteroidal. And, if it misses Earth at all, it will be a very close shave.

The Post Commander happens to have read the form where large meteorites are concerned. In a matter of two hours—no more—tens of billions of tons may hurtle down upon some unsuspecting metropolis; wherever the target may be, a crater some scores of miles across will be blasted out. A fireball nearly as wide as the crater will shower heat and hard radiation on the area. The district beyond the crater rim will be bombarded by a lighter scattering of debris. Earth tremors more devastating than any natural 'quake will ripple out across the continent. A Nation will be devastated, and any human within a hundred miles of the crater will be triply slain, first by X rays, next by blast, finally by incineration.

For ten seconds, Chiefie is paralyzed by sheer cold panic. Why, oh why must he, of all creatures ever born, be saddled with this load? But the Commander is made to the full measure of a man. Forewarning is his trade. If forewarning, plus modern transport, will save a single life, he will so save it.

The first step is relatively easy. The Commander lifts the hot radiophone. In two minutes he is through to the Inspector General, Federation Arm, in New York. Five minutes later every vital landline and radio channel on Earth is cleared and silent, its operator poised for action. Here, Chiefie is aided by the fact that he is following his normal chain of command, and probing past disciplined superiors who know him and trust each other.

What comes next is harder. The Grimaldi post is admirably equipped for detection and location. What it lacks is a computer which will draw a ballistic trajectory correct to the tenth decimal.

He knows where there is just such an instrument—in Traffic Control at the Copernicus City spaceport. There is now just about one hundred minutes to go before that meteor hits, or misses.

It takes Chiefie thirty-five of those minutes to establish a working link with Traffic Control. You think that is slow? Listen, brother—the speed with which Chiefie moves here is what wins him the Star of Honor in iridium instead of in gold. Did *you* ever try to operate one government department as servant of another? Gross Departures from Approved Channels and Serious Deviations from Normal Procedures are involved! The Commander has to raise Signals Superintendent at the Spaceport, and disabuse him of the idea that his leg is being pulled. He must then reach and similarly disabuse the Traffic Controller. The Computer Programmer, who just dived into a cup of coffee, has to be pulled out of it and briefed. The buck must be passed at every one of these steps. This sounds comic, but Chiefie finds small joy in the hassle. But he goes through with it, and is finally able to dictate his problem to the computer, several hundred miles away. If, my friend, you consider thirty-five minutes slow for all that, you've spent your life on Easter Island.



An hour to go. The Grimaldi radars do not compute, but they locate nearly to the thickness of the proverbial bee's wing. Smittie has been making them do just this, again, and again, and again, clocking the positions on the record with nano-second accuracy.

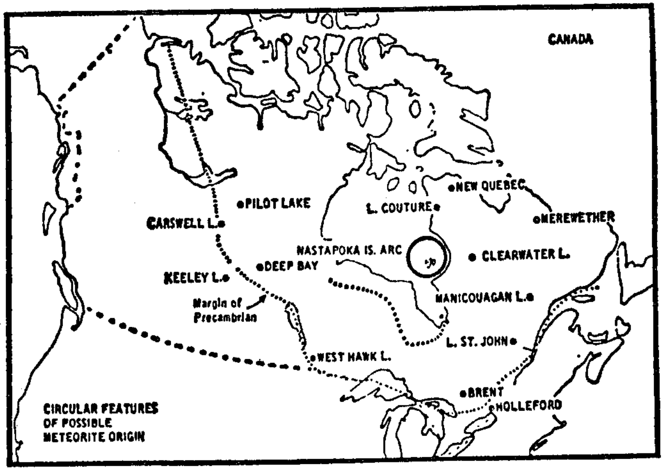
By M-minute minus 55, the Copernicus computer is defining the meteor's path with increasing accuracy, using Smittie's data.

A first solution comes through. It is real bad news. There is no doubt about it—the meteor *will* hit Earth.

By M minus 50, plots are coming in from the big lidars and radars up on Earth. They have probed for the intruder, found it, located it. Working together, the ganged instruments are fixing the course with still more precision. The best computers on Earth are now joining in a second extrapolation of the point of impact. This comes through at about M minus 40. The news is better; the new prediction is that the meteor will fall somewhere in the South Pacific.

Perhaps it is going to splash rather than thump. If you wonder why, hold out a stiffish curved wire by one end. Try to keep it rock-steady. At every imperceptible tremor of your hand, the far end of the wire sweeps through a considerable volume of space. This is how a courier capsule which deviates a skillionth of a degree at launch from Earth misses the moon by a hundred thousand miles. This is the reason for uncertainty about the meteor's precise target.

M-minute minus 30. The bolide is much closer now. Successive fixes have become more and more exact. The errors are steadily narrowing, corrections have lined out the trajectory more exactly. The meteor's position and vector are now known with all the accuracy which can be of any practical importance.




The last solution comes in. Tens of billions of tons are going to strike. They will fall at fifty kilometers per second, but will drop amost exactly midway between New Zealand and Chile —Longitude, 121° 25′ West, Latitude 42° 41′ South, plus or minus 9′ in each case.

Not a thump, but a mid-ocean splash.

Up on Earth, a man sitting in the thorniest worry seat in all history takes his index finger off the Panic Button.

The panic is over. . . .

OR IS IT?

The piece of fiction just presented is founded on the strictest fact. Earth has been repeatedly hit by very large meteorites, their speed unchecked by virtue of their enormous size. Evidence for this has been piling up for the past sixty years. Scores of able workers in other disciplines have dug hard for the data we now hold. Soon, the seeds which they are sowing will flourish as a new exact science—the study of Meteoritics. The odd point is, however, that none of these workers has yet noticed the simple fact which is crucial to the climax of my little story. The problem here is certainly



real, and is distinctly important. Something that matters has been overlooked.

I'm going to take you back to the beginning of the story. To follow its development to the present end, we are going to make a few calculations. Little more than simple arithmetic is needed for these.

That "little more" is knowledge of these easy facts:

1. That $e = \frac{1}{2} m \times v^2$. The energy of a moving body equals half its mass times the square of its velocity.
2. When the moving body is involved in a collision, the energy of movement degrades into heat. The exchange is at known rates for various materials.

The first evidence for a strike by a large meteorite was given by the Barringer brothers early this century. Here "large" means "ranging over 1,000 tons weight." The Barringers showed that the Canyon Diablo crater was formed by meteoric impact. Naturally, the demonstration met with the most pigheaded resistance from precisely those who should preserve the most open minds. Despite these people, the concept finally percolated . . . but even as late as 1930, the Barringer Crater could still provide a fresh theme for a story in the old *Amazing*.

Well over forty similar cases are now either well proven, or listed as suspect on very good grounds. Two or three more are added yearly.

Some, or all, of the following clues provide the evidence:

1. Cratering of a generally circular shape. Whatever the angle of collision, the meteorite's impact is violently explosive. Its speed, and thus the speed of the blast of superhot gases which results, vastly transcend those of chemical reactions. The power of the Barringer strike was about 2½ megatons of TNT, and it blasted a crater about 4,000 feet across.

You can model the process in miniature yourself. Spread a target of loose cement dust three inches thick on your garage floor. Shoot loose slugs of cement dust into this target from the mouth of a very small container. Getting the slugs to cohere yet hit fast will call for practice, or perhaps some ingenious contrivance. Once you get them hitting fast enough, you will produce *circular* craters in your target, whatever the angle of impact. Occasionally, material ejected from the crater will make chains of craterlets outside the crater rim, like those around the big lunar craters. Quite often you will reproduce central peaks within the craters, and, if you sprinkle a layer of limestone dust or some other distinctive powder over the target, you will now and again make replicas of the rays round the lunar craters.

2. The material of the crater floor is broken. This "breccia" grades from rock-flour at the surface to boulder-size at depth.

3. This disturbance is detectable under large craters even when all surface traces have been eroded, or covered by loess or by sedimentary rock. Gravimetric surveys show anomalously low densities beneath the crater floor.

4. Minute spherules of iron, 0.1 mm. or so across, which condense from vapors produced by the impact flare, may be distributed around the crater.

5. The unusual minerals, coesite and stishkovite, first identified near meteorite craters, are found only at these places. They are dense silicates created by the pressure of the explosion.

6. Rocks surrounding the crater are likely to be shattered in a unique fashion. Compression waves originating from the strike diffract on small irregularities within the rock. This then breaks into *shatter cones* pointing to the center of impact. This piece of evidence also outlives complete deletion of surface traces.

7. When the diameters of various types of explosion crater are graphed against their depths, the incidents group upon a quite remarkably smooth curve. This includes craters from small chemical explosions, from nuclear charges, from the terrestrial meteorite strikes, and finally the lunar craters. The curve *excludes* most volcanic craters—both the conical types, such as Vesuvius, and the Hawaiian shield craters such as Mauna Loa.

The Barringer Crater is very far from being the largest known on Earth. It could have been caused by a body weighing 10,000 tons, striking at nearly 40 kilometers per second.

The meteor which occasioned the Vredevoort Ring in South Africa was much bigger. Its volume has been estimated at a cubic mile. Blasting out the sedimentary strata, it exposed naked magma at the base of a pit scores of miles wide. At the tip of the ring, the strata were turned over to show the stratigraphic sequence in horizontal, concentric rings. The hell-pit then refilled with magma from the depths.



Larger events still have been claimed. For example, Hudson's Bay and the Japan and Weddell seas have been said to have originated in the same way. Mr. Rene Gallant, puts forward strikes by Junoesque bodies, at energies totaling more than $10^{33}$ ergs. This, by the way, is a quarter of the Sun's entire output of energy for an entire second! It equals the *complete* conversion to energy of a million tons of matter or the explosion of a hundred thousand million million tons—yes, seventeen zeros after the figure one—of TNT.

Very circumstantial proof should be given before these are accepted. If as little as one per cent of the energy of such an impact transferred as heat to the world's atmosphere, the air temperature everywhere would rise by about 200°C. My calculation here is approximate, since it ignores the work which the heat would do in expanding the atmosphere; but my one per cent heat allowance is obviously niggardly. Strikes by major asteroids seem to be the instant recipe for pasteurized planet. They also violate the law of parsimony. Nonetheless, you must notice that even the Vredevoort event yielded *more than a million megatons of TNT*.

It is calculated that meteorites as heavy as 1,000 tons and

**TEN CANADIAN CRATERS**

*(Not all of these are situated on the Shield)*

| Name | Diameter of circular feature as seen now | Estimated diameter of the original rim of crater | *Upper* limit of age of strike |
|---|---|---|---|
| HOLLEFORD | 2.35 km | 2.35 km | 5 megacenturies |
| NEW QUEBEC | 3.7 km | 3.7 km | 1-2 megayears |
| BRENT | 3.0 km | 3.7 km | 5 megacenturies |
| WEST HAWK | 3.3 km | 3.9 km | 5½ megacenturies |
| DEEP BAY | 10 | 10.5 km | 2½ megacenturies |
| LAC COUTURE | 14 km | 10 km | 6 megacenturies |
| CLEARWATER EAST | 21 km | 18 km | 4 megacenturies (Twin strike) |
| CLEARWATER WEST | 32 km | 32 km | 4 megacenturies |
| CARSWELL LAKE | 32 km | 30 km | 5 megacenturies |
| MANICOUAGAN | 60 km | 65 km | 3 megacenturies |

*After M. R. Dence, Dominion Observatory, Ottawa* up are all but unchecked by the atmosphere. They strike the ground with nearly all their original speed. This ranges from about 20 kilometers per second to just over 70 k.p.s. The higher figure is the maximum which any member of the solar system can attain at the Earth's distance from the sun. The limit for a body which moves in from the galaxy with some speed to begin with is clearly much higher. A few small meteors have, in fact, been tracked by radar at over 150 k.p.s.

As the meteorite dives to the surface, there will be a formidable pressure wave. At Mach numbers 60 to 200 the sonic boom will be awesome. But it will not only be short-lived; it will be dwarfed by the blast arising from the surface impact. The relatively small Siberian shower of 1908 flattened the conifers of the Taiga to a range of 30 miles.

There are many other effects:

(a) Heat. In a large strike, the instant flare of the impact is reckoned to convert more than a quarter of the total energy into prompt heat. You should notice that in the end almost *all* the energy will degrade into heat. There is an exception, see (e) below; and for some effects, the degradation will take a considerable time.

A feature of large strikes such as Vredevoort is that the fireball must be enormous. Think of it as that from a 250,000 megaton fusion bomb. It will probably not reach the diameter of 200 miles given by a cube-root-of-power comparison with an "ordinary" Hydrogen bomb. But its measurements will *certainly* exceed the total depth of the atmosphere and stratosphere together. As a result of this, the fireball will squat upon the target area, doming up into the ionosphere, but unable to rise. It will radiate terrific energy into space. Even when the fireball has at last cooled out, the target will glow for weeks and months—again radiating a good deal of energy into space.

(b) Severe earthquakes will damage the crust.

(c) Material will be ejected beyond the crater's periphery. This will range from large crustal blocks down to microscopic powder; some of this material will travel a long way.

(d) Volatilized matter and even plasma will be thrown out to space at escape speed. Here, see Ralph Hall's fact article, "Secondary Meteorites," January and February issues, 1964.

(e) There will be some exchange of impetus between the meteorite and the spinning Earth. Substantially, this would be confined to alteration of the Earth's axial tilt and rotation period. Even an impact by Juno would affect the orbital speed by only a few centimeters per second. The reference here is to Rene Gallant's book, "Bombarded Earth," published in London by Baker.



Not merely are staggering energies released. The explosion has high "brisance," is shatteringly intense. Tremendous temperatures combine with tremendous pressures. Ralph Hall explained that nuclear reactions will occur at the heart of the flare. These, I think, may just as well *absorb* energy as release it, but either way, there will certainly be a flood of X rays and neutrons. I suspect that these might leave faint but discernible traces in the surrounding rocks.

So far, my discussion has followed precedent. I have considered a *continental* strike—one which hits a land target area. What has so far been overlooked is that three-quarters of the Earth's surface is *ocean.*

*The odds are, therefore, three to one in favor of an ocean strike.* For the 40+ known land craters, there must have been 120+ strikes at sea. It is *certain* that some of these marine falls equaled or exceeded the power of the Vredevoort impact. But the count does not end here.

For a start, the large majority of explored craters are in North America, just three per cent of the World's surface. There are several reasons for this: one is the comparative failure of attention to the subject elsewhere. Another is the Canadian Shield—the widest area anywhere of bare, primeval rock, where the craters of gigayears are easy to find. In any case, we must obviously multiply the number of known falls not by a factor of three, but by thirty. Hold the total down to a probable 1,000 falls in all—750 of them were at sea. There have been a sizable number of Vredevoorts in the ocean.

Your first thought will be that an ocean strike is just a damped-off edition of a fall on land. Not on your life! It's distinctly different, *and* distinctly more lethal!

Unfortunately, craters in water have a way of filling up and leaving no evidence on the surface, whatever happens to the ocean bed. We'll just have to manufacture a model by mental experiment; see where a few calculations from known facts will take us. Gauss was too lazy to reach out his arm for his log tables; to save himself trouble, he memorized the lot. We'll do the opposite and construct an asteroid whose vital statistics will make the figuring easy. Just a baby one. As we build it, we'll take a good look at it, for it won't have long to live. On then, to Vredevoort Mark II.

Four cubic kilometers will do for the size. This is just under one cubic mile: about 0.96 cubic miles to be more precise. Weight will be of the essence, so density will count. We will carve our experimental meteorite from a core fragment of planet Number Five. Pure iron, but for a trace of heavier metal which increases the density to the convenient value of eight times water. Every cubic centimeter of asteroid will weigh eight grams. I am encouraged in adopting this composition by Dr. Robert Dietz. He claims that the Sudbury nickel deposits are remnants of a slow nickel iron meteorite, which was also the origin of local deposits of heavy metals.

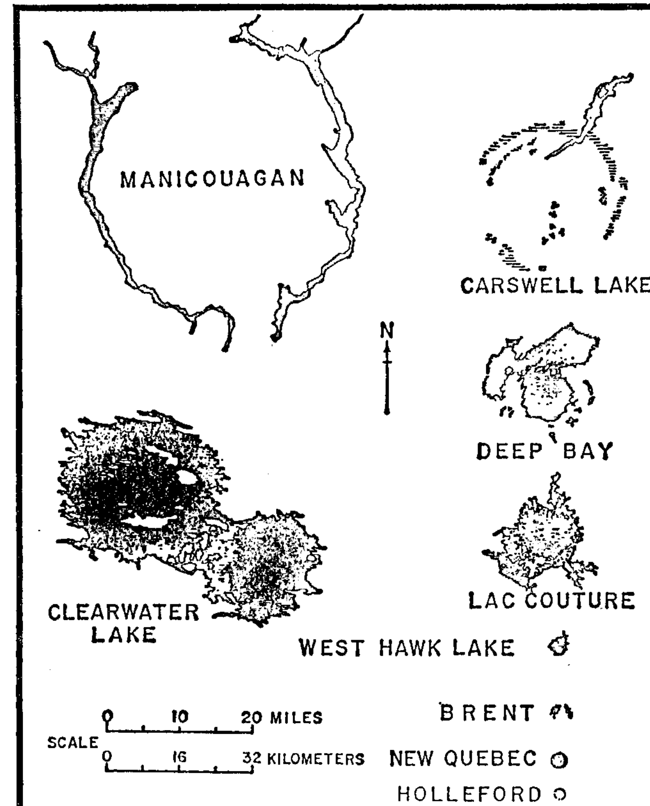
The shape is immaterial. Asteroids of this size are under no compulsion to be spherical, and the distribution of mass will not alter the impact energy. All the same, we'll take a good look at baby.

As carved out with tractor beams and superlasers the finished artifact is definitely a pill: a drum-shaped disk averaging a kilometer in thickness and three kilometers in diameter. The surface glints blackly evil, faceted and knobbly. Matching velocity to push it on course, we see that is spinning slowly. That notch on the rim will sight on Rigel in a few moments. We'll time the spin. Start the stop-clock now . . . 200 seconds.

Eighteen revs per hour. That's not very fast; the rim is only traveling at 100 m.p.h. But wrap that much rotation round a mass of tens of billions of tons, and you finish with quite a packet of angular momentum. Let's take a momentometer reading . . . the energy of spin comes out at $10^{23}$ ergs. Why, that equals about 2½ megatons of TNT! If any meteor scavenger thinks of looting this lump, he must first kill that rotation. He could do the job with his surplus Government H1 rocket engine, blasting for a month with about two million tons of propellant. It's hardly an economic proposition.

In fact, any landing whatsoever would be distinctly hazardous. At the rim, centrifugal acceleration is about a tenth Earth "G". At the pole, you might get away with a space-






suit landing; but even there, you must anchor a tether before going down. An electromagnet should hold, but as a confirmed belt-and-gallus man I would reinforce it with a gob of the latest plastic goo. The polar gravitation, little more than a quarter mile away from the center of gravity, is somewhat higher than one might guess. About one twelve-hundredth Earth normal. Fumble a tool as you draw it from your belt and it will only take a quarter minute to fall to the surface. Horrendous crash as spanner hits asteroid at five inches per second.

Speaking cosmically, Vredevoort II is a dust mote, but for all that we have mass with a capital M. Specific gravity 8, volume 4 cubic kilometers. The mass works out at $8 \times 4 \times (100{,}000)^3$ grams. $3.2 \times 10^{16}$ grams. Over 35 thousand million tons.

It sounds, and is, a considerable hunk of matter, but Hermes, Eros, Icarus, all asteroids penetrating the inner Solar System as they orbit, are all distinctly larger.

We will steer the 35 billion ton missile into mid-ocean at 50 kilometers per second. Our observation eyrie will have to be well out and well to the side. There is no foretelling the speed and coherence at which the jet of plasma will gush up from the impact flare. Three or four thousand miles *may* be safety distance.

At the end of the countdown, a tremendous glare of sheer violet radiance—a color few have witnessed outside the high energy labs—lights the ocean for four hundred miles round the target, throwing the tiny clouds into vivid relief. It lasts only the space of two heartbeats, leaving us dazzled, far away as we are. That is not the impact—that is incandescent air! Air so compressed when Vredevoort II rushes through it on the last lap to the ground as to glow in the violet, and beyond. Luckily, we are not placed to hear the sonic boom which accompanies the glow; at closer range the sound is such as to pulverize bone and homogenize living tissue.

Before our eyes recover, there is another, more brilliant flare of violet. The plasma-bolt is rocketing up into space. Even at this range, it flames too brightly to be watched, brighter and hotter by far than the surface of the sun. Here is a concentration of naked energy verging into the nuclear range. We are seeing it by the lower frequencies; most of the radiation is beyond the visible spectrum. Before it disperses and cools, the jet of stripped atoms travels so fast and climbs so high, that it seems to stand upon the ocean hundreds of miles tall—an incandescent column, rainbow tipped and haloed. This is perhaps the illusion of persistence of vision, but its glare lights the entire ocean from continent to continent.

Below it, the fireball is expanding. First it is a blue-hot pinprick, then a dazzling sun-white speck, of perceptible breadth even before the plasma bolt has cooled to invisibility. It grows as a roiling, incandescent chaos, which even the eye of the imagination finds difficult to penetrate. In its lurid glare, we see a faint ripple expanding across the cloudscape. From our distance, it moves at a seeming snail's pace, though its real speed is little short of Mach 1.



Our mental experiment will take us little further; only calculation will clarify the processes which follow the flare.

Since $e = \frac{1}{2}mv^2$, every gram of the meteorite's mass will carry: $\frac{1}{2} \times 1 \times (5 \times 10^6)^2$ ergs. This works out to $1.25 \times 10^{13}$ ergs per gram. Now multiply this by the total weight, $3.2 \times 10^{16}$ grams. The total energy comes to $4 \times 10^{29}$ ergs. This is very nearly *ten teratons, or ten million megatons of TNT.* (A megaton of TNT yields "only" $4.2 \times 10^{22}$ ergs.) For comparison, the largest earthquakes which have been measured since Milne invented the seismograph developed less than $10^{27}$ ergs; this power was spread over very great volumes of the Earth's crust and mantle.

We could express the energy as heat. A calorie is the heat needed to raise the temperature of a gram of water by 1° C. It equals 42 million ergs. So our experimental strike is going to produce $10^{22}$ calories. There is power enough, and to spare. What other effects follow those violet flares?

To begin with, the enormous heat of the impact will not only vaporize the mile or two depth of ocean at the bull's eye, it will also vaporize the crystal rocks below, clear through the Moho, and blow out the surrounding rocks as well. Beyond the area where the mantle is laid bare, rifts will expose hot magma.

The crater is as wide as Vredevoort in South Africa. Though more power is absorbed in producing plasma at the kernel of the event than in a land strike—fearful energy is needed to convert water into a plasma of hydrogen and oxygen nuclei—water *is* less dense than rock. Despite its incompressibility and high latent heat of evaporation, it is easier to shift en masse than rock. So although the seabed crater is somewhat shallower than that on land, it is just as broad. A blazing wound scores of miles wide scars the sea floor.

A ringed waterfall as high as the Alleghenies rushes in to quench it, its circumference that of a county boundary. The fiery furnace opened by this strike will *not* glow for weeks and months as it would on land; the torrents of ocean rush in, and change at once to pure steam. They stream up in a thin-walled sleeve which is as clear as air, as invisible as the gush of superheated vapor which flays the flesh from men's bones in a boiler-room catastrophe.

Here, the glass-clear gaseous water is sweeping up in volume enough to cloud a planet's atmosphere. The naked wound on the seabed glows white-hot through the wall of the frightful cylinder which encloses it. But inch by inch and foot by foot the waters sweeping in win. The column of steam still rushes up to the ionosphere, still spreads out across the heavens, but it steadily contracts. Beyond the rim of the inferno, crustal rifts are already exuding sills of lava across the ocean floor. Convulsions and seisms mount in cataclysmic fury surpassing the power of any natural quake.

All the waters of the oceans are set in oscillation. A mere volcanic eruption in the 1880s achieved this. Gigantic blast waves are ripping out far away from the crater. Dwindling in strength, they will circle the planet half a dozen times or more before they become indetectable. The turning world itself has quivered as it spins. Transfer of momentum will be small in a strike of this power. I'll neglect it.

The exact division of these different energies may not be clear. It will also fail to be of great influence on my argument. First let us consider certain thermal effects of the strike.

Remember that the meteorite delivers about $3\times10^5$ calories per gram: just under $10^{22}$ calories in all.

I take it that energy dissipated in deep Earth tremors, splashed back to space by the plasma jet, or radiated back to space from the impact flare and the fireball, is compensated by the heat gained from the magma bared by crustal damage.

The energy absorbed in massive displacement of ocean water, in tidal waves, in blast, and in local damage to the seabed, will in the end degrade to heat. This will occur soon enough for the heat to give direct backing to the impact flare; it will work immediately behind the flare in evaporating the ocean. The continuity here is, as it were, measured on a *climatic* time scale. The watch dial is calibrated in hours and days, not the split seconds appropriate to the impact.

This being so, every unit weight of the meteorite will cause the evaporation of about 600 units weight of the ocean. It takes about 600 calories to evaporate a gram of water, on average. Not merely to raise it to boiling point, but to turn the whole gram into vapor. You need over five times more heat



to free the molecules from the forces which bind them together in the liquid state than to raise ice to the boiling point. But the evaporation can take place *without* raising the water's temperature at all; as when the ocean turns into rain clouds. My figure of 600 calories averages the heat transfer in the two cases, both of which will occur in our meteorite incident. The calculation runs like this: $3\times10^5$ calories heat available per gram of meteorite$\div$600 calories to evaporate one gram of water$=$500 grams of water evaporated.

But every cubic centimeter of our meteorite weighs as much as eight cubic centimeters of water. This means that 4,000 *volumes* of water will be evaporated by each unit volume of meteorite. *The four cubic kilometer volume of Vredevoort Mark II will evaporate 16,000 cubic kilometers of ocean.* This is about 3,800 cubic miles!

You will obviously refuse to believe these figures, so let's check the calculations by another route. The total heat equivalent of the strike energy is $10^{22}$ calories. Dividing this by 600 calories per cubic centimeter evaporated, we get $1.6\times10^{19}$ cc.—16,000 cubic kilometers again. Now normal evaporation from all the oceans of the Earth by the sun's heat is just *under* a cubic kilometer per minute—rather less than a billion metric tons; sixty cubic kilometers per hour.

The meteorite equals the sun's work as a cloud maker for $16{,}000\div60=266$ hours, just over eleven days. This is just enough to provide an average rainfall of over one and a quarter inches upon the whole Earth, oceans and land together.

By itself, this would be a foul enough stormfall. Of course, in the nature of things, the rainfall would be anything but evenly distributed. You can make your own guesses at where the peak precipitations would occur and what their value would be. But the matter would be very far from closed by a single deluge of rain spreading across the planet.

When water vapor turns into rain, all those calories which were used in evaporating it are released to go to work elsewhere. This is the energy cycle which keeps a hurricane spinning; this is the force which lifts the cu-nim thunderhead higher than Everest. *For a while* the latent heat of evaporation is employed in moving air—wind-making.

Choose your own velocities for the winds generated by meteorite rainstorms. But don't imagine they will be gentle zephyrs. They will be very fierce and will rage across the world.

However, even this is not the crucial point in this question of release of latent heat. The crux is this: though the heat of the strike will in the end radiate back to space, radiation under constant cloud cover at biological temperatures is a fairly slow business. The following cycle will continue for some time before all the excess heat leaks off the Earth:

Heat absorbed by evaporation
Condensation
Release of latent heat for further evaporation
Long range weather forecast: Very wet, very windy, very cloudy. Period of forecast indefinite.

As if this were insufficient, another factor comes into play to reinforce the overall effect of the heat cycle: let me explain it.

In the year 1883, the volcano Krakatoa blew its top. I will refer again to this event in another connection, to make another standard comparison.

"Blew its top" is an all too literal statement. The detonation pulverized several cubic miles of the volcanic cone. Where this originally peaked at a 3,000 foot summit, the ocean now rolls over part of the base. The explosion was a mere volcanic incident—two or three megatons of TNT would do as much; the energy released was only $7 \times 10^{22}$ ergs.

A respectable proportion of the rock was shattered so finely that it hung twenty miles high in the stratosphere throughout the following decade. Doubtless some of it is still there.

There were noticeable effects. For the next ten years, sunsets and dawns were gaudier than usual the whole world over. It is said that over the same period, worldwide temperatures were very slightly lower than average.

Our model strike carries nearly six million times the energy released by Krakatoa.

The amount of solids thrown up by the meteorite will not be in the same ratio. They may, in fact, only be five or six thousand times as much as the pulverized volcanic cone. At first sight, the ratio of solids displaced may be thought to settle the amount of dust which is raised. This, however, is not the case. What will count is the minuteness with which the material is divided. A ridiculously small quantity of finely divided titanium oxide set free from naval smoke-floats will screen a naval task force from view.



Here the very high brisance of the meteorite explosion comes into play. Even a Barringer-size strike leaves rock-flour on the crater floor. Much of what is blasted out must be finer still. (Did you see the picture of the cloud of lunar dust raised by Lunik V?)

The fact that the strike is on the seabed will make little difference. Superheated steam blasts just as forcibly as other explosion gases. The steam jet cutting up to the ionosphere will scavenge all powder from the crater, and a great deal of ooze on the ocean bed miles from the crater will go up with it. Clearance will be more effective than in the case of the land-strike. Salt will be carried up by the steam jet, and will float as fine crystals on high. These will be joined by salt crystals which are residue of the sea water splashed across the heavens in bulk. There will also be a large contribution from microscopic particles of rock and metal which sublime from volatilized material. Even on the very moderate assumption that, erg for erg, Vredevoort II lifts only one per cent of the microscopic particles raised by Krakatoa, it will still throw up sixty thousand times as much fine powder.

Let's hack out an answer: Take a conservative ration of 100 cubic kilometers of rock powder, sublimed micro-droplets salt, and seabed ooze. Choose particles only a micron in size, or grind them down to size by blast or steam jet. Use multi-megaton blasts and steam jets and winds of tornado strength to scatter them across the stratosphere. The resultant haze teams up 200 particles thick over the entire surface. Every electron on the ground has 200 particles directly overhead. The aggregate thickness of the screen will only be a fifth of a millimeter: but did *you* ever read fine print through even one hundredth of an inch of granite?

*As a result of the impact a persistent and effective dust cloud will veil the stratosphere. It will float there for a period in no wise shorter than the decade after Krakatoa. The Earth's albedo will be effectively increased. A perceptible decrease in the solar heat reaching the surface for at least ten* *years seems to be certain.* Still speaking very literally, Vredevoort II puts Krakatoa in the shade.

The world's weather is quite delicately balanced on the solar constant, the value of solar radiation received at the surface in clear weather. This has changed in the past. There are graphs which match the Ice Age datings of the past megayear against the cumulative effect of such astronomical changes as rotation of the axes of the Earth's orbit, precession, and so on. The resultant changes in the solar constant calculated from these effects are small; but the two graphs match with broad fidelity. Small factors, then, affect the polar ice caps and other similar matters. Our dust-veil is going to keep the Earth colder for about ten years. This is certainly time enough for the polar ice caps to grow. Even when cloud-cover has long since dispersed and the dust-shroud has settled, this growth in the polar ice will leave the planetary albedo seriously increased; more of the sun's heat will be reflected back to space.

A long, long planetary cold spell is safely predictable, despite any comparisons which are made with the cloud-cover, dust-cover, or heaven-knows-what-cover shrouding Venus. (In passing, it seems that all was not well with the estimates of surface temperature made when Mariner flew by Venus. Oh well, sailors who make brief passes at the ladies often receive equivocal replies . . .)

At first sight, the mechanical effects of the strike may seem to concern the globigerina ooze and the fish which provide an involuntary bouillabaisse. Marine quakes and seisms would not appear to concern life on land. This view neglects the matter of Tsunamis.

Commonly miscalled a tidal wave, the tsunami is normally caused by a tremor in the ocean bed: a rise or settlement of a few inches, or a jerk along a fault of a few yards or so —the type of thing which causes an earthquake on land. But on one occasion at least, the tsunami has resulted from a volcanic detonation. Right first time—Krakatoa!

Whatever the cause, an oscillation of the ocean is generated. There is no mass transference of water. Characteristically, the vibration is of low amplitude but very long wavelength. The speed of waves at sea is determined by the wavelength which in its turn is affected by the depth of the ocean. Because of its very long wavelength, the tsunami moves very fast indeed. The low amplitude may make it imperceptible when it races past a mid-ocean vessel at four hundred fifty miles per hour. This does not prevent it from raising the purest kind of hell where it breaks on shore. Here it builds into a devastating breaker which may reach miles inland. Ocean-going vessels have been stranded miles from the beach. The Krakatoa tidal wave broke upon Indonesian coasts in rollers which reached heights well over a hundred feet. It was *visible* as far off as the Cape of Good Hope. It was clearly *detectable* in the English Channel. It was still just detectable after circling the world again.



The $4 \times 10^{29}$ erg punch delivered by Vredevoort II is expected to create quite a ripple. Mass displacement of the water, submarine quakes, and the pressure wave through the ocean will all contribute to the tsunami. The energy which it temporarily absorbs before restoring it as heat is conjectural. A reasonable allotment would be about one-sixth of the total power account sheet.

This will give it a force of $7 \times 10^{28}$ ergs, two orders of magnitude more powerful than the largest recorded earthquakes. As already mentioned, these were continental. They spread their effects through millions of cubic miles of crust and mantle. We just do not know what tsunamis they would have raised had they been shallow disturbances under the mid-ocean.

But we *do* know what the millionfold-weaker occurrence at Krakatoa achieved. Quite obviously, the volcano did not exert its total strength in raising the tidal wave. Even if we credit the tsunami with all the $7 \times 10^{22}$ ergs of the detonation, the meteorite tidal wave is a full millionfold stronger.

The tidal wave is a very efficient vehicle for transferring energy over long ranges. Frictional losses are fairly low, right up to the point where it climbs ashore to wreck the landscape. One sees it as an *area* rather than a *volume* phenomenon; roughly speaking, the third dimension is constant.

Let us, however, credit it with a decrement of distance cubed. This is conservative, being more appropriate to volume effects, like dynamite blasts in air. This decrement will make the meteoric tsunamis work at ranges the cube root of a million times those of the volcano: that is, at one hundred times the distance of the Krakatoa tidal wave. This gives it a global range in causing disaster. It will break at heights measured not in yards but in block-lengths on any shores in the middle distance, five hundred to one thousand miles away. Even at its antipodes it will wreak havoc comparable with that worked by Krakatoa at about one hundred miles range. Coastal belts all over the world—a sizable total area—will be in peril.

If the meteorite should fall within a confined ocean basin such as the Arctic, damage will recur. Before coming to rest, such a body of water will oscillate in a series of "seiches." The effect here depends on the natural frequency of the particular body of water. The series of waves would diminish in frequency—but the first few returns could all be catastrophic!

We had best abort the Vredevoort II mission while there is still time. Disintegrate that asteroid, Cadet Kinnison!

The ocean strike is clearly very different from the continental fall. The most vital distinction is this: the energy of the land strike is more violently localized and hence its destructive power is more carelessly squandered. On land, the enormous sessile fireball clings to the target surface, unable to rise because it runs out of atmosphere to rise in, even before it is fully expanded. Early in its career it is forced to spread out over the adjacent "craterscape," exposing a majority of its surface to space. So most of the heat radiates away from earth. A significant proportion of the total energy leaves the planet in this way. When the fireball has starved itself to extinction, the incandescent crater takes its turn in wasting energy in the same way over the weeks to come.

The marine fall works in a more efficient, synergic, cumulative manner. From the beginning its energy works with cruel economy. The radiation of the fireball is quenched and veiled and husbanded by steam and storm-wrack. Its heat is conveyed far and wide by the monstrous steam geyser. This also quenches and transfers the power of the ocean-floor inferno, and thus retains it on Earth. Rain follows rain, tidal waves recur, typhoons sweep again and again over a sunless world. In the districts swept by the tsunamis, the storms destroy the last chances of survival for all that grows or moves. The strike's power is transformed down to biological intensities, directed where it will harm the biosphere. When the hell-pit on the seabed is doused, and when, weeks later, the storms have died, dust and cloud veil the Earth. The long Fimbul winter begins.



My picture is unexaggerated. We consider the release of energies equal to the detonation of one megaton bombs pitched down at five-mile intervals over the entire surface of the world. True, even the ocean strike will distribute its energy less evenly than this. It is, however, precisely my case that it will come nearer to so doing than the continental impact. Most of the power of this operates to overkill an already blasted region, a district the size of a nation, but still a limited area.

Above all, remember that what I have depicted *has occurred many times*. The craters of the Canadian Shield are probably a more reliable guide to the number and timing of the past incidents than are those of North America as a whole. The Canadian Shield is a record sheet in stone; it has been ground clean, to receive the indelible and plainly legible account of more than two gigayears of meteoric history. It is about a million square miles in area, roughly one half of one per cent of the world's surface. There are craters of moderate size and upward scattered across it. One of these, Manicouagan, is in the Vredevoort size range. I leave out the larger Nastapoka Island Arc, well over one hundred miles in diameter, as well as Hudson's Bay itself. Five of these incidents seem to have occurred in the last five megacenturies, the post-Cambrian era; this is one every hundred million years on average. Multiply this by the ratio of size between the Shield area and the whole world; we then obtain the figure of two fair-sized strikes per megayear somewhere or other upon Earth. Events of Vredevoort strength will be distinctly more rare—perhaps one every five megayears—but the majority of these will happen at sea. When is the next due? Equally to the point, when did the last occur?

Here we owe a pertinent question to Mr. J. W. Campbell. It is my recollection that some years ago he posed the enigma of the Mammoths, whose frozen carcasses house undigested stomach contents. This is very puzzling indeed. The carcasses of Blue Whales are sometimes left unflensed in the cold Antarctic Ocean for just a few hours too long. When this delay occurs, the Whale's flesh is quite literally roasted within the insulating blubber by the heat of its own putrefaction.

Some whaling men acquire a taste for the gamey dish. For a distinctly smaller beast such as a Mammoth, the effect would be retarded by the operation of square/cube law. But it should still have its parallel. The well insulated stomach contents should so ferment as to become unrecognizable.

Yet Mammoth carcasses are found in both Siberia and Alaska—lying in frozen jumbles of muck and tree trunks in the permafrost—their stomach contents undigested and unfermented. I am told that on one stretch of the Alaska Highway the bulldozer drivers who cut the roadbed were forced to work in gas masks. They turned up so many carcasses of various beasties, that when these were exposed to normal day temperatures the whole area stank like an uncleared battlefield.

The situation presents other puzzles. Trees simply cannot grow in the permafrost. The vegetation with which the bodies are mixed belongs to zones several hundred miles nearer the Equator.

Nor have I ever been prepossessed with the notion that the Mammoth wore hair to keep warm. Present surviving representatives of its family run their metabolisms at only three per cent the rate of smaller Mammals. Their idea here is to avoid an unseemly, messy end in an explosion of metabolic steam. Square/cube law again. Had the Mammoth needed to keep warm, there would have been no need to evolve a coat of hair: a slight lift to the thermostat setting would suffice. Come to it, how does a beast the size of an elephant find enough browse on the tundra? Would even the Taiga sustain him? Do we know any animal bigger than a rodent which grazes pine needles? Picture the tundral Mammoth, which, having picked its daily half ton of whortleberries one by one, goes on to gather a bed of moss. He must have this if he is not to sink through the ooze to the permafrost and wake up with rheumatism.

The fact is that I will be unsurprised to learn that there *was* a calamitous change in climate that "coincided" with a catastrophe which "just happened" to arrive at the time of the demise of the Mammoths.

Our old friend Sprague de Camp has expressed great skepticism on this point. When Cosmic Catastrophe and Calamity is mooted as an easy answer to an enigma, I, too,



am skeptical. Like the Missourian, I want the evidence in my hand to clinch the proof.

An ocean meteorite strike *could* be the explanation here. Two of them if you like. Asteroids sometimes "twin"; the Clearwater Lakes in Canada, one thirty and the other twenty kilometers across, resulted from a double strike. The question is not whether it *could* have been the cause but whether it *was*.

Answers to the following questions could resolve the matter:

1. What is the altitude above sea level and the proximity to the sea or otherwise of known finds of Mammoth carcasses? *Carcasses* if you please. Dry bones will be irrelevant. We know that the prototype carcass was found *at the mouth* of the River Lena in Siberia, on the shores of the Arctic Ocean.

2. *Precisely* what vegetation and what its habitat is found within the corpuses delicti? Exactly what kinds of trees were jumbled with them in the permafrost, and what type of force is required to shear or uproot such trees like jackstraws?

3. Deep borings have been made in the ice caps of the Antarctic and Greenland. Have any surprises yet been provided by the counts and analyses of particles in any limited section of the drilled cores? What should be sought here is this: concentrations of rock dust and of spherules of sublimed rock and iron. These may total a depth of only a hundredth of an inch, perhaps a little less, in a core representing a decade's accumulation of ice. The iron particles would, of course, be magnetically separable from the ice-melt. The contaminated lengths as a whole might be separable from the column of cores on a conveyor belt basis, by optical methods.

4. There are known to be circularities on otherwise level and featureless ocean floors. What are the profiles of these, and can their ages be assessed?

5. Are there any widespread anomalies in the stratigraphical record of large coastal belts which are inexplicable by normal erosive and isostatic process?

You may well add questions to the list above. Significant contributions will foster the baby science of meteoritics.