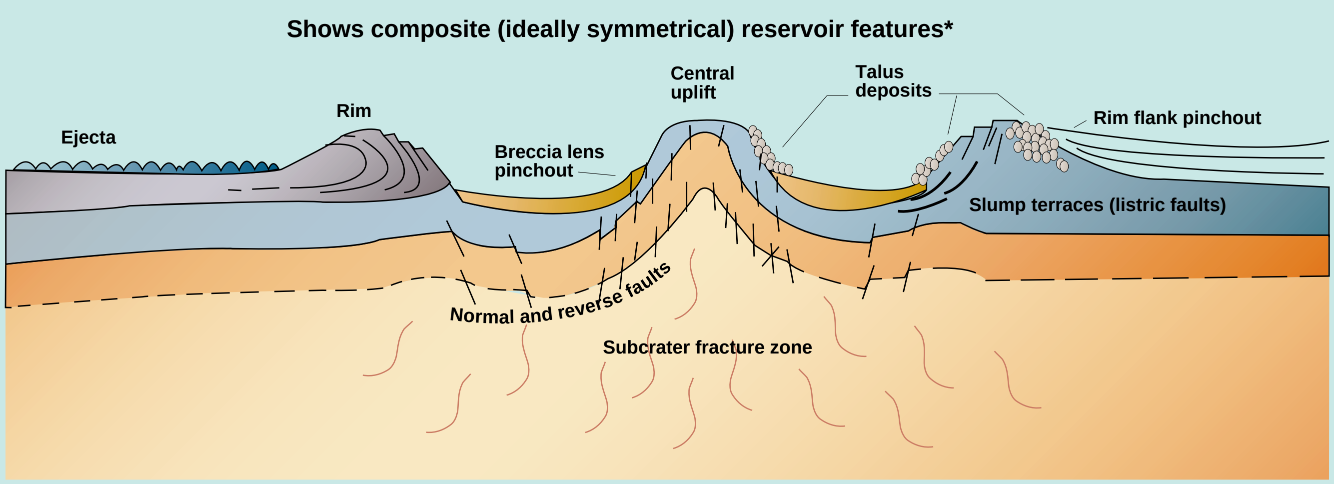
Fig. 1

CROSS-SECTION OF COMPLEX-TYPE METEORITE-IMPACT STRUCTURE



*Radial faults not included.
Source: Modified from Donofrio, 1981, and Brenan and others, 1975.

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North American impact structures hold giant field potential

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Seventeen confirmed impact structures occur in petroliferous areas of North America, nine of which are being exploited for commercial hydrocarbons. Production comes from impact-affected granites, carbonate rocks, and sandstones yielding from 30 b/d to over 2 million b/d of oil plus over 1.4 bcfd of gas. Reservoirs are found in central uplifts, rims, slump terraces, and ejecta and probably in subcrater fracture zones. Disrupted rocks in proximity to impact structures, such as Chicxulub in the Gulf of Mexico off Yucatan, also contain hydrocarbon deposits. In some cases hydrothermal activity attending impact events can diminish reservoir quality, and talus deposits resulting from erosion of the central uplift and rim afford alternative drilling targets. The drilling success rates for new field wildcats and total wells into confirmed astroblemes are about 21% and 77%, respectively. These figures approximate the industry's overall success rates for wells drilled during the past 5 years. Roughly 50% of confirmed astroblemes and astrobleme anomalies in petroleum provinces are commercial oil and gas fields.

Outstanding statistics include a 7,200 b/d drillstem test in the Ames impact structure, a 4.3 bcfd calculated absolute open flow potential test at the Sierra Madera astrobleme, and a well having a 2,850 ft oil column (1,600 ft of net pay) in the Red Wing Creek impact structure. Reserves are also impressive, ranging from 3 million bbl of oil at Steen River to 30 billion bbl of oil and 15 tcf of gas associated with Chicxulub. The current estimated gross income of oil and gas production from confirmed impact events in North America is $16 billion/year. To determine the hypothetical hydrocarbon potential from undiscovered or unrecognized astroblemes in U.S. petroleum basins, the exercise of overlaying the distribution pattern of Canadian Shield astroblemes onto the lower 48 states was performed. The results suggest, intuitively at least, the presence in basement rocks of impact structures with potential reserves ranging from 5 billion bbl to over 105 billion bbl.

This is modified from one of 41 full papers, expanded abstracts, and posters published in Oklahoma Geological Survey Circular 100, Ames Structure in Northwest Oklahoma and Similar Features: Origin and Petroleum Production (1995 Symposium), updated through 1997.

Introduction

Twenty five years have passed since the Red Wing Creek discovery revealed the prolific hydrocarbon potential of meteorite impact craters (astroblemes and impact structures).

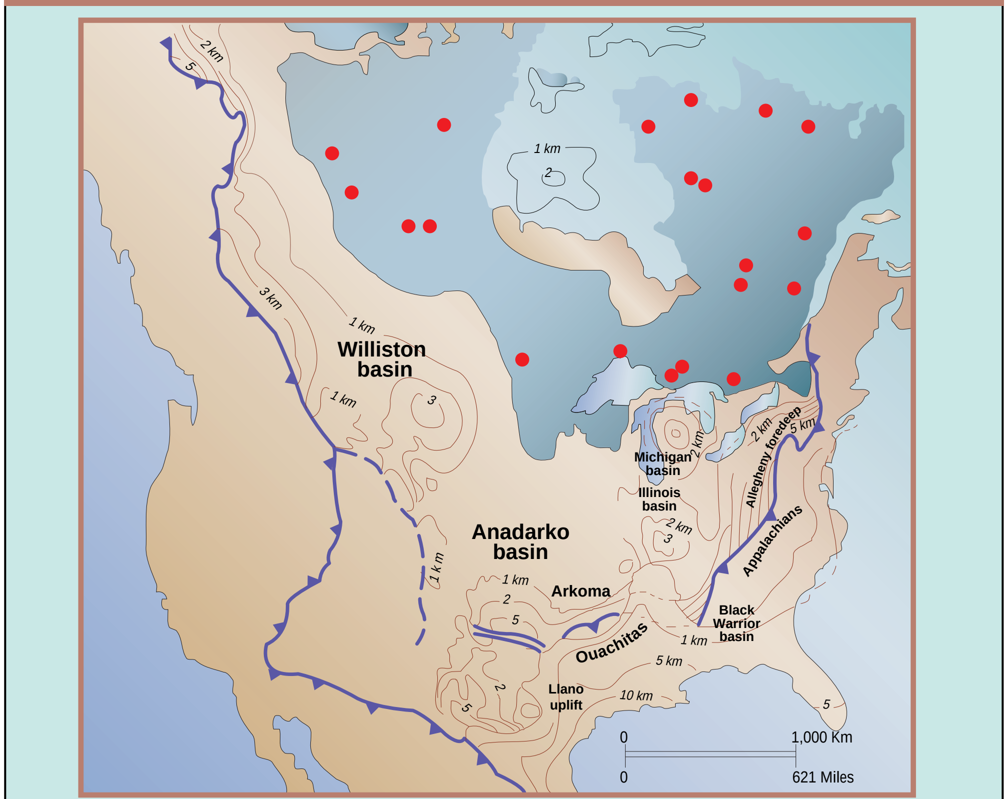
Commercial oil and gas discoveries in other impact structures, as well as recognition that certain existing fields resulted from impact, have provided a small but interesting data base for such esoteric structures.

Included in the data base are astrobleme anomalies. These are curious circular structures that lack evidence of shock metamorphism but may be of impact origin. In this article, these anomalies may include buried structures that mimic impact craters, such as calderas.

To bring organization and currency to information on producing impact structures, it was apparent that the data needed to be compiled and updated. Accordingly, this article reduces drilling results of producing impact structures and other related anomalies into table form, which should provide useful information for the profession. The review of drilling results includes a discussion of astrobleme features, drilling odds, hydrothermal considerations, and impact probability rates and concludes with an attempt to estimate the potential reserves in impact craters in the basement.

Fig. 2

DISTRIBUTION OF ASTROBLEMES ON EXPOSED PRECAMBRIAN CANADIAN SHIELD



Contours show the approximate depth below sea level of the unconformity between Precambrian basement rock and sedimentary cover. The contours in the Gulf Coast and Atlantic coastal margin show the depth to Paleozoic basement rocks.
Source: Base map modified from Suppe, 1986, and King and Edmonston, 1972.

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Producing astroblemes

North American onshore and offshore petroleum provinces include nine confirmed impact structures that are commercial oil and gas fields: Ames, Avak, Calvin, Chicxulub, Marquez, Newporte, Red Wing Creek, Sierra Madera, and Steen River (Table 1).

Marquez and Sierra Madera produce from below the base of their structures but are included here because of possible impact effects at depth. Calvin is included as confirmed on the basis of studies by Milstein;[1] Chicxulub, a confirmed astrobleme,[2] is considered to be a producing impact event on the basis of the nature of the areal oil fields that lie beyond the crater's outer rim. Also included for reference are two producing astrobleme anomalies: Viewfield and Lyles Ranch. Of these, the origin of Lyles Ranch (also known as Bee Bluff or the Uvalde structure) is the most controversial.[3]

The structures in Table 1 are shown with locations, diameters, impact ages, discovery year of hydrocarbons, various well counts, reservoir rock, producing depths, daily production, and primary (recoverable) reserves. Data were obtained from operators, participants, government and private organizations, and consultants with direct access to well information. Although some operators were unable or reluctant to release reserve figures, estimates for these fields are provided.

Over 1,000 wells, including stratigraphic tests, dry holes, injection wells, and producers, have been drilled to date to delineate the structures in Table 1. Some of the more salient results of these drilling efforts are briefly noted below.

Impact ages

Producing impact structures range in impact age from Cambrian-Ordovician for Newporte[4] to late Tertiary for Lyles Ranch.[5]

Within this time span, the ages of the structures are concentrated in the early Paleozoic, Mesozoic, and Cenozoic; as Table 1 shows, there is an absence of producing impact structures in the middle and late Paleozoic a gap of more than 200 million years during which hydrocarbon-prolific Pennsylvanian and Mississippian source beds were deposited in large areas of the North American craton.

Although Red Wing Creek produces from disrupted Mississippian beds, the impact event there is not Mississippian in age but occurred later—in the Jurassic-Triassic in this case. Impact craters formed in middle and late Paleozoic time have been found elsewhere but are apparently absent in petroliferous regions.

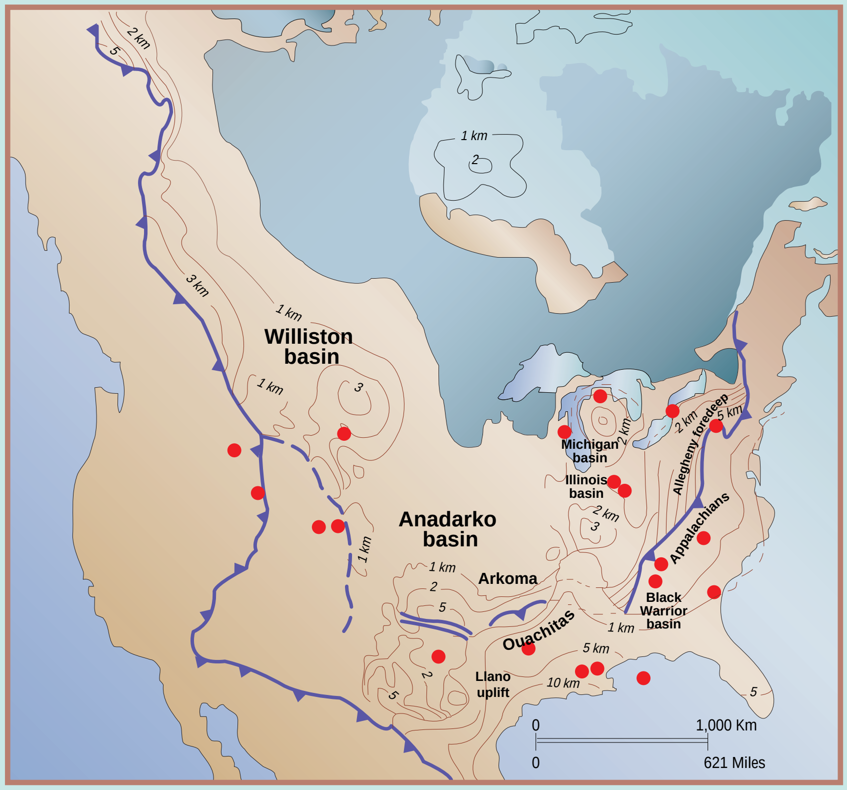
It could be argued that certain oil and gas fields have not yet been recognized as having an impact origin and that undiscovered hydrocarbon-bearing impact craters are also present.[6]

Discovery year

None of the structures in Table 1 was interpreted as an astrobleme when it was initially drilled. Of the 11 structures listed, hydrocarbons were discovered in 6 between 1972-78. The year 1972

Fig. 3

CANADIAN SHIELD ASTROBLEMES SHIFTED 15° SOUTH



Note the impact structures within petroleum provinces. Any shift or rotation of this astrobleme cluster into U.S. petroleum basins results in potential reserves ranging from 5 billion-105 billion bbl.

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is significant because it marked the phenomenal new field oil discovery at Red Wing Creek.

The 1977 discovery of Sierra Madera hydrocarbons was in Sierra Madera gas field below the structure's central uplift. Hydrocarbons had been discovered earlier in fields partially encompassing Sierra Madera, and the dates are provided in Table 1 notes.

Hydrocarbon discoveries and astrobleme confirmation lags have narrowed significantly because geologists now know what to look for. Avak, for example, was discovered in 1948 and is Alaska's oldest producing field.[7] Over 40 years later, shock metamorphism was recognized in its cores.[8] Avak remains the first gas-producing confirmed impact structure. Its counterpart for oil is Steen River in Northwest Alberta, where oil was discovered in 1968. This discovery was unrelated to shock-metamorphic studies in 1966, which were published in 1968.[9]

Initial discovery of (marginal) commercial hydrocarbons at Ames in 1990 preceded evidence for confirmed astrobleme status by about 2 years. Oil and gas fields older than Avak and those more recent than Ames may also be recognized as impact structures.

Producing depths

The producing depths of astroblemes range from 200 ft at Lyles Ranch to over 17,000 ft at Chicxulub (Table 1).

Excluding Chicxulub, Sierra Madera has wells approaching 13,500 ft and is the deepest. Both Sierra Madera and Lyles Ranch are unique gas fields in Texas. A search of available data showed that Lyles Ranch, which has a distinct surface expression, is the shallowest commercial gas field in Texas. It may be the shallowest overall, but this conclusion requires further study. LeVie[5] noted that the field is anomalous in a regional trend that includes serpentine intrusions. If Lyles Ranch were excluded from Table 1, then the Calvin structure in Michigan, with commercial oil at 800 ft, becomes the shallowest-producing confirmed astrobleme.

Flow rates, reserves

Sierra Madera also has a distinct surface expression[10] that is frequently referred to as the Sierra Madera disturbance.

Geologic complexities resulting from the impact event and regional tectonics appear to have affected gas reservoirs at depth. A gas well below the crater's south rim area, the Texas Pacific 6 Montgomery-Fulk drilled in 1975, held the state record for many years for calculated absolute open-flow potential.[11]

Actual flow is generally about one third calculated flow. PI[12] records indicate a calculated rate of 4.3 bcfd. In comparison, the average gas well in the Texas-Oklahoma area produces about 200 Mcfd, whereas the average gas consumption of a typical southwestern community consisting of 10,000 dwellings is about 1 bcf/year.

Also, records are held by Red Wing Creek in North Dakota and Ames in Oklahoma.

Red Wing Creek's 2,850 ft oil column (1,600 ft of net pay) in True Oil Co.'s 22-27 Burlington Northern well[13] is unmatched in North Dakota and apparently elsewhere in the U.S. An estimated 120 million bbl of oil are in place within Red Wing Creek's < 2 mile diameter reservoir area.

P. Page,[14] wellsite geologist on the D&J 1-20 Gregory well in the Ames impact structure, observed an unreported *open-flow* drillstem test in the upper 60 ft of a 204 ft pay zone that yielded over 100 bbl of oil in 20 min with no apparent drop in pressure (7,200 b/d of oil).

Though of short duration, this is the highest DST rate from a granite reservoir in North America and may be the highest worldwide. Comparable flow rates in similar lithology could not be found in the literature. Estimated reserves for this well are over 5 million bbl, assuming that its 500 b/d allowable is a prudent production rate.

With the exception of Chicxulub, Ames is the most prolific astrobleme at 2,600 b/d plus 3.1 MMcfd. Of the 40 producing wells, however, 6 completed in brecciated granite account for over half the daily oil production.

The most recent studies by V. Sharpton at NASA[15] put the maximum diameter of the Chicxulub structure in Mexico's Yucatan Peninsula at about 180 miles.

The reservoir rock is primarily dolomitized breccia,[16] which is believed to have

Producing impact structures in North America

Name*	Location	Diameter, Miles	Diameter, Km	Impact age	Hydrocarbon discovery year	Wells required for discovery	Active producing wells	Dry holes	Total wells	Success rate, %	Reservoir rock
(1) **Ames**	Major County, Okla.	8	13	E. Ordovician	1990	1	40	49	98	50	Granite, carbonates
(2) Avak	Point Barrow, Alas.	7.5	12	Cretaceous-Tertiary	1949	2	10	7	18	61	Sandstones
(3) **Calvin**	Cass County, Mich.	3.8	6.1	L. Ordovician	1978	2	30	25	91	73	Carbonates
(4) **Chicxulub**	Yucatan Peninsula, Mexico	180	300	Cretaceous-Tertiary	1974	6	453	93	658	86	Carbonates
(5) Marquez	Leon County, Tex.	7.9	12.7	E. Tertiary	1977	5?	6	4	10	60	Sandstones
(6) **Newporte**	Renville County, N.D.	2	3.2	Cambrian-Ordovician	1977	1	2	3	7	57	Granite, sandstones
(7) Red Wing Creek	McKenzie County, N.D.	5.6	9	Jurassic-Triassic	1972	3	14	14	34	58	Carbonates
(8) Sierra Madera	Pecos County, Tex.	8	13	L. Cretaceous	1977	4	20	10	65	84	Carbonates
(9) **Steen River**	N.W. Alta., Canada	15.5	25	M. Cretaceous	1968	7	2	25	29	14	Carbonates
(A) Lyles Ranch	Zavala County, Tex.	2.5	4	L. Tertiary	1979	2	4	5	14?	64	Sandstones
(B) Viewfield	S.E. Sask., Canada	2	3.2	E. Jurassic	1969	2	50	24	137	82	Carbonates

*(1)-(9) are confirmed impact structures. (A) Lyles Ranch and (B) Viewfield lack diagnostic shock metamorphism and are classified as astrobleme anomalies. Structures disrupting Precambrian basement rock are in bold. Success rates usually are determined by more than one operator. Refer to text and references for details of structures and reservoir rocks. †Production and well-count figures are through March 1995 unless stated otherwise.

Sources and notes correspond to listed order of structures: (1) Continental Resources, Inc.; Petroleum Information Corp. Production and well count figures are through August 1996. The strong natural water drive is affecting optimum production and recovery. (2) Alaska Oil and Gas Conservation Commission. (3) Michigan Geological Survey; Center Junction Corp.; Western Michigan University (4) Pemex. Early well records are unclear relative to pentration of key Lomas Tristes breccia or fractured interval. Apparently five deep wells were required for onshore discovery prior to exploration in adjacent offshore Bay/Gulf of Campeche, where hydrocarbons were discovered on the first well. Data shown, including discovery year, are for Bay of Campeche fields. Well count is through December 1994. Production figures are through November 1995. Production is from outside of outer rim within a distance of two crater radii to the southwest. (5) Texas Railroad Commission; Marathon Oil Co. Production is from below base of crater. Reserves not available; estimated. Diameter is from recent gravity studies by Wong

originated in part by interaction of impact-generated subsea seismic waves with platform carbonates.[17] Shoemaker[18] notes that researchers have now confirmed the impact origin of the Lomas Tristes breccia. This producing breccia occurs in (proposed) postimpact structural traps about 90 miles (within two crater radii) southwest of the outer rim in the offshore Bay of Campeche.

As of January 1996, remaining (proved) reserves for this area were estimated by Pemex at 27.2 billion bbl of oil (including condensate) and 11.3 tcf of gas.[19]

Of interest is that, about the same date, U.S. reserves were 22.9 billion bbl and 162.4 tcf. Thus, the oil reserves believed to be associated with the Chicxulub impact event exceed those of the entire onshore and offshore U.S. reserves, including Alaska's Prudhoe Bay. Current production from the Bay of Campeche is about 2.1 million b/d of oil (including condensate) and about 1.4 bcfd. This area constitutes the major part of Mexico's 2.8 million b/d production. Chicxulub also accounts for mostly all of the estimated $16 billion/year gross income from hydrocarbon production associated with North American impact structures.

Astrobleme features

Fig. 1 shows the astrobleme features where reservoirs can develop, and Table 2 lists producing examples.

Four such producing features have been confirmed to date: central uplift, rim, slump terraces and/or listric faults, and ejecta.

Listric faults are combined with slump terraces because this type of faulting, which is curvilinear and concave upward, usually produces slump terraces. Indirectly, sedimentary units draped over certain astrobleme features, such as the central uplift, may also form reservoirs.

In addition to Calvin, a possible drapeover example needing further study is the producing Heidt anomaly (Crater field) in Stark County, N.D.[20]

Five of the producing astrobleme examples in Table 2 disrupted Precambrian rock. Of these, Ames, Calvin, Steen River, and Chicxulub are complex-type structures with central uplifts, and Newporte is a simple bowl-shaped structure.

Ames and Newporte produce from both crystalline and sedimentary rock. At Ames, the central uplift produces primarily from brecciated Precambrian granite; the rim and ejecta produce from Ordovician dolomites. At Newporte, the rim rocks of Cambrian sandstones and brecciated Precambrian granite provide the reservoirs.

Chicxulub, Calvin, and Steen River have central uplifts of basement rock underlying sedimentary units but do not produce from Precambrian. Steen River produces from overturned and fractured Devonian dolomites in the rim,[21] and Chicxulub produces from Cretaceous dolomitized breccia affected outside of the crater.

Avak has a central uplift of metamorphic basement rock—a Paleozoic argillite—underlying sedimentary rocks. However, the structure produces from Jurassic sandstones in the rim area that were displaced by listric faults.[8]

Another example of this type of faulting is found at the Calvin impact structure, where listric faults resulted in slump terraces. The Devonian reservoir rock includes dolomitized algal mats, some areas of which have open flow channels 2 to 3 in. wide.[22] The configuration of the structure following impact influenced the depositional environment for reefal-type development.

Subcrater fracture-zone production has not been confirmed, but Marquez and Sierra Madera appear to be suitable candidates. The best gas production in both areas is either directly below the crater (Marquez) or below the peripheral rim area (Sierra Madera). Marquez produces from Early Cretaceous fluvial sandstones and shales, and Sierra Madera produces from Early Paleozoic fractured carbonates. Reservoir properties of impact-affected rocks can be enhanced at depth without noticeable seismic effects.

Briefly, some of the other impact features include rim-flank pinchout resulting from eroded rim rocks and marine transgressive deposits on a rim or rim arc's basinward flank, breccia lens pinchout created where the breccia lens abuts the crater wall updip, radial faults resulting from radial tension fractures (analogous to spokes on a wheel), simultaneous and overlapping craters resulting from multiple impacts or impact overprinting, and elongate or "butterfly"-shaped craters formed by low-angle impacts.

Table 1

y es	Total wells	Success rate, %	Reservoir rock	Producing depth, ft	Production Oil, b/d	Production Gas, MMcfd	Primary reserves Oil, million bbl	Primary reserves Gas, bcf
9	98	50	Granite, carbonates	8,400-9,500	2,600	3.1	25	15
7	18	61	Sandstones	2,600-2,800		1.3		39
5	91	73	Carbonates	800-900	110		5+	
3	658	86	Carbonates	8,300-17,000+ (11,500 avg.)	2.1 million	1,400	30,000	15,000
4	10	60	Sandstones	9,000 avg.	30	1.8	0.10-0.15	5-7
3	7	57	Granite, sandstones	9,150-9,600	280		15	
4	34	58	Carbonates	8,000-9,700	960	2.3	20	25
0	65	84	Carbonates	12,000-13,500		7.7		270
5	29	14	Carbonates	4,265-4,500	550		3-5+	
5	14?	64	Sandstones	200-500		0.068		2
4	137	82	Carbonates	4,160-4,300	575	0.26	10.5	4.5

(1994). (6) North Dakota Geological Survey; Eagle Operating Co. Production and well count figures are through November 1996. One recompleted well in Cambrian sandstones yields mostly all production. (7) North Dakota Geological Survey; True Oil Co. Secondary recovery using miscible hydrocarbon flooding was begun in 1982, prior to depletion of primary reserves. Total reserves not available. Using 120 million bbl of oil in place, the field may recover 35-60 million bbl of oil and 45-80 bcf of gas. (8) University of Texas of the Permian Basin; Melzer Exploration Co. Reserves are from four fields possibly linked in part to the impact event. Names and discovery years of fields are Elsinore, 1958; Pikes Peak East, 1972; GMW, 1976; Sierra Madera, 1977. Production is from below base of crater and rim area. (9) Mercantile Canada Energy, Inc. Structure is oblate, actual dimensions are 14.5 x 15.5 miles (23 x 26.5 km). Significant potential; needs more exploration. (A) Texas Railroad Commission. Production figures are through December 1994. (B) Saskatchewan Energy and Mines. 700,000 bbl of oil remaining for primary recovery. Secondary recovery, if initiated, is limited and may yield an additional 1-3 million bbl. The two pay zones already have a partial natural water drive.

As with conventional reservoirs, these features require source, seal, and trap. Unlike conventional reservoirs, geochemical studies by Castano and others[23] suggest that meteorite impacts can create closed basins that are favorable for the deposition of hydrocarbon source rocks. Producing examples appear to be Ames and Newporte.

It is proposed that almost all of the features in Table 2 are capable of producing hydrocarbons from basement rock. The exception is the subcrater fracture zone below the base of the crater. This feature is limited to whatever sedimentary column may be present because conventional source beds are not present beneath otherwise undisturbed Precambrian crystalline rock.[24]

Nonproducing astroblemes

Other impact events are known to have occurred in oil and gas prone areas. However, the timing for hydrocarbon sourcing, sealing, and trapping has not been conducive to formation of commercial deposits in some structures.

Within North American offshore and onshore petroleum provinces there are eight confirmed impact structures where commercial hydrocarbons have not been reported. These are Montagnais, Scotian Shelf;[25] Eagle Butte, Alta; Flynn Creek and Wells Creek, Tenn.; Kentland, Ind.; Middlesboro, Ky.; Serpent Mound, Ohio; and Kilmichael, Miss. The latter is tentatively included here as a confirmed astrobleme because, subsequent to studies by Robertson and Butler,[26] diagnostic shock-metamorphic features in quartz have reportedly been found. Verification is currently under way.

One of these structures may prove to have commercial potential. According to the Kentucky Geological Survey, the 3.6 mile diameter Middlesboro structure in Bell County, Ky., has a 15 Mcfd shut-in well completed in Mississippian siltstones at 3,200 ft. Two other wells were dry, but additional drilling may be forthcoming. The remaining astroblemes identified above were either dry, had shows, or may not have been adequately explored.

Other anomalies

Other structures exist that lack shock-metamorphic evidence but meet other geologic and geophysical criteria for astroblemes.

Some examples are Haswell hole, Colo.;[27] Panther Mountain, N.Y.;[28] Chimney prospect, Mont.;[29] Hartney, Man.; Elbow and Dumas, Sask.;[30] and Lamont and Selman, Okla.

Byler[31] showed numerous intact and discontinuous circular anomalies in North America, some of which may be remnant impact scars. Overviews and/or references for numerous astroblemes and astrobleme anomalies can also be found in Grieve and Masaitis,[32] Grieve and others,[33] and Koeberl and Anderson.[34]

An intriguing and controversial paper on the meteorite-impact theory as a viable alternative to plate tectonics theory can be found in Butler.[35] The list of astrobleme anomalies continues to expand, and candidate structures will be confirmed as information warrants.

Drilling odds

The tentative and limited information on confirmed impact structures in petroleum provinces indicates that 9 of 17 astroblemes (53%) are commercial oil and gas fields. However, it required about 42 wells into the 17 structures to establish which were commercial.

These numbers give a new field wildcat success rate of about 21% (9 hits out of 42 wells). Other wells into the 9 commercial astroblemes can be difficult to classify as exploratory or development. For example, most operators consider that drilling in the Ames impact structure is primarily exploration regardless of the separation distances among wells.

Therefore, the success rates in Table 1 are given for each structure as a percentage of all wells for that particular structure. For example, a total of 7 wells were drilled at Newporte, of which 3 were dry holes. Thus, 4 wells out of 7 (regardless of the categories) were successful, which gives a success rate of about 57%. Of the 4 completions, 2 are currently active.

The drilling success rates for producing astroblemes range from 14% at the remote Steen River structure to 86% at Chicxulub. The average success rate for total wells into all producing astroblemes is about 77%. Excluding Chicxulub, which accounts for two thirds of the total wells into producing astrobleme areas, the average success rate is about 58%.

In most cases, the success rates would have been higher if operators had been aware of what they were drilling from the outset. In comparison, the success rates for 127,253 U.S. wells drilled from 1990 through 1994 were about 20% for new field wildcats and 74% for all wells.[36]

As previously noted, 53% of confirmed astroblemes in petroleum provinces are commercial oil and gas fields. Of the 9 commercial impact structures, Table 1 reveals that 5 required between 1 and 3 wells for hydrocarbon discovery. The other 4 craters needed between 4 and 7 wells.

Considering the hydrocarbon potential of astroblemes, the drilling success rates are quite favorable. However, all producing astrobleme discoveries to date have been by accident, and the potential rewards of wildcat drilling come with a "Catch-22."

The drilling success rates are for confirmed astroblemes in petroleum provinces, not for astrobleme anomalies, which may or may not be bona fide astroblemes (e.g., solution collapse features, calderas). Unless the objective is confirmed as an astrobleme prior to or during drilling, the well may be headed into an anomaly having a lower (or zero) chance of success.

Impact craters having surface expressions may display shock metamorphism and can be studied prior to drilling, but buried structures require drilling, and the exploration may find that the objective is not a confirmed astrobleme.

What are the chances of finding commercial hydrocarbons in astrobleme anomalies?

Based on a preliminary check of published material, 6 of 12 curious circular structures in North American petroleum provinces are commercial oil and gas fields. All but one, a circular depression in Texas County, Okla.,[37] were previously mentioned in this article.

This tentative list suggests that 50% of astrobleme anomalies have been drilled successfully. The chances of hitting pay on the first well calculate at about 25% or better for anomalies of decreasing diameters. Combining confirmed astroblemes and astrobleme anomalies gives a total of (at least) 29 circular structures in North American onshore and offshore petroleum provinces. Of these, 15 are commercial oil and gas fields (about 52%). These figures could differ if relevant unpublished drilling prospects were included.

Table 2

Impact structure reservoirs

Impact feature	Producing example
Central uplift	Ames, Calvin, Red Wing Creek
Rim	Ames, Avak, Calvin, Newporte, Steen River, Lyles Ranch,* Viewfield
Ejecta	Ames, Chicxulub(?)
Slump terraces and/or listric faults	Avak, Calvin
Radial faults	Ames(?)
Drapeover	Heidt/Crater field*(?), Calvin
Subcrater fracture zone	Marquez (?), Sierra Madera(?)
Marine impact	Chicxulub breccia(?), North Sea turbidites(?)
Brecca lens pinchout	Not yet recognized
Rim-flank pinchout	Not yet recognized
Simultaneous and/or overlapping craters	Not yet recognized
Elongate or "butterfly" craters	Not yet recognized

*Impact origin not yet confirmed. All Calvin reservoirs are drapeover.

Hydrothermal factors

In rare cases high-temperature hydrothermal activity can enhance reservoir quality by rupturing overlying rocks.

An example of hydrothermal rupture is Blackburn oil field in Nevada, where carbonates overlying an ancient magmatic heat source were possibly fractured and brecciated by explosive hydrothermal action, i.e., ground water contacting a pluton became superheated and overpressured owing to the overburden.[38] This porosity-creating mechanism, however, is quite different from conditions at meteorite-impact sites.

Following an impact event, hydrothermal circulation is initiated within the target rocks. A boiling water table forms below the impact-melt sheet, and steam and water escape mainly at the rim in simple craters and in both the rim and central uplift of complex craters.[39] There is negligible pressure buildup, however, and the net effect of circulation activity is to plug fractures with mineral deposits.

Hydrothermal effects following impact events have not been duplicated in the laboratory, but experiments directed at understanding fault-zone sealing may afford insight into hydrothermal processes. Moore and others[40] studied the hydrothermal effects on a typical granite composed of plagioclase, quartz, and feldspar.

Extrapolation of data from fractured samples subjected to temperatures of 300 to 500° C. showed that permeability reductions of almost three orders of magnitude (1,000 times less) can occur within a few years in crystalline basement areas (such as the Canadian Shield). These permeability decreases are most likely caused by hydrothermal-related solution-transfer processes that redistribute minerals in rock and can result in negligible fluid flow approaching that of intact granite.

At the Ries crater in Germany, Pohl[41] calculated that some of the suevite took about 2,000 years to cool from 600 to 100° C. Hydrothermal activity measured there has been documented at other terrestrial impact structures, with estimated postimpact temperatures ranging from 100 to 700° C.[42]

Hydrothermal alteration of target rocks can occur in a fraction of the time it takes for temperatures at impact sites to reach ambient levels, and this alteration is invariably detrimental to reservoir quality.

Hydrothermal activity at impact sites can produce economic deposits of zinc minerals, for example,[32] but for potential hydrocarbon reservoirs, the fractured rock needs to remain open. As a general rule, hydrocarbon reservoirs are unproductive (or uneconomic) below a porosity of about 5%.

The permeability threshold for gas reservoirs is about 0.1 md and about 0.5 md for oil reservoirs. Values near the threshold, however, can be offset by large pay zones.

Both porosity and permeability are affected by hydrothermal activity, but the reductions in porosity are not as consequential as the reductions in permeability. An example of hydrothermal effects across a basement astrobleme is given in Donofrio[43] for the 8 mile diameter Deep Bay structure on the Canadian Shield. The rim core had a porosity of 8.5% and a permeability of 0.01 md; breccia off the flank of the central uplift (possibly talus) had 21.4% and 13.7 md; and the central uplift had 14.9% and 0.05 md. All three areas had adequate porosities, but only one area had adequate permeability.

Hydrothermal effects thus place constraints on drilling locations in impact structures, particularly those in basement rock. Moderate crater erosion prior to burial can enhance reservoir quality and form talus deposits on the flanks of central highs and peripheral rims, thus offsetting permeability reductions due to hydrothermal activity.

The most productive reservoir at Ames, for example, is a relithified granodiorite that is frequently referred to as brecciated granite or a rubble pile. This rubble condition may have resulted from exposure of the central uplift to subaerial weathering and erosion.[44] Similar material (probably talus) may form the carbonate rubble of the productive rim at the Viewfield structure.[43]

The central uplift at the Steen River basement astrobleme was penetrated near the center and found to be of competent, tight igneous rocks initially misidentified as volcanic rocks.[45] The central-uplift flanks at Steen River also need to be explored, and hydrothermal studies, including fluid-inclusion analysis, need to be undertaken at both it and Ames.

Determining the hydrothermal effects in sedimentary astroblemes and astrobleme anomalies such as Red Wing Creek and the Chimney prospect, respectively, would also be informative. Until more information is forthcoming, geologists should use the Ames experience when planning an exploration program for similar structures in basement rock.[46]

Impacts random?

Impact events are assumed to be random in time and space.

Impact probability rates of Cannon,[47] for example, using the density of Earth-crossing asteroids and cratering rates on other planetary bodies, suggest that at least 500 astroblemes the size of Ames should have been created in the conterminous states since the beginning of the Cambrian. The number preserved to the present will be considerably less, however.

Shaw[48] argued against the random nature of impact events and sampling bias and called attention to the ordered age grouping and positioning of craters on North America, Eurasia, and Australia. Shaw noted three spatial nodes that have persisted since the late Precambrian. These nodes represent the loci of mutual overlap of all age groups of known impact events and mark the intersection points of cratering swaths that encircle the Earth.

For example, the cratering nodes of North America, Eurasia, and Australia can be connected by a nearly circular swath during the Phanerozoic, suggesting that bolides are impacting limited areas. A possible explanation is that the orbital parameters of bolides are influenced by gravitational variations within the Earth.

Of interest is that the crater-age overlap forming the node for North America embraces mostly all petroleum provinces. If Shaw is correct, an abundance of astroblemes unpredicted by cratering estimates may exist in oil and gas prone areas.

Potential reserves of basement astroblemes

While the random vs. nonrandom issue is debated, an intuitive approach might be used to estimate the reserves in undiscovered or unrecognized U.S. impact structures in basement rocks. Fig. 2 shows the location of astroblemes on the Canadian Shield and several of the larger petroleum basins in the U.S. For illustrative purposes, the petroliferous areas are shown in their present-day configuration.

Crater names and dimensions can be found in Grieve and Robertson.[49] All of these astroblemes are developed in crystalline basement rock and range in impact age from Precambrian to Tertiary, with the majority dated as Paleozoic. Diameters range from 1.2 to over 84 miles, with half approaching or exceeding the 14 mile diameter of the Ries impact structure in Germany.

The Ries is mentioned because it illustrates the penetration effects of large bolides. Pohl and others[50] noted that the Ries crater was created by the impact of a 3,300 ft diameter stony meteorite that penetrated about 2,000 ft of sedimentary rocks and continued for another 2,100 ft into crystalline basement.

Seismic surveys have revealed that basement rock at the crater center has been brecciated and fractured down to about 20,000 ft. Impact events forming craters of this diameter or larger could penetrate deeply into petroleum basins and affect basement rock.

The impact structures in Fig. 2 have been studied in detail by the Geological Survey of Canada. From geologic and geophysical data, which include core studies, the volume of brecciated and fractured rock can be estimated and adjustments made for hydrothermal effects.

If it is assumed that the Canadian Shield astrobleme distribution is a fair representation of impact density for the larger, more resistant structures, the question to be answered is, "What would the potential reserves of these craters be if similar impacts had occurred in petroleum basins?"

The following parameters are used: a 50% crater erosional level before preservation by overlying sedimentary deposits; a threshold sedimentary cover of about 7,000 ft to provide the geothermal conditions for hydrocarbon generation; proper timing of impact event, source rock, and seal; and an oil recovery factor of 100 bbl/acre-ft (Ames granite reservoir is 130 bbl/acre-ft).

To evaluate the potential reserves, the Canadian Shield astrobleme cluster was shifted about 15° south (Fig. 3). Initially, this shift was selected because it is the point at which the most northerly crater of the cluster contacts the requisite overburden in a U.S. petroliferous area, the Michigan basin.

Likewise, Fig. 3 shows that such a shift displaces numerous astroblemes into onshore and offshore petroliferous areas. Potential reserves for this scenario are about 50 billion bbl of oil, an extraordinary figure more than double current U.S. reserves.

If we control (or subtract) the reserves in all basement rock, including granite washes, the drop in potential reserves is less than 1%. This result suggests that the volume of undiscovered basement hydrocarbons may be significantly higher than known basement reserves.

At first glance the practicing exploration geologist may reason that such fanciful superpositions are meaningless in the real world of exploration, but one cannot ignore impact densities of large astroblemes or the geographic distribution of petroleum provinces.

The only real challenge may come from optimistic geologists who claim that impact structures remain undiscovered and that they occur in greater numbers than are shown here. Of interest is that no matter to what degree or how far and wide the Canadian Shield astrobleme cluster is shifted or rotated into the area of U.S. petroleum basins, the potential reserves range from a low of 5 billion bbl to a high of over 105 billion bbl. If only a fraction of this potential exists, giant fields remain to be found.

The conditions leading to giant hydrocarbon accumulations in conventional reservoir rocks such as sandstones and carbonates appear to be fortuitous, but they do occur. According to one estimate, worldwide exploration has revealed that giants constitute only 0.6% of significant oil fields, yet they contain 84% of the reserves.[51]

Giants within the U.S. usually are defined as having at least 100 million bbl of recoverable oil or 1 tcf of recoverable gas. Before excluding the lower 48 states from such potential, geologists should consider Van Der Loop's resource base study[52] where she has noted, "although the biggest fields in any trend are usually the first ones found . . . if you do find something in a lower 48 frontier area, the chances that it will be big enough to keep are better than if you had found something in a mature trend."

For astrobleme anomalies, those chances could be much higher than the 4% or less success rate for conventional prospects in lower 48 frontier areas. As I stated over 15 years ago,[43] "suspicious gravity, seismic, and magnetic anomalies in basement should be penetrated and tested where drilling depth permits. These anomalies include elevated areas of basement as well as synclines . . . Detection of astroblemes by geophysical or geologic methods means that fractured reservoirs have been located . . . Unquestionably with some deep-basement impacts the capital expenditures will be considerable but the possible rewards can be enormous." Clearly such structures are of strategic importance to the U.S.[52]

The Canadian Shield cluster displacement exercise (Fig. 3) suggests that the potential for hydrocarbon reserves in impact craters in basement rocks may be significant and that, like conventional oil and gas fields, most of the reserves will be found in relatively few large structures.

Thus far, the largest producing confirmed astrobleme in the U.S. is Ames with a diameter of about 8 miles. Nonproducing confirmed impact craters larger than Ames have not yet been recognized in U.S. petroleum provinces. In U.S. areas outside petroleum provinces, the largest confirmed impact structure is the 54 mile diameter Chesapeake Bay crater in Virginia.

Where are the other large-scale impact structures comparable to those on the Canadian Shield?

Conclusions

The drilling record to date shows that, although producing impact structures are few in number, they have a disproportionate share of significant characteristics. These include:

1. The ability to form (or enhance) structure, reservoir rock, and possibly source rock independent of the regional geology;

2. Exceptional reservoir thickness, high yields, and flow rates;

3. Production (and potential production) from numerous types of reservoirs within, below, above, and beyond the structure; and

4. Reservoirs that include crystalline basement rock.

The drilling success rates in confirmed astroblemes for new field wildcats and total wells are 21% and 77%, respectively. These rates approximate the industry's average of 20% and 74% for the same categories.

The similarity in figures is not surprising considering that all producing astroblemes to date were found by accident with conventional exploration models and practices. After hydrocarbons were discovered came the realization that the structures had an impact origin.

To use astroblemes as an exploration concept, geologists need to reverse the sequence.

About half the confirmed astroblemes and astrobleme anomalies in petroleum provinces are commercial oil and gas fields and, on average, these structures required about 2-4 wildcats to find the pay. The number of wildcats appears to reflect the dimensions of included anomalies in this initial study. Like confirmed astroblemes, the database for astrobleme anomalies is small and inconclusive. This study was confined to North America, but these esoteric structures are productive elsewhere in the world and have similar implications for giant field potential.

The least explored horizon and final frontier for the petroleum geologist is crystalline basement. Two producing impact structures have already proven that this lithology can be a viable reservoir. Undiscovered basement (and sedimentary rock) astroblemes certainly exist and are capable of hosting giant oil and gas fields.

The known and potential dimensions of impact events need to be realized. Large-scale impact structures (or their remnants) approach linearity relative to regional geologic and geophysical coverage used in an exploration program. Recognition of a feature such as a rim arc is a challenge to explorationists, and the basinward flank of a large-scale rim segment is one of the crater areas where a giant field awaits discovery.

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