IMPACT CRATERS: IMPLICATIONS FOR BASEMENT HYDROCARBON PRODUCTION

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The impact cratering process results in unique structures and extensive fracturing and brecciation of the target rock which can be conducive to hydrocarbon accumulations. Examination of Viewfield and Red Wing Creek oil pools in North America reveals that they may have been formed by meteoritic impact in Paleozoic sediments. Additional hydrocarbon traps have most likely been produced by impact but have not been recognized as such because geologists are generally not familiar with crater structures and shock-metamorphic effects in rocks. It is proposed that petroliferous basement impact craters also exist and that despite arguments to the contrary, at least one may have already been found. Further discoveries are severely limited because of conservative exploration procedures, which characteristically avoid penetrating crystalline basement.

Core analysis from several large impact sites developed in crystalline rocks reveals that while permeability factors are marginal, the reservoir potential of these craters exceeds those of many of the largest known hydrocarbon accumulations. Preservation age studies of craters in conjunction with size frequency distribution curves implies that many will have been buried before erosional eradication. As with normally-fractured and brecciated basement areas, some will have accumulated hydrocarbons. In addition to classical source rocks flanking or overlying these potential reservoirs, recycled kerogen and the possibility of inorganic sources are also considered. A basement impact crater may afford a unique way of testing the inorganic hydrocarbon proposals.

Introduction

The revelations of the *Mariner, Viking* and *Voyager* space probes have shown the extent of cratering on bodies other than the moon. As the earth's atmosphere affords insignificant velocity retardation to relatively large incoming objects, it is assumed that the earth's pretransgressive basement configuration was extensively cratered as well and, despite erosional elements, that many of these impact scars are preserved by overlying sediments. The cratering phenomenon appears to be universal in scope and is indicative of catastrophic forces at work throughout the geologic record.

Random in time and space, impacts create, in the order of seconds, features which are largely independent of the regional geology. As the search for hydrocarbons continues to probe deeper than in the past, it becomes essential for geologists to recognize the

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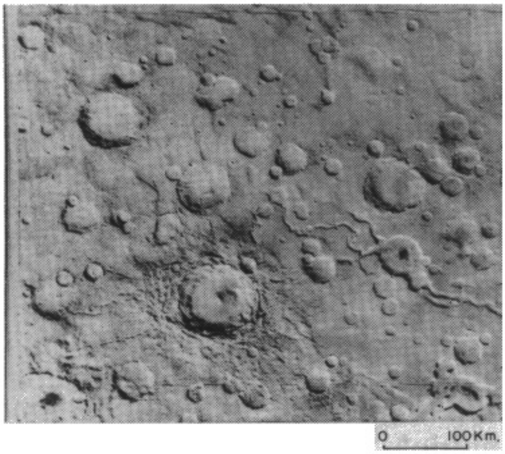

Fig. 1. The surface of Mars as photographed by Viking Orbiter from a distance of 22,000km. The large crater with the prominent central peak is Cerulli, which lies in the northern ancient terrain believed to be the oldest and most heavily cratered area on the planet. Similar cratering features are present in crystalline rock underlying the earth's sedimentary basins and can be suitable structures for hydrocarbon accumulations (NASA/Jet Propulsion Laboratory photograph).

dynamic forces from outside the earth that have modified petroliferous basins.

Economic Significance

The Baltysh depression in the Ukraine SSR has been recognized as a fossil meteorite crater and is well known as a locality for oil shales (sapropelites), the reserves of which constitute about three billion tons (Yurk, *et al.,* 1975). A number of other possible impact structures associated with mineral deposits in the Ukraine are being investigated.

In addition to the mineral resources of Sudbury, a Canadian probable impact crater containing over 75% of the Western World's nickel deposits, at least two commercial hydrocarbon-bearing structures in North America are suspected as being of impact origin. These are the Viewfield and Red Wing Creek structures of the Williston Basin. Three additional curious subsurface features currently are under investigation in two southern US basins.

The possibility of petroliferous impact craters in the sedimentary column has important implications for the most neglected of all potential reservoirs—crystalline basement. I propose that commercial hydrocarbons exist in basement impact sites, and that some of these structures will prove to contain major reserves.

The Cratering Record

Terrestrial cratering estimates have been made from impact probability rates of earth-crossing asteroids (Shoemaker, 1977), and from the occurrence of ancient probable impact sites of known age on the North American and East European cratons (Grieve and Dence, 1979). The data suggest that the production rate for craters 10km and larger is about (0.7 ± 0.35) X 10^{-14}sq km/yr whereas it approximates (0.35 ± 0.1) X 10^{-14}sq km/yr for 20km and larger diameter features. The size-frequency distribution, or mass distribution, of crater-forming meteorites follows a log-normal curve (Brown, 1960), which means that their population is composed of an increasing number of smaller bodies and a decreasing number of larger bodies. When combined with present meteoritic infall rates and extrapolated into the Precambrian, the calculations show that over 150,000 craters with diameters of 1km or larger will have been formed on the earth's land surface during the past 3 billion years. Of this number, over 3,000 will have dimensions greater than 10km of which approximately 60 will exceed 100km in size.

The accuracy of such cratering estimates was discussed by French (1968) who noted that impact probability rates for the past 2 billion years had predicted 20 craters with diameters greater than 5km on the Canadian Shield. Of this predicted number, 15 impact structures had been identified by 1968. Additional craters have since been recognized, bringing the current number to 20 (Grieve and Robertson, 1979).

Cratering Mechanics

Incoming extra-terrestrial bodies having masses greater than 10^8gm will retain their interplanetary kinetic energy while traversing the atmosphere and strike the earth's surface at velocities ranging from 15 to 70km/sec (Wetherill, 1977). Following impact, a catastrophic sequence of events is set in motion. These events have been observed in laboratory ballistics experiments by Gault *et al.* (1968) and show that upon impact the kinetic energy of the projectile is instantaneously transferred to the target surface in the form of heat and intense shock waves, which produce local pressures in the orders of megabar range. As these shock waves move radially outward they decrease in pressure and distribute the impact energy over a steadily-increasing volume of target rock. The complex interaction

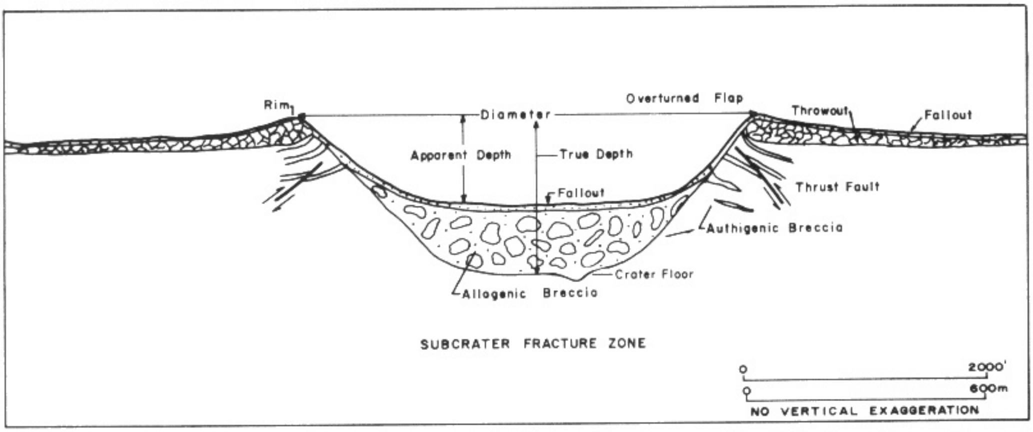

Fig. 2. Cross-section of Meteor Crater, Arizona, a simple-type impact crater (modified from Shoemaker and Eggleton, 1961).

of compression and rarefaction waves results in excavation of material, which creates an enlarging embryonic cavity. This excavation ceases when the pressure drops below the yield strength of the target rocks. Slumping, isostatic adjustments, and erosion with resultant infilling then proceed to modify the crater profile.

The term *shock metamorphism* has been created to describe all changes in rocks and minerals resulting from the passage of transient, high-pressure shock waves. French (1968) has described and classified these changes into three major groups. These are best developed in quartzofeldspathic rocks, are detectable in minute quantities from drill cores or cuttings, and can be preserved in rocks for up to 2 billion years:

1. *High pressure effects* are represented chiefly by the production of high-pressure polymorphs such as coesite, stishovite, and diamond, which can also be produced under static high-pressure conditions (indicative of the upper mantle). During normal rock metamorphism, however, pressures are usually lower than 10kb.
2. *High strain-rate effects* develop “planar features” in quartz and produce isotropic phases of quartz and feldspar (maskelynite).
3. *High-temperature effects* are produced by shock pressures so high that the resultant relaxation temperatures are hundreds of degrees above the normal melting points of the component minerals, thus initiating reactions such as the melting of quartz to lechatelierite (fused silica glass) and the decomposition of zircon to baddeleyite. Such features, while they are not direct evidence of high shock pressures, indicate the existence of temperatures in excess of 1,500°C, much too high for normal geological activity.

In addition to shock-metamorphic effects on the microscopic level, unusual conical fracture surfaces called *shatter cones* are often noted within impact sites. These are not to be confused with cone-in-cone, which are concretionary structures formed mostly in calcareous-type rocks. Shatter cones are usually not limited by lithology and according to Milton (1977) are produced within a shock pressure range extending from about 20 to perhaps 250kb. These are large-scale shock indicators whose proof of impact origin by direct association with meteoritic material has been reported fromseveral craters (Roddy and Davis, 1977).

Crater Morphology

Two basic classes of impact craters have been recognized on the earth and other planetary bodies—the simple and the complex variety. The term astrobleme (Dietz, 1961) is frequently used when referring to either type.

Simple craters are characterized by a bowl-shaped depression and a raised and overturned rim, a classical example of which is meteor crater in Arizona (Fig. 2). This feature is developed in sedimentary rocks and is about 1.2km in diameter, 180m deep, and has a raised rim of about 40m.

Shoemaker (1960), and Shoemaker and Eggleton (1961) have defined a number of terms from their field-studies of Meteor Crater and other impact sites. These include: *throwout,* rock debris ejected along ballistic trajectories; *fallout,* a relatively-thin veneer of

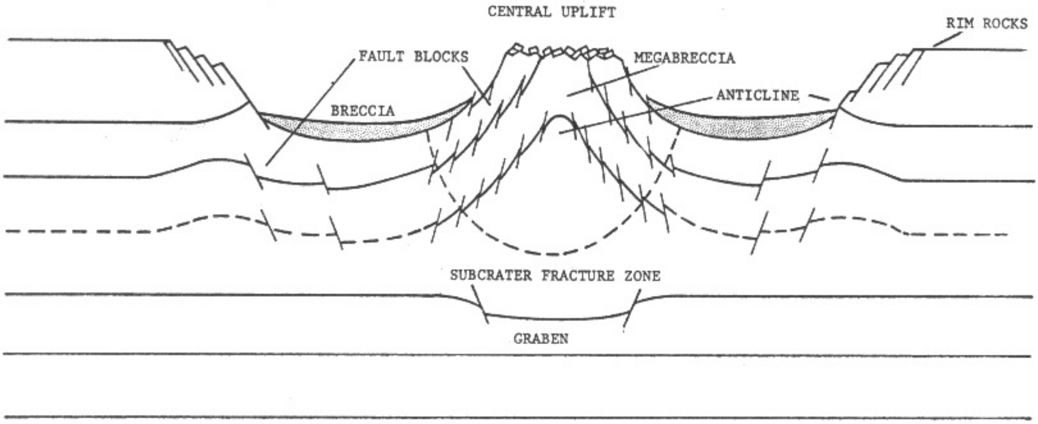

Fig. 3. Diagrammatic cross-section of a complex-type impact crater (modified from Brenan, *et al.*, 1975).

material formed by the free-fall of rock fragments ejected at high angles of elevation; *allogenic breccia,* a breccia composed of mixed fragments of rocks derived from different areas in the crater: and *authigenic breccia,* material in the crater which has essentially been brecciated in place.

At a crater diameter of approximately 4km in crystalline rock and 2 to 3km in sedimentary rock, a morphological change from simple to complex type occurs (Fig. 3), which results in a comparatively shallow crater having an uplifted central area or peak and a slumped or depressed rim (Dence, 1972). In field-studies of complex craters, Milton and Roddy (1972) note that central uplift commonly is 10-15% of the crater diameter. This results in a considerable displacement effect on the target rock.

Generally, complex structures up to approximately 30km diameter will have distinct central peaks or uplifts. Beyond this diameter, the central uplift may be replaced or augmented by a concentric series of uplifts and depressions, giving the structure a multi-ring form (Dence *et al.,* 1977; Grieve and Robertson, 1979).

By convention. a suspected impact crater in which meteoritic fragments have been found is classified *as proved.* If only shock-metamorphic features are detected, the crater is classified as *probable.* Any other criteria used in suggesting an impact origin such as structure, classify it as *possible.* The cumulative number of *proved, probable* and *possible* impact craters on earth now stands at 145 (Grieve and Robertson 1979 and personal communication). These include both surface and subsurface craters, many of which have only recently been recognized. The number of suspected impact sites continues to increase as geologists become more familiar with cratering mechanics and shock metamorphism.

Effects on Target Rock

In addition to the crater depression itself, the extensive crushing, fracturing and brecciation ability of hypervelocity impacts is evident from field investigations. This exogenic fracturing mechanism is distinct from normal terrestrial processes which commonly fracture rocks by crustal movement, unloading, weathering and volume shrinkage. Tests have shown that projectile impact or explosive detonation causes a compressive stress to traverse the rock and give rise to subsequent tensions. At locations in the rock where tensile stresses are high enough, inherent flaws in the material become unstable and begin to grow. As the cracks continue to extend, they begin to encounter one another and link up. As crack coalescence continues, chunks of material are isolated from the main rock body and, if near a surface, may be ejected at considerable velocity (Curran *et al.,* 1977).

Experiments of this nature indicate that the harder and less porous the rock, the greater will be the brittle fracturing. During natural hypervelocity impact, shock-induced pressure and temperature effects in rocks of various composition must also be considered. Chao (1968) noted that these effects can induce volatilization, melting, oxidation/decomposition reactions and hydrothermal alteration, the latter producing low-temperature minerals such as zeolites, chlorite, hematite and clay (Dence, 1972). In some cases, ore minerals are mobilized as the result of the disturbance and

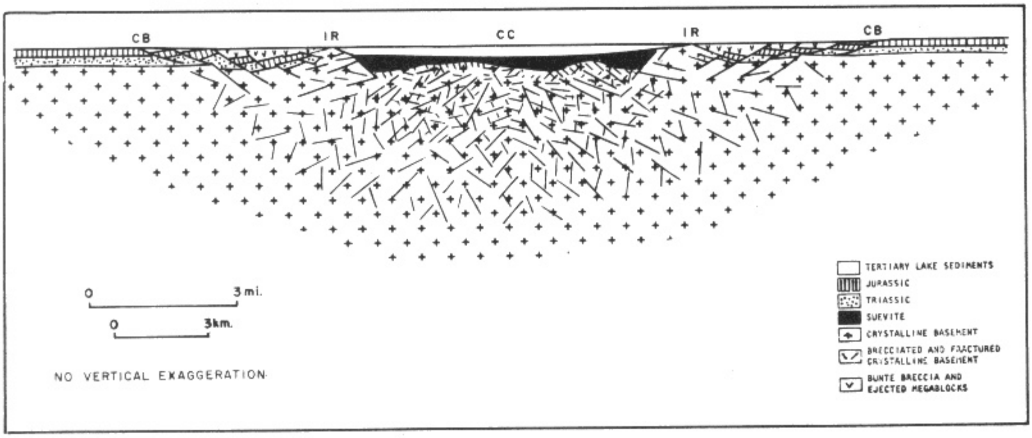

Fig. 4. Profile of the Ries Crater: CC=crater center, IR=inner ring, CB=crater boundary (from Pohl, *et al.*, **1977).**

may form vein or other deposits. Despite these potentially-detrimental reservoir factors, the impact process has important implications for petroleum geology in that an impact can instantaneously create porous and permeable rock from non-reservoir material, and also modify the structural configuration of the target rock independently of the regional geology. With large magnitude impacts the extent of these alterations is tremendous.

At the Ries Basin in Germany, for example (Fig. 4), the hypervelocity impact of an estimated 1km-diameter stony meteorite penetrated about 600m of sedimentary sequence and continued for another 650m into crystalline basement. The ensuing explosion excavated between 124cu km and 200cu km of rock, and produced a complex ringed crater 22-23km in diameter. Seismic measurements have revealed that basement rock at the crater center has been brecciated and fractured down to about 6km (Pohl *et al.,* 1977).

The extensive vertical brecciation and fracturing at an impact site is frequently augmented by a radial and concentric interconnecting fracture pattern in the target rock. This is best observed in small-scale cratering experiments conducted by Curran *et al.*, (1977), and can be seen in Fig. 5, which shows the typical pronounced effects of high-velocity impact on slabs of Arkansas novaculite, a hard, dense, polycrystalline quartzite. This pattern frequently extends well beyond the basal excavated area.

On a much larger scale, a similar example of this pattern occurs at Clearwater Lake, Quebec, where two complex ringed craters (30km and 25km diameter) were simultaneously formed in crystalline rock. As can be seen in Fig. 6, the limit of bedrock disturbance is not determined by the crater rims, but extends radially outward for two crater diameters. Frequently, a similar distance will be manifested by a radial drainage pattern emanating from some craters, which indicates the degree of control that craters can exert on the local topography. ("Local", however, is an entirely relative and often misleading term.) Fig. 7 shows the effect of a titanic impact on the "local" lunar surface. Cratering events of this magnitude in addition to creating mountainous basin rings and mega-terraces, are believed to be responsible for magmatic up-welling. Terrestrial equivalents to the lunar Orientale basin are not observable on the surface. Dence (1972) suggested that large-scale impacts may have occurred while the early continental crust was assuming its present form and that impact events possibly played a major role in the initial stages of continental formation.

Some of the larger probable surface impact sites are Manicouagan, Canada (70km diameter), Popigai, USSR (100km). Sudbury, Canada (140km) and Vredefort, S. Africa (also 140km diameter). In addition to thousands of smaller craters, there is no reason to believe why craters of these larger dimensions have not contributed to extensive worldwide basement modification.

The potential for structural and stratigraphic traps created by the impact process is readily evident in Figs 2 and 3. Under proper conditions, both simple- and complex-type impact craters have a significant potential as hydrocarbon reservoirs. This potential can be

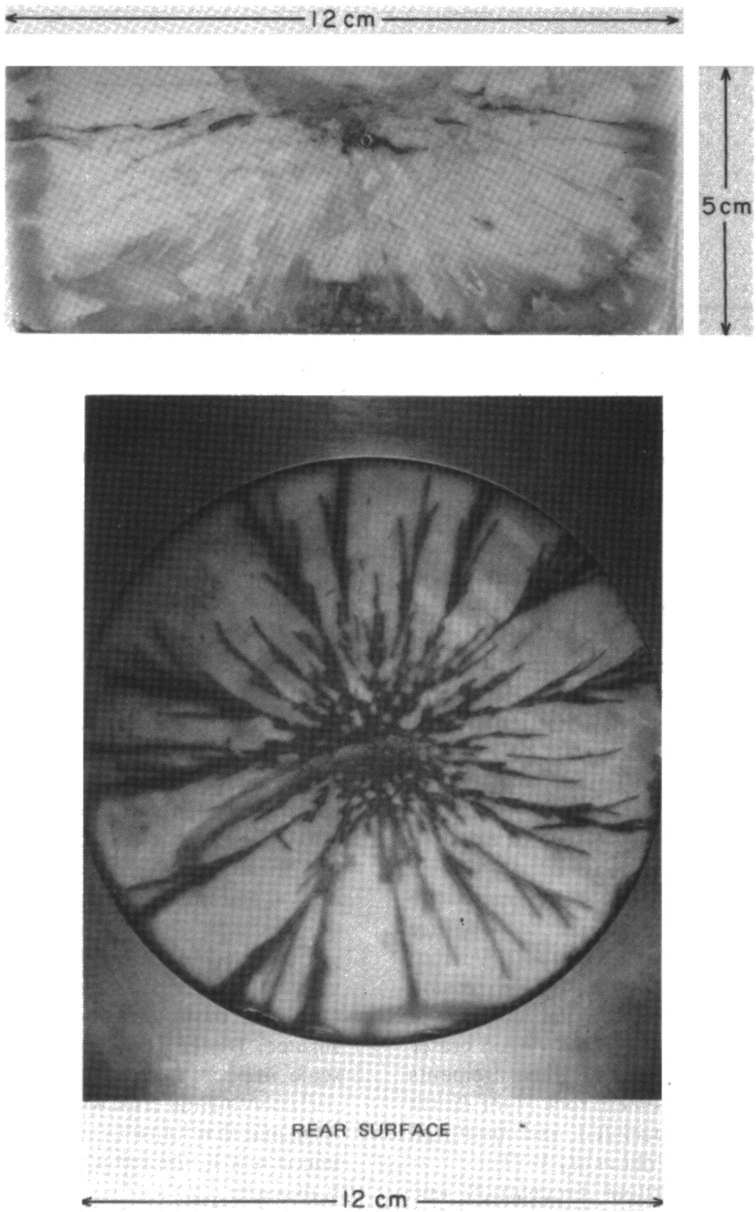

Fig. 5. Effects of impact generated shock on Arkansas novaculite (photograph courtesy of D. R. Curran).

appreciated by briefly examining several petroliferous structures suspected as being of impact origin, two of which are developed in sediments and one which is proposed to be a crystalline basement astrobleme. All three are found in the North American Williston Basin, where "pancake" stratigraphy often facilitates the detection of many subsurface structural anomalies.

Viewfield

The Viewfield oil pool was discovered in 1969 after a routine seismic survey indicated the presence of a subtle circular-shaped anomaly. Subsequent well control has shown that the feature is composed of three principal elements:

1. A deep cavity cut into Mississippian carbonates which has been filled by an

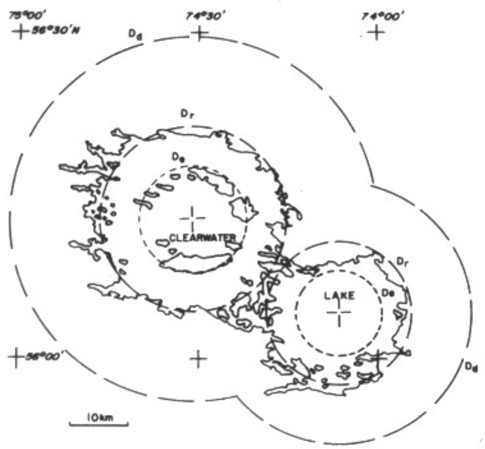

Fig. 6. Plan view of Clearwater Lake, Quebec: Dd the outer fracture zone marking the limit of bedrock disturbance: Dr the estimated position of the topographic rim prior to erosion; De, the limit of the excavated cavity. The cross marks the center of the central uplift in each crater (from Dence, *et al.*, 1977).

anomalously-thick Jurassic Watrous Red Bed section (Fig. 8).

2. An oil-bearing Mississippian carbonate breccia which forms a rim facies around the central cavity, and is located at the Watrous Red Beds time-stratigraphic level. (Fig. 9).
3. Mississippian beds which surround the cavity and rim facies. Oil-bearing Griffin beds are located at the Mississippian unconformity over most of the area; the underlying Stoughton beds also are oil productive in certain areas.

The rim facies isopach reveals an irregular lobe-like pattern radiating outward from the central cavity, with highest isopach values generally found midway between the inner and outer 0-foot contour intervals. It is interpreted to slump towards the central cavity, and in the 13-33 and 14-20 wells, lies between the same red beds filling the central depression near the 15-29 location (Fig. 8).

Pay thickness in the rim ranges from l2-170ft (3.6-52m) with some wells producing up to 400 brl/day. Core analysis of the breccia from these wells has shown an average porosity of about 14% and an average permeability of about 400 md. The rim facies is stratigraphically trapped by anhydrite and siltstone.

Adjacent to, and in some areas underlying. the rim facies is the oil-bearing Mississippian Griffin carbonate. Oil accumulation in these beds is largely unrelated to the Viewfield structure and the trapping mechanism is due to erosional truncation of the Griffin beds up-dip to the north. These beds are secondary objectives, with pay sections ranging from 15-55ft (4.6-16.7m).

Original oil-in-place of the structure exceeds 75MM brl of which about 20MM brl are recoverable. No wells have penetrated the Mississippian interval below the central depression. The extent of cavitation shown has

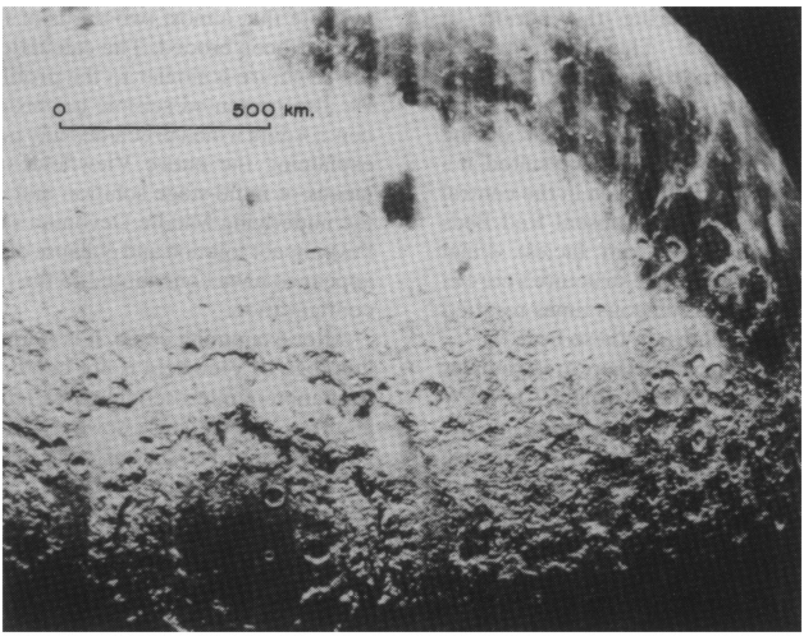

Fig. 7. The lunar Orientale multi-ringed basin (NASA photograph).

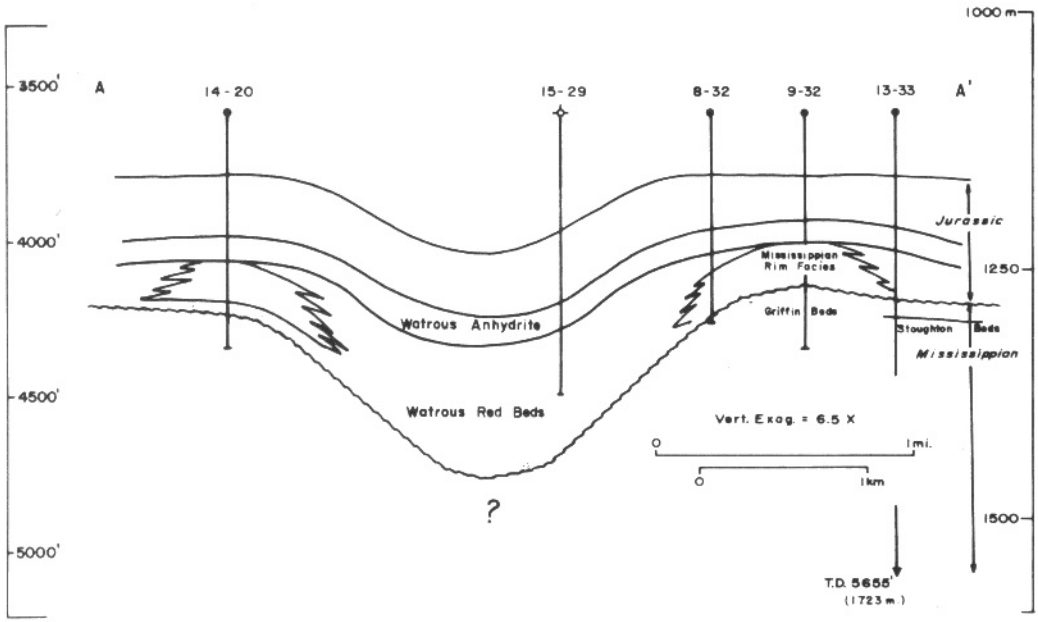

Fig. 8. Cross-section of Viewfield structure.

been estimated by applying Pike's (1977) equations derived from studies of explosion and meteorite craters. Crater depth will vary depending on the original diameter selected.

One of the unpublished endogenic theories for the evolvement and subsequent trapping mechanism of oil for Viewfield was developed by W. H. Clark (personal communication). He proposed a normal Cambrian-through-Mississippian deposition followed by localized upward movement during the period of Mississippian erosion. This uplifted area subsequently was eroded and limestone talus accumulated around the base of the eroding hill. Downward tectonic movement during Jurassic Red Bed deposition then resulted in a relatively-thick Red Bed section in the central depressed area and thin or absent Red Beds over the talus deposits (rim facies). Final downward movement of the structure's core in Late Jurassic-Early Cretaceous times resulted in an increased thickness in these beds.

At the present time, while there are examples of steep-sided, localized highs in SW Saskatchewan, there are none involving the small-scale uplift and subsequent collapse proposed for Viewfield. This feature appears to have formed independently of the regional tectonics and has the characteristics of a simple-type crater. The breccia, or talus, which forms the rim facies, however, may have been created following the impact event. Crater rims are formed by overturning of the target rock which, if brittle, can be fractured, but not usually brecciated to the degree shown in the Viewfield cores. If left uncovered, rim rocks will be eroded in a similar manner as any hill or elevated structure, however, and can become breccia or talus deposits.

Sawatzky (1972) proposed an impact origin for Viewfield and showed that the dimensions could be explained by employing empirically-derived explosion-crater equations which indicate that almost two-thirds of the original rim has been eroded. The calculated depth of the structure is similar to the profile in Fig. 8. He also presented seismic isochron and well-control data which precluded any possibility of explaining the entire Viewfield anomaly by means of multi-stage solution and collapse of the underlying Middle Devonian salt horizon. Post-impact solution and collapse did, however, appear to have contributed to the present-day configuration.

After examining cores, it is evident that the lithology of Viewfield is not conducive to the formation of microscopic shock-metamorphic features. Carbonates, however, do afford a good medium for shatter cone development, but when found in simple craters, their location is limited to the crater floor area. As previously noted, no wells have reached this depth in the central cavity.

The presumed lack of meteorite fragments at Viewfield could be a function of crater size rather than the Jurassic/Triassic impact age. If

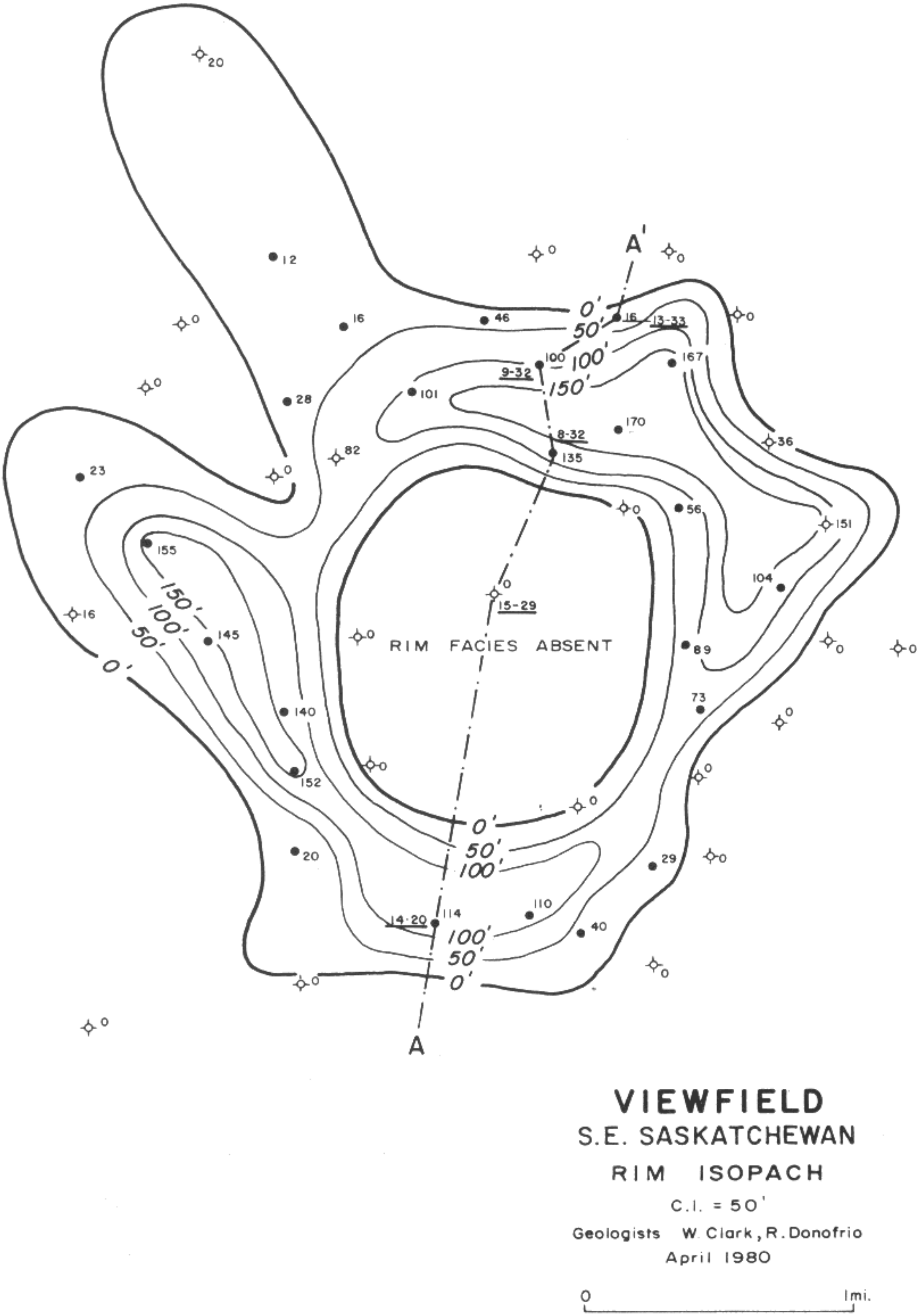

Fig. 9. Isopach of the brecciated Mississippian rim facies at Viewfield oil pool.

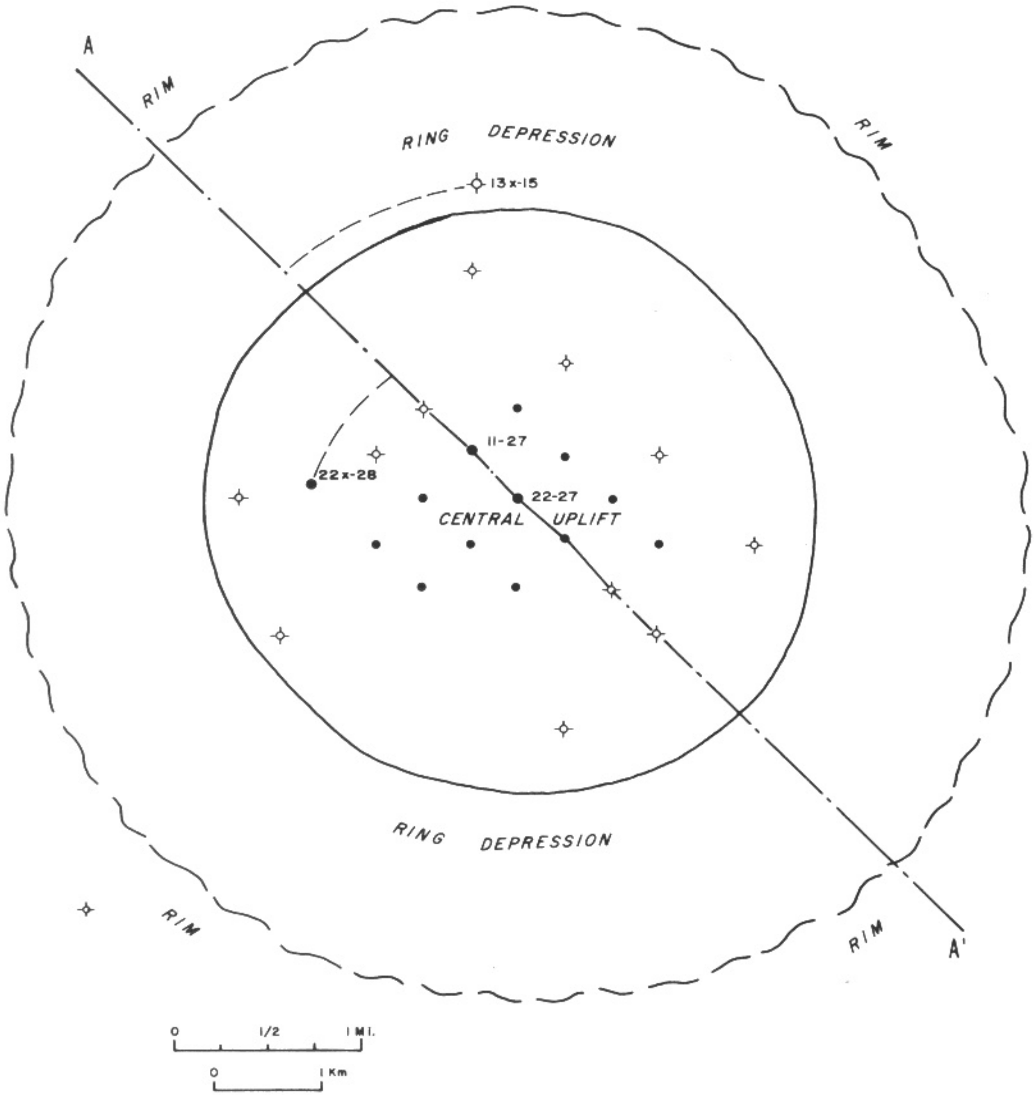

Fig. 10. Plan view of Red Wing Creek (modified from Brenan, *et al.*, 1975).

fragments originally existed in the breccia at Viewfield, they would probably remain because of preservation by later sedimentation. However, discrete meteoritic fragments have not been found in craters larger than Meteor Crater presumably because the initial energy at larger craters vaporizes or melts the meteorite. According to Grieve and Robertson (1979), only 13 *proven* impact craters have been found, all of which are Recent in age and none of which islarger than 1.2km in diameter.

Although the Viewfield structure does not appear adequately to be explained by normal endogenic tectonics, the process of elimination is insufficient to warrant impact classification other than *possible* to Viewfield. This category will remain until shock-metamorphic features are detected.

Red Wing Creek

Exploration of the Red Wing Creek structure was begun in 1965 after seismic coverage had revealed a pronounced anomaly. The first well, 22X-28 initially was abandoned as dry, and was followed three years later by the 13X-15 well, also dry (Fig. 10). A significant difference in the structural elevations and thicknesses of several beds was noted, but no further drilling took place until the leases were relinquished and acquired by another operator

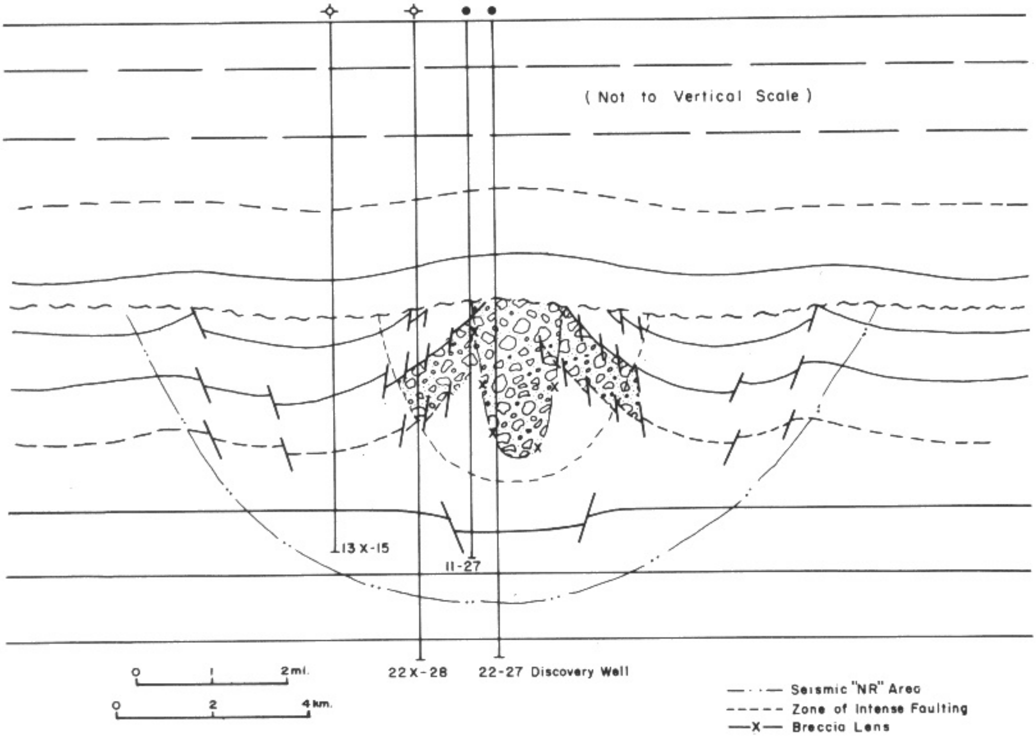

Fig. 11. Diagrammatic cross-section of Red Wing Creek (modified from Brenan, *et al.*, 1975).

about four years later.

The 22-27 well in this new exploration program was located about 2km east of the 22X-28 well. The primary objective was rumoured to be a small Ordovician structure believed to be present beneath an anomalous seismic zone interpreted as an area of intensive deformation. *En route* to the Ordovician, the well found an 823m (2,700ft) oil column in the Mississippian, 487m (1,600ft) of which was net pay. An initial production test in the brecciated carbonate flowed 750 brl/day of 41.8°API oil. The Ordovician structure turned out to be a velocity anomaly.

Additional drilling revealed the unique structure of Red Wing Creek (Fig. 11) and resulted in numerous theories of origin, which included everything from a fault breccia to a pregnant bioherm. After reviewing geological and geophysical data, Brenan *et al.*, (1975), proposed that the structure was of meteoritic origin. They noted that the 10km diameter structure could be divided into three main provinces: a central uplift surrounded by a ring depression which in turn is surrounded by an outer rim. These are summarized below:

1. The central uplift is about 6.5km in diameter and consists of a chaotic arrangement of thrust faults, moderate- to steep-dipping beds, and overturned beds. Based on log correlations, the structural pattern is interpreted as having a 1.6km diameter inner zone of intense deformation and uplift, away from which deformation decreases in both horizontal and downward directions. Within this area of maximum deformation which has created a mega-breccia, Mississippian carbonates have been thrust as much as 915m above regional subsurface elevation. The main productive area of the structure is confined to this mega-breccia. The original 22X-28 "dry well", however, is an exception; it was later recompleted as an oil well by another operator.
2. The ring depression is a syncline or graben which surrounds the central uplift. It is approximately 1.6km wide and is bounded by deformed rocks of the outer rim. The principal deformation evident in the ring depression is normal faulting, with fault blocks having moved inward towards the central uplift as well as downward. Displacements in the upper horizons range from 175 to 115m below expected regional elevations, and as much as 975m below

equivalent formations in the central uplift.

3. The outer rim surrounds the ring depression and is composed of mildly-deformed rocks. Formations in this area are 90-185m structurally higher than their equivalents in the ring depression. A discontinuous narrow anticline with 45-60m of closure parallels the boundary between the rim and ring depression. Seismic investigation has shown that it has a width of less than 1.6km at its widest location.

The Red Wing Creek structure can be classified as a *probable* complex crater, since the requisite shock metamorphic features have been detected in drill cores and cuttings. These features include distinct shatter cones and radiating concussion fractures in quartz grains. French *et al.* (1974) and Kieffer (1971) discuss the occurrence of the latter at meteorite impact sites and interpret the fracture pattern as the result of grain motion and contact during the passage of a shock wave. The impact age at Red Wing Creek is Jurassic/Triassic, and the size of the crater precludes survival of meteoritic fragments, thus preventing a *proved* impact crater designation.

Calculations show that the central uplift megabreccia has trapped in excess of 130MM brl of oil, virtually all of which is confined to a 1.6km diameter area. Recoverable reserve estimates range from 40-70MM brl. Additional pay zones are possible in this type of crater because of secondary structures resulting from vertical and horizontal deformation of the main producing interval. An alternative formation mechanism has been proposed by Bridges (1978), who noted the proximity of supposedly intersecting Precambrian strike-slip faults to the central uplift area, and suggested that Red Wing Creek is a *concentricline* of structural origin. He defined the term as a small structural uplift composed of concentric elements in which the dip is inclined either toward or away from a common center. These features are proposed as developing slowly over a period of millions of years at the intersection of strike-slip faults. The presence of shatter cones, shattered quartz grains and breccia at Red Wing Creek accordingly would not be due to shock, but attributed to fault movements.

This proposal is similar to the lineation argument which has been used to favor an endogenic origin for certain craters e.g., the Ries and Steinhem Basins (Bucher, 1963). In this argument, the occurrence of high-pressure, high-strain-rate, high-temperature rock phases and shatter cones are usually explained by long-term, low-pressure, conditions or unknown endogenic processes. Were it not for the tons of meteoritic fragments at Meteor Crater, the fault-line argument could also be proposed. Bucher initially believed Meteor Crater to be of endogenic origin, and considered the meteoritic débris to be unrelated to the depression. It did not take long for one of the founders of astrogeology, Gene Shoemaker, to convince him otherwise.

Relative to the petroleum industry, it makes little difference as to the exogenic or endogenic origin of certain craters. The important consideration is to recognize that these features are unique hydrocarbon traps having considerable economic potential. Therefore, while sufficient evidence for an impact origin is present at Red Wing Creek, the proposal by Bridges (1978), or similar lineation rebuttals for other craters, should not be discarded. In areas where strike-slip faults are believed to intersect, the explorationist should consider the possible presence of “pseudo-impact features”, recognize the hydrocarbon potential of such structures, and plan an exploration program accordingly.

Hypothetical Model

At Viewfield and Red Wing Creek, the suspected impacts occurred in the sedimentary column and resulted in normal, though relatively large, oil accumulations. A logical extension of the impact process is to apply it to crystalline basement and for the present, assume the same classical criteria espoused by the organic hydrocarbon theory.

According to Landes *et al.*, (1960), source rock, reservoir rock, seal and trap are the four essentials for any oil pool. The only major difference between basement rock and overlying sedimentary rock oil deposits is that in the former case the original oil-yielding formation (source rock) cannot underlie the reservoir. Normal basement-rock accumulations obtain their oil from one of three possible sources: (1) overlying organic rock from which the oil was expelled downward during compaction, (2) lateral, off-the-basement but topographically-lower, organic rock from which the oil was squeezed into an underlying carrier bed through which it migrated updip into the basement rock, and (3) lower-lateral reservoirs, from which earlier trapped oil was

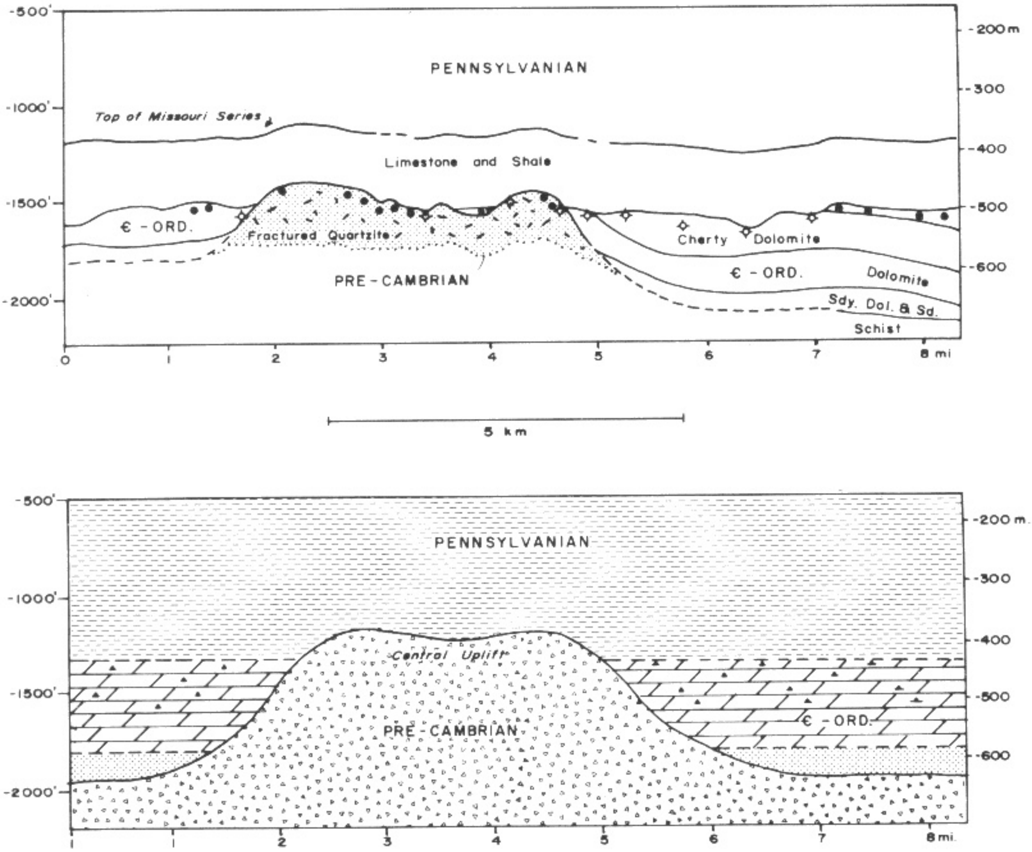

Fig. 12. Cross-sections comparing a petroliferous basement section in Kansas with the profile of a hypothetical complex impact crater in the same area (Upper diagram modified from Walters, 1963, by Landes, *et al.*, 1960).

spilled due to tilting, or to overfilling.

With the basic rules of organic origin, migration and accumulation in mind, a comparison is now made between a petroliferous basement section of the Central Kansas Uplift and a complex impact crater having similar dimensions (Fig. 12). The intention is to illustrate what might have occurred had an impact feature been present.

Tectonically, the Central Kansas Uplift is a broad arch which trends NW. It has a Precambrian crystalline core and is flanked by upturned and bevelled Cambro-Ordovician, Ordovician, and Mississippian sediments. Pennsylvanian sediments both abut against buried Precambrian hills and are draped over them in gentle anticlinal folds. The oil occurs in fractured Precambrian quartzites on the summits of these buried hills and is believed to have migrated into the quartzite from either the flanking Cambro-Ordovician beds or from the overlying Pennsylvanian rocks (Landes *et al.*, 1960).

The hypothetical complex impact crater used in the analogy has fractured and elevated the Precambrian prior to the deposition of the Paleozoic sequence. Provided the central uplift was moderately preserved, the proposed Cambro-Ordovician/ Pennsylvanian source beds could have been contiguous, with fractured and brecciated crystalline rock having much greater horizontal and vertical extent than that produced by endogenic processes. A smaller, simple-type crater, could have had a preserved elevated rim structure flanked or overlain by source beds as well. Depending on the depositional environment, elevated basement areas resulting from impact structures can also be conducive to reefal formation as well as affecting the configuration of overlying and adjacent sedimentation.

Considering the extent of source rocks overlying or in proximity to basement in many petroleum basins, conditions similar to the presented hypothetical model are probably not uncommon. The reader is requested to

Crater	Location	Diameter (Km)	Impact Age (my)	Preservation Level	Core Depth (m)	Core Location	Type Breccia	ø %	K (md)	Potential Reservoir Volume (MMBbls)
Brent	Ontario, Canada	3.8	450± 30	4	315	Upper Central Breccia Lens	Felspathic Gneiss	25.2	0.13	3,398(Avg)
					421	Middle Central Breccia Lens	Felspathic Gneiss	18.4	0.10	
Deep Bay	Saskatchewan, Canada	12.0	100± 50	3	430	Breccia Lens, off flank of Central Uplift	Garnetiferous Gneiss	21.4	13.70	7,680
					103	Crater Rim Base	Garnetiferous Gneiss	8.5	0.01	Non-productive
					443	Central Uplift	Garnetiferous Gneiss	14.9	0.05	Non-productive
Lake St. Martin	Manitoba, Canada	23.0	225± 40	4	135	Breccia Lens, off flank of Central Uplift	Granitic Micro Breccia	26.2	0.37	29,480
Ries Basin	Southern Germany	23.0	14.8± 0.7	2	Surface	Exposed Central Uplift	Suevite	33.0 34.2	10.90 11.50	34,580(Avg)

Table 1. Core analysis from exposed crystalline basement impact craters. Permeability less than 0.10 md is considered non-productive without open fractures (impact age and preservation level index from Grieve and Robertson, 1979): 2, ejecta partly preserved; 3, ejecta removed, rim partly preserved; 4, rim largely eroded, crater products preserved.

turn to Fig. 1 and imagine a marine depositional sequence over the photographed region. It should be evident that there is nothing exotic or unusual about reservoirs of this nature, as the impact process is simply an exogenic means of modifying crystalline basement. According to the biogenic theory, the presence of hydrocarbons will depend on the same rules that apply to normal petroliferous basement areas.

Core Analysis

With the assistance of NASA and the Canadian Department of Energy, Mines and Resources, a number of diamond drill cores were obtained from four currently-exposed basement impact craters, and subjected to routine core analysis. Cores were not available from any of the subcrater fracture zones nor from buried craters developed in crystalline rock; pressure drawdown and related material balance data also had not been taken. These few breccia samples are therefore not intended to be representative of basement astroblemes, but are suggestive of impact-generated temperature/pressure effects and unprotected crater age on reservoir properties (Table 1).

Hydrothermal alteration and decomposition products along with melt rock were noted in the Brent cores, and are mostly responsible for the low permeability factors. Similar alterations were noted in cores from the eroded crater rim base and central uplift at Deep Bay. A core from the breccia lens encompassing the central uplift however, showed the highest porosity and permeability at 21.4% and 13.70 md respectively. The Lake St Martin sample is pulverised basement rock and also showed extensive mineral alterations.

The sampled rock from the Ries crater originates in a homogeneous layer up to 400m thick and is termed a *suevite.* Pohl *et al.,* (1977) discuss the occurrence of this and other breccias at the Ries. It can be described as a depositional polymict breccia of predominantly basement material, containing glassy inclusions which give the appearance of volcanic tuff-breccia but can be distinguished in thin-section by the presence of distinct shock-metamorphic effects, some of which (Stoffler, 1971) indicate overpressures approaching 1,000 kb and temperatures (Chao, 1968) exceeding 1,500°C.

The prime reason for the marginal permeabilities in Table 1 is most likely the prolonged cooling of the breccias to ambient temperature following impact. Pohl (1977) calculated that one particular 200m thick suevite layer at the Ries took about 2,000 years to cool from 600° to 100°C. The mineral alterations with subsequent permeability reductions are understandable given these or similar conditions.

The reservoir potential of the larger partially-preserved astroblemes in Table 1 exceeds many of the most prolific conventional petroleum accumulations known. Even with the relatively small-diameter Brent crater, the calculated reservoir volume of almost 2MM acre-feet reveals the uniqueness of these reservoirs. Basement astroblemes of various dimensions invariably exist in the subsurface and have succeeded in accumulating hydro-

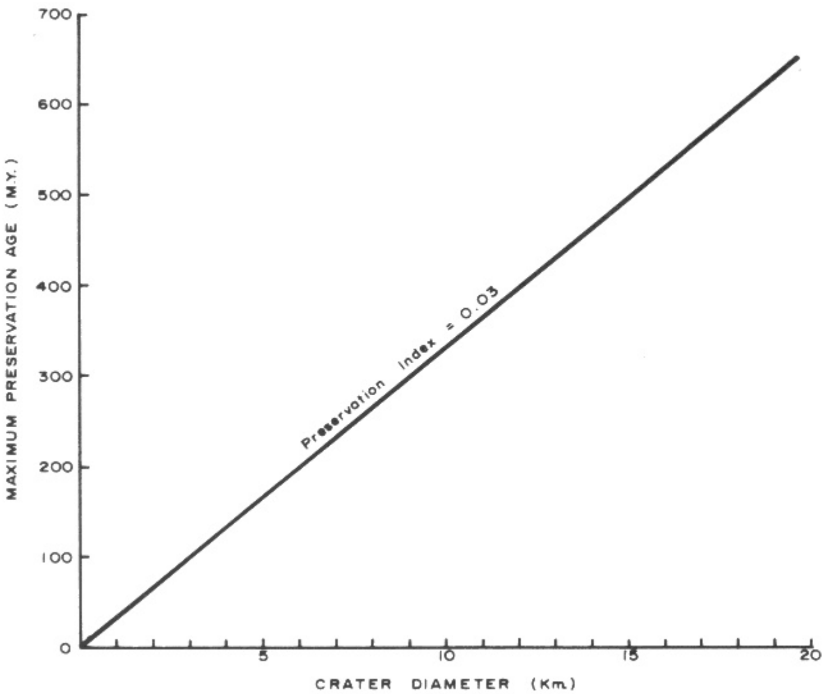

Fig. 13. Plot of maximum preservation age against crater diameter for probable impact structures (extrapolated from Grieve and Robertson, 1979).

carbons in these massive breccia lenses and central uplifts, as well as in the rim rocks of smaller simple-type craters.

Extensive open fractures, however, would not be necessary to enhance the reservoir properties of any fractured or brecciated reservoir. According to Daniel (1954) and Gorham *et al.,* (1979) depending on pressure, oil gravity and attitude of the fracture plane, a single Imm wide fracture intersecting a well bore can provide permeability sufficient to produce between 7,000 and 10,000 brl/day of oil.

Crater Preservation Age

In addition to pressure and temperature effects occurring in the target rock, the exposure time of an impact crater to weathering elements is an essential reservoir consideration. Exposure affects not only the porosity and permeability of the host rock but, in tectonically-stable areas, is the prime agent determining the degree of post-impact structural modification.

Fig. 13 shows a plot of maximum preservation age against crater diameter. The slope corresponds to a preservation index of 0.03, which was derived by Grieve and Robertson (1979) in a study comparing the age and erosional levels of 70 probable impact structures. For a I km diameter crater, the maximum exposed preservation age is about 30my,, whereas a 20km diameter crater will survive for about 600my. Referring to Table 1, it will be noted that the diameter of Brent is 3.8km, which corresponds to a maximum exposed preservation age of about 125my. The crater age, however, is 450±30my, indicating that the presently-exposed feature was covered for a lengthy period.

With simple craters, the rim will be eroded the fastest followed by gradual downcutting of the breccia lens which eventually will expose the crater substructure (Fig 14). At this erosional level, the impact feature will have lost its identity. As complex craters have subdued rims and pronounced central peaks, the latter will be eroded the faster. No published estimates have been made for the preservation age range of subcrater fracture zones. At this erosional level it would be comparable to a peneplain and the preservation age would depend on the depth and extent of fractures. The subcrater fracture zones of large craters such as the Ries would probably take billions of years to eliminate.

It will be noted in Fig. 14, that elimination of the rim at “B” level, still leaves the possibility

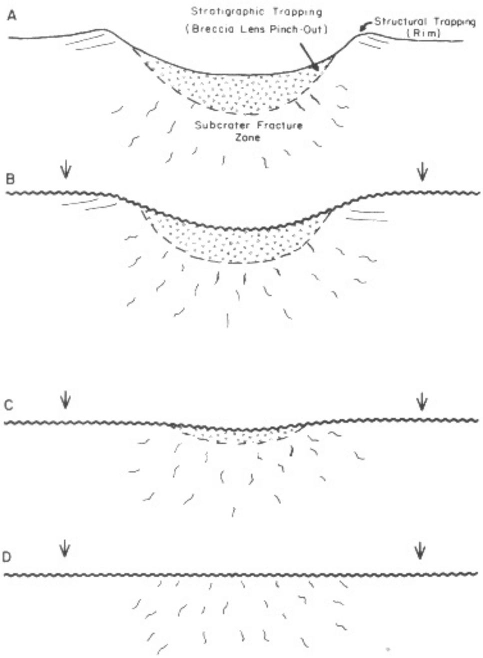

Fig. 14. Progressive crater erosion.

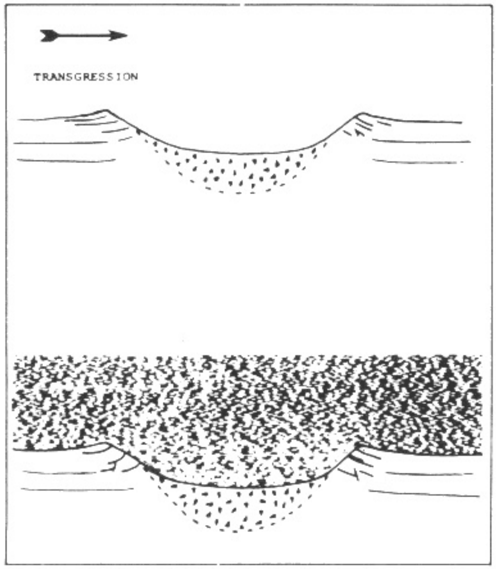

Fig. 15. The intact impact.

of stratigraphic trapping in the breccia lens area contiguous with the crater wall. Even downcutting into the crater substructure (D) may not totally eliminate the reservoir potential of either simple-or complex-type craters. Such *syncline* features developed in basin areas characterized by overpressured conditions which frequently favor downward hydrocarbon migration and tight cap rocks, should be considered prime drilling objectives as much as craters having preserved rims or central uplifts at higher structural elevations.

Ideal crater preservation lends itself to the term *intact impact* (Fig. 15). Factors favoring this condition would consist of a fresh astrobleme covered by a relatively rapid-moving transgression. For craters of increasing diameter, the exposure time can be extended without severely diminishing the integrity of the crater profile. Actively-rising continental areas are the least desirable for preservation purposes, whereas rapidly-subsiding basins favor the *intact impact.*

The previously-discussed Viewfield and Red Wing Creek structures both exhibit moderate erosional profiles developed in sedimentary rocks. An example of a similar erosional profile developed in crystalline rocks and buried by a marine transgression is now given.

Newporte

The Newporte structure (Des-Lacs Field) in Renville County, North Dakota, very probably originated by hypervelocity impact, and could represent the first discovery of a petroliferous basement astrobleme. A conceptual cross-section of the 3.2km diameter circular depressed structure is shown in Fig. 16.

According to Clement and Mayhew (1979), geophysical evidence indicated that the structural feature involved all early Paleozoic sediments and probably the Precambrian basement as well. The Larson 23X-9 wildcat was subsequently drilled to basement with primary objectives in the Ordovician. No encouraging recoveries of hydrocarbons were found in this interval, but the Cambro-Ordovician Deadwood sandstones, resting unconformably upon Precambrian schist,

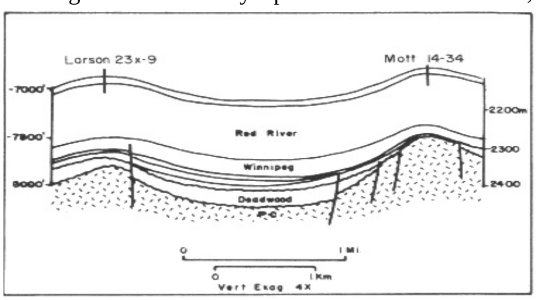

Fig. 16. Conceptual cross-section, Newporte field (from Clement and Mayhew, 1979).

flowed 233 brl of 30° gravity crude at an estimated rate of 166 brl/hr. The well was drilled about 130ft (40m) into basement with no further hydrocarbon shows. Another well, Mott 14-34, positioned on the other side of the structure, penetrated a "highly-fractured, vuggy and weathered Precambrian gneiss-schist sequence" nearly 350ft (106m) structurally high to Precambrian rocks in the Larson 23X-9 well. The Mott well was cored and drill-stem tested a flow of 202 brl of oil during an open period of 190 minutes. It was subsequently completed, pumping 40 brl/day of oil, 380 brl/day of water and 10 million cu ft/day of gas.

Core analysis of the Precambrian interval 9,094-9,099ft (2,771-2,773m) shows an average porosity of 4.7% and an average permeability of 0.48 md. Fluid production rates are incompatible with the low matrix values indicating that some of the fractures are open and interconnecting.

Clement and Mayhew (1979) favor "localized late Precambrian-early Paleozoic differential vertical-basement faulting" and not an impact origin for Newporte. This proposed endogenic mechanism is similar to one of the alternatives suggested for Viewfield, and necessitates an extremely localized circular uplift and subsidence. In both cases, the structures are not related to volcanics nor to the regional tectonics, and have the profiles of simple-type impact craters.

Detection of shock-metamorphic features in this structure would clarify its origin. The proposed target rock at Newporte is Precambrian gneiss-schist which is conducive to a variety of microscopic shock effects. Like shatter cones, which can also develop in crystalline rock, these shock effects are not found in rim rocks, but generally are restricted to the breccia lens or authigenic breccia of the crater floor. At present, no wells have penetrated this area.

Pike (1977) derived equations from experimental explosion and meteorite impact craters which can be used to estimate the apparent depth, if the original diameter is known:

$$R_i = 0.196\ D_r^{1.010}$$

where R_i = depth (km)

D_r= diameter (km)

As evident in the core description, the Newporte structure has been eroded, and consequently the present 3.2km diameter is larger than the original dimensions. If 3.0km is used as the uneroded diameter, an original apparent depth of 594m (1,950ft) is obtained. A well positioned above the Newporte depression would have to exceed 3,350m (11,000ft) in depth to encounter the top of the allogenic breccia where shocked features, if present, could be found. Another possibility is the presence of *pseudotachylites,* an injection breccia containing shocked material which is emplaced in fractures created during an impact event. This particular feature has been found in the rim area of at least two larger astroblemes and could be present in some of the Newporte cores. A thorough examination of available basement cores will be undertaken to clarify the origin of this structure. If an impact origin can be established, it will indicate that petroliferous basement astroblemes are more than mere speculation.

For the present, however, petroliferous impact craters in crystalline rock have not been reported. This does not necessarily mean that none has been found, but rather that none has been *recognized.* As the vast majority of geologists are unfamiliar with astrogeology, especially with regard to shock metamorphism, an accidental "bulls-eye" into a subsurface impact crater would usually see the feature attributed to some normal endogenic process. Encounters with "fault breccia", "cone-incone", "granite wash" and curious "volcanic" or "pyroclastic debris" are frequently noted in drilling reports and core analyses which, in view of terrestrial cratering estimates, raises the question as to just how accurately the lithology is being interpreted. An example of this confusion is illustrated by core analysis of an unusual basement feature in Alberta, Canada.

The Steen River Structure

The Steen River geophysical anomaly in NW Alberta was drilled and cored in 1963. This roughly-circular 22km diameter feature lies about 183m beneath the surface, where the basement is elevated about 760m above the regional Precambrian level. The surrounding area exhibits no other pronounced subsurface or surface features. Cores were cut at various intervals and sent to a leading Canadian laboratory for analysis. A copy of the original Detail Core Study was recently obtained, part of which appears in Fig. 17.

It will be noted in the description of the selected interval that the interpretation is "in volcanic", with mineral alterations attributed

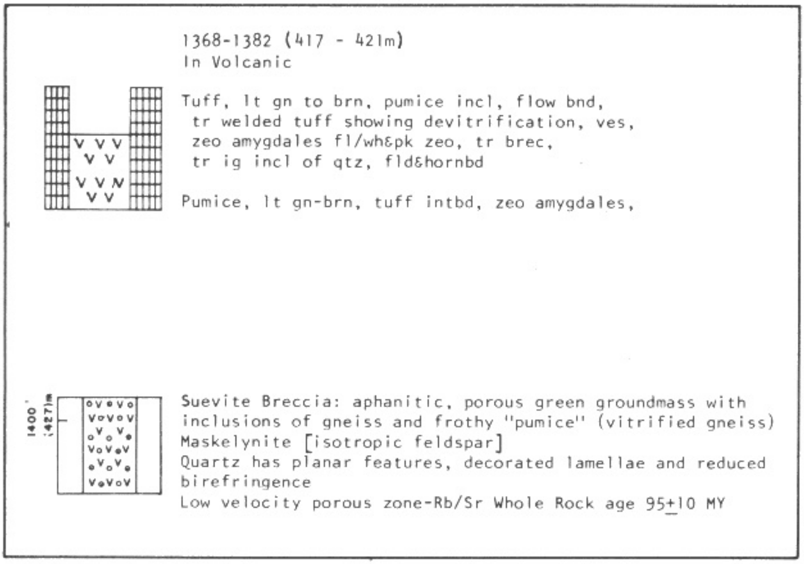

Fig. 17. Core descriptions of Steen River. The upper diagram is the original interpretation by a core laboratory. The lower diagram shows the correct description (from Winzer, 1972).

to igneous activity. Descriptions such as this appear throughout the report. The lower part of Fig. 17 shows another interpretation, in this case by a geologist familiar with shock metamorphism. It was concluded by Winzer (1972) that these rocks show all the main petrographic features found in terrestrial meteorite impact craters, with the exception of coesite, and that the absence of a terrestrial process capable of producing maximum shock pressures of 400-500 kb required for the noted shock-metamorphic effects, provides convincing evidence for an impact origin. Winzer's work confirmed the earlier studies by Carrigy (1968) who first proposed that the shock effects in Steen River cores were similar to those from impact structures.

Having recently examined a section of the same core, it is evident that the deformation is not due to or associated with true volcanism, but is the product of high-pressure shock waves in Precambrian crystalline rocks. The core location corresponds to the central uplift area in complex-type impact craters. One can only question how frequently errors of this nature are made during drilling operations into sedimentary and crystalline rock.

On the basis of probability, considering terrestrial cratering rates and the 3.3 million wells drilled into the earth's crust, it is with certainty that unrecognized impact features have been encountered and that many of these contain commercial hydrocarbons. Undoubtedly many explorationists have unknowingly penetrated impact features and, not finding commercial hydrocarbons on the first or second attempt have given up, only to have another operator move in and make the discovery. If the petroleum geologist encounters and is unable to recognize an impact crater, he cannot realize that the well is into a structure which is independent of the regional geology and possesses a unique geometry of its own. Housed within that unique geometry are potential pay zones of magnitudes which tend to dwarf classical geological features.

Recognition, however, constitutes only part of the problem. With basement impacts it would not be surprising if only an insignificant number of petroliferous astroblemes were ever found. The possibility that this could occur is directly related to the continued ignorance of crystalline rock hydrocarbon potential, something which I have termed the *basement syndrome.*

The Basement Syndrome

It is the overwhelming opinion of explorationists that basement rock is essentially "non-productive". Calculations show that crystalline basement currently supplies less than 1% of total world oil production, which would appear to justify stopping the drill bit short of entering it. Such justification however, is based on totally inadequate statistical information, and represents poor geological reasoning. The

BASIN	TOTAL WELLS DRILLED*	TOTAL BASEMENT WELLS	% WELLS DRILLED TO BASEMENT	MI²/ REGULAR WELL	MI²/ BASEMENT WELL	PRODUCTION TESTS IN BASEMENT
Williston (U.S.)	14,950	158	1.05	5.78	541	1
Denver/Julesburg	33,544	98	0.29	1.03	353	0
Powder River	20,761	21	0.10	1.01	1,004	0
Unita	1,847	5	0.27	3.64	1,343	0
San Juan	17,197	73	0.83	0.51	120	1
Big Horn	7,444	17	0.23	0.93	404	1
Green River	7,827	72	0.92	0.97	104	5
Paradox	3,919	41	1.04	3.50	331	0

Table 2. The basement syndrome *(well data compiled by Petroleum Information Corp. as of November 1979) 1 sq mi = 2.6 sq km.

explanation for the "non-productive" reputation of basement may not lie in the nature of the rock, but results from the routine practice of not drilling into it.

Table 2 shows the drilling compilation of various US basins used for this study. It is immediately evident that basement in these particular areas remains virtually unexplored; probably in no instances was it the primary objective of the well in question, and of the 107,489 cumulative wells drilled as of November 1979, only 485 (0.45%) penetrated basement. Of these 485 wells, 8 ran production tests in basement, which resulted in two completions.

Twenty years ago, Landes *et al.* (1960) documented a number of commercial basement oilfields (practically all of which were accidental discoveries), and attempted to alert geologists to the hydrocarbon potential of weathered and fractured crystalline rock. Table 2 is evidence that this advice was not heeded in the slightest. Further evidence is found in estimates of total world recoverable reserves (Grossling, 1976) which, exclusive of a few known petroliferous basement areas such as Venezuela and Algeria, only consider the volume of rock above basement as having any hydrocarbon possibility.

Basement production and reserves estimates will continue to be insignificant for as long as the practice of avoiding crystalline rock continues. The basement syndrome continues to dominate exploratory drilling, regardless of the basement depth. In addition to normal porous endogenic basement structures, one can only speculate about the number of pronounced and subtle basement features indicative of impact craters which were eliminated from consideration in Table 2 basin areas and other regions throughout the world.

Detection Methods

Seismic

Sawatzky (1977) gave the seismic profiles of several suspected astroblemes developed in the sedimentary column. Outside of Newporte (Clement and Mayhew, 1979), high-resolution seismic data of suspected buried basement craters either is not available or has not been recognized.

A method of circumventing this problem is to use processed seismic-section models, as these can reveal the expected signals from subsurface basement astroblemes at various erosional levels, overlain by differing sedimentary sequences. An example of this is shown in Fig. 18. The parameters used for this particular seismic model were taken from Brent crater, and include the crater dimensions and basement rock densities in the breccia lens and surrounding country rock. The erosional profile of Brent parallels "B" in Fig. 14. Burialdepth was programmed to about 12,500ft, with a normal marine sequence covering the feature. All seismic multiples are included in the model.

The low-velocity pullup will be noted towards the center of the breccia lens. Negative deflections at the top of the unconformity are due to the brecciated zone beneath higher velocity shales. Of interest to anyone familiar with seismic sections is that similar basement signals are occasionally observed in routine seismic surveys, suggesting the possible presence of impact cratersand consequently of potential reservoir material. As previously noted, a basement syncline profile of this nature should be a prime drilling objective.

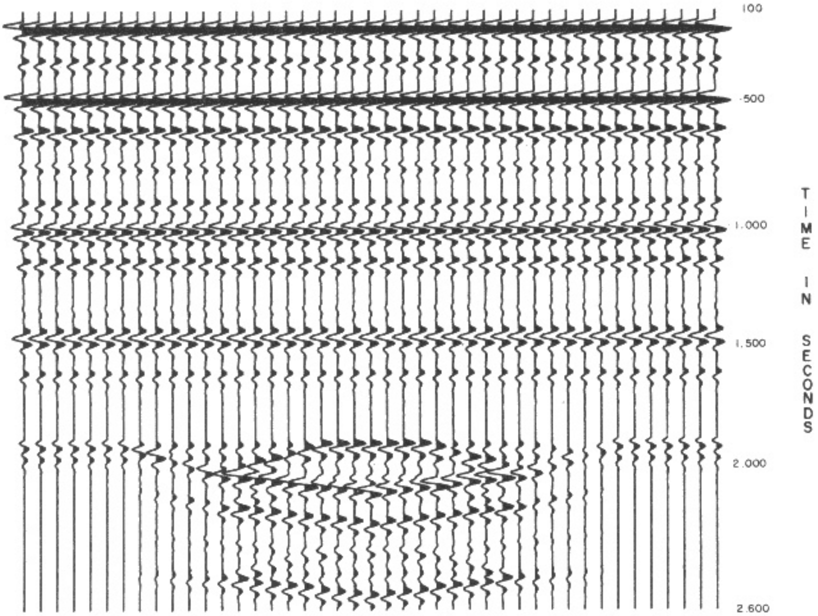

Fig. 18. Processed seismic section model of an eroded basement astrobleme overlain by a normal marine sequence. Plot is SEG standard with negative deflections to the right and shaded (courtesy of CSI PrIsm).

Magnetic

In addition to a thorough review of existing seismic records, emphasis should be directed towards the utilization of magnetic detection methods. While magnetic surveys are of little use in detecting impact craters in the sedimentary column, such surveys eventually should prove feasible in detecting impacts in crystalline basement.

Enhanced natural remanent magnetization (NRM) of suevites in comparison with the NRM of constituent rocks has been noted by Pohl *et al.* (1977). They believe this to be characteristic of suevitic impact breccias on earth, and propose that it is mainly due to the generation of magnetite by shock metamorphism and/or subsequent thermal metamorphism. Expounding on this, if the target rock contains hematite and experiences a shock pulse of between 400-500 kb, a transition from hematite to magnetite will result. Slow cooling of the rock material from above the Curie point of magnetite (580°C) to ambient temperature will result in domain alignment with the earth's magnetic field. The combined effect of shock and temperature thus results in a magnetization higher than the surrounding country rock, which usually is detectable by conventional magnetic instruments.

Another more enigmatic NRM-enhancing mechanism is that of Shock-lnduced Polarization, which is believed to be a phenomenon arising from impact in crystalline rock containing piezoelectric. dielectric, and ferromagnetic materials. According to Ivanov *et al.,* (1977), Shock-lnduced Polarization can be conSidered as an electrical current flowing through the shock-wave front. As the shock wave passes through a medium containing shock-polarized materials (e.g. quartz), the induced electromagnetic field could be fixed by the ferromagnetic components (e.g. magnetite). Previous experiments by Mineev *et al.*, (1968) confirmed that shock-compression of polycrystalline materials induces polarization in the direction normal to the shock-wave front. The net effect of this could be an enhanced remanent magnetization, possibly in some instances comparable in intensity to the hematite-magnetite transition. Intensive shock followed by rapid cooling would appear to be necessary to "lock-in" the polarization effect. Ivanov *et al.,* (1977) believe that Shock-lnduced Polarization is a possible cause of magnetic field anomalies detected near certain impact craters by the Soviet lunar probe *Lunokhod 2.* This mechanism could also be the explanation for the unusually-high remanent magnetization values of particular lunar samples discussed by Fuller (1974), as well as for certain tektites and impactites (Donofrio, 1977).

Gravity

The breccia lens of an impact crater consists of shattered rock, usually of lower density than the encompassing country rock from which it is derived. Normally, if a density deficiency exists, it results in a negative gravity anomaly. Dence (1972) noted that sedimentary fill may enhance the negative reading, which most clearly is developed in craters of moderate size. Large complex craters, however, may have an obscured negative anomaly due to a central uplift of denser rocks, erosion, or regional gravity variations (Sweeney, 1978).

Gravity studies of the Ries by Kahle (1969) show a striking, concentric, residual Bouguer anomaly pattern, having a value of about 0 at the crater periphery and progressively reaching about—18 mgal at the center. Similar patterns appear to be typical of well-preserved impact sites. Additional gravity investigations can be found in Innes(1961), Popelar(1972), Sweeney (1978), and Barlow (1979).

Implications of Inorganic Hydrocarbons to Basement Astroblemes

In addition to the *basement syndrome*, the orthodox approach to exploration based on the assumption that all hydrocarbons originate from biogenic sources may need to be rectified. This is not to advocate an inorganic origin for the earth's hydrocarbon resources, but rather to consider the possibility, however remote, that some hydrocarbon accumulations may have originated in part or entirely from abiogenic sources.

Inorganic hydrocarbon proposals speculate that deep disjunctive faults extending into the lower crust or upper mantle are the migration routes to reservoirs in the upper crust. Porfir'ev (1974), for example, noted many instances of oil discoveries in zones associated with deep basement faults. He cited examples of deep faults bordering platform grabens, such as the Limagne graben in France, the Baikal and Barguzin grabens in Siberia, the Rhine graben in West Germany, the Suez in Egypt, the Dead Sea in Jordan, the Reconcavo in Brazil, and the Fusin in China. Major oil accumulations attributed to deep faults resulting from the formation of mountain foredeeps or depressions were also noted. Among others, these included the pre-Urals, pre-Caucasus, western Canada, Iran and intermontane depressions such as California, western Tukmenia and Fergana.

More recently, Gold and Soter (1980), while agreeing that much of the earth's hydrocarbon supply is of biogenic origin, also noted the correlation between major hydrocarbon-producing regions and zones of present or past seismic activity. They state that many of the known hydrocarbon reservoirs, including those of Alaska, Texas, the Caribbean, Mexico, Venezuela, the Persian Gulf, the Urals, Siberia and SE Asia, lie on deformation belts, suggesting that abiogenic hydrocarbons are rising from deep within the earth along fissures in the crust.

Gold (1979) contended that if primeval methane had been the chief source of carbon, then the amount necessary to produce all the carbon in the sediments would be the equivalent of 20 million years of present day fuel consumption. His evidence for abiogenic methane is based partly on earthquake outgassing phenomena, and lends support to Robinson (1966) whose geochemical data suggested both an organic and inorganic origin for terrestrial hydrocarbons. The possibility of a dual origin for hydrocarbons has significant implications for impact craters in basement rock.

The fracture pattern emanating from an astrobleme provides an intricate network of migration channels into the breccia lens. The larger the impact event, the deeper this fracture network. An impacting body creating a 100km diameter crater or larger, for example, is capable of fracturing basement down to a depth in excess of 30km, thus literally "probing" the upper mantle. A basement astrobleme, therefore, (regardless of size) represents the only *known* potential reservoir in "proximity" to lower-crustal or upper-mantle activity. It is deep within this area that abiogenic hydrocarbons have been proposed to be synthesized by some, as yet inadequately explained, process. If migration is occurring along deep-disjunctive faults, then the presence of a basement impact crater in proximity to one of these proposed hydrocarbon conduits may afford an opportunity to test the abiogenic theory. Such a test is feasible with current drilling technology, and need not be limited to petroliferous areas.

Recycled Kerogen

If one prefers to adhere to organic concepts, then an additional method of accumulating hydrocarbons is suggested. In regions where crystalline basement is not directly overlain or flanked by classical source rocks, the possibility remains that impact structures could accumulate hydrocarbons without the necessity of being contiguous with fine-grained source beds. This could arise through *recycled kerogen* which was briefly mentioned by Sanders *et al.* (1976), and is further expounded below.

Sanders (personal communication) suggests that the recycling of kerogen is a possible mechanism for transferring organic matter to, and for generating petroleum within, terrigenous sandstone reservoirs without primary migration. This hypothesis requires two (or more) cycles of sedimentation and subsidence that are separated by an episode of uplift and erosion. In the first cycle, the kerogen forms at suitable depth from “raw” organic matter in fine-grained source beds as is presently thought. If these source beds are later uplifted and eroded, the kerogen particles are free to be transported at the surface and can accumulate in coarse-grained sediments. It is assumed that much of the recycled kerogen can survive weathering, as these sediments subsequently are buried, the recycled kerogen under optimum thermal conditions, can be converted to oil or gas.

The implication of Sanders’ recycled kerogen hypothesis is that porous rock can serve as both source and bed reservoir. This possibility suggests that a basement impact crater could be far removed from carrier beds, thus negating primary migration and still have petroliferous potential if flanked or overlain by coarse-grained sediments containing kerogen. The paleo-drainage system into a basin could determine if any source of kerogen was available.

The point being made in considering both inorganic and organic proposals is that if geological or geophysical evidence suggests the presence of a subsurface impact crater in crystalline (or sedimentary) rock, it should be drilled regardless of the presence, absence, or position of source beds. Unquestionably, with some deep-basement impacts, the capital expenditures will be considerable, but the possible rewards can be enormous. Based on average porosity values in Table 1, and considering the extent of subcrater fracture deformation, the reservoir potential of all fractured and brecciated rock in one 20km diameter crater exceeds the total recoverable reserves of the Middle East. Probability predicts that over 300 craters of this size and larger will have been formed on the earth’s land mass during the last billion years. The maximum exposure age of craters this size and larger is sufficient to assure that someone will have been buried before eradication. The lower preservation age limit of small-dimension craters is offset by their higher population numbers in any given time interval, thus also assuring that some will survive as well. Crater preservation is more than likely at both ends of the dimension scale.

Conclusions

The cratering process is fundamental to all the planetary bodies so far examined and was one of the dominant forces which sculptured the earth’s pre-transgressive basement configuration. This exogenic mechanism, in conjunction with normal terrestrial processes, assures the presence of many areas of fractured and brecciated crystalline rock which are conducive to hydrocarbon accumulations. An unknown number (possibly in the thousands) of astroblemes have been buried at various stages of erosion some of which, like Newporte, were in the right place at the right time. Had an even larger magnitude impact occurred at this location, petroleum accumulations of hundreds of millions of barrels could have resulted.

Geologists should become familiar with shock metamorphic effects, and be aware of the structural parameters associated with astroblemes. 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, especially in basins having overpressured conditions. Structural and reservoir considerations should take precedence over classical source rock arguments, and the possibility of unconventional hydrocarbon generation should be left open. This includes abiogenic synthesis as well as alternate biogenic mechanisms such as recycled kerogen, which eliminates the necessity of primary migration from fine-grained carrier beds. Both of these proposals run contrary to our basic concepts in petroleum geology.

Detection of astroblemes by geophysical or geological methods means that fractured reservoirs have been located. In basement rock, these features represent the closest known potential reservoirs to proposed upper-mantle abiogenic activity. The implications that these reservoirs could accumulate abiogenic hydrocarbons from the base of the structure upwards are profound and need to be tested.

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