

Economic deposits at terrestrial impact structures

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12.1 Introduction

This chapter represents an update of previous reviews (e.g. Grieve and Masaitis, 1994; Grieve, 2005; Reimold *et al.*, 2005) of natural resources associated with some terrestrial impact structures. This chapter, however, is not totally comprehensive with respect to the full economic value of terrestrial impact structures. A more comprehensive list is given in Reimold *et al.* (2005: Table 1), which lists 56 impact structures with 'economic interests', including structures that provide sites for recreational activities and/or serve as tourist attractions. This chapter also does not consider those structures that have been, or are being, exploited as a source of aggregate, lime or stone for building material (e.g. Ries in Germany, Rochechouart in France) or are a source of ground-water or serve as reservoirs for hydro-electric power generation (e.g. Manicouagan in Canada, Puchezh-Katunki in Russia). The economic value of such impact structures, however, can be considerable. For example, the electricity generated by the Manicouagan reservoir can reach the order of 5000 GWh yr^{-1} , sufficient to supply power to a small city and worth approximately US\$300 million per year, at current residential electricity prices in Canada.

Previously, Grieve and Masaitis (1994) and Grieve (2005) considered resource deposits at terrestrial impact structures in the following order: progenetic, syngenetic, epigenetic (Table 12.1). Progenetic economic deposits are those that originated prior to the impact event by purely terrestrial concentration mechanisms. The impact event caused spatial redistribution of these deposits and, in some cases, brought them to a surface or near-surface position, from where they can be exploited. Syngenetic deposits are those that originated during the impact event, or immediately afterwards, as a direct result of impact processes. They owe their origin to energy deposition in the local environment from the impact event, resulting in phase changes and melting. In recent years, there has been greater recognition of the role for post-impact hydrothermal activity at impact structures (e.g.

Ames *et al.*, 1998, 2006; Osinski *et al.*, 2001; Naumov, 2002; Abramov and Kring, 2004, 2007). Post-impact hydrothermal deposits are a logical result of heating due to the impact process and, thus, are considered here as syngenetic deposits. Thus, the remobilization of some progenetic deposits has blurred the separation between progenetic and syngenetic deposits. Epigenetic deposits result from the formation of an enclosed topographic basin, with restricted sedimentation, or the long-term flow of fluids into structural traps formed by impact structures. Commercial accumulations of hydrocarbons at terrestrial impact structures can result from a number of processes related to impact and are considered separately.

12.2 Progenetic deposits

Progenetic economic deposits in impact structures include iron, uranium, gold, hydrocarbons and others (Table 12.1). In many cases, the deposits are relatively small. Only the larger and more active deposits are considered here.

12.2.1 Iron and uranium at Ternovka

Iron and uranium ores occur in the parautochthonous rocks of the crater floor and in breccias at the Ternovka structure ($48^{\circ}08'N$, $33^{\circ}31'E$) in the Krivoj Rog region of the Ukraine, which is well known for its very large iron ore deposits (Nikolsky *et al.*, 1981, 1982). The structure is $375 \pm 25 \text{ Myr}$ old according to Nikolsky (1991) and was formed in a Lower Proterozoic fold belt. It is a complex structure, where erosion has removed most of the allochthonous impact lithologies and exposed the floor of the structure. The central uplift is, in part, brecciated and injected by dikes of impact melt rock up to 20 m wide. The annular trough contains remnants of allochthonous breccia, with patches and lenses of impact melt-bearing breccia (see Chapter 7 for an introduction to impactites). The present diameter of the structure is

Table 12.1 Genetic groups of economic deposits at terrestrial impact structures

Genesis	Principal mode of origin	Type of economic deposit
Progenetic	Brecciation	Building stone, silica
	Structural displacement	Iron, uranium, gold, oil, natural gas
Syngenetic	Phase transitions	Diamond
	Melting	Copper, nickel, PGEs, ^a tektite glass
	Hydrothermal	Lead, zinc, uranium, gold, PGEs, copper, nickel, zeolite, agate
Epigenetic	Confined sedimentation	Oil shale, lignite, calcium phosphate, amber
	Fluid flow	Oil, natural gas, fresh and mineralized water
	Regional sedimentation	Placer diamonds, tektites

^aPGE: platinum group element.

10–11 km and its original diameter may have been 15–18 km. There is, however, a smaller estimate for the original diameter of approximately 8 km by Krochuk and Sharpton (2003), who also reported a younger, single whole-rock ³⁹Ar–⁴⁰Ar date of 290 ± 10 Ma for an impact melt rock.

The iron ores at Ternovka have been exploited for more than 50 years through open pit and underground operations down to a depth of about 1 km. The ores are the result of hydrothermal and metasomatic action, which occurred during the Lower Proterozoic, on ferruginous quartzites (jaspilites) and some other lithologies, producing zones of albitites, aegirinites and amphibole–magnetite and carbonate–haematite rocks, along with the uranium mineralization. Post-impact hydrothermal alteration has led to the remobilization of some of the uranium mineralization and the formation of veins of pitchblende. The production of uranium ceased in 1967, but iron ore is still extracted, from two main open pits, Annovsky and Pervomaysk, with the target annual production in 2008 being 14 million tonnes of iron ore concentrate. The total reserves at the Pervomaysk open pit are estimated at 74 million tonnes, with additional reserves of lower grade deposits estimated at 675 million tonnes. The reserves at Annoysky are 450 million tonnes. Owing to impact-related brecciation and megablock displacement, blocks of iron ore are mixed with barren blocks. These blocks are up to hundreds of metres in dimension, having been rotated and displaced from their pre-impact positions. This displacement and mixing of lithologies has caused difficulties in operation and in evaluating the reserves. Conversely, impact-induced fracturing has aided in the physical extraction and processing of the ore.

12.2.2 Uranium at Carswell

The Carswell impact structure (58°27'N, 109°30'W) is located in the Athabasca Basin in northern Saskatchewan, Canada, about 120 km south of Uranium City. The Proterozoic-aged Athabasca Basin contains approximately 25% of the world's known uranium

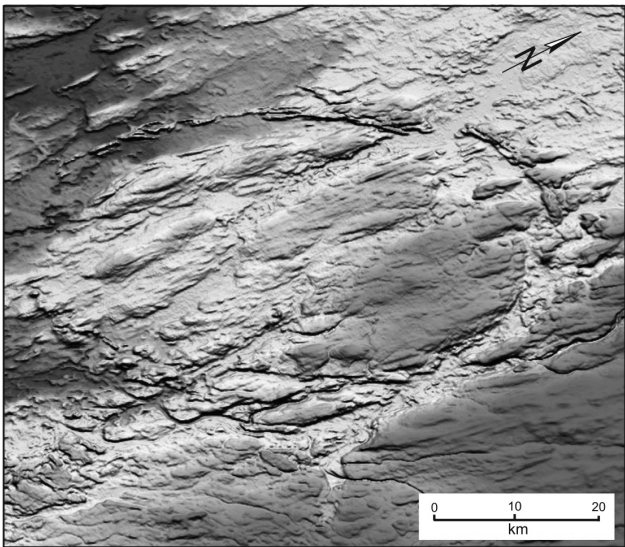


Figure 12.1 Synoptic image of the topography of the Carswell structure, based on the Shuttle Radar Topographic Mission. Reds and yellows are topographic highs and blues are lows. (See Colour Plate 28)

(Jefferson and Delaney, 2007). It is the richest known and second largest uranium-producing region in the world, after the Olympic Dam in Australia. Cumulative uranium production from the basin is approximately 1.5 billion pounds (~0.68 Mt) of uranium oxide. Details of various geological, geophysical and geochemical aspects of the Carswell structure, with heavy emphasis on the uranium ore deposits, can be found in Lainé *et al.* (1985). The Carswell structure, which has been eroded to below the floor of the original crater, is apparent in Shuttle radar topography as two circular ridges, corresponding to the outcrop of the dolomites of the Carswell Formation (Fig. 12.1). The outer ridge is approximately 39 km in diameter and is generally quoted as the diameter of the structure (e.g. Currie, 1969; Harper, 1982). It represents a minimum original diameter. The outer ring of the structure is about 5 km wide and forms cliffs 65 m high of the Douglas and Carswell Formations. Interior to this, there is an annular trough, occupied by sandstones and conglomerates of the William River Subgroup of the Athabasca Group. This trough is also approximately 5 km wide and rises to a core, approximately 20 km in diameter, of metamorphic crystalline basement.

The crystalline basement core consists of mixed feldspathic and mafic gneisses of the Earl River Complex, overlain by the more aluminous Peter River gneiss. Details of their mineralogy and chemistry can be found in Bell *et al.* (1985), Harper (1982), and Pagel and Svab (1985). The basement core is believed to have been structurally uplifted by a minimum of 2 km. From a detailed structural study of the Dominique–Peter uranium deposit near the southern edge of the crystalline core, Baudemont and Fedorowich (1996) estimated that the amount of structural uplift in that area was in the order of 1.2 km. Surrounding the crystalline basement core are units of the unmetamorphosed Athabasca Group of sediments. The inner contact with the basement core is

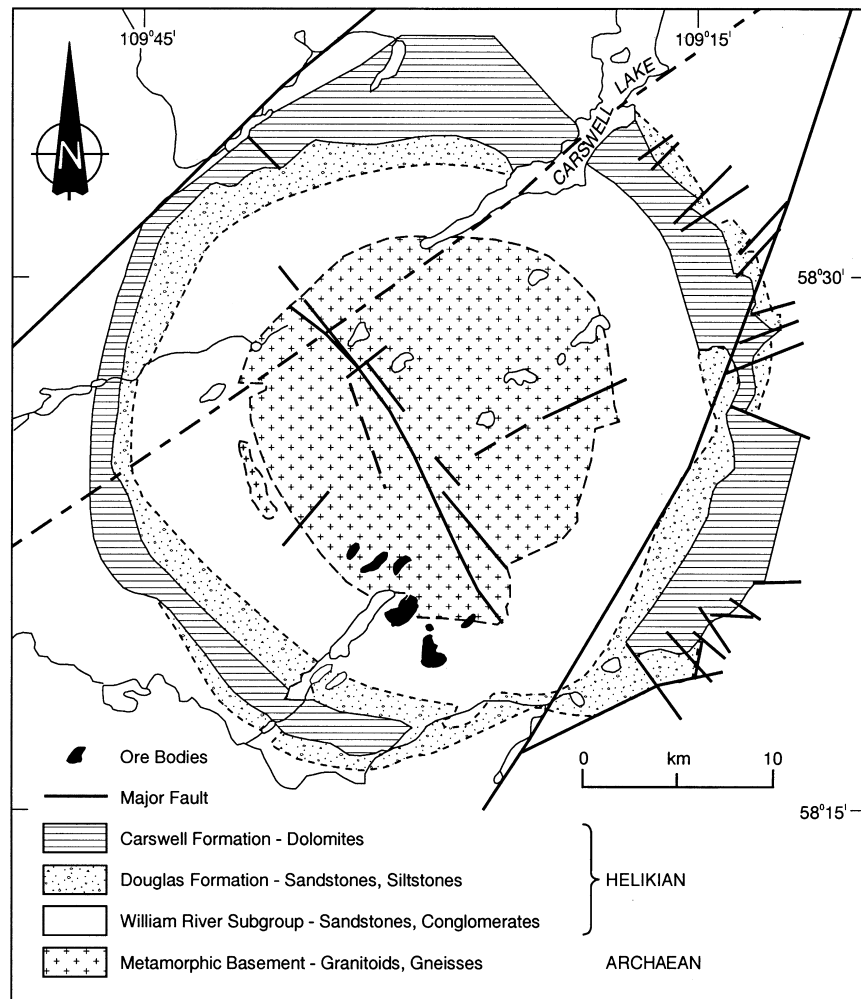


Figure 12.2 Schematic geologic map of Carswell, indicating uplifted crystalline core and down-faulted annulus of Carswell and Douglas Formations, which appear as the outer topographically high and low annuli respectively in Fig. 12.1. Also shown are the locations of the uranium ore deposits.

faulted and truncated in places and offset by radial faults. The outer contact of the Carswell Formation is also characterized by arcuate faulting, drag folding and local overturning of beds, as well as being offset by radial faults (Fig. 12.2). The outcrop of the Carswell and Douglas Formations, which are the uppermost units of the Athabasca Group, is unique to the area. They owe their preservation to having been down-faulted at least 1 km in the impact to their present position (Harper, 1982; Tona *et al.*, 1985). Brecciation is common at Carswell and affects all lithologies. Currie (1969) used the term 'Cluff Breccias', after exposures near Cluff Lake, to include autochthonous monomict, allochthonous polymict clastic and melt-bearing breccias, as well as clast-rich impact melt rocks (see Chapter 7). The latter three lithologies occur as dike-like bodies and the relationships between the various breccias are locally complex.

Within the Carswell structure, the known commercial uranium deposits (Fig. 12.2) occur in two main settings: at the unconformity between the Athabasca sandstone of the William River Subgroup and the uplifted crystalline basement core, and in mylonites

and along faults in the crystalline core. These deposits had grades from 0.3 to over 4% uranium oxide (average 0.6%) and have produced over 45 million pounds (~20.4 kt) of uranium metal (Jefferson and Delaney, 2007), worth over US\$2 billion at average 2009 prices. The original uranium mineralization in the Athabasca Basin, and at Carswell, occurred during regolith development in the Precambrian, with later remobilization due to hydrothermal activity in response to thermo-tectonic events (Bell *et al.*, 1985; Lainé, 1986). The original commercial uranium deposit discovered at Carswell, the Cluff Lake D deposit (Fig. 12.3), was a pre-existing or progenetic ore deposit that was brought to its present location by structural uplift in the Carswell impact event and subsequent erosion. The mineralization at Cluff Lake D is also associated with shear zones and faulting (Tona *et al.*, 1985). At the time of mining, it was the richest known uranium ore body in the world (Lainé, 1986). It closed in 2002, having produced 62 million pounds (~28.1 kt) of 'yellow cake', an intermediate milling product consisting mostly of uranium oxide, over its 22 year lifetime.

In their study of Dominique–Peter, the largest basement-hosted uranium deposit, Baudemont and Fedorowich (1996) recognized four episodes of deformation. Two of these were prior to mineralization, the third episode related to mineralization and the final episode related to the Carswell impact event. They noted that Carswell-related deformation reactivated earlier faults,



Figure 12.3 Aerial view in 1999 of DJX open pit and underground mine at Cluff Lake, Carswell, with the Claude pit in the background. Image courtesy of AREVA Resources Canada.

associated with the main mineralization. ‘Cluff Breccia’ also occurs commonly in the same fault structures as the uranium mineralization. Baudemont and Fedorowich (1996) found the association ‘striking, albeit complexing’. Mineralized material occurs within the ‘Cluff Breccias’, as veins of coffinite (Lainé, 1986).

It is not clear to what extent the Carswell impact event was involved in remobilizing the ores, beyond physical movement associated with fault reactivation during structural uplift. The basement-hosted ores are all associated with extensive regional alteration, indicative of hydrothermal fluid movement (Lainé, 1986). At present, the last of the known commercial uranium deposits within the Carswell structure is closed down. There are, however, additional active exploration targets, including reactivated faults, with pseudotachylitic breccia and/or ‘Cluff Breccias’ and uranium mineralization (Baudemont and Fedorowich, 1996). In addition to bringing what were originally ‘deep’ ore bodies to the surface, Carswell serves as a unique knowledge window into the nature of basement beneath the Athabasca Basin and, as such, serves as a guide to uranium exploration through out the entire basin (C. Jefferson, Geological Survey of Canada, personal communication, 2009).

12.2.3 Gold and uranium of Vredefort

The Vredefort structure, South Africa (27°0’S, 27°30’E; Fig. 12.4) consists of a 44 km diameter uplifted central core of predominantly Archaean granitic gneisses surrounded by an 18 km wide collar of steeply dipping to overturned Proterozoic sedimentary

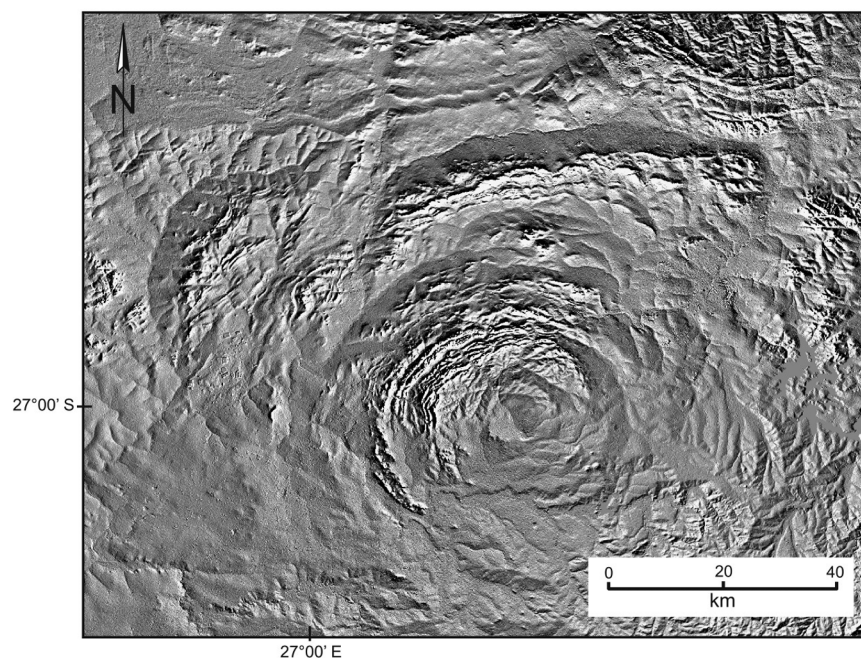


Figure 12.4 Greyscale synoptic image of the topography of the Vredefort impact structure, based on the Shuttle Radar Topographic Mission. Image has been illuminated from the centre to emphasize topographic features, related to anticlinal and synclinal structures, surrounding the centre of Vredefort. These features are not evident in the SE quadrant, where the impact structure is covered by post-impact Karoo Supergroup sediments and volcanics.

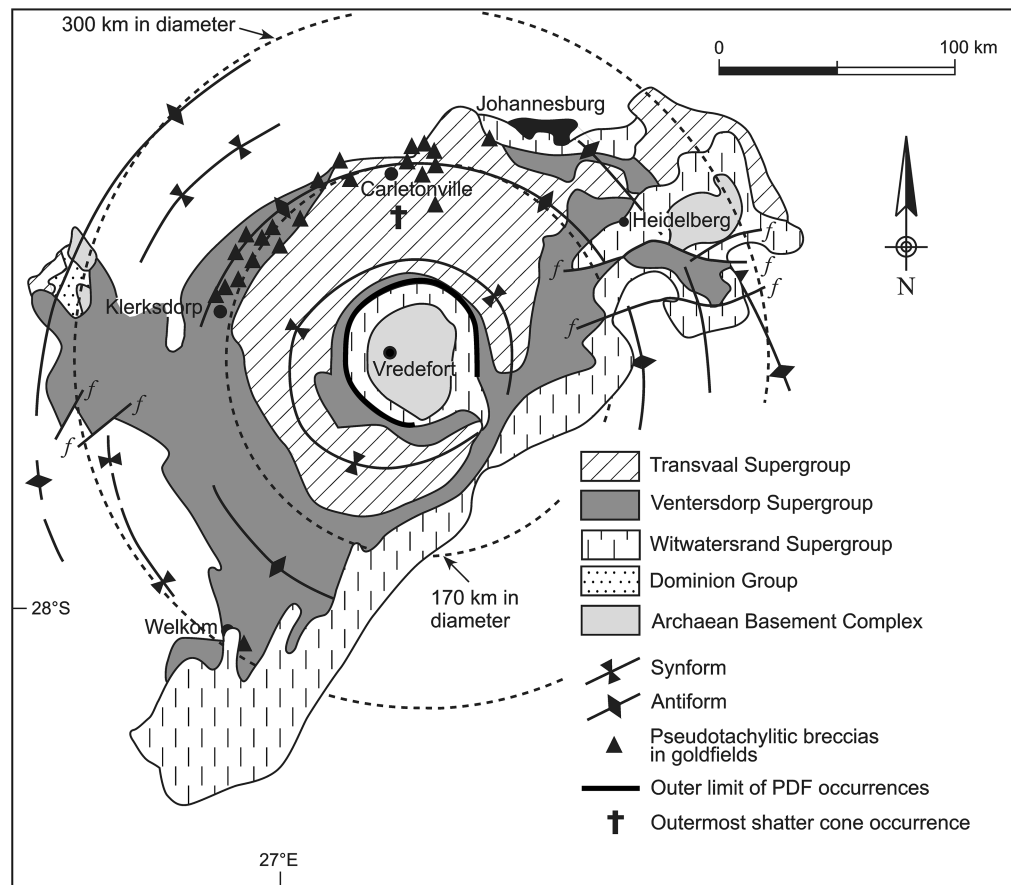


Figure 12.5 Schematic geologic map of the Vredefort impact structure, with the outcrop of the Karoo cover rocks removed. Also shown are the spatial extent of shatter cones and PDFs in quartz and the various circumscribing structures related to Vredefort and initially identified by McCarthy *et al.* (1986, 1990). The Vredefort goldfields describe the so-called ‘golden arch’, which passes through or close to Heidelberg, Johannesburg, Carletonville, Klerksdorp and Welkom. Modified from Gibson and Reimold (2008).

and volcanic rocks of the Witwatersrand and Ventersdorp Supergroup and a 28 km wide outer broad synclinorium of gently dipping Proterozoic sedimentary and volcanic rocks of the Transvaal Supergroup. Younger sandstones and shales of the Karoo Supergroup cover the south-eastern portion of the structure. The general circular form with an uplifted central core, the occurrence of stishovite and coesite, as well as planar deformation features (PDFs) in quartz and shatter cones (Chapter 8) have all been presented as evidence that the Vredefort structure is the eroded remnant of a very large, complex impact structure (e.g. Dietz, 1961; Carter, 1965; Manton, 1965; Martini, 1978, 1991; Gibson and Reimold, 2000, 2005). The most comprehensive and recent guide to the geology of Vredefort can be found in Gibson and Reimold (2008).

The Vredefort impact event occurred at 2023 ± 4 Ma (Kamo *et al.*, 1996). Based on the spatial distribution of impact-related deformation and structural features, Theriault *et al.* (1997) derived a self-consistent, empirical estimate of 225–300 km for the apparent diameter. A similar size estimate was derived by Henkel and Reimold (1998), based on potential field and reflection seismic data, and by Grieve *et al.* (2008), based on comparisons

and scaling between Vredefort, Sudbury and Chicxulub. These estimates effectively equate the impact structure to the entire Witwatersrand Basin. The Witwatersrand Basin is the world’s largest goldfield, having supplied some 40–50% of the gold ever mined. Since gold was discovered there in 1886, it has produced 47,000 t of gold and it still contains approximately 45% of currently known global reserves (Robb and Robb, 1998). The annual Witwatersrand gold production for 2002 was approximately 350 t, or approximately 13.5% of the global gold supply, and current reserve estimates are around 20,000 t of gold. Approximately 150,000 t of uranium has been mined, generally as a by-product of gold mining, with estimated reserves of 475,000 t (Reimold *et al.*, 2005).

Independent of impact studies at Vredefort, structural analyses have identified a series of concentric anticlinal and synclinal structures related to Vredefort (e.g. McCarthy *et al.*, 1986, 1990; Fig. 12.5). These Vredefort-related structures have led to the preservation of sediments of the Witwatersrand Supergroup from erosion (McCarthy *et al.*, 1990). The bulk of the gold has been mined from the upper succession of the Witwatersrand Supergroup: the Central Rand Group. The origin of the gold in the

basin is still debated. General gold distribution is controlled by sedimentary attributes of the Central Rand, but textures suggest both a detrital and an authigenic hydrothermal origin (e.g. Hayward *et al.*, 2005; Frimmel *et al.*, 2005), with pure detrital and hydrothermal models and combinations of the two having been proposed (e.g. Barnicoat *et al.*, 1997; Minter, 1999; Phillips and Law, 2000). Gold with clear detrital morphological features (Minter *et al.*, 1993) occurs with secondary, remobilized gold. This suggests that detrital gold was introduced into the basin but that some gold was subsequently remobilized by hydrothermal activity (Frimmel and Minter, 2002; Zhao *et al.*, 2006). Grieve and Masaitis (1994) speculated that some remobilization occurred due to the Vredefort event but were equivocal also as to the potential role of thermal activity resulting from the spatially and temporally (2.05–2.06 Ga) close igneous event associated with the Bushveld Complex.

More recent work has clarified the situation, with the Vredefort impact event forming both an important temporal marker and a critical element in the process of gold remobilization. Two thermal or metamorphic events affected the rocks of the basin. A regional amphibolite facies metamorphism predates the Vredefort impact event. A later low-pressure (0.2–0.3 GPa), immediately post-impact event, however, produced peak temperatures of $350 \pm 50^\circ\text{C}$ in the Witwatersrand Supergroup to greater than 700°C in the centre of the crystalline core at Vredefort. This post-impact activity is directly attributed to the combination of post-shock heating and the structural uplift of originally relatively deep-seated parautochthonous rocks during the Vredefort impact event (Gibson *et al.*, 1998). Reimold *et al.* (1999) applied the term ‘autometasomatism’ to describe the alteration associated with the hydrothermal activity. This activity remobilized the gold (and uranium) within impact-related structures and fractures, which provided channels for fluid migration. It has been recently argued, however, that such a redistribution of the gold was local in scale (Hayward *et al.*, 2005; Boer and Reimold, 2006; Meier *et al.*, 2009). A more detailed discussion of the effect of Vredefort-related hydrothermal activity can be found in Reimold *et al.* (2005). It is now evident the Vredefort impact event played a larger role in the genesis of Witwatersrand Basin gold fields (Frimmel and Minter, 2002; Frimmel *et al.*, 2005; Hayward *et al.*, 2005) than simply preserving them from erosion by structural modification (McCarthy *et al.*, 1990; Grieve and Masaitis, 1994).

12.2.4 Other structures

Several other progenetic or pre-impact deposits hosted by impact structures are noted in Grieve and Masaitis (1994) and Reimold *et al.* (2005). Although some have been mined in the past, they are generally small and currently inactive. One exception is the 118 million tonne Century Zn–Pb deposit, within the Lawn Hill impact structure ($18^\circ40'\text{S}$, $138^\circ39'\text{E}$), Australia. The deposit lies along the Termite Range fault, where it transects the outer reaches of the impact structure. Rhenium–osmium dating of the ores suggests a mineralization age of $1451 \pm 44\text{ Ma}$ (Keays *et al.*, 2006). The estimated age of the impact is around 500–520 Ma (Salisbury *et al.*, 2008). The impact led to some physical redistribution of the ores, the most spectacular occurrence being a 1 million tonne

fragment of ore suspended in brecciated limestone (Broadbent *et al.*, 1998). The impact may have also led to some minor hydrothermal redistribution of ore into overlying limestone and some 17 smaller vein-hosted Zn–Pb deposits situated along faults (Salisbury *et al.*, 2008). Physical redistribution of natural resources also affects mining operations at the Middlesboro structure ($36^\circ37'\text{N}$, $83^\circ44'\text{W}$) in Kentucky, USA. Faults associated with the structure result in a degree of unpredictability regarding the continuity of coal beds, with the sudden loss of coal, changes in dip and brecciation. Although not an unequivocal conclusion, the local rise in the rank of the coal at Middlesboro by some 20% could be from local post-impact heating (Hower *et al.*, 2009).

12.3 Syngenetic deposits

Syngenetic economic natural resources at impact structures include impact diamonds, Cu–Ni sulfides and platinum group and other metals (Table 12.1).

12.3.1 Impact diamonds

The first indication of impact diamonds was the discovery in the 1960s of diamond with lonsdaleite, a high-pressure (hexagonal) polymorph of carbon, in placer deposits (e.g. in the Ukraine), although their source was unknown at the time. In the 1970s, diamond with lonsdaleite was discovered in the impact lithologies at the Popigai impact structure ($71^\circ30'\text{N}$, $111^\circ00'\text{E}$) in Siberia. Since then, impact diamonds have been discovered at a number of structures; for example, Kara ($69^\circ05'\text{N}$, $64^\circ18'\text{E}$) and Puchezh-Katunki ($57^\circ00'\text{N}$, $43^\circ35'\text{E}$) in Russia, Lappajärvi ($63^\circ12'\text{N}$, $23^\circ42'\text{E}$) in Finland, Ries ($48^\circ53'\text{N}$, $10^\circ37'\text{E}$) in Germany, Sudbury ($46^\circ36'\text{N}$, $81^\circ11'\text{W}$) in Canada, Ternovka and Zapadnaya ($49^\circ44'\text{N}$, $29^\circ00'\text{E}$) in Ukraine and others (Masaitis, 1993, 1998; Gurov *et al.*, 1996; Langenhorst *et al.*, 1998; Siebenschock *et al.*, 1998). Impact diamonds originate as a result of phase transitions from graphite, or crystallization from coal, and occur when precursor carbonaceous lithologies are subjected to shock pressures greater than 35 GPa (Masaitis, 1998). The diamonds from graphite in crystalline targets usually occur in paramorphs, with inherited crystallographic features (Fig. 12.6) and as microcrystalline aggregates. At Popigai, these aggregates can reach 10 mm in size but most are 0.2–5 mm in size (Masaitis, 1998). They consist of cubic diamond and lonsdaleite, with individual microcrystals of 10^{-4} cm . The diamonds generated from coal, or other carbon in sediments, are generally porous and coloured.

Diamonds are most common as inclusions in impact melt rocks and glass clasts in suevite breccias. For example, at Zapadnaya, impact diamonds occur in dikes of impact melt rock in the central uplift and in suevitic breccias in the peripheral trough (Gurov *et al.*, 1996). Zapadnaya, approximately 3.8 km in diameter and $115 \pm 10\text{ Myr}$ old, was formed in Proterozoic granite containing graphite (Gurov *et al.*, 1996). At Popigai, the allochthonous breccias filling the peripheral trough are capped by diamond-bearing suevitic breccias and coherent bodies of impact melt rocks (Chapters 7 and 9). In the case of Popigai, the original

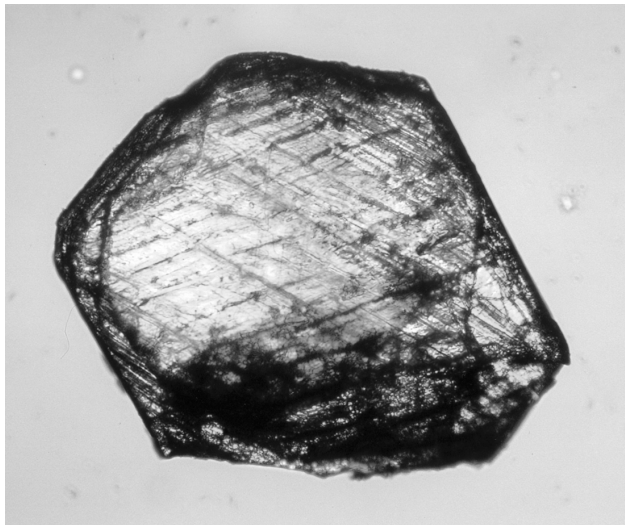


Figure 12.6 Impact diamond, showing slight etching along twinning boundaries, after graphite, from the Popigai impact structure. Long dimension is approximately 600 μm . Image from Koeberl *et al.*, 1997.

source of the carbon is graphite in Archaean gneisses. The diamonds at Kara, 65 km in diameter and 67 ± 6 Myr old, are from Permian terrigenous sediments containing coal (Ezerskii, 1982). Impact diamonds can also be found in strongly shocked lithic clasts in suevitic breccias; for example, at Popigai and Ries (Masaitis, 1998; Siebenschock *et al.*, 1998). In impact melt rocks at structures with carbon-bearing lithologies, diamonds occur in relatively minor amounts, with provisional average estimates in the order of 10 ppb, although the cumulative volumes can be enormous. Although diamonds associated with known impact structures are not currently exploited commercially, those produced by shock transformation of graphite tend to be harder and more resistant to breaking than normal cubic diamonds from kimberlites.

Hough *et al.* (1995) have reported the only known occurrence of cubic impact diamond from impact lithologies, again in impact melt-bearing breccias at the Ries structure. They also reported the occurrence of moissanite (SiC) grains. The cubic diamonds are skeletal in appearance and they attributed their origin to chemical vapour deposition of diamond onto SiC in the ejecta plume over the impact site. Based on carbon isotope studies, they considered the source of the carbon and other elements to be from sedimentary rocks, including carbonates, which overlay the crystalline basement at the time of the Ries impact. They calculated that the Ries suevite might contain 7.2×10^4 t of diamonds and SiC, in the proportion of 3:1. Other workers (e.g. Siebenschock *et al.*, 1998) failed to find either cubic diamond or SiC at the Ries. Silicon carbide has also been reported from the Onaping Formation at the Sudbury impact structure (Masaitis *et al.*, 1999). It is associated with impact diamonds that are a mixture of cubic diamond and hexagonal lonsdaleite from the solid-state transformation of precursor graphite in carbonaceous Huronian target lithologies by shock compression.

12.3.2 Cu–Ni sulfides and platinum group metals at Sudbury

The Sudbury structure in central Ontario is the site of world-class Ni–Cu sulfide and PGE metal ores and is Canada's principal mining district. The pre-mining resources associated with the Sudbury Igneous Complex (SIC) are estimated at over 1.5×10^9 t of 1.2% Ni, 1.1% Cu and 1 g t^{-1} Pd+Pt (Farrow and Lightfoot, 2002). There are also hydrothermal Zn–Pb deposits stratigraphically above the SIC (Ames and Farrow, 2007). Nickel sulfides were first noted at Sudbury in 1856. It was not until they were 'rediscovered' during the building of the trans-Canada railway in 1883, however, that they received attention, with the first production occurring in 1886 (Naldrett, 2003). By 2000, the Sudbury mining camp had produced 9.7×10^6 t of Ni, 9.6×10^6 t of Cu, 70×10^3 t of Co, 116 t of Au, 319 t of Pt, 335 t of Pd, 37.6 t of Rh, 23.3 t of Ru, 11.5 t of Ir, 3.7×10^3 t of Ag, 3×10^3 t of Se and 256 t of Te (Leshner and Thurston, 2002). The cumulative total worth of metals produced from Sudbury is estimated at around US\$300 billion, based on 2005 metal prices (Ames and Farrow, 2007).

The most prominent feature of the Sudbury structure is the approximately $30 \times 60 \text{ km}^2$ elliptical basin formed by the outcrop of the SIC, the interior of which is known as the Sudbury Basin (Fig. 12.7). Neither the SIC nor the Sudbury Basin is synonymous with the considerably larger Sudbury impact structure. The Sudbury impact structure includes the Sudbury Basin, the SIC and the surrounding brecciated basement rocks and covers a present area of greater than 15,000 km^2 . From the spatial distribution of shock metamorphic features (e.g. shatter cones; Chapter 8) and other impact-related attributes and by analogy to equivalent characteristics at other large terrestrial impact structures, such as Chicxulub and Vredefort, Grieve *et al.* (2008) estimated that the original crater rim diameter was 150–200 km. Even larger original diameters have been suggested (e.g. Tuchscherer and Spray, 2002; Naldrett, 2003). With the post-impact tectonic deformation and the considerable erosion, estimated to be approximately 10 km (Schwarz and Buchan, 1982), which has taken place at the Sudbury impact structure, it is difficult to constrain its original form. From its estimated original dimensions, it was most likely a peak-ring or a multi-ring basin (Stöffler *et al.*, 1994; Spray and Thompson, 1995; Grieve *et al.*, 2008).

Details of the geology of the Sudbury area can be found in Dressler (1984) and, most recently, Ames *et al.* (2008), while a summary of the salient points of the Sudbury structure and the SIC, in particular, can be found in Grieve (2006). Traditionally, the SIC has been subdivided into a number of phases or units. At the base, there is the Contact Sublayer, which has an igneous-textured matrix with inclusions of locally derived target rocks and cognate and exotic mafic to ultramafic rocks (Lightfoot *et al.*, 1997a,b). Uranium–lead dating of these mafic inclusions indicates an age equivalent to that of the SIC (Corfu and Lightfoot, 1996). Traditionally, included with the Sublayer are the so-called Offset Dikes of the SIC (Lightfoot *et al.* 1997a), which host 25% of the Ni–Cu–PGE resources at Sudbury (Farrow and Lightfoot, 2002). These dikes are most often radial to the SIC, but some are concentric. Some are extensive; for example, the Foy Offset can

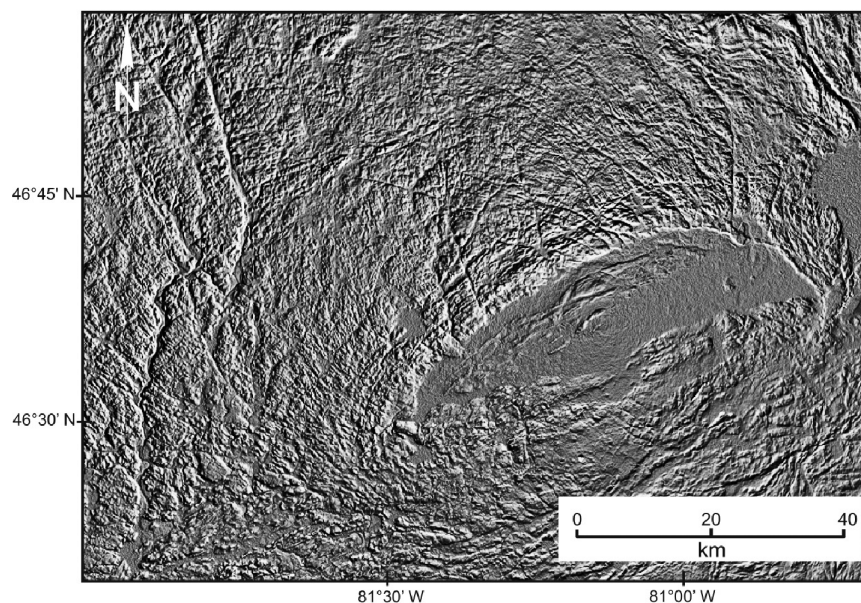


Figure 12.7 Greyscale synoptic image of the topography of the Sudbury impact structure, based on the Shuttle Radar Topographic Mission. Image has been illuminated from the centre as in Fig. 12.4. The most prominent feature is the approximately $60 \times 30 \text{ km}^2$ elliptical trace of the SIC and the interior Sudbury Basin.

be traced for approximately 30 km from the North Range of the SIC and varies from approximately 400 m in width near the SIC to 50 m at its most distal part (Grant and Bite, 1984; Tuchscherer and Spray, 2002). The Offset Dikes, however, do not have the same composition as the Sublayer and should be considered separately. They have compositions similar to the average SIC (Lightfoot and Farrow, 2002; Keays and Lightfoot, 2004) and are a 'quenched' phase of the SIC, which is the remnant of the impact melt sheet at the Sudbury structure (Grieve *et al.*, 1991).

Stratigraphically above the Sublayer lies the Main Mass of the SIC, which is relatively, but not completely, clast free. For example, there are rare quartz clasts with partially annealed PDFs (Therriault *et al.*, 2002; Chapter 8). Traditionally, the Main Mass has been divided into a number of sub-units: mafic norite, quartz-rich norite, felsic norite, quartz gabbro and granophyre. These terms for these sub-units are, in large part, actually misnomers on the basis of the modal quartz, alkali feldspar and plagioclase proportions, as plotted on a Streckeisen diagram. Only the Sublayer is gabbroic. The others fall into the quartz gabbro, quartz monzogabbro, granodiorite and granite fields (Therriault *et al.*, 2002). The nomenclature confusion arises from the fact that, like most impact melts of granitic/granodioritic composition, the mafic component of the melt crystallized as ortho- and clinopyroxene, although there are also primary hydrous amphibole and biotite. Therriault *et al.* (2002), who made their observations on continuous cores rather than discontinuous outcrop, also demonstrated, on the basis of both mineralogy and geochemistry, that the contacts between the various sub-units of the SIC are gradational. The details of the mineralogy and geochemistry support a cogenetic source for the sub-units of the Main Mass of the SIC, produced by fractional crystallization of a single batch

of silicate liquid (e.g. Lightfoot *et al.*, 1997a; Warner *et al.*, 1998; Therriault *et al.*, 2002).

The conclusion that the SIC and its ores are not mantle derived but crustal in composition is borne out by isotopic studies (Faggart *et al.*, 1985; Walker *et al.*, 1991; Dickin *et al.*, 1992, 1996, 1999). Cohen *et al.* (2000) analysed the Re–Os isotopes in ultramafic inclusions in the Sublayer of the SIC and concluded that they were also consistent with melting of pre-existing lithologies at 1.85 Ga. They also produced an imprecise crystallization age of $1.97 \pm 0.12 \text{ Ga}$ from a number of the inclusions, which, within its uncertainty, is equivalent to the 1.85 Ga crystallization age of the SIC (Krogh *et al.*, 1984). High-precision Os isotope studies of sulfides from several mines have confirmed their crustal origin from a binary mixture of Superior Province and Huronian metasedimentary target rocks (Morgan *et al.*, 2002).

Recently, Farrow and Lightfoot (2002) and Ames and Farrow (2007) reviewed the nature of the ore deposits at Sudbury and placed their formation in an integrated time-sequence model. They recognize: Ni–Cu–Co 'Contact' deposits associated with embayments at the base of the SIC and hosted by Sublayer and footwall breccia; Ni–Cu–Pt–Pd–Au 'Offset' deposits associated with discontinuities and variations in thickness in the offset dikes; and Cu–Pt–Pd–Au-rich 'Footwall' deposits that can occur in the underlying target rock, up to 1 km away from the SIC (Fig. 12.8). They also recognize a fourth deposit environment associated with pseudotachylitic Sudbury Breccia. For example, the Froid–Stobie deposit, which contained some 15% of the entire known Sudbury resources and produced 600 million tonnes of ore, is not hosted in a traditional Offset dike but rather in Sudbury Breccia (Scott and Spray, 2000).

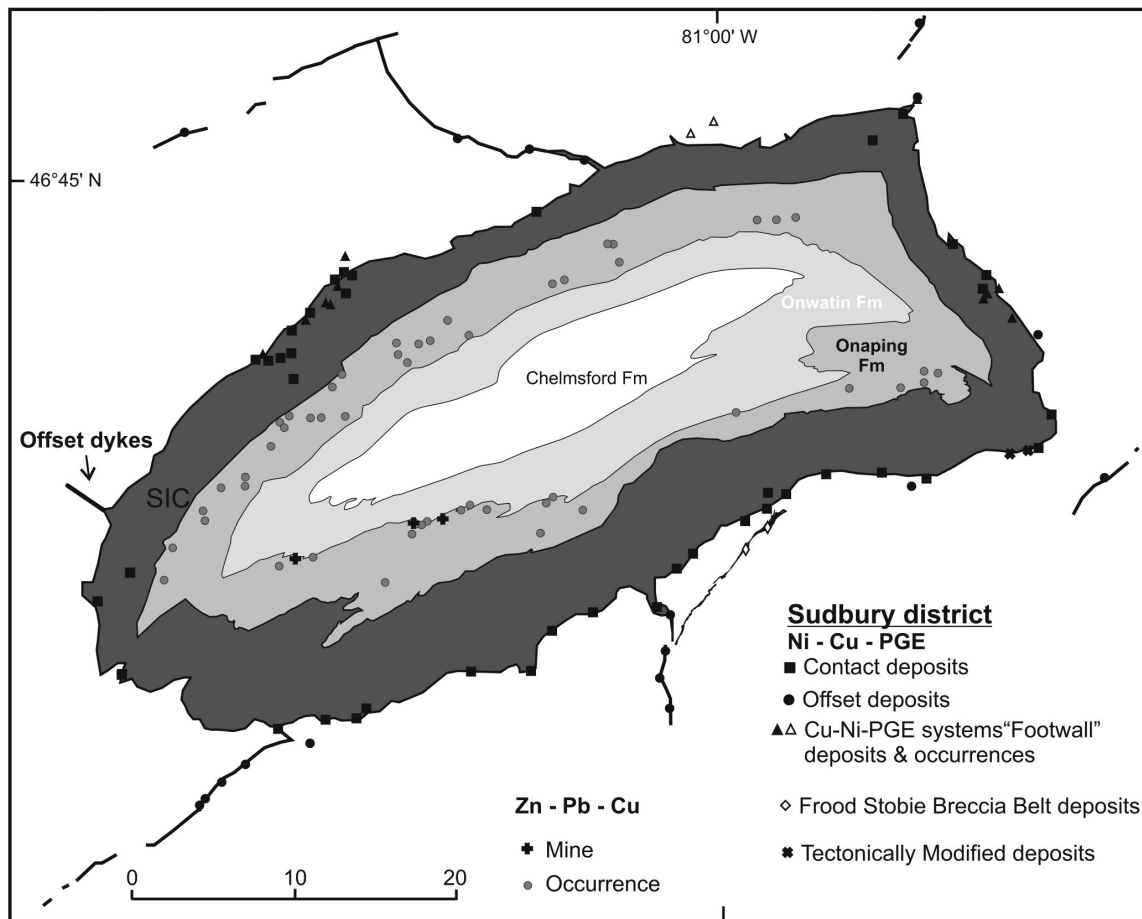


Figure 12.8 Simplified geologic map of the SIC and overlying post-impact sediments at the Sudbury impact structure. Shown are the locations of the various types of occurrences of Cu–Ni–PGE ores at the base of the SIC (see text for details) and the Zn–Pb–Cu hydrothermal mineralization overlying the SIC. The details of the parautochthonous target rocks (white) are not shown, but are Archaean granite–greenstone terrane and gneisses of the Superior Province in the north and Palaeoproterozoic meta-sediments and meta-volcanics of the Huronian in the south. Image courtesy D. Ames.

The Contact deposits consist of massive sulfides and are volumetrically the largest deposit type, hosting approximately 50% of the known ore resources. They include the Creighton and Murray deposits and North Range deposits of Levack and Coleman. The main economic Offset environments include the Copper Cliff and Worthington Offsets in the South Range, which, along with the Frood–Stobie, contain approximately 40% of the known ores at Sudbury. The Cu–PGE-rich Footwall deposits are volumetrically small (~10% of known ore in 2005) relative to the Contact deposits, but are extremely valuable bodies, as they are relatively enriched in PGEs, in addition to copper. They represent a relatively new ore environment, which is hosted in the brecciated footwall of the SIC and is best known in the North Range; for example, at McCreedy East and West, Strathcona and Levack, where they occur as complex vein networks or sulfide and low sulfide, high precious metal disseminations (Ames and Farrow, 2007). In the last decade, these Footwall deposits have been the focus of much of the exploration activity at Sudbury and were the only deposits mined at Sudbury in the latter half of 2009. There is increasing realization that hydrothermal remobilization played

a role in the genesis of the Footwall deposits (e.g. Farrow and Watkinson, 1997; Marshall *et al.*, 1999; Carter *et al.*, 2001; Molnar *et al.*, 2001; Hanley *et al.*, 2005; Ames and Farrow, 2007). This is consistent with the growing body of knowledge in support of hydrothermal activity driven by the 'local' crustal thermal anomaly that results from large impact events (e.g. Abramov and Kring, 2004; Chapter 6).

The recent work at Sudbury can mostly be fitted into the framework of the formation of an approximately 200 km impact basin at 1.85 Ga, with accompanying massive crustal melting producing a superheated melt of an unusual composition, which gave rise to immiscible sulfides. These sulfides settled gravitationally, resulting ultimately in the present Contact and Offset ore deposits. Complicating factors, but essential components of the evolutionary history of Sudbury, are the creation of a 'localized' but regional-scale impact-related hydrothermal system, which resulted in some ore fractionation and redistribution into the brecciated footwall rocks, and the deformation by the Penokean orogeny that took place shortly after the impact. The Zn–Pb–Cu ores in the post-impact sediments overlying the SIC are the result

of the hydrothermal system fuelled by the heat of the SIC (Ames *et al.*, 2006; Ames and Farrow, 2007). This upper hydrothermal system involved sea water, as opposed to the Cl-rich brines that played a role in the origin of the Footwall deposits at the base of the SIC (Ames and Farrow, 2007).

There are a number of small impact-related hydrothermal deposits (mostly Pb–Zn) at other impact structures (Masaitis, 1989; Grieve and Masaitis, 1994; Reimold *et al.*, 2005). The largest are the Pb–Zn deposits associated with the Siljan structure (61°02'N, 14°52'E) in Sweden. These deposits are hosted by Ordovician–Silurian carbonates in the annular trough at this 65 km diameter structure. The largest deposit consists of 0.3 million tonnes of 3% Pb and 1.5% Zn and is located near the town of Boda.

12.4 Epigenetic deposits

Significant epigenetic deposits are due mainly to the fact that impact structures can result in isolated topographic basins and can 'locally' influence underground fluid flow. Such deposits may originate almost immediately or over an extended period after the impact event and include reservoirs of liquid and gaseous hydrocarbons. There are also oil shales, various organic and chemical sediments, as well as flows of fresh and mineralized waters (Table 12.1). For example, oil shales are known at Boltysk (48°45'N, 32°10'W), Obolon (49°30'N, 32°55'W) and Rotmistrovka (49°00'N, 32°00'E) in the Ukraine (Masaitis *et al.*, 1980; Gurov and Gurova, 1991). They represent the unmaturing equivalent of the hydrocarbon reserves found at some other impact structures, such as Ames in the USA. The most significant reserves are at Boltysk, where there are an estimated 4.5 billion tonnes (Bass *et al.*, 1967). The oil shales are the result of biological activity involving algae in this isolated topographic basin resulting from impact. A more complete listing of such epigenetic deposits can be found in Reimold *et al.* (2005).

12.5 Hydrocarbon accumulations

Hydrocarbons occur at a number of impact structures. In North America, approximately 50% of the known impact structures in hydrocarbon-bearing sedimentary basins have commercial oil and/or gas fields. For example, the 25 km diameter Steen River structure (59°31'N, 117°37'W) in Alberta, Canada, has produced 3.5 million barrels of oil and 48.5 billion cubic feet of gas from wells on its rim, with an estimated 1.9 million barrels of oil and 4.5 billion cubic feet of gas as recoverable reserves. Oil and gas are produced from beneath the approximately 13 km diameter Marquez (31°17'N, 96°18'W) and Sierra Madera (30°36'N, 102°55'W) structures in Texas, USA (Donofrio, 1997, 1998), which have a combined estimate of reserves of 280 billion cubic feet of gas. Viewfield (49°35'N, 103°04'W; Fig. 12.9) in Saskatchewan, Canada (Sawatzky, 1977), which is a simple bowl-shaped crater (see Chapter 18), produces some 600 barrels of oil and 250 million cubic feet of gas per day. The recoverable reserves associated with Viewfield are estimated to be 10–20 million barrels of oil (Donofrio 1997, 1998). More than 500,000 barrels of oil have

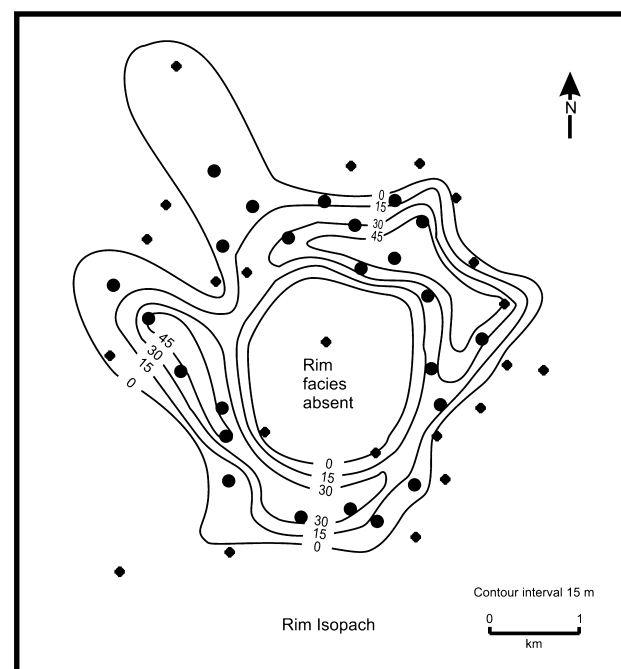


Figure 12.9 Thickness of rim facies at Viewfield impact structure. Black dots are producing wells. Diamond-shaped symbols are service or dry wells. Modified from Sawatzky, 1977 with permission from Elsevier.

been produced since 1978 from the Calvin structure (41°51'N, 85°57'W) in Michigan, USA, which is most likely an 8.5 km diameter complex impact structure (Milstein, 1988). Cloud Creek (43°11'N, 106°43'W), an approximately 7 km structure in Wyoming, USA (Stone and Theriault, 2003), has some hydrocarbons in its rim area, but the known amounts are not currently sufficient for commercial production.

Some specific structures in which hydrocarbon have accumulated under differing impact-related circumstances are discussed below.

12.5.1 Red Wing Creek

At the Red Wing Creek structure (47°36'N, 103°33'W) in North Dakota, USA, hydrocarbons are recovered from strata of the central uplift. Based on stratigraphy, Red Wing Creek is estimated to be 200 ± 25 Myr old, but the source of the hydrocarbons is in Carboniferous Mississippian strata; that is, 320–360 Myr old strata. It is a complex impact structure, approximately 9 km in diameter, with seismic records and drill-core data indicating a central peak in which strata have been uplifted by up to 1 km, an annular trough containing crater-fill products and a partially eroded rim (Brenan *et al.*, 1975; Sawatzky, 1977). As a result of a pronounced seismic anomaly, Shell Oil drilled the structure in 1965 on the NW flank of the central uplift. The drill hole indicated structurally high and thickened Mississippian and Pennsylvanian sections, compared with drill holes outside the structure. The well, however, was dry. In 1968, Shell drilled another hole in the NW in the annular trough. Here, the Mississippian was found

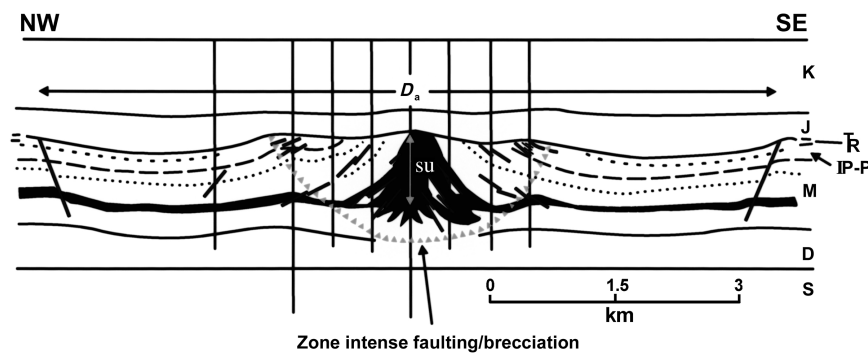


Figure 12.10 Two-dimensional schematic cross-section (no vertical exaggeration) of the 9 km diameter Red Wing impact structure. The amount of structural uplift is indicated by su. D_a is the apparent diameter. Strata: S, Silurian; D, Devonian; M, Carboniferous (Mississippian); IP-P, Permian; TR, Triassic, J, Jurassic; KL Cretaceous. Area bounded by small triangles corresponds to the volume of most intense deformation. The duplicated, faulted and brecciated Mississippian strata in the structural uplift are the zone of hydrocarbon production. Compare their thickness in the structural uplift with their thickness in the annular trough and outside the structure.

to be structurally low compared with the exterior. It was also dry and the structure, as a whole, was assumed to be dry. True Oil redrilled what was later recognized as the central uplift in 1972 and discovered approximately 820 m of Mississippian oil column, with considerable high-angle structural complexity and brecciation and a net pay of approximately 490 m. This is in contrast to the area outside the structure, which displays gentle dips and approximately 30 m oil columns. In this case, the hydrocarbon resources pre-existed the impact event but were physically displaced in the formation of the impact structure, resulting in enhanced accumulations of reservoir rocks in the central structural uplift.

The large oil column is due to the structural repetition of the Mississippian Mission Canyon Formation in the central uplift (Fig. 12.10; Brenan *et al.*, 1975). The impact-induced porosity and permeability result in relatively high flow rates of more than 1000 barrels per day. Cumulative production since discovery is over 20 million barrels of oil and 30 billion cubic feet of natural gas from 26 wells, of which 22 are still producing. Current production is restricted to about 300,000 barrels per year, to preserve unexploited reserves of natural gas. It is estimated that the brecciated central uplift contains more than 120 million barrels of oil and primary and secondary recoverable reserves may be 60–70 million barrels (Donofrio, 1981, 1998; Pickard, 1994). The natural gas reserves are estimated at 100 billion cubic feet. Virtually all the oil has been discovered within a diameter of 3 km, corresponding to the central uplift. Based on net pay and its limited aerial extent, Red Wing is the most prolific oil field in the USA, in terms of producing wells per area, with the wells in the central uplift having the highest cumulative productivity of all wells in North Dakota.

12.5.2 Avak

The Avak structure (71°15'N, 156°38'W) is located on the Arctic coastal plain of Alaska, USA. The structure has been known for some time as a 'disturbed zone' in seismic data (Lantz, 1981) and

hydrocarbons were discovered in 1949 (Donofrio, 1998). Evidence of shock metamorphism (see Chapter 8) was discovered in the form of shatter cones and PDFs in quartz (Kirschner *et al.*, 1992; Theriault and Grantz, 1995). The age of the Avak impact is around 90 Ma, based on what is interpreted as Avak ejecta in the sedimentary column in drill cores from 50 km east of the structure (Banet and Fenton, 2008). The structure itself has the form of a 10–12 km diameter complex impact structure (see Chapter 5). It is bounded by listric faults, which define a rim area, and has an annular trough and central uplift. In the central uplift, the Lower–Middle Jurassic Kingak Shale and Barrow Sand are uplifted more than 500 m from their regional levels. The central uplift has been penetrated by the Avak 1 well, which reached a depth of 1225 m. Oil shows occur in Avak 1, but the well is not a commercial producer. Kirschner *et al.* (1992) suggested that pre-Avak hydrocarbon accumulations may have been disrupted and lost due to the formation of the Avak structure.

There are, however, the South Barrow, East Barrow and Sikulik gas fields (Fig. 12.11), which are post-impact and are related to the Avak structure. They occur outside the structure and are due to listric faults in the crater rim, which have truncated the Lower Jurassic Barrow Sand and placed Lower Cretaceous Torok Shales against the Barrow Sand, creating an effective up-dip gas seal. The South and East Barrow fields are currently in production and primary recoverable gas is estimated at 37 billion cubic feet (Lantz, 1981). In this case, the hydrocarbon resource also pre-existed the impact event but, unlike Red Wing Creek, the commercial accumulations occur outside the structure in the rim area. Also unlike Red Wing Creek, the impact did not physically redistribute the resource to form an enhanced accumulation, but rather redistributed lithologies so as to provide a seal to the reservoir rocks.

12.5.3 Ames

The Ames structure (36°15'N, 98°10'W) is located in Oklahoma, USA, and is a complex impact structure (Chapter 5) about 14 km

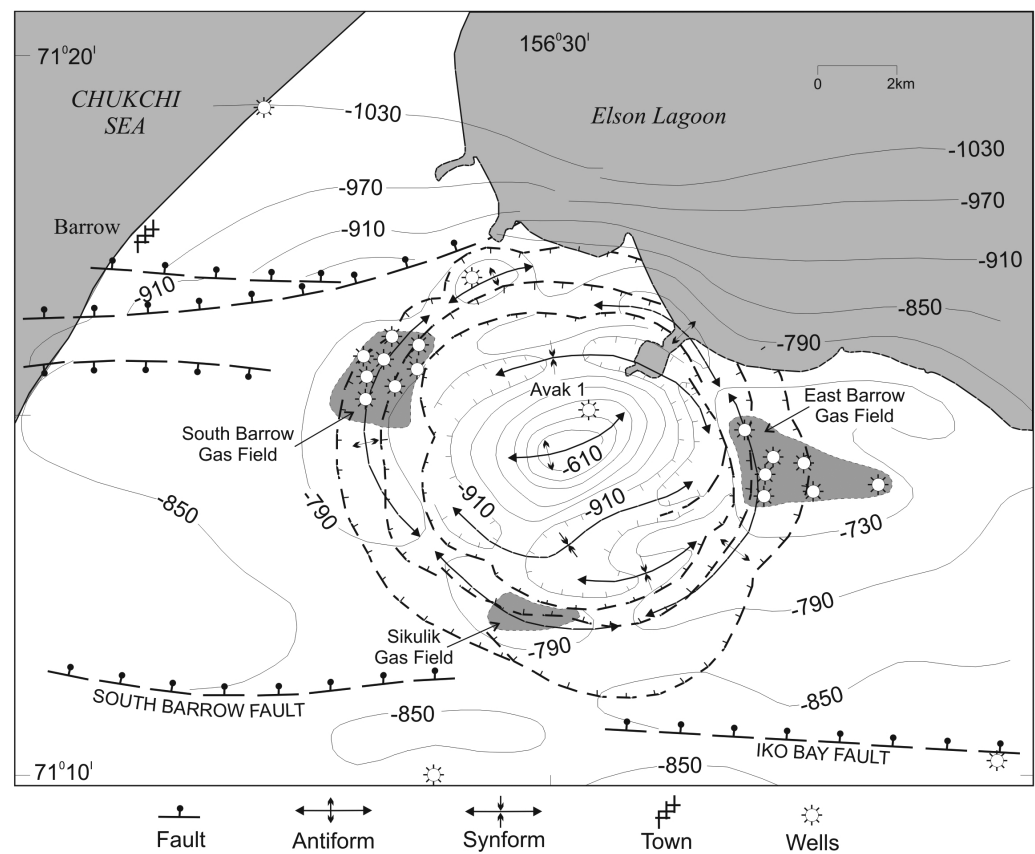


Figure 12.11 Bouguer gravity map (contours in milligals) of the Avak impact structure. The main structural features from reflection seismic data are also shown, with the rim locations of the gas fields (see text for details). Modified from Kirschner *et al.* (1992).

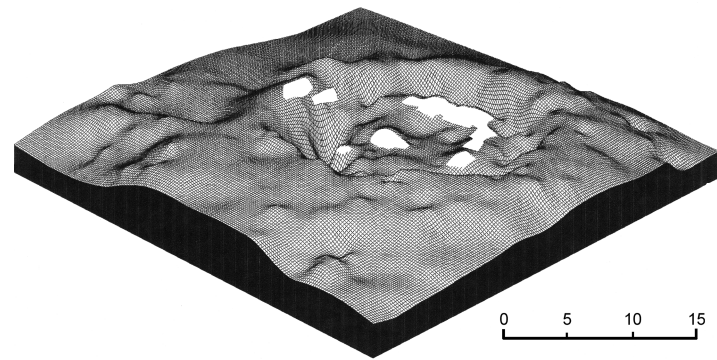


Figure 12.12 Three-dimensional mesh diagram of topography on the post-impact Sylvan shale at the 14 km diameter Ames impact structure. View is to the NW at 25° elevation, with 20 times vertical exaggeration. White areas are zones of hydrocarbon production in the underlying impact structure. Original source: Carpenter and Carlson (1997).

in diameter, with a central uplift, an annular trough and slightly uplifted rim (Fig. 12.12). It is buried by up to 3 km of Ordovician to Recent sediments (Carpenter and Carlson, 1992). The structure was discovered in the course of oil exploration in the area (Roberts and Sandridge, 1992) and is the principal subject of a compilation of research papers in Johnson and Campbell (1997). The rim of the structure is defined by the structurally elevated Lower

Ordovician Arbuckle dolomite; more than 600 m of Cambrian–Ordovician strata and some underlying basement rocks are missing in the centre of the structure due to excavation. The entire structure is covered by Middle Ordovician Oil Creek shale, which forms both the seal and source for hydrocarbons and may have produced as much as 145 million barrels of oil (Curtiss and Wavrek, 1997).

The first oil and gas discoveries were made in 1990 from an approximately 500 m thick section of Lower Ordovician Arbuckle dolomite in the rim (Fig. 12.12). Owing to impact-induced fracturing and subsequent weathering and karsting, the Arbuckle dolomite in the rim of Ames has considerable economic potential. For example the 27–4 Cecil well, drilled in 1991, had drill stem flow rates of 3440 million cubic feet of gas and 300 barrels of oil per day (Roberts and Sandbridge, 1992). Wells drilled in the centre failed to encounter the Arbuckle dolomite and bottomed in granite breccias of the central uplift and, closer to the rim, in granite–dolomite breccias. These central wells (Fig. 12.9) produce over half the daily production from Ames and include the famous Gregory 1–20, which is the most productive oil well from a single pay zone in Oklahoma at more than 100,000 barrels of oil per year (Carpenter and Carlson, 1997). Gregory 1–20 encountered an approximately 80 m section of granite breccias below the Oil Creek shale, with very effective porosity. A drill-stem test of the zone flowed at approximately 1300 barrels of oil per day, with a conservative estimate of primary recovery in excess of 5 million barrels from this single well (Donofrio, 1998). Approximately 100 wells have been drilled at Ames, with a success rate of 50%. These wells produce more than 2500 barrels of oil and more than 3 million cubic feet of gas per day. Conservative estimates of primary reserves at Ames suggest they will exceed 25–50 million barrels of oil and 15–20 billion cubic feet of gas (Kuyendall *et al.*, 1997; Donofrio, 1998). Hydrocarbon production is from the Arbuckle dolomite, the brecciated granite and granite–dolomite breccias and is largely due to impact induced-fracturing and brecciation, which has resulted in significant porosity and permeability.

In the case of Ames, the impact not only produced the required reservoir rocks, but also the palaeo-environment for the deposition of post-impact shales that provided the source of the oil and gas, upon subsequent burial and maturation (Curtiss and Wavrek, 1997). There are similarities between the Ames crater shale and locally developed Ordovician shale in the Newporte structure (48°58'N, 101°58'W) in North Dakota, USA, an oil-producing (~120,000 barrels per year) 3.2 km diameter simple impact crater in Precambrian basement rocks of the Williston Basin (Clement and Mayhew, 1979; Donofrio, 1998). The Ames and Newporte discoveries have important implications for oil and gas exploration in crystalline rock underlying hydrocarbon-bearing basins. Donofrio (1981, 1997) first proposed the existence of such hydrocarbon-bearing impact craters and that major oil and gas deposits could occur in brecciated basement rocks.

12.5.4 Campeche Bank

The Campeche Bank in the SE corner of the Gulf of Mexico is the most productive hydrocarbon-producing area in Mexico. The bulk of the hydrocarbons, from Jurassic source rocks, are recovered from breccia deposits at the Cretaceous–Palaeogene (K–P) boundary. This area includes the world-class Cantarell oil field (Santiago-Acevedo, 1980), which has produced over 11 billion barrels of oil and 3 trillion cubic feet of gas, between discovery in 1976 and 2006. Primary reserves may range as high as 30 billion barrels of oil and 15 trillion cubic feet of gas. Production from the K–Pg boundary rocks is from up to 300 m of dolomitized

limestone breccias, with a porosity of around 10%. Clasts of shocked quartz and plagioclase (Chapter 8) occur in the upper portion of the K–Pg breccias (Grajales-Nishimura *et al.*, 2000). This bentonitic bed, with shocked materials, is considered to be altered ejecta materials from the K–Pg impact structure Chicxulub, which lies some 350–600 km to the NE.

Grajales-Nishimura *et al.* (2000) proposed the following sequence of events for the K–Pg lithologies. The main, hydrocarbon-bearing, breccias resulted from the collapse of the offshore carbonate platform due to seismic energy from the Chicxulub impact. This was followed by the deposition of K–Pg ejecta through slower atmospheric transport. The upper part of the ejecta deposit was later reworked by the action of impact-related tsunamis crossing the Gulf of Mexico. Subsequent dolomitization and Tertiary tectonics served to form the seal and trap respectively for migrating Jurassic hydrocarbons. The net result was the creation of oil fields that produce more than 60% of Mexico's daily production and have reserves in excess of the entire onshore and offshore hydrocarbon reserves of the USA, including Alaska (Donofrio, 1998). The Cantarell oil field is now in decline, with production falling from a peak of around 2 million barrels per day in 2003 to 770,000 barrels per day in January 2009. In 2009, it was replaced by the adjacent Ku–Mallob–Zaap oil field as the most productive oil field in Mexico. Oil from the Campeche Bank fields accounts for the bulk of the over US\$50 billion of hydrocarbons (oil at \$70 a barrel) produced from North American impact structures per year.

12.6 Concluding remarks

Economic deposits associated with terrestrial impact structures range from world class to relatively localized occurrences. The more significant deposits were introduced under the classification progenetic, syngenetic or epigenetic, with respect to the impact event. There is, however, increasing evidence that post-impact hydrothermal systems at large impact structures are of importance, with respect to their potential to redistribute metals. Such hydrothermal systems and metal redistributions can serve to blur the clear distinction between purely progenetic, syngenetic and epigenetic ore deposits related to impact. Examples included the Witwatersrand progenetic gold deposits at the Vredefort impact structure and the syngenetic Contact Ni–Cu–Co ore deposits associated with base of the SIC and the Cu–Pt–Pd–Au-rich Footwall deposits, as well as the Zn–Pb–Cu deposits in the post-impact sediments overlying the SIC, at the Sudbury impact structure.

Although Vredefort and Sudbury are world-class mining districts, hydrocarbon production dominates (in economic terms) the value of natural resource deposits found at impact structures. Commercial hydrocarbon accumulations at impact structures are generally located in the central structural uplift of complex structures and in the rim areas of both complex and simple structures. While spatially localized, such accumulations occur for a variety of reasons, including the physical redistribution of existing reservoir and seal rocks, as well as brecciation to form potential reservoir rocks for migrating hydrocarbons. Many terrestrial impact structures remain to be discovered and, as targets for resource exploration, their relatively invariant morphological and

structural properties as a function of diameter, provide an aid to the development of efficient exploration strategies, particularly for hydrocarbons.

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