Impact-related ore deposits

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Abstract. Due to the energy transfer during an impact event, the earth surface is extensively modified at the location of collision. As a consequence, the potential of the formation of ore deposits at impact sites should be considered. Relative to the time of impact, the following classification has been proposed: progenetic, syngenetic and epigenetic deposits. Two world-class mining districts are discussed further: the Witwatersrand Au-U deposits and the Cu-Ni-PGE deposits of the Sudbury Complex. The deposits of Witwatersrand own their preservation to the Vredefort impact event and are therefore classified as a progenetic deposit, whereas the syngenetic Sudbury ore bodies are originated from an impact generated melt. At both localities the impacts led to hydrothermal activity which could be regarded as an epigenetic overprint.

1 Introduction – Impact site, an unusual geological setting

“Impact is an extraordinary geological process involving vast amounts of energy, and extreme strain rates, causing immediate rises in temperature and pressure that produces fracturing, disruption and structural redistribution of the target materials” (Grieve 2005). Strain rates can rise from $10^{-4}$ to $10^{-6}$/s and even higher due to shock metamorphism where the pressure in the surrounding rock can reach up to 10-60 GPa (French 1998). Stöffler et al. (1994) have proposed velocity of 20 km/s for the projectile of 14 km diameter for a given density of 3 g/cm$^3$ forming the Sudbury impact structure.

The formation of impact craters is divided into three stages (e.g., Melosh 1989). During the first stage (contact and compression stage), the kinetic energy of the projectile is transferred into the target rocks and a shock wave is generated. In this stage virtually complete melting and vaporization of the projectile occurs (French 1998). Within the next stage (excavation stage) the target rock is fractured, shattered and material is ejected outward leaving a transient crater behind. The crater collapses during the last stage (modification stage), which results in the formation
of the different crater types that are categorized according to their morphology: simple craters, complex craters (central-peak and peak-ring complex impact structures), and multi-ring basins. Various examples are listed e.g. by Hawke (2004) and Reimold et al. (2005). Up to date, no terrestrial multi-ring basins have been categorically identified, although Vredefort and Sudbury have been suggested as possible candidates (Hawke 2004).

“When the shock wave has passed and the pressure has returned to normal, spontaneous and complete melting occurs almost instantaneously throughout a large and approximately spherical volume of target rock” (French 1998). Depending on the projectile’s velocity, the diameter of the resulting crater and the composition of the target rocks, a melt will be generated with a volume which is 10 to 100 times the volume of the original projectile (Melosh 1989, French 1998). According to Melosh (1989), the proportion of the melt increases as the proportion of vapor decreases with an increasing crater size. In thick coherent impact-melt sheets differentiation can occur (Grieve 2005).
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Impact structures are in general circular (Hawke 2004). Because different geological processes can form circular structures, such as eruption of a volcano and complex folding, other diagnostic features need to be found. Impact breccias and inclusions of melted material cannot necessarily be the direct indicators. However, the effects of shock metamorphism are unique to meteorite impacts which include planar deformation features (PDFs) within grains of tecto-silicates, phase transition of minerals, production of diaplectic glass, occurrence of shatter-cones on a macroscopic scale as well as melting and formation of suevites (Grieve 2005).

2 Classification of impact related ore deposits

The following classification for impact-related ore deposits has been proposed by various authors (e.g., Grieve 2005, Hawke 2004, Reimold et al. 2005). It is based on the timing of ore formation relative to the impact event; accordingly, progenesis, syngentic and epigenetic deposits are distinguished.

Progenetic deposits are those, which are already in existence prior the impact event. Such deposits undergo modification, redistribution and structural displacement. The most striking example of this type is the Witwatersrand Basin, which got deformed by the Vredefort impact event (section 3.1). Other examples are Ternovka/ Ukraine (Fe, U) and Carswell/ Canada (U) (e.g., Grieve 2005).

The syngenetic type includes deposits, which formed during or immediately after the impact event. These owe their origin due to energy deposition in the local environment from the impact event, resulting in phase changes and melting (Grieve 2005). The formation of impact cubic diamonds or lonsdaleite is related to phase transition in carbonaceous lithologies (e.g., Popigai/ Russia). The most striking example of the syngenetic deposits is the Sudbury impact structure; this will be described further down in greater detail.

The third category of impact-related ore deposits are epigenetic and are associated with the formation of an enclosed topographic basin or long-term fluid flow (Grieve 2005). Economic important commodities that can be found in impact craters are oil or gas. Within the restricted environments of these craters, oil and gas source rocks can be deposited (e.g., Ames, Oklahoma/ USA). Impact structures can also represent structural traps for hydrocarbons (e.g., Red Wing Creek, Dakota/ USA) or the porosity of former dense rocks is increased as a result of the impact event (e.g., Campeche Bank, Gulf of Mexico). According to Hawke (2004), good producing fields are found in simple craters as well as complex craters.

It needs to be stressed that in most cases the material that comprises larger impactors does not contribute significantly to the formation of ore deposits, as it is almost completely vaporized or melted during the first stage of impact formation (see section 1 for reference). Despite this, the local Nama people had been using the Gibeon octahedrites (iron meteorite) to produce spear points and other weapons in southern Namibia (Schneider 2004). Obviously this effect remains very restricted.
3 Case studies

3.1 The Au-U deposits of the Witwatersrand Basin and the Vredefort Dome/ South Africa

The Witwatersrand Basin is located at the center of the Archean Kaapvaal craton, surrounded by several granitoid-greenstone terranes (Frimmel et al. 2005). Sedimentary rocks of the Karoo Supergroup cover the southeastern portion of the structure (Grieve 2005) and partly the Vredefort Dome which is situated right at the center of the Witwatersrand Basin approximately 120 km SW of Johannesburg (Fig. 2). According to Reimold et al. (2005), the currently mined strata (reefs) in the northern part of the Witwatersrand Basin generally dip between 15 and 20 degrees south, towards the Vredefort dome. During the 100 years of mining approximately 50,000 metric tons of Au has been recovered from reefs of the Witwatersrand Basin, the world’s largest goldfield, which supplied about 40 % of the Au ever mined in the world (Frimmel et al. 2005, Grieve 2005).

Fig. 2. Simplified geological map of the Witwatersrand Basin (Robb and Robb 1998).
3.1.1 Geology of the Witwatersrand Basin

The Witwatersrand Supergroup can be subdivided into the West Rand Group (WRG) and Central Rand Group (CRG). Its deposition was accompanied by syn-sedimentary folding and faulting which control the sedimentation style and stratigraphic thickness (Robb and Robb 1998). According to Frimmel et al. (2005), an angular unconformity is found between the metasedimentary rocks of the WRG and the underlying siliciclastic rocks of the Dominion Group, which represents a time gap of approximately 100 Ma. The whole sedimentary sequence of the WRG might have been deposited in a distal fluvio-deltaic and shoreface to off-shore environments at a passive margin setting with sedimentation lasting for 70 Ma until 2.9 Ga.

The WRG and the CRG are also separated by an unconformity. In contrast to the WRG, fluvial-deltaic processes dominated sediment deposition of the CRG (Frimmel et al. 2005). The sedimentation of the CRG has lasted for more than 120 Ma. Four of the seven sedimentary cycles of the Witwatersrand Supergroup belong to the CRG (Robb and Robb 1998). Each cycle is characterized by the formation of Au-bearing conglomerates, concentration of heavy minerals, degradation, reworking and upgrading. About 95% of Au is mined from the reefs of the CRG (Frimmel et al. 2005). The CRG attains a maximum thickness of 2880 m in the Vredefort area and thins out towards the southeast and southwest (Robb and Robb 1998). According to Frimmel et al. (2005), a greater variety of rock sources are proposed for the CRG which were deposited in a foreland basin and in a retroarc basin during the closure of the ocean between Pietersburg block to the north and annealed Witwatersrand-Kimberley block. The sedimentation of the upper CRG was accompanied by progressive uplift of the hinterland. About 2.7 Ga ago the flood basalts (Klipriviersberg Group) covered the Venterspost Formation, which unconformably overlies the CRG (Frimmel et al. 2005).

3.1.2 Postdepositional evolution of the Witwatersrand Basin

The deposition of the Ventersdorp Supergroup onto the CRG took place in an extensional environment, which resulted in the displacement of the underlying Witwatersrand strata (Robb and Robb 1998). After the Ventersdorp event the strata of the Transvaal Supergroup were formed. They include chemical sedimentary rocks of the Chuniespoort Group, deposited in a basin governed by thermal subsidence, and the volcano-sedimentary succession of the Pretoria Group (Frimmel et al. 2005). At 2.06 Ga the emplacement of the mafic to ultramafic volcanic rocks of the Bushveld Complex to the north of the Witwatersrand Basin followed the extrusion of the felsic volcanics of the Rooiberg Group. Enhanced fluid circulation can be assigned to all these events as it is supported by U-Pb ages of hydrothermal rutile, zircon and xenotime (Frimmel et al. 2005).

Only 40 Ma after the Bushveld magmatic event the Vredefort impact structure was formed which encompasses the bulk of the Witwatersrand Basin (Therriault et al. 1997). Features that verify this impact event are found from the circular uplifted central core. They include shatter cones, stishovite, coesite and PDFs in
quartz and zircon. Therriault et al. (1997) used some of these features to estimate a diameter of 110-140 km for the transient cavity and a 270-300 km diameter for the final rim of the impact crater. Due to deep erosion the original morphological elements can not be observed today. Fallback breccia and impact melt are also removed, which should be expected in impact sites of this size (Reimold et al. 2005). Only a series of narrow dikes such as the so-called Vredefort Granophyre remained, which are believed to be a remnant of impact-related melts (Therriault et al. 1997). Other dikes, veinlets or networks filled with pseudotachylitic breccia are abundant close to the Vredefort Dome, but are also found in the northern mining parts of the Witwatersrand Basin (Reimold et al. 2005).

According to Reimold et al. (2005), the Vredefort Dome itself is an eroded remnant of central uplift. Its diameter ranges from 45 to 50 km. It is composed of poly-deformed Archean granitoid gneisses and granites with fragments of mafic and felsic gneisses surrounded by a 20-km-wide collar of metasedimentary and metavolcanic strata of the Dominion Group. In the eastern, western and northern sector of the Vredefort Dome, the collar strata are subvertical to overturned whereas they dip 30°-40° SE in the southeastern sector (Lana et al. 2003). Furthermore, the Vredefort Dome is enclosed by the 50-70 km wide Potchefstroom Synclinorium within the Transvaal Supergroup. The Transvaal succession is characterized by penetrative cleavage, faults and by large-scale open folds which are associated with ductile shear zones and are tangentially arranged around the Dome for as much as 150-200 km (Reimold et al. 2005, Robb and Robb 1998). As already mentioned, erosion has removed much of the morphological features of the impact structure with estimated erosion depths of 8-11 km (Gibson et al. 1998). Thus, the formation of the large impact basin preserved the Witwatersrand Au-bearing strata from erosion (Reimold et al. 2005). Furthermore, the ejecta might have contributed to the prevention of erosion.

### 3.1.3 Mineralization and its origin

According to Hayward et al. (2005), the distribution of Au is controlled mostly by primary sedimentological features within the CRG. Heavy minerals have effectively been concentrated in coarse sand and gravel of large fan-delta complexes. Main ore components include pyrite, pyrobitumen, uraninite, brannerite and gold. The most common mineral within the reefs is pyrite, normally as the rounded compact variety. Except for this, euhedral to subhedral pyrite also occur close to hydrothermal alteration zones and especially in the Ventersdorp Contact Reef. The principal U-mineral within the reefs is uraninite, which is normally well rounded and in close spatial association with bitumen. According to Frimmel et al. (2005), gold shows similar textural variability as pyrite and uraninite. It also occurs as inclusions in secondary pyrite.

Today the “modified placer theory” is preferred as the genetic model, which is the synthesis of the primary introduction of ore minerals into the host rocks by fluvial transport and post-sedimentary thermal overprint (Frimmel et al. 2005, Reimold et al. 2005). Various hydrothermal activities may be related to geological processes prior the Vredefort impact event (see section 3.1.2 for reference). As a
consequence of the Vredefort impact event, extreme temperatures of 1000-1400 °C were proposed in the center of the Dome (Reimold et al. 2005). Temperatures of 300 °C are associated with hydrothermal systems within a distance of 40-60 km to the centre of the crater. Deformed minerals display multidirectional shattering that has affected the entire mineral assemblage present prior to hydrothermal induced mineral growth (Hayward et al. 2005). According to Frimmel et al. (2005), oil migration, together with Au and sulfide mobilization that were documented from several reefs, occurred during postpeak metamorphic fracturing that is most likely related to the Vredefort impact event. This event possibly also accounts for secondary permeability that has been documented for the intensive altered Ventersdorp contact reef (Gartz and Frimmel 1999). Hayward et al. (2005) mention that hydrothermal remobilization and chemical homogenization of gold occurred only over small distances during postdepositional evolution of the CRG as it is indicated by the chemical heterogeneity of gold and associated chlorite at various scales. Also the post-Vredefort hydrothermal activity was possibly very low as the pre-Vredefort dehydration has already affected the Witwatersrand strata (Frimmel et al. 2005). Thus, the influence of an impact-related hydrothermal system on the mineralization might be in general limited.

3.2 The Cu-Ni-PGE deposits of the Sudbury District/Canada

This district is named after the city of Sudbury which lies approximately 320 km north-northwest of Toronto. The Cu, Ni and PGE (Platinum Group Element) deposits of the Sudbury District belong to the world major Ni-Cu deposits (Eckstrand and Hulbert 2007). According to Goodfellow (2007), the 2005 production of the district reached 1,203 10^6 metric t ore at 1.3% Ni, 1.27% Cu and e.g. 0.7 g/t Pt. The cumulative value of ore extracted from this district over the 100 years production has been estimated to be over US$ 100 billion (Reimold et al. 2005).

3.2.1 Geology of the Sudbury District

The Sudbury Structure is widely regarded as a deformed remnant of an impact basin that was formed 1.85 Ga ago (Ames et al. 2008). It is considered to be at least a peak-ring impact basin with an original diameter of ca. 220 km (Stöffler et al. 1994) to 280 km (Reimold et al. 2005). The Archean Levack Gneiss Complex and the Cartier Batholith surround the northern and western margin of the structure (Fig. 3). Prior to the impact event, these basement rocks were unconformably overlain by the Paleoproterozoic Huronian Supergroup strata, which form the southern rim (Naldrett 2004). Close to the Sudbury basin, the Huronian rocks comprise mafic to ultramafic intrusions and mafic to felsic volcanic rocks, which are associated with the rifting of the Penokean Ocean (Ames et al. 2008). The present NE-SW elongated elliptical shape (about 27 x 60 km) of the Sudbury Structure might be largely due to the post-impact Penokean tectonism (Naldrett 2004). This tectonism also caused imbrication of the Sudbury Structure by NW-vergent thrusting on the South Range Shear Zone (Scott and Benn 2002).
Indications and evidence for the explosive nature of the Sudbury impact event are listed by Naldrett (2004). These include shock metamorphic features (PDFs, thotamorphic glass in shocked quartz, micro-diamonds and shatter cones), the Sudbury and Footwall Breccia as well as the basinal shape of the structure.

Directly related to the impact event is also the formation of the Sudbury Igneous Complex (SIC). According to Naldrett (2004), the SIC is a layered intrusion, which includes the Offset dikes, the Sublayer and the Main Mass. On the North Range the Main Mass grades from Mafic Norite at the bottom into Felsic Norite, Quartz Gabbro and Granophyre at the top. The lowest units on the South Range comprise Quartz-rich Norite and South Range Norite, which are followed by rocks similar to those of the North Range. Below the Main Mass, the (Contact) Sublayer can be found discontinuously around the Sudbury Complex. It is composed of norite that hosts inclusions of mafic to ultramafic rocks. The Sublayer reaches maximum thickness in troughs, which are referred to as Embayments. These are broad scale irregularities in the walls of the SIC which might represent terraces that formed within the inner wall of the complex craters (Hawke 2004, Naldrett 2004). The Offsets are radial or concentric dike-like bodies that extend up to 20 km from the Main Mass and are composed of quartz diorite (Naldrett 2004).

The Footwall Breccia forms a relatively thin layer of crushed country rock right below the Sublayer of the SIC. It is found in large parts on the North Range. The Sudbury Breccia occurs up to 20 km within the country rock outside the SIC (Naldrett 2004). It can also be classified as pseudotachylitic breccia (Reimold et al. 2005). In addition, pseudotachylytes are found in subconcentric zones within a maximum distance of 80 km outside the SIC (e.g., Thompson et al. 1998). Reimold et al. (2005) have mentioned that different zones of breccias possibly developed at different stages during the impact process, both at the time of shock compression and later modification.
The Granophyre is directly overlain by the basis of the Onaping Formation. The latter can be subdivided into four units: a basal zone (melt breccia, up to 300 m thick), “Grey Onaping” (suevitic breccia, 300-500 m thick), “Green Onaping” and “Black Onaping” (e.g., Stöffler et al. 1994). The thin layer of “Green Onaping” is interpreted as the collapsed ejecta plume. An Ir-anomaly was discovered within the upper 800 m of the crater-fill breccias (Ames et al. 2008). The “Black Onaping” zone contains 1-3 wt% C and has been reworked or re-deposited in an aqueous environment of the impact basin (Naldrett 2004). It is overlain by post-impact sediments of the Onwatin and Chlemsfort Formation.

3.2.2 Ore bodies and mineralization

The ore occurs mainly within broad zones at the base of SIC and in Offset dikes (Reimold et al. 2005). According to Naldrett (2004), ore bodies of the Marginal (Contact) deposits include Cu-rich zones in the footwall. Their position is controlled by the Embayments. Disseminated mineralization or stringers of massive ore occur within the Footwall Breccia and in fractures beneath the breccias (e.g., Strathcona mine/ North Range) as well as massive ore close to the footwall (e.g., Murray mine/ South Range). In contrast to the North Range deposits the As + Sb content and the Pt + Pd content of the South Range ore are higher, as well as the sulpharsenide minerals have much higher PGE contents in solid solution than sulphide minerals (Farrow and Lightfoot 2002, Naldrett 2004). Conversely, Sn-bearing accessory minerals are found in the Cu-rich footwall veins on the North Range. Ore zones of the Offset deposits (e.g., Copper Cliff Offset) form steep plunging, lens-like pods of massive to disseminated ore, which is associated with offset rocks rich in inclusions of Archean and Proterozoic rocks (Tuchscherer and Spray 2002). Compared to the Contact deposits the Cu/Ni ratio and the precious metal content (Pt-Pd-Au) are higher. The South Range Breccia Belt deposits (e.g., Frood-Stobie deposit) are described by Farrow and Lightfoot (2002) as a separate deposit type which tends to be extremely rich in PGEs.

The Fe-Ni-S minerals include pyrrhotite as host for all the other sulphide minerals like pentlandite and pyrite (Naldrett 2004). Chalcopyrite and cubanite mainly represent the Cu-Fe-S minerals. In the North Range ores, significant amounts of PGE’s can be found as solid solution in As-bearing minerals (Farrow and Lightfoot 2002). The dominant Pt mineral on the South Range is sperrylite, whereas moncheite tends to be more common on the North Range.

3.2.3 Evolution of the Sudbury Structure

About 1.85 Ga ago a meteorite impacted the Archean and Huronian rocks at the Sudbury site. The resulting transient crater measured approximately 60 km in diameter and was about 30-40 km deep (Stöffler et al. 1994). Due to the transition of the shock wave, the target rocks were melted and about 10,000-25,000 km$^3$ melt was produced (Ivanov and Deutsch 1999). According to Reimold et al. (2005), isotopic and geochemical data are consistent with the derivation of the SIC from pre-existing crustal material. In addition rare earth element patterns revealed
crustal signatures (e.g., Scott and Spray 2000). Also related to the impact event, intense brecciation occurred in the country rock, which resulted in the formation of the Sudbury Breccia. In the final phase of the excavation stage the Footwall Breccia formed, which was immediately overlain by the impact melt, violently spreading onto the crater floor and walls (Stöffler et al. 1994). According to Naldrett (2004), the rock’s melt filling the crater was about 500 °C above liquidus temperature. Superheat conditions that lasted for approximately 250,000 years led to a great degree of assimilation of country rock (Farrow and Lightfoot 2002, Naldrett 2004). The upper part of the melt sheet was overlain by suevitic breccia and felsic fall-back ejecta, whereas the lower, denser part of the impact melt might have contained more Huronian mafic volcanics and related intrusions. The chemical gradient in the impact melt could have resulted in a compositionally stratified magma with separate convecting layers as it was suggested by Naldrett (2004). Grieve (2005) mentioned that the ‘disequilibrium’ composition was an original property of the impact melt in contrast to former models involving endogenic magma. Cooling of the intense convecting magma might have led to the immiscibility of sulphides, which were entrained in a stagnant boundary layer along the walls of the magma body, concentrated in the Embayments and soaked into Footwall Breccia (Naldrett 2004). Scavenging was so efficient that the Main Mass Norite is effectively depleted in Ni, Cu and PGEs (Farrow and Lightfoot 2002).

During its cooling, the SIC evolved into a heat engine that provided both heat and magmatic volatiles (Farrow and Lightfoot 2002). According to Ames et al. (2008), past-producing VMS-like Zn-Pb-Cu Errington-Vermilion deposits formed in the sedimentary rocks of the crater which were modified by the hydrothermal activity. This activity lasted for approximately 5 Ma after the impact, as the regional semiconformable alteration zone of these deposits was dated to be 1848.4 ± 1 Ma (Ames et al. 2008). Also, Ni-Cu-PGE deposits below the complex were modified by the hydrothermal fluids which generated Cu-PGE-Au concentrations and Cu-rich veins enriched in Pt, Pd and Au in the permeable, fractured and brecciated zones of the footwall (Ames et al. 2008, Molnár et al. 1997).

4 Concluding remarks

Impact structures have considerable economic potential, but exploration potential is limited by the relative small number of such structures known (Grieve 2005). For both the Au-U deposits of Witwatersrand and the Cu-Ni-PGE deposits of the Sudbury Structure, a clear link with regard to impact events is verified. But it remains difficult to estimate to which extend they are modified by impact-induced hydrothermal systems as it does not seem possible to define parameters that could distinguish unambiguously between the results of an impact-triggered hydrothermal mineralization event and one that is the result of other geological processes (Reimold et al. 2005). Also, the estimation of the original size of these impact structures is complex due to intense erosion and tectonic deformation, respectively.
References


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