The potential for mineral exploration and extraction in Antarctica

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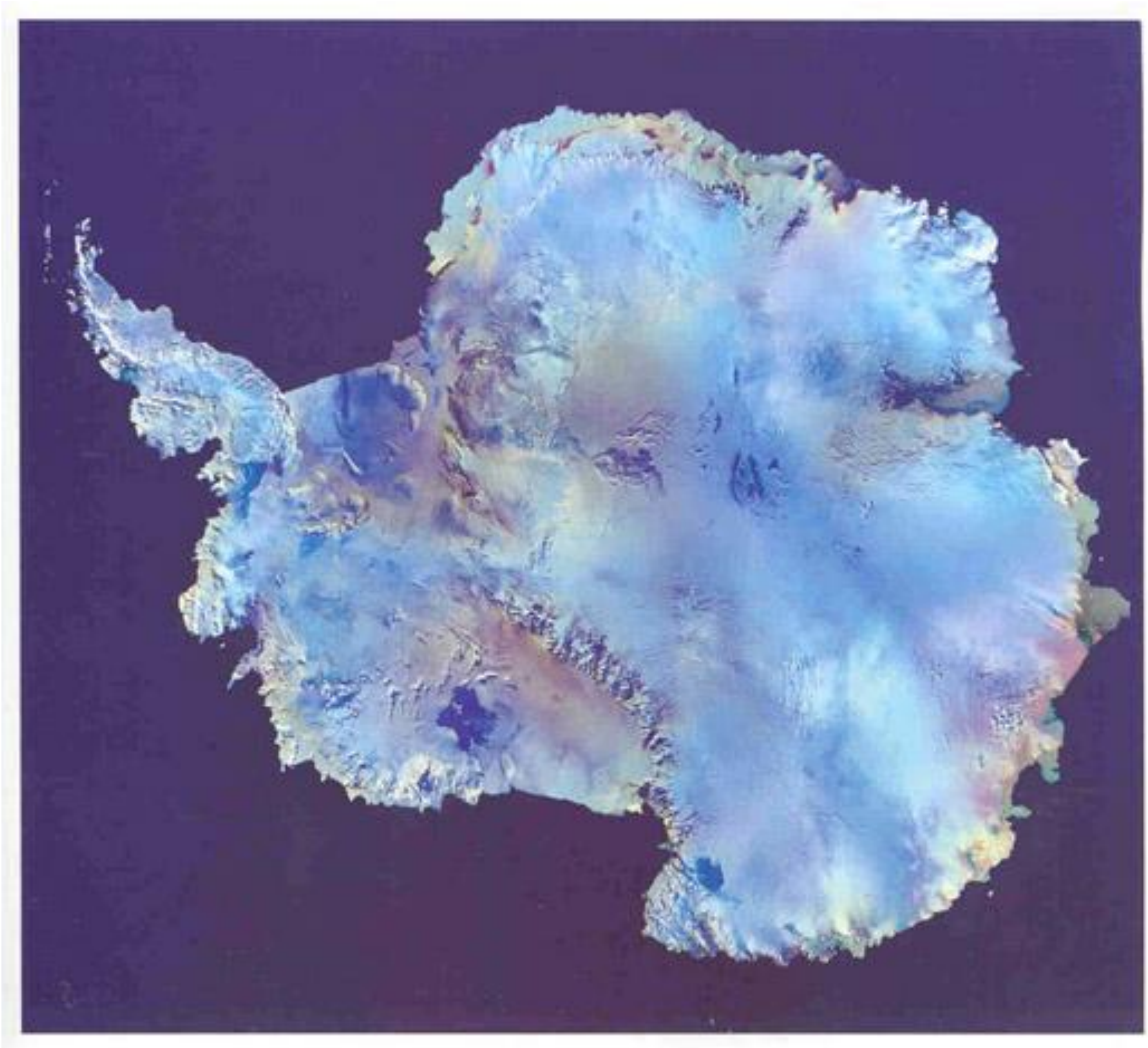

Introduction

Antarctica is the only continent in the world which does not have a history of mineral production, it is also the only continent with no known economically exploitable deposits and where no resources have been explored by drilling (Rowley, Ford, Williams, & Pride, 1983). Its isolation and extreme conditions have protected it to a large degree from the exploits of humans. In addition the exploration and mining for minerals on the continent is illegal under the Antarctic Treaty System. However, with the world's growing human population and the growth of wealth within nations with historically low levels of consumerism coupled with the possibility of future exhaustion of mineral resources on the other continents it is possible that Antarctic may not always be so far from the grasps of mineral prospectors in the future. This paper will have a look at what documented and speculated mineral occurrences are in Antarctica and what their economic potential could possibly be, so that we can make an educated guess about what the future could be for Antarctic minerals. It will give a brief review of some of the more economically interesting mineral occurrences which are known to occur on the continent and will try to give some idea of what the potential for undiscovered resources could be. Concentrating mainly on copper, platinum and iron ore, as these appear to have the best potential on the continent, this paper examines the world markets for these minerals to try and get a feel for what the future may hold for metal supply and demand from these markets. It will look at some of the difficulties and extreme costs which would be associated with a minerals industry in Antarctica as these difficulties could possibly make the exploration for, or extraction of minerals from the continent impossible. The idea is to look at the continents geological potential versus its associated difficulties and by examining the expected future state of the world's resource markets to come to some conclusion about the future economic potential of Antarctica's minerals. This paper has not taken into account the legal framework surrounding Antarctic minerals or the moral and social implications of a minerals industry on the continent.

Comparisons between Antarctica and other Gondwana continents

Given that Antarctica was once part of the Gondwana super continent and that the other Gondwana continents have considerable mineral resources it is fair to assume that the Antarctic continent must contain similar resources. In reconstruction models of Gondwana it can be seen that Antarctica is located in the centre of Gondwana, the correlation of proven mineral provinces in other southern hemisphere continents indicates that Antarctica should hold equivalent regions (Rowley, Williams, & Pride, 1983). It is a fair assumption that the mineralising geological processes that acted on the other Gondwana continents have also been active in Antarctica (J. Splettstoesser, 1985).

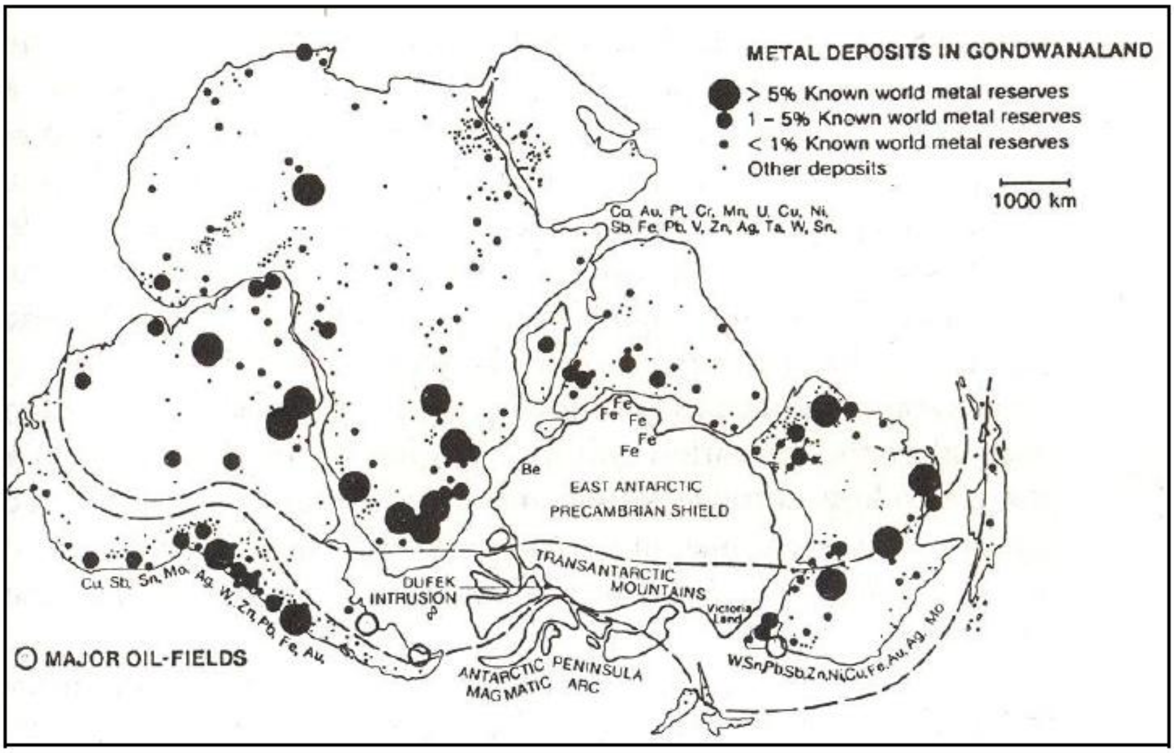

Figure one: Reconstruction of Gondwana showing the locations of major mineral provinces in the Gondwana continents and their proximity to the Antarctic continent which presumably holds similar resources. Taken from Willan, MacDonald and Drewry (1990).

Overview of the possible economic geology of Antarctica

No other continent on the Earth is devoid of substantial mineral resources (Wright & Williams, 1974) and for this reason it must be assumed that there are mineral resources in Antarctica. Roughly one per cent of Antarctica is exposed rock (Crockett & Clarkson, 1986) and these are the only areas considered viable for mineral prospecting or mining. The mineral potential which lies underneath the ice sheets will not be given detailed examination as it is not regarded as economically interesting at this stage, due to being covered by kilometres of ice. Only the few areas of exposed rock are considered worth talking about when considering the potential of a minerals industry in Antarctic. East Antarctica which is covered by the East Antarctic Ice Sheet has possible coal resources and large amounts of exposed rock in the Transantarctic Mountains. This Transantarctic metallogenic province as defined by (Rowley, Ford, et al., 1983) also includes platinum and other metals associated with a layered mafic intrusion named the Dufek intrusion. The East Antarctic iron metallogenic province from (Rowley, Ford, et al., 1983) includes Banded Iron Formation (BIF) rocks from Enderby Land to Wilkes land along the east coast and a ferrous vein province in Queen Maud Land. West Antarctica has more exposed rock mostly in the Antarctic Peninsula and off lying islands, this area has the potential for porphyry copper style mineralisation in the northern Antarctic Peninsula and was referred to by (Rowley, Ford, et al., 1983) as the Andean metallogenic province. These three regions and the most prospective areas within each will be compared for their mineral potential.

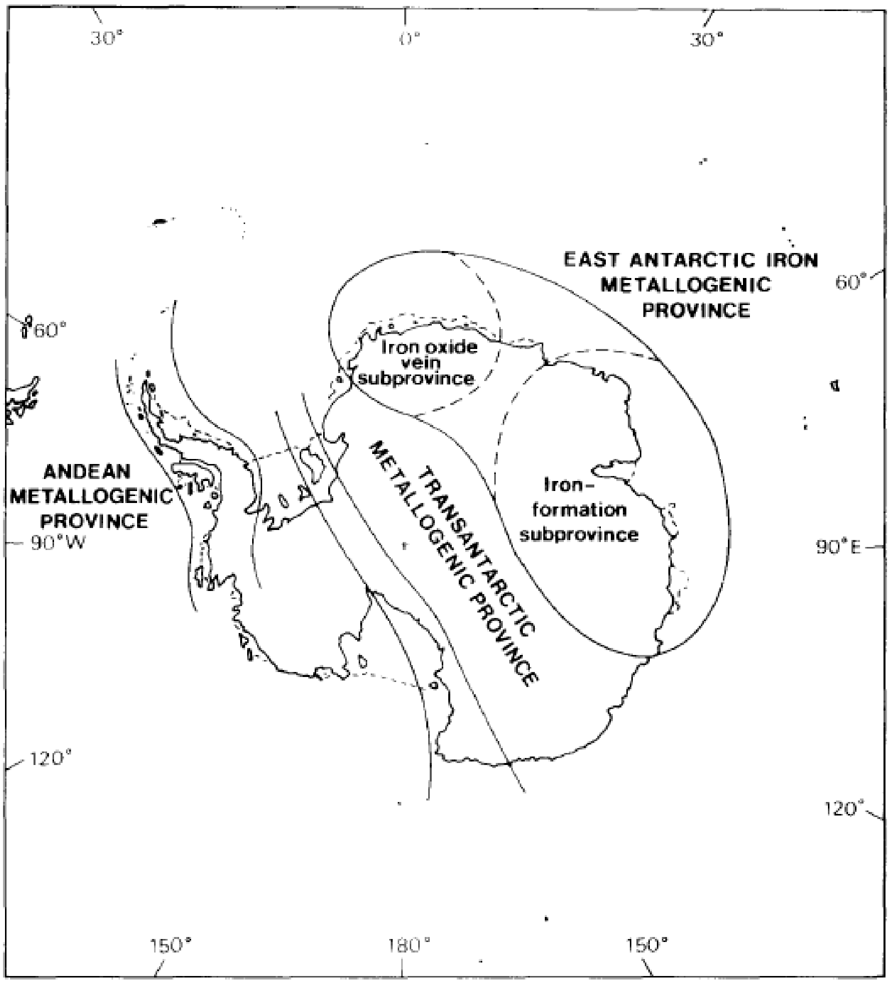

Figure two: The three metallogenic provinces of Antarctica from (Rowley, Ford, et al., 1983).

East Antarctica is composed largely of a Precambrian craton (Crockett & Clarkson, 1986). This Archean craton could be expected to have similar resources as other Gondwana cratons such as the Yilgarn in West Australia which is well endowed with gold and other mineral resources. However most of the Antarctic craton is covered by the East Antarctic Ice Sheet (EAIS). The rocks of East Antarctica are for the most part not commonly exposed except in the Transantarctic Mountains and along the coast (Rowley, Williams, et al., 1983). The Transantarctic Mountains form a mountain belt along the boundary with West Antarctica. Deposits in Precambrian areas of the other Gondwana continents which were located next to East Antarctica while it was part of the Gondwana land mass include among others BIF rocks in Australia, India and Africa and Platinum Group Element (PGE) deposits in the Bushveld Complex of South Africa. What follows is an examination of the potential for iron ore in the far east of Antarctica, PGE deposits in the Dufek intrusion of the Pensacola Mountains as well as for porphyry copper and hydrothermal deposits in the Antarctic Peninsula as these are considered to hold the best potential for mineral resources on the continent.

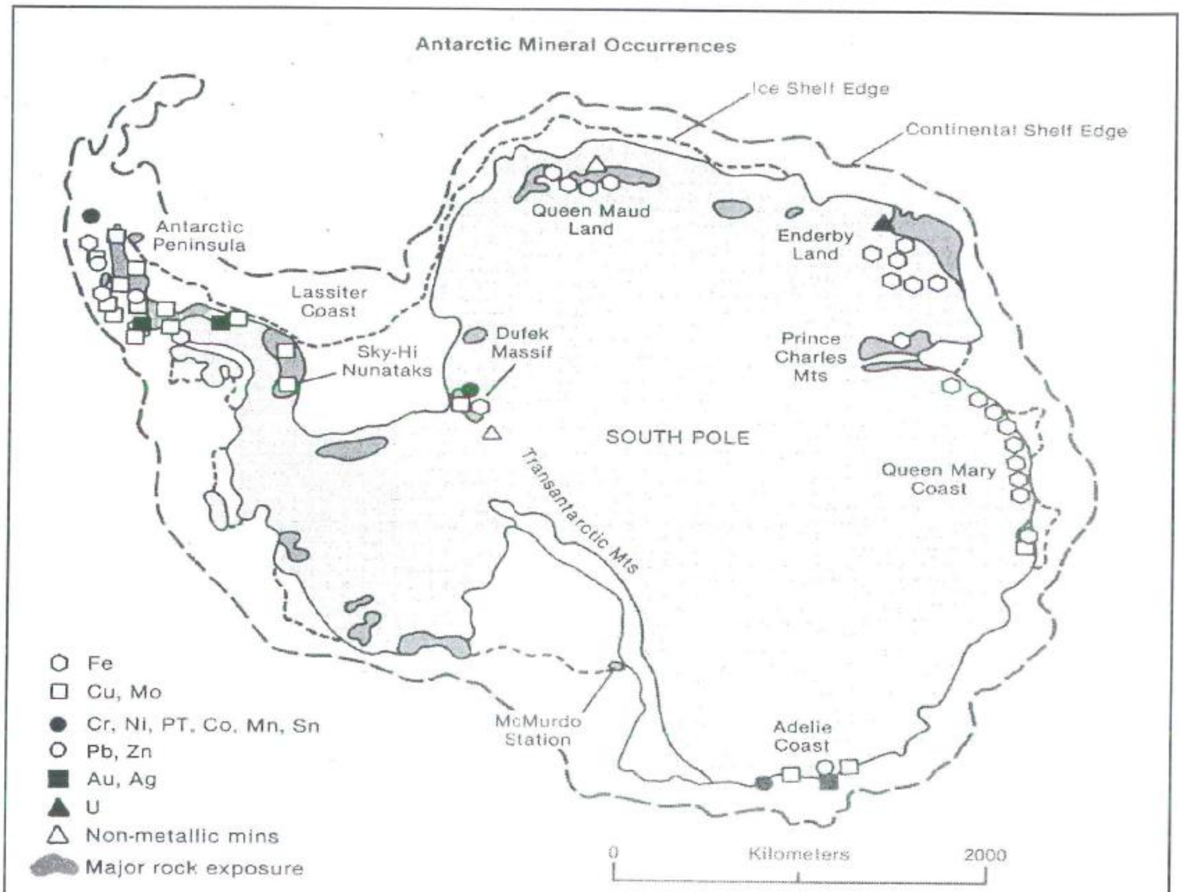

Figure three: Mineral occurrences recorded in Antarctica, note the concentration of iron recorded from Enderby Land and the Queen Mary Coast, also the heavy concentration of metals within the Dufek Massif and the Antarctic Peninsula. Taken from (Curtin, Hayes, Jakob, H, & Schleich, 2003).

The potential for Iron ore in Antarctica

The only two mineral resources which have known occurrences comparable to exploitable deposits in other parts of the world are coal and iron in East Antarctica (Kameneva & Grikurov, 1983). It was believed by Rowley et al., (1983) that the large volume and low grade ores such as iron ore and coal were the most likely to be exploited in Antarctica. However both coal and Iron ore are found in large supply and better quality ore in other parts of the world and good potential for exploration and discovery still exists on the other continents.

Banded Iron formation rocks are found on the east coast of East Antarctica from Wilkes Land round to Enderby Land and the largest of these deposits are found on Mount Ruker. In Queen Maud Land an iron-oxide vein sub-province has been identified which contains magnetite veins thought to possibly hold related sulphide minerals (Rowley, Williams, et al., 1983). It was considered by Russian geologists that there are good chances of finding a major iron deposit in Queen Maud Land (Wright & Williams, 1974). In addition substantial amounts of BIF rocks have been interpreted to be underneath the ice-sheet from aeromagnetic surveys (Splettstoesser, 1982). Geophysical exploration has been an important tool for mineral exploration on all of the Earths continents, the potential to explore for iron ore underneath the Antarctic ice sheets presents probably the best example of how geophysics could be utilised for mineral exploration in Antarctica as iron deposits have distinctive magnetic and gravitational anomalies.

Antarctica presumably has the potential for an iron region similar in size to the Pilbara of Australia unfortunately most of this mineral wealth in the form of BIF deposits is covered by ice and can only be guessed at by geophysics. Of the known outcropping occurrences of iron bearing rocks in Antarctica Mount Ruker is the largest and gives us a good example of what any prospective iron ore industry could expect to deal with in Antarctica.

Mount Ruker

Chemical analysis of samples taken from Mount Ruker by Tingey (1990) were considered to be reasonably representative of the deposit and had a range of %24.1 Fe to %45.9 Fe and an average iron content of %33.5 which is low compared to world standards. Samples taken by other researches from the Newman Nunataks and Vestfold Hills produced even less impressive Iron grades (Tingey, 1990). In Australia for example no ores with less than %50 Iron content have been aimed at or purposefully mined. The phosphorous content of the Antarctic iron deposits is high and this is considered undesirable for steel making. Also Mount Rukers geographic position on the inland side of the Fisher Glacier means it would be difficult to access for economic exploitation (Tingey, 1990). It was believed by Tingey (1990) that the high cost of mining and transportation from this location coupled with the low quality ore would make development of these resources unlikely.

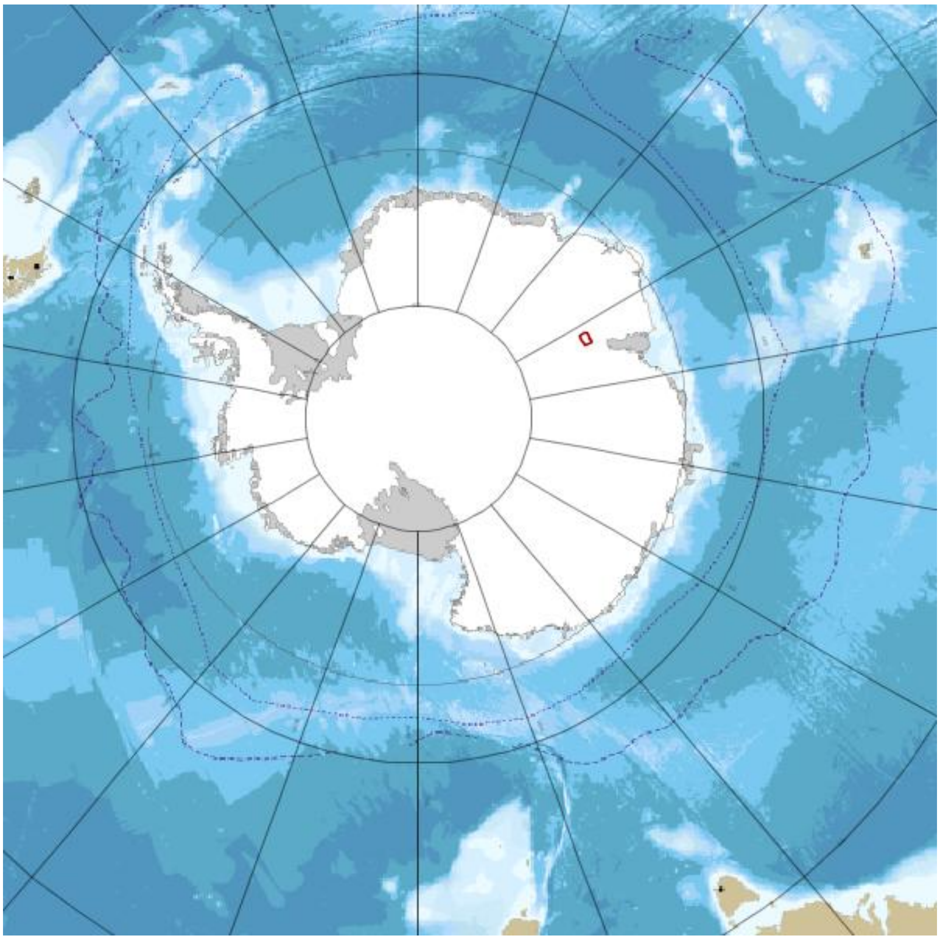

Figure four: Mount Rukers location in Antarctica take from ("Cat.No:L31 in 'ANARE Catalogue of Maps and Hydrographic Charts 1997',").

Australia is the nearest land mass to the Mount Ruker deposits and this area is within the Australian Antarctic Territory. Due to its relative proximity if any nation were to look economically at these deposits it could be Australia. However Australia contains massive iron ore deposits in the Pilbara region of West Australia and it is very unlikely that this nation or any other would consider the Mount Ruker or other iron ore deposits in Antarctica to be economically interesting at this stage. The poor quality of the iron deposits and their terrible geographic location make them unattractive to any serious investor. However iron is a hugely important metal and the world demand for this metal is increasing every year while the resources become depleted.

Economics of iron ore

Iron is perhaps the most important metal to world industry accounting for roughly %95 of all metal used by modern society. The most common use for iron is for steel making which up to %98 of the extracted ore is used for. Therefore the demand for iron ore is dependent on the production of steel. The developing nations have the greatest demand for iron ore with China consuming the most iron followed by other developing nations such as Brazil and India, this growing demand is created primarily by infrastructure projects requiring steel (Yellishetty, Ranjith, & Tharumarajah, 2010). The

United States Geological Survey (USGS) estimated in 2008 that the worlds economically recoverable iron ore reserves to be at 165,347 Mt, which with the 2008 production levels was expected to last for 79 years (Yellishetty, et al., 2010). However a different model by Yellishetty et al., (2010) assumed that iron ore production would increase exponentially in the future this model matches the steady increase in production between 1950 and 2005. They made their own estimates on how long it would take world iron ore resources to deplete assuming this exponential growth in production rather than the steady rate of production that the USGS used in their calculations. Yellishetty et al., (2010) calculated that the worlds identified iron ore reserves would last for 49 years. What is certain from these studies is that the projected increase in demand for iron ore caused by increasing steel production in developing nations is unsustainable with current resources and technology.

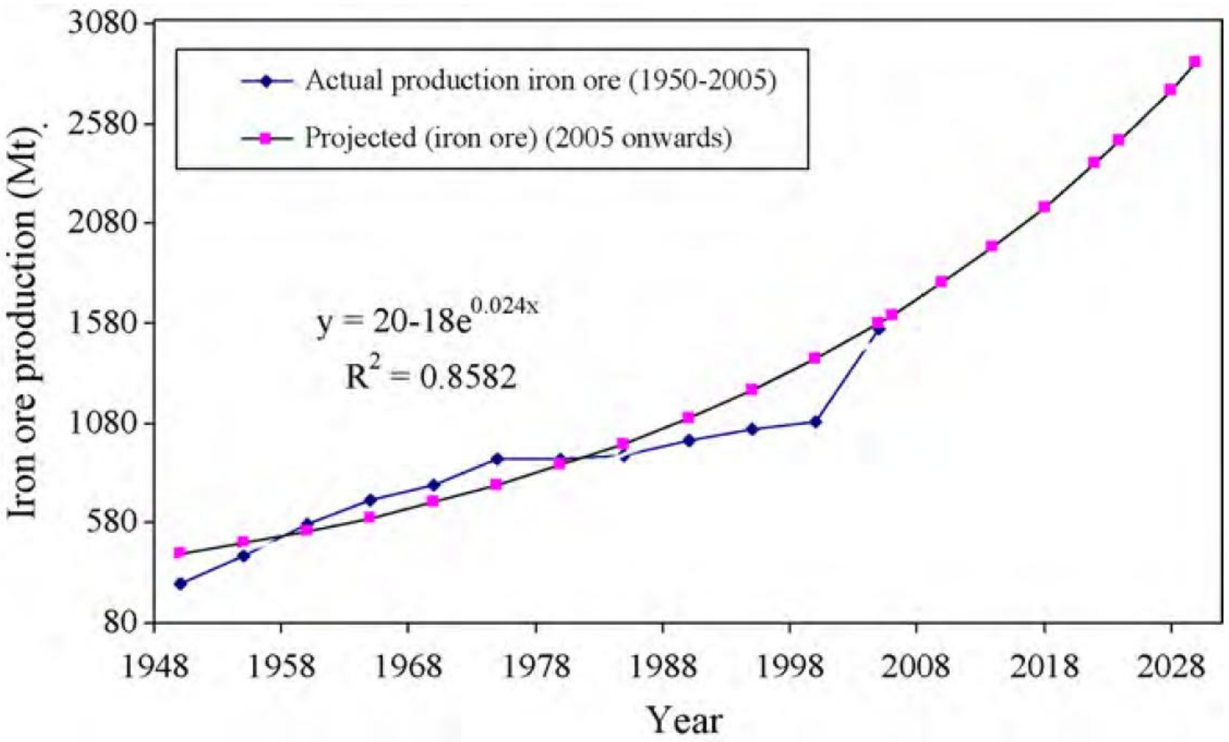

Figure five: The projected exponential iron ore production model from Yellishetty et al., (2010) and the actual world production.

Of the known occurrences of iron in Antarctica Mount Ruker presents the best example of a deposit which would be of economic interest on a different continent. At the present moment and into the near future the potential iron ore deposits in Antarctica are not economical or at all attractive to investors. They appear to be poor grade deposits and would present major problems due to the geographic location. With the projected increase in demand for iron ore mostly from developing nations the market seems to be unsustainable with predictions of global depletion of this type of ore certainly within the century. It is of course impossible to know what the demand for any commodity will be in the distant future and what technological or exploratory advancements will be made to increase world reserves. There is a slight possibility that if demand for iron does increase exponentially and reserves on the other continents are seriously depleted then explorers and producers may start to look more closely at Antarctica for future iron extraction.

Coal in Antarctica

The Transantarctic Mountains hold thick beds of coal in the Beacon Supergroup and these beds are considered to be roughly equivalent to the coal of the Karroo in Southern Africa (Crockett & Clarkson, 1986). Research on the coals have found them to have a high sulphur and ash content and are considered by experts to not be of high quality (*Antarctic resources*, 1973). The quality of the coal so far studied would disallow its use for coking or gasification (Wright & Williams, 1974). There are also coals of a similar age located in the Prince Charles Mountains (J. Splettstoesser, 1985). The coal deposits located in the Transantarctic Mountains are not considered economically interesting due to the logistics concerned with exploiting the large amounts of ore needed and also because the world contains large coal reserves on the other continents (Splettstoesser, 1982). It is not considered likely that they will be economical in the foreseeable future due to the low quality of the coal beds and that they are located in Antarctica. The only potential that can possibly be seen for these coal beds is that if any significant population was to one day settle on the continent then perhaps they could use the coal locally for heating and power generation.

The Dufek intrusion

The Dufek intrusion is located in the northern Pensacola mountains (Ford, 1983) it is a layered mafic intrusion mostly of gabbroic composition which is thought to be more than 50,000 km squared in area (Ford, Mays, Haffty, & Fabbi, 1982). This complex has many similarities with other layered mafic intrusions around the world which hold economic mineral deposits (Ford, et al., 1982). It has been compared by many authors to the highly valuable Bushveld Complex in South Africa and due to these similarities is thought to possibly hold resources of PGE as well as copper, tin, nickel, vanadium, and chromium (Ford, et al., 1982). Almost all known layered mafic igneous complexes of this nature contain metal deposits which are economically exploitable and apart from the Bushveld Complex the Dufek is believed from interpreted geophysical data to be larger than any other known complex of this type on the Earth (Ford, 1983). Other examples of layered mafic intrusions which have been economically exploited include the Stillwater in the United States and the Sudbury in Canada (Wright & Williams, 1974).

Similar complexes in other parts of the world which are much smaller than the Dufek contain important metallic resources. The very large size and similarities with the Bushveld Complex and other layered mafic igneous complexes has encouraged much speculation about the Dufeks potential for mineral resources (Ford, 1983). However only a small fraction of the Dufek intrusion is exposed and any economically interesting deposit has yet to be found (Ford, et al., 1982). It is considered by Ford et al., (1982) that PGE would be of the greatest interest for possible extraction from the Dufek complex. In other intrusions of this type PGE have been found to become concentrated at certain stratigraphic levels due to differentiation of the magma (Ford, 1983). Although no significant concentrations of PGE have been found in the Dufek it is believed that the exposed portion of the Dufek intrusion correlates roughly with the upper portion of the Bushveld Complex and that the stratigraphic variation of elements in the Dufek are similar to those in other mafic layered complexes. This stratigraphical comparison with other similar complexes indicates that the unexposed lower areas of the Dufek would be of highest potential for containing mineral resources. It is speculated that rocks equivalent to the Merensky Reef which holds much of the Bushveld complex's PGE ore could lie 100-700m below the exposed section of the Dufek complex (M. De Wit, 1986).

The difference in age between the Dufek and the Bushveld has led some authors to suggest that the two complexes are not comparable for potential resources. The Dufek is Middle Jurassic in age 175-170 million years old (175-170 Ma) which is closely related in age to the volcanics of the Ferrar Group also in the Pensacola Mountains (Ford, 1990). While the Bushveld is proterozoic in age at 2.1 billion years old (2.1 Ga) and the Stillwater is 2.7 Ga (J. De Wit, 1985). According to the principle of 'metallogenic epochs' the Dufek should only be compared to intrusions of a similar age (D Beike & Rozgonyi, 1990).

The Dufek intrusion has enormous potential for mineral resources; if its PGE concentration is found to be comparable to the Bushveld complexes then the Dufek would represent one of the major concentrations of PGE in the Earth's lithosphere.

Hypothetical mining of the Dufek

It was considered by Rowley et al., (1983) that it would be much more expensive to operate a copper or iron mine in Antarctica than a PGE mine as these commodities have lower unit prices than PGE so the transportation cost becomes much higher. A study on the practicality and economic potential of a hypothetical PGE mine located within the Dufek intrusion was conducted by Beike (1990) and later evaluated by Beike and Rozgonyi (1990). He proposed a method of transportation for all mining equipment, personnel, buildings and concentrate to be performed by helicopter and heavy cargo plane which would only fly in the Antarctic summer. The ore concentrate would be flown to the Weddell Sea coastline on Berkner Island and from there be transported by cargo ships to smelters. Power supply would be from diesel generators and water supplied by pumping sea water to the site from a 1000m bore hole in the nearby Ronne Ice Shelf (Dieter Beike, 1990). Comparisons for the mining environment were made by Beike and Rozgonyi (1990) with that of the Polaris zinc mine in the North West Territories of Canada, which shut in 2002. An underground mine was considered favourable due to an open pit mine having an uneconomical strip ratio and also because creep in frozen ground could be expected to cause slope stability problems in an open pit. Additionally an underground mine would be less exposed to the harsh climate which could cause serious problems for personnel and mining equipment.

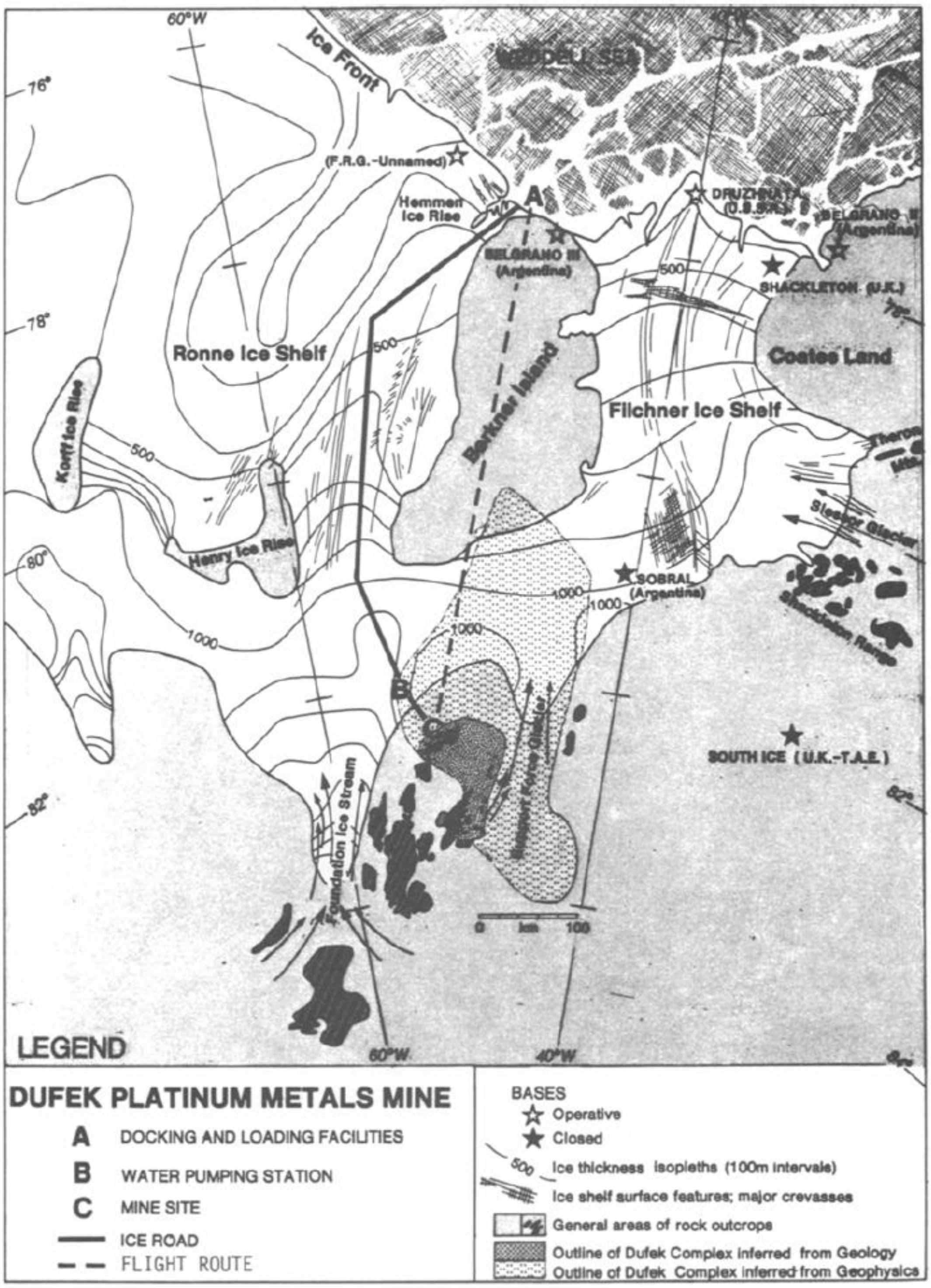

Figure six: A map of the hypothetical mine in the Dufek complex, note the geographic location of the Dufek complex is helpful for water supply from below the Ronne Ice Shelf and transportation from the north of Berkner Island. Also note the large size of the Dufek inferred from geophysics. Figure taken from Beike and Rozgonyi (1990) who adapted this map from De Wit (1985).

It was believed by Beike and Rozgonyi (1990) that with modern mining technology the exploitation of Antarctic minerals was possible. In one of their hypothetical economic scenarios in which the price of PGE increased by %50 on the 1990 price they deducted that a platinum mine was economic. A study done by De Wit (1990) concluded that a hypothetical platinum mine in the Dufek could be economical if the 1983 platinum price continued for 26 years. Although it was believed that it would be some time before any serious minerals industry was developed in Antarctica due to the risks associated with such an investment, and due to the higher economic potential of other parts of the world to supply this type of ore (M. De Wit, 1990). Ford (1983) calculated that it would cost roughly three times as much to extract PGE from a hypothetical mine in the Dufek intrusion as it would from a similar ore body in the United States.

The Dufek intrusion would definitely have been intensely explored if it were located nearly anywhere on Earth apart from in Antarctica. Geographically the mining of the Dufek would be much easier than in inland areas of Antarctica due to its proximity to the coast. It is relatively near to transportation via the Weddell Sea and to infrastructure in South America. The location near to the coast means that transportation to and from the area would be much simpler than to inland parts of the continent. If enough discoveries were made then the possibility of operating several mines within a small area similar to the situation of the Bushveld complex exists within the Dufek. The operation of several mines near to each other would push costs down as the mines could share some infrastructure such as roads and ports and could possibly share transportation costs. However what needs to be considered is the human demand for platinum and if the metal will ever be valuable enough to make any operations in Antarctica economically rewarding enough on a scale needed to attract serious investors. There are already places in the world which are mined for PGE and it may be possible that these deposits will be able to extract enough ore to meet future demands.

The Platinum market

South Africa is the world’s top producer of platinum due to its possession of the Bushveld complex, this nation supplied %77 of the worlds platinum output in 2007 (Cenc, 2008). The biggest demand for platinum comes from the automobile industry as it is used as a catalyst in the combustion of hydrocarbons (Cenc, 2008), however platinum is also an important metal in hydrogen cells (Yang, 2009). If combustion engines are replaced with hydrogen cells then platinum will still be a critical mineral to the automobile industry. The price of platinum is like most commodities controlled mostly by its supply and demand, however platinum is also linked to the price of oil, gold and to the ratio between the Euro, the US dollar and the South Africa Rand (Cenc, 2008). In most of its industrial uses without significant compromises to performance platinum is irreplaceable. Normally the only practical substitutes are other PGM (Yang, 2009). Almost every year since 1999 the world demand for platinum has been higher than the supply, in 2001 for example the demand for platinum was 11.5 Million Grams (Mg) higher than the supply this caused an additional 11.5 Mg to be removed from inventories (Yang, 2009).

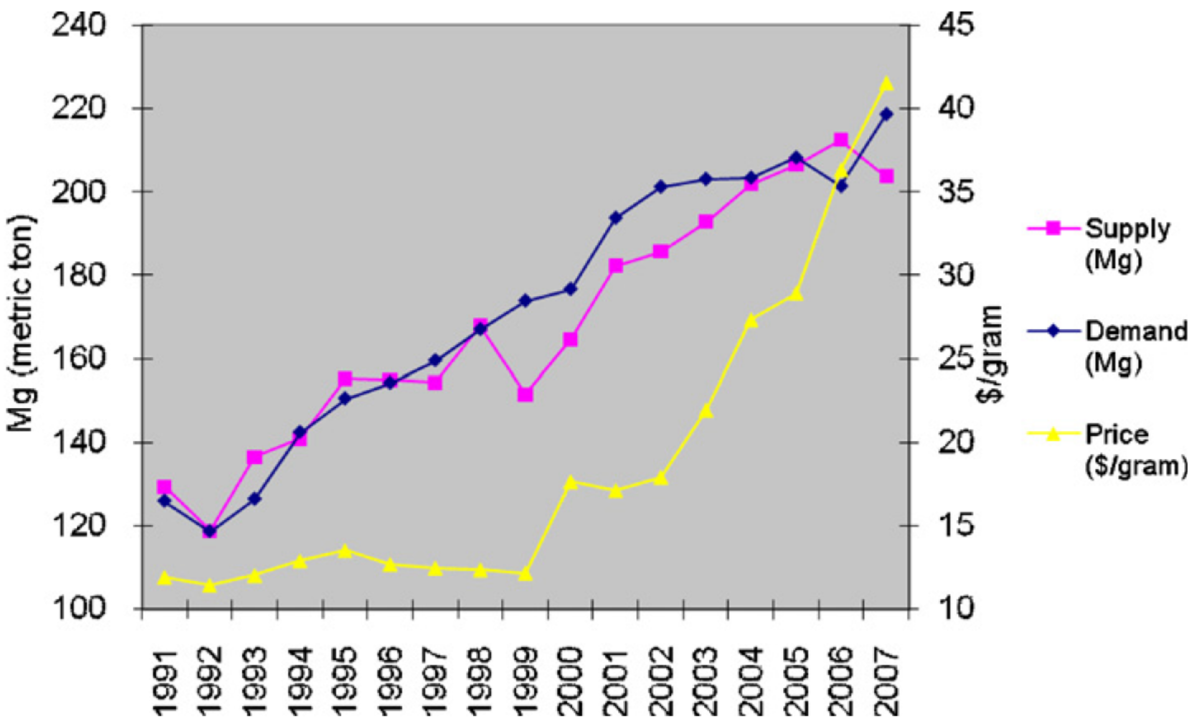

Figure seven: Platinum supply, demand and price between 1991 and 2007 note that the demand has been higher than supply between 1999 and 2005 and again in 2007. Taken from Yang (2009).

The most efficient fuel cell cars require about ten times as much platinum as gasoline cars (Yang, 2009). In hydrogen fuel cells there is no feasible substitute for platinum, it was predicted by Yang (2009) that the mass production of hydrogen fuel cells would trigger a platinum crisis and that the supply of platinum would be a large obstacle to any hydrogen economy. It was also predicted by Gordon, Bertram and Graedel (2006) that platinum is the most likely metal which with increasing scarcity could create limitations to new technologies.

It is evident that platinum is a very valuable and practical metal. Currently the world supply of platinum is dependent on just a few sources, the South African Bushveld complex being by far the major supplier. Platinum is crucial to the automobile industry for combustion engines and if hydrogen fuel cells are adopted then this will increase the demand for platinum. As there is a lack of substitutes platinum has an inelastic demand meaning that the level of demand will not change significantly with a change in price (Yang, 2009). Given that there are few areas in the world considered geologically promising for platinum extraction and its importance to the world markets it appears that the Dufek intrusion could easily become an interesting target for future prospectors. A major event on the PGE market such as the platinum crisis predicted by Yang (2009) or a natural or political disaster in South Africa could lead to a platinum shortage and a very large increase in commodity price would lead the Dufek to become a very interesting region economically. If the world population continues to demand more platinum than miners can supply then the price will continue to climb and world stocks could become depleted. The platinum price appears to be set to continue to rise and if this pattern continues then mineral operations in the Dufek will in the future become economical if they are not already.

Potential mineral resources of the Antarctic Peninsula

The rocks of the Antarctic Peninsula in many ways resemble the Andes mountains, the geology is dominated by volcanic and plutonic rocks which are the products of subduction of the Pacific plate beneath mostly continental lithosphere (Crockett & Clarkson, 1986). The Andean orogen continues into the northern Antarctic peninsula via the Scotia arc (Hawkes & Littlefair, 1981). Thus the Antarctic peninsula has a similar tectonic and geologic setting to the heavily mineralised Andes Mountains of South America (Rowley, Williams, et al., 1983). Mineral deposits similar to those in the South American Andes should be expected on the peninsula. The Antarctic Peninsula and its off-lying islands are considered highly prospective for porphyry copper, molybdenum, lead and zinc as well other minerals, it is also relatively ice free compared to the rest of the continent (Rowley, Williams, et al., 1983). A number of porphyry-copper style occurrences have been documented along the peninsula (Crockett & Clarkson, 1986) and the porphyry copper mineralisation forms a well defined belt along the west coast of the northern Antarctic peninsula and its off-lying islands (Hawkes, 1982).

As the Andes contain many ore deposits and some of them very large, the geologically related Antarctic Peninsula was considered by Wright and Williams (1974) to be the most favourable area for mineral exploration in Antarctica. Porphyry copper style deposits are favoured for exploration in Antarctica by Crockett and Clarkson (1986) as a relatively low level of geological exploration can discover large resources and Rowley et al., (1983) also concluded that the most likely economic discoveries in Antarctica will be porphyry copper deposits in the Antarctic Peninsula. However the geological setting of the Antarctic peninsula is more similar in nature to the southern portion of the Andes than it is to the northern portion (J. Splettstoesser, 1985). As the northern Andes have a much higher concentration of large mineral deposits than the southern Andes so the Antarctic Peninsula is not regarded by Rowley et al., (1983) to be as prospective as it once was.

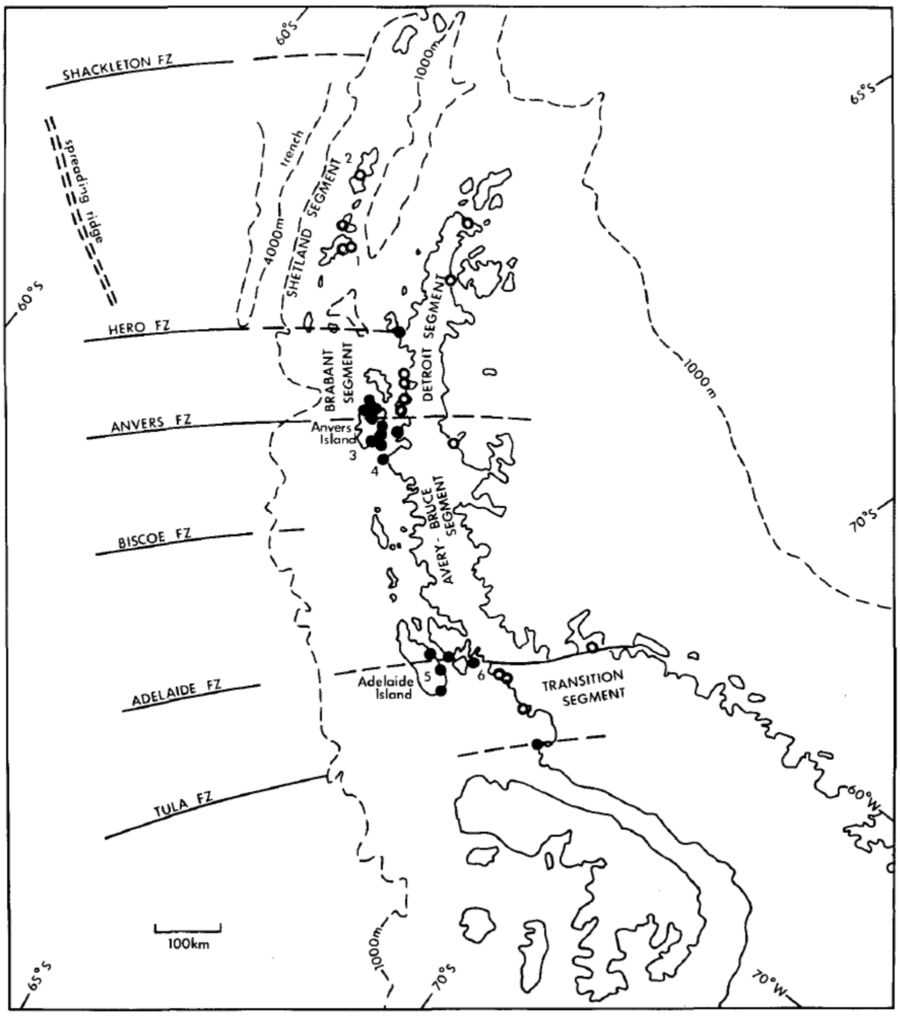

Figure eight: The Antarctic Peninsula and the South Shetland Islands showing distribution of mineral occurrences. Open circles represent Cu, Pb and Zn mineralisation. Solid circles are areas of Cu mineralisation spatially related to Cretaceous or Cenozoic granites. Taken from Hawkes (1982).

By comparing regions around the world which have known porphyry copper deposits Singer et al., (2005) devised an equation which could be used to estimate the number of porphyry copper deposits in a given area if that area has the correct prospective geology. It was estimated that there is a ninety percent chance of at least four and a ten percent chance of at least thirty four porphyry copper deposits in the exposed regions of the Andean belt of Antarctica (Singer, Berger, Menzie, & Berger, 2005). However these equations did not take into consideration the fact that due to the huge cost of exploration and extraction in Antarctica an occurrence which is economic anywhere else in the world may not necessarily be considered as an economic deposit in Antarctica.

The northern Antarctic Peninsula presents one of the best prospects for a minerals industry in Antarctica in the form of porphyry copper deposits or related hydrothermal deposits. The peninsula has relatively little ice cover when compared with the rest of the continent and has very favourable geology; there is the potential for major discoveries in this region. It has a mild climate when compared with other regions of Antarctica and is relatively near to international ports and heavily industrialized nations in South America namely Chile and Argentina. Both Chile and Argentina are mining nations and have experience in the climes and geology of the Andes Mountains which are comparable to the Antarctic Peninsula. Geographically these two nations are well positioned if the Antarctic Peninsula were to be opened up for mineral exploitation, with nearby ports and smelters in South America which could be used to process ore from Antarctica. However there are large copper reserves within the other continents on Earth and prospectors would only begin to look at the Antarctic Peninsula should the copper price become much higher due to increased demand or lack of supply of this metal.

The economics of copper

The main use of copper is in electrical wires used for the transport of electricity but it is also used in plumbing, machinery and in alloys (Gordon, Bertram, & Graedel, 2006). Most of the worlds copper has been consumed by developed nations but as developing nations begin to consume in a similar fashion so the demand for copper has increased. It is predicted by Gordon et al., (2006) that if the entire world population was to gain the developed world's demand for copper then all of the copper in the Earth's lithosphere would need to be extracted for use and near one hundred percent recycling of the metal would be needed from that time onwards. Their data also showed that the demand for copper per capita was increasing in the already developed western world.

Copper is a highly practical metal which is used extensively throughout the world it appears that the world demand for copper will continue to grow into the future. Given the geological similarities with the Andes mountain chain and already recorded mineral occurrences there is a good possibility of porphyry copper deposits in the Antarctic Peninsula. It is possible that a large and high grade copper mine in the area could well be economic in the future. A major obstacle for any deposit in Antarctica is the question of proprietorship of any deposit and the potential for disagreement over this is already well demonstrated in this area with Chile, Argentina and England all claiming the Antarctic Peninsula within their own Antarctic territories. Chile and Argentina would be at an obvious geographic advantage if the peninsula were to open up to a minerals industry. The Chuquicamata copper mine in the north of Chile is the largest copper mine in the world with an estimated 12.5 Gt resource (Sillitoe, 2010) the discovery of a similar deposit in Antarctica could potentially be hugely profitable. However anything short of a very large discovery like this will not be interesting to investors in the near future as there are still easily exploited copper deposits on the other continents.

Gold in Northern Victoria Land

For the first time gold was described in Antarctica outside of the Antarctic Peninsula by Crispini et al., (2007). This gold bearing quartz mineralisation named the Dorn gold deposit is located in northern Victoria Land and is thought to be associated with subduction along the paleo-Pacific margin of Gondwana. This active margin of Gondwana also produced similar gold deposits in eastern

Australia and the South Island of New Zealand, northern Victoria Land being at the time adjacent to these areas (Crispini, Capponi, Federico, & Talarico, 2007). No mention was made by Crispini et al., (2007) of the possible extent underground or the monetary value of this gold occurrence. The main gold-quartz vein was up to 2m wide and 250m long and the gold is clearly visible in photos indicating a high grade (Crispini, Federico, Capponi, & Talarico, 2011).

Gold is a highly valuable metal on todays markets and if this vein were discovered on any of the other continents it would most likely have been studied, drilled and mined very quickly. The Italian study of the Dorn gold deposit demonstrates the potential for scientific parties to make discoveries in Antarctica which could be economical in the future. However the extent of such deposits cannot be known without exploratory drilling which is illegal on the continent.

Natural constraints on mineral discoveries in Antarctica

Until the 1980s there was four decades worth of geological investigations conducted in an effort to find evidence of mineral resources worth exploiting in Antarctica, in this time nothing was found which created any interest from serious industry (Crockett & Clarkson, 1986). It was thought by Wright and Williams (1974) that due to the low percentage of exposed rock in Antarctica that the chance of any sizeable discovery is low. They examined the density of mineral deposits in the other Gondwana continents and in comparison with the ice-free area of Antarctica concluded that the statistical chance of a major discovery was low. Since almost the entire continent is covered by ice sheets, almost all mineral deposits in Antarctica are protected from extraction with current technology. If in the very distant future technology and metal prices allow for exploration and extraction underneath the ice sheets then the potential resources could likely be comparable to Australia due to the size of the area and similar geological history. There are however some geological factors apart from the overlying ice sheet which further conspire against the chances of major discoveries in Antarctica. For instance altered and mineralised rocks are due to their nature likely to be softer than un-mineralised rocks and are therefore likely to erode more quickly and be located in the lower areas which are currently covered by ice (Rowley, Williams, et al., 1983). The occurrence of placer style deposits which are common economic deposits on the other continents are considered very unlikely in Antarctica as normally these deposits require recent alluvial activities (Rowley, Williams, et al., 1983). Also many of the valuable deposits on the other continents are formed as a result of supergene enrichment which relies on meteoric water acting on the near surface within the recent geological past. Due to the glaciations of Antarctica such deposits have probably been removed or may never have been formed (Wright & Williams, 1974). Further to this geochemical exploration of soils and rivers which is a powerful exploration technique useful on all of the other continents would be of very little use in Antarctica due to the relative absence of soils and rivers.

Political factors

An Environmental Protocol was agreed upon by the Consultative Parties to the Antarctic Treaty in October 1991 (Cullen, 1993). This Madrid protocol which bans all mining and mineral exploration in Antarctica came into force in January 1998. The ban is for an indefinite time and can be modified at any time if all parties agree. If at least three quarters of the Consultative Parties agree then a review conference will be held after fifty years ("Australian Antarctic Division: Leading Australia's Antarctic Progrm,"). The motivation behind this protocol is to protect Antarctica from environmental damage which could result from mining (Cullen, 1993). So while a minerals industry in Antarctica is currently illegal there is the possibility that this could change.

The concept of mining in Antarctica poses many problems on the international and national political stage. Internationally the Antarctic treaty currently bans any prospecting for or exploitation of minerals in Antarctica, if this were to change then the question of which nation owns what could cause disagreement and this could be hugely destabilising to the harmonious relationships which currently exist between nations operating in Antarctica. It may become impossible to ignore the questions of sovereignty if a mineral industry were to develop. Also within some nations the majority of people are currently opposed to any mining in Antarctica and this would cause democratic governments to act accordingly. If a very large and profitable deposit was discovered in Antarctic then it is fair to assume that governments in capitalist nations would re-consider the legal position on mining in Antarctica. However it is very unlikely that any large discovery will be made until proper geological exploration aimed at discovery is undertaken and this is currently illegal.

Commercial obstacles

Antarctica poses huge technical and financial problems to any mineral industry hoping to operate on the continent. This paper will not go into the finer details of the costs associated with any potential operation in Antarctica but just hopes to demonstrate that they are very large indeed. The elevated costs associated with difficulties in polar mining in the Arctic would be increased in Antarctica. Among other increased costs there would be labour supply issues, environmental conditions, lack of infrastructure, transportation, isolation, energy production, fresh water supply, waste disposal and problems associated with the extreme weather and snow.

Transportation issues associated with moving equipment, people and ore huge distances from any mining area to working ports and markets would perhaps be the major problem with any minerals operation in Antarctica. Any mining on the continent would be a long way from potential markets meaning very large distances between mine sources and markets. Ports in Antarctica are very rare and only operate during the summer months, Ice breakers would be needed for any ports used during these summer months. Roads would be needed if ore was to be transported by trucks and any land transport would be very difficult. These logistical problems would restrict the areas which could be economic for exploitation perhaps constraining the industry to more accessible coastal areas. These transportation issues have led some authors such as Beike and Rozgonyi (1990) to suggest that mineral operations in Antarctica may need to rely on aircraft for all transportation including ore haulage from mining areas to Antarctic ports. However aircraft transport would be impossible during the polar winter.

Due to the extreme isolation of Antarctica any mining operation would need to be self-sufficient to a level not needed on the other continents where local populations are present or at the least easily reached by roads or airports. There is of course no indigenous population in Antarctica and any exploration or mine site would find it difficult to find skilled people to work the operations without paying extremely high wages. They would need to bring workers in on contracts similar to how the Antarctic research bases currently work. Any housing and domestic services needed to accommodate these workers could also be similar to these national research bases.

There are no local energy resources or power distribution in Antarctica so any site would need to provide its own power and this again would be very expensive but not impossible. Large diesel operated power generators would seem to be the most likely source of power.

The lack of Fresh water would be a major problem in any Antarctic mine, normal mining and ore processing techniques create a large demand for fresh water. This lack of water would be a serious factor to consider (Crockett & Clarkson, 1986). In the hypothetical PGE mine in the Dufek intrusion considered by De Wit (1985) water was pumped to the mine site from a well drilled through the Ronne Ice Shelf. This method for supply of water would restrict mining operators to within practical reach of the ice-shelves or ocean shore.

Waste disposal is another major factor which could constrain any operation. Mining producers many waste products and the disposal of waste in an environmentally conscious and regulated industry is difficult anywhere. These difficulties would be increased in the unique Antarctic natural environment and more so again as environmental issues are expected to be taken more seriously in Antarctica than anywhere else. There would need to be very well regulated environmental requirements to protect the fragile ecosystem and this would increase costs.

Due to the extreme weather conditions there is a need for a larger than normal inventory of spare parts for machines and infrastructure (Crockett & Clarkson, 1986) due to increased wear and tear. Snow accumulation has been found to impede operations in northern Sweden and this would be another factor which could create difficulties (Crockett & Clarkson, 1986). Also difficulties of operating during the polar night or of only running operations during the polar summer must be considered.

Exploration drilling in Antarctica would be technically difficult and the transportation of heavy drilling machinery and equipment to prospective sites would be very expensive. However recent experimental drilling programmes such as the ANDRIL and the Lake Vostok drilling demonstrate that extremely technical drilling in Antarctica is possible and that some well financed parties are interested in it. The costs of exploration would be much higher than in other regions of the world and this is an original cost which is incurred before any assurance of profit.

Finally it would be difficult to market any operations in Antarctica, any prospecting or mining company must rely on investors and stake holders. A company would find it very difficult to gain public support for mining in Antarctica and may have difficulties finding investors. In addition there is no history or experience of mining on the continent so potential investors would be apprehensive about putting money into a venture which could have unforeseen problems associated with the Antarctic environment.

These costs must be enough to make the prospect of investing in an Antarctic minerals industry fairly unattractive to companies and investors. It would be considered a high risk area with little chance of good return and this would be enough to scare off investors unless any large changes in mineral demand make exploration for and development of deposits more financially attractive. Due to the financial factors concerned with Antarctic operations any deposit would need to be of much higher quality than what is needed on the other continents for profitable extraction.

Overview of the world's mineral markets

If there are mineral deposits within Antarctica then the value of these deposits will go up and down with changes in metal prices. If a certain metal becomes valuable enough then the ore of an Antarctic deposit may become valuable enough to offset the extreme costs associated with exploration and mining within the continent. The price of minerals fluctuates mostly as a result of demand and supply similar to most commodities. It is apparent that world demand for mineral resources is growing and should do so into the foreseeable future, however the rising prices will drive advancements in technology and exploration as well as encourage recycling, there is a very real possibility that constantly advancing technology and associated new discoveries can keep up with the expected increases in demand as it has done thus far.

As the world population grows so its demand for minerals becomes greater, compounded on this is the growing wealth of developing nations and their increasing desire for material goods. The extraction levels of minerals is driven by the demand for mineral resources and this demand is rising in the middle and upper income nations and growing in the low-income nations due to their development (Prior, Giurco, Mudd, Mason, & Behrisch, 2011). It seems fair to speculate that developing nations will eventually require the same level of metals as developed nations. It is believed by Gordon et al., (2006) that world-wide stocks of many metals (including resources yet to be extracted from the lithosphere) will not be enough to support a "developed world" quality of service for all of the world's human population. It is also their belief that current metal prices do not reflect the scarcity of metal ores but that in the future metal prices will eventually rise considerably as the remaining ore in the lithosphere continues to diminish. It has been calculated that the rate of extraction of many rare metals from the earth's lithosphere has increased by more than %3 per year for the last fifty years (Gordon, et al., 2006).

Metals do however have the potential for recycling and reuse, unfortunately a lot of metal enters land-fills and other waste heaps where it is not economically recoverable. In a more efficient future we may be able to recycle almost all of the metal used. Also improving technologies and techniques in mining and milling along with changing economic factors and new discoveries have caused the world's reserves of nonferrous metals to increase every year. In many cases this increase in reserves has been at a similar rate to extraction (Gordon, et al., 2006). Due to these advances in technology and metal reserves the long term price trends for most minerals in inflation adjusted prices have remained fairly flat and some have even decreased (Tilton, 2003).

The human population has an increasing appetite for minerals and the demand could be expected to grow with the growing human population and the growing wealth of much of this population. On the one hand this seemingly unstoppable growth in demand for metal resources would lead to the conclusion that eventually Antarctic resources will easily become economical and very attractive to investors. But on the other hand developments in technology have thus far been able to keep inflation adjusted metal prices reasonably consistent in the long term. While improving technologies and increasing metal prices will most likely make extraction from Antarctica economically viable it will also lead to new discoveries and re-classification of un-extracted deposits on the other continents. Any serious increase in the real value of mineral resources could lead to a resource in Antarctica to change from sub-economic to economic but it will also cause marginal deposits on the other continents to become viable for extraction.

Peak minerals

The theory of 'peak minerals' predicts a time when production of mineral ore will not be able to meet the demand from the human population and so a 'peak' in production is reached. The idea is that as a particular metal is exploited from the earth its production is cheap and easy when first exploited and production becomes progressively more expensive and difficult through time as it becomes rarer in the earth's lithosphere (Prior, et al., 2011). It is believed by Prior et al., (2011) that the falling quality of Australian copper, gold, zinc and other ores coupled with an increasing input of capital, labour, energy and other factors shows that 'peak minerals' may already have been reached for certain metals in Australia. A fall in ore grades and an increase in costs equals a fall in productivity which may signify the first stages of resource exhaustion in Australia from Topp et al., (2008) as quoted by Prior, et al., (2011). In the most extreme example of peak minerals where the supply of mineral resources cannot meet the demand then the price of minerals can be expected to sky rocket. If this scenario was to continue for many years then it seems that the extraction of metals from Antarctica would not just be profitable but inevitable. However this is not considered likely in the near future as advancing technologies coupled with new discoveries should ensure that the supply of minerals keeps up with the demand.

Conclusion

Antarctica is a large continent that was once part of the Gondwana land mass and like all of the Gondwana continents it must contain considerable mineral deposits. However almost the entire continent is covered by ice and this means that very few regions can be considered when envisaging a future minerals industry in Antarctica. The areas considered by many authors to be the most interesting and those studied in detail in this paper include the northern Antarctic Peninsula for porphyry copper, the Dufek intrusion for PGE and the eastern coast of East Antarctica for iron. There are huge complications associated with any operations in Antarctica and a minerals industry would face enormous costs which would probably make any economical operation in the current day impossible. In the near future it also appears unlikely that minerals will be mined, or explored for in Antarctica unless some large change in the world markets takes place, this could be caused by war or disaster which may lead to necessary minerals being extracted without consideration of profits, this of course seems unlikely. In the long term it appears that the human demand for metals will continue to increase possibly putting pressure on Antarctic resources, although it also appears that technology and new discoveries on the other continents may be able to keep up with this demand. Copper from the Antarctic Peninsula could one day be economical if a major discovery was made but due to its large supply on the other continents coupled with improving technology and new discoveries/re-evaluation of older deposits it is hard to say whether or not the peninsula will ever be attractive to investors. Platinum from the Dufek complex appears the most likely to be mined in the distant future as it is hugely important to the automobile industry and this metal only occurs in extractable concentrations in rare conditions. The iron occurrences are not currently considered attractive at all due to being of low quality and poorly located. Iron ore is also well represented on other continents. However the world population has an unsustainable demand for iron ore to make steel and this could one day lead to depletion of iron resources on the other continents. If iron resources do become seriously depleted on the other continents then prospectors may begin to look at Antarctica, however this would be many decades into the future at least. The Madrid protocol deems any mineral exploration or extraction in Antarctica illegal this may or may not change in the future. The chance of discovery is very low or even impossible without proper geological exploration aimed at economic discovery and this type of exploration is illegal under the current political governance of Antarctica. Looking into the distant future it is impossible to predict what will be the situation. The demand for metals must increase with a growing population and with the developing nations looking to one day consume in a similar fashion to the developed world. However with constant improvements in technology, recycling and more efficient use of metals then metal supply from the other continents may be able to keep up with demand and perhaps Antarctica will remain forever the only un-mined continent on the Earth.

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