Exploration for offshore heavy mineral sands by Grupo Minero Esmeralda Colombiana, Colombia

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Licences and licence applications of interest to Grupo Minero Esmeralda Colombiana (GMEC) are distributed along a 500 km stretch of the northern Colombian coast. GMEC has utilized a licence of about 18 km² some 18 km to the southwest of the mouth of the Magdalena River as a test site for off-shore heavy mineral sands potential where some 80 hand samples were acquired from a 500 x 500 m grid and marine magnetic geophysical data was collected at every 10 m along lines at 100 m spacing.

XRF results show an elemental iron average of 21.52%, magnetic fraction average of 26.8%, and magnetite equivalent of 16.5%. Titanium dioxide results average at 4.3%, and consistently elevated gold values. The data suggest that almost 80% of the iron in the samples is contained within magnetite and a proportional relationship between elemental iron and titanium dioxide may indicate significant titanomagnete content. These data and their interpretation may suggest that heavy mineral sands have been transported by longshore currents and deposited and reworked within longshore troughs from a basic igneous source, and provide positive indications for the economic potential of the test site and region for iron- and titanium-bearing minerals and gold.

Table I
Formulae, typical impurities and the specific gravity for minerals commonly associated with heavy mineral sand deposits

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Ideal formula</th>
<th>Major impurities</th>
<th>SG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ilmenite (Fe²⁺TiO₃)</td>
<td></td>
<td>Mg, Mn, V, Nb, Fe³⁺</td>
<td>4.7–4.8</td>
</tr>
<tr>
<td>Rutile (anatase – low T polymorph)</td>
<td>TiO₂</td>
<td>Nb, Ta, Sn, Fe</td>
<td>4.2–5.5 (3.8–4.0)</td>
</tr>
<tr>
<td>Pseudorutile (Fe³⁺TiO₃)</td>
<td></td>
<td>Mg, Mn, Fe³⁺ Cr, OH⁻, (H₂O, Al₂O₃, SiO₂)³⁻</td>
<td>3.3–3.8</td>
</tr>
<tr>
<td>‘Leucoxene’ (not a valid mineral species)</td>
<td>An alteration product and mixture of Fe³⁻Ti oxides</td>
<td>Most ‘leucoxene’ is anatase or rutile</td>
<td>4.3–4.6</td>
</tr>
<tr>
<td>Zircon (ZrSiO₄)</td>
<td></td>
<td>Hf, Fe, Al, U, Th</td>
<td>4.6–4.7</td>
</tr>
<tr>
<td>Monazite (CePO₄)</td>
<td></td>
<td>La, Y, Ca, Th, U, Al, Fe³⁺</td>
<td>5.0–5.3</td>
</tr>
<tr>
<td>‘Spinel’ (general name for mineral group with the formula – AB₂O₄):1</td>
<td>Fe³⁺Cr₂O₇ – chromite</td>
<td>MgCr₂O₄ – magnesiochromite</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>Fe³⁺Al₂O₄ – hercynite</td>
<td>Mn, Zn, Fe³⁺</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>MgAl₂O₄ – spinel</td>
<td></td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>Fe²⁺TiO₃ – ulvöspinel</td>
<td></td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>Fe³⁺Fe²⁺O₄ – magnetite</td>
<td></td>
<td>5.2</td>
</tr>
<tr>
<td>Garnet (Fe³⁺₄Al₃Si₃O₁₂)</td>
<td>Fe³⁺₄Al₃Si₃O₁₂(Al₂O₃)OH</td>
<td>Ca, Mn, Mg, Ti, Cr, Fe³⁺, OH⁻</td>
<td>3.5–4.3</td>
</tr>
<tr>
<td>Staurolite (Fe²⁺₃Al₃Si₃O₁₂(Al₂O₃)OH)</td>
<td>Fe²⁺₃Al₃Si₃O₁₂OH</td>
<td>Fe³⁺, Mg, OH</td>
<td>3.7–3.8</td>
</tr>
<tr>
<td>Tourmaline (NaFe³⁺₃Al₃Si₃O₁₂(OH)₃ – schorl)</td>
<td>NaFe³⁺₃Al₃Si₃O₁₂(OH)₃</td>
<td>Mg, Mn, Li, F⁻</td>
<td>3.0–3.2</td>
</tr>
<tr>
<td>Sillimanite (kyanite – high P polymorph)</td>
<td>Al₂SiO₄</td>
<td></td>
<td>3.2–3.3 (3.5–3.6)</td>
</tr>
<tr>
<td>Goethite (FeO · OH)</td>
<td>Fe²⁺</td>
<td>Si, Mn³⁺, Al</td>
<td>4.3</td>
</tr>
<tr>
<td>Quartz (SiO₂)</td>
<td></td>
<td>Al, Fe³⁺, Ti</td>
<td>2.6–2.7</td>
</tr>
</tbody>
</table>

*These species are commonly co-precipitated with, or adsorbed onto the alteration product during weathering.
shoreline, deposits are typically 100 or 200 metres wide, 5 to 20 metres thick and 2 to 20 kilometres long. Heavy mineral grades vary from several per cent to 90 per cent. Dunal deposits close to the shore tend to be larger, more irregular and lower grade. These deposits typically contain percentages of high specific gravity minerals that vary from 10 wt% to 35 wt% with economies of scale being the main advantage for larger deposits (Rozendaal et al., 1999). Ilmenite (TiFeO$_3$) is typically the principal product, with zircon (ZrSiO$_4$) and rutile (TiO$_2$) as co-products and high quality pig iron and monazite as possible by-products. Ilmenite, rutile and ‘synthetic rutile’ (upgraded ilmenite) are the most important sources for titanium dioxide and are an indirect source of titanium metal (Tyler and Minnitt, 2004).

Colombia is a globally significant producer of nickel although the Colombian mining industry is dominated by the production of coal, natural gas and crude petroleum. Colombia is historically recognized as the world’s leading exporter of emeralds but it is not known for heavy mineral sands exploration and until recent political changes Colombia was not a subject of international exploration interest. Today, leading international mining houses such as AngloGold Ashanti Limited, BHP Billiton Plc, Xstrata Plc and Vale do Rio Doce hold significant interests in Colombia.

GMEC’s interest in heavy mineral sands began with anecdotal information regarding black sands along the Caribbean coast near Baranquilla. Black sands are heavy mineral sands in which quantities of the darker heavy minerals such as magnetite, titanomagnetite, ilmenite and rutile may be sufficient for economic recovery.

**Background**

**Caribbean black sands in Colombia**

Caribbean Colombia is principally drained by the Magdalena, Sinú, and Atrato rivers (Figure 1; Restrepo and López, 2008). The Magdalena River measures 1612 km and...
Martinez estimated sand migration rates to be as high as 430 m/yr. Coastal sand bodies formed, shifted and accreted. Evidence shows that the western delta front retreated and compressional tectonics (Vernette). The basin is characterized by sedimentation, slumping and marginal lagoon systems and beach ridges and the receiving the Magdalena Fan (Shepard, 1973; Martinez et al., 1990). The Atrato River drains a basin of 35 700 km² and occupies a considerable portion of the Pacific basin, but the river empties into the Caribbean via the Urabá Gulf. The Atrato River has an area of 672 km² and a river-dominated delta with bird-foot morphology (Restrepo and López, 2008). The Sinú River delta has a sub-aerial area of 26 km² and is classified as a river and wave-dominated system and delivers its sediments into the largest portion of the continental shelf (Serrano, 2004).

Tectonically, Caribbean Colombia is characterized by the convergence of the South American and Caribbean tectonic plates and the Panama–Colombia border area near the Atrato river delta is one of the most seismically active areas in northwestern South America (Trenkamp et al., 2002).

Most of the rivers entering the Caribbean in this region turn sharply to the west-southwest at their mouths and flow parallel to the shore behind barrier bars before entering the ocean, reflecting the predominant northeasterly winds and currents which cause northeast-to-southwest longshore drift (Martinez et al., 1990). Black sands are said to have begun to appear along the stretch of coast near Puerto Colombia after the channel at the mouth of the Magdalena River was stabilized by a large jetty system which was completed in 1955 and provided a deep water channel that allows large shipping to reach the main port at Barranquilla. Martinez et al. (1990) studied the changes in the Magdalena River mouth and coastal sand bodies. Photographic evidence shows that the western delta front retreated and coastal sand bodies formed, shifted and accreted. They estimated sand migration rates to be as high as 430 m/yr (Martinez et al., 1990). Martinez et al. (1990) considered that the jetty system was at least indirectly responsible for these changes but that the transported sands which lead to the buildup of downstream sand bodies may have been derived from the immediate vicinity of the jetty system, the retreating delta front of the Magdalena River, the continental shelf, or elsewhere as a result of the changes in wave patterns produced by the jetty system. Today, black sand beaches dominate from Barranquilla towards Cartagena in the southwest (Figure 1).

GMEC’s areas of interest

Most of GMEC’s areas of interest are located in the area between Puerto Colombia, to the west of the mouth of the Magdalena River, and Cartagena (Figure 1). These are easily accessed via of Barranquilla, one of Colombia’s major cities. There are an additional two licences along the coast to the south of Cartagena, and a further three near the mouth of the Atrato River. The licence areas are generally offshore, with some containing onshore areas. Licence areas that are close to the shore generally comprise shallower water with average water depths of about 8 m and those further offshore have water depths of up to 150 m. The licences are distributed along a total coastal length of approximately 500 km. To date GMEC’s exploration has focused on assessing permit AIS-141 as a test site for heavy mineral sands suitable for magnetic recovery.

Analogue marine iron sands and gold placer deposits

Current operating heavy mineral sand mines are located onshore and commonly associated with surficial beach, dune, paleo-beach, paleo-dune or paleo-river material for the recovery of zircon, rutile, leucoxene and ilmenite, in order of relative value, e.g., Iluka Resources Limited (Iluka) in Australia (and the USA) and Exxaro Resources Ltd in South Africa. Pig iron is a typical by-product. There are, however, several large operations which focus on the recovery of iron sands, i.e., sands with economic concentrations of iron-bearing minerals e.g., mining on the north coast of KwaZulu-Natal, South Africa, which is operated by Richards Bay Minerals and the Waikato North Head and Taharoa mines of New Zealand (Carter, 1980; Lawton and Hochstein, 1993) which are operated by New Zealand Steel, and Cardero Resources Corp is expected to commence production at the Pampa el Toro iron sands project in Peru in the near future (Cruise and Hoffman, 2008). Richards Bay Minerals are said to have undertaken offshore exploration; however, no information about this work was publicly available at the time of writing.

A strong demand for iron in recent years, particularly from China, has led to the opening or reopening of lower grade iron deposits (30% Fe<64%) worldwide and exploration has expanded to included banded iron formation which has a typical iron grade of 20–40% Fe e.g., the recently released resource estimate for the Numbara and Simbili targets at African Minerals Ltd’s Tonkolili iron ore project in Sierra Leone have been estimated to have a combined resource of 4.7 billion tons (Mt) grading 29.9% Fe Total, 25.1% Fe Mag, 45.1% SiO₂ and 4.7% Al₂O₃ (SRK Consulting (UK) Ltd, 2009). There has even apparently been interest in the production of iron ore from heavy mineral sands tailings at Iluka’s projects in Australia (Sydney Morning Herald, August 22, 2008).

At this time no offshore iron sands exploration is known to be underway although the Australian explorer, De Grey Mining Ltd., has entered into an option to purchase the 640 m² Fortescue Island exploration licence application, which has been interpreted (from aeromagnetic data) to contain unconsolidated iron oxide minerals derived from the offshore in situ erosion of the Brockman Iron Formation, the principal onshore source of high grade, haematite iron ores in Australia (Taylor et al., 2001). Historically, material derived from the onshore erosion of the Brockman Formation (with a combined resource of 38 Mt @ 62% Fe derived from several discrete lenses) was mined by Hamersley Iron Pty Limited from 1992 to 1998 at Brockman Syncline No. 2 Detritals (Butt et al., 2001).

Worldwide, economic marine gold placer deposits are rare and the Nome gold placer deposit, Alaska, is one of the most well-known marine examples. From as early as 1897–1962, the Nome area produced about 5 million ounces of gold and mining between 1897 to 1990 produced
118 078 fine oz (a fine ounce is a troy ounce of 99.5% pure gold) with an average recovered grade of 824 mg/m³ (Cronan, 2000; Zhou et al., 2007). The offshore area of anomalous gold mineralization at Nome is orientated parallel to the coast over an east-west distance of about 25 km, reflecting the footprint of recent glacial deposition, the source of the gold. The average background grades are in the tens of mg/m³, with the highest concentrations and coarsest particles are in sediments which lie between and on lobes of glacial material near the shore and are associated with the coarsest gravels. The grades at Nome are considerably more erratic than those of most alluvial gold placers worldwide and magnetite and ilmenite are closely associated with the gold. Recent work at the Nome deposit by Zhou et al. (2007) provides for a placer gold resource between 113 767 oz (with a cutoff grade of 1 000 mg/m³) and 2 309 664 oz (with a cutoff grade of 0 mg/m³) with average grades which range from 1.929 g/m³ (with a cutoff grade of 1000 mg/m³) to 0.233 g/m³ (with a cutoff grade of 0 mg/m³).

**Sediment sampling methods and analysis**

**GMEC sediment sampling methods**

GMEC planned and executed a field sampling programme over permit AIS-141 in August and September 2008. The sampling procedure was not determined or verified by SRKES. Eighty sand samples were collected from a 500 x 500 m grid covering the permit area (Figure 2). Sampling was undertaken by two scuba divers accompanied by a geologist who did not dive. The sampling site was located by utilizing a handheld Garmin GPS 76 situated in a small boat from which the scuba divers would descend to the seabed directly below the boat. The diver followed a sampling procedure whereby a hole was excavated to a maximum depth of about 100 cm and sand material was collected from the base to the top of the excavation, excluding surficial debris or mud, to produce a sample of approximately 2.5 to 5 kg. The sampled material was placed in a plastic bag whilst underwater. For each sample GMEC planned for the following information to be recorded: sample number; coordinates; depth of cover to sand; depth of hole; quality of sample (nominally as weak, average, good). Sea depth was measured using a flagged rope. No details of local current, sea conditions or visibility were recorded but it is understood that the sea state was generally quite rough with large swells and turbulent water during the sampling.

**SRKES sediment sampling methods**

SRKES visited GMEC’s northern areas of interest between the 20th and the 30th October 2008 from Barranquilla to Cartagena as well as the application area, JHC-11581, located to the south of Cartagena with the aim of observing GMEC’s sampling procedures and to review the local geology and logistical considerations. SRKES sub-sampled GMEC’s previously collected 80 samples from AIS-141 and added four new samples indicated by SRKES and GMEC’s previously collected 80 samples from AIS-141, excluding surficial debris or mud, to produce a sample of maximum depth of about 100 cm and sand material was collected within the original sample bag and a sub-sample of between 500 and 800 g was taken and placed into a clean sample bag. New sample numbers were assigned (from AIS-001 to AIS-083). SRKES was unable to visit the south-western application areas including those near the Atrato river due to time and logistical constraints. Due to the limitations of boating equipment available and the large areas involved, only a land-based reconnaissance of the northern permit application areas was undertaken. Several beaches along the coast were also visited.

**Sample analysis**

All samples were prepared and analysed by OMAC Laboratories in Ireland. Samples were firstly dried and milled to <100 μ (code P4). Samples were then analysed by XRF for major oxides (Fe₂O₃, Al₂O₃, CaO, Cr₂O₃, K₂O, MgO, MnO, Na₂O, P₂O₅, SiO₂, TiO₂) with LOI at 100°C. The method used was borate fusion X-ray fluorescence (code BF/XRF). Silver (Ag) was prepared with aqua regia digestion and analysed by Flame Atomic Absorption (code GAR). Gold (Au), platinum (Pt) and palladium (Pd) were analysed by fire assay with ICPAES/MS (code PG).

Davis Tube tests were undertaken to determine the magnetic fraction of the samples and Satmagan analysis was performed in order to determine concentrations of magnetic iron (magnetite equivalent). The Satmagan data were calibrated by the Davis Tube test results in order to calibrate the data specifically for the project material. OMAC carried out repeat analyses on every 10th sample and the sample batch included three laboratory standards and three laboratory blanks.

**Geophysical survey**

Permit AIS-141 was the first area surveyed by GMEC and data was acquired by Moscow State University geophysical consultants without SRKES involvement between the 17th and 27th of November 2008 (Lygin, 2009). Survey parameters were:

- **Survey vessel**—from 17 to 20 November a 9 m fibreglass boat was used and from 21 to 27 November a 13 m fibreglass boat which was better able to handle the sea conditions was utilized
- **Magnetometers**—two SeaSPY Marine Magnetometers towed in longitudinal gradient mode with 10 m spacing between magnetometers in combination with a Geomatrix G858XS as the base station
- **Sampling frequency**—marine magnetometers at 1 sec and base station at 20 sec
- **Survey vessel velocity**—<15 km/h
- **Water depth measurements**—pressure and depth sensors incorporated within magnetometers
- **Towing distance from vessel**—40 m
- **Navigation**—Garmin Etrex Legend Cx GPS
- **Coordinate system**—WGS85 UTM Zone 18P
- **Survey line orientation**—east-west with north-south check lines and
- **Survey line spacing**—100 m within the permit area and increased to 500 m outside the permit area with 1 000 m check lines.

The survey was complicated by variable and difficult weather and sea conditions. It is understood that the sea state was generally quite rough with large swells and turbulent water which compromised the ability to maintain the magnetometers at their optimum depth and tracking, potentially causing some deterioration of data quality.

The geophysical consultant, Mr Lygin of Moscow State University, applied standard processing routines to the data including diurnal corrections using base station data, lag shift to correct for the difference between the position of the magnetometers and the navigation instruments on board the boat, and levelling to remove corrugation between lines in the data.
Regional geology

Colombia covers large areas of the South American, Caribbean and Nazca tectonic plates (Figure 1). The submerged portion of Colombia’s territory lies in the Pacific Ocean and Caribbean Sea and covers a total area of 828,660 km². The emerged land, consisting mainly of rocks of the South American plate, covers an area of 1,143,748 km² and comprises the Andean region and the Llanos plains. Most workers recognize a Late Jurassic rift stage related to the separation of North and South America, a protracted Cretaceous period of passive-margin formation following the rift event, a Palaeogene period of oblique collision between a westward-moving Caribbean island arc and the passive margin of South America, and a Neogene period of strike-slip faulting and Andean uplift to form the Andean region of Venezuela and Colombia (Ferero et al., 2002). Andean uplift in Colombia formed the Colombian Massif which divided into three mountain ranges, from youngest to oldest: Cordillera Oriental (eastern mountain range), Cordillera Central, and Cordillera Occidental (western mountain range).
range), Cordillera Central (central mountain range) and the Cordillera Occidental (western mountain range) separated by valleys. The Cordillera Oriental is dominated by sedimentary units and was developed by the end of the Tertiary period.

The Llanos Plains are divided into three subregions: the northern area, Macarena mountains and the southern area. The northern area is located between the Andes and the Guyana Shield and is characterized by savanna-like plains. It formed during the Tertiary period and is mostly covered with Quaternary sand and clay eroded from the Andes. The Macarena Mountains area is centrally located within the Llanos plains and forms an area of elevated topography oriented north-south and covering an area of 120 km long and 30 km wide. The mountains contain some of the oldest geological formations in Colombia with rocks from the Lower Precambrian forming part of the Amazon craton. The southern area comprises the Putumayo and Amazon River basins which are covered by dense jungle.

Local geology

Since this paper focuses on GMEC’s work between Cartagena and Barranquilla, this section concentrates on the local geology for the region between Cartagena and Baranquilla which comprises Palaeozoic to Recent age sedimentary rocks of the San Jacinto Belt in the east which are separated from the marine and littoral deposits of the Sinú Belt in the west by the Sinú Lineament (Figure 2; Ferero et al., 2002). The belts have historically divided into three anticlines but the Geological Survey of Colombia (Ferero et al., 2002) divides the region into tectonic blocks, separated by transverse faults, in accordance with their tectonic characteristics. The San Jacinto belt has been divided into the Lurucu, el Carmen, and Sincelejo blocks, and the Sinú belt into the Turbaco and Baracuaco blocks. The entire region is distinguished by three zones of differing deformational characteristics, although the general stress regime was compressive in the direction east-west, whereby the San Jacinto and Sinú Belts are dominated by an imbricated thrust fault system, although the Sinú Belt is less deformed. The Dique Depression is considered to have been generated by inferred normal faulting.

The extensive marsh deposits to the east of Barranquilla, on the eastern side of the Magdalena River, are considered to contain sediments derived from deltaic and alluvial deposits associated with the Magdalena River. Quaternary terrigenous and reef carbonates and calcareous sandstones occur in the Puerto Colombia area. To the west of Puerto Colombia is an area of beach sands and gravels that represent the ongoing formation of a spit which may be associated with remobilization of sediments derived from the Magdalena delta. Near to Cartagena, older Miocene and Eocene rocks comprising arenite, shale and mudstone are over lain by extensive deposits of alluvial material and beach sands and gravels.

Results and interpretation

XRF analytical results

The results from the analysis 83 samples from permit AIS-141 including four samples collected under SRKES
supervision are provided in Table II. AIS-141 data indicates that the average percentage for elemental iron is 21.52% Fe, the magnetic fraction is 26.8%, and magnetic iron (magnetic equivalent) is 16.5%. These data suggest that almost 80% of the iron in the samples is contained within magnetic phases. Values for magnetic equivalent and magnetic iron are above 50% of the total magnetic fraction and may indicate that a proportion of magnetic iron is intimately associated with other minerals (Figure 3). There is a proportional relationship between elemental iron and titanium oxides (Figure 3) which suggests that the material analysed may contain significant titanomagnetite and is supported by correlations between iron and other oxides such as chrome. Such correlations may indicate that the magnetic material was derived from mafic rocks. Elemental iron grades are heterogeneously distributed.
across permit AIS-141 with higher grades predominantly located in the western half of permit AIS-141 and there appears to be a directional increase in grade towards deeper waters, particularly towards the northwest, which correlates with the distribution of magnetic iron and is similar to the distribution and grades of titanium oxide (av. 4.3% TiO₂) (Figure 3). These trends may be a function of the physiochemical similarities of iron and titanium oxides or indicate an intimate physical relationship, e.g., the agglomeration of particles, or intimate chemical relationship, e.g., the presence of titanomagnetite.

SRKES has carried out limited studies into the geochemical variance of elemental iron grades in order to obtain information with respect to the optimal sample spacing for future exploration. This work indicates that the distribution of higher grade material is relatively sporadic and that a sample spacing of 300 m may be more appropriate for future resource estimation. This exercise also revealed that there is an approximate trend to the distribution of iron grades at 110–290º and this may also have an impact on future sampling spacing. It is recommended that more detailed studies on variance are carried out as part of the design of future exploration programmes.

Analytical results for Au, Ag, Pt and Pd have shown consistently elevated Au values, above detection results in three samples for Pt (AIS001, AIS043, and AIS065), and above detection results in one sample for Ag (AIS78) (Table II). Gold data and their distribution are highly variable and requires significant work in order to define its mode of occurrence and economic potential (Figure 3).

Magnetic survey results

The processed data (Figure 4) shows a clear increase in the total magnetic field from south to north, which may represent a regional trend—it is usual for magnetic intensity to increase northwards from the magnetic equator (Telford et al. 1990). There are a number of high amplitude anomalies present, labelled ‘B’, which, due to their isolated nature and high amplitude may not be related to geological or sedimentary features, but instead, may indicate the presence of artificial features or debris on the seabed. Small narrow high amplitude linear anomalies have been labelled ‘C’ and comprise a series of anomalies that may represent linear zones of material with increased magnetic content or indicate the presence of underwater cables or pipelines, although no cables or pipelines are known to be present.

SRKES filtered these data with a first order trend removal function in order to remove the north-south trend. In addition an upward continuation of 10 m was applied to adjust the gridded data to give the effect of positioning the magnetometer 10 m higher than it in fact was during data acquisition in order to minimize potential noise and highlight potential genuine magnetic features and trends. The anomalies labelled ‘B’ and ‘C’ remain, and the
western-most anomaly ‘C’ appears to be broader which may indicate that the area of magnetic material is more laterally extensive than suggested by Figure 4. Areas labelled ‘A’ may represent zones of increased magnetic material. In general, the range of values observed in the datasets is small and this suggests that the magnetic material may be present across the entire area or it is too thin to generate significant variation in the magnetic field.

Magnetic material model

The geophysical consultants who had acquired the magnetic and bathymetric data (Figure 4) modelled the thickness of magnetic material as a layer utilizing Moscow State University in-house mathematical software. Given the limited geological and regional geophysical information available several broad geological assumptions, particularly with respect to the magnetic properties of the material surveyed, were made in order to model the data and therefore the model can provide only a conceptual approximation for the thickness of magnetic material. The key assumptions and their significance were:

1. It was assumed that the magnetic response of the modelled layer is constant at each survey site and across the entire area of permit AIS-141. Factors that would cause variations in the magnetic response of the modelled layer, however, include variations in the percentage of magnetic minerals within the sands and variations in the mineralogy of sand minerals. There are no data to support the assumption that the magnetic response of the modelled layer is constant.

2. It was assumed that all of the magnetic anomalies in the dataset were caused by the presence of magnetic minerals within the sand. The magnetic anomalies may have been caused by magnetite and other magnetic minerals which have a different magnetic response compared to magnetite, such as titanomagnetite, or buried magnetic materials.
Underlying geological units or structures may also cause magnetic anomalies. There are no data to support the assumption that all of the magnetic anomalies in the dataset were caused by the presence of magnetic minerals within the sand.

Until suitable data are incorporated into the model a reliable estimate for the thicknesses of magnetic material within the sands cannot be obtained from these data. The minimum modelled thickness of the magnetic layer is between 0.5 m and 2 m thick and trends across the centre of permit AIS-141 in an east-west direction and the maximum modelled thickness of the magnetic layer varies from <1 m to over 10 m. The geophysical consultant concluded that there may be a good correlation between the topography of the sea floor and the thickness of the modelled magnetic layer, i.e. an increase in magnetic layer thickness is associated with topographic lows such as depressions or trenches on the sea floor, and a decrease in magnetic layer thickness is associated with topographic highs. Bathymetric data show a series of northeast-trending ‘trenches’ and a more subtle easterly-trending depression, all of which appear to correlate to increased thickness of the magnetic layer.

Discussion

Correlations between geochemical and magnetic data

There do not appear to be strong or obvious correlations between the sampling results and magnetic data in permit AIS-141. However, there are three potential correlations of note:

- A correlation may be interpreted between material of increased magnetic content in the western part of the permit and an area of variable values in the total magnetic field which may indicate the presence of varying or increased quantities of magnetic material. Such an interpretation is also supported by an increase in thickness of the modelled magnetic layer and bathymetric lows in the same area.
- A northeasterly trend in higher elemental iron grades may be correlated with an increase in both the thickness of the modelled magnetic layer and bathymetric lows.
- A relatively higher elemental iron grade may correlate with a ‘B’ anomaly near the north-western corner of permit AIS-141. Such an interpretation may suggest that ‘B’ anomalies indicate the presence of magnetic material; however, higher elemental iron grade samples do occur within areas of very low magnetic response.
Depositional environment

Heavy mineral sands deposits typically form under alluvial, fluvial, or marine conditions (Guilbert and Park, 2007). The depth of water across permit AIS-141, as derived from the bathymetric data, varies from <1 m to over 10 m which places it, geomorphologically, in a beach and shoreface (or nearshore) zone setting (Boggs, 2007; Figure 5). Most heavy mineral marine sand deposits form as a result of the combined effects of longshore currents and onshore wave-wind-storm action (Guilbert and Park, 2007; Figure 5). Longshore currents move both heavy and light minerals as a mixed sediment load according to the size, specific gravity, durability and abundance of each mineral in the source unit and the ratio of dark, heavy, fine-grained durable minerals to other sediment may vary widely between layers. Longshore currents move parallel to the shore following longshore troughs, which are shallow troughs in the lower part of the surf zone orientated parallel to the strand line. The transport of sand on beaches by longshore currents under different surf conditions indicates their relative influence: where the longshore current and wave motion exert equal influence sediment movement will be at an angle to the coastline, under high-velocity (>60 cm/ s) longshore currents, and where longshore current velocity is <30 cm/s and onshore-offshore motion of waves controls the sediment grain transport (Boggs, 2007; Figure 5).

Combinations of wave-wind-storm action concentrate the heavy minerals. Wind is generally ineffective but storm tides can be highly effective as they can suspend and carry minerals in high energy turbulent wave action. A storm tide will carry all material beachwards but backflow will proportionally carry more of the lighter material resulting in deposition of the heavier material. Typically, only the heavier, higher-equivalent-hydraulic-diameter particles are lodged in storm-generated high-tide strand lines. The size, grade and extent of a given deposit are complex functions of the source of supply, relative coastline-mean sea level stability, and the frequency, energy, consistency of direction, and reproducibility of storms (Guilbert and Park, 2007).

The northeast-southwest trending deeper bathymetric data in permit AIS-141 probably represent longshore troughs produced during conditions where the longshore current and wave motion exert an equal influence on sediment transport. The proposed correlation between material of increased magnetic content in the western part of permit AIS-141 which is supported by an increase in thickness of the modelled magnetic layer and bathymetric lows in the same area may be interpreted to suggest that heavy mineral sands are being transported by longshore currents and deposited and reworked within longshore troughs under conditions where longshore current and wave motion exert an equal influence on sediment transport.

Provenance of Caribbean black sands

One of the principal factors contributing to the modern interest in provenance studies is the affect that source rocks have on the overall quality of the detrital heavy minerals they produce e.g., Ni, Cr, V and Co contents are important in ilmenite chemistry, as abundance of these elements in ilmenite makes it unsuitable for the pigment industry. Boggs (1987) indicates that particular suites of heavy minerals can be utilized for source-rock determination. For example:

- **Alkaline igneous source rocks**—a suite comprising apatite, biotite, hornblende, monazite, rutile, titanian, pink tourmaline, and zircon
- **Basic igneous source rocks**—a suite consisting of augite, chromite, diopside, hypersthene, ilmenite, magnetite, and olivine
- **Metamorphic source rocks**—a suite consisting of andalusite, garnet, staurolite, topaz, kyanite, and sillimanite
- **Sedimentary source rocks**—a suite comprising barite, iron ores, leucoxene, rounded tourmaline, and rounded zircon.

Minerals that have been particularly utilized in the provenance studies of heavy mineral placers include ilmenite, zircon and rutile. For example, the heavy mineral assemblage and geochemistry of ilmenite from Honnavar beach, Karnataka, on the central west coast of India were studied by Hegde et al. (2006) in order to understand their provenance. The heavy mineral assemblage of ilmenite, magnetite, zircon, hornblende, epidote, spherule, kyanite, garnet and staurolite was considered to indicate its derivation from mixed sources of gneissic/granitic, basic and high-grade metamorphic rocks. The trace element content of Co, Cr, V and Ni in ilmenite was interpreted to suggest a gneissic to basic provenance. The grain morphology of the high-grade metamorphic minerals such as garnet, kyanite and staurolite were considered to have been reworked and derived from the offshore/palaeo-beach and brought to the beach deposit by combined action of longshore current and wave motion. Zircon geochemistry can also be utilized because there is a general trend of increasing REE abundance in zircons from ultramafic through mafic to granitic rocks and trace elements such as Y, Ce, U, Eu, Yb, Sm, Nb, and Ta in zircons are influenced by source rock type and (Belousova et al., 2002). The lithology of source rocks can be determined using Nb and Cr contents in rutile, because the most important source rocks for rutile, metapelites and metabasites, imprint a distinct Nb and Cr signature in rutiles (Zack et al., 2004).

Although data is limited, the XRF analyses may be interpreted, on the basis of correlations between Fe, Ti, Cr and Ni to suggest that basic igneous rocks may be potential primary source rocks for Caribbean black sand minerals.

Anecdotal evidence about the recent appearance of black sands along the Caribbean coast suggests that depositional processes have changed significantly in modern times and may provide for an intermediate source for the black sands material, i.e., a heavy mineral sands depositional site which changed to a site for sediment removal after the construction of a jetty system at the mouth of the Magdalena River in 1935. No specific work has been carried out to date in respect of this hypothesis although Martinez et al. (1990) considered that the Magdalena River jetty system was at least indirectly responsible for build-up of sand bodies downstream from the Magdalena River and that these sands may have been derived from the immediate vicinity of the jetty system, the retreating delta front of the Magdalena River or the continental shelf.

**Significance of gold**

Gold data at permit AIS-141 are highly variable and significant work is required in order to define its mode of occurrence and economic potential. Gold placer deposits are typically low grade (0.05-0.25 g/t Au) and concentrations are highly variable both within and between...
individual deposits. Gold is typically fine grained (< 0.5 mm diameter) and well rounded; coarser grains and nuggets are rare. Worldwide, economic marine gold placer deposits are rare and the Nome gold placer deposit, Alaska, is one of the best known marine examples. Records suggest that over 5 million ounces of gold have been recovered from Nome and magnetite and ilmenite are closely associated with the gold which was sourced from recent glacial deposition.

Economic potential

Although the initial work carried out at permit AIS-141 has not been undertaken to international standards, it does, however, provide indications for the potential of the permit and region. Current data indicates the presence of iron-bearing (av. 21.5% Fe) material in association with titanium-bearing material (av. 4.3% TiO₂). The magnetic fraction averages 26.8% and the magnetite equivalent averages 16.5%. Resource data on competitors is scant although these data are higher than grades published by Cardero Resources to date from the Pampa el Toro iron sands project in Peru where the magnetic fraction of active dune material averages 11.0% and that of Quaternary sands averages 7.7%. Magnetic concentrates from Cardero’s Pampa el Toro iron sands project have average values of approximately 61.5% iron (Fe), 4.3–6.41% titanium oxide (TiO₂), 0.2–0.28% phosphate (P₂O₅), 2.41–4.34% silica (SiO₂), 1.22–1.82% alumina (Al₂O₃), 0.61–1.14% magnesium (MgO), 0.4–0.55% manganese (MnO) and 0.01% sulphur (S) (Cruise and Hoffman, 2008). Given that an acceptable magnetic fraction may have been attained and titanium oxide grades are similar to those for magnetic concentrates from the Pampa el Toro iron sands project, the potential for relatively cheap labour in Colombia and the expectation of relatively low extraction costs for the dredging of ore materials present in sands for iron ore is largely dependent upon tonnage. To date no resource estimate work has been undertaken and is dependent upon future sampling to international standards.

Economic marine gold placer deposits are rare and at this time gold data at permit AIS-141 are highly variable and require significant work in order to define the mode of occurrence and economic potential of potential gold mineralization.

Conclusions

The sampling and geophysical data obtained from GMEC’s activities allow the following conclusions to be drawn:

- GMEC has obtained 80 samples on an approximately 500 m x 500 m grid at one of their permit areas, AIS-141, which confirm the presence of iron- and titanium-bearing minerals and gold in potentially economic quantities
- GMEC have carried out a marine magnetic survey at one of their permit areas, AIS-141, which correlates with some areas of higher iron and titanium oxide grades; however, the magnetic survey cannot be used to produce reliable estimates for the thickness of any magnetic layers until sufficient data are available
- GMEC have undertaken a bathymetric survey at one of their permit areas, AIS-141, which shows some correlation with the presence of magnetic material and higher iron and titanium oxide grades and suggests that these materials were deposited in longshore troughs
- GMEC has the advantage of utilizing permit AIS-141 as a test site for developing suitable exploration methods for this type and style of deposit enabling future work to proceed in an efficient and cost-effective manner.

Future work

SRKES is currently involved in the design and management of an exploration programme suitable which includes vibrocore drilling for the future estimation of resources. This will lead to a ‘fatal flaw’ study, resource estimate and preliminary economic assessment of the project. This work will require input from mining engineers, mineral processing engineers and dredging specialists and allow for any potential difficulties or issues to be identified and assessed at an early stage in the development of the project.

References


LYGIN, I. Results of hydro-magnetic survey in the area AIS-141. Gravity and Magnetic Laboratory, Geophysical Department, Geological Faculty, Lomonosov Moscow State University. 2009.


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