GEOCHEMICAL SURVEYS IN MOZAMBIQUE: A DATA COMPILATION PROJECT

by

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The existing regional geochemical survey data of Mozambique have been compiled into a digital format as part of the Geochemical and Industrial Mineral Surveys project (GIM). The work was financed by AfDB and implemented in 2005-2007 by the GTK Consortium, in close collaboration with the National Directorate for Geology (DNG). Most of the surveys were carried out in the 1980s using variable analytical methods and sampling strategies. In total, geochemical regional sampling covers approximately 30% of the country but, unfortunately, analytical data are missing for several surveys.

As the data collected from different sampling programmes was only stored as hard copy maps and data tables without digital geographical references, the majority of the maps had to be scanned and georeferenced for data capture. The spatial and analytical data were obtained by on-the-screen digitization using the ArcGIS programme and stored in the GIM Geochemical Database (GIM_GDB) consisting of two main components: (1) the Survey Information Table (SIT), containing general survey specifications (i.e. metadata), and (2) the Analysis Data Tables (ADTs). In older surveys from the 1980s only the base metals have typically been analyzed. This is complemented by reanalyzing some one thousand selected old samples for Au, Pd and Te by the GIM project.

In addition to the data compilation, a new stream sediment survey was carried out for training purposes as part of the GIM project. It covered about 5000 km² and included 430 composite samples taken from pre-defined and pre-numbered locations, each representing a cell 10 km² in size. This was followed by a detailed soil survey in five anomalous areas, including 1262 samples and 41 km² in total.

The compiled spatial geochemical data were classified and plotted as various elemental maps and correlated with different geological units utilizing the results of the recent geological mapping projects of Mozambique (GTK Consortium, Norconsult Consortium (NGU-BGS) and Council for Geoscience). The integrated geochemical data indicated several potential anomaly areas for future exploration. The GIM_GDB is commercially available to interested companies from DNG.

Key Words (GeoRef Thesaurus AGI): geochemical surveys, stream sediments, soils, geochemical anomalies, data interpretation, data bases, Mozambique.

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As part of the Mineral Resource Management Capacity Building Project of Mozambique, the Geochemical and Industrial Mineral Surveys (GIM) project was carried out in 2005–2007. The project, valued at USD 1.5 million, was financed by the African Development Bank (AfDB) and implemented by the GTK Consortium consisting of the Geological Survey of Finland (GTK) and Gondwana Ltda as a local partner. The main objective of the project was to increase private mining sector investments in Mozambique by providing the basic background information for exploration companies by compiling the existing geochemical data from earlier surveys into a digital format. Additionally, new geochemical studies, including regional stream sediment and follow-up soil surveys, were implemented for training purposes in collaboration with the National Directorate for Geology (DNG) (see Korkiakoski et al. 2008, Korkiakoski 2007 and 2006).

Wide areas of Mozambique (totalling about 800,000 km²) have been targeted over the years for regional and more detailed, exploration types of geochemical surveys. The early 1980s in particular was an intensive period of activity and about 30% of the country has now been covered by regional geochemical surveys. The geochemical surveys with available analytical data carried out in Mozambique have concentrated on northern crystalline bedrock areas and are indicated in Fig. 1. As most of the available geochemical data were originally only available as hard copy maps and data tables, the majority of the maps had to be scanned, georeferenced and digitized for the final data capture. Unfortunately, the geochemical data for several surveys were missing.

The previous surveys were rather heterogeneous in terms of sampling methodologies and analytical procedures. As early geochemical programmes normally targeted base metals, the element combination was usually limited, and gold was not analysed.

The outcome of the project, the digital and easy-to-use GIM Geochemical Database (GIM_GDB), compiling the existing geochemical data of Mozambique, is commercially available to exploration companies at the DNG. The results also include interpretation of geochemically interesting target areas for further exploration (Korkiakoski 2007). These anomalous areas are geologically correlated with the outcome of the recent geological mapping projects by the GTK Consortium (2006a-d, see also this volume), Norconsult Consortium and Council for Geoscience (CGS).

Training has been an integral part of the GIM project. In addition to the specific training courses and lectures, participation of the DNG staff in all project phases was the main element of the learning process. It included the use of Geographical Information Systems (GIS) in digital, on-the-screen data capture and software applications (ArcView and ArcGIS) in the planning, implementation and interpretation of geochemical surveys. The field methodologies and use of GPS as an integral part of the sampling process have been described in detail in a separate GIM Field Manual (Korkiakoski & Salminen 2006).

DATA EVALUATION AND COMPILATION

At an early stage of the project it was found that only a very minor proportion of the existing geochemical data was in digital format; most of the data were stored as hard copy maps. Initially, the archives of the DNG and National Directorate of Mines (DNM) were checked and available geochemical data sets were collected and evaluated. The geochemical surveys that were included in the digital processing (data capture) were separated from those that were manually stored in the existing DNG archives. The relevant and usable information (metadata) of each geochemical sampling programme, including sampling density, sample media, field methodology, analytical methods and element combination, have been compiled and transferred into the Survey Information Table (SIT- Table 1).

Those geochemical maps selected for digital processing were scanned and georeferenced. Georeferencing was carried out with ArcMap 8.3 using the river systems of the TM satellite images as a base. The field correlation of the TM images had been carried out earlier by the geological mapping projects (areas LOT 2 and 3, see Pekkala et al. 2008) using easily recognizable features such as bridges, river and road crossings as reference points. Following the coordinate system used by the mapping projects, the UTM/WGS84 – Zone 36S was applied. The distribution of the different survey areas was digitally stored into a polygon type of ArcView shapefile.
DATA CAPTURE

As most of the geochemical data at DNG/DNM were originally only available as hard copy maps, the data capture was carried out by on-the-screen digitizing of the scanned and georeferenced maps. In normal cases, this included two stages: (1) digitizing the sample locations from georeferenced geochemical maps into the ArcView shapefiles (point type), and calculating the coordinate values of each sampling point, followed by (2) capturing and tabulating the analytical data into spreadsheet tables. These data sets were combined into the point type of ArcView shapefiles with ArcMap 8.3 or ArcView 3.2 (cf. Fig. 1).

Due to the heterogeneity of the data sets in terms of element combinations, analytical methods, accuracy and other factors, individual and separate data tables, termed Analysis Data Tables (ADTs), were formulated for each geochemical sampling programme.

The ADTs include the following information:
- sample numbers (original, if available),
- georeferenced coordinates (UTM-WGS84-Zone 36S, metric system), and
- analytical results of each available element

The collected and captured data were combined into the GIM Geochemical Database (GIM_GDB) consisting of the following major components: a Survey Information Table (SIT) and Analysis Data Tables (ADTs).

Fig.1. The sampling points of major geochemical surveys in Mozambique with captured digital analytical data. The number of captured sampling points and sample types (Ss = Stream sediment) are shown together with the organization / company. For details of each survey, see Table 1.
Table 1. The Survey Information Table (metadata) of the major captured geochemical surveys. *) The values in parenthesis indicate the number of samples in digital format.

<table>
<thead>
<tr>
<th>Company / Organisation</th>
<th>Type</th>
<th>Area</th>
<th>Province</th>
<th>Year</th>
<th>Sampling method</th>
<th>*) No of Samples (digital)</th>
<th>Area (km²)</th>
<th>Samples/ km²</th>
<th>No of Elements</th>
<th>Analytical method</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>GTK-DNG (GIM)</td>
<td>Regional</td>
<td>Inchope</td>
<td>Manica</td>
<td>2005</td>
<td>Stream sediment (Ss) sampling based on 10 km² cell (most representative site in each cell)</td>
<td>450 with 25 dupl. + 18 regional</td>
<td>5 000</td>
<td>0.08</td>
<td>30/36/3</td>
<td>ICP-EAS with Aqua regia leach at 90 °C, XRF and GFAAS for Au, Pd and Te</td>
<td>Pre-defined sites (5 sub-samples over 200 m); GPS orientation</td>
</tr>
<tr>
<td>GTK-DNG (GIM)</td>
<td>Follow-up based on regional</td>
<td>Inchope</td>
<td>Manica</td>
<td>2006</td>
<td>Follow-up soil sampling in 50 x 100, 100 x 200 or 500 x 100 m² grids (5 subareas)</td>
<td>1262 + 85 dupl.</td>
<td>41</td>
<td>variable</td>
<td>30/36/3</td>
<td>ICP-EAS with Aqua regia leach at 90 °C, XRF and GFAAS for Au, Pd and Te</td>
<td>GPS and GID-aided sampling</td>
</tr>
<tr>
<td>Hunting team</td>
<td>Regional</td>
<td>Tete</td>
<td>Tete</td>
<td>1981-1983</td>
<td>Ss sampling concentrated in areas of interest including follow-up.</td>
<td>6 033 (5320 incl. 65 HMC)</td>
<td>55 000</td>
<td>0.126</td>
<td>&gt;9</td>
<td>AAS. Digestion varied</td>
<td>1050 samples reanalyzed for Au, Pd and Te</td>
</tr>
<tr>
<td>UNDP</td>
<td>Regional</td>
<td>Angonia-Macanga</td>
<td>Tete</td>
<td>1981-1982</td>
<td>Active Ss; 300 g sample collected, dried and sieved into -80 mesh</td>
<td>8070</td>
<td>0.55</td>
<td>26; in pilot study 15 elements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ashanti Goldfields</td>
<td>Regional</td>
<td>Gorongosa</td>
<td>Manica</td>
<td>1996</td>
<td>Ss; 2 kg samples</td>
<td>1109</td>
<td>2370</td>
<td>0.5</td>
<td>1</td>
<td>BCL. (Bulk Cyanide Leach)</td>
<td>Au only</td>
</tr>
<tr>
<td>Ashanti Goldfields</td>
<td>Follow-up exploration</td>
<td>Bandire, part of Rotanda-Mavita</td>
<td>Manica</td>
<td>1998</td>
<td>Soil sampling; 1) 800x100m² grid, followed by 2) 400x100m² grid</td>
<td>1) 640</td>
<td>1) 96</td>
<td>2</td>
<td>6.6</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Ashanti Goldfields</td>
<td>Regional</td>
<td>Gorongosa</td>
<td>Manica</td>
<td>1998</td>
<td>Ss sampling</td>
<td>543 total (366)</td>
<td>1666</td>
<td>1.7</td>
<td></td>
<td></td>
<td>Au only</td>
</tr>
<tr>
<td>SGM</td>
<td>Regional</td>
<td>Mavita</td>
<td>Manica</td>
<td>1970-1973</td>
<td>Ss sampling</td>
<td>(1837)</td>
<td>287</td>
<td>4.6</td>
<td>4</td>
<td></td>
<td>Elements as pie charts</td>
</tr>
<tr>
<td>Aquater (Italia)</td>
<td>Regional</td>
<td>Nampula, Zambézia</td>
<td>Nampula, Zambézia</td>
<td>1981-1983</td>
<td>Sampling in two phases, A and B; Ss (3-6 kg) was sieved into -80 mesh</td>
<td>28 546 total; (15123 Ss)</td>
<td>A: 18 750 B: 29 250</td>
<td>TOT: 48 000</td>
<td>0.31</td>
<td>24</td>
<td>Ss; Quanometer (= ICP 3400) 14015; AAS 10357</td>
</tr>
<tr>
<td>Tecnosynesis (Italia)</td>
<td>Regional</td>
<td>Lugenda River</td>
<td>Niassa, Cabo Delgado</td>
<td>1978-1979</td>
<td>Ss; two sub-samples with 100-200 m distance from the central part of the river</td>
<td>395 Ss 199 Ss</td>
<td>60 000</td>
<td>11.0065</td>
<td>2) 0.0033</td>
<td>16 + 3</td>
<td>XRF + Gamma spectrometer for 100 Ss samples</td>
</tr>
<tr>
<td>Stanchenko/BRGM (France)</td>
<td>Regional</td>
<td>Niassa, Cabo Delgado, Zambézia, Nampula</td>
<td>Niassa, Zambézia Nampula</td>
<td>1970-1973</td>
<td>Ss sampling and HMs, Ss samples; 1 sample / 2 km². For Stanchenko 1 sample/6 km²</td>
<td>50 306; plan, 49 799; collected (1969)</td>
<td>101 000</td>
<td>0.5 (0.02)</td>
<td>4 in Maputo + 22 in Orleans</td>
<td>AAS Perkin Elmer spectrometer. In Orleans semi-quantitatively 22 elements by ICP Quantimeter</td>
<td>Stanchenko study with 1969 samples showing St. Dev. Details not known</td>
</tr>
<tr>
<td>LKAB (Sweden)</td>
<td>Regional and follow-up</td>
<td>Inchope-Doeroi</td>
<td>Manica</td>
<td>1979</td>
<td>&lt;0.5 mm Ss and organic material. (plant roots). Follow-up in 6 areas</td>
<td>241</td>
<td>428</td>
<td>0.8</td>
<td>3+1 (roots)</td>
<td>XRF (sorted minerogenic material) and ICP (roots; dry weight-ashed)</td>
<td>Nb, Sn and Ta. La from plant roots</td>
</tr>
<tr>
<td>CGSDNG</td>
<td>Regional</td>
<td>Namuno-Balama</td>
<td>Cabo Delgado</td>
<td>1996</td>
<td>Helicopter sampling of soil (2-3 kg). GPS; ± 100 m</td>
<td>1544</td>
<td>1 801</td>
<td>0.9</td>
<td>24</td>
<td>XRF, Philips PW 1606 spectrometer</td>
<td></td>
</tr>
<tr>
<td>BHB</td>
<td>Regional</td>
<td>Namapa</td>
<td>Nampula, Cabo Delgado</td>
<td>1997-1998</td>
<td>Ss sites 3-5 km apart, 2 kg sample + 1 kg sample; 1 mm for BCL and -80 mesh for ICP.</td>
<td>159 Ss, 25 HMC</td>
<td>2091</td>
<td>0.1</td>
<td></td>
<td>BCL; 11 ICP; 24</td>
<td>BCL; Bulk Cyanide Leach</td>
</tr>
<tr>
<td>BHB</td>
<td>Regional</td>
<td>Muloce</td>
<td>Cabo Delgado</td>
<td>1997-1998</td>
<td>Ss sites 3-5 km apart, 2 kg sample + 1 kg sample; -1 mm for BCL and -80 mesh for ICP.</td>
<td>184 Ss, 21 HCM</td>
<td>2972</td>
<td>0.07</td>
<td></td>
<td>BCL; 11 ICP; 24</td>
<td>BCL; Bulk Cyanide Leach</td>
</tr>
</tbody>
</table>
SURVEY RESULTS

The results of the data compilation and interpretation of different geochemical surveys carried out in Mozambique over the years are presented in the following chapters (cf. Fig. 1). The general outcome of the project has been earlier briefly described by Korkiakoski (2006), Korkiakoski et al. (2008) and Manjate & Mujui (2006). Besides the compilation of data from earlier survey, the following chapters also summarize the results of the new stream sediment and follow-up soil surveys carried out as part of the GIM project.

It should be noted that only those elements and element associations that are considered to be the most anomalous are included in this discussion. For more detailed description and follow-up interpretation, please refer to the final report of the GIM project and attached GIM_GDB data DVD (Korkiakoski 2007). For reference to the metadata of each specific survey, see Table 1.

GIM field survey

The GIM field survey area is situated in the border zone between the Manica and Sofala Provinces, central Mozambique. The area, referred as Inchope, is known for its Nb-Ta-bearing tin-pegmatites and also includes the Monte Xiluve carbonatite complex and the alluvial gold deposits of Rio Muda (Korkiakoski 2007 and 2006). The area of an earlier LKAB geochemical stream sediment survey (LKAB 1980), with analyses of La, Sn, Nb, and Ta, is within the study area.

Fig. 2. GIM stream sediment survey and follow-up soil sampling areas 1-5 (red). Areas 1-4 were selected on the basis of anomalous gold values (shown as yellow dots) of the GIM Ss survey, whereas area 5 represents a follow-up survey of an earlier LKAB tin study (LKAB 1979 and 1980) shown by red stars (units in ppm). The claim areas are also shown. For the location, see Fig. 1.
Sampling was carried out in two stages, including (1) regional stream sediment and (2) follow-up soil surveys. For both survey types, sampling sites were digitally pre-selected and pre-numbered using GPS for field orientation and site location. The field procedures and sampling methodologies are described in detail in the GIM Field Manual (Korkiakoski & Salminen 2006).

The regional stream sediment (Ss) survey covered about 5000 km². In total, 430 pre-defined Ss sampling sites, each representing a cell size of 10 km², were sampled. Each sample consisted of five sub-samples collected at 50 m intervals over a distance of 200 m. The follow-up soil survey, carried out in five target areas, covered 45.1 km² in total and included 1262 samples. Selection of the soil survey areas was predominantly based on the GIM Ss survey; four out of five targets were related to anomalous gold values, and one was based on results of the earlier LKAB study with elevated Sn values (up to 0.5%) (Fig. 2). The sampling density varied between target areas but sampling was performed using regular 50 m x 100 m to 500 m x 1000 m grids.

The sample material was processed in the field into the < 2 mm fraction using a plastic sieve.

The training of DNG geochemists and field teams played an important role in the GIM field survey and they are now able to independently carry out objective-oriented, GIS-aided geochemical surveys.

Analytical methods

After preliminary preparation of the samples at the DNG Laboratory in Maputo, they were taken to GTK Laboratories (now a separate company named Labtium Oy) in Finland for multielement-multi-method analysis including ICP-AES, GFAA (Au, Pd and Te) and XRF. After drying the samples at 70 °C, they were sieved to the <0.180 mm grain size and ground in a tempered carbide steel grinding vessel. ICP-EAS analysis was performed after partial aqua regia leach at 90 °C and GFAAS analysis after aqua regia leach at 20 °C, using a 5g sub-sample and Hg-coprecipitation. The methods have been described in detail in the Final Technical Report of the GIM project (Pekkala et al. 2007).
GIM stream sediment survey

The statistical data of the GIM stream sediment survey showed that median Cu content is 31.1 ppm, the maximum value being clearly anomalous at 190 ppm. The comparable values for Zn are 48 and 179 ppm. Sixty-four percent of the gold values are below the detection limit of 0.5 ppb and only 5% of the samples are above 2.1 ppb. The major element data analyzed by XRF shows that the median content is 62.6% for SiO₂, 13.7% for Al₂O₃, 5.9% for Fe₂O₃ and 2.5% for K₂O. Some elements, such as Cu and Fe, seem to correlate with certain geological units/rock types (cf. Fig. 3).

Economically the most interesting results of the GIM study are related to gold contents and several anomalous areas were detected by the Ss survey, which also form the basis for the follow-up soil survey (see Fig. 2). An unusually high gold value of 2.3 ppm was detected in one of the tributaries of River Muda, in the centre of the study area. On the geological map (cf. Fig. 3) this anomalous area is related to the Inchope orthogneisses (P₂Bₜₙₚₖₚₚₖ) occurring together with siliciclastic metasediments (P₂Bₜₙₚₚₖₚₚₖ). Unfortunately, due to the existing claim, it was not possible to carry out a follow-up survey for that sample.

GIM soil surveys

In GIM soil sampling, the sample weight was 0.5-1 kg. Samples were taken from the depth of 50 cm and dry-sieved through a 2 mm plastic sieve in the field. The samples were coded according to the pre-defined numbering system and collected using a regular sampling grid.

The compositional variation and ranges of the base metals Cu, Zn and Pb between different target areas are presented in Fig. 4. Gold contents in the GIM soil survey were typically low and only 161 samples (13%) out of 1262 had values over 1 ppb. Most of the anomalous values occurred in the eastern area 1 including the highest content of about 1 ppm (1040 ppb). In other areas values only rarely exceeded 10 ppb. The tin anomalies revealed by the earlier LKAB study (LKAB 1979 and 1980) were confirmed by the GIM study. The total XRF contents correlated locally well with some geological units.

Fig. 4. Compositional ranges of the main ore elements (Cu, Zn and Pb) between GIM soil survey areas 1-5.
Hunting Team survey

The geochemical surveys carried out by the Hunting Team in 1981–83 were concentrated in 20 selected target areas (Fig. 5). The georeferenced location data of the Hunting Team samples has been captured and calculated for 5333 samples, of which 5258 samples have been joined with analytical results of the original digital data table with values for Cu, Pb, Zn, Ni and Co (Hunting Geology and Geophysics Ltd 1984).

On the basis of the drainage systems, 1066 samples were selected from the stored Hunting Team samples by the GIM project for additional analysis. These samples were analyzed for Au, Pd and Te by GFAAS. Unfortunately, only 19% (202) samples had Au values above the detection limit of 0.5 ppb, leaving the majority (81% / 864) of the samples below that value. This proportion is markedly lower than that obtained from stream sediment sampling by the GIM project, where 36% of the Au values exceeded 0.5 ppb.

Results

The summary statistics of the analytical results of the Hunting Team data are presented in Table 2. When comparing maximum values with the median, it can be noted that Cu (42 times the median value) and particularly Ni (190 times the median value) occur locally as highly anomalous points.

As shown in Fig. 6, copper forms clustered anomalies in two target areas: western Mucanhavuzi (area 6) and eastern Mufa-Boroma/Monte Muandi (areas 17 and 18). In the latter area, Cu forms a NE-SW trending anomalous zone shown in detail in Figure 7. Geologically high Cu values are related to the carbonatites occurring between the 1046 ± 20 Ma old Chogocoma granite and the Tete Gabbro-Anorthosite Suite. The maximum Cu value of 971 ppm was recorded, however, close to the carbonate-hosted Chidue Cu-Au-occurrence, 20 km NE of the target areas 17/18 outlined in Fig. 6.

The highest Ni contents (maximum 0.42%) indicated by the Hunting Team survey are all associated with the Atchiza mafic-ultramafic Suite, situated on the western part of Tete Province displayed in Fig. 8 (target area 4). The geological units and Ni anomalies of the Suite are shown in detail in Fig. 9. The same area also includes the highest values of Pd (132 ppb) and Co (390 ppm). It has to be noted that the generally high Ni level is at least partly related

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Fig. 5. Target areas of the Hunting Team survey in Tete Province shown in red. The sampling points outside the specific target areas are shown in blue.
Table 2. Summary statistics of the analytical results from the Hunting Team survey. Analysis by AAS. Au, Te and Pd were analyzed by GFAAS at the GTK laboratory. Note *: The value 1.5 ppm used in calculations for samples with Te < 2 ppb (11%).

<table>
<thead>
<tr>
<th>Element</th>
<th>Cu ppm</th>
<th>Pb ppm</th>
<th>Zn ppm</th>
<th>Ni ppm</th>
<th>Co ppm</th>
<th>Au ppb</th>
<th>Te ppb</th>
<th>Pd ppb</th>
</tr>
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<tbody>
<tr>
<td>N</td>
<td>5251</td>
<td>5251</td>
<td>5251</td>
<td>5251</td>
<td>5251</td>
<td>1066</td>
<td>1066</td>
<td>1066</td>
</tr>
<tr>
<td>Missing</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4196</td>
<td>4196</td>
<td>4196</td>
</tr>
<tr>
<td>Mean</td>
<td>30.3</td>
<td>5.4</td>
<td>57</td>
<td>121.2</td>
<td>19.5</td>
<td>12.6*</td>
<td>6.3*</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Std. Deviation</td>
<td>30.3</td>
<td>20.5</td>
<td>42.7</td>
<td>455.1</td>
<td>36.5</td>
<td>&lt;0.5</td>
<td>22.6*</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Minimum</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>&lt;0.5</td>
<td>2</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Max/Median</td>
<td>42 x</td>
<td>20 x</td>
<td>21 x</td>
<td>190 x</td>
<td>28 x</td>
<td>52 x*</td>
<td>52 x*</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Maximum</td>
<td>971</td>
<td>101</td>
<td>1068</td>
<td>4199</td>
<td>390</td>
<td>434</td>
<td>327</td>
<td>132</td>
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<tr>
<td>Percentiles</td>
<td>25</td>
<td>13</td>
<td>2</td>
<td>34</td>
<td>10</td>
<td>7</td>
<td>&lt;0.5</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>23</td>
<td>5</td>
<td>50</td>
<td>22</td>
<td>14</td>
<td>&lt;0.5</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>39</td>
<td>8</td>
<td>69</td>
<td>47</td>
<td>23</td>
<td>&lt;0.5</td>
<td>13.4</td>
</tr>
<tr>
<td></td>
<td>95</td>
<td>84</td>
<td>34</td>
<td>134</td>
<td>547</td>
<td>110</td>
<td>1.8</td>
<td>42.2</td>
</tr>
</tbody>
</table>

Fig. 6. Copper content (in ppm) in stream sediments as defined in the Hunting Team study in 1981–83. Values were determined by AAS. The Chidue gold occurrence is related to the anomaly zone (red circle) situated 20 km N of the rectangular area outlining the target areas 17 and 18, shown in detail in Fig. 7.

to Ni originating from Ni-bearing silicate minerals such as olivine, which is the major constituent of the Atchiza ultramafic rocks. Due to its geological nature and highly anomalous Ni values, the Atchiza Suite can be considered as a good potential target for nickel exploration.

The new analyses for Au, Pd and Te of the selected Hunting Team samples carried out by the GIM project indicate that the western target areas have most prominent and concentrated anomalies and can therefore be considered economically interesting (Fig. 10). The highest gold value of 434 ppb has been detected in the Mucanhavuzi target area 6, east of Atchiza. The analytical results also show that several other anomalous samples (about 40 out of 202 samples with Au contents above the detection
Fig. 8. Nickel contents recorded in the stream sediment survey by the Hunting Team. The highest values (up to 0.42%) are concentrated in target area 4, comprising the Atchiza mafic-ultramafic Suite. The outlined area with anomalous nickel contents is shown in detail in Fig. 9.

Fig. 7. Copper content in target areas 17 and 18; location shown in Figs 5 and 6. The rocks consist of minor, NE-SW-trending Cretaceous carbonatites (Crch, red brown), occurring in the contact zone between the Chogocoma granite (P.T.gr, dotted pinkish brown) and Tete gabbro-anorthosite Suite (P.Tgh, light blue). Geology based on GTK Consortium LOT 2 mapping.
Fig. 9. Nickel anomalies detected in the stream sediment survey by the Hunting Team in target area 4. Geologically, the area consists of the Atchiza ultramafic-mafic Suite. The highest anomalies are related to the Neoproterozoic Atchiza dunite (P1Ad, greenish brown). Other major rock types include the pyroxene gabbros (P1Ag, light brown), porphyritic Monte Inchinga granite (P1Jg, dark brown), and Lower sediments (P1T, green). Geology based on GTK Consortium mapping.

Fig. 10. Gold content (in ppb) of the 1066 reanalyzed Hunting Team samples. The results indicate that the western Mucanhavuzi target area 6 outlined in red (For details, see Fig. 11) has the most prominent gold anomalies. Samples analyzed by GFAAS at the GTK laboratory.
limit of 0.5 ppb) are concentrated in the same specific target area, which is also typified by high Cu values. Geologically, it consists of rocks belonging to Mesoproterozoic Fingoé supergroup comprising mafic/ultramafic metavolcanic rocks, mica schists and gneisses or calc silicate gneisses and schists with some metasediments intercalated with felsic volcanic rocks (Fig. 11).

In summary, based on the above geochemical results, the Muchanhavuzi area can be considered to have potential for gold and copper exploration.

**UNDP survey**

The captured UNDP survey data in Angonia-Macanga area in the north-eastern part of the Tete Province (for location, see Fig. 1) included 1441 stream sediment samples analyzed for Cu, Zn, Mo, Pb, Ni, Co and Cr by AAS (Chakrabarti 1983). The statistics of the data are presented in Table 3. The median value for Cu is 9 ppm, the maximum being clearly anomalous at 264 ppm. The comparable values for Zn are 24 ppm and 344 ppm, respectively.

Based on recent CGS mapping, the eastern part of the sampling area consists of Mesoproterozoic Angonia group metasedimentary rocks, including banded quartz-feldspar and amphibolitic gneisses and Neoproterozoic Ulônguè Suite igneous rocks (anorthosites, syenites and amphibolites). The Mesoproterozoic plutonic units, forming the western part of the UNDP sampling area, belong to the Desaranhama Group of the Furancungo Suite. The
Table 3. Summary statistics of the geochemical data from the UNDP survey. Values below the detection limit of 1 ppm are omitted from the calculations.

<table>
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<tr>
<th></th>
<th>Cu ppm</th>
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<th>Mo ppm</th>
<th>Pb ppm</th>
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<td>715</td>
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</tbody>
</table>

dominant rock types are biotite-hornblende orthogneisses, porphyritic or biotite granites and granodiorites.

The distribution of Zn contents is plotted on an elevation map and displayed in Fig. 12. High Cu values are heterogeneously spread out and do not show any particular concentration. In contrast, Zn values form a distinct anomaly in the western part of the UNDP sampling area. Since the Ni values are also highest in the same area, these features could together indicate some economically interesting targets for a follow-up survey.

![Zinc content (in ppm) in the UNDP stream sediment survey plotted on an elevation model shown by grey tones. NE corner of Tete Province. For location, see Fig. 1.](image-url)
Ashanti Goldfields Rotanda-Mavita survey

The Ashanti Goldfields survey in Rotanda-Mavita covered an area of 2370 km² (Gonçalves 1988a, 1988b and 1988c). In total, 1109 Ss samples were collected, giving a sampling density of about one sample/2 km². Samples were analyzed only for gold using Bulk Cyanide Leach (BCL) as the digestion/analytical method. Sixty-one (61) per cent of the samples had gold values below 1 ppb. The regional study showed that the Bandire area had elevated gold values up to 180 ppb and a follow-up soil survey was carried out. The first 800 m × 200 m follow-up sampling grid was complemented with more detailed 100 m × 50 m sampling. As a result, the Bandire gold occurrence was located within the anomalous area. Presently, this alluvial gold enrichment is utilized by local artesanal miners (Lehto & Gonçalves 2008).

The geology of the Ashanti Goldfields study area combined with gold contents from the Ss survey is shown in Fig. 13. The area with the highest gold contents forming the first follow-up soil survey is shown by a rectangular zone with a yellow-brown colour. Geologically, the area hosting the Bandire Au occurrence consists of both Archaean and Proterozoic domains. The western Archaean rocks are typified by granitoids (A3Vpg, red) and paragneisses (A3Mpgn, light purple), whereas the eastern Proterozoic domain consists of migmatitic paragneisses (P2BCmi) shown in blue.

Fig. 13. Ashanti Goldfields Au exploration survey in the Rotanda-Mavita area, Manica Province. The dominant rock types consist of Archaean granitoids (A3Vpg, red) and paragneisses (A3Mpgn, light brown) in the west and Proterozoic migmatitic paragneisses (P2BCmi, blue) in the east. The rectangular area of the follow-up soil survey, hosting the alluvial Bandire gold occurrence, is indicated by a yellowish-brown colour. For location, see Fig. 1.
Ashanti Goldfields Gorongosa survey

Ashanti Goldfields has also carried out regional gold exploration in the Gorongosa area of Sofala Province (Ashanti Goldfields 1996). This work included 366 sampling points, which were analyzed using Bulk Cyanide Leach (BLC) with 2 kg samples. Both stream sediment and soil samples were collected and sieved for analysis to the -80 mesh fraction. The highest gold values were associated with Proterozoic paragneisses.

SGM survey

The samples collected by SGM in Sussundenga District in Manica Province have been analyzed by AAS for Zn, Ni, Co and Cu (Leal 1972, SGM 1970). The digitally captured data consists of 1836 sampling points. This work has partly overlapped the regional stream sediment survey of Ashanti Goldfields in the Rotanda-Mavita area (cf. above). Geologically, the SGM survey area is characterized by Archaean paragneisses with quartzitic intercalates (A3Mpgn, pink), granitoids (A3Vpg, red) and gabbros (A3Vgb, brown) associated with some subordinate ultramafic metavolcanic rocks (A3MHuv, green) and TTG gneisses (A3Vgn, light green) (Fig. 14). Proterozoic rocks consist of muscovite-biotite schist (P1Zss, light yellow) and quartzites forming the topmost peak of the nearby mountains.

The captured results showed that the median values were 40 ppm for Cu and 60 ppm for Zn. The maximum values were clearly anomalous at 195 ppm and 203 ppm, respectively. Maximum Ni contents were unusually high at nearly 0.4%. Copper occurs as several clustered anomalies around the

![Image](image.png)

Fig. 14. SGM nickel plots on a detailed geological map situating about 10 km W of the Ashanti Goldfields follow-up soil survey area shown in Fig. 13. Note that only the two southernmost Ni anomalies are related to gabbroic rocks (A3Vgb, brown), whereas the northernmost anomaly is associated with Archaean paragneisses with quartzitic intercalates (A3Mpgn, light purple). Other Archaean rocks include granitoids (A3Vpg, red) and some subordinate ultramafic metavolcanic rocks (A3MHuv, green) and TTG gneisses (A3Vgn, light green). Proterozoic rocks consist of muscovite-biotite schist (P1Zss, light brown) with quartzite intercalations. Geology based on GTK Consortium mapping.
study area, but some of them are concentrated in the Bandire area where high gold values were detected by Ashanti Goldfields (Fig. 13). Both Zn and particularly Ni values of the SGM data indicate well concentrated, clustered anomalies.

It is interesting to note that two out of three nickel anomalies displayed in Fig. 14 are geologically related to the gabbro intrusions. In contrast, the most prominent northern nickel anomaly is, according to the geological map, related to Archaean paragneisses. This anomaly could also be caused by an unexposed mafic-ultramafic or gabbroic body and not an ore deposit. Despite this, these high (0.2–0.4%) and clustered Ni anomalies form an interesting and well-defined follow-up exploration target.

Aquater survey

The stream sediment survey by Italian Aquater (Aquater 1983) was one of the few studies where data were originally available in a digital format. The survey was carried out in Zambézia and Nampula Provinces (for location, see Fig. 1). It included four 1:250 000 scale map sheets and four additional 1:50 000 scale map sheets covering about 50 000 km². The total number of original samples in the data table was 15 454, of which 15 123 samples have been included in the Aquater ADT. The samples have been analyzed for 24 elements, but not systematically; more than 10% of the samples lack analysis for Ni, Pb, Cu, Co and Cr, and only half of the samples have been analyzed for Zn. Arsenic, Sb, Ce, V and Mo have been analyzed only occasionally. Original Ss samples, weighing 3–6 kg, were sieved to the -80 mesh fraction for analysis, which was carried out either at the National Chemical Laboratory, Maputo, or alternatively at the DNG laboratory in Quelimane. Analytical methods were either Quantometer (=ICP 3400) or AAS. The sampling was performed in two stages and the sampling density was variable, as illustrated in Fig. 15. All this is reflected in the variation in analytical accuracy levels between the map sheets and some of the analytical results must therefore be considered as only semi-quantitative.
Some of the Zn values indicated by the Aquater survey are clearly anomalous, including 40 samples exceeding 500 ppm. The highest Zn values (maximum 0.55%) are related to the metasedimentary Molócuè group rocks or their contact areas in the NE or SE corners of the study area (Fig. 16). For Cu, anomalous values are less well defined and only 8 samples have values above 500 ppm. However, several of these are associated with high values of Zn. The most prominent clustered Cu anomaly occurs in the central part of map sheet 1638. Geologically, this area is characterized by metamorphic banded biotite gneisses and migmatites of the Nampula Complex. The main clustered Pb anomalies are situated in the centre of map sheets 1537 and 1638. However, an individual maximum value of 1200 ppm is located in the SW corner of map sheet 1537.

As a whole, the analytical accuracy of the Aquater data does not seem to be consistent, as shown by the clear differences in assay levels between the map sheets. Besides different analytical methods, this might at least partly be related to the fact that sampling was carried out in two project phases. For detailed interpretation of the data, it should be divided into smaller parts and results from different map sheets should be treated separately. Economically, the most interesting outcomes appear to be related to high Zn values in the north-eastern corner of the study area (Fig. 16).

**Tecnosynesis survey**

The Tecnosynesis data was originally collected to support the evaluation for the possible development of hydropower in Lugenda River in Niassa and Cabo Delgado Provinces and not for exploration purposes (Tecnosynesis 1980). It included 188 stream sediment and 396 soil samples, totalling 584 samples. The stream sediment samples consisted of two sub-samples collected from the central part of the river channel separated by a distance of 100-200 m. All samples have been analyzed for Al₂O₃, SiO₂, K₂O, Fe₂O₃, P, Ti, Mn, Nb, Sr, Cu, Ni, Pb, Zn, V, As, and Sn by XRF. Furthermore, 87 stream sediment samples. The stream sediment samples consisted of two sub-samples collected from the central part of the river channel separated by a distance of 100-200 m. All samples have been analyzed for Al₂O₃, SiO₂, K₂O, Fe₂O₃, P, Ti, Mn, Nb, Sr, Cu, Ni, Pb, Zn, V, As, and Sn by XRF. Furthermore, 87 stream sediment
samples have been analyzed by gamma spectrometer for Th, U and K.

For some reason, a large proportion of samples have been collected as duplicates from the same locations. These include about 30 stream sediment and 120 soil duplicates. When comparing the analytical results between the duplicates, it was noted that the compositional differences between the sample pairs is marked. Due to this heterogeneity, the Tecnosynesis data cannot be considered very reliable. This might be the result of variable or undefined sampling procedures. Additionally, it seems that the sampling has been carried out along roads, which probably resulted in some contamination effect, at least for certain elements like Pb.

The results of the Tecnosynesis study, together with comparison between duplicate samples, clearly show that the sampling material has not been homogeneous. This is reflected, for instance, in the wide range of overlapping SiO$_2$ content, being 35–94% for stream sediments and 34–94.5% for soil samples. These numbers indicate that the sampled material classified as soils has occasionally been extremely quartz-rich and probably represented material from sorted stream sediments (sand) and not soil.

Economically, the most interesting values appear to be related to Zn, the maximum contents being 198 ppm for soil and 229 ppm for stream sediment (Fig. 17).

Fig. 17. Zinc content in soil (left) and stream sediments (right) in the Tecnosynesis geochemical survey. For location, see Fig. 1. The grid indicates the national 1:250 000 scale map division.

The Stanchenko survey covers the same area as the old BRGM study, which unfortunately lacks the analytical data. It is also not known how the Stanchenko work was carried out or whether the samples were the same as those collected by BRGM, because no report was stored. The results of the Stanchenko study are represented as separate elemental maps stored in the DNG map library. Element values are displayed as standard deviation classes for V, Zn, Cr, As, B, Be, Co, Cu, Ga, Li, Ni, P, Sc and Mn, the actual data being missing.

The Stanchenko study area included 130 000 km$^2$, covering most of the Nampula Province and also parts of Cabo Delgado, Niassa and Zambézia Provinces (for location, see Fig. 1). The sampling density was generally relatively homogeneous but denser in the NE corner of the study area, being 1 sample/66 km$^2$ on average. In total, 1969 sampling points were digitized from scanned element maps and standard deviations were tabulated and stored in the GIM_GDB.

Some examples of the results for major ore elements are displayed in Figure 18, illustrating the distribution of Cu, Zn, and Ni classified according to the standard deviation. Element anomalies are widely distributed, and as the sampling methodology and sample representativeness is not known, it is difficult to evaluate the economic importance of the anomalies. It can be stated that Cu forms clustered anomalies in the SE part of the study area, whereas zinc appears, together with Ni, to have a NE-SW trending anomaly zone in the western Cabo Delgado Province.
Fig. 18a. Copper content as standard deviation classes in the Stanchenko survey covering parts of Nampula, Cabo Delgado, Niassa and Zambézia Provinces. Base grid according to the national 1:250 000 and 1:50 000 scale map sheet division.

Fig. 18b. Zinc content as standard deviation classes in the Stanchenko survey.
CGS-DNG survey

The CGS-DNG survey in Cabo Delgado Province was carried out in 1996 and reported by De Waal (1996). It included 1574 soil samples collected from two sub-areas covering 573 and 1128 km², totalling 1800 km². Sampling was carried out using a helicopter. Sampling points were located using GPS with an accuracy of ±100 m. The sampling media was soil, the original sample weight being 2–3 kg. The samples were analyzed using XRF so they give a good correlation with the bedrock, as can be seen in Figs 19 and 20.

General statistics from the CGS-DNG survey are presented in Table 4. The results plotted on the geological map show high and economically interesting Cu and Zn anomalies, the maximum values being 459 and 930 ppm, respectively (Figs 19 and 20). High Zn and Cu values are both geologically related to Neoproterozoic Xixano Complex consisting of sedimentary quartz mica gneisses and schists, which are locally graphite-bearing (P3Xqm, green). The other dominant rock type in the CGS-DNG study area is plutonic amphibolite gneiss (P3Xag, light brown) belonging to the same era and complex as the sedimentary gneisses mentioned above. A concentrated Pb anomaly is geologically associated with granitic gneiss belonging to the Montepuez Complex (P3MPgr). The Monte Mapacane granite intrusion (P3XMgr, red) occurs between the sampling areas.

Table 4. Statistics of the selected elements produced by the CGS-DNG soil survey. XRF analysis. Values below the detection limit are omitted from the calculations.

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<tr>
<th></th>
<th>TiO₂ %</th>
<th>MnO %</th>
<th>Fe₂O₃t %</th>
<th>Sc ppm</th>
<th>V ppm</th>
<th>Cr ppm</th>
<th>Ni ppm</th>
<th>Cu ppm</th>
<th>Zn ppm</th>
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<td>62</td>
<td>20</td>
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</table>
Fig. 19. Copper contents (in ppm) from the CGS-DNG soil survey plotted on a geological map. For general location, refer to Fig. 1. The highest Cu values are related to the Neoproterozoic Xixano Complex consisting of sedimentary quartz mica gneisses and schists, which are locally graphite-bearing (P3Xqm, green). For other rock types, see the text. Geology based on Norconsult Consortium (NGU-BGS) mapping (LOT 1).

Fig. 20. Zinc contents from the CGS-DNG soil survey plotted on a geological map. The anomalous area is delineated by the black rectangular line. For geology, see the text.
LKAB survey

The LKAB survey area is situated within the GIM regional survey area and covers 480 km² (LKAB 1979, 1980). It included 243 samples of minerogetic material in drainage systems (Ss) that were analyzed for Sn, Nb and Ta. Additionally, La and Sn contents were analyzed from organic material (plant roots). The maximum Nb content was 1414 ppm, three samples having values around 200 ppm, but in general they were low (< 8 ppm). The situation was the same with Ta, with only four samples having values >100 ppm, the maximum being 750 ppm. The highest Sn contents (maximum 0.5%) were related to the samples with maximum Nb and Ta values originating from the vicinity of an exhausted tin mine. On the basis of the analytical results, LKAB made recommendations for field work areas. For comparison, one of the GIM soil survey areas targeted the LKAB tin anomaly (cf. Fig. 2).

BHB Namapa survey

The BHB gold survey in Namapa area, in the border zone between the Cabo Delgado and Nampula Provinces, included several stages (BHB 1999). Stream sediments were collected in two, partly overlapping areas. Both stages indicated gold anomalies situated in the north-eastern part of the study area (Fig. 21). The results of the detailed follow-up soil survey are shown in Fig. 22. Geologically, gold anomalies seem to be related to the Neoproterozoic plutonic mafic granulites of the Ocuá Complex shown in brown in Fig. 22.
FINAL OUTCOMES AND INTERPRETATION OF THE ANOMALOUS AREAS

In addition to the extensive training component of the GIM project, the most important concrete outcome is the data compilation stored in the digital and easy-to-use Geochemical Data Base (GIM_GDB). It consists of two main components: (1) the Survey Information Table (SIT) containing general survey specifications (i.e. metadata) and (2) the Analysis Data Tables (ADTs) including the actual analytical and coordinate data from different surveys. ADTs for different projects have been grouped into a specific lyr type of file that can be easily added into an ArcGIS Map document from the GIM_GDB.

The final results of the GIM geochemical survey consist of the following outcomes stored on the GIM_DVDs (available from DNG):
- GIM Geochemical Database (GIM_GDB) and related geochemical maps
- Final report of the GIM project (Korkiakoski 2007)
- GIM Final Technical Report (Pekkala et al. 2007)
- GIM Field Manual (Korkiakoski & Salminen 2006)
- Scanned and georeferenced original geochemical maps (digital)

Recommendations for future exploration targets

On the basis of the geochemical data sets of Mozambique, as compiled and interpreted during the GIM project and discussed in more detail in this paper, the recommended exploration targets for future surveys are summarized in Fig. 23. For additional information of mineral resources potential of Mozambique, see Lehto & Gonçalves (2008, this volume).
ACKNOWLEDGEMENTS

I would like to express my sincere thanks to my Mozambican counterparts and colleagues Vicente Manjate and Salomão Mujui for their involvement and input into all phases and activities of the GIM project, particularly the data capture and field activities. They have done their share with enthusiasm and a positive attitude and can be considered as qualified geochemists. Through the experience they have gained during the GIM project they are now able to plan and conduct any future objective-oriented geochemistry project independently using modern GIS aided methods. In addition, I would like to express my gratitude to DNG management and field teams, without whose contribution the objectives of the project would not have been met. Professor Reijo Salminen is thanked for his comments and corrections to the manuscript.

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