A GIS-Based Exploration Initiative to Help Steer Sustainable Development: a Pilot Project for Indonesia

Researchers:	**Arianne Ford*, Steven Micklethwaite*, Bernadetta Devi** and Phill McKenna****
School/Centre:	* Centre for Exploration Targeting ** Sustainable Minerals Institute
University/Institutions:	* The University of Western Australia ** The University of Queensland

Key themes:	Governance and Regulation Community and Environmental Sustainability
Key countries:	Indonesia
Completion:	January 2015

Research aims:
This research sought to provide:

- mineral prospectivity maps for an area of South East Sulawesi
- maps combining mineral prospectivity with factors relating to sustainability
- recommendations on future needs for improvements in analysis

For further information on this action research:

Contact person: Arianne Ford
arianne.ford@jcu.edu.au

IM4DC
Action Research Report

International Mining for Development Centre

FUNDED BY
Australian Government
Department of Foreign Affairs and Trade
Australian Aid

IMPLEMENTING PARTNERS
The University of Queensland Australia
The University of Western Australia

Summary of Action Research Activity

A GIS-based exploration initiative to help steer sustainable development: a pilot project for Indonesia

In Australia, mineral exploration opportunities have been enhanced by (1) the release of pre-competitive data in the form of Geographic Information System (GIS) databases, and (2) analysis of that data in the form of prospectivity maps. Such maps may be used to attract investment dollars into the region from exploration companies and also assist in providing advice for government agencies in terms of where to focus future budgets.

The aim of this pilot project, focussed on South East Sulawesi, was to build on these examples of pre-competitive data releases, to not only provide new geoscience products but also, for the first time, to integrate data relevant to environmental, community and infrastructure development. This would allow mineral prospectivity maps to be generated that highlight target areas based on both geology and factors relating to sustainability, which ultimately have a significant impact on the ability of mining companies to explore and operate within a region (e.g. the social license to operate).

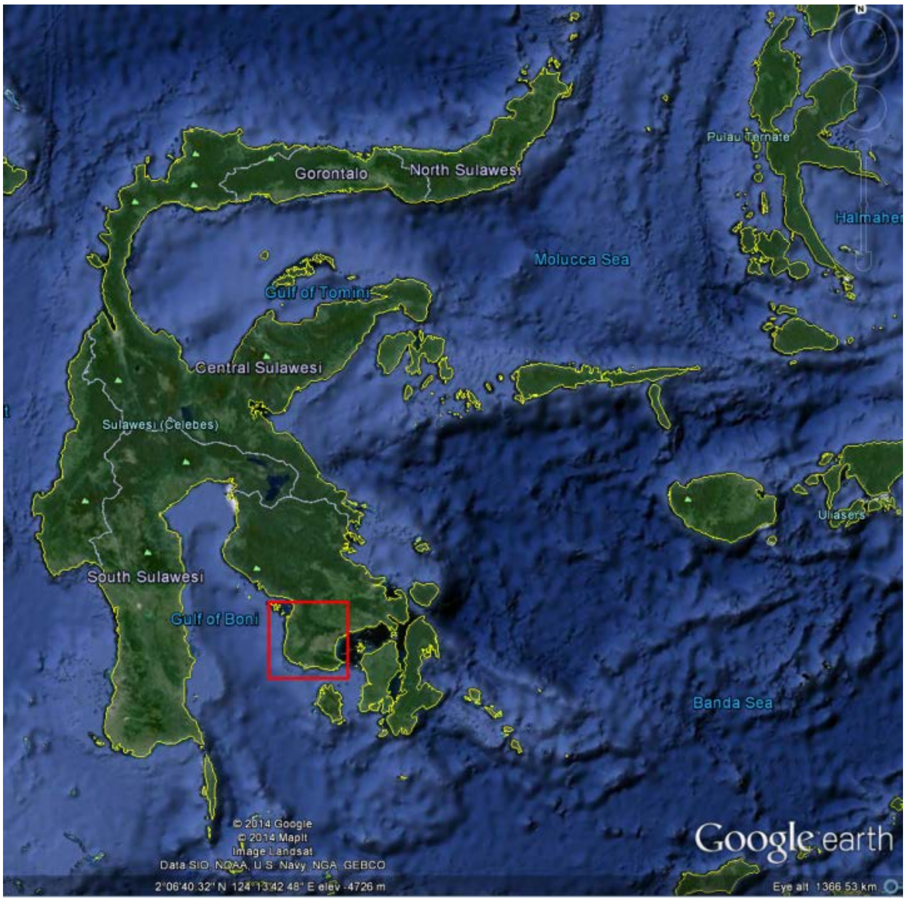
Specific deliverables from the project were:

1. an assessment of the quality of the existing geoscientific data
2. the generation of mineral prospectivity maps for South East Sulawesi, Indonesia. These aimed to include aluminium, nickel, copper, and gold
3. the generation of 'sustainable mineral prospectivity maps' sensitive to local environment, community and infrastructure information, for South East Sulawesi, Indonesia
4. a report on key areas for sustainable mineral potential and recommendations on critical data required to advance the analysis
5. the release of new maps via the IM4DC server
6. a visit to South East Sulawesi and Pusdiklat Geologi, Bandung, to communicate project results and the methodology with key stakeholders

Centre for Exploration Targeting (M006)

School of Earth and Environment
The University of Western Australia,
35 Stirling Highway, Crawley, WA 6009

A GIS-Based Exploration Initiative to Help Steer Sustainable Development: A Pilot Project for Indonesia



Report prepared by:

Dr Arianne Ford and Dr Steven Micklethwaite
Centre for Exploration Targeting
The University of Western Australia
Crawley WA, 6009

Dr Bernadetta Devi and Dr Phill McKenna
Sustainable Minerals Institute
The University of Queensland
Brisbane QLD, 4072

January, 2015

Contents

Disclaimer 2
Introduction 3
Review of Data for Southeast Sulawesi 5
- Geological Maps 5
- Structural Maps 5
- Geophysical and Remote Sensing Images 6
- Geochemistry 7
- Mineral Deposits 7
- Administrative Maps 8

Targeting Models 8
- Laterite Nickel Targeting Model 9
- Laterite Iron Targeting Model 9
- Orogenic Gold Targeting Model 9
- Placer Gold Targeting Model 10

Prospectivity Analysis 10
Discussion 18
Outcomes & Recommendations 19
References 20

Disclaimer

This report has been prepared for the recipient based on information provided by it. The information contained in this report is to be used by the recipient solely for the purpose for which it was supplied, and shall not be disclosed in whole or in part, to or by any other party without the written permission of the author to the form and context in which it is disclosed.

The University of Western Australia has acted as an independent researcher in providing this report and in no other capacity. It shall not be liable for any loss (financial or otherwise), suffered as a result of reliance on the information contained in this report, unless such loss arises from the proven misconduct or negligence on the part of the author.

The opinions expressed in this report have been based on the information supplied to The Centre for Exploration targeting (CET) by the International for Mining Development (IM4DC) Server. The opinions in this report are provided in response to a specific request from IM4DC to do so. CET has exercised all due care in reviewing the supplied information. Whilst CET has compared key supplied data with expected values, the accuracy of the results and conclusions from the review are entirely reliant on the accuracy and completeness of the supplied data. CET does not accept responsibility for any errors or omissions in the supplied information and does not accept any consequential liability arising from commercial decisions or actions resulting from them.

Introduction

Indonesia is of great interest for mineral exploration and the global mining sector, offering opportunities for economic growth and employment in the region. In Australia, similar exploration opportunities have been enhanced by (1) the release of pre-competitive data in the form of Geographic Information System (GIS) databases, and (2) analysis of that data in the form of prospectivity maps. An example of just such a pre-competitive prospectivity data release is presented by Joly et al. (2013), and Ford and Miller (2014).

The aim of this project was to build on these examples of pre-competitive data releases, to not only provide new geoscience products but also, for the first time, to integrate data relevant to environmental, community and infrastructure development with geologically formulated prospectivity maps. This allows mineral prospectivity maps to be generated that highlight target areas based on both geology and factors relating to sustainability, which ultimately have a significant impact on the ability of mining companies to explore and operate within a region (e.g. the social license to operate). It should be noted that these outcomes are highly influenced by the availability and quality of data. The project was a joint collaboration between the Centre for Exploration Targeting at the University of Western Australia (CET/UWA) and the Sustainable Minerals Institute at the University of Queensland (SMI/UQ), with assistance from the regional Energy and Mineral Resources Agency, and Regional Development Agency, both in Kendari, South East Sulawesi, Indonesia. Specific deliverables on the project were:

1. an assessment of the quality of the existing geoscientific data
2. the generation of mineral prospectivity maps for South East Sulawesi, Indonesia. These aimed to include aluminium, nickel, copper, and gold
3. the generation of 'sustainable mineral prospectivity maps' sensitive to local environment, community and infrastructure information, for South East Sulawesi, Indonesia
4. a report on key areas for sustainable mineral potential and recommendations on critical data required to advance the analysis
5. the release of new maps via the IM4DC server
6. a visit to South East Sulawesi and Pusdiklat Geologi, Bandung, to communicate project results and the methodology with key stakeholders.

Geoscientific data is often acquired by national and provincial geological surveys but remains underutilized due to a lack of resources or in-house expertise. One way to utilize this data is to produce prospectivity maps which can assist with mineral exploration and land management decisions. Such prospectivity mapping exercises have previously been undertaken with the Geological Survey of Western Australia for the similar purpose of attracting investment dollars into the region from exploration companies (e.g. Joly et al., 2013; Witt et al., 2014). Prospectivity maps also assist in providing advice for government agencies in terms of where to focus future budgets. The mineral potential maps generated give an indication of where further data acquisition and analysis may be of most practical use or where more field mapping may be necessary. This project sought to take this a step further and produce 'sustainable mineral prospectivity maps' by accounting for geological, metallogenic, environmental, agricultural and infrastructure factors in the data analysis.

The project area for South East Sulawesi, as defined by this project, is shown in Figure 1.

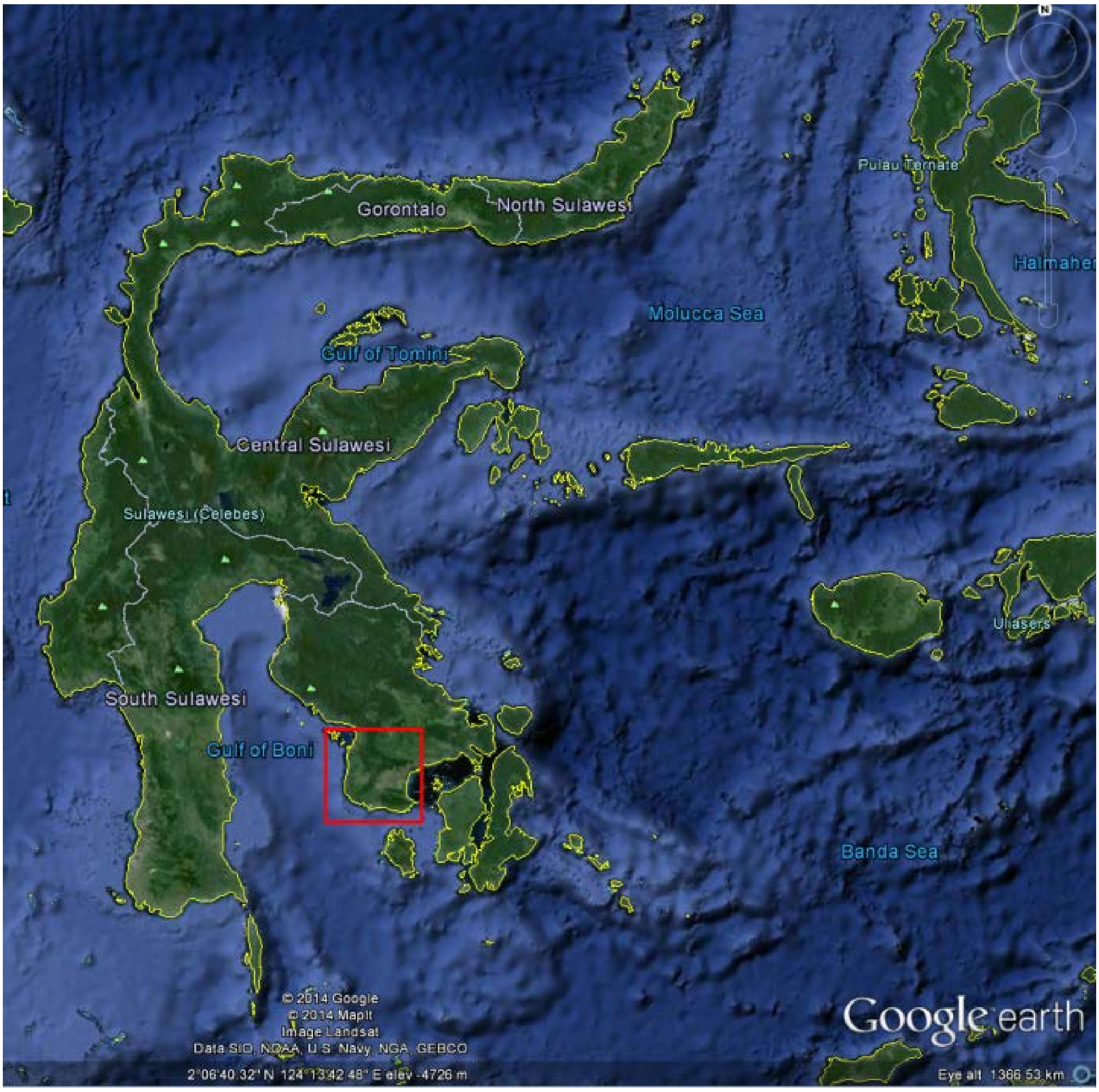


Figure 1: South East Sulawesi study area focused on the Bombana region (shown in red).

Review of Data for Southeast Sulawesi

The data compilation for South East Sulawesi, provided by the regional Energy and Mineral Resources Agency office in Kendari, contains many datasets. However, the quality of these datasets is variable, and their coverage incomplete and inconsistent over the South East Sulawesi study area. In order to be of practical use in the prospectivity mapping exercise, the datasets used had to have complete coverage over the study area and have a relatively homogeneous level of detail in the mapping.

A summary of the various datasets is provided below:

Geological Maps

Geological map coverage for the South East Sulawesi region was available from the regional Energy and Mineral Resources Agency office in Kendari. The geological map provided was at 1:250,000 scale and included the formation name and age. No detailed information was contained within the GIS table relating to the lithology or stratigraphy. It is understood that this information is available on the hard copy version of the map, but not in the digital version. ***It is recommended that the GIS table be updated with this information by the regional Energy and Mineral Resources Agency office in Kendari.***

On a visit to Kendari by Arianne Ford (CET/UWA), a meeting was held with a representative from the central Indonesian geological survey office in Bandung and it was implied that the central survey office has a more detailed 1:50,000 geological map over the Bombana region. This map is understood to be substantially different to the 1:250,000 map discussed above. Although it was made clear that this map exists, it was not provided to this project within the necessary timeframe.

As such, the 1:250,000 scale geological map of South East Sulawesi was used in the prospectivity mapping exercise for the Bombana region.

Structural Maps

One structural map for the South East Sulawesi region was present in the data compilation provided by the regional Energy and Mineral Resources Agency office in Kendari. This structural map was produced by the local geologists and has some inconsistencies with the 1:250,000 scale geological map over the area. Cross-validation of the structural map with the available free air gravity data from Scripps Institute of Oceanography at the University of San Diego[1] highlighted that some major boundaries had not been included in this structural map (major structural boundaries are a key control on the location of major mineral deposits).

The structural map was revised during the course of the project through interpretation of the 1:250,000 geological map, as well as the available gravity data, as highlighted in Figure 2. This was used as an input layer in the prospectivity analysis and has been made available on the IM4DC server.

[1] http://topex.ucsd.edu/WWW_html/mar_grav.html

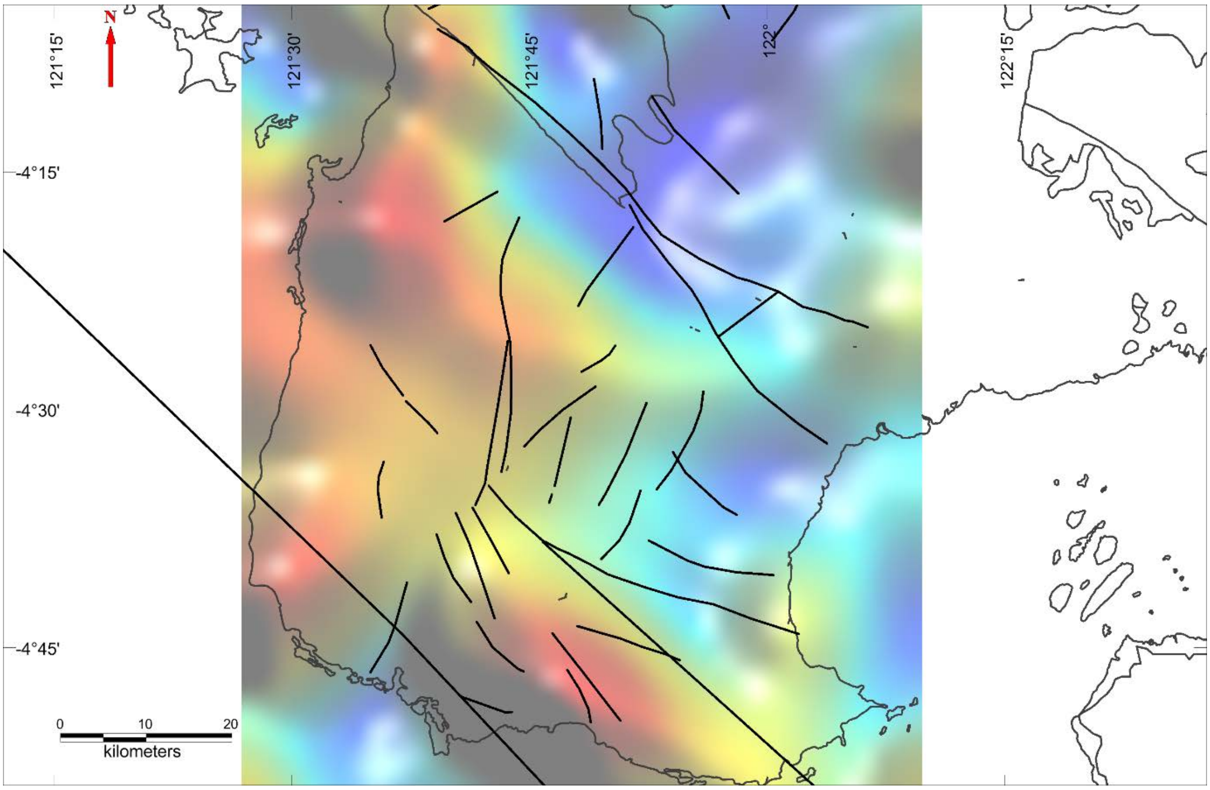


Figure 2: Revised structural interpretation for the Bombana region of South East Sulawesi showing the faults superimposed on the available gravity image.

Geophysical and Remote Sensing Images

A gravity dataset was available from the regional Energy and Mineral Resources Agency office in Kendari. This dataset was a Bouguer gravity anomaly map over the eastern part of Indonesia, from East Kalimantan to West Papua. However, this map was not in digital format and only available as a paper copy. Additionally, the resolution of the map was coarse and not suitable for an analysis of either the Bombana region or South East Sulawesi in a broader sense.

In addition to the existing gravity dataset from the regional Energy and Mineral Resources Agency office in Kendari, a free air gravity map was produced from freely available data at Scripps Institute of Oceanography at the University of San Diego. This dataset was able to highlight detail from which a structural analysis could be performed to revise the existing structural map over the Bombana region (Figure 2).

During the visit to Kendari by Arianne Ford (CET/UWA), the representative from the central geological survey office of Indonesia in Bandung indicated that aeromagnetic data over the South East Sulawesi region existed in their office. However, this data was not provided within the timeframe for this project. ***It is strongly recommended that the regional Energy and Mineral Resources Agency office in Kendari take steps to acquire this aeromagnetic data from the central agency.***

Additional remote sensing data from the regional Energy and Mineral Resources Agency office in Kendari included a digital elevation model (DEM) generated from shuttle radar topography mission (SRTM) data, and a Landsat image over the Bombana region. A detailed map of the rivers in South East Sulawesi was generated from the DEM and SRTM data, and included in the analysis.

Due to the size of the Bombana study area, limited outcrop and the coarse resolution of the Landsat imagery, this data is insufficient for the purposes of a preliminary alteration mapping exercise. In order to generate an alteration map over the Bombana region, higher resolution spectral data such as Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) should be purchased and processed. ***The central geological survey agency in Bandung has the expertise to undertake the data processing necessary to generate these alteration maps from ASTER.***

Geochemistry

The regional Energy and Mineral Resources Agency office in Kendari supplied geochemistry data for a portion of the Bombana region. However, the map contained only 20 data points with major element concentrations. These points were strongly clustered around a single known placer gold deposit and the map was not a viable input for the prospectivity mapping exercise.

Although a number of companies are working in Bombana Regency, and are required to submit their geochemical data to the regional Energy and Mineral Resources Agency office, it is clear that the data is not being made available to the relevant authorities.

A representative from the central Indonesian geological survey office in Bandung indicated that their 2015 budget was to include a systematic geochemical survey of Sulawesi. This survey is said to include soil and stream sediment collection and analysis. ***It is recommended that the regional Energy and Mineral Resources Agency office in Kendari submit a request to the central agency for a focused geochemical survey in Bombana Regency.***

Mineral Deposits

Despite exploration in the Bombana region for gold mineralization, and existing mining operations, no up-to-date mineral deposit map is available from the regional Energy and Mineral Resources Agency office in Kendari.

A scanned and georeferenced paper map of historic workings is available, but this was found to be woefully out of date and did not include the location of any of the known placer deposits in the region. Visual inspection of a hard copy map during a visit to Kendari suggests that the locations of all of these deposits are known and simply need to be digitized appropriately.

A spreadsheet containing the location of 20 known mineral occurrences in the South East Sulawesi province was provided by a consultant, Theo Van Leeuwen. While the data contained within the spreadsheet appears to be of high quality, only four gold occurrences are listed for the entire province, with the remainder largely relating to nickel laterite mineralization. Given the limited number of gold occurrences contained within the spreadsheet, it is not feasible to use it as a direct input into the prospectivity mapping exercise. This data was used as part of a validation process of the prospectivity maps generated.

As an additional method for verifying the accuracy of the prospectivity maps generated in this study, the locations of the 20 geochemical anomaly points were used in the absence of a mineral deposit database.

It is strongly recommended that the regional Energy and Mineral Resources Agency office in Kendari take steps to digitize the locations of the known mining operations in the Bombana region for incorporation into a spatial database.

Administrative Maps

A comprehensive list of administrative maps was available for South East Sulawesi, provided by the Regional Development agency in Kendari. These included: political and administrative, environmental data, landuse, transportation infrastructure, water resources, and energy infrastructure maps. Although there are many objects contained within the maps, there was often limited information attached in the corresponding attribute tables. Also absent was metadata providing information such as the coordinate system, date that shapefiles were produced and the source of the spatial data. Much of the social data provided in reports and documents could be included in the GIS layers, such as population statistics, ethnicity and the indigenous status of the population.

The administrative data was reviewed by Bernadetta Devi (SMI/UQ), and Phillip McKenna (SMI/UQ) for relevance and accuracy.

Targeting Models

Based on a combination of relevant literature and the the geoscience data as discussed above, a series of targeting models were generated for different styles of mineralization within the Bombana study area.

Limited information is available on the regional scale geology or metallogeny of the South East Sulawesi region, at least in the public domain. Searches for relevant literature online produced little of practical use for developing mineral exploration targeting models at such a large scale. ***Although, it should be noted that it is the understanding of the authors that much of this information exists, but resides outside the public domain.*** More comprehensive literature on the geology and mineralization exists for the North Sulawesi region, and for West Papua, where more significant economic mineralization is known to exist (e.g. large porphyry copper deposits being developed by western exploration and mining companies).

Targeting models were produced for laterite nickel, laterite iron and gold for the South East Sulawesi region. However, based on data availability, only models for orogenic and placer gold in the Bombana region were able to be implemented. It is possible that copper mineralization is present in the region, as sub-economic copper mineralization is known to be present elsewhere in Sulawesi, although not enough information relating to its regional geological setting could be found in order to develop a targeting model. Although there is likely potential for other styles of mineralization within South East Sulawesi, not enough information was available in the literature from which a targeting model could be generated.

Discussion with geologists in Kendari during the visit by Arianne Ford (CET/UWA) revealed that many consider that there is potential for low sulfidation epithermal gold mineralization in the Bombana region. At the present time, this is based solely on the presence of a geothermal hot spring in the region. However, it is noted that there is no evidence of volcanic rocks in the area, and there is nothing to indicate that there is potassium enrichment which is considered to be a critical criteria for the exploration of low sulfidation epithermal gold deposits. Potassium enrichment can be mapped using radiometric and alteration maps. ***It is suggested that if exploration for low sulfidation epithermal gold mineralization in the Bombana region is to progress, a radiometric survey be***

undertaken, and the ASTER data over the region purchased and processed to generate alteration maps.

The targeting models for laterite nickel, laterite iron, and orogenic and placer gold are discussed further below.

Laterite Nickel Targeting Model

Laterite nickel mineralization is located throughout the South East Sulawesi region (van Leeuwen and Pieters, 2011). The mineralization is thought to be Pliocene to Late Miocene in age, and is related to the presence of ultramafics in the region. Nickel is hosted in the upper limonite zone of the laterite profile, which has a Fe content of 45-47%, and is depleted in SiO_2 and MgO due to intense weathering. A complex structural setting and serpentinization are thought to assist with causing volume collapse, leading to further weathering.

The following datasets should be considered critical for exploring for laterite nickel:

- Geology
- Structure
- Digital terrain model
- Geochemistry (major and trace element)

Based on the available data for the Bombana region, this model was not possible to implement. The detail of the 1:250,000 scale geological mapping available is insufficient to map out the required geology.

Laterite Iron Targeting Model

Limited information on the setting of the laterite iron mineralization in South East Sulawesi is available. Based on a review of mineralization presented by van Leeuwen and Pieters (2011), it is suggested that the iron laterite occurs in tectonic depressions within a peridotite terrain. These deposits have low nickel content (< 1%).

The following datasets should be considered critical for exploring for laterite iron:

- Geology
- Structure
- Digital terrain model
- Geochemistry (major and trace element)

Based on the available data for the Bombana region, this model was not possible to implement. The detail of the 1:250,000 scale geological mapping available is insufficient to map out the required geology.

Orogenic Gold Targeting Model

Known gold mineralization in South East Sulawesi occurs in Bombana Regency. Although current mining is focused on alluvial mineralization at Bombana, which occurs in the Lower Miocene Langkowala Formation, the source of the gold has not been determined. Based on proximity to greenschist metamorphic rocks, granites, and an alteration zone that includes silicification, clay sericte-silica, carbonate-calcite and carbonization, we suggest that the source of the gold is likely orogenic. Based on this, an orogenic gold targeting model was implemented.

The following datasets should be considered critical for exploring for orogenic gold:

- Geology
- Structure
- Digital terrain model
- Geochemistry (major and trace element)
- Alteration

Based on the available information over the Bombana region, a structural map was generated, and the Cretaceous-Tertiary metamorphic rocks extracted from the 1:250,000 scale geological map.

Placer Gold Targeting Model

Current mining in the Bombana region is focused on placer gold mineralization, which occurs in the Lower Miocene Langkowala Formation. The locations of potential trap sites for accumulation of the gold can be interpreted from deviations in rivers and streams.

The following datasets should be considered critical for exploring for orogenic gold:

- Geology
- Structure
- Digital terrain model
- Geochemistry (major and trace element)
- Rivers and streams

Based on the available information over the Bombana region, a structural map was generated and the Langkowala Formation extracted from the 1:250,000 scale geological map. Additionally, a map showing the rivers was used to represent the possible flow pathways and deviations in the rivers extracted as potential trap sites.

Prospectivity Analysis

Given the absence of a suitable mineral deposit database for the Bombana region, the prospectivity mapping exercise was limited to a knowledge-driven approach. The method implemented in this study of the Bombana region in South East Sulawesi was the fuzzy logic method. Fuzzy logic does not rely on the existence of a robust mineral deposit database like data-driven methods such as weights of evidence or neural networks, but instead relies on the knowledge of an expert geologist in order to determine the inputs for the prospectivity map. The geologist must select the data layers that they believe to be the most important for the style of mineralization being targeted. Subsequently, it is the decision of the geologist to determine what critical thresholds must be applied (e.g. what distance from a fault may be considered to be favourable for the formation of a structurally controlled mineral deposit) and what weighting to assign the different areas of favourability.

Previous studies indicate that the best practice is to assign a class weight, map weight and uncertainty weight to each favourability class with values in the range between 0 and 1. Each class within a map is assigned an individual *class weight* indicating its relative favourability; this can represent decreasing favourability as you move further away from the feature of interest. Each map is then assigned a *map weight* which indicates how important that map is relative to other maps; this could indicate that the faults may be considered more important than the host rock. Finally, each map is then assigned an *uncertainty weight* which represents a measure of the quality of the input map. The class weight, map weight and uncertainty values are then multiplied together in order to generate a fuzzy membership value (or weight) for each favourability class in each map.

The maps are then combined using a fuzzy operator (Bonham-Carter, 1994), which produces a prospectivity map for the style of mineralization of interest. For this case study, the fuzzy PRODUCT operator was used to generate all of the prospectivity maps.

For the Bombana region, the data layers and their parameters for orogenic gold mineralization are listed in Table 1. The corresponding orogenic gold prospectivity map is shown in Figure 3. The data layers and their parameters for the placer gold prospectivity map are shown in Table 2, with the corresponding placer gold prospectivity map shown in Figure 4.

Table 1: Prospectivity mapping parameters for orogenic gold mineralization in the Bombana region of South East Sulawesi

Input Layer	Distance	Class Wt.	Map Wt.	Uncertainty Wt.	Fuzzy Membership
Distance to Fault	0-2 km	0.98	0.90	0.60	0.5292
	>2 km	0.01	0.90	0.60	0.0056
Distance to Metamorphic Unit	0-3 km	0.95	0.80	0.70	0.5320
	>3 km	0.01	0.80	0.70	0.0054

Table 2: Prospectivity mapping parameters for placer gold in the Bombana region of South East Sulawesi

Input Layer	Distance	Class Wt.	Map Wt.	Uncertainty Wt.	Fuzzy Membership
Distance to Langkowala Formation	0-3 km	0.95	0.80	0.70	0.5320
	>3 km	0.01	0.80	0.70	0.0056
Distance to Fault	0-2 km	0.98	0.90	0.60	0.5292
	>2 km	0.01	0.90	0.60	0.0054
Distance to River	0-5 km	0.70	0.80	0.75	0.4200
	>5 km	0.01	0.80	0.75	0.0060
Distance to River Divergence	0-500 m	0.70	0.80	0.75	0.4200
	>500 m	0.01	0.80	0.75	0.0060

A map (Figure 5) indicating the sustainability of the Southeast Sulawesi region was generated using the parameters shown in Table 3. The input parameters used were based on input from staff at CET/UWA, SMI/UQ, and the Regional Development agency in Kendari, making best use of the limited data available.

Table 3: Sustainability map parameters for Southeast Sulawesi

Input Layer	Distance	Class Wt.	Map Wt.	Uncertainty Wt.	Fuzzy Membership
Distance to Protected Forest Area	0-5 km	0	0.99	0.90	0
	>5 km	0.90	0.99	0.90	0.8019
Distance to Residential City	0-2 km	0	0.99	0.95	0
	>2 km	0.95	0.99	0.95	0.8935
Distance to Residential Village	0-1 km	0	0.99	0.95	0
	>1 km	0.95	0.99	0.95	0.8935
Distance to Road	0-3 km	0.95	0.80	0.90	0.6840
	>3 km	0.40	0.80	0.90	0.2880

The sustainability map (Figure 5) was then integrated with each of the prospectivity maps generated in order to produce a sustainable prospectivity map for orogenic gold (Figure 6) and placer gold (Figure 7).

The input data layers and the subsequent prospectivity maps generated have been published as freely available precompetitive datasets on the IM4DC server.

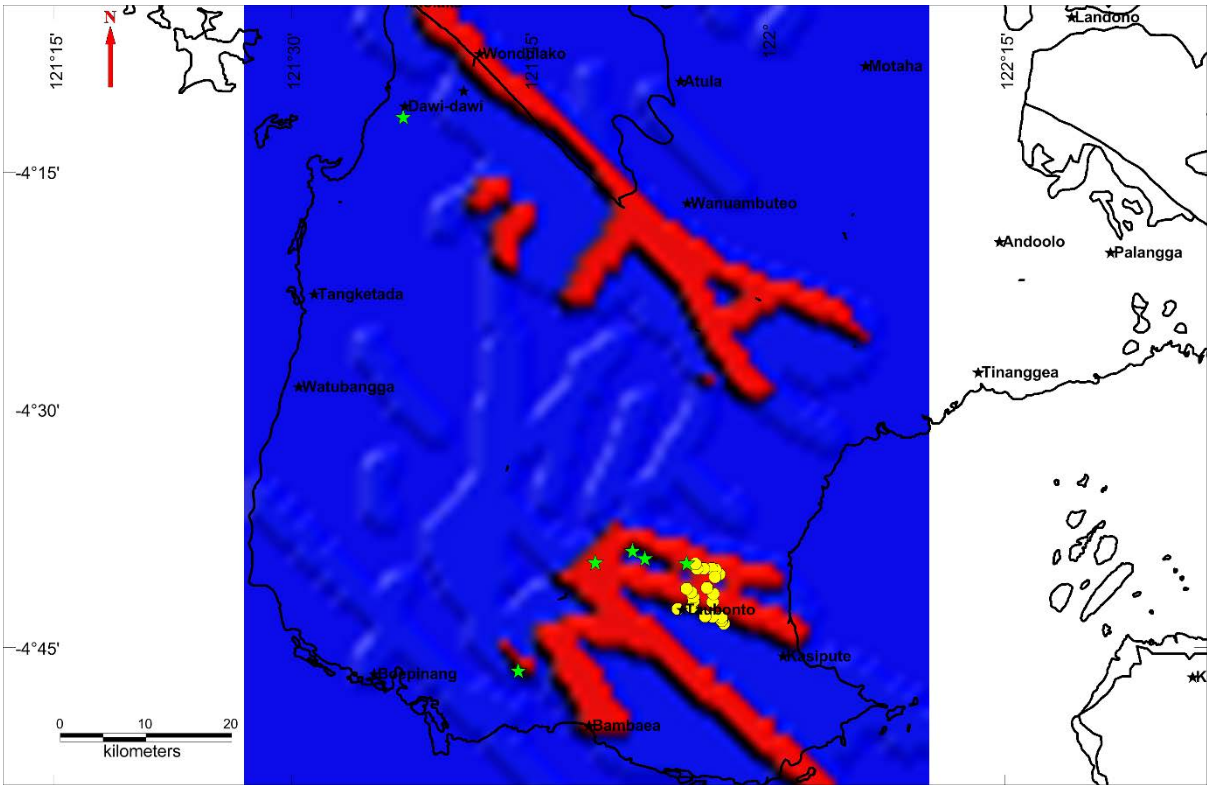


Figure 3: Orogenic gold prospectivity map for the Bombana region in South East Sulawesi using the parameters in Table 1. The location of known gold occurrences (green stars) and geochemical sample points (yellow circles) are shown on the map as a validation measure. The red areas indicate a higher prospectivity for orogenic gold.

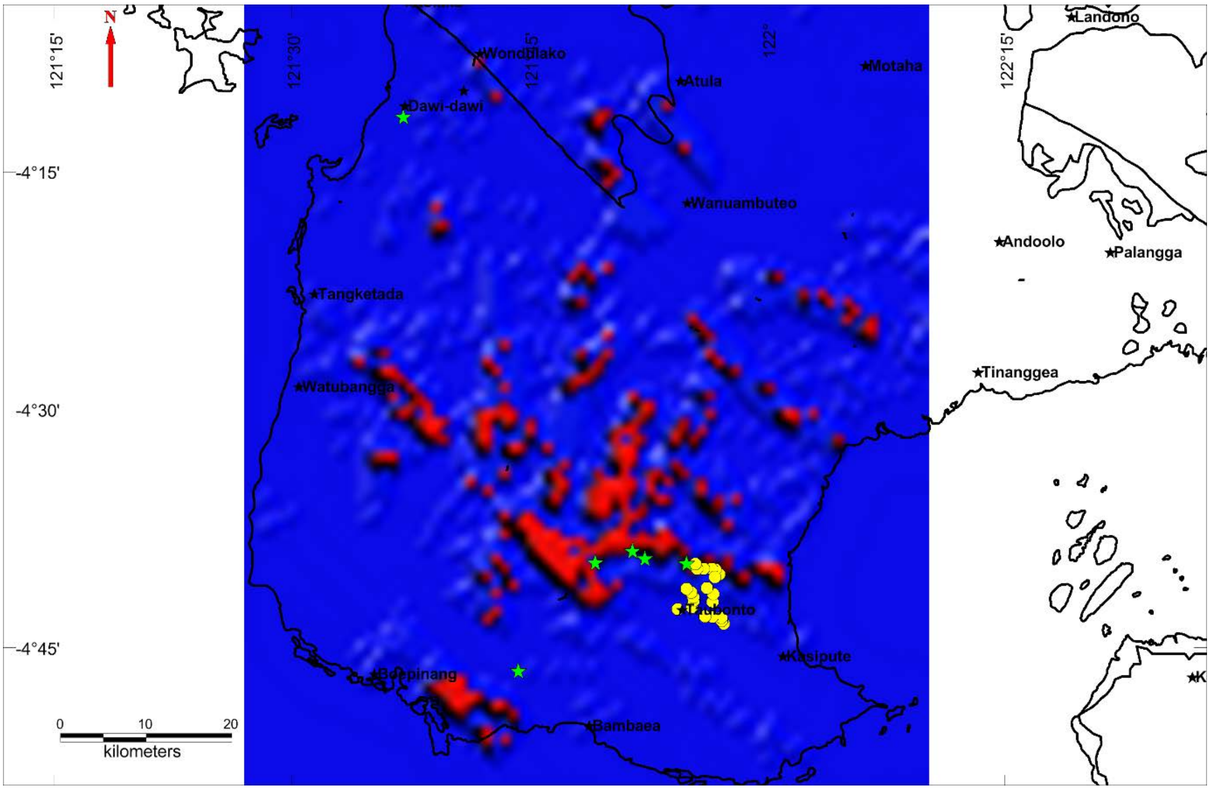


Figure 4: Placer gold prospectivity map for the Bombana region in South East Sulawesi using the parameters in Table 2. The location of known gold occurrences (green stars) and geochemical sample points (yellow circles) are shown on the map as a validation measure. The red areas indicate a higher prospectivity for placer gold.

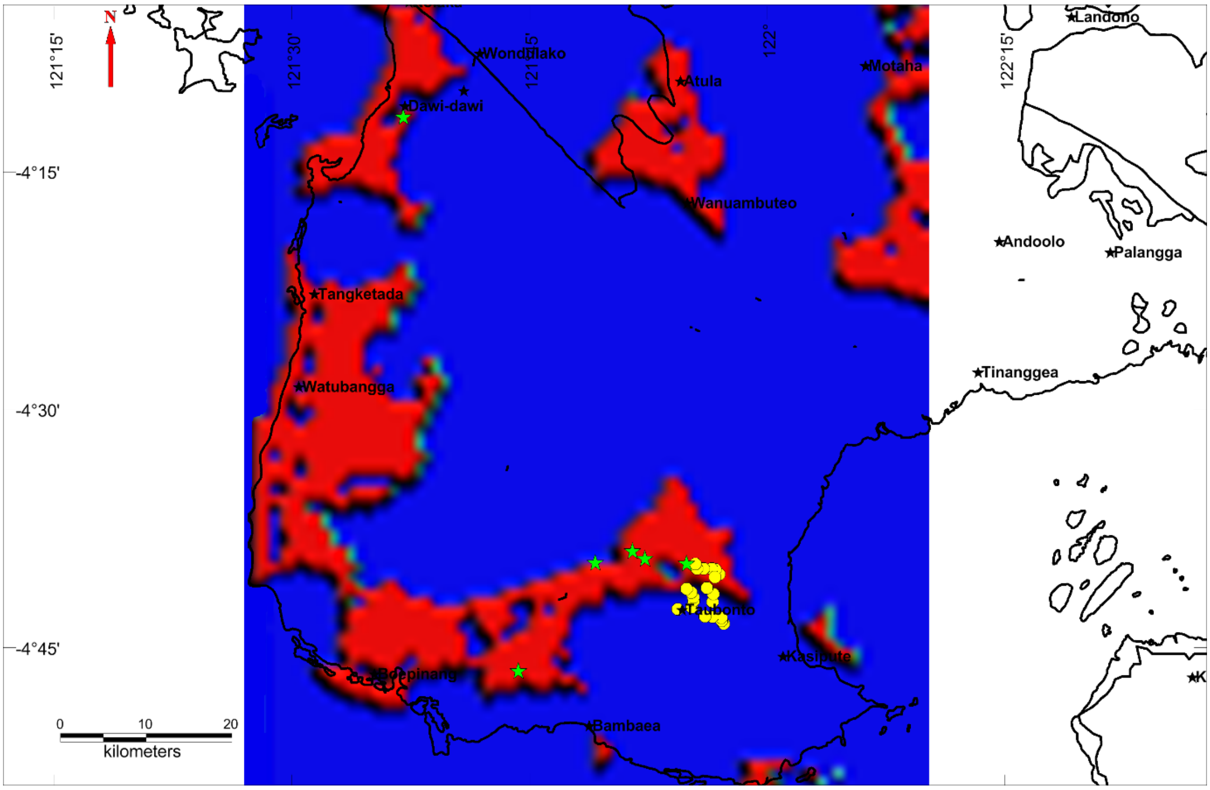


Figure 5: Sustainability map for South East Sulawesi using the parameters in Table 3. The location of known gold occurrences (green stars) and geochemical sample points (yellow circles) are shown on the map. The red areas indicate zones that are more favourable for exploration and mining based on sustainability criteria.

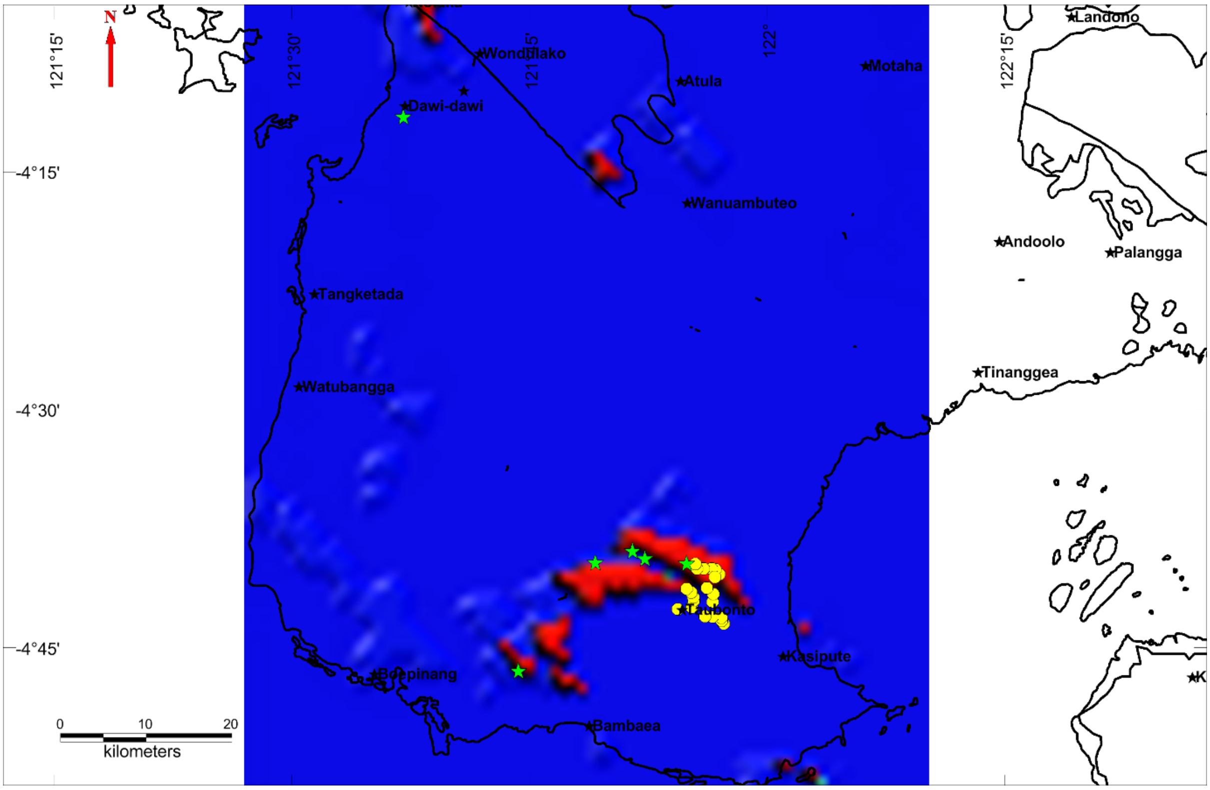


Figure 6: Sustainable prospectivity map for orogenic gold in the Bombana region of South East Sulawesi. The location of known gold occurrences (green stars) and geochemical sample points (yellow circles) are shown on the map. The red areas indicate zones of sustainable prospectivity for orogenic gold.

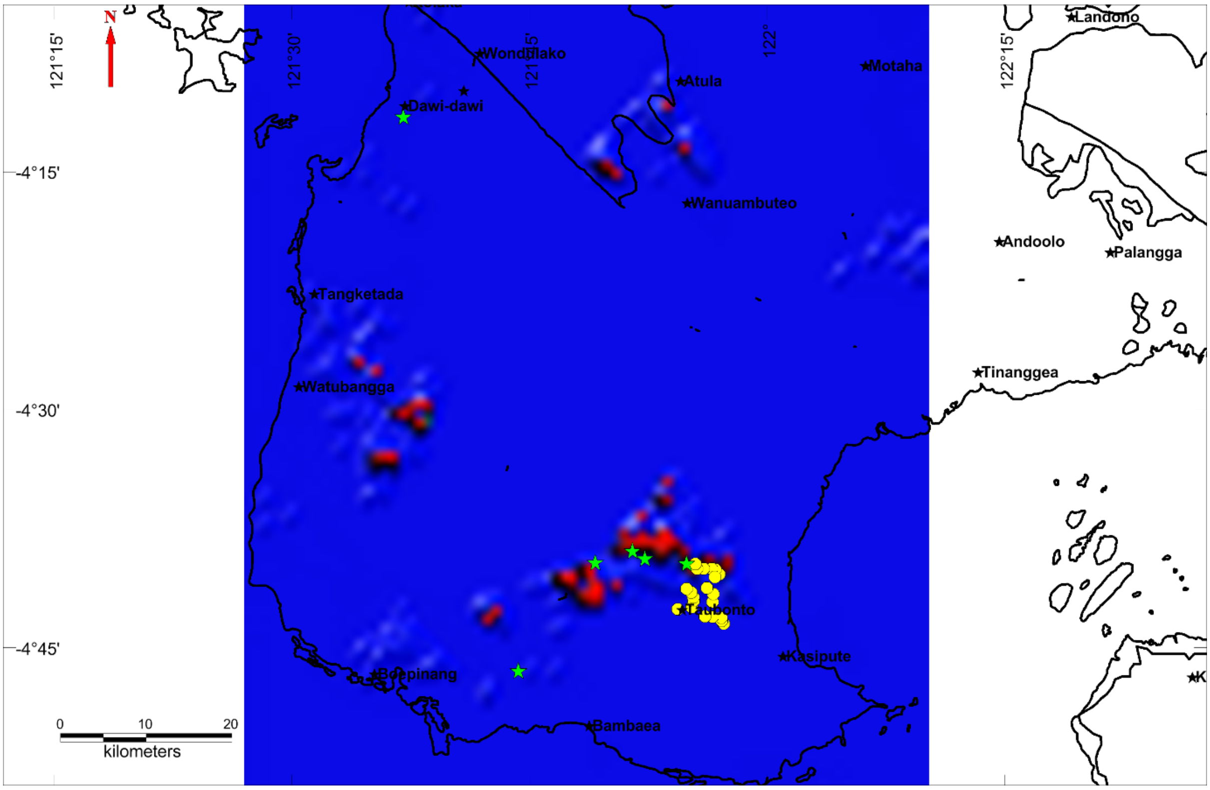


Figure 7: Sustainable prospectivity map for placer gold in the Bombana region of South East Sulawesi. The location of known gold occurrences (green stars) and geochemical sample points (yellow circles) are shown on the map. The red areas indicate zones of sustainable prospectivity for placer gold.

Discussion

The prospectivity maps in Figures 3 and 4 based solely on geological criteria clearly highlight areas of increased prospectivity for orogenic and placer gold mineralization within the Bombana region of South East Sulawesi.

Results of the prospectivity mapping for orogenic gold mineralization show a large, highly prospective region close to the known mineralized areas, as indicated by the known gold occurrences and geochemical sample points (Figure 3). This is due to the presence of metamorphic rocks and the proximity to structures. The known mineralization appears to be proximal to NW to WNW trending structures, and additional areas of increased prospectivity are seen along similar trending structural corridors both to the north and south of the known gold occurrences and geochemical anomalies. These areas of increased prospectivity represent opportunities for further investigation for orogenic gold mineralization.

Areas of increased prospectivity for placer gold are distributed throughout the Bombana region (Figure 4). All but one of the gold occurrences are predicted by the placer gold prospectivity map. It is interesting to note that the known geochemical anomalies in the area are poorly predicted by the prospectivity map. It is unclear whether this is an artefact of the data quality, or an issue relating to the targeting model parameters used (Table 2). It is also possible that the fact that these geochemical anomalies are well predicted by the orogenic gold prospectivity map and not the placer gold prospectivity map, that they are in fact related to the original source of the placer gold. Many areas away from the known gold occurrences and geochemical anomaly locations, predominantly to the west, are highlighted on the placer gold prospectivity map. These areas represent opportunities for further investigation for placer gold mineralization.

Taking into consideration the measures of sustainability (Table 3; Figure 5), the search space for mineral exploration is shown to be restricted. While proximity to roads is considered to be favourable, proximity to cities, villages, and protected forest are seen as non-favourable. Although proximity to rivers may be considered a critical sustainability criterion, this feature has already been included in the mineral potential maps. The feature may be included in the sustainability maps in future studies; however this would demand it be removed from the geological targeting model to avoid overfitting to that particular criteria. When the sustainability map is combined with the prospectivity maps for orogenic and placer gold mineralization, the search space is shown to be considerably reduced (Figures 6 and 7). It is interesting to note in the sustainability map in Figure 5 that a number of the geochemical sample points are located in an area that is considered restricted, as these sample locations are indicative of existing exploration efforts. It is unclear whether this is an artefact of the quality of the maps used as input into the sustainability map, or whether the parameters used to define the sustainable areas are overly restrictive (Table 3).

Figure 6 clearly shows a region of increased prospectivity for orogenic gold mineralization in the existing Bombana gold district, when sustainability factors are considered. It is noted that there are two additional areas of increased prospectivity to the north which appear to be related to the Kolaka fault.

The sustainable placer gold prospectivity map in Figure 7 shows a considerably reduced exploration search space when sustainability factors are considered. Much of the area highlighted as prospective is proximal to the existing Bombana gold district, with small areas of increased prospectivity to the north, north-west, and south-west.

Figures 6 and 7 should be used as a guide for mineral exploration in the Bombana region of South East Sulawesi. Although not a product that delineates drill targets, the reduced search space for orogenic and placer gold mineralization provides an indication of where further high resolution reconnaissance mapping and sampling should be focused. This should be investigated, while taking into consideration measures of sustainability and existing land-use, in order to create positive community engagement.

Outcomes and Recommendations

Based on the results of the sustainable prospectivity mapping exercise, the following outcomes and recommendations are reported:

- The sustainable prospectivity maps generated in this project broadly correlate with known regions of orogenic and placer style gold mineralization.
- Accounting for sustainability factors allows the exploration risk in South East Sulawesi to be reduced. This data is now provided in a pre-competitive public database (http://opendata.im4dc.org/).
- The target areas highlighted in Figures 6 and 7 are of sufficiently small size that exploration companies should be able to make rapid on-the-ground assessment of the exploration potential in the new areas at relatively low cost.
- Further fieldwork over the highlighted prospective areas by mineral exploration companies is needed in order to obtain the higher resolution geological mapping, a comprehensive geochemical sampling program and high resolution geophysical surveys necessary to delineate more focused exploration targets.
- Better data sharing arrangements are needed between the regional Energy and Mineral Resources Agency office in Kendari and the central agency in Bandung. During the course of this project, it was made clear that the central agency has access to data that is considered critical for mineral exploration; however, this data was not being accessed by the regional office in Kendari.
- Reports and books produced by the regional Energy and Mineral Resources Office, and the central agency should be made more easily available in the public domain. Information on the regional-scale geology and mineralization in South East Sulawesi (particularly the Bombana region) published in scientific journal articles and books is limited. Making these reports and books easily available online, even at a small cost, would improve accuracy of the targeting models used in the prospectivity analysis.
- A geochemical sampling program across the Bombana region of South East Sulawesi is recommended. In order to reduce the search space for economic mineralization, the analysis of both major and trace elements is of critical importance. This may also open up the exploration search space for other commodities and styles of mineralization.
- Acquisition of ASTER data over the Bombana region is recommended, to be processed for the purposes of mapping hydrothermal alteration patterns. This data can be purchased for minimal cost given the small size of the Bombana region, and the central Energy and Mineral Resources Agency office in Bandung has the capacity to do the data processing.
- Sufficient metadata should be maintained for all of the maps. As an example: for all of the administrative datasets, keep a spreadsheet or database containing the name of the ESRI Shapefile (or MapInfo Table), with a short explanation of what the data in each file represents, the accuracy of the data and when the dataset was created.
- Digital geoscience data should be published online. One of the benefits of GIS-based prospectivity mapping is that it is a relatively low cost exercise compared to field mapping and laboratory

work. However, this cost benefit is negated if extended travel is necessary to acquire the data in person. By making this data available online for download, even for a small cost, the cost benefit may be maintained.

- The South East Sulawesi sustainable prospectivity analysis provided here is a proof-of-concept trial for an approach that could be developed across the whole of Indonesia. In order to be successful, an Indonesian-scale project would require access to digital geological and sustainability datasets from every province, along with strong linkages between Federal and Province experts and agencies. If the outcomes of such a project are delivered freely as pre-competitive datasets for industry, the result could encourage long term industry investment in exploration. Ideally the data required for such a project would include: geological maps, structural maps, geophysical data (aeromagnetics, gravity, radiometrics), remote sensing data (Landsat, ASTER), geochemical data (major and trace elements) and digital elevation models.

References

Bonham-Carter, G., 1994, Geographic Information Systems for Geoscientists: Modelling with GIS. Oxford, Pergamon Press, 398 p.

Ford, A., and Miller, J.M., 2014, A GIS-based Mineral Prospectivity Analysis of Central Africa. Report prepared for the International Mining for Development Centre, June 2014. URL: http://im4dc.org/action-research-reports

Joly, A., Denith, M.C., Porwal, A., Spaggiari, C.V., Tyler, I.M., and McCuaig, T.C., 2013, An integrated geological and geophysical study of the west Arunta Orogen and its mineral prospectivity. GSWA Report 113. URL: http://www.dmp.wa.gov.au/4726.aspx

van Leeuwen, T.M., and Pieters, P.E., 2011, Mineral Deposits of Sulawesi. *In*: Proceedings of the Sulawesi Mineral Resources 2011 Seminar. MGEI-IAGI, 28-29 November 2011, Manado, Indonesia, pp. 1-120.

Witt, W.K., Ford, A., Hanrahan, B., and Mamuse, A., 2014, Regional-scale targeting for gold in the Yilgarn Craton: Pt 1 of the Yilgarn Gold Exploration Targeting Atlas. GSWA Report 125. URL: http://www.dmp.wa.gov.au/4726.aspx