MAPPING SOUTH SUDAN PRECAMBRIAN BASEMENT ARCHITECTURE USING SATELLITE-DERIVED GRAVITY DATA

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Abstract

Freely available satellite gravity data augmented with acquired land gravity data were used to map the basement architecture of South Sudan. The potential field data enhancement methods used in this study are horizontal gradient, tilt angle, and analytical signal, which provided the capability of delineating major geologic structures, lithologic boundaries, and tectonic lineaments that can be visually identified by edge-detection processing methods.

Qualitative interpretation of satellite-derived Bouguer gravity data has aided mapping of the basement geology of South Sudan, and the results are consistent with the known oilfields and areas of Precambrian basement complexes. Consequently, the information would aid in identifying additional mineral prospective areas, where more detailed gravity, magnetic, electromagnetic, and seismic surveys can be carried out; the combination of these data will assist decision makers in matters related to land use, mineral titles, and exploration of natural resources.

1. Introduction

The geophysical mapping in this study is aimed to expose the basement architecture and relate major structures in South Sudan and those extending into neighboring countries of east and central Africa. Mapping of basement morphology in the study area will aid in assignment of mineral title blocks in the country, especially in regions that are occupied by sedimentary basins in swampy lowlands with no rock exposures.

Since this study is targeting mapping of basement rocks in South Sudan, and due to lack of geoscientific data in most of the study area (Figure 1), there was a need to utilize satellite gravity data because of their vast coverage and cost-effectiveness.

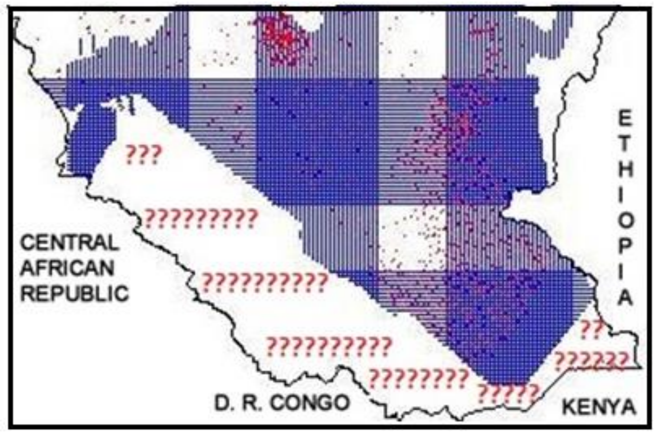

Figure 1. Potential field data coverage of South Sudan showing magnetic data grids (blue lines) and gravity data stations (red points). The question marks represent zones with no data coverage.

2. Geology of the study area

South Sudan constitutes part of the East African orogenic belt, which comprises the Arabian-Nubian Shield (ANS) in the north and the Mozambique belt in the south (Stern, 1994). This Neoproterozoic crust resulted from the collision between east and west Gondwana and extends to several countries (e.g., Ethiopia, Eritrea, Egypt, Somalia, Saudi Arabia, and Yemen). The ANS is characterized by the following:

i. Occurrence of arc assemblages associated with ophiolites and granitoids.
ii. Rejuvenated older crustal terranes.
iii. Accumulation of sediments and /or volcanic rocks in aulacogens or tectonic basins, which subsequently were metamorphosed and deformed.

The final accretion of the different island arcs caused strong tectonic deformation during what is known as the Panafrican orogenic period or cratanization that occurred in the Precambrian. Most Panafrican structures correspond to chains that either have a northeast-southwest (left-lateral transpression) or north-south to northeast-southwest (left-lateral transpression) strike. There were widespread postorogenic granitic intrusions following the Panafrican orogeny (Kröner 1985).

3. Processing of Gravity Data

The processed data in this study are the free-air satellite gravity data derived from the “DNSC08 Global Gravity” of the Danish National Space Center, which has been augmented with EGM08 over land [1].

The main aim of constructing a Bouguer anomaly map from the free-air gravity anomalies is to eliminate the large effect of topography in free-air anomaly data [2] [3], which masks the anomalies caused by subsurface sources. A Bouguer anomaly map derived from the satellite data can also be compared with the Bouguer anomaly map produced using ground gravity data which is referred to here as Getech data, particularly in areas that are well covered by gravity surveys in South Sudan. In case the Getech Bouguer gravity map shows good correlation, then the extensive coverage of the satellite-derived Bouguer gravity map could be used to delineate geologic structures as well as in mapping basement architecture in other parts of the study area that are lacking ground gravity data.

The Getech data were derived from land gravity stations, with a resolution of 5 minutes (~10 km). Bouguer reduction density of 2.67 g/cm3 was applied to the data (D. Ravat, 2011, personal communication).

The correction applied to the free-air anomaly in order to convert it into a complete Bouguer anomaly map consists of the following steps using the Geosoft Oasis Montaj package:

1. Bouguer slab correction (Bullard A), which assumes a slab of finite lateral extent, constant density, and thickness equal to the elevation of the data location with respect to sea level, is applied.

2. The curvature correction (Bullard B), which replaces the Bouguer slab with a spherical cap of the same thickness to a distance of 166.735 km, is applied.

3. The terrain correction (Bullard C), which accounts for the effect of surrounding topography in the Bullard A and B corrections, is applied above and below the point of calculation (Nowell, 1999). Land terrain corrections with a regional DEM GTOPO30 model (gtopo30 is 30 arc-second latitude/longitude or approximately 1 km spacing), are applied.

The Bouguer gravity maps based on satellite data (Figure 2) and Getech data (Figure 3) show similar high and low anomalies in the central part of the study area where the oil-fields are located. There is no correlation in areas known to lack data, however; these areas have been labeled by question marks in Figure 1.

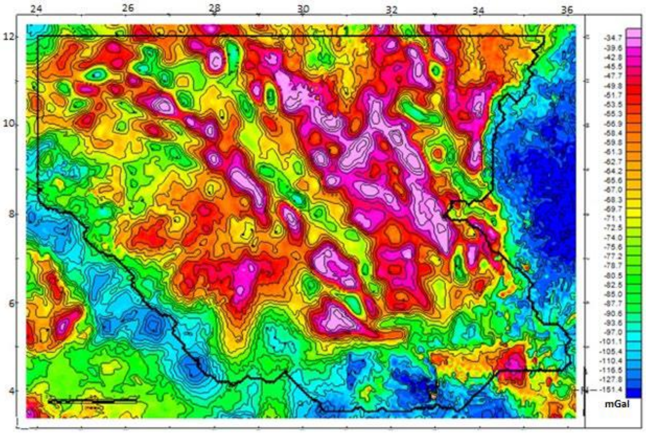

Figure 2. Complete Bouguer gravity map of the study area and vicinity produced from DNSC08 global gravity data.

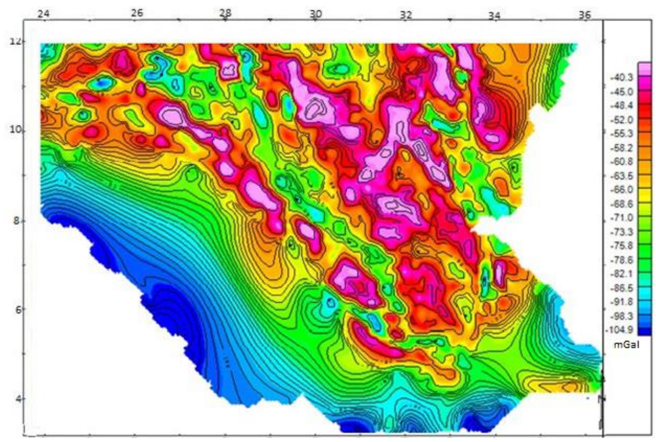

Figure 3. Bouguer anomaly map from data provided by Getech.

The two gravity datasets (satellite and ground) were compared in profile form with successive low-pass filters of 20, 50, 100, 150, 200, and 300 km wavelength. The profile in Figure 4 demonstrates wavelength content and fidelity of satellite data because it extends across both the Muglad (MG) and Melut (MT) rift basins. The results show that the low-pass filter with a wavelength > 20 km produced the best visual correlation between the two datasets, although a few shorter-wavelength feathers are displaced and there are very large regional differences (Figure 5).

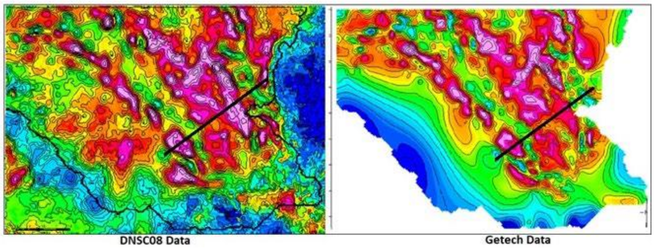

Figure 4. Location of profiles used for comparison of DNSC08 and Getech Bouguer anomaly gravity maps.

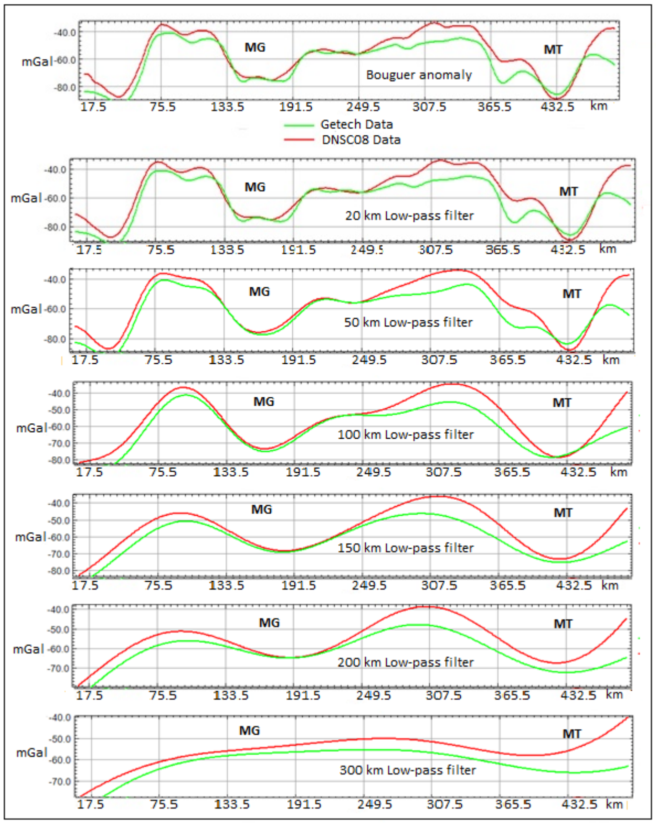

Figure 5. The profile in Figure 4 before and after application of successive low-pass filters.

4. Analysis of Gravity Data

The gravity data were analyzed by applying filters that are available in the Geosoft program. There are many methods to enhance potential field data; some are applied to the profile, whereas others are applied to gridded data. Each method has its advantages and disadvantages [2]. Generally, there is no single method for interpretation of potential field data, but some methods may be better suited to a particular case study than other methods, depending on the purpose and quality of the data.

The methods used in this study are horizontal gradient, tilt angle, and analytical signal. Theoretical and mathematical details of these methods can be found in the literature by authors including Roest and Pilkington (1992), Blakely (1996), Verduzco et al. (2004), and Nabighian et al. (2005). These interpretation methods were selected because of their capability of edge detection and depth determination of sources, such as

delineation of geologic structures, lithologic boundaries, rock intrusions, accretional boundaries, or tectonic lineaments that can be visually identified by edge-detection processing methods.

The horizontal gradient filter was applied to the gravity field data in the northeast- southwest direction with the aim of obtaining the expression of any of the major linear geologic structural patterns of the Precambrian basement and lithologic boundaries in the study area that are mostly trending northwest-southeast. Results using the horizontal gradient filter are shown in Figure 6.

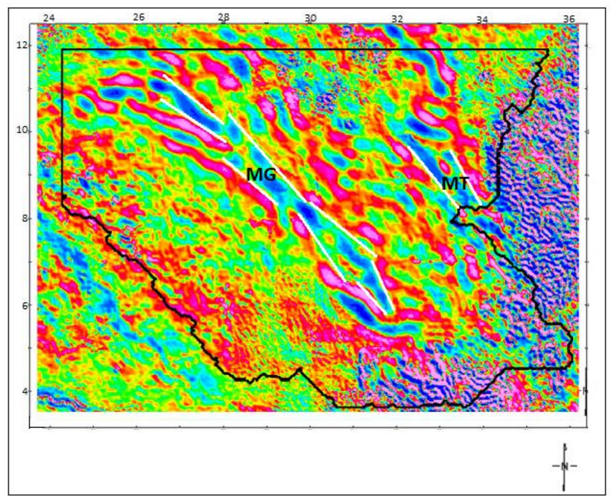

Figure 6. Horizontal gradient of Bouguer anomaly taken in the northeast-southwest direction showing northwest-trending geologic features (e.g., the Muglad and Melut rift basins).

The tilt-angle derivative filter displays the inverse tangent of the ratio of the first vertical derivative to the horizontal gradient [4] Zero contour of the tilt-angle derivative marks the edges of sources [5]. The filter was applied to highlight variations in geology and structure in the study area, as shown in Figure 7, which portrays clear northwest trends of blue and red features representing sedimentary basins and basement rocks, respectively. Figure 7 also shows a clear correlation between the tilt-angle derivative map and the rift basin index map, which illustrates that both the Muglad and Melut rift basins are composed of other smaller sedimentary sub-basins separated by basement ridges. Likewise, in various gravity maps of the study area there are high-gravity anomalies separating low-gravity anomalies corresponding to those ridges and sub-basins, respectively.

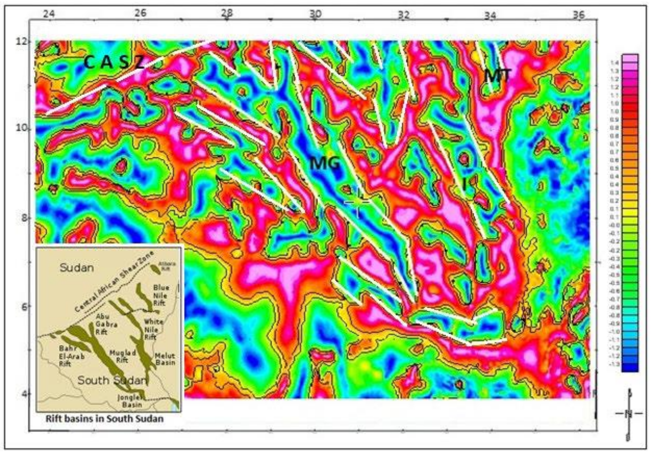

Figure 7. Tilt-angle derivative of the Bouguer anomaly map of the study area correlated with locations of rift basins in South Sudan and Sudan shown in the index map.

The analytic signal is also a derivative filter, which leads to suppression of low wavenumbers, and thereby delineates areas of basement high and deep basement. The advantage of this method is that its maxima occur directly over faults and contacts, regardless of the structural dip present [4] [6]. The application of the method on Bouguer anomaly (Figure 8) shows basement architecture with shallow basement (red colors) and deep basement (blue colors). The Muglad and Melut rift basins are shown (Figures 4, 5, and 6) and basin-margin fault structures are delineated as white lines.

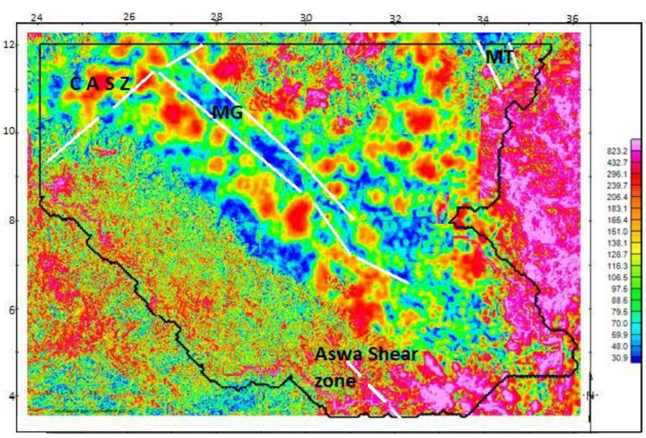

Figure 8. Basement topography determined from applying analytic signal to gravity data. Shallow basement areas are in shades of red and deeper parts are in shades of blue. Locations of the Central African Shear Zone (CASZ) and the Aswa Shear Zone are shown.

5. Interpretation of Gravity Data

Both gravity maps, Getech and DNSC08, depicted in Figure 4 reveal that a series of major northwest-trending linear gravity anomaly patterns dominates a large part of the study area, along with a few orthogonal northeastern trends that are discontinuous. The sedimentary basins (Muglad and Melut) are easily identified on both satellite and Getech maps by their negative gravity anomalies, which are oriented in the dominant trend of northwest-southeast. These basins are mainly separated by high-gravity anomalies of the same trend (Figures 2, 3, 4). The topography of the central part of the study area is almost uniformly low; consequently, alternating negative and positive gravity anomalies in combination with analytic signal variation suggests that the subsurface may have features such as horst and graben blocks, some of which have been detected by seismic surveys and confirmed by drilling in the oilfields [7] [8].

The basement complex units in South Sudan are shared with neighboring countries and contain a continental-size shear zone (Aswa), many sutures, accretionary structures, and reworked Proterozoic crust (Figure 9), all of which have potential for harboring minerals [9]. All these different rock units are revealed on gravity maps as variations in density, depending on their respective contrasts with the surrounding rocks.

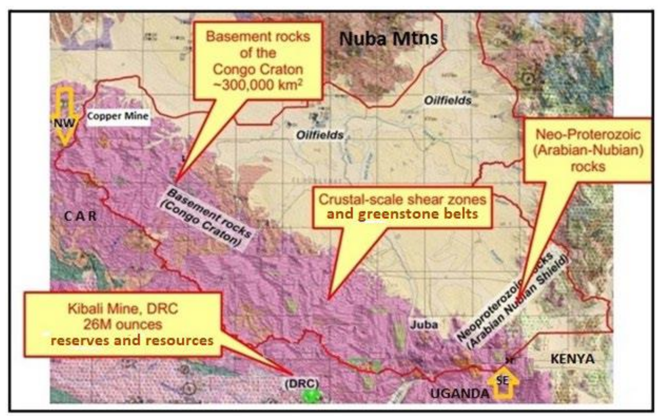

Figure 9. Precambrian basement geology and structural elements in South Sudan (after Equator Gold, 2015).

6. Discussion and Conclusion

Processing and interpretation of the satellite-derived gravity data for the purpose of mapping basement morphology can augment exploration, hence reducing risks by avoiding excessively deep ore zones and focusing on anomalous areas of intrusive rocks, contact metamorphism, and linear geologic structures.

DNSC08 gravity data augmented with EGM2008 free-air gravity anomalies over land were processed, and the resulting Bouguer anomaly map compares well with the Bouguer anomaly map from Getech data for the Sudan and South Sudan and thus can be used for interpretation of features with wavelengths > 20 km. The maps show major northwest-trending anomalies corresponding to the Muglad and Melut rift basins, which are separated by high-gravity anomalies of the same trend believed to represent shallow basement rocks in the form of horsts and grabens [10] [11] [12].

Analysis techniques including analytic signal, tilt angle, and horizontal gradients were applied to the data, and resulting maps revealed major rift basins with boundary structures, including faults (Figures 6–8).

Observations from the Gravity Field and Steady-State Ocean Circulation Explorer satellite observations have been utilized to map geologic units around the Congo Craton that was the nucleus of Gondwana; the craton has a thick lithosphere against which crustal deformation occurred [13].

The different geologic units in this region have been studied by Kadima et al. (2011) and results generally show that younger sedimentary units exhibit lower density and have an average density of 2.35 g/cm3 due to compaction. In comparison, metamorphic units, and magmatic units (e.g., basalts) have higher density in comparison to granites which have an average density of 2.65 g/cm3.

Figure 10 shows selected geologic units that are expected to generate variations in the bulk density in the region [14]. The most important geologic units that are shared by Congo, Uganda, and South Sudan have been numbered as unit 3 on Figure 10 and comprise sediments of east African rifts (e.g., the Muglad and Malut

Basins in South Sudan). Another unit, designated as 11 in Figure 10, is the Kibalian basement, comprising a greenstone belt with syn-tectonic granites, and some amphibolite outcrops (upper Precambrian), corresponding to the Precambrian basement trending northwest-southeast in the Republic of South Sudan.

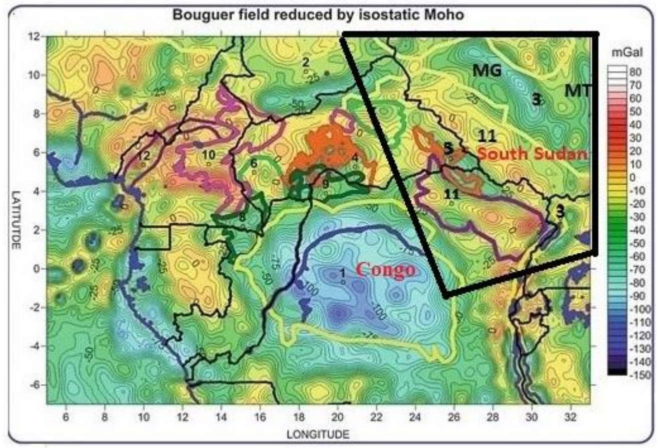

Figure 10. Comparison of the Bouguer field indicated by the Gravity Field and Steady-State Ocean Circulation Explorer satellite, reduced by isostatic Moho, to several of the geologic units from the UNESCO geologic map (Commission for the Geological Map of the World, 1990). The Muglad (MG) and Melut (MT) rift basins of South Sudan and the Kabilian basement unit (11), together with unit 3 representing East African Rift sediments, are identified. The shared area of rock units is marked by a black polygon. Other geologic units identified by numbers on the map are outside the region of interest. (After Braitenberg, 2012).

The lateral extent and considerable thickness of these basement rock units are related to major geologic and tectonic events during the evolution and accretion of the Congo Craton [15]; hence, such events contribute to the diversity in rock densities that are of prime importance in a gravity survey. The Bouguer field reduced by isostatic Moho shown in Figure 10 shows correlation of various gravity anomalies corresponding to different rock densities representing denser basements rocks—e.g., the Kabalian (high anomaly) and lighter basin sediments that occur in the Muglad and Melut Basins in South Sudan (low anomaly) [14]. “Isostacy” is the term used to describe a state of equilibrium between the Earth’s crust and the underlying mantle [16]. The isostatic correction of gravity anomaly removes the mass compensation of the topographic effects from Bouguer anomaly, assuming Airy isostasy, and allows the focus to be on intracrustal density variations. The remaining isostatic anomalies in the map after reduction of the Bouguer field by isostatic Moho suggest the presence of geologic features of anomalously high or low density relative to the surrounding crust and sediments, which in turn can be further interpreted by modelling [17] [18].

Similarly, the Republic of South Sudan can benefit from airborne surveys by embarking upon a program of geologic, geophysical, and geochemical mapping, which is critical for providing geologic information to be used in solving problems related to its natural resources and environmental and socioeconomic development issues.

The government has mandated that the Directorate of Geological Survey in the Ministry of Mining carry out such mapping programs. Academia, companies, and local and national governments should cooperate, however, in setting out short- and long-term programs, including setting priorities for geologic mapping at both local/state and national levels.

The Directorate of Geological Survey should collect all data, maps, and reports of South Sudan that are being kept in databases of the Republic of South Sudan, since it is now a sovereign state. The available information will constitute the basic data for future use in planning and exploitation of natural resources. In addition, the data could be used to assess and mitigate hazards, risks, and natural disasters.

Important questions concerning mapping are: What kind of mapping is a priority?

Why? Where? When? and How? Currently, much of the land has not been surveyed or mapped at all. So airborne surveys are cost- and time-effective and will provide the basic data needed for promotion of exploration activities in the republic. Priority areas should be where there are already clues of mineral potential, and most important, in areas where the security is stable. This will make fast-tracking of sustainable mineral development possible, to contribute to the nation's economic development. Such mapping programs can be successful through cooperation of specialized regional and international firms and institutions willing to undertake such projects by contracts or other mutually acceptable agreements. Execution of airborne geophysical surveys depends on regional infrastructure and overcoming limitations, including political instability and hazards.

Qualitative interpretation of satellite-derived Bouguer gravity data has aided mapping of the basement geology of South Sudan, and the results are consistent with the known oilfields and areas of Precambrian basement complexes. Consequently, the information would aid in identifying additional mineral prospective areas, where more detailed gravity, magnetic, electromagnetic, and seismic surveys can be carried out; the combination of these data will assist decision makers in matters related to land use, mineral titles, and exploration of natural resources.

This study has shown that regional geophysical mapping using satellite-derived gravity data is feasible for South Sudan, because data are available for free and processing and interpretation software is available. Information about regional gravity anomalies has been confirmed by the study, and geologic understanding of the region has improved; it has also helped demarcate priority areas for further detailed airborne geophysical mapping to help mineral exploration in the country.

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