GEOLOGICAL MAPPING IN ARID REGIONS OF AFRICA USING SATELLITE DATA - INTEGRATION OF VISUAL AND DIGITAL TECHNIQUES

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ABSTRACT

Landsat-MSS data were used for preparing a geological map of entire Egypt at a scale of 1 : 500 000 in 20 sheets. This endeavor comprised production of optimized imagery for visual interpretation and field checks, as well as creation of digital mosaics of the whole country for base maps. Geometric control points were obtained during geologic field work from Transit satellites. Landsat-TM data, utilized in a present project in northeastern Sudan, provide improved spectral discrimination and higher spatial resolution. Color-ratio imagery is used for detection of gossans and gold-bearing quartz veins. Satellite, field, and elevation data are input into a GIS together with geophysical and petrologic data. Classification of lithology and subsequent map production is significantly improved by the integration of these information levels.

1. INTRODUCTION

Since the launch of ERTS-1 opened "a new window on our planet" (Williams & Carter, 1976) in July, 1972, geologists have made extensive use of the geometric and thematic information provided by the digital image data of Landsat MSS and TM. Landsat MSS data with their coarser resolution are a good choice for regional geologic analysis, both for structural as well as for lithologic investigations. TM data, on the other hand, provide improved information on spectral anomalies and smaller terrain features. From the beginnings of remote sensing, visual interpretation techniques familiar from "photogeology" were used for deriving information from the image data. With the growth in computer power and availability during the last decade, digital data processing significantly increased the quality of image representation, classification and geometric accuracy. In this way, remotely sensed data can be operationally employed for regional geologic mapping and exploration, especially in arid and little explored areas.

2. MAPPING IN EGYPT

After preliminary studies on applications of early Landsat-1 imagery to small-scale geologic interpretation in the Tibesti Mountains, Chad, resulting in a satellite interpretation map (List, Roland & Helmcke, 1974; List, Helmcke, Meißner et al., 1978), a pilot project was started in Egypt using standard image interpretation methods for preparing a first geologic map of southwestern Egypt at 1 : 500 000 scale (List et al., 1982, 1984). In this project, the image data used for interpretation were MSS standard products in the form of photographic data.

Any interpreter who has worked with these early standard products has made the experience that the image quality was not really good enough for proper identification of geologic details or minor spectral differences in lithology. Also the image geometry was not up to map standards even at small scales.

Thus in 1981 a mapping project was started in cooperation with CONOCO with the intention to produce a geologic map of entire Egypt at 1 : 500 000 that would conform to international mapping standards. The map was to consist of 20 sheets covering an area of 2° by 3° each. The following objectives were set for the final map:

- To produce geometrically corrected digital mosaics as a map base guaranteeing topographic accuracy;
- To adopt a format of the map sheets conforming to the international World Map grid;
- To carry out adequate field work to be able to properly classify and correlate the sedimentary and basement rocks;
- To perform the geologic interpretation and compilation on high-quality color composite imagery for best results; and
- To complete the entire project possibly within 6 years.

2.1 Geologic setting and map philosophy

Egypt is an arid country with an area of more than 1 million km² (see fig. 1). Only 3% of the land surface, namely the Nile valley and the Delta, are covered by vegetation.

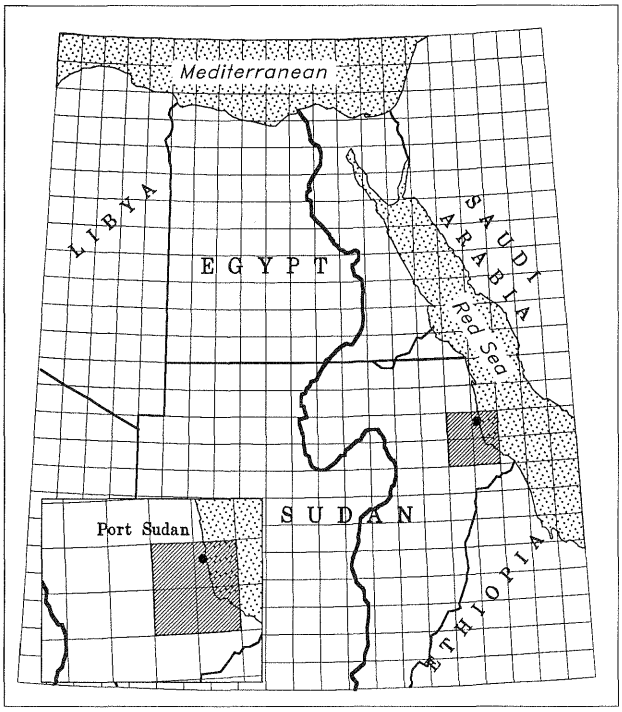


Fig. 1: Sketch map showing Egypt and the actual study area in Sudan.

While this lack of vegetation cover facilitates the use of remotely sensed data, the fact that about two thirds of the country are made up of rather flat-lying sedimentary rocks, thus permitting the extrapolation of field data to larger areas by satellite image interpretation, is more important in this context. The basement rocks in the Eastern Desert along the Red Sea, on the other hand, required a considerably higher percentage of field work due to the more irregular way the lithologic units of the basement complex are distributed.

Normally the production of a small-scale map is the final step in a long and tedious process working in a "bottom-up" manner by compilation of a great number of already existing large-scale maps. Thus the final small-scale map is a generalized version of many mosaic-like pieces of detailed maps.

In the present project, however, detailed large-scale maps were not available for most of the country. Consequently, a "top-down" approach had to be used. This meant that basically small-scale data had to be used throughout the mapping, and that the extent of field and laboratory work was guided by question of just how much detail could be shown at the final map scale (List, Meißner & Pöhlmann, 1989).

In order to meet the objectives lined out above, a two-way approach was used. One line of work was the collection of geologic information from image interpretation and field work, for which optimized color composites without geometric corrections were utilized, and the preparation of the final map. The second line was the preparation of a semi-controlled image map in 80 sheets at a scale of 1 : 250 000. This product was to serve as "work sheets" on an intermediate level in want of any available maps with sufficient detail.

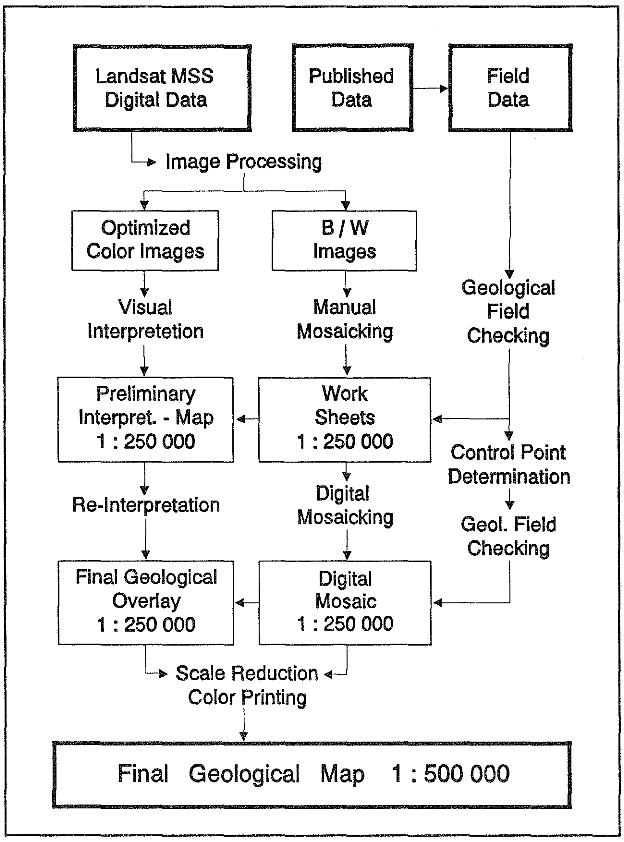


Fig. 2: Simplified flow diagram for the preparation of the 1 : 500 000 scale Geological Map of Egypt.

2.2 Image processing and interpretation

Remotely sensed data provide information on objects of the earth's surface, based on sensor characteristics and their spectral reflectance properties. Lithologic differentiation by means of Landsat MSS data is not very satisfactory due to their limited spectral resolution. Therefore, digital classification rarely gives satisfactory results when applied to geology. Visual interpretation, while rather tedious and difficult, is still the best tool in the hands of an experienced interpreter. It can take into account not only spectral but also textural properties of image segments and, what is even more important, can make full use of the "expert knowledge" in the interpreter's mind.

A prerequisite for successful visual interpretation is, of course, imagery that is geared to the interpreter's needs. Such imagery can be derived from digital data by means of image processing. In the present case it was aimed at obtaining "optimized" color imagery from early Landsat MSS data by noise removal, histogram stretching and mild edge-enhancement filtering. Interpretation itself was performed on 1 : 250 000 color transparencies using light tables and clear overlays for annotations. The film transparencies were prepared by photographic enlargement from color composite masters, plotted on an Optronics Colorwrite film plotter.

2.3 Preparing the map base

As mentioned, one of the objectives of the final map was that its topographic accuracy should conform to international map standards. That meant that digital mosaics would have to be created, requiring an appropriate number of control points identifiable in the imagery. Since such mosaics could only be prepared toward the of the project, an intermediate level in the preparation of the final map was introduced.

To this end, a map at the scale of 1 : 250 000, comprising 80 "work sheets", was prepared from black-and-white MSS images. Uncorrected imagery was used for generating a semi-controlled image mosaic with an overlay of existing topographic information from published maps and field surveys, e.g. for new roads or settlements. These work sheets also served as a base for field work and compilation of interpretation data.

2.4 Field and laboratory work

Due to the remoteness of most of the area, field work had to be planned and executed in an expedition-like style. A major consideration was to conduct the field trips in the most effective way possible. Small field parties typically consisting of a team of 2 to 4 four geologists and a mechanic were set up, using two or three four-wheel drive vehicles and a sturdy field truck carrying fuel and water. Duration of field trips was 3 to 6 weeks. Since no base camps were made and only flying camps were used at night, large areas could be covered during these trips and a considerable amount of information gathered in a short time.

Rock and stratigraphic samples were collected for subsequent laboratory analysis. All in all, the results of over 200 man months of field work were input into the map. Part of the field work was carried out by post-graduate students of the Free University and the Technical University of Berlin under a research project (Sfb 69) funded by the German Research Foundation.

For orientation in the field, color enlargements of the Landsat MSS data at 1 : 250 000 were used, together with the work sheets at the same scale (see 2.3). The preliminary interpretation of the geology that was performed in the laboratory prior to the field trips was checked against the field evidence and, whenever necessary, corrected. This ground truth was subsequently used for re-interpretation of the imagery also making use of the results of the laboratory analyses; if necessary, the entire process was repeated.

During geologic field work control points for the ensuing geometric correction and mosaicking were determined in the field. This was done by means of satellite receivers using the Transit navigational satellites. The receivers were set up at nightfall at predetermined locations. In the morning, the position of the selected landmark selected could be read from the receiver. Accuracy (1 σ standard deviation) for control point measurement was typically around 5 m, more than sufficient for the 80 by 80 m pixels of Landsat MSS.

2.5 Production of the final map

The completion of the final map involved three steps: Preparation of a digital base map, preparation of the geologic overlay, and color printing.

As a base map for presentation of the geologic information digital image mosaics were created for each 1 : 500 000 scale map sheet. Using ground control points measured during geologic field work (see 2.4), the Landsat MSS data were georeferenced and mosaicked. After radiometric corrections for removal of brightness differences between the individual frames, digital image mosaics were produced as a basis for the 20 map sheets. Each mosaic typically consisted of 9 Landsat frames. For the entire map covering more than 1 million km², over 80 Landsat frames were georeferenced, radiometrically corrected and mosaicked together. The positional accuracy of the mosaics was within 100 and 150 m RMS, which is quite satisfactory for a 1 : 500 000 scale map.

The geologic information was primarily gathered from visual interpretation of optimized color images, enlarged as color film transparencies to a scale of 1 : 250 000, the scale of the work sheets (see 2.3). Using transparent overlays and light tables for interpretation, all relevant geologic features like lithologic units and their boundaries, faults and fractures were annotated on these overlays. As already mentioned, compilations of the interpretation were taken to the field, checked, and corrected. Using this field evidence and laboratory results, the image data were re-interpreted until a reliable and unambiguous picture of the geology emerged.

The final interpretation was then transferred to the image mosaics for each sheet, equally enlarged to the scale of 1 : 250 000. Since the mosaics contained enough physiographic information, this transfer could be accomplished in a highly accurate way. The resulting geometrically corrected line map was then reduced to the final 1 : 500 000 scale.

From this product, the color printing plates were produced. Since offset printing was used, the more than 130 different colors representing the lithologic units could be created from three screened printing plates for cyan, magenta and yellow, greatly simlifiying the printing process. More details can be found in List, Meißner & Pöhlmann (1989). The published map in 20 sheets, each one covering an area of 2 x 3°, are available through Egyptian General Petroleum Corporation, Cairo, Egypt.

2.6 Conclusions from the mapping project

The production of a fairly detailed geologic map of an entire country of considerable size at the scale of 1 : 500 000 proves the operational applicability of remote sensing for project of this size. The project took about 7 years to complete, not counting three years for a preceding pilot project for producing a preliminary geologic interpretation map at the same scale (List et al., 1978, 1982).

Landsat MSS data, if limited in terms of spectral and spatial resolution, proved sufficiently accurate for providing the basis for a small-scale map of this type. Since the time the project was begun more than 10 years ago, enormous progress has been made in digital processing techniques as well as in sensor technology. Today, it would be an interesting question if the considerably higher cost of data acquisition and processing for Landsat TM imagery would not be offset by savings in interpretation and field time.

It is obvious that this project involving more than 200 man months of field work could not have been executed by means of remote sensing techniques alone. It is equally obvious, however, that it could never have been finished within the time frame and the funds availabale without making extensive use of satellite data and digital image processing.

3 MAPPING IN SUDAN

Based on the experiences described above, geologic work in Sudan was started in cooperation with the Geological Research Authority of Sudan (GRAS) in late 1990 under a Special Research Project (Sfb 69), funded by the German Research foundation. While these research activities encompass the entire northern part of Sudan, the project described here is mostly concerned with the basement area of the Red Sea Hills, west and southwest of the town of Port Sudan.

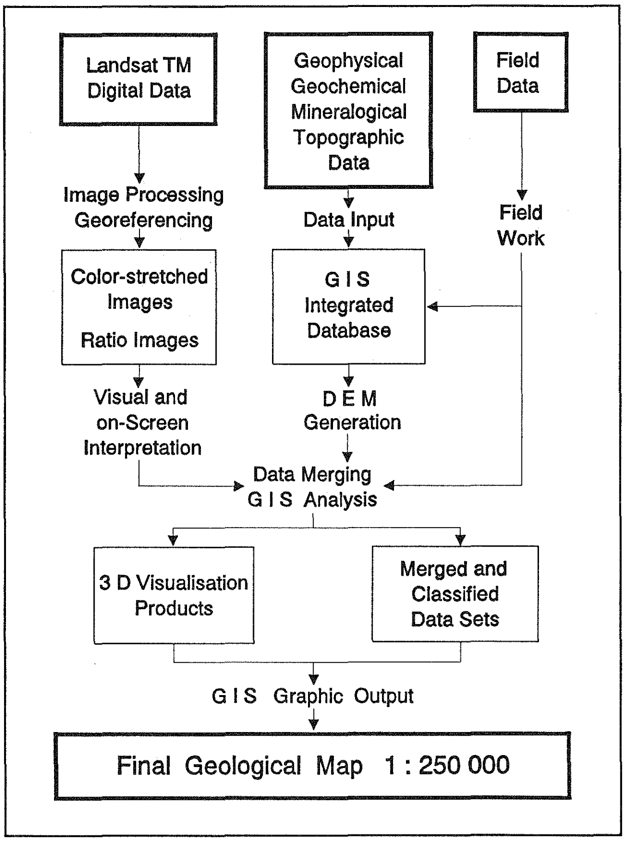


Fig. 3: Simplified flow diagram for the preparation of the 1 : 250 000 scale pilot map sheets of Sudan.

The emphasis of the project is on the application of Landsat TM data to geologic and mineral exploration in the basement rocks, taking advantage of their higher spectral and spatial resolution. Color-stretching by band decorrelation (Gillespie et al., 1986; Haydn, 1982) and color-coded ratio images (Gillespie et al., 1987; Sabins, 1985) provide considerably better image products for visual image interpretation.

In addition, the gain in geologic information by using GIS technology for the integration of digital terrain models, geophysical, geochemical and petrographic data in addition to visual interpretation and field work is being studied. The project is still going on and thus only some interim results can be presented here. One of the objectives of the study is mapping but only a few 1 : 250 000 sheets are planned as a pilot map based on remote sensing and GIS technology.

3.1 Geologic setting

The study area (see fig. 1) is part of the Arabian-Nubian shield and includes the Ariab/Oshib-Nakasib structural zone. It is characterized by major suture zones and related ophiolites (Stern et al., 1989). There is an assemblage of three major SW-NE-striking units, the Oshib ultramafic complex, the Ariab-Arbaat volcano-sedimentary series, and the Awat-Asoteriba volcanic series, all metamorphosed in the greenschist facies. These units are intruded by different generations of granitic plutons. Of special interest in this area are mineral deposits of massive sulfide ores and gold-bearing quartz-barite layers, associated with the shear zones (Cottard et al., 1986).

Due to the arid climate, the rocks are well exposed throughout the area, if covered by desert varnish and weathering crusts. The relief is in the order of 1000 m or more.

3.2 Visualization of data

Visual interpretation of image data relies heavily on the quality of the imagery. Therefore, visualization of information contained in the imagery is of paramount importance. The improved spectral and spatial resolution of Landsat TM data as compared to MSS permits the creation of significantly improved imagery, resulting in higher detail and better reliability of interpretation products. Especially the combination of different visualization techniques can provide impressive geologic information not available from earlier satellite data.

3.2.1 Color contrast stretch

The representation of the information contained in the various spectral bands of a TM image can be achieved in a simple and easily interpretable way by creating a color composite image, in which 3 bands are color-coded in red, green and blue, respectively. Due to the high correlation among the individual bands, a major percentage of the colors of such a three-color combination produces black resp. gray. This leads to a rather smudged appearance of the color image and low color saturation. A transformation of the red, green and blue colors in the so-called RGB color space into an intensity, hue, and saturation (IHS) space allows decorrelation of the three source bands and stretching of color saturation (Haydn et al., 1982, Gillespie et al., 1986). After re-transformation into the RGB color space an image with much higher color saturation is obtained that renders more information for the interpreter. The usefulness of such "spectral maps" (Kaufmann & Schweinfurth, 1986) in geology is well established.

In the present project, spectral bands 7, 4, 1 coded R, G, B, respectively were selected. In this instance, this combination provided better results than the usual combination of bands 7, 3, and 1. Saturation was stretched with a factor of 2 during transformation.

3.2.2 Combination of image data with a DEM

In the interpretation of aerial photographs - photogeology -, the fact that a threedimensional image is being interpreted greatly improves the process of information extraction. With the exception of stereo SPOT imagery with tilted look directions, height information from satellite stereoscopic imagery is generally unsatisfactory due to the unfavorable ratio of stereo base to sensor altitude. A combination of the satellite image with a digital elevation model (DEM) can partly offset this disadvantage.

To this end, existing topographic maps at a scale of 1 : 100 000 with 25 m contour lines were digitized, and a DEM with a cell size of 30 by 30 m, corresponding to the pixel size of the Landsat TM image, was generated under ARC/INFO. The georeferenced TM image, color-stretched by the process described above, was then draped over the DEM using the Terra-Mar MicroImage processing system, resulting in a rather graphic representation of the landscape and the spectral reflectance properties of the individual lithologic units, as shown in fig. 4 on the color plate.

3.3.3 Color-ratio imagery

As mentioned, the Ariab district contains mineral deposits of polymetallic sulfide ores, as well as several gold occurrences in quartz-barite layers, some of which are economically interesting (e.g. the Hassai gold mine).

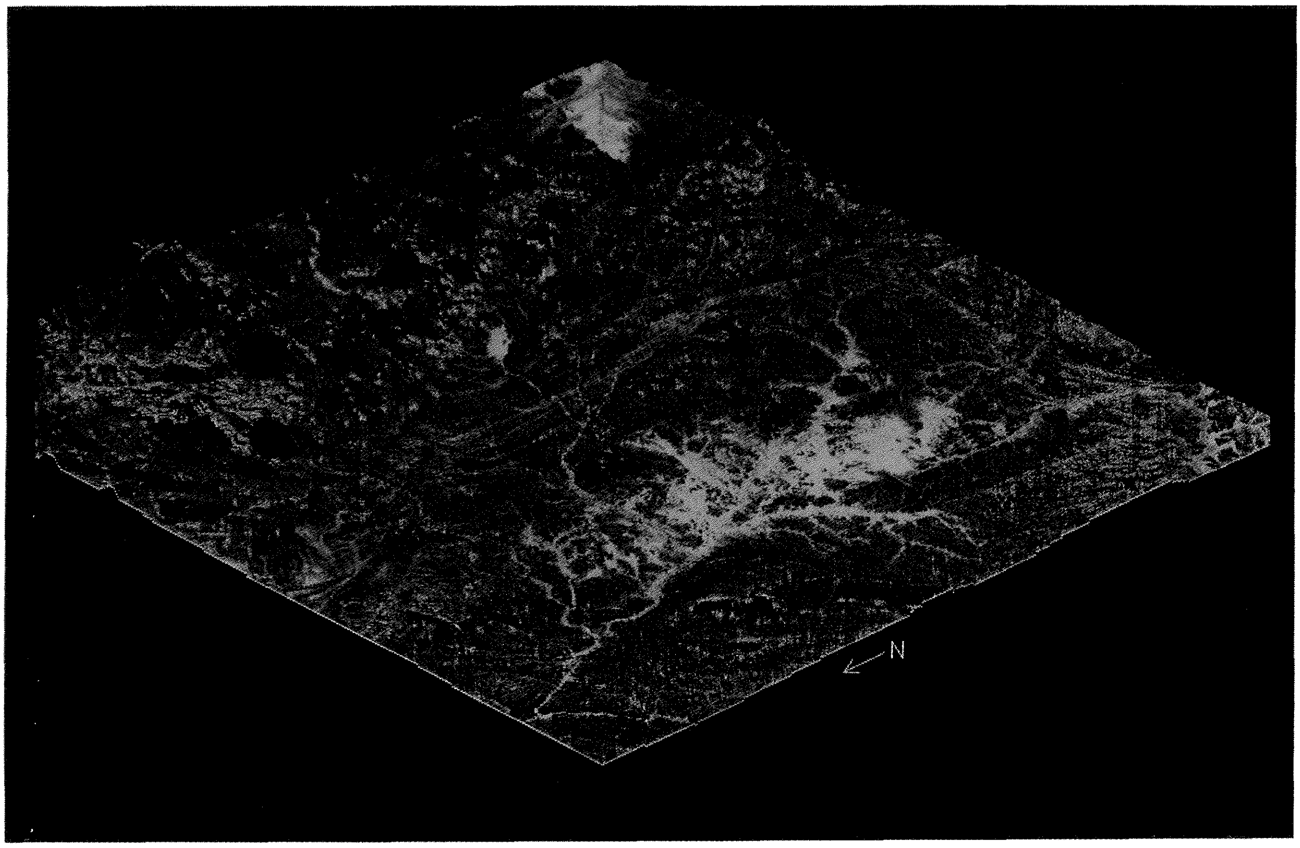
For a subset of Landsat TM scene 172-047, acquisition date January 1, 1989, a color ratio-image was created for enhancement of gossans associated with the sulfide bodies. In a modification of a ratio combination found useful by Sultan et al. (1987) in similar geologic settings, band ratios 5/7, 5/1, and the product of 5/4 x 5/3 were used and coded with red, green and blue. Subsequently, the three bands were transformed into the IHS color space where saturation was stretched by a factor of 2. For intensity, the original band 7 was substituted and the resulting image transformed back into RGB space. In this combination, gossans are clearly visible, showing a distinctive red color (fig. 5, on the color plate).

Comparing the resulting map to occurrences known from field studies executed by the French BRGM, it turned out that all gossans identified in the field were also highlighted on the ratio image. In addition to the already known occurrences, a number of new ones was detected on the image and subsequently verified in the field.

3.3.4 Visualization of geophysical data

Geophysical data of the study area are available in the form of small-scale maps. Even if these data are not detailed enough to significantly contribute to the interpretation of the geology at larger scales as shown in figs. 4 and 7, they are very valuable for the 1 : 250 000 scale geological maps the production of which is planned.

The existing geophysical data are Bouguer gravity maps and aeromagnetic maps at a scale of 1 : 500 000. Geocoded 3D surfaces were created from these maps by digitizing the isolines and generating 3D models.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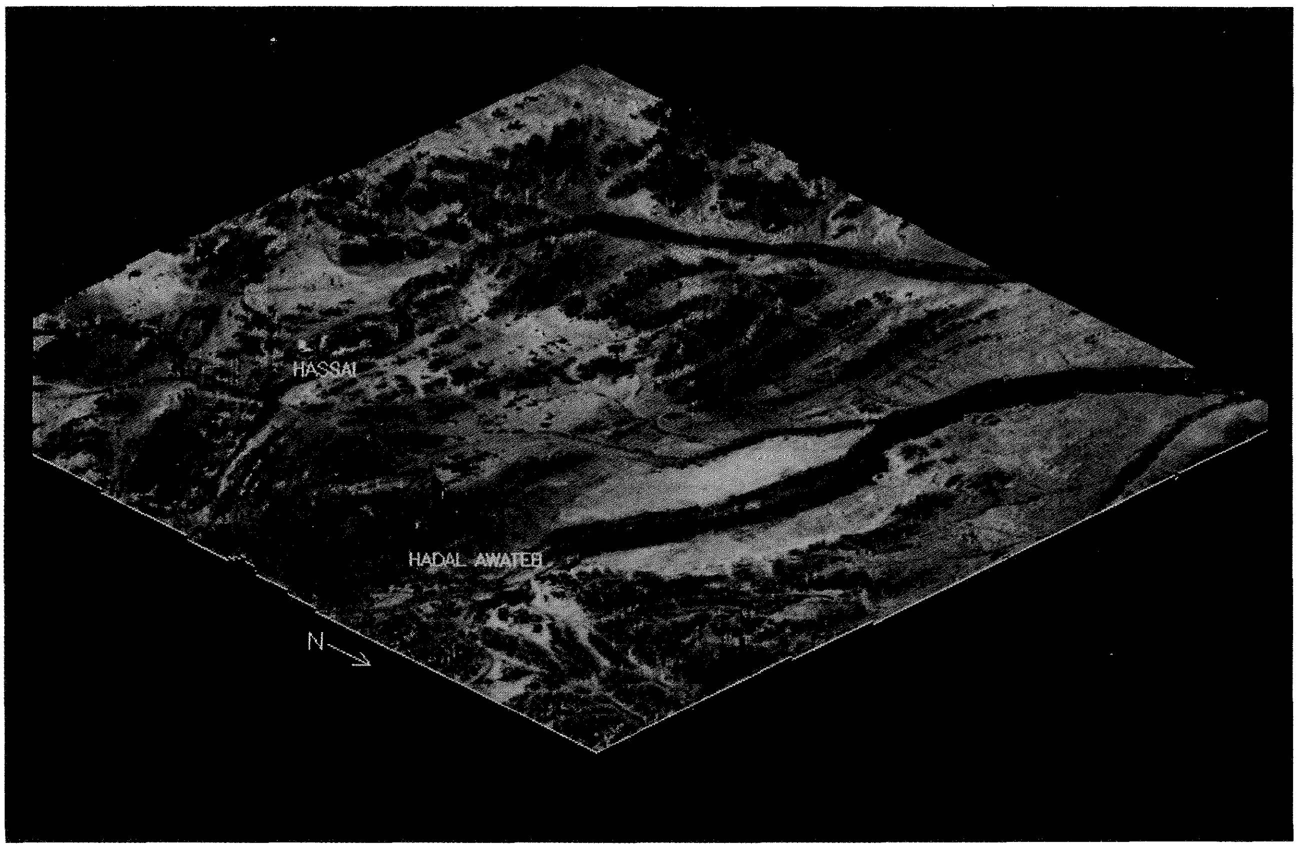
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An example of a 3D model of the aeromagnetic ΔT anomalies is shown in fig 6. Block size corresponds to the 1 : 250 000 sheet Port Sudan, 1° x 1°30'; look direction is toward NE. The low ΔT values corresponding to a major SW-NE striking suture line, separating metavolcanics and metasediments in the north from volcanic rocks in the south, are clearly visible. The Wadi Amur area, shown in detail in fig. 8, is situated in the southwestern corner of the block. All in all, the geophysical data provide valuable information for small scale geologic studies, like for the planned 1 : 250 000 scale geological maps. Due to the coarse sampling grid they are less suited for information extraction at larger scales.

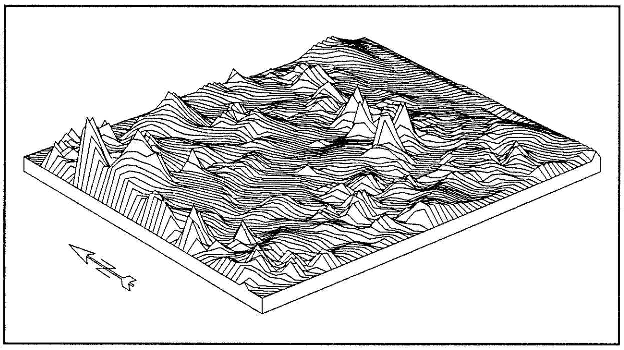

Fig. 6: 3D model of aeromagnetic ΔT anomalies of the area W of Port Sudan. Block size is 1° x 1° 30'.

3.3.5 Geochemical and mineralogical data

Samples for geochemical analysis were taken along a 25 km cross-section in the Ariab-Arbaat volcano-sedimentary series, using a 500 m grid. Several element combinations were plotted against the geology, showing good correlation of geology and geochemistry. More data will be needed in order to construct a meaningful picture of element distribution since the interpolation between the sample points in the GIS leads to incorrect values .

Thin-section petrology of rocks is also recorded in the GIS. It is essential, among other things, for judging abnormal values in the geochemistry and for selecting additional sampling points for ensuing field work.

3.3.6 Additional information sources

Texture plays an important role in visual interpretation of geologic features. Digital texture classification is also viable; however, due to inherent problems (window size versus boundary definition) the results are better suited to classification of larger areas. Small features, even with pronounced textures, are suppressed. Texture analysis was performed on a TM band 4 image by means of a 9 x 9 variance filter on the Terra-Mar MicroImage system. The resulting image was median-filtered and interpreted visually (fig. 7). The major lithologic units correspond to the ones seen in the geologic interpretation map (see fig. 8).

Interpretation of aerial photographs is being used in conjunction with the interpretation of satellite data. The scale of the photographs is in the order of 1 : 70 000. There are some areas close to the Red Sea coast that are blanketed by clouds on the TM image. Here the aerial photographs provide a means of extending the interpretation from the cloud-free parts of the TM image into the cloud-covered region. Since the b/w photographs contain very little spectral information, cloud-free Landsat MSS data were used for additional information and for interfacing the photographic interpretation to the rock units discriminated on the satellite imagery.

Due to the central perspective of the aerial photographs, the interpretation data obtained from them are subject to radial distortion and changes in scale caused by relief. For transforming these data into a proper geocoded format, a photogrammetric 3rd-order stereoplotter (ZEISS Stereotop) was used. Control points were taken from existing topographic maps at a scale of 1 : 100 000. In this way, all lines were transformed to map projection and subsequently digitized for merging with the other geocoded data.

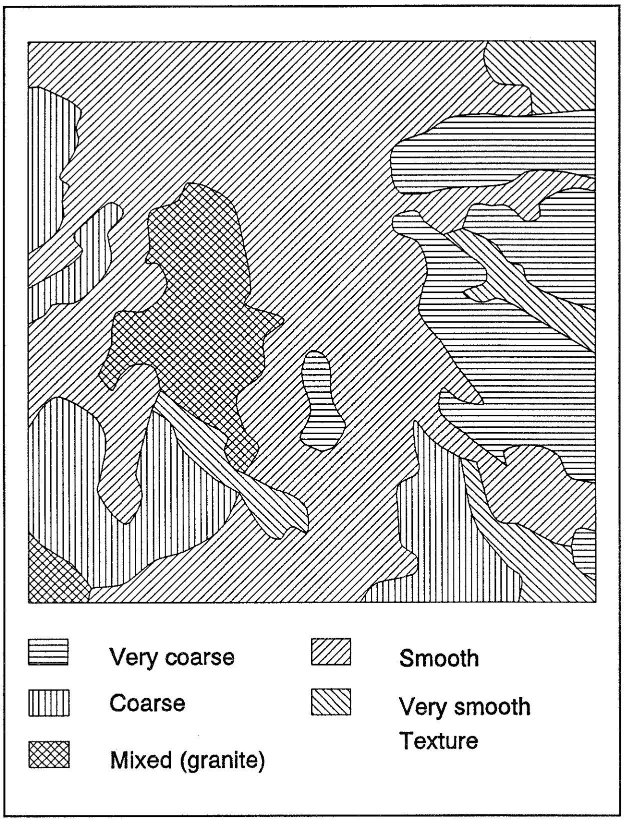

Fig. 7: Interpretation of a texture classification of TM band 4 data of the Wadi Amur area; block size is 30 x 30 km².

The TM data were also subjected to principal component transformation. The resulting imagery was found to convey less information to the interpreter than the ratio imagery described above. Therefore, PCA imagery was not further used for interpretation.

Not surprisingly, similar results were obtained from digital classification by the maximum likelihood algorithm. In the end, the classified imagery provided less information than what was obtained from visual interpretation. This, of course, holds true only with respect to the discrimination of regional geologic features, like the subdivision of different types of metamorphic rocks or intrusives. When it comes to the detection of local spectral anomalies, like gossans or hydrothermally altered outcrops, digital classification does indeed point out such anomalies in a reliable and consistent way.

During the progress of the work, the results of detailed geologic field surveys carried out by Sudanese geologists prior to our own field work became available. This valuable information, complementing the data collected during the limited time spent in the field by the authors, will be used to strengthen the existing knowledge base for the final map.

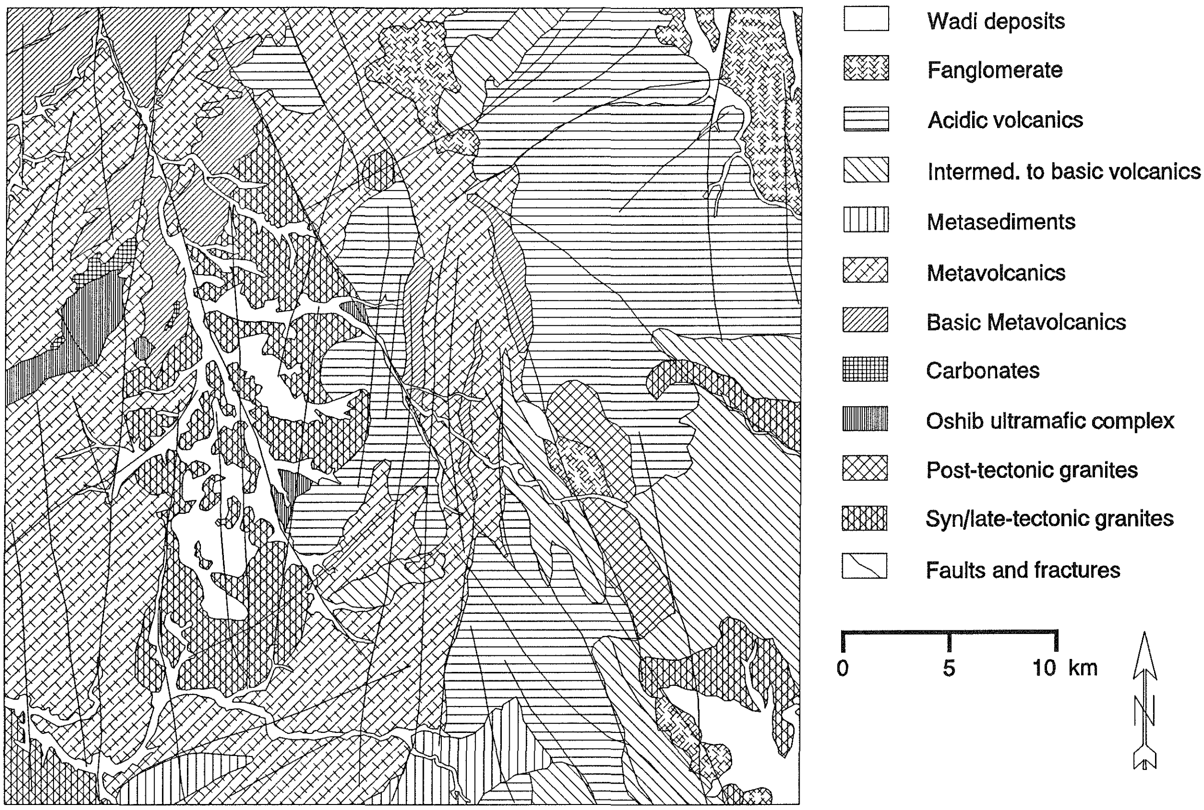

Fig. 8: Geology of Wadi Amur area from visual interpretation of satellite data, aerial photography, and field studies; block size is 30 x 30 km², corresponding to the area shown in figs. 4, 5, and 7.

4 CONCLUSIONS

A VAX-based geographic information system (ARC/INFO) together with a PC-based system (Atlas*GIS) is being used in the preparation of the geologic map of northeastern Sudan and for handling the considerable amount of data; a facility that was not available during the mapping project in Egypt. The use of Landsat TM data and of a GIS for geologic mapping offers considerable advantages in many stages of the mapping process:

- The superior information content of Landsat TM data in comparison to MSS is obvious. The interpretation becomes easier and the results are more reliable; the amount of expensive field work can be reduced.
- Using a GIS, part of the visual interpretation can be performed directly on the screen. This makes the use of different images for interpretation, like color-stretched and color ratio images, rather uncomplicated; the results of the interpretation of one data set can equally be used on the other set. In addition, any interpretation data from image overlays can be digitized and merged in the GIS data base.
- Storage and retrieval of all relevant data, from field measurements of structural features to petrographic and geochemical analyses, is greatly simplified. Essential information can thus be accessed and used during interpretation.
- The resulting map can be corrected and upgraded as the work proceeds. Output of intermediate map products by the GIS at different scales (e.g. fig. 8) is uncomplicated, and "maps on demand" can be delivered at any time.
- The various information levels held in the GIS can be used for classification by logic combination of different data sets. In this way, classification can take into account more than just spectral or textural data.
- The final map can be produced quickly and economically by proceeding in a straight line from digital data created by the GIS to a raster plotter, directly obtaining screened plots for printing. No manual cartographic work is necessary for the time-consuming creation of the screened color printing plates.

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