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Reconnaissance Geomorphologic Mapping of the Sahl Al Matran Area, Saudi Arabia, on the Basis of Remote Sensing Data

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ABSTRACT. This study demonstrates the applicability of remote sensing methods for geomorphological investigations of an area within Sahl Al Matran Quadrangle, Northwestern Saudi Arabia including the city of Al Ula.

The contribution presents details of the methodological approach which served to elaborate the data bases, process, analyze and evaluate the data in terms of geomorphology. Geomorphologic classification system is elaborated and used for interpretation mapping of landforms and the results are supported by multidirectional photographs.

This study was undertaken in a scale of 1:100,000, focus being on the provision of synoptic rather than on detailed results.

Introduction

A fundamental prerequisite for natural resource development, terrain evaluation, land use planning, and resource utilization of a country is a thorough knowledge of its geology and geomorphology (Klimaszewski, 1979). For the Kingdom of Saudi Arabia, such a framework is either not or poorly constructed. Studies related to geomorphology of the Arabian Peninsula are rather limited; moreover, they are either very general (*e.g.* Brown, 1960; Saad and Zotl, 1978; Jado and Zotl, 1984) or addressing a very restricted but specialized field (*e.g.* Alwash *et al.*, 1986; MOAW, 1983; MOAW, 1985, USGS 1972) or covering a very limited local area (*e.g.* Zaidi, 1983).

The delineation of geomorphological features for large regions by conventional field methods is laborious and time-consuming (Easterbrook, 1969). On the other hand, the same task can be performed rapidly and at much lower cost by applying well established image analysis techniques to satellite remote sensing data. Additionally, many geomorphological features are of regional scale, and hence are better visualized and mapped by analyzing synoptic data sets than by analyzing local field data (Verstappen, 1977).

To achieve the geoscientific objectives, the proposed work has been divided into the following 7 principal tasks :

1. Data acquisition and review of existing literature;
2. Empirical selection and adaption of algorithms for the digital processing of satellite data;
3. Generation of a satellite image in photographic format in the scale of 1:100,000;
4. Visual delineation of the morphological features using the satellite image, aerial photographs in the scale of approximately 1:60,000 and a photomosaic, scale 1:100,000;
5. Field verification and validation;
6. Geoscientific analysis of the maps based on remotely-sensed data to assess the region's geomorphic framework;
7. Cartographic elaboration by adding further existing geographic information (infrastructure, geographic grid, geographic locations *e.g.* mountains, wadis, localities, etc.), offset printing of the satellite image in combination with the interpretation.

Location of the Investigation Site and Available Remote Sensing Data

The study area is situated in the North-Western part of the Hijaz region of Saudi Arabia extending between latitude 26°07′N and 26°38′N and longitude 37°36′E and 38°13′E. It is located in the Western part of the geological map of Sahl Al Matran Quadrangle, Sheet 26 C, compiled by Hadley (1987). The location and index maps of Sahl Al Matran Quadrangle and the study area are presented in Fig. 1.

The study area is covered by the two Thematic Mapper scenes path 172/row 42 and path 171/row 42 ordered from EOSAT, CCT's acquisition date February 9, 1991 (171/42) and January 1, 1989 (172/42), Fig. 2. This selection had to be done considering: the necessary combination of the two scenes for covering the whole study site; the required similar illumination conditions and superficial reflection characteristics and the good atmospheric transmission in Saudi Arabia due to relatively low temperatures and connected little atmospheric moisture. Universal Transverse Mercator, UTM projection was chosen for geometric correction of the data. This processing provides an accuracy similar to topographic maps up to scale 1:50,000.

The black and white available aerial photographs dated back to the year 1957 had a scale of approximately 1:60,000 and were flown with an overlap of 60%. The de-

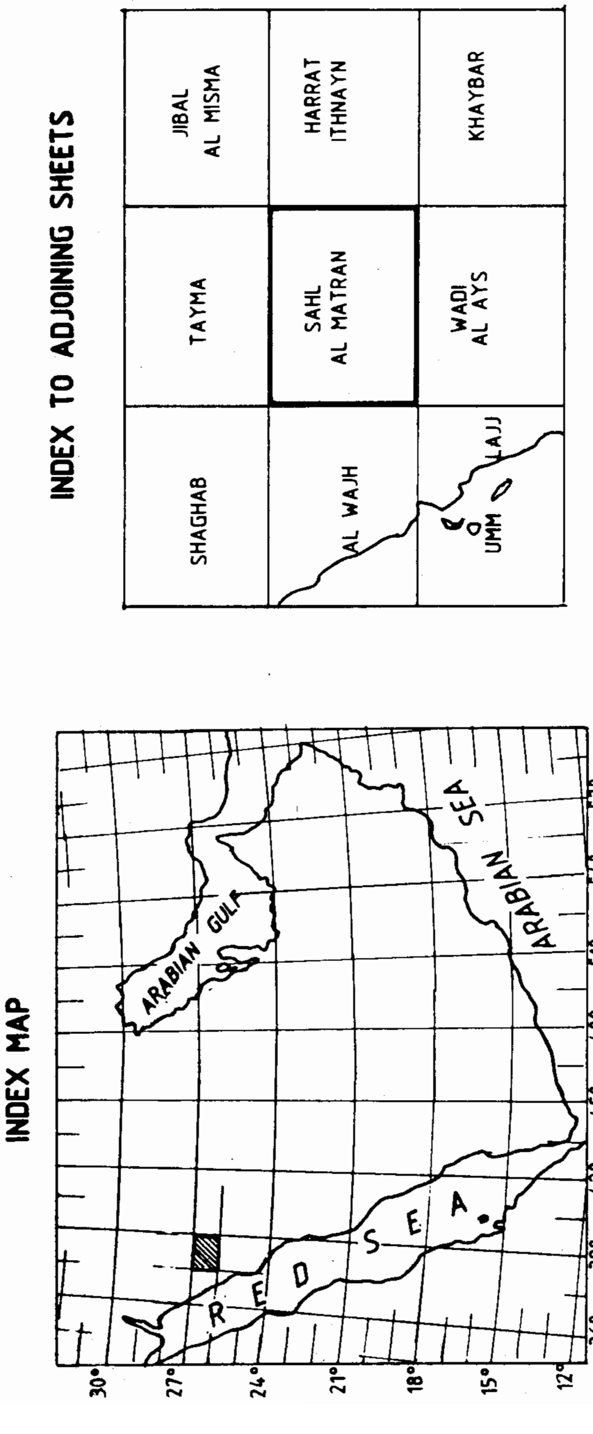

FIG. 1. Location of test area.

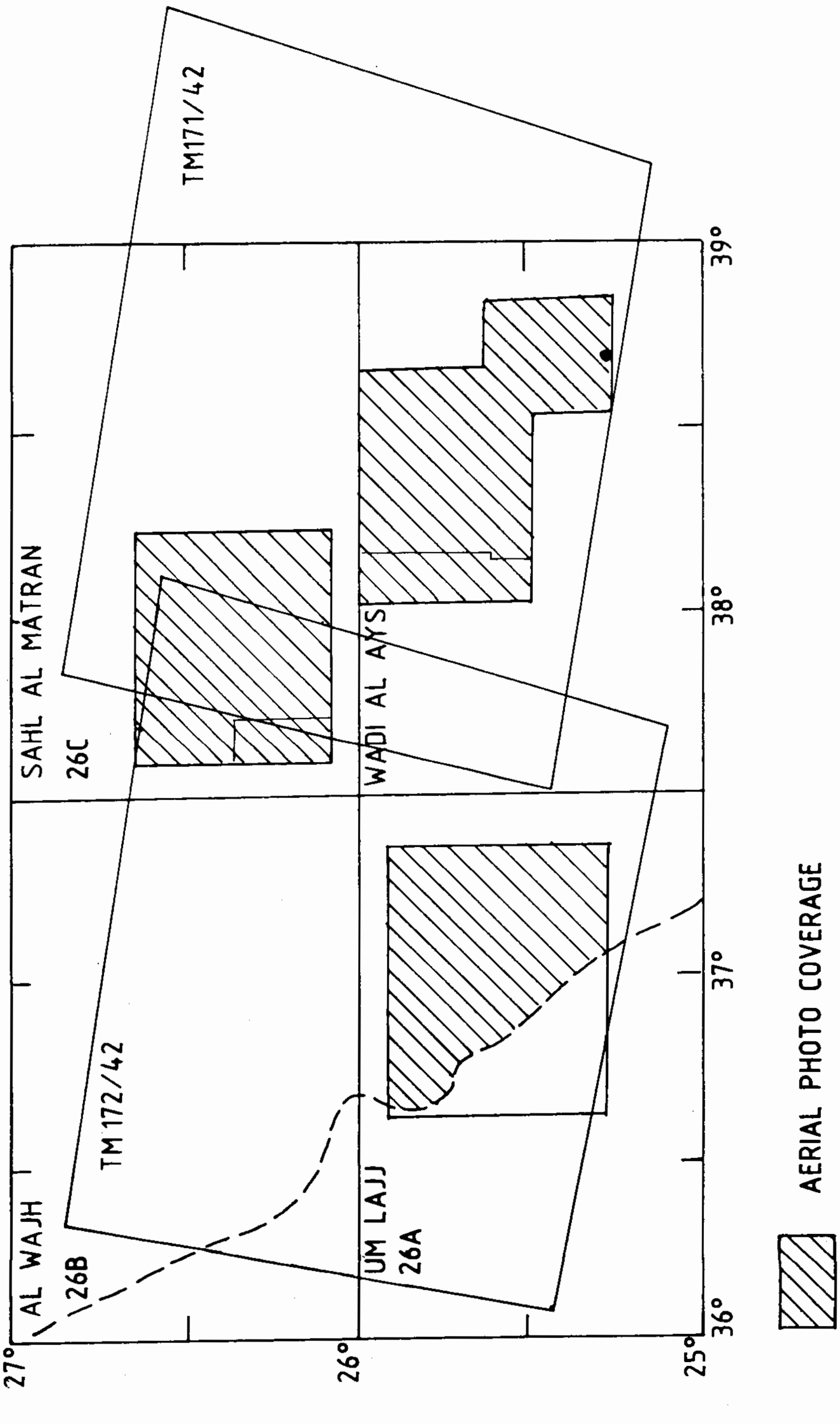

FIG. 2. Thematic mapper data coverage of the test area.

fined study area was covered by approximately 60 stereo pairs. Additionally, an uncontrolled mosaic of the aerial photographs was compiled in the scale of 1:100,000.

Digital Image Processing

Considering that the intention to apply the approach used for Sahl Al Matran area also for other areas of high geoscientific/geomorphologic interest, a condition was laid down when developing the processing method, that it should provide good distinguishability in terms of geomorphologic classification for Saudi Arabian terrain in general. Also, because a map presentation of the satellite image was envisioned, an aspect, which should not be underestimated, an aesthetic colour combination was to be achieved.

By backchecking with further areas covered by the two Thematic Mapper scenes, the following approach proved to yield the best result:

(a) registration of section of each TM scene, *i.e.* a 2416 × 1867 pixel section of TM 171/42 and a 2340 × 2052 pixel section of TM 172/42, resulting in a merged file of 2496 × 2774 pixels with some overlap;

(b) localization of ground control points in the overlapping area, registration of the 2 sections, then applying cubic convolution and nearest neighborhood resampling; a geometric correction of scene 172/042 became necessary to match that of scene 171/042; because the geometric properties of the two scenes were not equal, since the various sensors on board the satellite have different imaging geometries;

(c) both sections were then combined with the help of a "stitch" program, yielding an image file of 2496 × 2774 pixels size;

(d) The seam of the images, where they were put together, was then adapted with a "smoothing" low-pass filter;

(e) the statistics of both images were computed, leaving out the seam area;

(f) the low-pass filtered image was copied into the merged image;

(g) gray levels were added to the Western section of the merged image in order to overcome the spectral differences;

(h) statistics of the assembled scene were calculated;

Then the first principle axis of all bands (beside # 6) was computed and stretched, before bands 5, 4 and 2 were fed into the computer as RGB components, coupled with a stretching to 8 bit.

An Intensity, Hue, Saturation IHS transformation followed and a statistics computation of the principle axis and the stretched RGB combination were carried out. The saturation was enhanced, then filtered by using a 3 × 3 pixel sized addback-high-pass before introducing the complex processed principle axis component into the IHS transformation as Intensity. A retransformation to the RGB system for photographic display completed the processing.

The resulting image in the scale of 1:560,000, a contact copy of the original, is presented in Fig. 3.

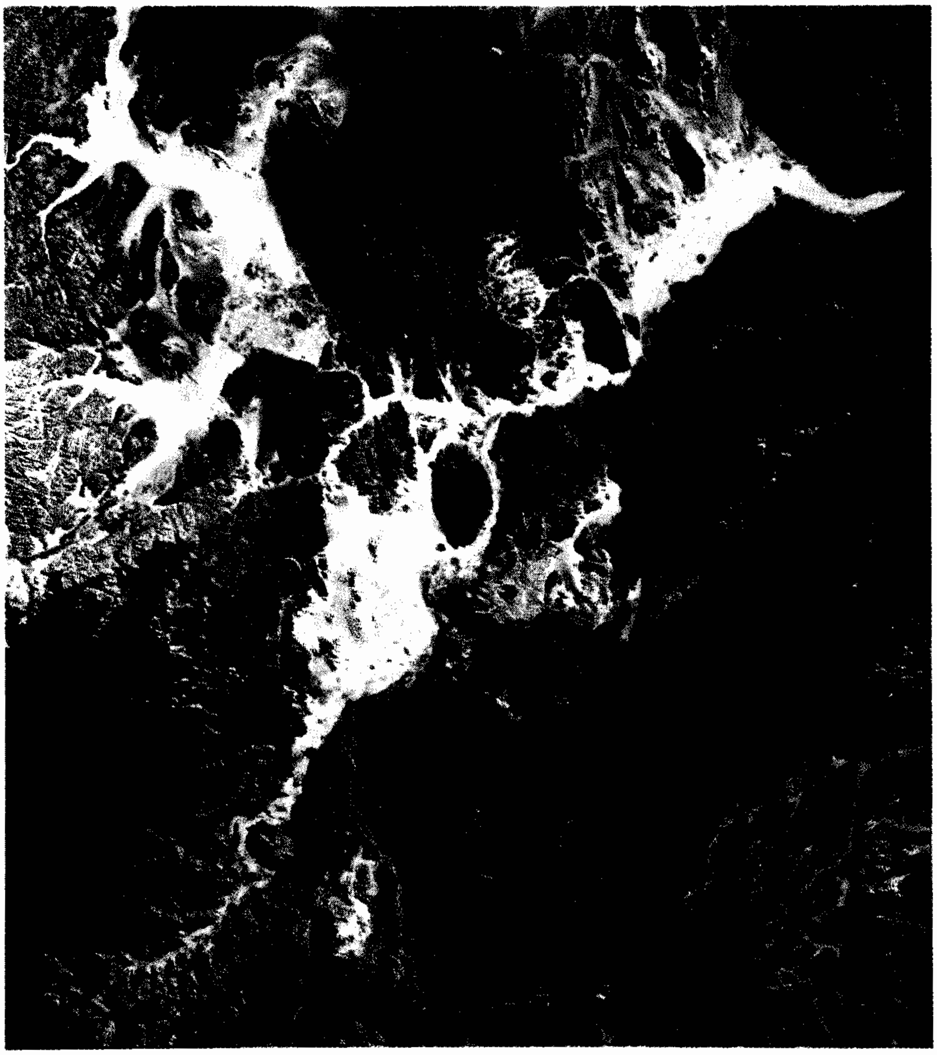

FIG. 3. Image processing of the investigation area. Approximate scale 1:560,000.

Geomorphologic Interpretation of Sahl Al Matran Area

General

The geomorphological image interpretation (Verstappen, 1977) was undertaken in order to derive necessary information on morphogenesis, morphography, morpholithostructure and morphochronology. Besides the processed satellite images, black and white photographic prints on Kodak Aerographic 2443 film at the scale 1:60,000 were additionally analyzed with the aid of mirror stereoscope and stereomicrometer in order to obtain some morphometric data. The study of available reference information in form of previous research reports and cartographic documents was carried out during the initial stage of the work (Daires, 1985; Hadley, 1987; Kemp, 1981).

A preliminary geomorphological classification system was elaborated and used for interpretation and mapping of landforms. The system, based on genetic and morphographic criteria was intended to be hierarchical, logical, homogeneous and sufficiently flexible for applications not only within the investigation area, but also for whole Western Saudi Arabia. The system underwent several improvements during the interpretation of images and the field work and in its final form appears as a legend of reconnaissance geomorphological map (Table 1).

TABLE 1. Reconnaissance geomorphological map legend.

I. *Structure-related tectonic landforms originated by endo- and egzogenetic process (structural-denudational landforms)*
1. Mountains developed on predominantly intrusive, deformed rocks (Type A)
2. Mountains developed on predominantly extrusive, metamorphic and/or sedimentary, deformed rocks (Type B)
3. Foothills and rugged uplands
4. Plateaux flattops
5. Planation surfaces and/or piedmonts
Landform elements :
Table rocks and buttes
6. Structural escarpments
Fault-line scarps
Hogbacks and cuestas
– prominent
– eroded
Crests and ridges
– sharp
– rounded
Breaks of slopes
– prominent
– gentle
Morphologically expressed lineations
7. Plutons

TABLE 1. Contd.

Landform elements :
Dikes
II. *Volcanic landforms*
1. Lava plateaux and mess (harrats)
2. Eroded scarps with lava ridges and ravine cuts bordering harrats
3. Craters and cinder cones
III. *Fluvial and fluvio-denudative landforms*
1. Polygenetical desert plains
2. Braided channels in large wadis
3. Alluvial terraces plains
4. Internal draining channels
5. Talus slopes and cones
6. Plays
IV. *Eolian landforms*
1. Dunes
2. Eolian covers
V. *Thalasogenetic (littoral coastal) landforms*
1. Coastal plains with marine terraces
2. Tidal plains and salt marsh plains
3. Marine beaches
VI. *Organogenetic landforms*
1. Barrier and fringing reefs
2. Coral islands and atolls
VII. *Anthropogenetic landforms*
1. Built-up and industrial areas
2. Agricultural areas
3. Transportation network and facilities
VIII. *Waterforms*
1. Lagoons
2. Open sea

The draft delineation of geomorphological units was done on transparent overlays with the aid of Staedtler(s) pens with permanent, waterproof inks. Black, solid lines were used to mark the borderlines of landform units. Also black, conventional signs and symbols based on modified geomorphological classification adapted after Klimaszewski (1963, 1982) and Fairbridge (1968) were used to represent selected landform units and elements. Blue colour was applied to represent waterforms and red conventional symbols to enhance the spatial extent of distinct morphological categories.

The resulting interpretation overlays regarded as preliminary (reconnaissance) geomorphological draft maps were then subjected to further field verification. During the field mission the overall geomorphological character of the study sites was generally examined. Extensive travels along previously selected routes and in situ observations aimed at the correction of interpretation results and elimination of uncertainties. Analyses of multi-directional group photographs of the landscape taken during this field mission helped additionally to increase the understanding of landforms complexity and orientation. Necessary corrections were introduced on draft maps and these documents were then subject to standardized cartographic and printing procedures aimed at production of reconnaissance geomorphological image map (georeferenced satellite image with superimposed, monochrome (white) thematic symbols and signs). These maps might in their present form be regarded as valuable documents providing information about what landforms are and serve as basis for reasoning on what landforms mean. The term "landform" is understood here according to the classical definition of Way (1973). It is a terrain feature formed by natural processes, which has a definable composition and range of characteristics that occur wherever that landforms are found.

Results of the Reconnaissance Geomorphologic Mapping in Scale 1:100,000

Like the whole quadrangle depicted on 1:250,000 geologic map, the investigated area is located along the Northern edge of the Arabian Shield. The Northern part of the study area is covered by extensive sandstone plateaux gently dipping Northward and incised by valley bottoms of braided wadi channels infilled with unconsolidated detritus of alluvial and colluvial origin. They appear in light orange tones in the satellite data processing, and have a characteristic texture.

Part of the outcropping sandstone tablelands built up from the flat laying, layers situated south of Al-Ula is presented on the photo of Fig. 4. Surrounding slopes are covered with weathered and eolian deposits and partly vegetated with scarce, xerophitic plants. This fact is reflected in colour and tonal changes observable on the satellite image of the area.

At least four different sandstone formations (Cambrian Siq and Quraira and Ordovician Ram and Umm Saham) are geologically identified but only two morphologically expressed levels are clearly observable on satellite images as tablelands and buttes (colour, tone, form). Minor sandstone plateaux and inselbergs built up of the same rock formations and apparently representing the same age are located at the central part of the mapped area.

Due to the highly specific character of this landscape and its unique geological and geomorphological history the area was classified as a separate geomorphological category within the structure-related landforms originated by both endo- and egzotectonic processes and called "Plateaux and flattops of equal elevations built up of sandstones with well developed fractures and joint patterns".

Detailed information on mineralogical composition, stratigraphy and distribution of this formation are contained in the geological reports quoted by Hadley (1987). At this stage, it is noteworthy to mentioned that according to the previous investigations this Paleozoic sandstone plateau covering the northern part of the study area as well as several outlier buttes situated in its central and southern part overlaid uncomform-

FIG. 4. Outcropping sandstone tablelands south of Al-Ula.

ably old, peneplained paleosurface composed of Precambrian and early Paleozoic shield rocks. These rocks were subjected to the long and substantial weathering at or near the sea level in arid to temperate climatic conditions. The aggregate thickness of the sandstone formations within the study area is estimated to be approximately 600 meters.

Another highly characteristic feature of the investigated area is the occurrence of two large Tertiary basalt fields situated in its Northern and Southern part.

The Northern flat-laying, basalt plateau known as Harrat al Uwayrid unconformably overlies the aforementioned sandstone formations and extends North-Westward from approximately 26°30′ near Al Ula, where its thickness is about 13 meters. In its central part the thickness of the basalt flow must be much greater especially along the volcanic covers extending further north-westward from the study area and surrounding volcanic cones exceeding 1900 meters above the sea level (Coleman and Gregory, 1983 and Coleman *et al.*, 1983). However, no direct measurements of the basalt flow have been undertaken.

The Southern basalt plateau called Harrat Hurayrah rests mainly on eroded Precambrian basement rocks and not on the Paleozoic sandstones as in the case of the Harrat al Uwayrid. Thickness of this basalt flow varies from approximately 30 meters to more than 400 meters. General NW-SE trend of Harrat Hurayrah results from

Precambrian and Phanerozoic faulting and therefore is morphologically related to postvolcanic erosional-denudational processes responsible for the formation of Wadi al Jizl and Wadi al Hamd further in the southeast. Essentially, stratigraphic, textural and petrographic characteristics of these basalts are the same as those of the basalts of the Harrat al Uwayrid. Both of these basalt flows resulted from a volcanic event during Miocene when the Arabian plate became again active. It is reported that basaltic volcanism continued episodically into the Holocene and that "some basalt flows are found in incised wadis formed during Miocene and post-Miocene uplift of the western part of the Arabian Peninsula" (Brown, 1970; Schmidt *et al.*, 1982; Hadley, 1987). More detailed information on textural and mineralogical character of these basalt flows is reported by Hadley (1987). The typical landscape of Harrat al Hurayrah is shown on the photos of Fig. 5 and 6. Apart from the extensive basalt flows and sandstone plateaux the greater part of the area consists of a highly dissected, rugged mountainous and hilly terrain (jabals) built up from basically Precambrian, mainly Proterozoic and early Paleozoic rocks. These rocks evolved in intracratonic setting approximately 900-500 m.y. ago (Kemp, 1981) were deformed during late Precambrian and early Paleozoic collisional event known as the Najd orogeny during which the Najd faulting system was established.

In geomorphological terms the area is relatively uniform in its basic character and it forms an early Paleozoic peneplain reshaped during the subsequent geological events (periods of multiple folding, faulting and metamorphism). Landscapes de-

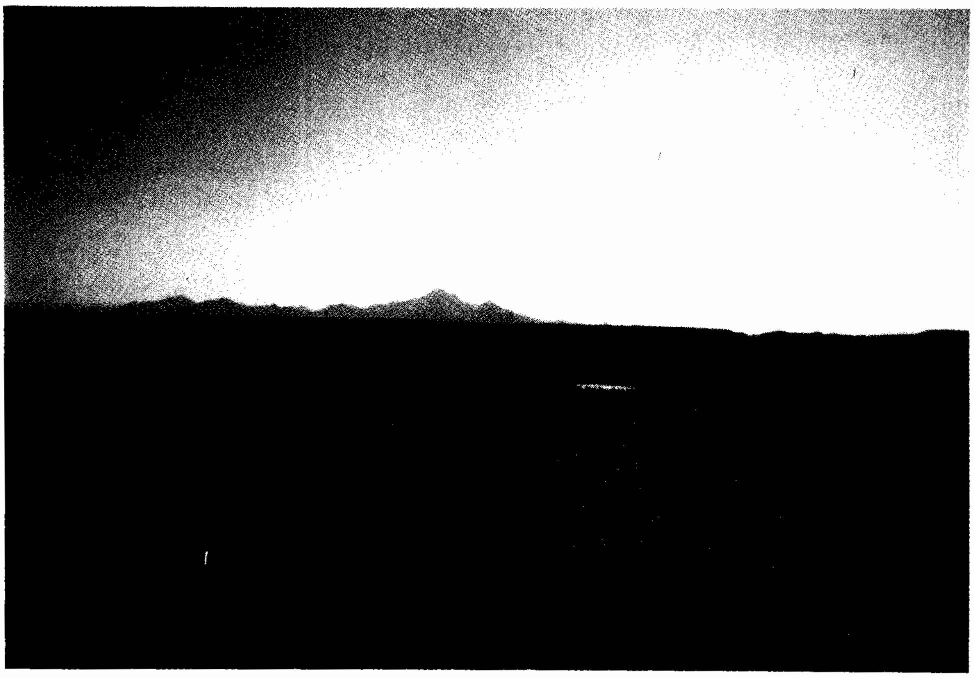

FIG. 5. Flat lying basalt flows of Harrat Hurayrah. Eruption cones are visible on the horizon line. Slopes of the incised valley at the front reveal underlying basement rocks.

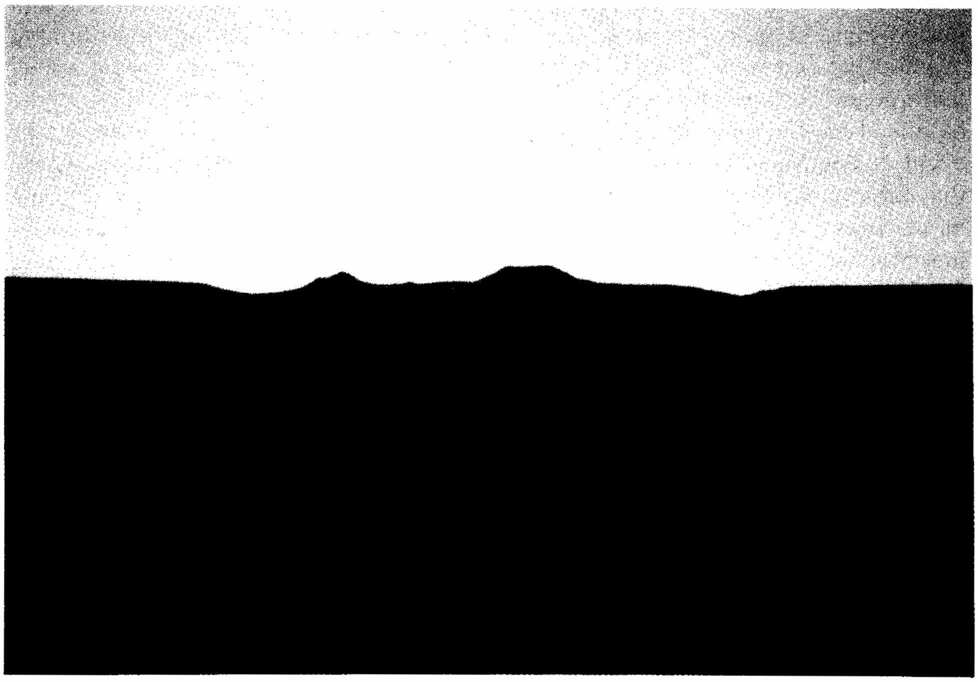

FIG. 6. Flat surface of Harrat Hurayrah covered with sharp-edged pebbles resulted from mechanical weathering of basaltic rocks.

picted on the reconnaissance geomorphological map and belonging accordingly to the adopted classification system to the same major category of structure-related (tectonic) landforms were further subdivided into three classes. This subdivision was based not only on, sometimes hardly differentiable, morphological but also on petrographical criteria.

Most of the area was classified as "Dissected foothills and rugged uplands developed on deformed, jointed and foliated metavolcanic, sedimentary, metasedimentary and/or metapyroclastic rocks with sharp, frequently parallel crested ridges and entrenched valleys". Typical landscape characterizing this class is shown on photo of Fig. 7.

Mountainous regions visible on the satellite image in the central part of the study area were mapped as "Dissected mountains developed on predominantly extrusive, metamorphic and/or sedimentary deformed rocks with well defined peaks, crests and steep-sided, rock-cut, spurred valley walls". This second class is characterized by bolder relief features and higher amplitudes of height than the previously described one. However, it must be stated that the origin, morphological and structural development of these two landform classes were essentially quite similar. General view of this class is presented in the photo of Fig. 8. The last remark holds true also for the

FIG. 7. Dissected foothills and rugged uplands in the central part of the study area.

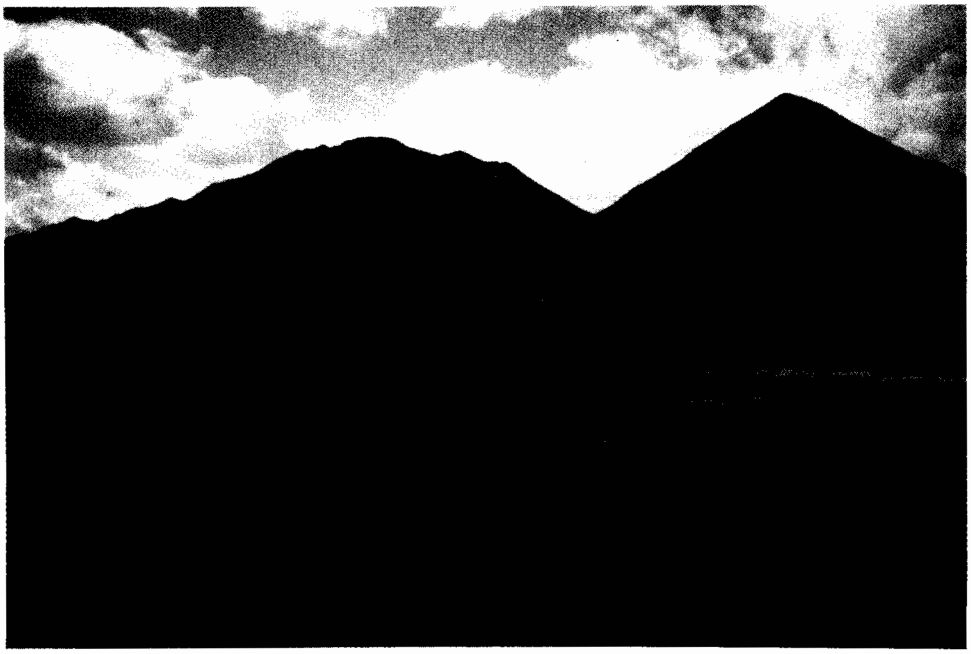

FIG. 8. Dissected mountains and braided channels of large wadi divided with small outcropping hogback (first plan).

third structure-related, denudational landform presented on the reconnaissance geomorphological map. This class called "Dissected mountains developed on predominantly intrusive, deformed rocks with well defined peaks, crests and steep-sided, rock-cut, spurred valley walls" occurs in the south-western part of the image and its overall morphological character is not so self-evident. On the satellite image as well as on the aerial photographs the region appears as highly eroded, dissected planation surface. However, petrographic criteria (area is built up from granodiorites and monzonitic rocks) and in situ observations of several bold forms justified the inclusion of this region into the aforementioned class. Part of this region with characteristic, erosional features developed on crystalline, intrusive rocks is presented on photo of Fig. 9.

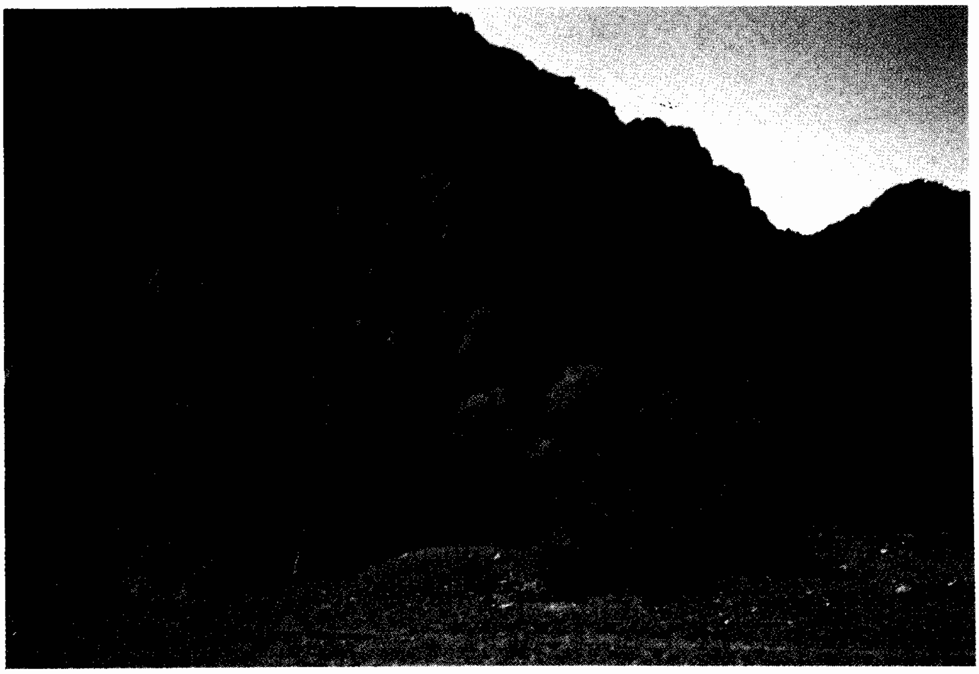

FIG. 9. Dissected mountains. Visible are exfoliated crystalline rocks. Situated southwest of the study area.

Highly characteristic for all aforementioned major landform classes are typical structure-related landform elements such as well defined crests and ridges developed on interbedded, tilted or flat laying, differentially eroded rocks. Vertically outcropping layers from the so called hogbacks are shown in Fig. 10. Tilted differentially eroded layers form characteristic cuestas, sharp and rounded crests and ridges (Fig. 11). Flat-laying or slightly tilted layers subjected to differential erosion from the various types of tablelands and buttes known also as monadnocks, inselbergs or garas.

The last but not the least morphologically characteristic feature of the investigated area is the presence of vast pligenetical desert plains which surround bedrock out-

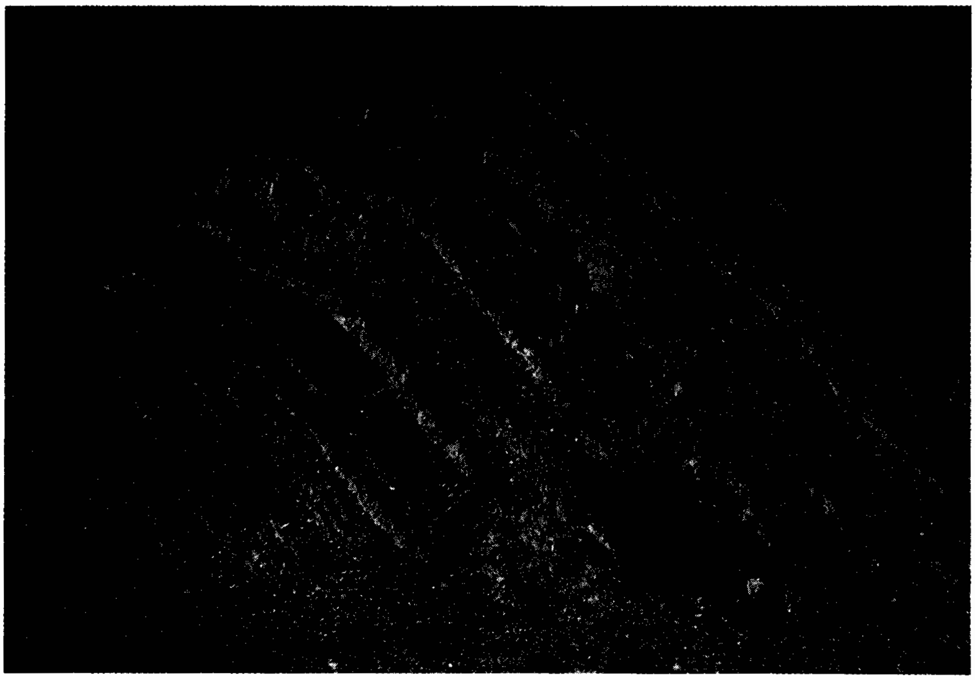

FIG. 10. Hogback (landform element).

FIG. 11. Sandstone tablerocks and flattops.

crops and rejuvenated pediment slopes forming flat or gently rolling open surfaces covered with Quaternary alluvial and colluvial deposits. In some places weathering processes led to the development of so called desert pavements, duricrusts, deposits of unconsolidated chert clasts and silicified coquina, varnished, poligenetic rock debris, etc. Typical poligenetical desert plain of Wadi al Jizl (Fig. 12) and the outcropping foothills are shown in photo of Fig. (13). Several levels of incised, dissected erosional and depositional pediments (glacis d'erosion, glacis d'accumulation) might be identified. They are composed from the differentially grained material shed from the main outcrops and ranging from coarse-grained grus adjacent to granitic plutons to medium and fine grained material deposited further down the slopes.

This differentiation and dependance of colluvial deposits from the parent rocks is manifested on the satellite images in form of the colour and tonal changes. On aerial photographs these changes are sometimes additionally expressed as minor breaks of slopes but actually they are rather hardly visible in the field.

Conclusions

An elaborated geomorphological classification system – which underwent several improvements during processing – was elaborated and used for interpretation, mapping, and discussing the landform classes.

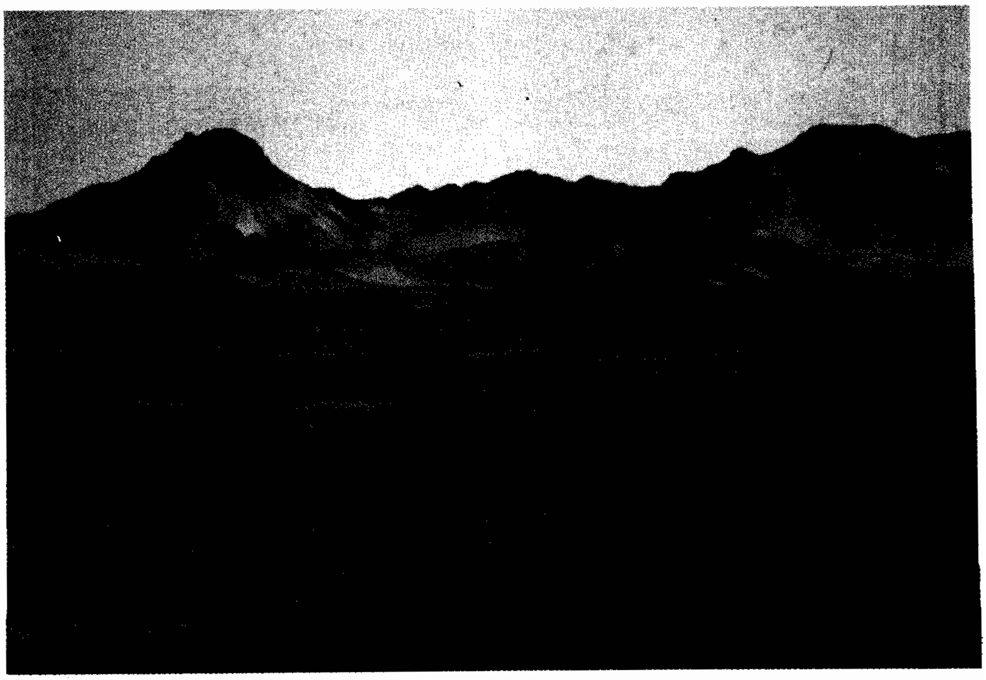

FIG. 12. Wadi Al Jizl. Poligenetic desert plain, dissected foothills and rugged uplands. Noteworthy is the colour variation of the plain which results as complex tonal pattern observable on the satellite imagery.

FIG. 13. Varnished desert pavement.

Four different sandstone formations were geologically identified, but only two morphologically expressed levels were clearly observable on satellite images besides two large Tertiary basalt fields on the northern and southern parts.

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دراسة استطلاعية لإعداد خريطة جيومورفولوجية لمنطقة سهل المطران ، المملكة العربية السعودية ، مبنية على أساس بيانات الاستشعار عن بعد

عاصم يحيى بخارى
كلية علوم الأرض
جامعة الملك عبد العزيز ، جدة – المملكة العربية السعودية

المستخلص : تبين هذه الدراسة إمكانية استخدام وتطبيق الاستشعار عن بعد في البحوث الجيومورفولوجية لمنطقة تقع ضمن مربع سهل المطران ، في المنطقة الغربية للمملكة العربية السعودية وتدخل فيها مدينة العلا .

وتشرح الدراسة بالتفصيل الخطوات والإجراءات العملية التي اتخذت لاستخدام بيانات قواعد المعلومات ومعالجتها وتحليلها وتقييم النتائج من وجهة النظر المورفولوجية .

كما تم تطوير نظام التصنيف الجيومورفولوجي واستخدامه في تفسير خرائط التكوينات الأرضية ، وقد ساندت الصور الفوتوغرافية متعددة الوجهات النتائج التي توصل إليها .