Shuttle Imaging Radar Views of Some Geological Features in the Arabian Peninsula

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ABSTRACT

The Space Shuttle Endeavor, carrying Shuttle Imaging Radar (SIR), has imaged selected parts of the Earth during two missions in April and October, 1994. The SIR instrument acquired remote sensing data in L, C and X bands. The main objective of the experiment was to assess the utility of radar images for multiple geologic, hydrologic and environmental applications. The geologic interpretation of the L-band image strips, over the Arabian Peninsula, reveals faults, folds, joints, details of harrats (basalt flows), karst terrain, and drainage systems beneath thin sand cover which are not visible on other remote sensing images (Landsat and SPOT) and are not shown on existing geologic maps.

INTRODUCTION

The Arabian Peninsula is a largely remote and barren terrain which is extensively covered by sand. Airborne photography and remote sensing images (Landsat and SPOT) have been effectively used in many parts of the Peninsula to map geologic, hydrologic and environmental features. These techniques, however, are not generally effective in imaging features which are covered by sand.

The Shuttle Imaging Radar (SIR) has the capability to penetrate sand cover and is sensitive to terrain textural factors. Therefore, SIR images complement and enhance the interpretation of other remote sensing data and provide a new and unique view of the Earth’s surface.

The Research Institute of King Fahd University of Petroleum and Minerals participated in the National Aeronautics and Space Administration (NASA) science plan to evaluate SIR-C/X-SAR data for paleodrainage and geologic mapping purposes on the Arabian Peninsula. Results of the earlier SIR-A and SIR-B missions are discussed by Ford et al. (1983 and 1986). The SIR-C/X-SAR radar system is described by Jordan et al. (1995) and some preliminary results of the experiment are discussed by Evans et al. (1994).

This paper presents some of the results derived from recent studies of the April and October, 1994 SIR-C missions over the Peninsula.
SIR-C radar images were compared to Landsat images and geologic maps to identify the new information available. Faults, joints, folds, domes, formation contacts, unconformities, karst terrains, sabkhas, dunes, harrats (volcanic cones, craters and flows) and other geological and topographic features are readily apparent on the radar strips. Paleodrainage features are also enhanced by the radar. In many instances, geological features showed clear surface expression on radar images, whereas published geologic maps and Landsat images exhibit no indication or only problematical clues to such structures.

Table 1
SIR-C Imaging Parameters of Strips

| Strip Number | SIR-C Mission | Resolution Along (m) | Resolution Cross (m) | Length (km) | Width (km) | Incidence Angle (degrees) | Track Direction (degrees) | Look Direction (degrees) | Figure No in Text |
|--------------|---------------|----------------------|----------------------|-------------|------------|---------------------------|---------------------------|------------------------|-------------------|
| 27.10        | SRL-2         | 103                  | 54                   | 2,060       | 86         | 37                        | N32.8E                   | Right                 | 9                 |
| 33.70        | SRL-2         | 98                   | 56                   | 900         | 91         | 35                        | S32.4E                   | Left                  | 10, 11            |
| 91.30        | SRL-1         | 139                  | 76                   | 1,630       | 63         | 57                        | N33.1E                   | Right                 | 8                 |
| 97.60        | SRL-1         | 110                  | 87                   | 2,800       | 75         | 47                        | S36.1E                   | Right                 | 5, 7              |
| 113.70       | SRL-2         | 91                   | 87                   | 2,630       | 57         | 22                        | S34.4E                   | Right                 | 6                 |
| 145.50       | SRL-1         | 71                   | 82                   | 3,100       | 58         | 51                        | S35.8E                   | Right                 | 4                 |

Figure 1: Index map of Shuttle Imaging Radar SIR-C radar strips and images presented in Figures 4 through 11.
GEOLOGY OF ARABIAN PENINSULA

The main geological elements of the Arabian Peninsula are shown in Figure 2. The westernmost region of the Peninsula consists of a narrow coastal plain along the Red Sea. Extension and spreading in the Red Sea and Gulf of Aden are accompanied by anti-clockwise rotation and northward translation of the Arabian Plate. The movement of the Arabian Plate causes compression, folding, thrust faulting and suturing in the Taurus-Bitlis-Zagros fold and thrust belts.

The Precambrian Arabian Shield covers most of the western region of the Peninsula. It was formed by accreting volcanic arcs and continental terrains in the Late Proterozoic, approximately 500 to 900 million years ago (Stoesser and Camp, 1985). Basalt flow rocks, cinder cones and vents comprising the harrats (lava fields) are found in the Arabian Shield. These are the result of crustal fractures which accompanied the opening of the Red Sea.

Paleozoic strata crop out along the edge of the shield. The Cambrian to Devonian sequences are mainly clastics. Near the end of the Carboniferous, the eastern platform was broken into a series of north-trending horsts and grabens during the “Hercynian” orogeny (McGillivray and Husseini, 1992). After erosion, the truncated edges of older Paleozoic strata were covered by the carbonates of the Permian Khuff Formation.

The Arabian plate has remained a relatively stable platform through Mesozoic and Cenozoic time, resulting in remarkably widespread and uniform deposition interrupted only by subtle unconformities.
Regional dip across Saudi Arabia is less than 1° eastward with strike of Mesozoic strata curving around the axes of the Central Arabian Arch (Figure 2).

The sedimentary section is relatively thin near the Arabian Shield, with eastward thickening to more than 8 km near the Arabian Gulf. Facies change toward the Arabian Gulf reflect continuous subsidence to the north and east in Mesozoic and Cenozoic time. Geological maps demonstrate downwarping toward the east continuing into modern times, as evidenced by eastward thickening of Cenozoic strata (Goff et al., 1995). Since late Miocene time, the downwarping has been accelerated as a result of subsidence of the northeast edge of the Arabian plate related to the development of the Zagros Mountains.

Extensive regions of the Arabian Peninsula are covered by sand. The satellite image in Figure 3 (National Oceanic and Atmospheric Administration NOAA-7 recorded on 19 March, 1983) shows that nearly one-third of the Arabian Peninsula is covered by aeolian sands and indicates how important the sand penetration capability is in such areas. Three “sand seas” are the Nafud Desert in the northwest, Ad Dahna Desert in Central Arabia and Rub’ Al Khali in the southern half of the Peninsula (Duff, 1993).

Figure 3: Satellite image (NOAA-7) of the Arabian Peninsula shows that nearly one-third of the region is covered by three "sand seas": Nafud Desert, the Ad Dahna Desert and the Rub’ Al Khali Desert. The white regions indicate cloud cover.
EXAMPLES OF SIR-C RADAR IMAGES

The following examples demonstrate the nature of the information which is derived from the SIR-C radar images. The SIR-C mission and strip numbers are provided in the figure caption of each example discussed below and Table 1. Unlike Landsat images, SIR images are displayed in black and white. The 2-pronged arrows shows flight direction (F) and look direction (L).

TERTIARY AND QUATERNARY BASALTS

Basalt lava fields (harrat) of western Arabia, with their characteristic bright radar return, are cut by many prominent faults (Figure 4). On the regional scale, volcanic vents and cones are aligned along some faults, and many of them are breached by flows. Faults and joints in the Eocene cherty limestone, seen in Figure 4, are remarkable because of their strong expression on the radar image. In contrast only a few faults are shown on older geologic maps prepared without using satellite images (USGS, 1963).

The faults are parallel to the Red Sea (North 25° West). They cut the basalts, many of which have ages of less than 2 million years (Jado and Zötl, 1984), and are thus younger than the basalts. The agricultural area in the lower right corner is near Al Jawf, the largest town in the area. Duricrust (caliche), with its characteristic smooth gray appearance, is widespread throughout this area at the north edge of the Nafud "sand sea".

Figure 4: Image SRL-1, Strip 145.50. N25°W trending faults (red) are parallel to the Red Sea and cut the basalt lava fields (harrats). For location see Figure 1.
AD DAHNA SAND SEA

In northwest Saudi Arabia, sand sheets, at the northeast edge of the Nafud sand sea (Figure 3), smear dark streaks across the light gray background of the Upper Cretaceous Aruma Limestone (Figure 5). The outcrop of the Aruma Limestone is partly visible beneath the sand. In contrast this subcrop appears covered on Landsat images and on geologic maps.

The dark streaks are thicker sand developments in linear dunes, which is a good example of sand penetration by the L-band radar (Dabbagh et al., 1995, 1996). Wadis flow northward down the dip slope of Aruma Limestone. Wadi Khirr is the widest and deepest wadi in the area; it is believed to be a paleodrainage. In the lower right corner of the image, black radar response is due to thick aeolian sands in the Nafud "sand sea".

Figure 5: Image SRL-1, Strip 97.60. Dark streaks correspond to sand sheets which cover the Cretaceous Aruma Limestone. For location see Figure 1.
RIYADH AND DHRUMAH-NISAH FAULT SYSTEM

The capital city of Riyadh, Saudi Arabia, is seen to the left as areas of bright, square-shaped returns in the image below (Figure 6). To the southeast, the Dhrumah-Nisah Fault Zone breaches Cretaceous limestone outcrops with the unusually wide valley located at or near the crest of the Central Arabian Arch (Figure 2). Southward from this major fault system, there is a marked change in strike of the strata and dips are southeastward on the south flank of the Central Arabian Arch.

The Wadi Sahba fault, the eastward extension of the Nisah fault, was formerly hidden beneath Quaternary alluvium and sand of Ad Dahna sand sheets and dunes, but is now clearly seen on SIR-C L-band radar in Figure 6. The Wadi Sahba fault is described in Figure 8.

Figure 6: Image SRL-2, Strip 113.70. Seen here is the Saudi Arabian capital Riyadh which appears as areas of bright, square-shaped returns. The Dhrumah-Nisah Fault System extends further east where it joins the Wadi Sahba fault. For location see Figure 1.
MAJMAAH GRABEN

The Majmaah Graben, 170 km northwest of Riyadh, is sharply defined in Figure 7. It is also seen on Landsat images and maps. This south-trending fault system makes a curve eastward and joins the Drumah-Nisah fault system to the southwest of Riyadh, seen earlier in Figure 6. The southern extension of the Majmaah Graben is less clear due to sand and alluvium cover.

On the radar image, the Majmaah Graben can be more confidently related to the Drumah-Nisah fault system to the south beneath thin sand cover. The graben cuts Upper Jurassic carbonates and the Upper Cretaceous Aruma Limestone. The fault in Figure 7 is not apparent on geologic maps or Landsat images, although obvious here.

The Nafud Ath Thuwayrat “sand river” trends from northwest to southeast along a strike valley, a favored habitat for several other “sand rivers” trending around the Central Arabian Arch (Figures 2 and 3).

Figure 7: Image SRL-1, Strip 97.60. The Majmaah Graben is a south-trending fault system which curves eastward to join the Dhrumah-Nisah fault system (Figure 6) and, further east, the Wadi Sahba fault system (Figure 8). For location of the images see Figure 1.
GHAWAR ANTICLINE

The south plunging tip of the Ghawar anticline is expressed with Mio-Pliocene carbonate outcrops along the axis (Figure 8). Ghawar field is the world’s largest oil field (100 billion barrels) with productive area extending more than 200 km northward from this strip. Structure at depth in Paleozoic strata is a north-trending horst formed mainly in the Hercynian orogeny at the end of the Paleozoic. Important growth also occurred as fault block adjustments in the Cretaceous and Miocene-Pliocene time.

The Ghawar anticline is expressed at the surface as draping of Tertiary strata over the deep horst block. In Figure 8 the karst development in the Hofuf Formation along the crest of the anticline is evident.

Wadi Sahba is marked by the alignment of center-pivot agricultural plots. A large alluvial fan, which probably developed in Early Pleistocene (Al Sayari and Zötl, 1978), is clearly seen on the mouth of Wadi Sahba where it joins to the plain. Except for the linear nature of Wadi Sahba and the apparent, abrupt south termination of the Ghawar anticline, the Dhrumah-Nisah-Sahba fault is not directly visible here and can only be inferred below Quaternary gravels.

Figure 8: Image SRL-1, Strip 91.30. Southern termination of the Ghawar Anticline occurs along the Wadi Sahba fault system. For location see Figure 1.
AL JAWB PAEODRAINAGE

At the south edge of the Jafurah "sand sea" and the north edge of the Rub’ Al Khali, Miocene-Pliocene sandstone, limestone, shale and marl are cut by the east-northeast trending Pleistocene Al Jawb paleodrainage channel. In Figure 9 the channel appears in sharp dark contrast against lighter tones of the Miocene-Pliocene outcrops. Some tributaries in the upper left originate about 45 km to the northwest.

The remarkably straight trace of the Al Jawb main valley suggests fault control. This paleodrainage system is not obvious on maps. Once recognized on radar images its elements may be recognized on Landsat. Although less apparent, gravel-filled Wadi Sahba paleodrainage also cuts obliquely across the Quaternary gravel plain. The paleodrainage formed by coalescing alluvial fans with distributary wadis flowing eastward toward the Arabian Gulf.

Little detail can be seen in the Rub’ Al Khali. Large, dark, barchan and barchanoid dunes and sand ridges, in the Jafurah "sand sea" to the north of Al Jawb channel, are clearly displayed. The radar penetration of thin sand sheets of the Jafurah sand sea reveals the underlying light tone of the Miocene shale and marl.

Figure 9: Image SRL-2, Strip 27.10. The straight face of the Al Jawb paleodrainage channel suggests a fault-controlled feature. For location see Figure 1.
Umm As Samim Salt Flat

At the southeast edge of the Rub’ Al Khali (Figure 3), inland sabkhas (salt flats) extend over large areas between the mega-barchan dunes. In Figure 10 the bright return from Umm As Samim sabkha is from the rough, crusty salt-gypsum surface. It is the largest and best-known of the inland sabkhas. All streams from the mountains of Oman and highlands of the Hadramaut are directed toward the Umm As Samim sabkha and Rub’ Al Khali desert (Al-Lamki, 1996).

Together with the inter-dune sabkhas of the Rub’ Al Khali, the area forms a huge inland “salt lake” or evaporitic basin very near sea level. The bright area seen on the radar strip is smaller than that shown on geologic maps. Gray peripheral areas around the bright center of Umm As Samim sabkha also show the previously larger extent of the salt flats in times of greater rainfall. In the upper left corner of the image, star-shaped dunes are clearly visible, whereas mega-barchan dunes are prominent eastward.

Figure 10: Image SRL-2, Strip 33.70. The Umm As Samim sabkha is the largest and best-known in the Rub’ Al Khali. For location see Figure 1.
HABHAB METEORITE CRATER

The Huqf uplift in Oman consists of Precambrian rocks, in its core, and folded Paleozoic and Mesozoic strata along its edge. The Paleozoic and Mesozoic outcrops give a varied dark and light radar return in the lower-left portion of the image (Figure 11). Oligocene limestone surrounds the northern border of Huqf uplift in the image.

The Habhab impact crater is sharply defined by black, concentric circles. This crater is a well-known geologic feature and a more detailed view is presented in Petroleum Development Oman’s volume, Oman’s Geological Heritage (Clark, 1990). Other more indistinct circular patterns suggest the possibility of other impacts; however, the many black spots (sinkholes) and irregular drainage pattern are interpreted as karstification of the outcropping Oligocene limestone.

Figure 11: Image SRL-2, Strip 33.70. Habhab meteorite impact crater seen in the middle of the image. For location see Figure 1.

CONCLUSIONS

This study demonstrates the geological application of the Shuttle Image Radar data in the Arabian Peninsula. The method is useful in detecting and delineating near-surface faults, folds, basalt flows, karst terrains, drainage systems, and other geological or geomorphologic features which are thinly covered by aeolian sands. The radar data provides new insights which are generally in close agreement with published geologic maps by the US Geological Survey and Landsat images.

Penetration of thin (1 to 2 m) sand sheets is especially revealing of unmapped geological features. Thick sand areas, however, are commonly dark and featureless in SIR images, probably due to the smoothness of the sand surface. Integration of SIR with Landsat/SPOT images and geophysical/geological surveys, and comparison of X-band, C-band and L-band data in the future would be beneficial.

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