Improving geological mapping of the Farasan Islands using remote sensing and ground-truth data

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ABSTRACT

We integrated satellite imagery (Landsat-8) with ground-truth data to produce a detailed and complete geological map of the Farasan Islands, off the Red Sea coast of Saudi Arabia at a scale of 1:100,000. This new map improves upon past efforts by expanding the mapped lithologies on the islands into four categories. We used different techniques to enhance this lithological differentiation, including band combination with ratio stretching and supervised classification techniques based on direct field validation. The former was used to distinguish differences in reflectance values across sets of bands to create a classification image from typical reflectance patterns. The geological feature boundaries were constrained by open-source high-resolution satellite imagery (WorldView-2) as well as field observations. The resulting map clearly distinguishes between different geomorphic and geologic features, including lineaments and lithologies. As the Farasan Islands are relatively remote and not easily accessible, with an area of 739 km², these imagery-analysis techniques were an effective tool for using remote sensing data to produce new and better mapping products of this important area.

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1. Introduction

Remote sensing is the science of obtaining information about Earth’s surface features (e.g. Zhang & Srikharan, 2005) through scanning an object or feature by a sensor that is not physically in contact with it (e.g. Nagarajan, 2010). Using various sensors, remote sensing images present data that may be analyzed to obtain information about features under investigation. The data can be of many types, including variations in electromagnetic energy, force, or acoustic wave distributions (Lillesand, Kiefer, & Chipman, 2014; Siegal & Gillespie, 1980). Image processing can greatly enhance the value of remotely collected data to enable the interpreter to make full use of them (Lillesand et al., 2014; Nagaraj & Yaragal, 2008). One form of processing is classification, a data analysis technique that can be used to define and/or recognize classes or groups of features or members that have certain characteristics in common. Image classification can be supervised or unsupervised (Foody, 2004; Lee & Lewicki, 2002; Schowengerdt, 1983); in the former, the identity and location of features classes or cover types are known beforehand through fieldwork or other means.

Satellite images have proven valuable for different geological applications such as the mapping of lithological units, lineaments, structures, and the seafloor (Abrams & Siegal, 1980; Lillesand et al., 2014; Smith & Sandwell, 1997). In particular, the use of Landsat satellite images over the past half-century has been proven to be useful for geologic purposes. Many authors have investigated different combinations of Landsat bands for remotely mapping geological and lithological units (e.g. Biswas, 1987; Ferrari, 1992; Harris, 1994; Kenea, 1997).

There are two main approaches to mapping from images, one based on image units and the other on lithofacies units (Aravindan & Ganesh, 2014; Drury, 1993; Lachowycz et al., 2015). Occasionally there is sufficient detail to recognize general shapes resulting from surfaces involved in the flow of fluids at different viscosities, including water, ice, lava, and landslips (McFeeters, 1996; Scambos, Dutkiewicz, Wilson, & Bindschadler, 1992; Siegal & Gillespie, 1980). In general, the vast majority of geological boundaries reflect either roughly parallel compositional layering or discordances that cut across that layering, such as faults, igneous contacts, or unconformities (Barisin, Leprince,
Remote sensing images can aid in the collection of geologic data in important but difficult-to-access locations such as the Farasan Islands in the Red Sea (Figure 1), which include a marine sanctuary protecting rare coastal mangroves and endangered terrestrial and aquatic species. In this paper we present the first detailed and complete geological map of the Farasan Islands (Main Map) by extracting geological information from satellite images which were validated by fieldwork; various previous maps exist but with limitations in their data and coverage. Our results suggest that the Farasan Islands’ lithology can be divided into four geological units. As the islands are an environmentally and tectonically sensitive location (Almalki & Bantan, 2015; Blank, Johnson, Getting, & Simmons, 1987; British Admiralty Chart and Publication [BACP], 1997), our improved geologic map could be used by geologist, biologists, and land managers to make better choices about conservation, protection, development, and exploration.

2. Geomorphology and geology

The Farasan Bank in the southern Red Sea is about 50 km from the south-western coast of Saudi Arabia (Figure 1). Almost 90 islands of various sizes have been recorded in this archipelago by the Saudi Wildlife Authority and the bathymetric chart of the Red Sea (BACP, 1997). Only the two largest islands, Farasan Alkabir and Sagid, are permanently inhabited. Most of the islands have low topographic relief (see Main Map) and are covered by Plio-Pleistocene coral reef limestone deposits rising above the sea (Almalki & Bantan, 2015). The shoreline surface is an almost continuous set of reef terraces intermixed with raised beaches. Inland from the coast, the plain rises on a gradient and limestone fault blocks form the highest points of the islands with a peak elevation of 49 m. Overall, the islands are wide and flat with shallow bays (Figure 2). Some locations include collections of low coral cliffs with well-vegetated gullies between them; rocky coastlines and sandy bays are also present (Figure 2).

Figure 1. WorldView-2 satellite image showing the location of the Farasan Islands provided by DigitalGlobe through the ESRI World Imagery service with a resolution of 0.5 m, captured between 2010 and 2013.
Farasan Islands. This map classified the area as part of the Jizan quadrangle in south-western Saudi Arabia, with only two types of sediments: (1) sand in the beach zones with subordinate silt and clay in sabkhas and (2) coral reef limestone. A complete map of the islands was produced by Seltrust Engineering Limited at a scale of 1:500,000 (Ministry of Petroleum and Mineral Resources, 1986), also with only two classes of sediments: Quaternary sabkhas and undivided Miocene-Quaternary deposits. Another map published by the U.S. Geological Survey at a scale of 1:2,000,000 (Pollastro, Karshbaum, & Viger, 1998) and covering part of the Arabian Peninsula, showed Quaternary fluvial deposits as a single lithologic unit covering the whole area of the islands.

Figure 2. Selected field photos showing different landforms of the islands: (a) Sandy beach arranged in the form of simple sand dunes or in the form of longitudinal bar which represent the youngest surficial deposits in the islands, (b) Coral reef limestone cover much of the surface of the main islands and a number of small islets, (c) Lateral view of emergent salt dome, (d) Tensional fractures located along the edge of the salt dome, (e) Limestone ridge regulated by a natural coastal dam of mangrove, (f), (g), and (h) Different view of extensional fault system and limestone tilt-blocks.
3. Data and methods

We used satellite data (Landsat-8; 15 m resolution; Figure 4) and remote sensing techniques including false-color composite production with ratio stretching and supervised classification to create an improved geological map of the Farasan Islands. The Landsat-8 satellite images were downloaded from the USGS website and processed using ArcGIS software. The images were interpreted visually with the aid of observations and sample from key localities to ground-truth the different lithological features. We also used open-source higher resolution satellite imagery from WorldView-2 satellite sensors with 0.5 m resolution provided by DigitalGlobe using the ESRI World Imagery service (Figure 1) to constrain the boundaries of geological features. The topographic base of the map (see Main Map) was derived from the Shuttle Radar Topography Mission data with a resolution of 30 m (e.g. Becker et al., 2009).

The Landsat-8 image data (Figure 4) of the Farasan Bank area were obtained between 11/09/2015 and 12/03/2016. The area was covered by three scenes: path 167/row 48, path 167/row 49, and path 168/row 48. The satellite acquires images in nine spectral bands with a spatial resolution of 30 m for bands 1–7 and 9, and a spatial resolution of 15 m for panchromatic band 8 (including three infrared bands, two thermal bands, and three visible bands). Only six bands (visible bands 2, 3, and 4 and infrared bands 5, 6, and 7) were used in this study; ultra-blue band 1, band 9, and the thermal bands (10 and 11) were not included. These bands' wavelength ranged between the visible (0.45–0.67 μm) and the infrared (0.85–2.29 μm).

All image data in this study were registered within Universal Transverse Mercator (UTM) zone 38 and rectified with the World Geodetic System WGS 84 datum (Tao, 2000; Van Wie, & Stein, 1977). In addition, we constructed an image mosaic of two or more overlapping images to create a single-image representation of the entire area.

Ground-truth data were based on our previous geological studies of the Farasan Islands (Almalki et al., 2015; Almalki & Bantan, 2015; Bantan, 1999; Bantan & Abu-Zied, 2014) as well as further sample collection for this study together with observations and image validations conducted directly in the field.

3.1. Digital image processing

Image processing is generally used to assist visual interpretation and highlight specific information or improve image presentation, for example, by maximizing the contrast between light and dark portions of an image, or highlighting a specific data range or spatial area (e.g. water vs. land) in an image. The processing of digital data can be achieved using different techniques, including image enhancement that increases

![Figure 3](https://example.com/figure3.png)
the visual distinction between features in a scene (Moik, 1980). Longer wavelength reflected-infrared Landsat-8 bands (bands 5, 6, and 7) show poor water penetration, while land areas appear bright in these bands due to reflectance from vegetation and the absence of absorption from water. Thus, we used bands 5, 6, and 7 for separating land areas from water. We also applied a linear contrast stretch enhancement to individual colors separately for each band, and tested different band combinations to find the most useful composite. Further contrast was achieved by applying band ratios. The most useful combinations were 5/7 (0.85/2.11 μm), 2/3 (0.45/0.53 μm), and 2/2 (0.45/0.45 μm). A false-color composite of the contrast-stretched 7, 5, and 3 and 5, 6, and 7 bands were the best combinations for geological mapping (Figure 4(c,d)). After that, we used the supervised classification process to distinguish differences in reflectance values across sets of bands to create a classification image from typical reflectance patterns. This procedure requires detailed knowledge of the area and good ground-truth information.

3.2. Map enhancement

Although the previous image processes were useful to enhance the images’ visualization, it was necessary to perform different filtering processes on the classified images due to the medium resolution of the Landsat images, which were the main source for the classification process. This filtering involved two techniques: automated and manual. In the former, we converted the classified image (Figure 5(a)) to vector format and enabled a simple and smooth polygon filtering (Figure 5(b)). In the latter, the manual adjustment of the lithology features was mainly based on the WorldView-2 satellite image in order to enhance the boundary between different lithological units (Figure 5(c)).

3.3. Classification

Ground-truth data collected for this study, as well as our previous geologic observations (Almalki et al., 2015; Almalki & Bantan, 2015; Bantan & Abu-Zied, 2014) on the Farasan Islands, suggest that the islands
can be classified into four lithological units; these were the basis of our classification and interpretation from the satellite images. Furthermore, it was difficult to detect other deposits from satellite images alone, such as the clay unit found mainly in the Rasa Hassis area (see Main Map), due to their small surficial exposure and/or their geomorphology. Thus, ground-truth data were essential for such areas in order to obtain the most accurate information.

Taking into consideration different criteria such as the textures identified from our field observations and age of sediments based on previous geological dating (Figure 3), we divided the area into: (1) sand and/or silt, (2) sandy limestone, (3) reef limestone, and (4) clay containing gypsum or anhydrite. In this approach, a subclass of the Quaternary limestone (Blank, Johnson, Gettings, & Simmons, 1985; Dabbagh et al., 1984; Khalil, 2012) which is the major lithologic unit on the islands was divided into two classes (sandy limestone and reef limestone) because of the different texture in these units. Clay and evaporate deposits (mainly gypsum and anhydrite beds less than 0.5 m thick cropping out beneath the coral reef limestone) are all older formations (Tertiary/Miocene), as determined by previous studies (e.g. Almalki & Bantan, 2015; Coleman, 1993; Dabbagh et al., 1984; Skipwith, 1973). Overall, our interpreted map (Main Map) makes a good distinction between different geomorphic and geologic features of the Farasan Islands, particularly the reef limestone, sandy limestone, and coastal sediments.

3.4. Lineament mapping

Lineament analysis is an important part of geological mapping (e.g. Kassou, Essahaouai, & Aissa, 2012) and methods for extracting lineaments using remote
sensing techniques are well known (Hubbard, Mack, & Thompson, 2012; Nagal, 2014; Okereke, Ikoroh, Chinyere, & Okorafor, 2015; Rameshchandra Phani, 2014). Automated techniques have been used to detect lineaments from satellite images (e.g. Wang & Howarth, 1990; Zlatopolsky, 1992), but visual interpretation and manual digitization is still the most effective way to extract geological lineaments because most automatic techniques cannot differentiate between geological and non-geological lineaments (e.g. roads). Therefore, we visually identified most of the islands’ lineaments (see Main Map) from field work and digitized them using both Landsat-8 and WorldView-2 images. Nevertheless, the previously described image enhancements allowed us to map a large number of geological lineaments.

Two major lineament structures were recognized from the resulting map, including faults or fractures and dome-like structures which may relate to salt deformation (e.g. Almalki & Bantan, 2015; Dabbagh et al., 1984). The highest density faults or fractures identified were oriented in an NW–SE direction, corresponding to the overall direction of structures in the Red Sea area. In general, the faults give rise to linear ridges and form sharp topographic features more than 20 m high in some places. Salt domes range from 3 to 35 km in diameter, forming elliptical or circular shapes and bounded by linear fractures dipping towards the center of the dome; it has been suggested that this pattern formed as a result of diapirism (e.g. Almalki et al., 2015). Based on our field observations it is clear that the morphology of the coast is affected by diapirism (e.g. Dullo & Montaggioni, 1998). Further, some of the lineaments near to the coastline have been interpreted to represent palaeoshoreline features as a result of sea-level change (Almalki & Mahmud, 2017).

4. Conclusions

The Farasan Islands, off the Red Sea coast of Saudi Arabia, represent a complex geological platform as multiple tectonic forces led to the formation and structural architecture of the islands. We used remote sensing data and ground-truthing to map the geological features of these islands. The satellite images were an effective data source that facilitated the preparation of lithological and lineament maps. Our new geological map expands the known scope and detail of the islands’ geology by dividing the area into four lithological units: (1) sand and/or silt, (2) sandy limestone, (3) reef limestone, and (4) clay containing gypsum or anhydrite; previous maps distinguished at most two lithologic units. The digital processing techniques used to prepare this new map included enhancement, false- and true-color composites, and ratio stretching as well as supervised techniques. Composites of bands 7, 5, 3 and 5, 6, 7 displayed as red, green, and blue, respectively, from Landsat-8 images were useful for mapping different units within carbonate lithologies. The band ratio combination 5/7 was very successful in discriminating between different lithologies. Open-source high-resolution WorldView-2 satellite imagery was useful for constraining the boundaries of geologic features. The resulting geological lineaments map of the Farasan Islands improves our understanding of local structural features and their relationship with the regional geological setting. Our higher quality geologic data may influence management choices in tectonically and environmentally sensitive areas like the Farasan Islands.

Software

ESRI ARCGIS 10.3 was used to process the Landsat 8 data and construct and lay out the geological maps.

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Disclosure statement

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