

# Geological Mapping Using Morphological Characteristic of Lithostratigraphic Units through Radar Remote Sensing

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## Abstract

Traditional field-based methods for geological mapping have become obsolete and are now primarily used for quality control purposes. Geological maps at various scales are currently generated using remote sensing technologies and satellite image processing. In optical remote sensing, only hyperspectral images are typically employed for geological purposes; however, due to their limited spatial resolution, fieldwork is still required to supplement morphological and lithological information. Synthetic Aperture Radar (SAR) data, as part of microwave remote sensing, provide surface geometry and allow discrimination of alteration zones based on material composition. To achieve this, backscatter modeling of radar waves according to surface material and roughness is essential. Several models, ranging from theoretical to semi-empirical, have been proposed for this purpose. This study evaluates the effectiveness of surface geometry modeling and its impact on the accuracy of alteration zone delineation in the geological structures of Khoumroj, Kuh-e Siah, and Khartang. Based on the computations, the deviation between radar-based alteration zone delineation and ground truth is estimated at less than 10% for formations with rugged lithology and around 25% for those with softer lithological compositions. Overall, this method is strongly recommended as a substitute for field surveys in the final stages of geological map production following spectral analysis.

**Keywords:** Synthetic Aperture Radar (SAR), Lithology, Morphology, Geological Mapping

## 1. Introduction

Field surveys play a vital supporting role in geological mapping with hyperspectral remote sensing. They help refine the boundaries between rock formations and add detailed lithological (rock-type) information. However, hyperspectral images often lack the spatial resolution needed to distinguish between different rock types, especially in areas with complex geology. Some formations weather and erode more easily than others, soft rocks like marls and clays form smooth surfaces, while harder rocks like gypsum or anhydrite resist erosion and appear rugged. This contrast in surface roughness is crucial for geological interpretation, but it's not visible in standard optical or hyperspectral imagery.

While high-resolution optical images can theoretically capture surface texture, using them across large geological regions is costly and inefficient. Moreover, relying solely on optical data makes it difficult to identify overlapping formations and produce accurate maps.

Radar imagery, specifically microwave remote sensing, offers a powerful alternative. Radar sensors detect surface geometry and roughness through backscattered signals and polarization, allowing us to distinguish materials based on texture and

structure. Unlike optical sensors, radar works regardless of sunlight and can penetrate clouds, making it ideal for continuous monitoring. By modeling radar backscatter in different polarizations, we can quantify surface roughness and separate geological zones based on their erosional features.

Because optical imagery alone can't reliably identify lithological boundaries, due to differences in composition, weathering resistance, and erosion, this study turns to radar's ability to detect geometric patterns. We use models based on surface dielectric properties and micro-relief to enhance geological interpretation.

Specifically, we apply the Integral Equation Model (IEM) to X-band Synthetic Aperture Radar (SAR) data from the TerraSAR satellite. Our study focuses on the Khoumroj, Kuh-e Siah, and Khartang anticlines in the Inner Fars region of the Zagros Fold-Thrust Belt. We evaluate how well radar data improves the mapping of alteration zones and overall geological accuracy. While SAR's ability to distinguish surface roughness depends on rock type, the results for this region are presented in detail.

## 2. Backscatter Modelling and Surface Parameters

The radar backscatter from terrain surfaces is influenced primarily by two factors: surface geometry (i.e., roughness or

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smoothness) and the dielectric properties of the material. The relationship between the backscattered radar signal and these surface variables can be expressed through empirical, semi-empirical, or theoretical models (Hajnsek, 2007).

### 2.1. Methodology for Surface Roughness Characterization

Radar signal polarization allows for differential backscatter based on both surface geometry and moisture content. However, these differences are not readily visible in SAR images and require modeling to interpret effectively. One of the most widely used models in this regard is the Integral Equation Model (IEM). According to Fung et al. (1992), the IEM relates the radar backscattering coefficient to surface roughness parameters, a constant dielectric value, and the local incidence angle. The co-polarized backscattering coefficient, as defined in the updated formulation by Fung et al., is given by (Fung,2004) (Eq.1):

$$\sigma_{pp}^0 = \frac{k^2}{4\pi} e^{-2k^2\sigma^2\cos^2\theta} \sum_{n=1}^{+\infty} |I_{pp}^n|^2 \frac{W^{(n)}(2k\sin\theta \cdot 0)}{n!}$$

Where:

$$I_{pp}^n = (2k \sigma \cos\theta) f_{pp} \exp(-k^2\sigma^2\cos^2\theta) + (k \sigma \cos\theta)^n F_{pp}$$

- $pp$  refers to polarization (either  $hh$  or  $vv$ )
- $k$  is the wave number,
- $\lambda$  is the radar wavelength,
- $\theta$  is the local incidence angle,
- $\sigma$  is the root-mean-square (rms) surface height (roughness),
- $W^{(n)}$  is the Fourier transform of the  $n$ -th power of the surface autocorrelation function (Ghafouri,2017),
- $f_{hh}$ ,  $f_{vv}$ ,  $F_{hh}$ , and  $F_{vv}$  are polarization-related scattering terms as described in the referenced works.
- $R_h$  and  $R_v$  are Fresnel reflection coefficients,
- $\varepsilon$  is the surface dielectric constant (Barret,2009)

Due to the nonlinear nature of Equation (1), analytical inversion for retrieving surface parameters is not feasible. Therefore, empirical or semi-empirical methods must be employed. One of the most effective approaches is the use of a lookup table. In this method, backscatter values are precomputed for a range of surface roughness and dielectric constants using Equation (1), and the surface parameters are then retrieved via reverse matching from this lookup table (Mazaheri,2014).

### 3. Study Area and Data

To implement the proposed methodology, three geological structures, **Khourmoj**, **Kuh-e Siah**, and **Khartang**, located in Fars Province, southern Iran, were selected as the study area (Figure 1). The Khourmoj, Kuh-e Siah, and Khartang anticlines are located within the Inner Fars zone of the prolific Zagros Fold-Thrust Belt (ZFTB). According to the comprehensive geological mapping and synthesis by the Geological Survey of Iran (GSI) and global studies from entities like the U.S. Geological Survey (USGS) and the World Geological Map (CGMW), the structural

architecture of this region is characterized by a series of parallel, NW-SE trending anticlines and synclines.

These folds formed primarily during the Miocene to Pliocene epochs due to the collision of the Arabian and Eurasian plates. The deformation involves a thick sequence of Phanerozoic sedimentary rocks, particularly from the Cambrian to the Pliocene, which have been folded over a layer of Late Precambrian to Early Cambrian Hormuz salt, acting as a major decollement horizon. This structural style defines the "Simply Folded Belt" of the Zagros, where the anticlines of interest represent typical structural traps for hydrocarbons and clearly expressed geomorphic features.

Lithologically, the stratigraphic column exposed in these anticlines, as detailed in GSI quadrangle maps and corroborated by international petroleum industry studies, is dominated by a succession of Cenozoic carbonate and evaporite rocks. The core of the anticlines often exposes the Eocene to Oligocene Asmari Formation and the younger Miocene Gachsaran Formation. The Asmari Formation, a primary reservoir rock in the Zagros, consists of massive, fractured limestone and dolomite.

Geographically, the area lies within the coordinates of **E 51° to E 52° longitude** and **N 28° to N 29° latitude**, situated in the *coastal Fars zone* of the Zagros Fold-Thrust Belt, southwest Iran. The approximate positions of ground-truth measurements are shown in Figure 1 overlaid on a Google Earth image.

Microwave data used in this study were acquired from TerraSAR-X satellite in X-band with **dual polarization** (HH and VV). Based on the formulation provided in (Ghafouri,2017), radar backscatter coefficients can be calculated directly from the SAR imagery.

In addition, geological formation boundaries were extracted and verified using a **1:50,000-scale geological map** and stratigraphic cross-sections provided by the **Exploration Directorate of the National Iranian Oil Company (NIOC)**.

### 3.1 Field Measurements and Morphological Profiling

To better understand the rocks in our study area and how their surfaces behave, we spent time in the field walking along carefully selected paths, known as geological transects. These routes were chosen to follow the natural contours of the land, which meant they often curved, dipped, or changed direction to match the terrain's shape. As we moved along each path, we observed where one type of rock ended and another began, recording the sequence in which different formations appeared. We also paid close attention to how each surface felt, whether it was rough, smooth, jagged, or soft, and documented these textures for every rock type we encountered. This helped us connect what we saw in the rocks to how the land itself was shaped.

To make sure our observations were accurate and consistent, we used a standardized approach. We logged the GPS coordinates of each measurement point and took photographs to visually document the textures and transitions we observed. These steps helped us confirm that the changes in surface texture truly

reflected differences in rock type. We also collected rock samples from important spots along the way. Back in the lab, we analyzed these samples to double-check our field interpretations and to learn more about their physical characteristics, like what minerals they contained, how coarse or fine the grains were, and how porous the rocks were. By combining what we saw in the field with what we learned in the lab, we gained a much clearer picture of the geological diversity in the area.

This rigorous field campaign was specifically designed to create a robust "ground truth" dataset for calibrating our radar backscatter model. The measured surface roughness (RMS height) for each lithology, detailed later in Table 1, served as the essential validation point against which the IEM model's estimates were compared. For instance, the pronounced textural contrast we documented between the rugged, blocky outcrops of the Bakhtiari Conglomerate and the smooth, weathered slopes of the Mishan Marl provided a clear physical basis for understanding the differing radar backscatter responses from these units. Without this direct field verification, the model's outputs would remain abstract numerical values; our fieldwork anchored them in observable geological reality.

Furthermore, the transects were strategically planned to cross critical geological boundaries that are notoriously difficult to map using optical data alone. A key objective was to traverse the contacts between formations like the Sarvak and Ilam, which are spectrally similar but often differ in erosional resistance and micro-topography. By physically walking and measuring across these transitions, we were able to capture the subtle, yet cartographically crucial, morphological shifts that signal a change in lithology. This approach proved invaluable for testing the core hypothesis of our study: that SAR data could detect these texture-based boundaries where hyperspectral imagery fails, thereby adding a decisive layer of information for refining the geological maps of the complex Zagros Fold-Thrust Belt. **Figure 1** shows the locations of the surveyed profiles, overlaid on a geological map and a high-resolution SPOT satellite image of the area.

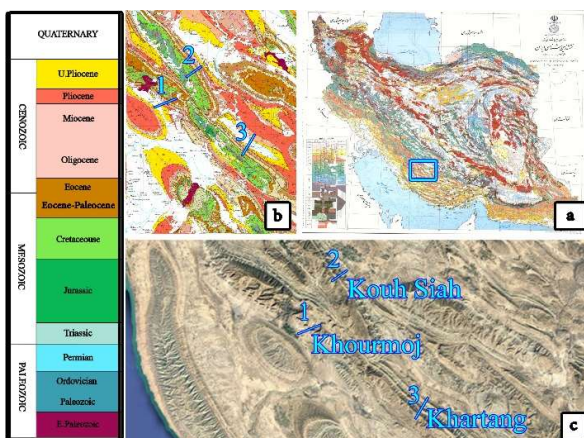


Figure 1. Location of the study area over the geological structures of *Khourmoj*, *Kuh-e Siah*, and *Khartang*, within longitudes **E 52° to E 54°** and latitudes **N 28° to N 30°**. (a) Position of the study area on the geological map of Iran. (b) Measurement sites 1, 2, and 3 on the regional geological map, including lithostratigraphic

sequence legend. (c) Sites 1, 2, and 3 along with structural names overlaid on a SPOT satellite image.

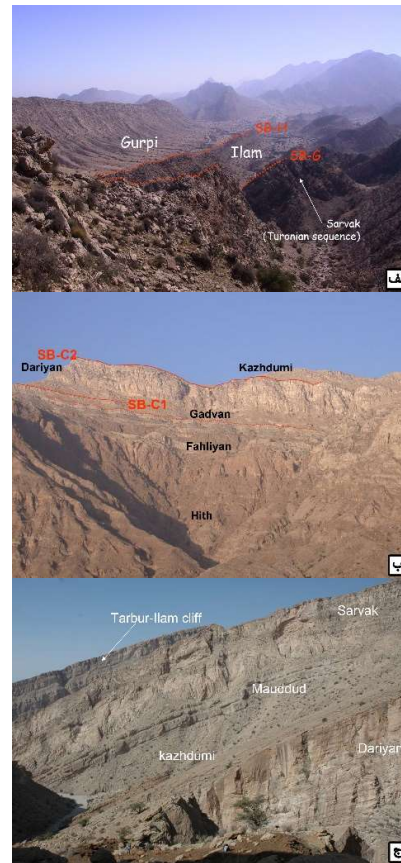


Figure 2. Stratigraphic sequence of geological formations overlaid on images of the study area.

The arrangement of lithostratigraphic units along the transect is shown in Figure 3. Additionally, the approximate RMS surface roughness height for each lithostratigraphic unit along the transect is detailed in Table 1.

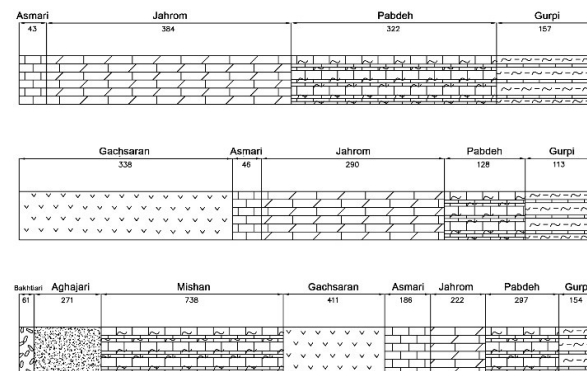


Figure 3. Morphological lithology measurement profiles in the study area based on stratigraphic cross-sections 1, 2, and 3, whose locations are shown in Figure 1 on the geological structures of *Khourmoj*, *Kuh-e Siah*, and *Khartang*, respectively.

Among these formations, the boundary between certain units, such as the Sarvak and Ilam formations, is not distinguishable using optical imagery due to their very similar chemical compositions. The backscattered spectral signatures of these lithostratigraphic units are nearly identical, making them inseparable by spectral methods. However, their surface roughness differs, which can be detected through the RMS height measurements of surface roughness.

Section No.	Section ID	Structure	Formation	From (m)	To (m)	Thickness (m)	Dominant Lithology
1	F12-045	Khourmuj	Asmari	0	43	43	Limestone
			Jahrom	43	427	384	Dolomite
			Pabdeh	384	706	322	Argillaceous Limestone / Marl
			Gurpi	706	863	157	Limestone / Marl
2	F12-025	Kuh Siah	Gachsaran	0	338	338	Gypsum
			Asmari	338	384	46	Limestone
			Jahrom	384	674	290	Dolomite
			Pabdeh	674	802	128	Marl
			Gurpi	802	915	113	Limestone / Marl
3	F12-063	Kuh Khartang	Bakhtiari	0	61	61	Conglomerate
			Aghajari	61	332	271	Sandstone
			Mishan	332	1070	738	Marl
			Gachsaran	1070	1481	411	Gypsum
			Asmari	1481	1667	186	Limestone
			Jahrom	1667	1889	222	Dolomite

Table 1. Field measurements of surface roughness for geological lithostratigraphic units along stratigraphic cross-sections (Martinez,1999).

### 3.2. Surface Roughness Estimation

Radar backscatter modeling is primarily dependent on surface roughness parameters and the dielectric constant. Considering the dry climate conditions at the time of sensor acquisition and the well-known lithology of the study area based on existing geological maps, constant dielectric values ( $\epsilon$ ) were adopted from referenced dielectric measurement studies (Mazaheri,2017) for use in calculations. By assigning this parameter in Equation (1), the dielectric constant can be treated as a known value, thereby reducing the number of unknowns in the equation from three to two.

No.	Lithology	Dielectric Constant ( $\epsilon$ ) study1	Dielectric Constant ( $\epsilon$ ) Study2	Dielectric Constant ( $\epsilon$ ) Study3
1	Dolomite	4	5	10
2	Limestone	7	17.5	14.1
3	Limestone / Marl	5	22.9	7.9
4	Gypsum	10	12.7	14.1
5	Conglomerate	7	17.5	14.1
6	Marl	25	6.4	5.1
7	Argillaceous Lst. / Marl	21	7.9	6.5
8	Sandstone	14	12	10.5

1	Dolomite	4–6	3–5	5
2	Limestone	4–6	2–6	5
3	Limestone / Marl	4–6	4–8	5.5
4	Gypsum	–	–	6.5
5	Conglomerate	5	–	4
6	Marl	10–11	–	9.5
7	Argillaceous Lst. / Marl	–	4–5	2
8	Sandstone	2–3	3–4	3

Table 2. Dielectric constant ( $\epsilon$ ) values for lithologies present in the study area based on various references.

Therefore, the difference in surface roughness is an effective parameter causing variation in radar backscatter from lithostratigraphic unit surfaces. This roughness is characterized by two parameters:  $\sigma$  (the root mean square height deviation of the surface, rms-height) and  $l$  (the correlation length as the surface autocorrelation function parameter). With availability of dual-polarization images, a system of two equations with two unknowns can be solved, enabling the calculation of surface roughness parameters.

By applying classification based on the computed roughness parameters, a geomorphological map can be generated. The estimated surface roughness from the IEM model varies along the transect according to the color scale provided in the legend. The discrepancy between the roughness values calculated by the IEM radar backscatter model and approximate ground measurements, as summarized in Table 3, is generally less than 15%, except for the Quaternary alluvium which shows a deviation of approximately 35%.

Lithostratigraphic Unit	Bakhtiari	Aghajari	Gachsaran	Jahrom	Asmari	Pabdeh	Gurpi	Mishan	Aghajari
Dominant Lithology	Marl	Sandstone	Conglomerate	Gypsum	Dolomite	Limestone	Argillaceous Limestone / Marl	Marl	Sandstone
Field-Measured RMS Height (cm)	50.9	18.8	24.1	14.1	6.5	15.3	5.1	10.5	
IEM Model-Estimated RMS Height (cm)	49	17.5	22.9	12.7	7.9	14.1	6.4	12	
Percentage Difference (%)	4%	7%	5%	10%	21%	8%	25%	14%	

Table 3. RMS height measurements for lithologies present in the study area.

#### 4. Improvement of Alteration Zones Discrimination

By using the IEM model to analyze radar data, we can now measure the surface texture of rock formations and combine this with their chemical makeup from spectral images. This combined approach is a game-changer for telling apart different alteration zones, which often look the same spectrally but have very different physical textures. For instance, our method clearly separated the rough, durable Bakhtiari Conglomerate from the much softer Mishan Marl, a distinction that would be nearly impossible using optical imagery alone. In essence, by giving us a concrete number for surface roughness, the radar data provides a reliable, physical way to draw boundaries that were once blurry on geological maps.

This new layer of morphological information makes our geological maps significantly more accurate. For tough, rocky units, our radar-based boundaries were over 90% correct compared to field data. This is a major upgrade from maps based only on spectral data and means we can drastically cut down on the time and cost of sending teams into the field for verification. Furthermore, because we can now detect fine-scale textures, we can produce maps at a much higher resolution, revealing subtle variations and small-scale features within formations that were simply invisible before.

Ultimately, this technique adds a vital new tool to the geologist's toolkit. While traditional methods are great for identifying minerals, they miss the textural story written by erosion and rock strength. Our radar-based approach fills that gap, creating a much more complete and trustworthy picture of the subsurface. This was proven in the challenging terrain of the Zagros mountains, where it successfully told apart rock layers that had fooled other methods. It shows that this isn't just an extra step, but a powerful core method for drawing precise maps. This lets us use our field resources smarter, targeting only the most complex areas instead of surveying everything. Looking ahead, this approach can be used in any dry, exposed region around the world. The next step could be to combine different radar frequencies to analyze texture at multiple scales. By fusing radar's eye for shape with spectroscopy's eye for composition, we are moving closer to a future of highly automated, precise geological mapping, making it easier and faster to explore even the most remote landscapes.

#### 5. Conclusion

Although processing optical satellite imagery has been the primary method for producing and improving geological maps in recent years, it lacks the capability to discriminate lithological textures, surface morphology, and alteration zones based on material properties. In this regard, microwave remote sensing or radar remote sensing using Synthetic Aperture Radar (SAR) imagery can be employed to acquire this information by estimating surface roughness.

The capability to discriminate lithological texture, surface morphology, and alteration zones is an opportunity offered by SAR data processing. Different frequency bands provide roughness/softness or surface morphology information at various

scales. In this study, X-band TerraSAR data with dual polarizations (HH and VV) were utilized. Using lower resolution C-band data alongside the X-band may also enhance discrimination.

For lithological unit discrimination using microwave data technology, microwave backscatter from the Earth's surface must be modeled based on material type and surface roughness. This study employed the Integral Equation Model (IEM), one of the most commonly used models in this field, and evaluated its capability to distinguish alteration zones in the Khoumroj geological structure through field measurements on existing stratigraphic sections.

Higher accuracy of the proposed method was observed for the Bakhtiari, Mishan, and Aghajari formations, indicating its better suitability for lithologies with predominantly rougher behavior. In contrast, discrimination of the Pabdeh formation showed higher error rates, a fact also confirmed in referenced studies. Overall, this level of accuracy in the workflow for preparing and completing geological maps is notable. Undoubtedly, using microwave remote sensing imagery is an effective step in enriching geological mapping processes, significantly reducing the volume of field operations.

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