A proposed new Precambrian skarn deposits in the Arabian shield

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Research Article

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Abstract

The volcanosedimentary arc-related skarn deposits are the predominant types in the Arabian Shield (AS). However, the post-amalgamation extraordinary marine basins with carbonate successions exist in the AS, intruded by different types of granite plutons, and dissected by major shear zones. Therefore, all the recipes for skarn deposits are mature at the contact between the carbonate succession in the marine molasse basins and granite plutons. Magnetic data and ASTER data were integrated with the geochemical database to locate the preliminary areas for further exploration in the Murdama basin. The Murdama basin (72,000 km$^2$), which is the locality for the Murdama limestone, has a higher magnetic anomaly at the contact with post-Murdama granite batholiths, but the magnetic anomaly becomes significant at the contact with the Idah granitic suite. The shallow-seated structural magnetic lineaments within the Murdama basin and at the eastern boundary of the basin are controlled by the Najd fault system (NFS). The calc-silicate mineral alteration zones were evolved at the contact between the Murdama group and the Idah suite, with no extent for the alteration zones along the fracture network or at the contact with the Abanat suite. Meanwhile, the Idah suites are the causative plutons for the Qitan and An Nimriyah South reduced skarns that were recorded from the Murdama basin. The preliminary results from this study based on the integration of different datasets suggest the existence of reduced skarn deposits at the contact between the Murdama basin and Idah causative plutons.

1. Introduction

Skarn deposits are irreplaceable sources for Sn and W, have significant provenance for Mo, Pb, Zn, Cu, Au, and Fe, and provide REEs, U, F, and Ag (Jiang et al., 2019; Meinert, 1995, 1997). These deposits are substantial for industry, including high-tech equipment, defense systems, renewable energy, and transport. There are four main factors controlling the formation of skarn deposits: Firstly, the causative intrusion type and volatile content, degree of fractionation, and redox state of the magma (Legros et al., 2020; Shu et al., 2019). Secondly, the wall rock permeability and structures that provide pathways for the fluids; the composition of the wall rock; and its redox state (Chang et al., 2019; Nie et al., 2022). Thirdly, the distance from the intrusion (Chang et al., 2019), and fourthly, the depth of the formation at which skarn deposits had evolved (Meinert et al., 1997; Zhou et al., 2017). The metal association depends mainly on the fractionation of the magma and the redox state of both the magma and country rocks (Meinert et al., 1997). Accordingly, the metal association is classified into four categories: 1) Mo – W – Cu – Zn – Pb, and this type exists in oxidized, moderate to strong fractionation conditions (Chang et al., 2019; Ma et al., 2017); 2) Fe – Cu (± W) – Au – Zn – Pb, and this category favors oxidized, weak to moderate fractionation condition (Chang et al., 2019; Fitzherbert et al., 2021); 3) Sn – W – Zn – Pb, and this type occurs in reduced, strongly fractionation environment (Jiang et al., 2019); 4) Au – Zn – Pb, and this association exists in reduced, weak to moderate fractionated conditions (Chang et al., 2019).

The Arabian-Nubian Shield (ANS; Fig. 1) is considered as a high-stand land during Gondwana assembly ca. 630 Ma, perhaps except for the eastern part of the Arabian Shield (AS) (Johnson et al., 2011). The eastern part of the AS was a low-stand tract with voluminous marine basins of a Neoproterozoic age,
intruded by different phases of intrusions. The contact between igneous intrusions and the Neoproterozoic marine sediments in the post-amalgamated molasse basins is proposed to be a target for economic ore deposits, including Au, Ag, Cu, Mo, W, and Fe. Up to 55 g/t Au (average 7–10 g/t) were recorded from skarn deposits in NE Russia (Goryachev et al., 2018), and Ag with a grade of 113 g/t were estimated from Mongolian skarn deposits (Batkhishig, 2021).

Skarn deposits exist in volcanosedimentary arc-related successions in the Arabian Shield, except for Jibal Qitan, An Nimriyah South, and Kirsh skarn localities (Fig. 2). Al-Madhiq calcic skarn evolved at the contact between granite and mixed volcanosedimentary succession (Ahmed, 2002), where major shear zones played as pathways that facilitate the circulation of fluids. Al-Madhiq skarns are a proximal exoskarn that evolved in oxidized conditions and hosts W (Ahmed and Hariri, 2006). Bahrah garnetiferous skarn are pertain to an island arc setting, with sheared and brecciated wall rock, and the ore deposits evolved as a result of superimposed thermal metamorphism events (Surour and Moufti, 2011). Jabal Ash Shumt skarn is located in the Hulayfah group, which is an island-arc volcanosedimentary succession, and the skarn deposits are attributed to granite plutons and regional metamorphism events (Moufti, 2013). Other localities for the arc-related successions that host skarn deposits include Al Amar, Hamra, As Safra, Bi‘r Ash Shumt, and Jabalul Hamat (Table S1). Jibal Qitan garnetiferous skarn is located at the contact between Qitan granite and the Murdama group limestone (Miller and Arnold, 1988). Sn - W mineralization is dominant in Qitan skarn, and there’s a possibility for potential mineralization in the subsurface at the contact between granite and the Murdama limestone (Miller and Arnold, 1988). There are different types of post-Murdama granites, so there’s a higher possibility for the skarn deposits at the contact between these intrusions and the Murdama limestone.

ASTER data have been used extensively for the lithological mapping and exploration of alteration minerals (Abrams and Yamaguchi, 2019; Aboelkhair et al., 2020; Ghazala et al., 2021; Aboelkhair et al., 2021). The reconnaissance of hydrothermal-related alteration zones was conducted for different ore deposits using ASTER data, including skarn deposits (Cudahy et al., 2002; Liu et al., 2012; Moradpour et al., 2022; Yajima, 2014), porphyry copper (Beygi et al., 2021; Chen et al., 2021; Wang et al., 2020), and volcanogenic massive sulphide (Rajendran and Nasir, 2017). Furthermore, ASTER data were used to identify minerals, such as carbonate and quartz (Ninomya, 2003; Ninomya et al., 2005; Rockwell and Hofstra, 2008), and the ferric iron oxides (Rowan and Mars, 2003). Magnetic data were used for lineament mapping (Abdullahi et al., 2019; Eldosouky et al., 2022; Essa et al., 2022; Essa and Elhussein, 2019, ), at different crustal levels (Eldosouky et al., 2022; Sehsah et al., 2022), and estimating the depth (Abdelrahman et al., 2003a&b, Abdelrahman and Esaa, 2005). Furthermore, magnetic data has been used for estimating the sedimentary cover thickness (Aboud, 2012), and ore deposits exploration (Essa et al., 2022; Gobashy et al., 2020; Mehanee et el., 2021;Yang et al., 2020). Consequently, magnetic data has been applied to skarn deposits exploration (Gunn and Dentith, 1997; Martelet et al., 2021).

Therefore, undertaking such a detailed study to locate skarn deposits in the Murdama basin based on different datasets, which is the largest post-amalgamation marine basin in the ANS with intercalation of limestone, will propose new areas for prospecting, and this is the first time to undertake such a study. The
primary objective of this research work is to investigate economic skarn ore deposits using the integration of geologic studies, potential data analyses, and remote sensing data.

2. The Geologic Setting of Murdama Basin

The Murdama basin covers an area of about 72000 km$^2$ and is located in the Afif Terrane (Johnson, 2003). The basin is the largest in the ANS, lies above the pre-Neoproterozoic Khida terrane to the west, is covered by Cenozoic cover to the SE, and consists of a thick volcano-sedimentary succession (Johnson et al., 2011). The basin consists of two units; Afif formation at the base of the basin; and this lower unit consists of calc-alkaline acidic to basic volcanic rocks; and the Murdama group lies at the top of the basin and consists of sedimentary sequence, mainly sandstone, conglomerate, and limestone (Johnson, 2003; Johnson et al., 2013). The Murdama basin lies unconformably above Cryogenian rocks, namely the Dhiran formation, Nafi formation, Hillit formation, Dhukhnah gneiss, Rika formation, Tays formation, Kabid formation, Khishaybi suite, Nasaf suite, Jidh suite, Labab and Kilab complexes, Suwaj suite, and Surayhah complex. The Murdama basin overlayed by the Jibalah group, the Jurdhaiya group, and Ediacaran rhyolite; the basin is intruded by the Al Khushaymiyah complex, the Idah suite, the Abanat suite, the Ruwaydah suite, Gharamil monzogranite, Uraynibi syenogranite, and the Haml suite of alkali feldspar granite.

Najirah granite is a volcanic arc granite that evolved in an active continental margin setting (Robinson et al., 2015). Najirah granite is exposed in the eastern part of the AS, and exists as two large batholiths intruding Ad Dawadimi terrane. There's no direct contact between the Murdama limestone and Najirah granite in the study area, but these two batholiths underlie the Abt formation. Najirah granite is pre-Abt formation, but both the Abt formation and Najirah granite are dissected by the Ar Ruwaydah suite. Idah suite is small plutons that are exposed in the eastern part of the AS; this type of granite is limited to the Afif and Ha'il terranes, dissecting mainly the northern part of the Murdama basin, with no record in the southern part of the Murdama basin. The Idah suite is mainly alkali granite that evolved as a post-orogenic granite (Robinson et al., 2015). The Al Khushaymiyah complex is exposed in the Afif terrane, with no record in other terranes. The intrusion volume increases southward and dissects the central and southern parts of the Murdama basin, with no extent northward. The Abanat suite is a post-orogenic granite that exists mainly in the Ha'il, to the north of the Afif terrane, and the distribution of such magmatism decreases southward in the Afif terrane. Abanat plutons dissect the central and northern parts of the Murdama basin (Fig. 3). The Khishaybi suite is a relatively large batholiths that exist in the Afif Terrane, dissecting the northern part of the Murdama basin. The Murdama basin is graded from older volcanosedimentary succession at the base of the basin in the west to younger marine at the eastern margin (Johnson et al., 2011). Skarn deposits exist in the eastern part of the AS, and the wall rock conditions are controlled by faults and shear zones that pertain to the Najd fault system (NFS). The NW direction of the mineral zones is attributed to the NFS, which facilitates the circulation of fluids, and the emplacement of post-orogenic granites. However, there are different types of post-Murdama granites, but the Al Khushaymiyah complex and Idah suite are the main causative plutons for the skarn deposits in the
Murdama basin (Table S1). The Idah suite is the causative plutons for the Jibal Qitan and An Nimriyah South reduced skarn while Al Khushaymiyah complex is the causative plutons for the Kirsh oxidized skarn in the Murdama basin (Fig. 2; Table S1). Therefore, there's a higher possibility for the skarn deposits at the contact between the Murdama group and the causative plutons of the Al Khushaymiyah complex and Idah suite.

3. Methodology

3.1 Magnetic Data

The magnetic method is dependent on changes in the earth's magnetic field caused by lateral variations in the magnetization of the subsoil (Hinze et al., 2013). Both contributions from sources at higher depths and contributions from sources of interest at lower depths can be found in magnetic measurements. Magnetic anomalies are used to map faults and analyze the structures that are the source of the anomalies (Eldosouky et al., 2020; Pham et al., 2022; Sehsah and Eldosouky, 2022; Sehsah et al., 2019; Sehsah et al., 2022). Reduce to the pole (RTP), regional-residual separation, analytical signal, and tilt derivative techniques are some of the processing techniques that were used to structurally analyze magnetic data.

In order to process and interpret the magnetic data, four advanced techniques were applied. Since these measurements are unreliable, it is impossible to evaluate magnetic raw data directly. Instead, to better display anomalies, the primary magnetic field must be removed and gradients must be computed. The methodical steps in the processing of magnetic data begin with the fast Fourier transformer's conversion of the corrected data from the space domain to the frequency domain (Geosoft, 2015). Reduction to the pole, regional-residual separation, tilt derivatives, and the analytical signal are some of these methods. To get more accurate results, these methods must be used before interpretations. If noise is present in the observed data, these methods based on the derivative of the field may produce different conclusions. The measurement uncertainty, the elimination of the main and external fields, and the estimation of the noise-enhancing gradients are some of the possible origins of this noise.

3.1.1 Reduced To the Pole (RTP)

The total magnetic intensity map (Fig. 4a) contains an embedded effect of latitude variation due to the dipole of the magnetic field. To reduce this effect, we transform the data to an imaginary location just above the magnetic pole of the earth. This transformation is referred to as reduction to the pole (RTP). The total magnetic intensity data are filtered to remove the dipolar effects of the total magnetic field of the earth to be reduced to the northern magnetic pole, using the inclination and declination values of 34.24 and 2.71, respectively. Except for a few anomalies that change their orientation to the north due to the elimination of the study area's declination, the reduced-to-the-pole magnetic map does not significantly differ from the total intensity magnetic map (Fig. 4b).
3.1.2 Analytical Signal Technique

The filtering or processing of an analytical signal is another technique for magnetic data that makes it possible to get additional information compared to those obtained from the magnetic map (Fig. 5a). The basement depth and subsurface structural trends directly above the borders of the magnetic sources are the main interest of this technique. This technique assumed that the presence of 2D structures was related to geologic contact, dike, and horizontal cylinder structures (Nabighian, 1972; Salem and Ravat, 2003; Salem et al., 2002). This method primarily depends on the magnetic field's first-order horizontal and vertical derivatives, as well as the magnetization's source direction. The horizontal location of the isolated sources is typically precise; however, only certain source types are accurate in terms of vertical position.

The square root of the sum of the squares of the vertical and horizontal derivatives of the total magnetic field is the definition of the analytical signal (AS) in its general form;

\[ AS = \sqrt{dx \ast dx + dy \ast dy + dz \ast dz} \]

where AS is the analytical signal, dx, dy, dz are the vertical and horizontal derivatives of the magnetic field.

3.1.3 Tilt Derivative Technique

Another method for enhancing subsurface structural magnetic lineaments and determining the depth of the basement contacts is the tilt derivative technique (TDR) (Fig. 5b). The source was considered to be a buried (2D) vertical contact model with vertical magnetization and no remnant magnetization (Salem et al., 2007). It is reliant on the overall magnetic field's vertical and horizontal derivatives over the geologic contact. Nabighian (1972) provides the following equation for the horizontal and vertical derivatives of these contacts, which are positioned at a horizontal location of \( h = 0 \) and at a vertical depth of \( z_c \):

\[
\frac{\partial M}{\partial h} = 2KFc \frac{zc}{h^2 + zc^2} \quad \text{and} \quad \frac{\partial M}{\partial Z} = 2KFc \frac{h}{h^2 + zc^2}
\]

where \( h \) and \( Z \) are the horizontal and vertical locations of the contact, respectively, \( K \) is the susceptibility contrast, and it is the magnitude of the magnetic field. The parameter \( c \) is given by \( c = 1 - \cos i \sin 2A \), where \( A \) is the angle between the positive h-axis and magnetic north, \( i \) is the ambient field inclination, \( \tan i = \tan i / \cos A \), \( d \) is the dip (measured from the positive h-axis), and all trigonometric quantities are in degrees. Substituting the above derivative terms into the tilt equation and assuming a reduced to the pole magnetic field, it can be shown that,

\[ \theta = \tan^{-1} \left[ \frac{\frac{\partial M}{\partial Z}}{\frac{\partial M}{\partial h}} \right] \quad \text{and} \quad \theta = \tan^{-1} \frac{h}{Zc} \]

According to the relationship between the horizontal location and the vertical depth, this equation suggests that the tilt angle value may range between 0 and 45 (zc). The tilt angle is zero above the geologic contact's borders (horizontal location = 0), and it is equal to 45 when the horizontal location (h)
equals the vertical depth \((zc)\). According to this equation, contact-like structures can be defined by the location \((h = 0)\) and depth (half the physical distance between 45 contours) of the magnetic tilt angle contours.

This method has four distinct advantages: (1) it can compute the depth of these geologic contacts and identify the most dominant structural trends; (2) it is less sensitive to noise because it depends on the first-order derivative as opposed to methods that use the second or third orders of derivatives; (3) it is not dependent on the window size selection like the Euler method, where there is no issue with solution clusters; (4) The distance between zero and \(+45\) or \(-45\) contours correlates to the depth to the top of the vertical contact model, whereas the half-distance between 45 contours approximates the source depth determined from TDR for vertical contacts (Salem et al., 2007).

### 3.1.4 Regional-Residual separation

After producing the RTP map, the Butterworth filter was used to extract the regional (deep-seated magnetic sources) (Fig. 6a) and residual (shallow-seated magnetic sources) (Fig. 6b) components from the observed total intensity magnetic measurements using Geosoft, 2015. The Butterworth filter is used to filter the current Reduced to the Pole Magnetic Data. The degree of the filter function is set to 8 (the default), and the central wave numbers of the filter are 0.03 and 0.042 (cycle/ground unit), respectively.

### 3.2 Remote Sensing Data and techniques

ASTER level-1B Registered Radiance at the Sensor (AST_L1B) and ASTER L2 Surface Reflectance VNIR and Crosstalk Corrected SWIR (AST_07XT) products images were downloaded from the NASA Land Processes Distributed Active Archive Center (LPDAAC). The image was acquired with a cloud cover 0.0% on December 04, 2002, at 07:48:29 am. All processing steps applied to satellite data were processed for geological and alteration mapping using (EXILIS ENVI 5.3) software. Various spectral mapping techniques were applied in the study area, including Spectral Information Divergence (SID), Spectral Angle Mapper (SAM) and Constrained Energy Minimization (CEM).

The highest-potential economic minerals are mainly associated with alteration zones. Field geological work revealed that these zones have a very limited spatial extent. Therefore, they are hardly discriminated against when using conventional processing tools. Hence, there is a need to discriminate the minerals associated with the alteration zones using more accurate spectral classification tools like SID, SAM, and CEM.

Spectral Information Divergence (SID) is a spectral classification technique that utilizes a divergence metric to compare pixels with reference spectra. If the divergence is small, then it is more probable that the pixels are similar. However, if the measurement exceeds the maximum divergence threshold, the pixels will not be classified (Chang, 1999). SAM is an automated classification technique that compares image spectra to known spectra or training classes. It computes the spectral angle between the image spectrum, which represents an unknown material, and the reference spectrum, which represents a known
material, treating them as vectors in n-dimensional spectral space where n denotes the number of bands (Kruse et al., 1993). The Constrained Energy Minimization (CEM) approach maximizes the response of the target spectrum while minimizing the response of all other features, treating them as an unknown background (Ren, et al., 2003).

In the current study, the Spectral Information Divergence, Spectral Angle Mapper, and Constrained Energy Minimization techniques were applied to both VNIR-SWIR stack datasets to discriminate included alteration zones in the study area, and the spectra of the JPL library spectra were resampled to match the ASTER VNIR-SWIR spectrum. These spectral mapping techniques were used for alteration mineral mapping in the study area, including wollastonite, garnet, pyroxene, and epidote.

4. Results

4.1 Magnetic anomalies and fluid pathways framework

One of the most popular geophysical methods for examining the Earth's interior is the magnetic method (Aboud, 2012; Essa and Diab, 2022a, b; Essa and Elhussein, 2017; Essa et al., 2022). It can be used to solve a wide range of subsurface exploration issues, including those involving horizontal magnetic differences between the base of the Earth's crust and the top meter of soil. In order to evaluate a magnetic map qualitatively, one must first visually examine the shape, trend, and defining characteristics of each individual abnormality. The sharpness of the anomaly is revealed by the anomaly's sharpness and the contours' length and aerial extent (Nettleton, 1976). The total magnetic intensity map (TMI) of the study area with a scale of 1:25000 is suitable for representing most of the magnetic anomalies in the study area. This map displays a sharp shift in magnetic intensity, which could be a result of changes in lithology or basement topography, and depicts an alternating collection of high and low magnetic anomalies with various amplitudes, patterns, and wavelengths. The study area has magnetic values between −210 and 42nT. The research area's southeast, southwest, central, northeastern, and northwestern regions (Fig. 4a) are home to circular and elongated magnetic anomalies with the highest amplitudes (42nT) (pink1 hue). These elongated, circular symmetry outlines are the result of a geologic body. It can be a plug or a dyke, and the elongation should show the strike's direction (Reford and Sumner, 1964). Due to the existence of a thick sedimentary succession of homogenous rocks, the study area's southwest and center had the lowest value of magnetic anomalies (-210nT). The alternating of negative and positive magnetic anomalies suggests the presence of fault contact that divides the study area into multiple blocks with various magnetizations.

The studied area's lithological variety and the existence of a dense sedimentary succession in its central and southeast regions both contribute to the uneven distribution of magnetic values there. The research area is characterized by a wide variety of magnetic values, as seen by the reduced-to-the-pole magnetic map, which spans from (-227 to 120 nT). The studied area's highest magnetic amplitude value is 120nT, which is distributed throughout (pink color), while its lowest value, which is present in the central and southwest (blue color) and is directed in the NE-SW direction, is -227nT. (Fig. 4b). There are a lot of high
anomalies (red in color) in the studied area's northwest and southeast, which are oriented N-S and NW-SE, respectively.

There are different types of granitic plutons in the study area. They have higher magnetic anomalies than the anomaly related to the volcanosedimentary succession of the Murdama basin. Meanwhile, the Abanat suite has lower anomaly values than the Idah suite, which has the highest magnetic anomaly over the study area. Al Khushaymiyah complex has a higher anomaly similar to the Idah suite, and there's a high anomaly in the Murdama basin at the eastern part of the basin near Al Khushaymiyah, but Jurdhawiya separates both of them. The NW linear extent of this anomaly predicts the presence of a structurally controlled intrusion at the subsurface; while the lowest magnetic anomaly exists in the western part of the Murdama basin.

The analytical signal enhanced the direction and extent of the anomalies along the peripheries of granitic plutons, where the Idah suite and Al Khushaymiyah complex have the higher border anomalies. Meanwhile, the AS confirmed the presence of a structurally controlled basement anomaly underneath the eastern part of the Murdama basin. There's a low anomaly in the RTP map that became a higher linear anomaly in the AS map with a NW direction at the contact between the Murdama and the Suwaj suite and to the SW of the Idah suite pluton in the eastern part of the study area.

The TD technique enhanced the subsurface structural magnetic lineaments; curved to relatively circular structural magnetic lineaments exist at the porphyries of granitic plutons. The Idah, Abanat suites, and Al Khushaymiyah complex have higher circular magnetic lineament with no exception. The eastern part of the Murdama basin has extensive subsurface lineaments with a NW trend and this may be related to the shallow depth of the subsurface basement. The later NFS related magmatism.

The regional separation unravels the presence of NE-SW deep-seated magnetic source, and this direction is parallel to the boundary between Ha'il and Afif terranes, so the source of the deep-seated anomaly may be derived from the arc-related basement. The highest anomalies related to the shallow-seated magnetic sources are located at the boundaries of the granitic plutons, and the results of such separation predict the existence of the Al Khushayimah complex at shallow depths underneath Jurdahawiya, below the eastern part of the Murdama basin. There are relatively high anomalies at the contact between the Idah and Abanat suites underneath the eastern boundary of the Murdama basin.

The analytical signal map (Fig. 5a) is more accurate in identifying the trends of these anomalies because it more clearly depicts the edges of magnetic anomalies when compared with the reduced pole magnetic map. This map shows that the higher AS values are found across the study region (in pink), while the lowest values are found in the northeastern portion of the study area (blue color). The NNW-SSE trend is the major trend resulting from the AS, which is related to the NFS trend. The tilt derivative map (Fig. 5b) can provide the principal trend more simply and plainly than the reduced to the pole magnetic map because it can be visually inspected and qualitatively interpreted to identify the edges of magnetic anomalies and fault contacts. The studied area is subject to a significant NNW-SSE subsurface structural trend.
The subsurface structural trends exiting in the RTP map (Fig. 4b) do not differ from those leaving in the Low-Pass (regional) magnetic map (Fig. 6a), i.e., they are consistent with the regional magnetic map. Several long-wavelength and low-frequency magnetic anomalies with various shapes, trends, and magnitudes may be seen on the regional magnetic map (Fig. 4a). The structure and makeup of the deep causal sources could be inferred from the form and frequency of these anomalies. The important subsurface structural trends that have an impact on the deep-seated structures are shown on the regional magnetic map. This map is characterized by two major sets of NE–SW and NNE–SSW trending faults. These subsurface trends are related to the NFS trend.

Many positive and negative magnetic anomalies can be found on the high-pass (residual) magnetic component map (Fig. 6b). These anomalies are primarily seen in the study area's center and western regions and feature semi-circular and elongated morphologies. In this image, there are numerous linear magnetic anomalies that are connected to shallow-seated tectonic formations. The trends bordering the residual anomalies are nearly NE–SW, N–S and NW–SE anomalies, which occupied the southern and western parts of the map area.

4.2 Types and extent of alteration minerals

Skarns are commonly formed by hydrothermal alteration at the contact between carbonate rocks and the causative granite magmas, and this interaction produces calc-silicate minerals such as wollastonite, garnet, and pyroxene (Einaudi and Burt, 1982; Ghosh and Upadhyay, 2022; Hammarstrom et al., 1995; Whitney and Olmsted, 1998). Therefore, skarns are commonly found near igneous intrusions, and along fractures and shear zones (Cocco et al., 2022), based on the source of the hydrothermal fluids (Baker and Lang, 2003). Meanwhile, the intercalation of carbonate within the protolith suggests shallow crustal levels, thus shallow geothermal systems (Deb et al., 2020; Sillitoe and Bonham Jr, 1990). Wollastonite usually occurs as a product of the interaction between silica and calcite reactants (Deer et al., 1997). The existence of silica as a reactant suggests SiO$_2$ supersaturated causative magmas, and based on the distribution of the previously recorded skarns in the Murdama basin; the Idah suite and the Al Khushaymiyah complex are the main causative magmas. Wollastonite exists extensively at the contact between the Idah plutons and the Murdama group at the western corner of the study area (Fig. 7a). Although the NFS exists as a network dissecting the central part of the Murdama basin and at its eastern faulted contact against the Suwaj suite, there's no record for the wollastonite. The limited extent of the wollastonite to the Idah suite contacts suggest the saturation of their magma with silica, and this is supported by the existence of skarn deposits at Qitan and An Nimriyah South (Fig. 2), as a result of the Idah causative plutons (Table S1). There's no record for the wollastonite at the contact of the Al Khushaymiyah complex (Fig. 7a), because there's no direct contact between the Murdama group and the Al Khushaymiyah complex in the study area (Fig. 3).

Garnet is a common proximal constituent of metasomatized carbonate rocks (Meinert, 1997). Garnet exists at the western corner of the area under investigation, with relatively the same location as wollastonite (Fig. 7b). There's no existence of the garnet away from the contact between the Idaho suite
and the Murdama group, and there's no effect on the fracture network related to the NFS for the circulation of the hydrothermal fluids in the central part of the study area. Meanwhile, the faulted contact between the Murdama and the Suwaj suite is garnet-free, and the Al Khushaymiyah complex has no effect on the country rocks (Fig. 7b). Pyroxene minerals are common distal skarn constituents (Ciobanu and Cook, 2004; Meinert, 1997). Pyroxene exists in the northwestern part of the study area, but to a relatively greater extent than wollastonite and garnet, which extends away from the contact between the Idah suite and Murdama group (Fig. 8a). It's clear that the northwestern part of the investigated area in the Murdama basin has extensively higher hydrothermal alteration activity, and the existence of the calc-silicate minerals at relatively the same contacts between the Idah suite and the Murdama basin, suggests that the Idah suite is the causative plutons for the skarn deposits at the study area in the Murdama basin. Meanwhile, the previously recorded skarn deposits in the Murdama basin at Qitan and An Nimriyah South (Table S1), confirm the ability of the Idah suite to be causative plutons at contact with the Murdama group. Meanwhile, the barren fracture system that is controlled by the NFS suggests that the hydrothermal fluids were derived from the Idah suite magmas. Furthermore, the Al Khushaymiyah complex, which is the causative plutons for the Kirsh skarn does not affect the Murdama group (Table S1), because there's no direct contact between the Murdama group and the Al Khushaymiyah complex, where the Jurdhawiya formation exists between both of them in the study area. Meanwhile, the faulted contact between the Murdama and the Suwaj suite is skarn-free (Fig. 8b).

5. Discussion

5.1 Arc – volcanosedimentary to post – amalgamation marine basin skarns

However, the AS has significant post-amalgamation marine basins, i.e., the Murdama basin; most of the skarn deposits are mainly related to arc-volcanosedimentary successions, except for a few localities were recorded from the post-amalgamation Murdama basin (Fig. 2). During the late Neoproterozoic ca. 650 Ma, the ANS experienced the transition from volcanosedimentary arc deposition systems to volcanosedimentary deposition in post-amalgamation molasse basins (Johnson et al., 2011; Johnson et al., 2013). Late Cryogenian–Ediacaran (650 – 542 Ma) marine molasse basins are predominant in the AS, with a voluminous average thickness of about 4 km (Johnson et al., 2011). The Murdama, Bani Ghayy, Fatima, and Ablah groups are the main types of localities for marine post-amalgamation basins in the AS (Fowler and Hamimi, 2021). Late Ediacaran granitic suits are cutting the marine basins, including the Al Khushaymiyah complex, the Idah suite, the Abanat suite, the Ruwaydah suite, and the Ghamril monzogranite. Skarn deposits are the most common deposit type at the contact between carbonates and late intrusive rocks (Meinert, 1995, 1997; Meinert et al., 1997). Meanwhile, the basins are variably experiencing brittle deformation with common cleavage and lineation, and such fractures are ideal pathways for hydrothermal fluids circulations, thus the possibility of precipitating skarn ore deposits in high grades increases. Meanwhile, the Idah and Al Khushayimah are the main causative plutons for the skarn deposits in the Murdama basin at Qitan, An Nimriyah South, and Kirsh (Fig. 2; Table S1). Therefore,
skarn deposits are expected to exist at the contact between the Idah, Al Khushayimah, and the Murdama group. However, the mapping of alteration mineral zones reveals the existence of skarn-related calc-silicate minerals at the contact between the Idah suite and the Murdama group, with no record for skarn indicator minerals at the periphery of the Al Khushayimah complex (Figs. 7 & 8). Meanwhile, the Jurdhawiya formation separates the Al Khushayimah complex from the Murdama group, preventing direct contact between both of them (Fig. 3). The barren fracture system that is controlled by the NFS suggests that the hydrothermal fluids were derived from the Idah suite magmas because the alteration mineral zones exist at the contact between the Idah suite and the Murdama group.

5.2 Magma fractionation and redox state

The redox state of both the country rocks and the causative magma controls the type of mineralization that is being evolved at the contact between them. Nickel plate mine is an example of a reducing state for both the host rock and the wall rock, so Au is the most common ore in such conditions (Ettlinger et al., 1992). In the Cu skarn prospect in the Philippines, the conditions are oxidizing with more garnet in such a system (Braxton et al., 2018; Chang and Meinert, 2009; Cooke et al., 2011). The type of magma controls the type of ore that is being evolved; Au and Sn favor the reducing conditions, but Au - Sn associations are rare because Au is related to mafic magma while Sn is related to felsic magma (Chang et al., 2019). Cu - Mo associations are related to oxidized magma, but Mo favors less oxidized and highly fractionated magmas, while Zn - Pb prefers both oxidized and reduced conditions, with various degrees of fractionation. Skarn deposits exist in volcanosedimentary arc-related successions in the Arabian Shield, except for Jibal Qitan, An Nimriyah South, and Kirsh skarn localities (Fig. 2; Table S1). Meanwhile, there are different types of post-Murdama granites, so there’s a higher possibility for the skarn deposits at the contact between the causative intrusions and the Murdama limestone, but the Al Khushaymiyah and Idah suites are the main causative intrusions for the skarn deposits in the Murdama basin (Table S1). Jibal Qitan and An Nimriyah South are reduced skarns in the Murdama basin that were induced by the Idah suite (Fig. 2; Table S1) and are dominated by Sn - W mineralization (Miller and Arnold, 1988). However, the Al Khushaymiyah complex is an oxidized causative magmas, and this complex is the causative magma for the Kirsh oxidized skarn (Table S1). The geochemical signature of the post-Murdama intrusive suites, based on the analysis of the geochemical database (Table S2), confirms the redox state for both the Al Khushaymiyah and Idah suites (Fig. 9). The redox state based on the ferric/ferrous ratio Fe₂O₃ / (Fe₂O₃ + FeO) (Meinert, 1995) suggests a reducing effect for the Idah suite, and an oxidizing effect for the Al Khushaymiyah complex (Fig. 9). In the investigated area, the Idah suite intrudes the Murdama group, while the Al Khushaymiyah complex isn’t intruding the Murdama group, so reduced skarn deposits are proposed to exist at the contact between the Idah suite and the Murdama group (Fig. 8b), based on their significant magnetic anomaly, the extent of the mineral alteration zones, and

6. Conclusions

The integration between magnetic, remote sensing, and the published geochemical data give the following conclusions:
1. Skarn deposits are proposed to exist in the AS.
2. The Idah suite has the most significant magnetic anomaly among the post-Murdama intrusive suites.
3. The skarn deposits exist adjacent to the Idah suite in the study area.
4. The contact between the Murdama basin and the post-Murdama intrusive suites is barren.
5. The skarn deposit in the study area was triggered by the Idah suite, and the Idah suite

**Declarations**

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**References**


Figures
Figure 1

Terrestrial, marine, and mixed post–amalgamation basins in the Arabian–Nubian Shield (ANS), dissected by the Najd fault system (NFS) (Johnson et al., 2011; Johnson, 2003; Johnson et al., 2013). Marine basins exit in the eastern part of the Arabian shield (AS), where the Murdama basin (~ 72,000 km²) is the largest molasse basin in the ANS.
Figure 2

Skarn deposit locations in the Arabian shield (AS) from (Ahmed, 2002; Ahmed and Hariri, 2006; Hummel and Ankary, 1972; Lemiere et al., 1990; Miller and Arnold, 1988; Moufti, 2013; Nehlig et al., 1999; Surour and Moufti, 2011; Williams, 1984). Overall, the arc-related skarns are oxidized except for Al Madhiq. Meanwhile, three localities were recorded from the Murdama basin (1-3), namely Qitan (1), An Nimriyah South (2), and Kirsh (3). Qitan and An Nimriyah are reduced, and both of them are related to Idah causative plutons, while the Kirsh oxidized skarn is triggered by the Al Khushaymiyah suite.
Post-Murdama intrusions include the Idah suite, Al Khushaymiyah suite, and Abanat suite, where there's no direct contact between the Murdama group and the Al Khushaymiyah. Meanwhile, the Idah suite intruded the Murdama group, and this suite is the causative pluton for the reduced skarns recorded northward in the Murdama at Qitan and An Nimriyah South.

Figure 3

Geologic map of the study area after (Johnson, 2003; Johnson et al., 2013).
Figure 4

a) total intensity magnetic map for the northern part of the Murdama basin; b) reduced to the pole (RTP) map

Figure 5

a) Analytical signal (AS); b) tilted derivative analyses for the RTP anomaly.
Figure 6

Regional – residual separation a) regional separation; b) residual separation.

Figure 7

a) Wollastonite mineral zone; b) garnet mineral zone. Spectral Angle Mapper (SAM) is in red, Constrained Energy Minimization (CEM) is in green, and Spectral Information Divergence (SID) is in blue.
Figure 8

a) Clinopyroxene mineral zone; the colors as in Fig. 7; b) the proposed skarn deposits at the contact between the Idaho suite and the Murdama group, based on the integration of Spectral Angle Mapper (SAM), Constrained Energy Minimization (CEM), Spectral Information Divergence (SID), and the magnetic anomaly of the Idaho suite.
Figure 9

Redox state for the post–Murdama granite causative magmas; the geochemical analyses from (Robinson et al., 2015); for the complete analyses refer to (Table S2), where analyses with Fe₂O₃T were excluded from the plotting. The redox index based on the Fe₂O₃ / (Fe₂O₃ + FeO) vs. SiO₂ after (Meinert, 1995)

Supplementary Files

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- TableS1.docx
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