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Multi-Data Integration for Delineating Listweanization Alteration Zones and Associated Gold Mineralization in the Um-Khasila Area, Central Eastern Desert, Egypt

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Abstract

Listweanization of ultramafic rocks commonly results in diagnostic alteration mineral assemblages that serve as key indicators of potentially economic mineralization. This study employed ASTER and Landsat 7 ETM+ multispectral data to delineate listweanization alteration zones. Most alteration mineral spectra were extracted using selective Principal Component Analysis (PCA), while the ASTER thermal infrared band ratio (14:12) facilitated silica isolation. ASTER successfully identified argillic, phyllic, and propylitic alteration alongside carbonates and silica, whereas Landsat 7 identified undifferentiated clays and iron oxides. Remote sensing results were subsequently validated through fieldwork and confirmed by petrographic investigations and X-ray diffraction (XRD) analysis, which proved to be an essential approach to facilitate mineral exploration. Furthermore, a fire assay was carried out on rock chip samples, followed by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) for Au quantification and confirmation of potential gold mineralization. This revealed that higher Au concentrations (up to 944 ppb) are spatially and genetically associated with highly altered carbonate-silica-iron oxide alteration zones coinciding with talc carbonate and listweanite. In contrast, fresh ultramafic and least-altered serpentinite protoliths have depleted gold concentrations (1-5 ppb).

The integrated multispectral satellite datasets (ASTER and Landsat 7 ETM+) with fieldwork, petrography, and laboratory analyses (XRD and ICP-AES) improved the precision of delineating key alteration mineral zones associated with listweanization. This joint workflow provides a reliable framework to rapidly prioritize gold exploration targets in the study area and analogous ophiolite-granite-greenstone terranes globally.

Keywords: Ophiolites; Metasomatism; Silica-Carbonate alteration; Listweanite; Gold mineralization; Remote sensing.

1.Introduction

Metasomatic and hydrothermal alteration processes generate mineral assemblages that facilitate the detection of ore mineralization and can be effectively mapped using multispectral remote sensing[1-6]. Listwaenite is a silica-carbonate metasomatic rock that forms when serpentinized peridotite interacts with CO_2- and S-rich fluids, typically found along fault and shear zones. It is mainly composed of Mg-bearing carbonates (magnesite, ankerite, and dolomite), quartz and/or fuchsite (Cr-muscovite), in addition to Cr-spinel, disseminated sulfides, and accessory minerals[7-12]. Listwaenite is particularly significant due to its strong spatial and genetic links to gold mineralization. Consequently, this potential target requires detailed geospatial mapping and further verification through comprehensive geological investigations, geochemical analyses, and drilling programs.

Integrating ASTER and Landsat-7 (ETM+) data significantly enhances the detection and mapping of listweanization zones. ASTER VNIR, SWIR, and TIR band datasets reveal diagnostic spectral features of (Al-OH, Mg-OH, Fe-OH, Si-OH, SO_4, and CO3)-bearing mineral groups, including clays, carbonates, phyllosilicates, and sulfates[13-19]. The ASTER thermal bands proficiently capture the major reflectance and absorption features of silica[20-22]. Furthermore, Landsat-7 effectively maps iron oxides/hydroxides and clay alteration zones[23-26]. In mineralized provinces, processing of ASTER and Landsat-7 (ETM+) data using techniques such as principal component analysis (PCA) and band ratioing yields significant results in discriminating rock units and delineating alteration zones[3,6,17,27-29]. These processing methods have been used by several researchers to discriminate alteration zones associated with metasomatic rocks (talc-carbonate and listweanite), thereby identifying prospective targets for gold mineralization[1,26,30-32]. Despite the extensive exploration across the Arabian-Nubian Shield (ANS), the precise spatial relationships among listweanization, alteration zones, structural control, and gold mineralization remain poorly understood. To address this gap, this study aims to evaluate the potentiality of the listweanization-related alteration signature as a predictive tool for detecting and prioritizing prospective gold targets by: (i) extracting spectral information, (ii) validating results with field, petrographic, and XRD data, and (iii) correlating detected alteration zones with gold assay data obtained using fire assay coupled with ICP-AES for Au quantification and confirmation of the potential occurrence of gold mineralization.

2.Geologic setting and fieldwork

The East African Orogen (EAO) is a major Pan-African orogenic event characterized by a sequence of Neoproterozoic orogens associated with the development of Gondwana. The ANS constitutes the northern part of the EAO and consists of juvenile Neoproterozoic crust developed during the closure of the Mozambique Ocean[33]. The Egyptian Eastern Desert (EED) constitutes the northwestern part of the ANS (Fig. 1). The ANS comprises ophiolitic suites that provide insight into its geological evolution[34]. Egyptian ophiolites are frequently metasomatized via interaction with H_2O- and CO_2-bearing fluids[12,35-37]. The Um Khasila ophiolites, the subject of this study, are located in the Central Eastern Desert of Egypt, south of Gabel Atud and north of Wadi Abu Muraywah and Wadi Garf (Fig. 1). The area consists of ophiolitic rocks within a metasedimentary succession forming an ophiolitic mélange that is thrusted over metavolcanics and is intruded by a metagabbro-diorite complex (Fig. 1). The ophiolitic ultramafic rocks are mainly represented by serpentinized harzburgite and its alteration derivatives. Um Khasila serpentinites occur as dismembered greenish-black to grey, elongated slices trending WNW-ESE. They are partially to completely carbonatized along thrust contacts and shear zones (Fig. 2a). Serpentinites are typically massive, but along shear zones and peripheries, they become sheared, foliated, and folded (Fig. 2b). The serpentinites are bounded from the south by fault contacts dipping north, against the volcaniclastic metasediments of Wadi Abu Muraywah (Fig. 2c).

Talc-carbonates and listwaenites are the main metasomatic alteration products of serpentinites in the area (Fig. 1). Talc-carbonates occur as creamy white to reddish-brown and have a weathered, porous surface due to iron oxide staining and carbonate dissolution (Fig. 2d). Fracture-filling carbonate veins served as pathways for CO_2-rich fluid that led to carbonation (Fig. 2e). Talc-carbonate is commonly found along the thrust contact with metavolcanic and metasediments (Fig. 2f). Listwaenites mostly occur as gray to reddish-brown dike-like bodies trending NW-SE, NE-SW, and ENE-WSW, ranging from meters to hundreds of meters long, but frequently occur as unmappable, discontinuous lenses (Fig. 2g-i). The large blocks of hard, resistant, fine- to medium-grained listwaenites commonly exhibit varying degrees of hematite, carbonate, and silica alteration (Fig. 2j).

The metagabbro-diorite intrusion into the ophiolitic mélange is suggested to have contributed to the metasomatism of the Um-Khasila by facilitating circulation of CO2-bearing fluids. It is partially carbonated along the contact with metasomatic rocks (Fig. 2k) and partially silicified,

with non-mineralized, low-dipping milky quartz veinlets. It occurs in multiple pulses and is intruded by fresh olivine gabbro-norite, particularly at the Gebel Atud peak[37,38].

Later basaltic and andesitic dykes related to the younger fresh post-collisional gabbroic intrusion[39] crosscut the early serpentinites and their alteration derivatives (Fig. 2l). The metavolcanic rocks are predominantly intermediate in composition and are locally silicified and foliated. The ophiolitic package overthrusts metavolcanics, where tuff equivalents intermingle with serpentinite along the thrust contact (Fig. 2k, m). The thrust contact between metavolcanics and metasomatic rocks frequently represents a promising area for gold mineralization.

A series of thrust faults, strike–slip faults, and fault-related folds deformed the Um Khasila area (Fig. 1), dominated by WNW-ESE and NW-SE-oriented thrust faults. The NNE-and ENE-trending thrusting direction of ophiolites in the study area aligns with those in the upper southern part of the CED[40] and coincides with the listweanite dyke-like bodies' trend. However, thrusts with steeply inclined fault planes have uncertain thrusting/nappe movement, but it could be inferred from thrust-related anticlines. The fold axes of these anticlines commonly share a WNW-ESE and NE-SW trend, while the NW–SE fold axis trend is rare. Um Khasila sinistral strike-slip faults and shear zones represent the subsequent deformation event in the area and are characterized by sub-vertical foliation. Their NW-SE to WNW-SSE trend commonly aligns with the Najd fault system[37].

Um-Khasila exhibits intense metasomatic alteration mainly represented by hematite, silica, and carbonate (Fig. 2n), in addition to clay, chlorite, and epidote alteration. Metasomatically altered zones are mainly structurally controlled and spatially associated with economic mineralization, especially where carbonate, silica, and hematite alteration predominate. There is still debate about the key point of the source of carbonate-bearing fluids. Previous studies suggest a mantle-derived source generated either at a mid-ocean ridge or in subduction-zone environments[41]. In contrast, Zoheir and Lehmann[10] proposed that metasedimentary rocks in contact with serpentinites acted as a crustal source for carbon-rich metasomatizing fluids.

3. Materials and methods

3.1 Remote sensing techniques

This study uses a combination of satellite spectral data, including a pair of ASTER L1T Daytime scenes and a single Landsat-7 ETM+ scene. The scene designations and acquisition dates

are summarized in Supplementary Table S1. The satellite data predates the intense artisanal activity, allowing a spectral signature with minimal ground disturbance.

3.1.1 Image pre-processing

ASTER L1T imagery underwent radiometric calibration and atmospheric correction using the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) algorithm[42]. Following these processes, the imagery was resampled to 30 m resolution and subsequently layer-stacked for further spectral analyses. The Landsat-7 ETM+ scene was radiometrically calibrated and atmospherically corrected to achieve surface reflectance using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS)[43]. Image positional accuracy was verified using ground control points (GCPs), resulting in Root Mean Square Errors (RMSE) of 2.417 m and 2.878 m in the X and Y directions, respectively. An RMSE of less than 12.5 m per pixel indicates a high geometric accuracy for subsequent image analysis[44,45].

3.1.2 Image Processing

3.1.2.1 Principal component analysis (PCA)

Principal component analysis (PCA) is a multivariate statistical method that minimizes redundancy in multispectral datasets by transforming correlated reflectance data into a smaller set of uncorrelated principal components (PCs)[46,47]. These PCs are derived from the eigenvectors of a covariance matrix[48] and ranked in descending order of the variance they explain. In the context of hydrothermal alteration mapping, only the first four principal components (PC1–PC4) were selected for subsequent processing, as higher-order components tend to be predominantly noisy. In the PC image analysis, the magnitude and sign of eigenvector loadings in the diagnostic reflective and absorptive bands for specific minerals are crucial for refining mineral identification[49]. Consequently, alteration-related pixels appear bright or dark in the PC image depending on the loading (sign and magnitude) of these diagnostic bands, which determines the overall PC loading score, whether it is positive (bright pixel) or negative (dark pixel)[50,51]. To improve the signature of the alteration minerals as more easily recognizable bright areas, component images with negative loading contributions, which result in dark anomalous areas, were negated. Using the USGS spectral library and based on the total set of curve peaks and troughs, a selective PCA technique was applied to ASTER-selected band subsets to effectively characterize argillic, phyllic, propylitic, and carbonate alteration species. The Crosta-Loughlin

PCA method was applied to Landsat-7-selected band subsets to map clay and iron hydroxides/oxides alteration species[24,26,51,52]. The specifics of the bands used will be discussed further in the Results and Discussion sections.

3.1.2.2 Silica Band Ratio

Band ratioing is a straightforward yet effective remote sensing technique in which the digital number of a given pixel in a particular band is divided by the corresponding number of the same pixel in another band[52-55]. The band ratio technique efficiently reduces topographic effects and enhances spectral contrast between target objects; hence, it is widely used to discriminate hydrothermal alteration minerals and for lithological mapping[25,26,56,57]. In this study, we generated a silica index by computing the ASTER thermal bands (14:12) ratio, which represents the major absorption and reflectance bands for silica, respectively[20,22,58].

3.2 Fieldwork and mapping

During fieldwork, we conducted detailed traverse mapping of the area and collected a total of 53 samples from various rock units and altered zones. Additionally, 15 rock chip samples were selected for Au assay analysis, focusing on both highly altered and least altered zones. Field verification of remote sensing results was conducted using a suite of alteration image products displayed in an advanced offline GPS navigation and field management application (Alpin Quest field app).

3.3 Analytical techniques

3.3.1 Petrographic investigation

Petrographic investigations were conducted on each collected sample using a LEICA DM4500P polarized optical microscope with a built-in camera. The objective of the petrographic examination was to characterize the alteration mineral assemblages and their textural relationships to identify the nature, intensity, and spatial evolution of the altered zones.

3.3.2 X-ray diffraction (XRD)

XRD analysis was performed at the facilities of Geology Department, Faculty of Science, Suez Canal University on back-packed powder mounts to characterize the alteration mineral phases using a Philips PW1370 X-ray generator fitted with a PW 1390 channel control, a PW1050 vertical goniometer, and a digitizer. XRD data were collected over a range of 6° to 73° 2θ, utilizing a step size of 0.0330° 2θ and a scan step time of 1 second. The measurements were conducted with

an accelerating voltage of 45 kV and a beam current of 40 mA. The radiation sources employed were Cu Kα1,2 (with wavelengths of 1.54060 Å and 1.54443 Å, respectively) and Kβ radiation at 1.39225 Å. Qualitative evaluation of the mineral phases was performed using X'Pert HighScore® (version 3.0.5) and the International Center for Diffraction Data (ICDD) database. Seven representative raw XRD diffractograms were stacked after background subtraction, and then a uniform scale factor was applied across all samples to normalize peak intensities while preserving relative peak heights.

3.3.3 Fire assay and Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES)

Gold assay was conducted at the ALS commercial laboratory in Loughrea, Co. Galway, Ireland, using fire assay on a 30-g sample aliquot followed by Inductively Coupled Plasma–Atomic Emission Spectrometry (ICP-AES) quantification according to the ALS Au-ICP21 method.

4. Results

4.1 Alteration mapping

4.1.1 ASTER alteration mapping

The ASTER selective PCA analysis mapped alteration zones including kaolinite, Sericite, chlorite, epidote, and carbonate species. The Eigenvector loadings of the selected ASTER VNIR–SWIR bands are presented in Supplementary Table S2. Applying PCA to bands 1, 4, 6, and 7 delineated kaolinite-bearing (Argillic) hydrothermal alteration zones. The Eigenvector loadings reveal that PC3 exhibits a strong negative contribution in band 4 (-0.794) and moderate positive contributions in bands 6 (0.402) and 7 (0.451), which represent the diagnostic absorption bands (Table S2-a). Kaolinite appears as dark pixels in PC3 greyscale images; thus, it was negated to enhance these zones as bright pixels (Fig. 3a and b). Sericite-bearing (phyllic) alteration zones were identified using ASTER bands 1, 4, 6, and 8. Eigenvector statistics show that PC4 is the most informative PC for sericitic alteration, with a strong negative loading in band 6 (−0.801) and moderate positive loadings in bands 4 and 8 (0.532, 0.265), respectively (Table S2-b). These oppositely signed loadings typically correspond to the spectral features of Al-OH-bearing minerals, with reflectance differences between bands 4 and 8 enabling improved mapping of sericite zones. PC4 negation highlighted these zones as bright pixels (Fig. 3c and d). Co-response

of kaolinite and sericite might occur due to the similar Al–OH absorption features of these minerals.

Carbonate-bearing zones were mapped by applying PCA to bands 4, 6, 8, and 9, revealing that PC3 is the most informative PC, with a strong negative loading in the distinctive absorption band 8 (-0.719) and moderate positive contributions in bands 6 and 9 (0.612, 0.324), respectively (Table S2-c). Carbonate-bearing pixels were negated to appear bright (Fig. 4 a and b). Propylitic alteration (chlorite and epidote) was mapped by applying PCA to bands 1,4,8, and 9. The PCA results show that PC4 is the most spectrally informative component for propylitic alteration. It exhibits a strong spectral contrast between diagnostic bands, with a strong positive loading on Band 8 (0.612) and a strong negative contribution from Band 9 (–0.759), corresponding to the diagnostic spectral absorption of Fe, Mg (OH)-bearing minerals (Table S2-d). In the PC4 image, propylitic-bearing pixels appeared dark; therefore, it was negated to display the anomalies as bright pixels (Fig.4 c and d).

Silica alteration was delineated using the ASTER (TIR) band ratio 14:12 applied to a daytime scene, which identifies silica alteration through variations in thermal emissivity of altered rocks. This ratio was found to be effective for extensive and wide silica-flooded areas rather than thin silicified listweanite dyke-like bodies and associated thin individual quartz veins, since the minimum detectable altered area exceeds 8,100 m^2 due to the low resolution (90 m) of ASTER TIR bands (Fig. 5a and b).

4.1.2 Landsat alteration mapping

In this study, the Crosta-Loughlin method uses a combination of Landsat-7 input bands to map clay- and iron-hydrothermally altered zones. PCA applied to Landsat-7 bands 1, 4, 5, and 7 mapped the Clay alteration zones effectively. Eigenvector loadings show that PC4 is the most informative component, with a strong positive contribution (+0.71) from band 5 and a strong negative contribution (−0.66) from band 7 (Table S3a), consistent with clays high reflectance in band 5 and strong absorption in band 7. Therefore, clay-rich zones appear as dark pixels in the PC4 image and were displayed as bright pixels by negation ($PC4^{-1}$) before thresholding (Fig.6a and b). Iron oxide alteration mapping using bands 2, 3, 4, and 5 reveals that PC4 is the most informative PC. Eigenvector loadings show a strong negative loading (−0.68) in band 1 and a strong positive loading (+0.71) in band 3 (Table S 3b), consistent with the spectral behavior of iron

oxide minerals and enabling discrimination of Iron-rich zones. Negating PC4 images transforms iron-dark pixels into more easily recognizable bright areas (Fig. 6c and d).

4.1.3 Thresholding

A cutoff threshold was determined using an integrated approach that combined histogram analysis, statistical parameters (mean and standard deviation), and geological constraints (See Supplementary Table S4). The results were presented as alteration intensity and anomaly images (Fig. 3–6). The alteration intensity variable is represented by a continuous color gradient, transitioning from purples and blues (low intensity) through greens and yellows (moderate intensity) to oranges and reds (high intensity). Applying these calculated thresholds to these maps highlights zones of high alteration anomaly in red, moderate in green, and low in blue. Even the blue zones in the anomaly images represent relatively high-intensity values, since the cutoff threshold is generally above the 90th percentile.

4.1.4 Lineament extraction

The automated lineament distributions were extracted using the PCI Geomatica (version 2018) LINE algorithm with the following optimal parameters: filter radius (RADI) = 5, edge gradient threshold (GTHR) = 25, curve length threshold (LTHR) = 20, line-fitting error threshold (FTHR) = 3, angular difference threshold (ATHR) = 20, and linking distance threshold (DTHR) = 40; the parameter values used are given in Supplementary Table S5[59-63].

The LINE algorithm was applied to the ASTER scene with these parameters to automatically extract linear features, yielding the statistics shown in Supplementary Table S6. According to the rose diagram analysis, the extracted lineament map was dominated by E–W (52.3% of total length), NW–SE (21.3%), and minor NE–SW and N–S trending linear features (Fig. 7a-d). It was further converted into a lineament density map (Fig. 7b) using the Kernel Density Estimation algorithm in QGIS (version 3.44.6) to highlight structurally complex zones that control the circulation of alteration and mineralization. Superimposing the gold assay results on the lineament density map revealed a close spatial association with the medium- to high-density zones, indicating structurally controlled gold mineralization.

4.2 Petrography and mineralogy

The alteration mineral assemblage identified through petrographic investigation is consistent with findings from XRD analyses and remote sensing data. This evidence aligns with the globally documented models of ultramafic metasomatization[11,12,64].

Serpentinization of harzburgite, facilitated by reaction with H_2O dominated fluids, results in the replacement of the original magmatic olivine and orthopyroxene by a lizardite, chrysotile, bastite, and antigorite mineral assemblage, obliterating the original magmatic textures (Fig. 8a-c). Talc-carbonate is later formed through the reaction of serpentinites with CO_2-rich fluids. It is characterized by an alteration mineral assemblage of talc, magnesite, antigorite, kaolinite, and chlorite ± dolomite and ankerite (Fig. 8d-f). Talc-carbonate commonly exhibits brecciation, cataclastic textures, shearing, and/or foliation. The foliation around the magnesite porphyroblasts is commonly rotated, suggesting post-carbonation deformation (Fig. 8f). With prolonged carbonation, listweanite developed through the reaction of early-formed talc-carbonate with CO_2-dominated fluids, resulting in significant carbonate dissolution, quartz precipitation, and rock hardening. In this stage, the predominant mineralogical constituents include quartz, dolomite, magnesite, talc, and kaolinite ± fuchsite (Cr-muscovite) (Fig. 8g-i). Quartz-carbonate veins reveal evidence of post-carbonation deformation, characterized by grain stretching and vein displacement (Fig. 8g and h). In the metagabbro-diorite complex, chlorite, epidote (clinozoisite), and calcite commonly replace the original magmatic plagioclase, clinopyroxene, and hornblende, indicating propylitic alteration. (Fig. 8j-l).

4.3 X-Ray Diffraction Analysis (XRD)

XRD analysis revealed a progressive sequence of metasomatic alteration, consistent with both petrographic observations and remote-sensing imagery. From least to most intensely altered, the sequence comprises partially serpentinized harzburgite, serpentinites, talc-carbonate, and listweanite, each with a distinct mineral assemblage summarized in Supplementary Table S7.

Partially serpentinized harzburgite is characterized by prominent forsterite peaks with subordinate clinochrysotile peaks (Fig. 9, S28). In contrast, the serpentinite alteration stage is dominated by antigorite peaks, indicating progressive serpentinization during which serpentine phases completely replaced the primary magmatic olivine (Fig. 9, S25). The transition from hydration to carbonation is primarily recorded in the carbonatized serpentinite, which exhibits an assemblage of antigorite, talc, and magnesite (Fig. 9, S30). Talc-carbonate rocks record a more advanced alteration stage, marked by the complete replacement of antigorite and the dominance

of magnesite and talc peaks (Fig. 9, S27). The listweanization stage is characterized mainly by a talc-magnesite-quartz assemblage (Fig. 9, S16), while a more advanced silica-carbonate alteration stage is indicated by peaks of quartz and dolomite ± magnesite (Fig. 9, S35 and S32). During this ultimate stage, quartz and carbonate phases completely replace primary silicate minerals, accompanied by a contemporaneous increase in quartz and carbonate peak intensities.

4.4 Gold Concentration and Distribution

Supplementary Table S8 provides gold concentration results, coordinates, lithology, and alteration of the rock chip samples. These were further superimposed on the remote sensing alteration maps to highlight lithologic, structural, and alteration controls on gold enrichment (Figs. 3-7). Less-altered ultramafic rocks and serpentinites show very low gold concentrations, typically 1 to 5 ppb, indicating that the primary protoliths are poorly mineralized. However, metasomatically altered rocks, particularly talc-carbonate rocks and listwaenites, exhibit elevated gold (Au) concentrations up to 944 ppb, especially compared with their unaltered counterparts. Additionally, altered metavolcanics along the thrust contact with metasomatic rocks also demonstrate significant Au enrichment (78 ppb). Notably, highly altered carbonate and hematite ± silica alteration samples yield the highest Au values. The altered granodiorite intrusion also shows gold enrichment (261 ppb), where clay, kaolinite, sericite, and hematite are the dominant alteration minerals.

5. Discussion.

Significant spatial and genetic relationships exist between gold mineralization in the EED and silica-carbonate alteration (listweanization) of ophiolites. These alterations occur in conjunction with shear zones, thrust contacts, and granitic intrusions, thereby enhancing the potential for hosting ore minerals[1,65-68 69].

The Um Khasila study area encompasses an array of ophiolitic rocks within a metasedimentary and metavolcanic succession, with an intrusion of a metagabbro-diorite complex (Fig. 1). The ophiolitic ultramafic rocks are mainly represented by serpentinized harzburgite and serpentinites. In the Um-Khasila area, metasomatic alteration products of serpentinites are primarily exemplified by talc-carbonates and Listwaenites (Fig. 1). These listwaenites are attested as potential targets for gold mineralization. These metasomatic alteration zones were delineated by integrating fieldwork, multispectral remote sensing imagery, petrographic investigations, XRD data, and gold assay analysis to confirm associated mineralization.

Applying remote sensing techniques to ASTER and Landsat datasets for the EED effectively differentiates lithological units using principal component analysis and band-ratio methods[70,71]. The selected subsets of ASTER and Landsat-7 bands utilized in the PCA processing provide accurate discrimination and mapping of metasomatic listweanization zones and coexisting alteration zones within the study area (Figs. 3 -6). The ASTER band subset (1, 4, 6, and 7) highlighted the Argillic (Kaolinite)- altered zones (Fig. 3a and b), whereas the (1, 4, 6, and 8) subset effectively enhanced the Phyllic (Sericite)-bearing zones (Fig. 3c and d). Carbonate alteration zones were clearly delineated using the (4, 6, 8, and 9) band subset (Fig. 4a and b), whereas propylitic (epidote and chlorite) altered zones were significantly mapped using the (1, 4, 8, and 9) band subset (Fig. 4c and d). Furthermore, the undifferentiated clay and Iron-oxide alteration zones were efficiently delineated using the Landsat-7 band subsets (1, 4, 5, and 7) and (2, 3, 4, and 5), respectively (Fig. 4a - d). Overall, the successful delineation of alteration/metasomatic zones demonstrated the PCA capability when applied to appropriate bands that capture the diagnostic absorption characteristics of alteration minerals.

A series of alteration intensity and anomaly images were generated using specific threshold values for each mineral (Table A4) and were superimposed with the gold assay data (Table A8) to assess the spatial relationship among alteration-species anomalies, high lineament density zones, and anomalous gold assay results (Figs. 3 -6).

Carbonate and iron-oxide alteration anomalies (Fig. 4b and 6d, respectively) spatially coincide with metasomatized talc-carbonate and listweanite, which are characteristically associated with high-lineament-density (structurally controlled) zones. These zones typically represent the thrust contact between metasomatized ophiolites and associated metavolcanics and often emerge as promising areas for mineralization. These areas exhibit significant anomalous Au concentrations (up to 944 ppb), thereby corroborating the genetic link between listweanization and orogenic gold mineralization. Similar gold-bearing listweanites have been reported in the EED; the Barramiya mine has recorded concentrations of up to 11 ppm[1], whereas the Bir Umq listweanite of the western Arabian Shield also exhibits gold levels up to 3.7 ppm[68]. Several studies have reported that listweanization plays a key role in gold enrichment[1,9,65,69]. However, Boskabadi et al.[67] suggested that serpentinite carbonation may result in Au depletion through fluid migration.

Sericite and kaolinite alteration anomalies (Fig. 3b and d, respectively) also occur in high-lineament-density zones (Fig. 7b), manifesting as small, discrete, partially overlapping zones.

Notably, a significant gold-bearing zone (up to 261 ppb) is associated with a granodiorite intrusion in contact with carbonatized serpentinites (Fig. 1). This zone was recently reported as "Little Sukari," a newly discovered gold deposit hosted in a sericite-pyrite-altered granodiorite intrusion, bearing resemblance to the main Sukari mine deposit[72]. Chlorite-epidote propylitic alteration anomalies (Fig. 4d) are confined to the metagabbro-diorite intrusion located southeast of Gebel Um-Khasila (Fig. 1); however, the associated Atud metagabbro shows low-intensity propylitic alteration (Fig.4c). Propylitic alteration observed in the Atud metagabbro-diorite is masked by the intruded fresh gabbroic circular peak[37,38].

Silica alteration occurring within listweanization zones is typically associated with a cogenetic carbonate alteration, a relationship substantiated by petrographic investigations and XRD results rather than remote sensing imagery. The minimum detectable area of silica alteration using the low-resolution ASTER TIR band ratio (14:12) exceeds 8,100 m^2, which is effective for widely flooded silica zones (Fig. 5). However, it is improbable that silica anomalies associated with the listweanite dyke-like ridges can be successfully mapped using this method. Thus, conducting a hyperspectral drone survey might be effective after spectral analysis of a suite of listweanite samples to assess spectral feasibility.

Furthermore, the integrated ground-truthing fieldwork, petrographic investigations, and XRD results validated the remote sensing findings and recorded a progressive paragenetic metasomatic/alteration sequence, evolving from mantle-derived harzburgite to fully carbonated and silicified listweanite. This progressive sequence is evidenced by gradual changes in peak intensities, notably the elimination of primary ultramafic and serpentine mineral peaks, accompanied by a contemporaneous increase in the peak intensities of quartz and carbonate minerals. This observation aligns with globally documented models of ultramafic metasomatism within listweanized zones[11,12,64,73].

Prospective gold targets are expected to occur in areas where intense carbonate-silica-iron oxide alteration coincides with metasomatic rocks and high lineament-density zones. In addition, areas exhibiting a geological context comparable to that of the Sukari area represent promising targets for further exploration and evaluation.

In summary, the integrated approach employed in this study effectively facilitates and accelerates the target-generation stage of mineral exploration, demonstrating its relevance in similar geological settings. Nevertheless, follow-on exploration, underscored by rigorous

geochemical sampling and systematic drilling, is critical to validate and refine the identified targets.

The widespread, well-documented recurrence of gold-bearing listweanite zones in ophiolitic belts worldwide points to a repeatable metallogenic process, extending the applicability of the proposed workflow developed in this study to broader geological contexts. Across the ANS, comparable alteration has previously been linked to gold mineralization based on fluid inclusion and stable isotope studies, where dominant carbonation and silicification, together with iron-oxide alteration, reveal a well-established alteration-mineralization model. Accordingly, our approach can serve as an effective reconnaissance exploration tool, especially for listweanite-related gold systems across the ANS ophiolitic terranes and similar settings worldwide.

6. Conclusion and recommendations

Listweanization process of ultramafics has attracted attention as a prospective setting for gold mineralization. In this study, the integration of PCA-processed ASTER and Landsat-7 satellite imagery proved highly effective for identifying and delineating these alteration zones. Consequently, this integration enables a precise characterization of the mineral assemblages associated with these potentially mineralized zones. Image processing techniques revealed that the Um-Khasila area is characterized by a range of alteration types, including argillic, phyllic, propylitic, iron oxide, and carbonate alterations. These remote sensing findings were rigorously validated through field geology and petrographic investigations, along with XRD and gold assay data. Notably, carbonate and iron-oxide alteration zones exhibit a strong spatial and genetic correlation with gold mineralization, with concentrations reaching up to 944 ppb. This mineralization predominantly occurs at the thrust contact between metasomatic rocks, specifically talc-carbonate and listweanite, and metavolcanic rocks. Additionally, the sericite-kaolinite-altered granodiorite intrusion demonstrates significant gold concentrations, reaching up to 261 ppb. The ASTER TIR band ratio (14:12) effectively mapped widely flooded silica zones; however, it is not effective in delineating silica alteration related to listweanite dyke-like bodies. To enhance Silica alteration detection capabilities, the implementation of a hyperspectral drone survey is recommended.

Thus, the optimized multispectral remote sensing workflow used in this study provides a cost-effective and time-efficient approach for targeting and prioritizing the most prospective zones for further gold exploration.

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Author Contributions

All the Authors have participated in Conceptualization and Previous work. M.I. Shalaby: Field mapping, Sampling, prepared figures. M.I. Shalaby, M.M. ElOmla: Petrography, Investigation, Validation. M.I. Shalaby, S.A. Shata, M. M. Hassan: Analysis, data interpretation and processing. M.I. Shalaby, M.M. Hassan: writing the original manuscript. All the Authors have participated in Visualization and the final review and editing.

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Supplementary Information

Figures caption

Fig. 1 | Geology and regional location of the Um-Khasila area. a Geologic map compiled from integrated field traverse mapping, petrographic, and satellite imagery data analyses. **b** Location of the study area within the regional map of the ANS[34].

Fig. 2 | Field photographs of the Um-Khasila area. a Panoramic view of the southern side of the Um-Khasila area showing the gradual alteration of serpentinite to talc-carbonates. **b** Map scale thrust-related anticline within sheared serpentinites with a NE-SW-trending fold axis. **c** Um Khasila carbonatized serpentinites and Garf highly sheared volcaniclastic metasediments. **d** Creamy white talc-carbonate with cavernous, weathered surface in contact with serpentinites (Sp). **e** Chrysotile (Ctl) veins within serpentinites (Sp) overprinted by carbonates (Carb), characterizing the gradual carbonation of serpentinites into talc-carbonates. **f** Large-scale artisanal work highlighting the thrust contact between talc carbonate and metasediments. **g** Panoramic view of the ophiolitic mélange comprising talc carbonates and listweanite dyke like body thrusted over carbonatized metasediments with preserved serpentinite pockets/ lenses within talc carbonates. **h** Large-scale artisanal work exposing the thrust contact between metasomatic (talc-carbonate and listweanite) rocks and altered metasediments. **i** Listweanite dyke like body exposed along the ridge overlying the talc–carbonate. **j** A sharp contact between talc-carbonate and listweanite with characteristic hematite (hem), carbonate (Carb), and silica (Sil) alteration. A close-up view showing visible gold. **k** Ophiolites (mainly represented by listweanite) thrusted over the metavolcanics and intruded by the metagabbro-diorite (MGD) complex. **l** A mafic dyke crosscutting the talc-carbonate. **m** Thrust contact between metasomatic rocks and silicified foliated intermediate metavolcanics with preserved serpentinite (Sp) lenses. **n** Hand specimens showing the transition from peridotite to listweanite with their associated alteration minerals.

Fig. 3 | ASTER selective PCA imagery. a Negated PC3 image displaying kaolinite (argillic) alteration intensity. **b** Pattern of kaolinite anomalies with a cut-off threshold of 174. **c** Negated PC4 image displaying sericite (phyllic) alteration intensity. **d** Pattern of sericite Anomalies with a cut-off threshold of 150.

Fig. 4 | ASTER selective PCA imagery. a PC3 image displaying carbonate alteration intensity. **b** Pattern of carbonate anomalies with a cut-off threshold of 176. **c** PC3 image displaying propylitic (chlorite and epidote) alteration intensity. **d** Pattern of the chlorite and epidote anomalies with a cut-off threshold of 190.

Fig. 5 | Silica ASTER (14:12) band ratio imagery displaying: a Silica intensity variation**. b** Silica anomaly pattern extracted using a cut-off threshold of 110.

Fig. 6 | Landsat 7 selective PCA imagery. a Negated PC4 image displaying clay alteration intensity. **b** Pattern of clay anomalies with a cut-off threshold of 180. **c** Negated PC4 image displaying Iron oxide alteration intensity. **d** Pattern of iron oxide anomalies with a cut-off threshold of 175.

Fig. 7 | Lineament extraction from the ASTER scene. a Lineament distribution map. **b** Lineament density map superimposed with the gold assay results. **c** Rose diagram of the lineament set frequency. **d** Rose diagram of the lineament set cumulative length.

Fig. 8 | Photomicrographs of the Um-Khasila metasomatized ophiolitic rocks. a Partially serpentinized harzburgite, in which olivine (Ol) and orthopyroxene were replaced by chrysotile (Ctl), brucite, and bastite (Bst). **b** Late chrysotile (Ctl) veins cross-cutting a matrix of early lizardite (Lz) pseudomorph after olivine. **c** Antigorite replaced by magnesite (Mgs) and minor talc (Tlc), with fracture-filling magnetite (Mag). **d** A typical talc-carbonate rock shows complete replacement of serpentine phases by an aggregate of magnesite (Mgs) and talc (Tlc) flakes. **e** Speckled kaolinite

(Kao) filling the secondary porosity resulting from carbonate dissolution. **f** Magnesite (Mgs) porphyroblasts and relic antigorite (Atg) surrounded by strained talc (Tlc) with rotated foliation. **g** Magnesite (Mgs) vein faulting, suggesting a post-carbonation deformation event. **h** Quartz-dolomite (Qz-Dol) veins characterizing the listweanite silica-carbonate alteration phase. **i** Undulating quartz (Qz) vein cross-cutting a magnesite (Mgs) megacryst. **j** Metagabbro showing a replacement halo of clinopyroxene (Cpx) by hornblende (Hbl) and chlorite (Chl). **k** Berlin blue chlorite (Chl) and higher-order calcite (Cal) alteration replacing the original magmatic minerals**. l** Clinozoisite (Czo) crystals replacing primary plagioclase and amphibole.

Fig. 9 | XRD diffractograms show a gradual replacement of primary ultramafic and serpentine mineral peaks (S28 and S25), and the dominance of quartz and carbonate peaks in the highly altered samples (S27, S16, S35, and S32). Supplementary Table S7 provides sample IDs, coordinates, lithology, and identified mineral phases for the analyzed samples.

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