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Geological control of massive sulfide mineralization in the Neoproterozoic Wadi Bidah shear zone, southwestern Saudi Arabia, inferences from orbital remote sensing and field studies

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Abstract

This study combines new field and orbital remote sensing data to determine geologic controls on sulfide mineralization in the Wadi Bidah Mineral District (WBMD) located in the Neoproterozoic (900–550 Ma) Arabian Shield of southwestern Saudi Arabia. The brittle and ductile deformation of these massive sulfide deposits and host rock reflect tectonic events occurring in the Arabian Shield during the Neoproterozoic (900–550 Ma). Remote sensing data were used in conjunction with GIS software (ARCVIEW) to map lithologic units and mineral deposits, analyze and define regional structural trends, and establish geologic controls on sulfide mineralization. Orbital remote sensing data sets include scenes from Landsat 7 and ASTER. The sulfide deposits of the WBMD are found within a group of felsic volcaniclastics. A marble unit within the felsic volcaniclastic group is used as a marker horizon. Based on the distribution of the sulfide deposits relative to the marble unit, all sulfide deposits appear to be stratabound. Deposits have been folded and faulted into their present positions. Structural control of mineralization appears to be limited to post-mineralization folding and shearing.

Keywords: Sulfide deposits; Gossan; Saudi Arabia; Remote sensing; Mineral exploration

1. Introduction

The Wadi Bidah Mineral District (WBMD) lies in the southwestern part of the Neoproterozoic (900–550 Ma) Arabian Shield of Saudi Arabia and consists of a north-trending belt, 70 km long and 20 km wide, between latitudes 20° and 21° north and longitudes 41° and 41° 30′ east (Fig. 1).

This study combines new field and orbital remote sensing data to determine geologic controls on sulfide mineralization in the WBMD. Geologic controls on mineralization in the WBMD may include structure (Johnson and Vranas, 1984), lithology and stratigraphy (Jackaman, 1972). Relationships between the layered rocks and deposits of the district can demonstrate whether or not the deposits are stratabound and have undergone the same ductile and brittle deformation as the layered host rock. The distribution of the deposits relative to a marble unit can also demonstrate whether or not the deposits are hosted in the same lithologic group and occupy the same stratigraphic horizon.

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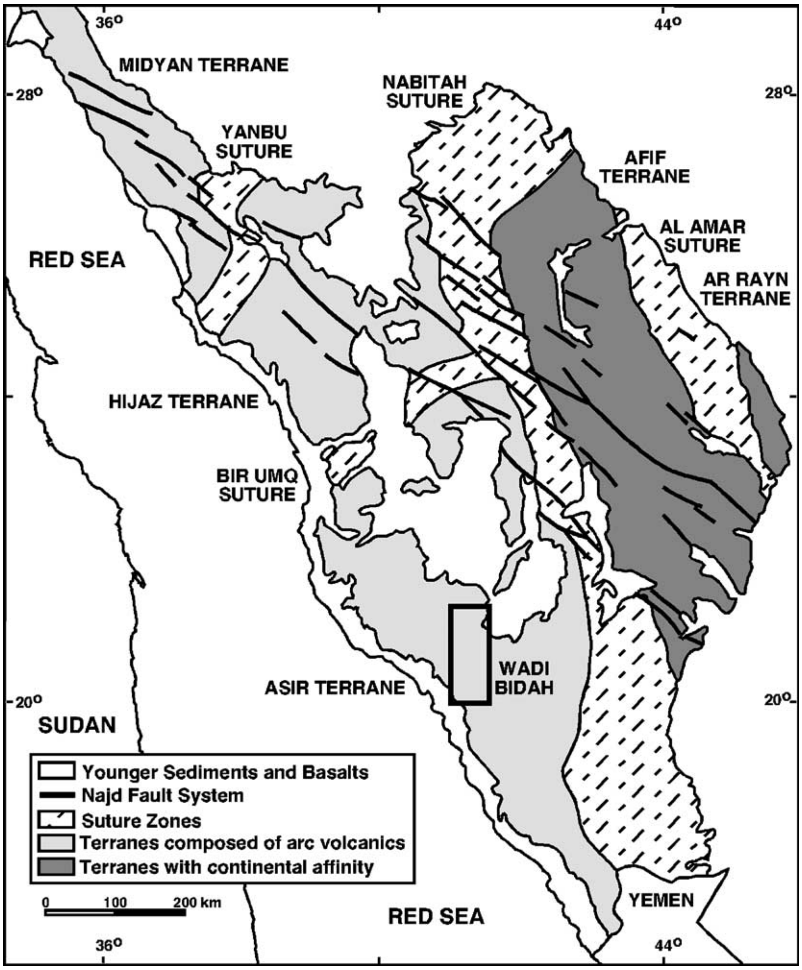

Fig. 1. Location of Wadi Bidah Mineral District within the Asir terrane of the Arabian Shield (Modified after Stoeser and Camp, 1985).

2. Tectonic setting and geology

The Arabian Shield (Fig. 1) is composed of intra-oceanic arc/back-arc basin complexes and microcontinents welded together along north- and east-trending sutures (Abdelsalam and Stern, 1996). The sutures separate five tectonic terranes (Camp, 1984; Stoeser and Camp, 1985). The Midyan, Hijaz, and Asir terranes are composed largely of arc volcanics, sedimentary and intrusive rocks. The Afif and Ar Rayn terranes are composed of arc volcanics accreted to older continental basement.

The WBMD is part of an island arc system in the Asir terrane, which was active between 950 and 800 Ma (Agar, 1992). The Asir terrane consists of stretched and sheared volcanic, sedimentary and plutonic rocks that are tightly to isoclinally folded about north-trending axes and cut by numerous north-trending brittle-ductile shear zones (Johnson, 1999a). Wadi Bidah (Fig. 2) formed in and parallels one of these north-trending sinistral shear zones (Johnson, 1999a).

Beziat and Donzeau (1989) subdivided the WBMD into three major lithologic groups from east to west (Fig. 3): Group 1—mafic volcanic rocks; Group 2—felsic volcaniclastics; and Group 3—epiclastic and felsic volcaniclastics. Regionally, lithologic groups become younger to the west (Beziat and Donzeau, 1989). Group 1 is assigned to the Khumrah

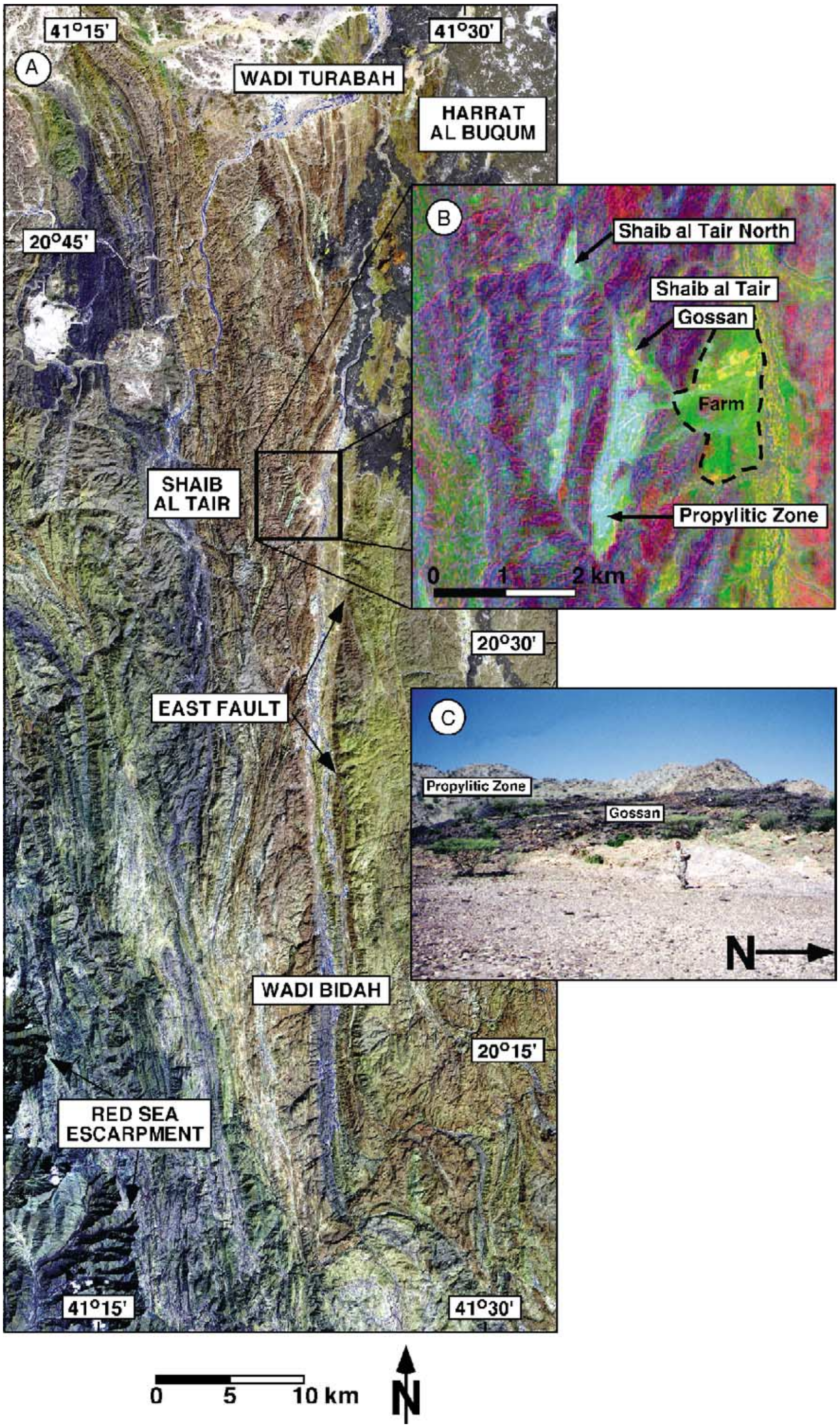

Fig. 2. (A) Landsat 7 (7-5-4) color composite image of the WBMD. (B) ASTER (4/2-4/5-5/6) band ratio image of the Shaib al Tair prospect illustrating the ability to differentiate the propylitic alteration zone, and gossan from the host rock. The propylitic zone appears light blue, the gossan (iron-rich zone) appears yellow, and the host rock (schist) has a purple hue in this image. (C) Field photograph (March 1999) looking west across the Shaib al Tair prospect showing the propylitic zone, and gossan.

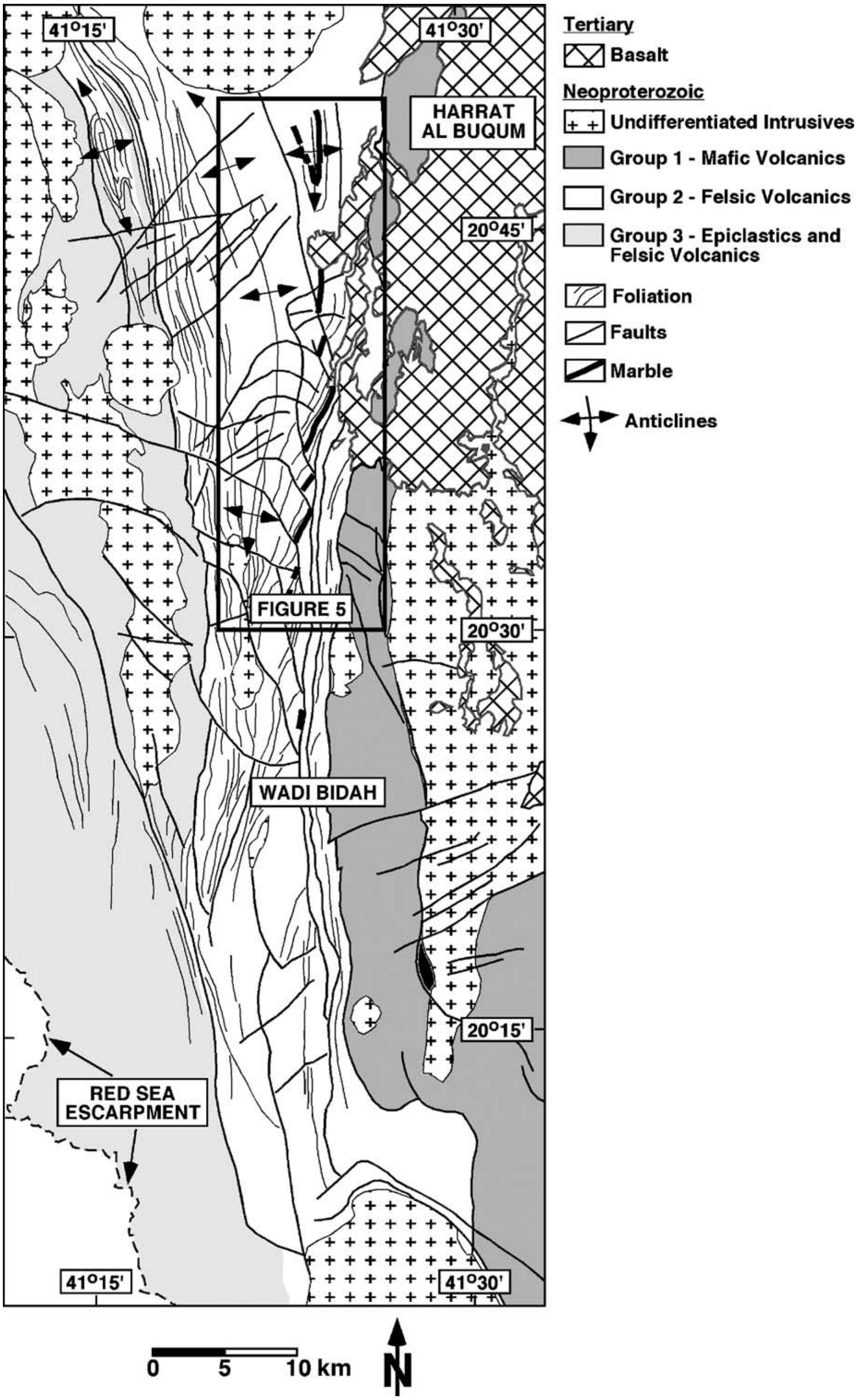

Fig. 3. Geologic map from interpretation of the Landsat 7 (7-5-4) color composite image.

Greenstone and groups 2 and 3 are assigned to the Hawiyah formation (Johnson, 1999b; Ziab and Ramsay, 1986). These lithologic groups had previously been named the Baish (group 1) and Baha (groups 2 and 3; Beziat and Donzeau, 1989), the Sharq, Bidah and Gharb (Jackaman, 1972) and 'Older Volcanic Rocks,' 'Metasedimentary Rocks,' and 'Younger Volcanic Rocks' (Earhart and Mawad, 1970).

Camp (1984) interpreted the Khumrah Greenstone (group 1) to be the product of back-arc spreading and basaltic volcanism associated with the opening of a marginal sea, which he called the Bidah interarc basin. The Khumrah Greenstone is a bimodal suite composed of chemically immature low-K tholeiite and sodic dacite and rhyolite (Roobol et al., 1983). The Hawiyah sediments (groups 2 and 3) are the result of contemporaneous erosion and deposition in the back-arc basin environment (Camp, 1984).

Regional metamorphism in the WBMD attained greenschist facies (Beziat and Donzeau, 1989). Intrusive rocks of the district are granites, diorites, tonalites, and granodiorites (Johnson and Vranas, 1984). Tertiary volcanism produced the flood basalts of the Harrat al Buqum (Fig. 2) in the northeastern part of the district (Johnson, 1999a).

Volcanogenic massive sulfide base metal mineralization exists in all five terranes of the Arabian Shield (Agar, 1992). Jackaman (1972) describes the WBMD deposits as stratabound, with ore-bodies related to stratigraphic horizons, and minor structural control of mineralization. The deposits have been described as syngenetic deposits related to volcanism (Earhart and Mawad, 1970; Jackaman, 1972; Kiilsgaard et al., 1978; Moore, 1978; Riofinex, 1979). Moore (1978) and Roubichou et al. (1989) suggest that the rhyolite domes near the Mahawiyah and Mulhal deposits were the felsic intrusions that supplied the metals of the deposits. The approximate age of these deposits is between 855 and 815 Ma, the age of Dhuqiyah complex, which intrudes the Wadi Bidah rocks (Fleck and Hadley, 1982; Radain et al., 1987).

Beziat and Donzeau (1989) divided the WBMD deposits into three types: (1) exhalative deposits (e.g. Gehab, Shaib al Tair and Mulhal), consisting principally of gossans in proximal felsic volcanic facies, and representing the majority of deposits; (2) distal volcanosedimentary deposits associated with disseminated to submassive sulfides (e.g. Rabathan); and (3) deposits related to shear zones and quartz veins associated with other deposits.

3. Materials and methods

Fieldwork was conducted in February 2000. This work included collecting structural data, sampling gossans, hydrothermally altered and unaltered rocks, mapping locations of deposits and marker units, and recording locations of deposits and samples with handheld GPS units.

Structural data for the WBMD were plotted on equal area stereonets (Fig. 4A), in order to determine regional and local characteristics of the ductile deformation. A marble unit that runs along the west side of Wadi Bidah south from Wadi Turabah (Fig. 3) to the middle of the WBMD was mapped during field work (Fig. 5). Three sections of this unit were mapped in detail (Fig. 5): marble section one, M1, is the most northern section of marble mapped; marble section two, M2, outcrops south of M1 and is the next section of marble with mesoscopic scale folds; and marble section three, M3, is the most southern section of marble mapped during this study. These sections of marble form mesoscopic scale folds. The marble unit was used to determine mesoscopic characteristics of ductile deformation and the effects of later brittle deformation on the layered rocks in the district. The marble serves as a marker horizon, which forms parasitic folds on the regional structure. The marble appears to be part of the same supracrustal sequence as that containing the sulfide deposits found in the WBMD. If the sulfide deposits are stratabound, they should mimic the ductile deformation of the host rock and marble unit. The marble unit is easily recognized in the field and exhibits both ductile and brittle phases of deformation. In the north the unit is more than 60 m thick. This unit thins to the south, becoming less than 1 m thick south of the Shaib al Tair prospect. Jackaman (1972) indicates on his maps of the area, that the marble unit continues to the south of M3 for approximately 10 km.

Remote sensing data sets used in this study include scenes from LANDSAT 7 and ASTER. Images were produced with standard data processing techniques, which included the use of color composites, band ratios, density slices and supervised classification. The

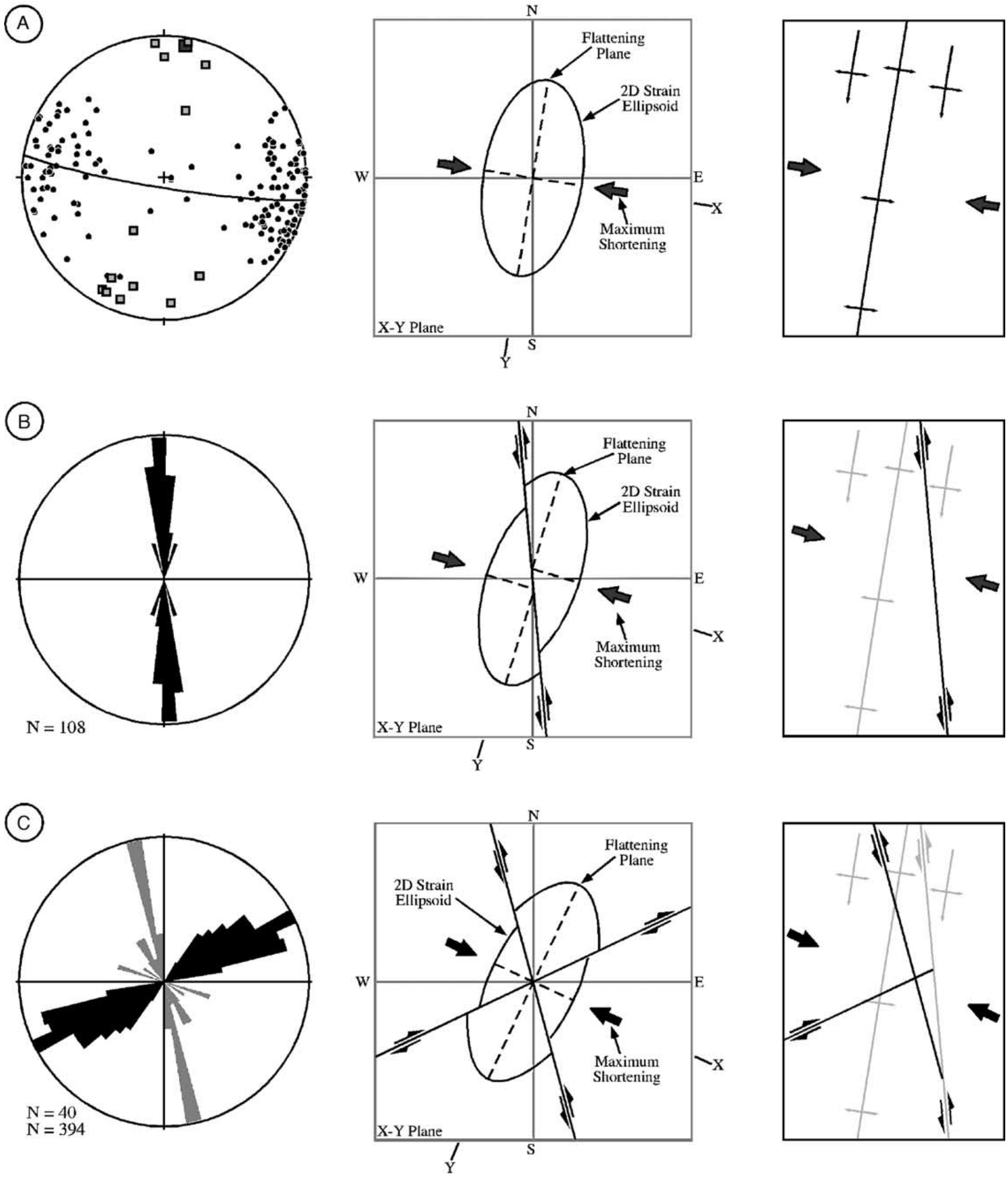

Fig. 4. (A) Equal area stereonet of the structural data collected in the field, February 2000. Black circles represent poles to bedding. Small, gray squares are measured bearing and plunge of fold axes. Large, black square is the calculated bearing and plunge of the regional fold axis. 2-D strain ellipsoid showing orientation of maximum shortening indicated by the field data. Simplified geologic sketch of regional ductile deformation. (B) Rose diagram of faults for the main Wadi Bidah shear zone. Data from the lineament analysis of the Landsat 7 (7-4-2) color composite image. 2-D strain ellipsoid showing orientation of maximum shortening indicated by the lineament analysis. Simplified geologic sketch of first phase of brittle deformation. (C) Rose diagram for synthetic–antithetic sets of faults due to continued shortening. Data from the lineament analysis of the Landsat 7 (7-4-2) color composite image. Simplified geologic sketch of second phase of brittle deformation.

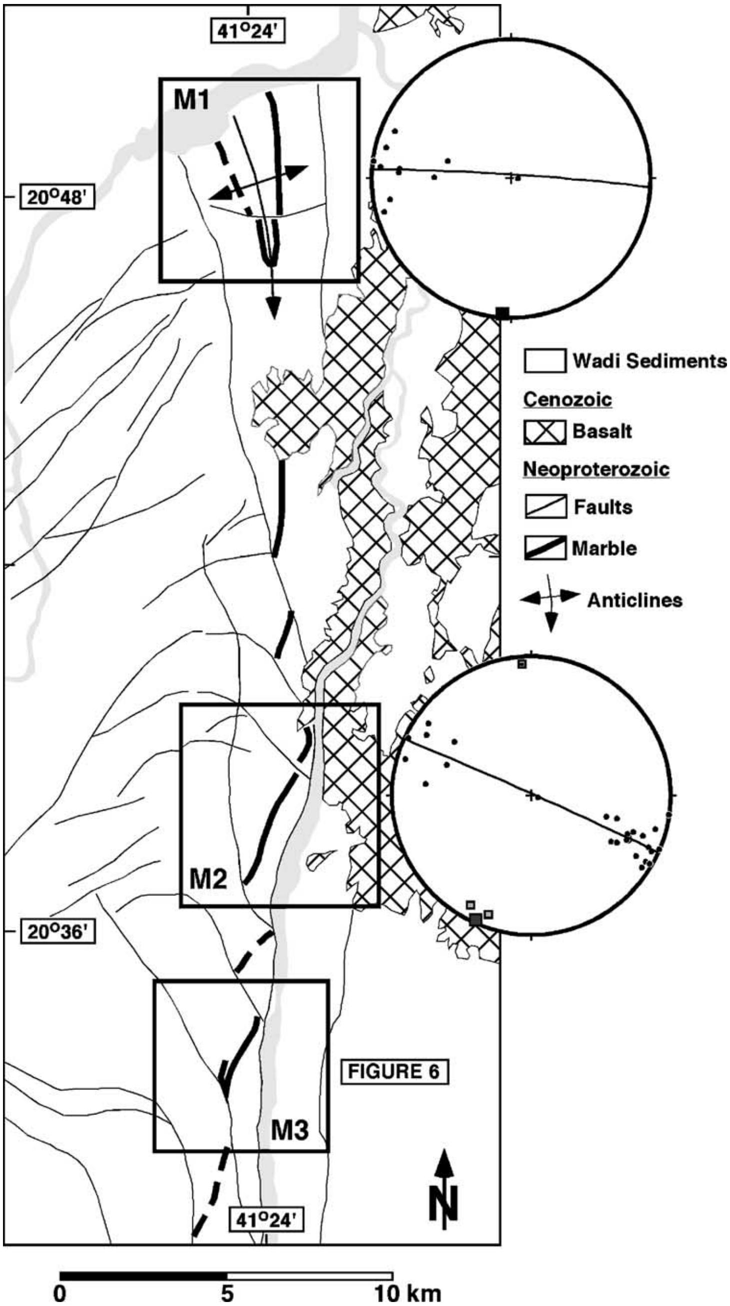

Fig. 5. Detail of Fig. 3 showing the marble unit and locations of M1, M2, and M3 (a dashed line where marble unit is inferred). Equal area stereonets of marble sections M1 and M2 illustrating ductile deformation of the marble. Stereonet symbols same as Fig. 4A.

remote sensing data were used in conjunction with geographic information system software (ARCVIEW) to map lithologic units and mineral deposits, analyze and define regional structural trends, and establish geologic controls on mineralization in the WBMD. The entire WBMD is covered by one Landsat 7 scene (185 km × 185 km), so this scene was used to produce images of the entire WBMD and for lineament analysis. ASTER scenes are smaller and only one scene covering the southern half of the WBMD could be acquired, but the improved spectral resolution of ASTER allows the analyst to better differentiate the alteration zones and gossans from the host rock (Volesky et al., submitted for publication). The ASTER (4/2-4/5-5/6) band ratio image of the Shaib al Tair prospect best differentiates the propylitic alteration zone and gossan from the host rock (Fig. 2B; Volesky et al., submitted for publication).

Orbital remote sensing at visible and near infrared wavelengths is based on the spectral reflectance of objects on the earth's surface (Drury, 1993). There are two ways to use remote sensing data to prospect for mineral deposits (Sabins, 1999). First these data can be used to map geology and the faults and fractures that can localize some types of ore deposits. Examples of this type of exploration include work in the Arabian Shield (Moore, 1983), Montana (Rowan et al., 1991) and Zaire, Zambia and Angola (Unrug, 1988). Fault traces can quickly be mapped on the remote sensing images yielding fault orientations. A lineament analysis was conducted by constructing rose diagrams from orientations of fault segments 2.5 km long giving a cumulative length orientation of the faults (Fig. 4B and C). Landsat 7 (7-5-4) and (7-4-2) color composite images were used for the lineament analysis, because these combinations differentiated the three lithologic groups and clearly showed the geomorphological expression of the faults.

Second, these data can be used to recognize hydrothermally altered rocks by their spectral signatures. Landsat 7 and ASTER images are especially useful for identifying two assemblages of minerals, iron minerals and the minerals found in hydrothermally altered rocks, which include calcite, clay, and chlorite-rich zones (Sabins, 1999). Examples of directly identifying hydrothermally altered rocks include work in the Arabian–Nubian Shield and Eritrea (Abdelsalam and Stern, 1999; Abdelsalam et al., 1997), Saudi Arabia (Blodget et al., 1978; Griffiths et al., 1987; Raines and Allen, 1985), Jordan (Abdelhamid and Rabba, 1994; Kaufmann, 1988), Sonora, Mexico (Bennett et al., 1993), Chile, Peru, and Bolivia (Eiswerth and Rowan, 1993; Knepper and Simpson, 1992), and Nevada (Rockwell, 1989).

The massive sulfide deposits of the WBMD have a surface expression in the form of an iron-rich cap or gossan and an associated zone of hydrothermal alteration, which forms clay, calcite, and chlorite-rich zones at Shaib al Tair (Fig. 2B; Coumoul et al., 1989). The gossans and associated alteration zones have distinct spectral signatures and are often large enough to be detected with orbital remote sensing platforms, such as Landsat 7 and ASTER (Volesky et al., submitted for publication). The use of remote sensing data to prospect for mineral deposits in the Arabian Shield is facilitated by the arid environment, which prohibits the growth of vegetation and development of soil that would obscure the underlying geology.

4. Results

The structural data were combined with the remote sensing images to create the geologic map of Wadi Bidah (Fig. 3). Use of the remote sensing images to map the geology of the WBMD clearly shows that the district is divided into three lithologic groups. These lithologic groups are separated by faults. The East Fault separates groups 1 and 2 (Fig. 2).

The structural data indicate that the WBMD is comprised of subvertical-layered rocks, which have been folded and faulted into a N/S-trending belt (Fig. 4A). Folds, such as the anticline designated M1 (Fig. 5), on the east side of the WBMD and the anticline opposite M1 on the west side of the district (Fig. 3) can easily be identified on remote sensing images. The S_0/S_1 schistosity creates the obvious layering of the group 2 rocks. The trend and plunge of the regional fold axis was calculated to be 009/6 by fitting a great circle to the poles to bedding data (Fig. 4A). Regional folds are upright and tight.

Ductile deformation of the marble unit includes the development of upright isoclinal folds in the southern part of the unit, while in the north an open, east-verging anticline, M1, was formed (Fig. 5). The calculated trend and plunge of the M1 fold axis is 184/2. M2 is

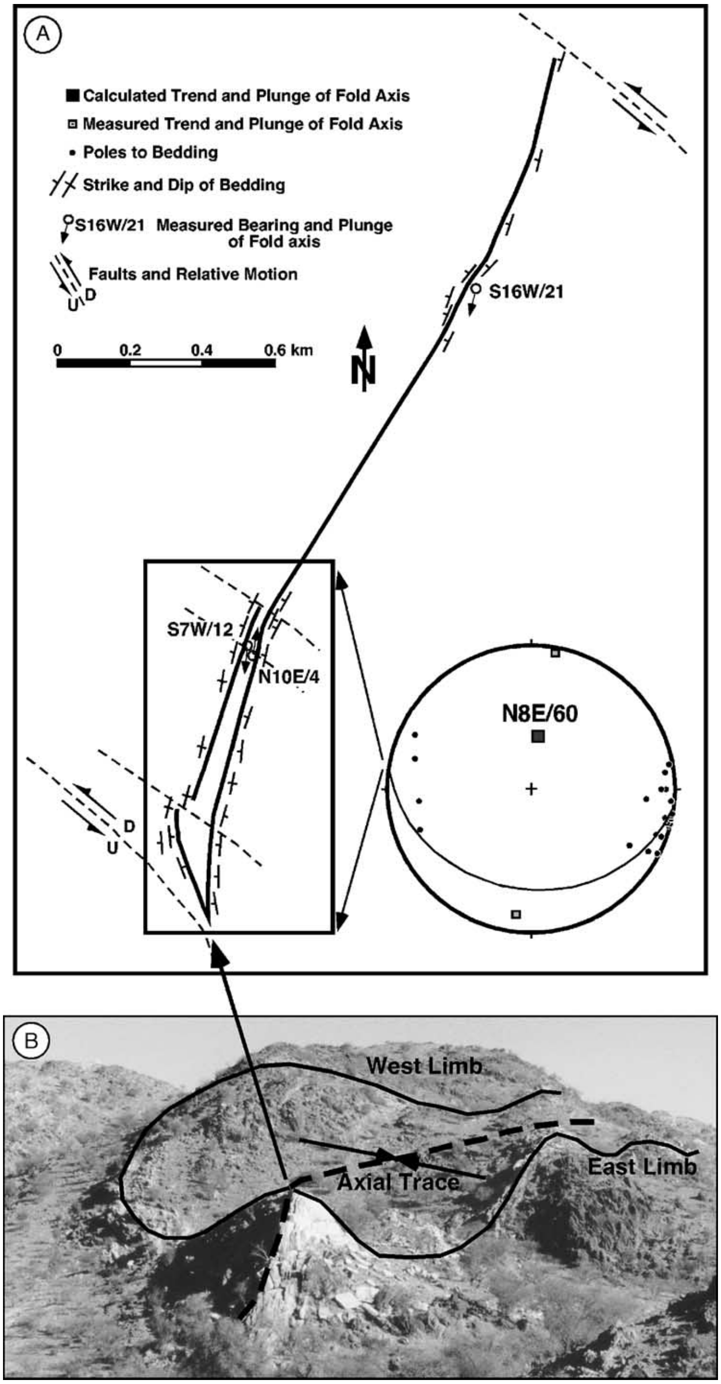

Fig. 6. (A) Simplified geologic map of the marble section M3 with an equal area stereonet for the southern end illustrating drag folds in strike-slip and dip-slip directions. (B) Field photograph (February 2000) of marble section M3 indicating the limbs and axial trace of the syncline formed in M3. Looking north at the nose of the syncline.

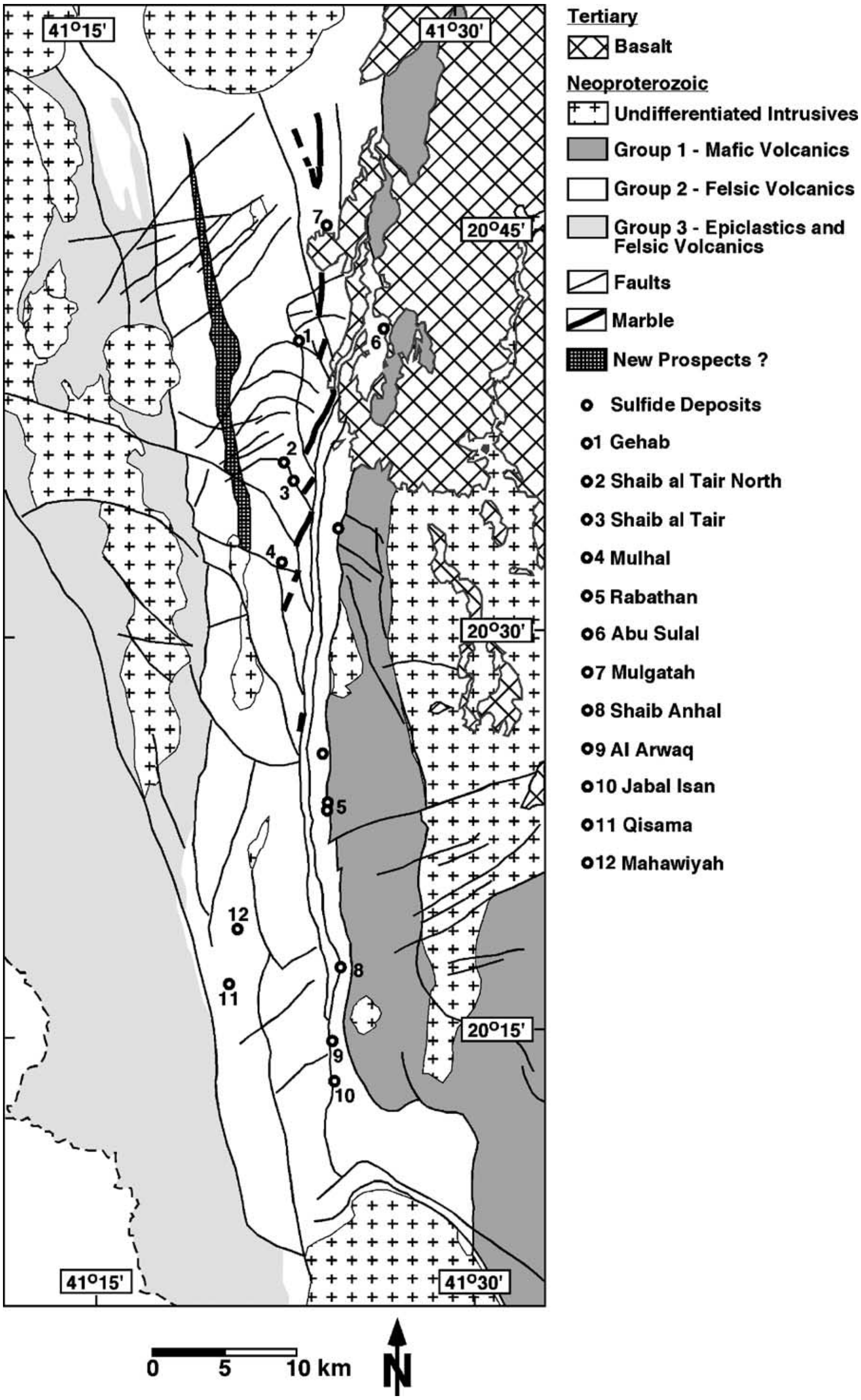

Fig. 7. Geologic map from interpretation of the Landsat 7 (7-5-4) color composite image indicating locations of deposits visited during fieldwork, marble unit, area with suspected new prospects, and major faults.

composed of a series of tight isoclinal folds, which have a calculated trend and plunge for the fold axis of 204/1 (Fig. 5). M3 (Fig. 6) is an isoclinal fold, which forms a north-plunging syncline. The nose of the fold is cut by a northwest-trending sinistral fault (Fig. 6). Drag folds in both strike-slip and dip-slip directions are developed in the marble unit. As a result, the plunge of the fold axis plunges steeply north near the southern end of M3. The plunge flattens and then changes plunge direction to the south at the northern end of M3. For the southern part of the M3 fold, which terminates at a sinistral strike-slip fault, the calculated trend and plunge of the fold axis is 008/60 (Fig. 6). The field measurements of the trend and plunge for fold axes traveling north along the marble unit are 010/4, 187/12, and 196/21 (Fig. 6).

Lineament analysis of the WBMD remote sensing images suggests there are four significant populations of faults with bearings of 65°, 95°, 165°, and 175°. Faults bearing 175° make up the faults of the main shear zone and have been described as left lateral strike-slip faults by Johnson (1999a). The faults bearing 165° have large sinistral offsets, typically 1.5 km and form a synthetic–antithetic set with the faults bearing 65°, which have dextral displacements of tens of meters (Jackaman, 1972). The faults bearing 95° have no measurable offset on the images and are probably associated with formation of the 165/65 synthetic–antithetic faults.

The mineral deposits of the WBMD are separated into two belts (Fig. 7). The Rabathan belt is a north-trending belt of deposits east of Wadi Bidah near the East Fault, which separates the group 1 and 2 rocks (Fig. 2). The belt, which includes Gehab, Shaib al Tair and Mulhal is a north-trending belt within group 2, west of Wadi Bidah. Deposits in this belt occupy a stratigraphic horizon approximately 2 km west of the marble unit (Fig. 7). This uniform stratigraphic separation indicates that the deposits are stratabound and have undergone the same ductile and brittle deformation as the marble unit. Fig. 7 indicates the locations of known massive sulfide deposits visited and located with GPS coordinates during fieldwork in February 2000. These are more than half of the known massive sulfide deposits listed in the Saudi Geological Survey Mineral Occurrence Documentation System (MODS) for the WBMD. Possible marble and hydrothermal alteration on the west limb of the regional anticline suggests new prospects may be located on the western limb (Fig. 7). Existence of new prospects on the western limb could not be confirmed during fieldwork, because of limited time.

5. Discussion

All the sulfide deposits of the WBMD are found in lithologic group 2. The marble unit within lithologic group 2 was used as a marker horizon. Based on the distribution of the sulfide deposits on the west side of Wadi Bidah relative to the marble unit, all sulfide deposits appear to be stratabound. Stratigraphically the massive sulfide deposits are lower (older) than the marble unit. Evidence for this relationship includes the orientation the Shaib al Tair deposit with a propylitic zone west of the deposit indicating a younging direction toward the east and the marble (Coumoul et al., 1989), the position of the deposits on the east limb of a regional N/S anticline indicates younging direction is towards the east (Riofinex, 1979; Smith et al., 1983), and truncated cross-bedding in a shale unit near the Rabathan deposit (Smith et al., 1983) indicates a similar stratigraphic succession.

The sulfide deposits of the WBMD are separated into two belts (Beziat and Donzeau, 1989). Proximal deposits are found in a belt west of Wadi Bidah. This belt includes the Gehab, Shaib al Tair, and Mulhal deposits. These proximal deposits are found in the same stratigraphic position relative to the marble unit, approximately 2 km to the west of the marble (Fig. 7). Distal deposits are found in a belt east of Wadi Bidah. This belt includes the Abu Sulal and Rabathan deposits. Distal and proximal deposits both appear to be confined to single stratigraphic horizons, so the deposits may have been produced by the same felsic volcanic episode and have subsequently been folded and faulted into their present position.

Roubichou et al. (1989) suggests that hydrothermal processes at Mulhal ended with the emplacement of mafic rocks. These mafic rocks consist of dikes and sills of andesite-basalt, which cut the felsic rocks and in places evolve into flows. If all deposits formed during the same felsic volcanic episode, then emplacement of this mafic complex may have ended hydrothermal processes throughout the WBMD.

Based on analysis of the field data and lineament analysis of the remote sensing images, the structural evolution of the WBMD includes at least three Neoproterozoic deformational events, which are illustrated in Fig. 4. The first phase of deformation, D_1, a ductile phase of deformation resulted in the development of tight to isoclinal folds, due to east-west compression (Fig. 4A) and development of S_0/S_1 schistosity. The second phase of deformation, D_2, a brittle phase of deformation caused by continued east-west shortening resulted in the formation of the main north-south sinistral Wadi Bidah shear zone (Fig. 4B). The third phase of deformation, D_3, a brittle phase of deformation resulted in development of synthetic–antithetic fault sets due to continued SE-NW shortening (Fig. 4C).

Jackaman (1972) and Smith et al. (1983) both point out that the Gehab and Mulhal deposits have been folded. Folding appears to be a post-mineralization process and has no significant control on sulfide mineralization in the WBMD. All sulfide deposits have also been affected by post-mineralization faulting and shearing. Structural data indicates that drag folds have formed in both strike-slip and dip-slip directions along the sinistral fault in the marble unit, M3, so have affected deposits in a similar manner. The drag fold in the Shaib al Tair North deposit is evident along the sinistral fault, which shears the southern edge of the deposit (Fig. 2B). Faults do not appear to significantly control sulfide mineralization in the WBMD.

6. Conclusion

All sulfide deposits visited during fieldwork are found in the felsic volcaniclastic, lithologic group 2. Uniform stratigraphic separation between the marble unit and the sulfide deposits on the west side of Wadi Bidah indicate that the sulfide deposits are stratabound. The main geologic control of sulfide mineralization in the WBMD appears to be stratigraphic. The deposits and marble unit have been deformed in a similar manner by the same ductile and brittle deformational events. Structural deformation is a post-mineralization process with no control on sulfide mineralization. Analysis of the remote sensing images indicates continuation of alteration zones and marble outcrops on the western flank of the regional anticline, suggesting new prospects may be found on the western side of the WBMD.

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