DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Lithofacies and depositional environment of the Maraghan Formation, and speculation on the origin of gold in ancient mines, An Najady area, Kingdom of Saudi Arabia

by

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Open-File Report 87-177

Report prepared by the U.S. Geological Survey in cooperation with the Deputy Ministry for Mineral Resources, Saudi Arabia

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

1/ USGS, Denver, CO

1987

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ABSTRACT

The Upper Proterozoic Maraghan formation of the Murdama group is subdivided into five lithofacies units over an area of about 750 sq km near An Najady, in the northern Arabian Shield. The Maraghan formation is composed mainly of sandstone, siltstone, shale, and lesser amounts of limestone, dolomite, and carbonate-cemented sandstone, and becomes finer grained upward. The base of the Maraghan is not exposed in the study area. The lowest exposed unit, lithofacies A, is dominated by coarse-, medium-, and fine-grained sandstone and lesser amounts of siltstone, shale, and interbedded limestone and dolomite. Beds in lithofacies A form fining-upward sequences that decrease in maximum grain size upward. Lithofacies B, which gradationally overlies lithofacies A, is dominantly a fine-grained sequence that is characterized by siltstone and shale, with lesser amounts of fine-grained sandstone. Beds of limestone and dolomite are rare; some zones of medium-grained sandstone occur locally. Lithofacies C overlies lithofacies B with a gradational contact and shows a west-to-east facies change. In the western part of the area, lithofacies C is fine-grained sandstone, siltstone, and shale, containing locally thick zones of brecciated limestone and dolomite; a pinkish tan dolomite is at the base, and a thick gray dolomite pod at Jabal Rahail forms a local carbonate unit that may have been tectonically thickened. In the eastern part of the area, sandstones are coarse- and medium-grained; fining-upward cycles prevail, and carbonate occurs as thin, lenticular beds at the base of cyclic beds. Locally, sections as thick as 10 m are dominated by coarse- or medium-grained sandstone. Lithofacies C appears to thicken toward the east. Lithofacies D, which gradationally overlies lithofacies C, is composed mainly of medium- and fine-grained sandstone, siltstone, and shale. Carbonate-bearing beds are rare, although carbonate pods along the bounding thrust fault in the northwest part of the basin may be part of lithofacies D. Fining upward cycles dominate clastic rocks. In western exposures siltstone and shale are dominant, but in eastern exposures medium- and fine-grained sandstone are more common. Lithofacies E, the uppermost of the facies units mapped, is composed mainly of graded sequences of coarse- and medium-grained sandstone, fine-grained sandstone, siltstone, and shale. Limestone and dolomite occur as cement in sandstone beds or as lenticular concretions.

The depositional environment of rocks of the Maraghan Formation was probably an extensive mudflat drained by braided channels. Carbonate mounds and possibly algal reefs developed between distributary channels. Barrier islands may have bordered the mudflat to the east and southeast.

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Ancient gold mines occur as gold-quartz vein deposits mainly in fine-grained rocks of lithofacies B and D. The ancient workings at An Najady occur in a fine-grained zone within Lithofacies A. Five samples of shale analyzed for gold, contained concentrations that ranged from less than 4 ppb to 11 ppb. These preliminary results suggest that hydrothermal fluids may have mobilized gold from shale of Maraghan rocks during intrusion of small stocks. The potential for gold occurrences of unknown size and concentration appears to be highest near silicic stocks and buried intrusive bodies, or within fine-grained carbonaceous rocks, and syngenetic volcanic rocks of the Maraghan formation.

INTRODUCTION

In the northern part of the Arabian Shield, the Muradama group consists mainly of fine-grained clastic rocks and lesser amounts of carbonate rocks. The Maraghan formation, which forms the upper part of the Murdama group in this area, had not been subdivided by previous workers. The study area is approximately bounded by Wadi Ash Shi'bah on the west, Jabal Witidah on the north, Jabal Qitan on the east, and Wadi ar Rumah on the south. The irregularly shaped study area is enclosed by the following coordinates: latitudes 25°52' and 26°15' N. and longitudes 41°55' and 42°20' E. (fig. 1).

Five lithofacies, A through E, were distinguished on the basis of preliminary geologic mapping of an area of about 750 sq km near An Najady (fig. 1). Lithofacies A at the base of the section studied, is composed of coarse-grained sandstone, carbonate-cemented sandstone, sandy carbonate, fine-grained sandstone, and siltstone. Lithofacies B is a fine-grained unit that consists mostly of fine-grained sandstone, siltstone, shale, and rare beds of limestone or dolomite. Lithofacies C is dominated by medium-grained sandstone, fine-grained sandstone, siltstone, and shale; coarse-grained sandstone is less common than medium-grained sandstone, and carbonate-bearing beds are scattered throughout the sequence. An upper fine-grained unit, lithofacies D, consists mainly of siltstone and shale, with lesser amounts of fine-grained sandstone and local carbonate-bearing beds. Lithofacies E at the top of the section, is coarse-grained unit that contains coarse- and medium-grained sandstone, fine-grained sandstone, siltstone, and shale. In general, the entire sequence of the upper Murdama group in the An Najady region becomes finer-grained and less carbonate-rich upward. All lithofacies are finer grained toward the top of the units. The top and base of the Maraghan formation are not exposed in the area studied. Thickness estimates were not calculated for these lithofacies because numerous tight, small- and medium-scale folds occur in the map area, and lacking better structural control estimates could be much in excess of actual lithofacies thickness.

Results of this study on lithofacies and inferences based on a small number of geochemical samples enhance the possibility that gold in quartz veins could have been remobilized from fine-grained clastic rocks of the upper Murdama group. Fine-grained lithofacies B and D, contain nearly all of the known ancient workings in this area; the workings exploited gold in quartz veins that are associated with intrusive bodies. The concentration of gold in fine-grained rocks of the Murdama group ranges from a trace to 11 parts per billion (ppb). Gold may have been remobilized from shale in the fine-grained facies of the Maraghan formation by hydrothermal processes as magma intruded the clastic rocks.

PREVIOUS STUDIES

Most of the previous geologic work in the area of An Najady concentrated on completing the regional structural and stratigraphic framework. Williams (1983) showed the distribution of rocks of the Murdama group in the Samirah quadrangle, sheet 26/42C, (scale 1:100,000), which encompasses the northern part of the study area of this report. The Uglat as Suqur quadrangle, sheet 25/42A (scale 1:100,000) mapped by Cole (1985) shows the distribution of conglomerate, and overlying carbonate and coarse-grained sandstone in the southern part of the study area. Quick and Doebrich(in press) and Williams and Simonds, (1985) showed the distribution of the upper Murdama group in the southeastern part of the Wadi Ash Shi'bah quadrangle, sheet 26E, (scale 1:250,000), which encompasses the western part of this study area. Geologic mapping by Williams (1983) subdivided the Murdama group in the northern basin into the Hibshi formation at the base and the Hadiyah formation above. Exposures of marble were correlated with the Faridah marble known from the central part of the basin (Delfour, 1977; Greene, 1983). Later mapping by Johnson and Williams (1984), Pallister, (1984), and Cole (1985), suggested that the Hibshi formation may not be part of the Murdama group and is possibly younger; the name Maraghan formation was proposed to replace the name Hadiyah formation.

Studies on gold veins of the An Najady area were conducted by Smith and others (1984). Results of their work suggested that the numerous gold deposits in the region were formed by late-stage hydrothermal activity related to local intrusive bodies, and that the source of gold found in veins might have been from the sedimentary host rocks, the Maraghan formation. More recent studies (Williams and Simonds, 1985) report that gold occurs in altered granodiorite at the Shi'bah prospects (fig. 1).

PRESENT INVESTIGATION

The present study was undertaken to determine if the upper part of the Murdama group could be subdivided into lithofacies assemblages that could be traced laterally across structures, and to determine if rocks of the Maraghan formation contained gold in low concentrations. Mapping was done on photomosaic maps sheets 261, 262, and 285 at a scale of 1:50,000. Seven days of field work in March, 1985, were devoted to regional mapping of lithofacies and to sampling rarely exposed shale beds in the Maraghan formation. The general geology of the region was adapted from Williams (1983), Cole (1985), and Quick and Doebrich(in press). Analytical data on gold concentrations were provided by laboratories of the Deputy Ministry for Mineral Resources in Jiddah under the direction of K. J. Curry, USGS. The graphite furnace and atomic absorption method was used to determine gold concentrations to 4 ppb.

ACKNOWLEDGEMENTS

This project was performed in accordance with a work agreement between the Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia, and the U. S. Geological Survey for investigation of mineral resources on the Arabian Shield. P. L. Williams suggested the Murdama basin as a potential host for disseminated gold occurrences, and he provided much stimulating discussion and

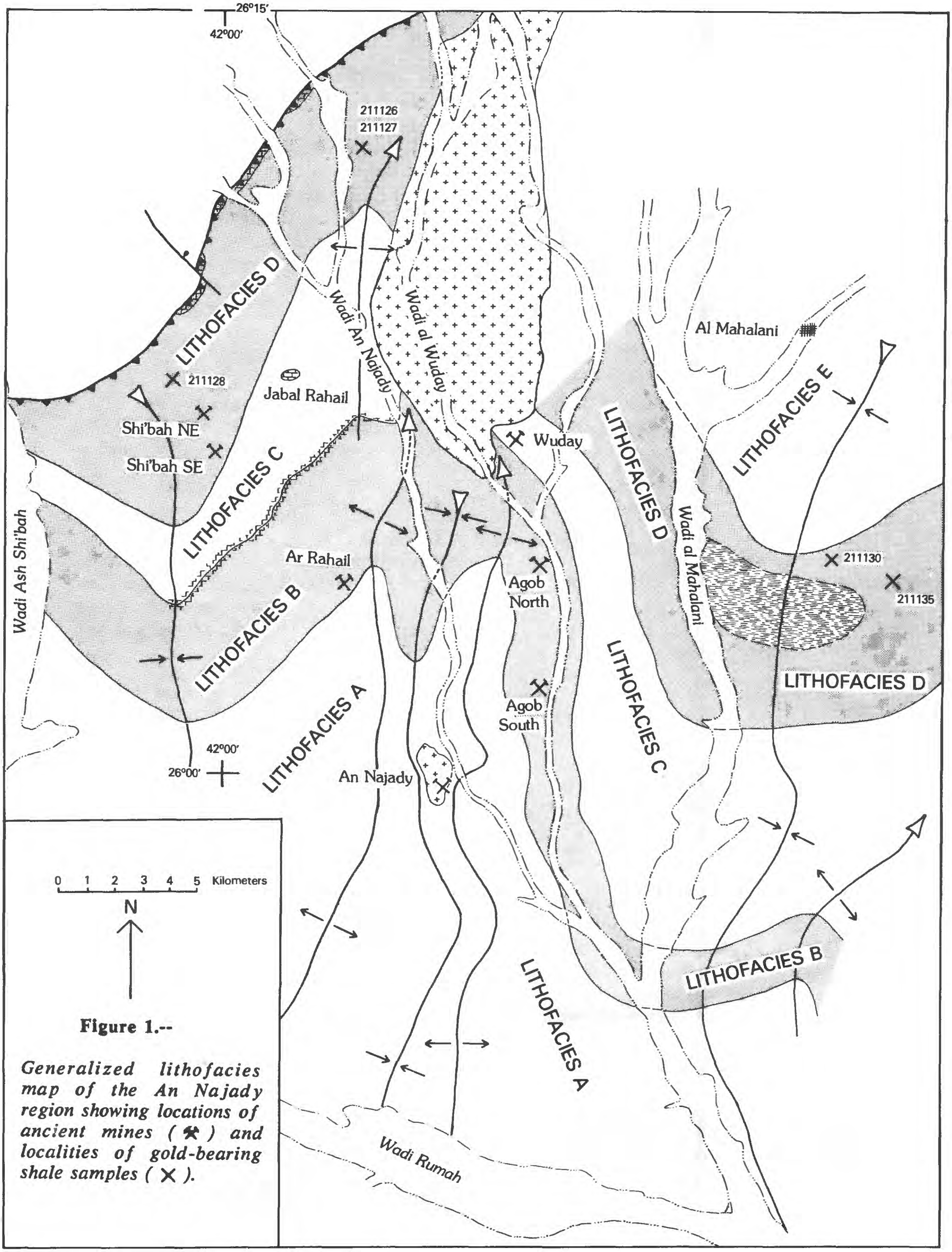
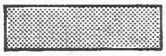


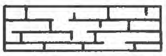
Figure 1.--

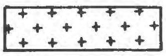
Generalized lithofacies map of the An Najady region showing locations of ancient mines (⚒) and localities of gold-bearing shale samples (X).

EXPLANATION

 Fine-grained lithofacies B and D

 Coarse-grained lithofacies A, C, and E

 Prominent limestone or dolomite beds or pods

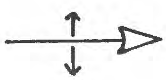
 Intrusive rocks

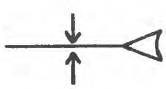
 Approximate area of metamorphosed rocks that probably overlie a buried pluton

Contact, dashed where covered by younger deposits

 Thrust fault. Sawteeth on upper plate. Dashed where covered by younger deposits

 High-angle fault. Ball and bar on apparent downthrown block

 Anticline, showing approximate axial trace. Large arrow gives direction of plunge and small arrows give direction of dip of limbs. Axial trace dashed where covered by younger deposits

 Syncline, showing approximate axial trace. Large arrow gives direction of plunge and small arrows give direction of dip of limbs. Axial trace dashed where covered by younger deposits

Approximate border of active drainages and Quaternary deposits

unpublished data that facilitated this work. W. H. White, J. C. Cole, and C. W. Smith provided useful guidance during phases of this work. Special thanks are due the personnel of Special Flights of Saudia Airlines and to Ray Samorra, the helicopter pilot, for the extra effort they made to complete this work. Quick return of analytical data by analysts A. Baraja and S. Qubai, under the supervision of K. J. Curry, is greatly appreciated.

DESCRIPTION AND DISTRIBUTION OF LITHOFACIES

In the vicinity of An Najady, the fining-upward sequence of the Maraghan formation is dominated by three coarse clastic lithofacies that enclose two finer grained lithofacies. These informally divided units have been traced laterally over about 40 km across a series of large anticlines and synclines that have north trending axial traces (fig. 1). Each lithofacies is also a fining-upward sequence of rocks. In general, the amount of calcite and dolomite interbeds decreases upward through the five lithofacies. Coarse-clastic lithofacies appear to thicken from west to east and the lower fine-grained lithofacies appears to become coarser grained and thinner toward the east.

The composition and texture of clastic rocks of the Maraghan formation have been summarized by Williams (1983), Johnson and Williams (1984), Cole (1985), and Greene (in prep.). Generally, sandstone beds are classified as lithic graywacke, which have varying percentages of quartz, volcanic rock fragments, feldspar, and matrix. Among framework grains, volcanic rock fragments dominate and range from about 85 percent (Greene, in prep.) to about 50 percent (Williams, 1983). Quartz forms between 5 percent (Greene, in prep.) and 30 percent (Williams, 1983) of the framework grains, and feldspar forms between 5 percent (Greene, in prep.) and 20 percent (Williams, 1983). Sandstones characteristically contain a matrix of fine-grained chlorite, clay minerals, silt-sized grains, and carbonate minerals; the relative percentages of these components vary considerably (Williams, 1983; Johnson and Williams, 1984; Cole, 1985). The composition of siltstone and shale has not been studied. Cole (1985) determined that individual grains in sandstone beds range from angular to subangular, and sorting of grains is poor to moderate.

Carbonate occurs as interbeds of limestone or dolomite in nearly all of the lithofacies; the relative abundance of carbonate beds decreases upward through the section. Although petrographic and X-Ray data were not obtained on carbonate-bearing rocks, field evidence suggests that calcite or dolomite can dominate in individual carbonate beds. Limestone is commonly dolomitic and iron-rich, which becomes reddish brown after weathering, and reddish brown-weathering dolomite commonly contains calcite. Both types of carbonate beds contain clastic material; the most prominent contaminant is sand, as individual dispersed grains or as discrete beds. Carbonate beds contain crossbedding in which foresets are defined by laminae of sand. Some carbonate beds are lenticular but have flat upper surfaces. Some carbonate appears to form concretions, which have rounded shapes and which preserve bedding laminae. Commonly sandstone beds are cemented by calcite or dolomite. Primary carbonate beds appear to be gradational with secondary carbonate of concretions and calcite- or dolomite-cemented sandstone. Primary and secondary carbonate is most common in the coarse-grained parts of fining-upward cycles in most lithofacies.

In general, rocks of the Maraghan formation are brownish green and greenish gray. Carbonate-cemented sandstone weathers to brownish and reddish-brown colors, but these rocks are greenish on fresh surface. The rocks are regionally metamorphosed to the lower greenschist facies (Williams, 1983). Adjacent to intrusive bodies, contact metamorphism has changed rock colors to dark-grayish green and very dark gray. Impure carbonate beds of the Maraghan formation are metamorphosed to calc-silicate hornfels near intrusive bodies, whereas pure carbonate beds are metamorphosed to calcite or dolomite marble.

LITHOFACIES A

Lithofacies A is characterized by coarse- and medium- grained sandstone; in the lowermost exposed part of the unit course-grained sandstone is most common. Lenticular limestone and dolomite beds are most common in the lower part, although carbonate-bearing beds occur throughout this unit (fig. 2).

Typically in the lower part of this lithofacies, coarse-grained sandstone and interbedded carbonate dominate in the lower parts of fining-upward cycles and these beds are overlain successively by medium-grained sandstone and fine-grained sandstone. Siltstone and shale beds occur rarely at the tops of fining-upward cycles. Coarse-grained sandstone beds and interbedded carbonate are as thick as 1 m in the lower part of this lithofacies (fig. 2), but higher in the sequence the thickness of basal parts of fining-upward cycles is 10-20 cm. Medium- and fine-grained sandstone of the upper parts of cycles ranges between 20 and 50 cm throughout this lithofacies. The base of cycles is usually defined by channeled contacts in which fine-pebble- and granule-bearing coarse-grained sandstone overlies medium- or fine-grained sandstone of the underlying cycle.

Figure 2.--*Photograph of interbedded coarse-grained sandstone and carbonate bed in the lower part of lithofacies A.*

Limestone and dolomite beds, and carbonate cemented sandstone beds usually range between 5 cm and 1 m thick in the lower part of this facies unit. Trough and planar crossbedding are common sedimentary structures in the lower part of this sequence.

Above the lower coarse-grained part of lithofacies A, fining-upwards cycles dominate in the sequence. These cycles consist of medium-grained sandstone at the base, and are overlain by fine-grained sandstone or siltstone with a sharp, but rarely channelled contact. Planar crossbedding, ripple cross-lamination, and planar lamination are the most common sedimentary structures in these finer grained rocks. Interbeds of primary carbonate and carbonate-cemented sandstone range between 1 and 8 cm thick and carbonate beds are more sparsely distributed in the upper part of this unit. Fine-grained sandstone, siltstone, and shale occur at the tops of fining-upwards cycles near the top of lithofacies A. Finer-grained rocks occur at several places in this facies, and they consist of cycles having fine-grained sandstone at the base overlain successively by siltstone and shale. These finer-grained sequences probably grade laterally into coarser grained rocks more typical of this lithofacies. A fine-grained sequence occurs at An Najady, but these sequences were not mapped separately during this reconnaissance study.

LITHOFACIES B

Lithofacies B is composed mostly of fine-grained rocks that consist of fine-grained sandstone, siltstone, and shale; medium-grained sandstone and thin, discontinuous beds of limestone or dolomite occur rarely. Because rocks of this lithofacies weather more easily than the carbonate-bearing rocks of under and overlying facies, exposures that show bedding features are rare, and estimates of relative amounts of shale, siltstone, and fine-grained sandstone are not reliable.

This lithofacies is dominated by sequences of interbedded siltstone and shale beds of which range between approximately 0.2 and 1.0 m thick. Resistant-weathering rocks are dominated by siltstone and contain lesser amounts of shale. Resistant beds alternate with non-resistant weathering shale that contains lesser amounts of siltstone. Sporadically distributed thin beds (1-3 cm thick) of fine-grained sandstone and lenticular beds of limestone or dolomite (1-5 cm thick) occur in shale and siltstone. Some bodies of medium-grained sandstone, attain a thickness of several meters, but no stratigraphic pattern was determined for occurrence of these sandstone zones. Shale and siltstone beds are thinly laminated, and contacts between beds are planar. Sandy beds contain ripple cross-lamination and planar laminations. Diagenetic carbonate cement is not common in rocks of this lithofacies.

In the western part of the study area, the top of this unit underlies a prominent pinkish tan-weathering, massive, pure dolomite of lithofacies C. Over most of the study area, lithofacies B grades upward into the sandy rocks of the overlying lithofacies without the intervening pinkish dolomite.

LITHOFACIES C:

Lithofacies B is characterized by fine-grained sandstone, siltstone, shale, and thick pods of limestone and dolomite in western exposures, and by coarse-, medium-, and fine-grained sandstone, siltstone, shale, and lesser amounts of carbonate-bearing rocks in eastern exposures. The change in dominant rocks types appears to be gradational between western and eastern exposures.

A distinctive pinkish tan- and whitish pink-weathering, dense, pure dolomite, which was traced as a marker bed by P. L. Williams (oral commun., 1985), occurs at the base of lithofacies C in the western part of the area. This dolomite marker ranges between 3- and 10-m thick and is thickest at the western end; eastward the dolomite thins gradually, and cannot be traced farther east than Wadi Najady.

In western exposures, this lithofacies is dominated by fining-upward cycles of medium- and fine-grained sandstone, siltstone, and shale. Bedding cycles range between 0.5- and 2-m thick. Basal contacts of some cycles may represent shallow channels that were cut into underlying shale beds to form gently undulating contacts. Few primary structures were found in this part of lithofacies C. Pods of gray-weathering limestone and gray-, tan-, or pink-weathering dolomite are characteristic of this lithofacies. Most of these lenticular carbonate bodies range between 0.5- and 15-m thick and are irregularly distributed through the clastic sequence. Internal structures are generally obscure in carbonate pods, although some of these pods are mainly breccia and microbreccia. The largest of these carbonate pods is the brecciated and laminated dolomite at Jabal Rahail. Williams (oral commun., 1985) estimated this dolomite pod to be about 200 m thick at Jabal Rahail. Most of the dolomite at the Jabal is brecciated, and only parts of the dolomite preserve faintly visible, very thin lamination.

In the eastern part of this lithofacies the relative proportion of coarse- and medium-grained sandstone is greater, and the proportion of carbonate pods and beds is less than in the western part. Fining-upwards sequences dominate the vertical succession of rocks, but complete graded sequences that grade from coarse-sandstone at the base to shale at the top are rare. Some sandstone bodies are as thick as 10 m and are dominated by medium- or fine-grained sandstone and lenticular beds of coarse-grained sandstone, siltstone, or shale. Carbonate-bearing rocks are lenticular and thin (5-8 cm thick). Most of the carbonate-bearing rocks are calcite- or dolomite-cemented sandstone, although some carbonate-filled channels are present. Locally, limestone and dolomite concretions are common. Large, laterally traceable limestone or dolomite pods are rare in eastern exposures of this facies unit.

Lithofacies C appears to thicken toward the east as the grain size of sandstone beds increases toward the east. This trend of thickening toward the east seems to be accommodated by a concommitant thinning of the underlying lithofacies B. Lithofacies C appears to grade upward into the overlying fine-grained lithofacies D.

LITHOFACIES D

Lithofacies D is characterized by prominent fining-upwards cycles that contain a greater proportion of fine-grained clastic rocks than the underlying facies unit. Carbonate-bearing rocks are rare, and siltstone and shale are dominant in western exposures, whereas medium- and coarse-grained sandstone increase in proportion to the east (fig. 3).

Fining-upwards cycles are characterized by a medium- or fine-grained sandstone at the base that ranges between 10 cm and 1 m thick, which overlies a shale or siltstone bed with a sharp planar contact (fig. 3). The basal sandstone grades upward into siltstone and shale that ranges between 20 cm and 1 m thick. Sandstone beds contain ripple cross-laminations and planar lamination. Siltstone and shale beds are thinly laminated. Medium- or coarse-grained sandstone forms the basal sandstone beds at some places, and some non-cyclic coarse- and medium-grained sandstone beds occur widely distributed through the facies.

Carbonate-bearing beds are dominated by gray-weathering limestone or dolomite concretions and by calcite- or dolomite-cemented sandstone. Gray-weathering, lenticular limestone beds range between 1-6 cm thick and they are present in some basal sandstone beds. Rare gray-weathering limestone beds are as thick as 1-2 m in western exposures. Several thick pods of sheared marble occur along the thrust fault in the northwestern part of the map area (fig. 1), (Williams, 1983), but because these carbonate rocks may be bounded by faults their stratigraphic position is not certain and relations of the carbonate pods to rocks of lithofacies D is not known.

From west to east, this facies appears to coarsen by an increase in the proportion of fine- and medium-grained sandstone and a decrease in the proportion of siltstone and shale. The fining-upwards cycles are most prominent in the western part of this facies unit.

Lithofacies D is truncated by a thrust fault along the northwestern boundary of the study area; therefore, lateral changes in thickness cannot be estimated for this unit. Lithofacies D appears to grade upward into overlying lithofacies E.

LITHOFACIES E

Lithofacies E, the uppermost lithofacies, is dominated by beds of coarse-, medium-, and fine-grained sandstone that grade upward into siltstone and shale beds (fig. 4). Although this facies unit is generally coarser grained the lithofacies B and D, it contains more fine-grained detritus than do lithofacies A and C.

Typically, coarse- or medium-grained sandstone overlies a shale bed with an uneven and sharp contact. Coarse-grained sandstone, if present in the basal layer, grades progressively into medium-grained sandstone, fine-grained sandstone, siltstone, and shale. Individual graded sequences range between 0.5 and 1.5 m thick. Medium-grained sand commonly forms the bulk of a graded unit, and prominent, complete fining-upwards cycles are a characteristic feature of this facies.

Carbonate beds and carbonate-cemented beds are distributed throughout this facies as thin, rare limestone or dolomite-cemented sandstone beds or as lenticular-shaped concretions. Lenses of bedded gray limestone are present in the lower sandy beds of some graded units (fig. 4).

The top of this lithofacies unit is truncated by a thrust fault along the northern and northwestern boundary. Thus, variations in thickness cannot be determined from available data.

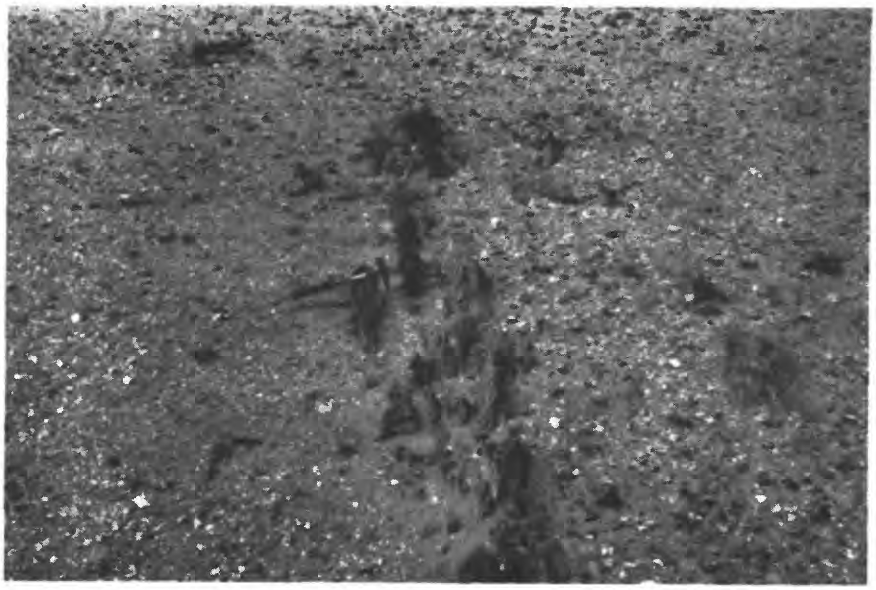


Figure 3.--*Photograph of interbedded medium-grained sandstone, carbonate-cemented sandstone, siltstone, and shale in the uppermost part of lithofacies D. Shale sample at this locality contained detectable gold at less than 4 ppb.*

Figure 4.--*Photograph of interbedded medium- and fine-grained sandstone, siltstone, and shale with a limestone concretion in lithofacies E.*

INTERPRETATION OF DEPOSITIONAL ENVIRONMENT

A preliminary interpretation of the depositional environment of the Maraghan formation, based on regional reconnaissance of the Murdama depositional basin, suggested that the Maraghan was deposited in a shallow-water lagoonal, lacustrine, or marine environment (Wallace and Rowley, in prep.). Results of this study further refine the earlier interpretation and suggest that rocks of the Maraghan formation were deposited in an extensive near-shore mudflat that was dissected by distributary channels. Deposits of carbonate, some of which may have been of algal origin, formed in channels and in interdistributary parts of the mudflat. The term "mudflat" is used instead of "tidal flat" because tidal activity cannot be demonstrated from the available data. Interpretation of depositional environments in the An Najady area is based on the types and distribution of sedimentary structures, relations of rock types, and similarities to deposits described from other sedimentary basins.

Lithofacies A shows an upward change from a high-energy environment in the lower part to a medium-energy environment in the upper part. Abundant channel-filling sandstones, trough and planar crossbeds, ripple cross-lamination, fining-upward cycles, and coarse grain sizes suggest that transport in channels began with a high-energy surge that gradually decreased in transport power (Simons and others, 1965). The great lateral extent of many composite sandstone beds suggests migrating channels were braided and wide, and had gently sloping banks. Some sandstone beds might represent Prograding offshore bars or washover fans associated with barrier islands as described in Recent and Pleistocene estuarine deposits by Clifton (1982, p. 179-189) and by Weimer and others (1982, p. 191-245) in modern deposits and in Cretaceous and Mississippian rocks. Carbonate in channels may have been in the form of carbonate mud or algal mats as shown by Shinn (1973, p. 179-191) in lagoonal deposits near Qatar. Carbonate beds that overlie the tops of fining upward cycles may have been deposited as blankets of carbonate mud or silt in interdistributary areas during periods of submergence on the mudflat. Similar deposits have been described by Shinn (1973), and by Evans and others (1973, p. 233-277).

The upper part of lithofacies A, as well as lithofacies C and E, were deposited in similar environments and were characterized by aggradational sedimentation, but distributary channels were probably shallower and broader than in the lower part of lithofacies A. Fining upward sequences of medium- and fine-grained sandstone, siltstone, and shale reflect less transport power than was common in the lower part of lithofacies A. Small-scale planar crossbedding, ripple cross-lamination, and parallel lamination in sandy beds suggest deposition in broad shallow channels or in sand veneers that prograded over muddy beds of the mudflat as described by Thompson (1968) from the Gulf of California and by Weimer and others (1982, p. 191-245) from modern deposits and from Cretaceous rocks in the Rocky Mountains. Finer grained, more argillaceous parts of these lithofacies may represent areas of topographic depressions on the mudflat between distributary channels that accumulated mainly suspended sediment during periods of immersion.

Limestone and dolomite beds and thick pods are more prominent in lithofacies C than in the other lithofacies; these carbonate bodies may have been lime- or dolomite-mud buildups in the terminology of Heckel (1974), which formed in shallow-water mudflats. Lime-mud buildups can be preserved in currentdominated environments because the mud is resistant to erosive forces. The natural cohesiveness of fine grained, non-lithified material and the presence of binding organisms, such as algae, which commonly form a surface film on the mud prevents suspension of accumulated lime mud (Heckel, 1974, p. 136-139). Carbonate mud is a common deposit between tidal channels in modern sediment of the Persian Gulf; the fine-grained carbonate formed from reworked biogenic debris and from transported Tertiary carbonate (Shinn, 1973). The thick deposit of dolomite at Jabal Rahail could represent an algal buildup that was large enough to be considered a reef. Non-brecciated parts of the dolomite are very thinly laminated and these laminae could be the remains of algal mats. Although the abundant breccia and microbreccia associated with Jabal Rahail is considered by P. L. Williams to be of tectonic origin (written commun., 1985), the breccia could be of sedimentary origin and part of a reef front. Sandstone beds that strike toward Jabal Rahail become more carbonate rich toward the Jabal, which suggests that deposition of sand was contemporaneous with formation of the carbonate mass at Jabal Rahail.

Lithofacies B and D appear to have been deposited in lower energy conditions than lithofacies A, C, and E. The dominance of fine-grained sandstone, siltstone, and shale, planar bedding contacts, ripple cross-lamination, and planar lamination in the fining-upward cycles suggests that sand veneers prograded over the mudflat repeatedly and that distributary channels may have been ephmeral. Thick zones of non-cyclic medium-grained sandstone in both lithofacies may have been deposited as beach-dune ridges on the mudflat, or as barrier sand bodies on the windward side of the mudflat as described by McCubbin (1982) from the Texas Gulf Coast, and by Harms, and others (1975, p. 97-100). An eastward increase in the proportion of medium- and fine-grained sandstone in lithofacies D may have resulted from winnowing of fine-grained detritus from mudflat sediment along an east or southeast shoal.

This preliminary interpretation of the depositional environment of the Maraghan formation suggests that the extensive mudflat may have shoaled to the east or southeast in the eastern part of the map area. Measurement of three trough crossbeds from distributary channels in the lower part of lithofacies A suggests transport directions to the southeast and south, which generally agrees with the suggestion that open water, and perhaps shallow-water deposits, should occur to the east and southeast of the An Najady region in the Maraghan formation. However, south of the map area, the lower part of the Maraghan formation was uplifted along faults, and conglomeratic rocks of the Maraghan overly older rocks according to Cole (1985). Lateral equivalents of these probable mudflat deposits are not present south of the map area.

The depositional environment assigned to Late Proterozoic rocks of the Maraghan formation near An Najady is similar to depositional environments interpreted from Middle and Late Proterozoic sequences in the western United States. Middle Proterozoic rocks of the Belt basin in the northwestern United States and adjacent Canada, preserve evidence of shallow-water and subaerial mudflat environments in a sequence of rocks that has similar sedimentary structures, carbonate-bearing sequences, and fining-upwards cycles as the Maraghan formation (Schmidt and others, 1983; Winston and Wallace, 1983). In Late Proterozoic rocks of the Great Basin and Death Valley region, shallow-water platform deposits and algal reefs were developed in strandline environments that included quiet-water algal mat deposits and algal reef deposits dominated by tidal currents (Wright and others, 1978). Interpretation of depositional environments of Late Proterozoic rocks in Utah and southeastern Idaho, which were described by Crittenden and others (1971), suggest that quartzites were deposited in strandline and terrestrial environments, whereas carbonate, siltstone, and shale were deposited in shallow-water and mudflat environments.

OCCURRENCE OF DISSEMINATED GOLD IN THE MARAGHAN FORMATION

Shale and siltstone samples were randomly collected from lithofacies B and D to determine if these fine-grained rocks contained concentrations of gold. Sample sites were not preselected because the distribution of lithofacies was not known at the time mapping was in progress and because exposures were poor. Five samples were taken from surface exposures of weathered rock and represent chip samples collected through shale beds of the uppermost parts of fining-upwards bedding sequences. Some samples contained shale from multiple beds in several fining-upwards sequences. The locations from which shale samples were collected are on figure 1. These samples were collected from some of the few localities where shale was exposed at the surface (fig. 2). Brief sample descriptions and analytical data are given below.

211126 Contact-metamorphosed shale and siltstone....Au detected, below 4 ppb

211127 Contact-metamorphosed shale and siltstone....Au detected, below 4 ppb

211128 greenish shale, not contact-metamorphosed....Au 11 ppb

211130 greenish shale, not contact-metamorphosed....Au detected, below 4 ppb

211135 greenish shale, not contact-metamorphosed....Au 7 ppb

Samples 211126 and 211127 may not be representative of gold contents of rocks of the Maraghan formation because these samples were collected near the large Mahalani granodiorite pluton. The gold in those samples could have been introduced by metamorphic or hydrothermal fluids, or gold could have been depleted from the sedimentary rocks by migration of hot fluids. Samples 211128, 211130, and 211135 were far removed from known plutonic or volcanic bodies and the rocks showed no contact metamorphic effects. The concentrations of gold in those rocks may be representative of gold concentrations in other fine-grained rocks of the Maraghan formation.

Comparison of gold concentrations from rocks of the Maraghan formation with concentrations in other argillaceous rocks is difficult because determination of average gold content of argillaceous rocks is subject to numerous qualifications. The gold content of fine-grained rocks varies according to provenance, organic content, and sedimentary environment, and few accurate data have been collected from non-mineralized argillaceous rocks (Boyle, 1979, p. 43). A summary of data on the occurrence of gold in rocks of the earth's crust was presented by Boyle (1979, p.44, table 15), and on the basis of 1356 samples he determined an average value of 8 ppb for shale, mudstone, siltstone, and argillite. Pyritic black shale, pyritic graywacke, and sulfidic schist showed an average gold content of 132 ppb based on analytical results of 19 samples. Argillaceous rocks from the Wolkberg Group (Transvaal Supergroup), South Africa, had an average gold content of 2.5 ppb, and a unit of carbonaceous silt and shale had an average gold content of nearly 90 ppb; the carbonaceous silt and shale were considered to be a possible proto-ore for nearby gold-quartz reefs by Minnitt and others, (1973). Gold concentrations in arenaceous rocks averaged 22 ppb according to Minnitt and others (1973). The range of gold concentrations determined for the Maraghan formation is comparable to the average value determined for non-carbonaceous shale, mudstone, siltstone, and argillite, but much less than for carbonaceous rocks that were considered to be source rocks for mineralization of gold-quartz reefs in the northeastern Transvaal, South Africa.

Relations between the distribution of lithofacies B and D of the Maraghan formation and the occurrence of known vein gold deposits may be fortuitous, but it is possible that gold may have been mobilized from shale and siltstone of the fine-grained lithofacies by hydrothermal activity associated with small intrusive bodies (fig. 1). Ancient mines at Agob south and Agob north, and extensive workings at Ar Rahail occur in lithofacies B. Previous mining activity at Wuday occurred in rocks of lithofacies C that are transitional from lithofacies B. Gold occurs in quartz veins and in altered granodiorite at Shi'bah east and Shi'bah northeast in lithofacies D, (J. Grootenboer, written commun., 1985, cited in Williams and Simonds, 1985). Several intrusive bodies at these places showed extensive hydrothermal alteration, and it is possible that the hot fluids moved gold from the host sedimentary rocks and concentrated it in quartz veins near the tops of the small plutons.

RECOMMENDATIONS FOR GOLD EXPLORATION

These geological and analytical data suggest that three main directions of research might be used to pursue exploration for potential gold deposits in and near the Maraghan formation. First, the nature of occurrence, distribution, and levels of concentration of gold should be confirmed, and stratigraphic studies of the Maraghan formation should be completed. Second, detailed geologic mapping should be used to locate very small intrusive bodies that were not discovered during reconnaissance phases of mapping, and geophysical interpretations should be used to locate buried intrusive rocks that may not be detectable from surface mapping. Third, sedimentologic data should be evaluated to determine if carbonaceous rocks occur in the basin and if exploitable concentrations of gold might have been controlled by sedimentologic factors in the Maraghan depositional basin. These types of studies would narrow the range of exploration targets in this large basin.

An early phase of regional research on gold occurrences in the An Najady area should center on the Maraghan formation. Stratigraphic studies and reconnaissance sampling of shale beds should be extended to complete maps of the distribution of lithofacies in the basin, and to provide an understanding of relations between lithofacies and occurrences of gold-bearing veins and disseminated gold. Detailed sampling and mineralogic analyses should determine where, and in what form, gold occurs in sedimentary rocks of the formation. Because the fine-grained rocks of this formation are poorly exposed, trenches will be needed to sample across several non-metamorphosed sections of fine-grained and coarse-grained lithofacies. Gold, if present in the source terrane of the Maraghan formation, might have higher concentrations in coarse-grained rocks. Alternatively, if gold was precipitated from water in the sedimentary basin, fine-grained rocks might have the highest gold concentrations.

Reconnaissance investigations suggest that gold-bearing veins are associated with the tops of intrusive bodies, so intrusive rocks at shallow depths are primary exploration targets. An area of metamorphosed rocks was located by geologic mapping (fig. 1) that may locate a buried intrusive body (M. F. Kane, oral commun., 1985). Metamorphosed Maraghan rocks adjacent to large intrusive bodies, such as the Jabal Qitan granite pluton, might have potential as exploration targets in some of the covered areas along the contact between intrusive rocks and the Maraghan formation. Several small, poorly exposed silicic and intermediate porphyry bodies were located during this study and some of these stocks may be potential targets for further sampling. Volcanic rocks that were extruded during deposition of the Maraghan formation (Williams, 1985), have potential for disseminated gold deposits because hydrothermal fluids may have concentrated gold in volcanic rocks or in sediment along contacts with volcanic rocks.

Sedimentologic studies, which should be completed with stratigraphic and lithofacies analysis, may aid in locating additional exploration targets. Sedimentologic data should be collected to evaluate sediment distribution patterns and to assess the potential for occurrence of disseminated gold deposits of commercial grade. Sedimentologic and stratigraphic studies should attempt to locate stratigraphic zones that might be carbonaceous or have contained organic matter at the time of deposition, inasmuch as these zones would have the greatest potential for the occurrence of commercial grades of disseminated gold. Ruppel (1985) suggested an association between carbonate buildups of probable algal origin and occurrences of disseminated gold in Middle Cambrian rocks of southwestern Montana, which suggests that the origin and gold resource potential of carbonate rocks in the Maraghan formation should be investigated.

DATA STORAGE

DATA FILE

Data and work materials used in preparation of this report include reconnaissance maps and analytical results and are archived as Data-File USGS-DF-06-14, which is stored at the office of the U.S. Geological Survey Mission in Jeddah, Saudi Arabia.

MINERAL OCCURRENCE DOCUMENTATION SYSTEM (MODS)

No MODS entries were made as a result of the work described in this report.

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