Prospectivity of Batinah Coast of Oman for Volcanic Hosted Massive Sulfide (VHMS) Deposits

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Abstract:

Central and south Batinah coastal areas are mostly covered with rocks of Hawasina and Samail nappes obducting over autochthnous Formations of Arabian plate. Hawasina nappe is composed of late Permian to Jurassic Formations comprising sandstone, shale, chert, limestone, basalt, andesite and keratophyre. Samail nappe is thrust over the Hawasina nappe and composed of complete ophiolite suite of rocks. Samail volcanic sequence hosts Cu-Au-Ag mineralisation (VHMS) and forms uppermost part of Samail ophiolite sequence. Copper deposits of Oman have supplied copper metal over a span of ancient time to Sumerian and Roman empires Samail volcanic unit shows three major events of basaltic effusion namely they are Lower Volcanics (SV_1), Middle Volcanics (SV_2) and Upper Volcanics (SV_3). All the units show intercalated thin metalliferous sedimentary chert/shale layers deposited during pause of eruptive active. Post nappe formations consist of Upper Cretaceous and Tertiary Formations composed of polymict conglomerate, marl and limestone. These are covered by Quaternary sediments comprising terrace and fan deposits called wadi sediments.

Tectonic developments of Samail Nappe were in different stages. Stage-1 included formation of Samail ophiolite on the sea floor, stage-2 included obduction of Samail ophiolite and stage-3 contains post emplacement deposition of younger cover sediments. Samail ophiolite was formed in the spreading ridge of Tethys sea from Early to Middle Cretaceous period (92-97 Ma). During this stage Hawasina basin was formed and subsequently obduction took place in stage-2 which was followed by deposition of Supra-Ophiolite sediments.

Volcanic Hosted Massive Sulphide (VHMS) mineralization occurs in Samail Ophiolite sequence and shows evidence of stratigraphic control and mineralization occurs at the contact between two lower volcanic units of Samail ophiolite. In the present paper Geology of northern Oman Mountains and Batinah coast has been discussed with an attempt to describe salient features of associated VHMS mineralization. Wide alterations zones are found on the footwall and hanging wall side of mineralization consisting epidotisation, chloritisation, silicification and kaolinisation. Massive sulphide mineralization is associated with synvolcanic faults which acted as conduits for passage of hydrothermal solutions. Metalliferous sediments and zones of alterations can be used as guide for search of massive sulphide. Source of VHMS is seen within the sheeted dyke complex and through pipe like zone of epidote, quartz and magnetite rock.

Since massive sulphide mineralization is not exposed on the surface for searching copper indirect methods of exploration are useful e.g. landsat imagery, magnetic and EM survey, geochemical and ground geophysical prospecting. *Cover rocks are very thick hence geochemical leakage anomalies may not be present but geochemistry of volcanic rocks and intercalatory thin metalliferous sediments could be successfully used as guides in exploration for copper.* Volcanogenic Massive deposits are known as i) Volcanic Associated, ii) Volcanic Hosted and iii) Volcano Sedimentary Hosted Massive Sulphide

deposits. They form from metal rich fluids associated sea floor hydrothermal convection system.

Key Words: Batinah, Samail Ophiolite, Nappe, VHMS, Conduit, Alterations

Physiography: The area under study comprises Northern part of Oman Mountains lying on the eastern edge of the Arabian plate. Northern part of the Oman Mountains which extends up to Oman gulf is called Batinah coast**.** The western half of the Batinah coastal area is underlain by Tectonites and Cumulate sequences forming rugged mountainous region and central and southeastern part of the area underlain by Sheeted dyke complex and Samail volcanic rocks which forms low hilly region. The eastern part consists of low hills composed of Supra ophiolite sediments and Late Cretaceous to Tertiary sediments which from hilly and terraced land (Figure 1). Wadis flow in the east direction and drain into Gulf of Oman. Four river terraces are found along the wadis.

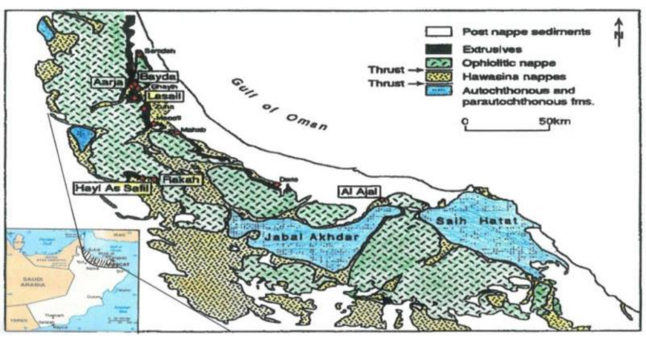

Figure-1 Geological Map of Northern Oman and Batinah Coast after Calvez and Lescuyer, 1991

Geological Setting: Oman Mountains lie on the eastern edge of the Arabian plate. They are part of Alpine orogenic belt and were formed by obduction of fragment of the Tethyan oceanic floor (Samail ophiolite) over the Arabian plate during late Cretaceous. The beginning of obduction has been dated 90 Ma (Lanphere, 1981). Allochthon comprise nappes thrusted over authochthonous succession.

Allochthon is subdivided into:

Supra Ophiolite Sediments

Samail Nappe

Samail Ophiolite

Samail ophiolites were thrusted over Hawasina nappe and subsequently sliced into four imbricated thrust sheets. The main units of ophiolite are Samail volcanic rocks (top), Sheeted dyke complex, High level gabbro, cumulate sequence and Tectonites (bottom).

Supra ophiolite sediments mainly consist of olistoliths. Termination of nappe emplacement was marked by deposition of late Cetaceous to Tertiary sediments called as Supra ophiolite sediments (Figure 1).

Startigraphy

Samail Nappe has been subdivided into Samail ophiolite and Supra-ophiolite sediments. These units have unconformable contact. Samail ophiolite is composed of Tectonites, Cumulate sequence, High level gabbro, sheeted dyke complex. Samail volcanic rocks have been classified into three units which are Lower Volcanic rocks (SV_1), Middle Volcanic rocks (SV_2) and upper volcanic rocks (SV_3). Lower volcanic rocks formed at the ocean spreading ridge.

Tectonites form base of the Samail ophiolite. Tectonites are overlain by cumulate sequence. Tectonites mainly consist of serpentised harzburgite and dunite. Harzburgite show banding comprising alternate olivine rich and orthopyroxene rich layers and exhibit granular, porphyroblastic texture. Magnesite veins are also noticed.

Cumulate Sequence is underlain by Harzburgite with irregular contact. It comprises cumulate layered gabbro which is composed of clinopyroxene gabbro and minor interlayered olivine gabbro, dunite and peridotite. Layering is few millimeters to few centimeters thick. It shows orthocumulate texture having euhedral plagioclase and clinopyroxene gabbro (gabbro with large quantity of clinopyroxene) and minor interlayered olivine gabbro, dunite and peridotite. Layering is few millimeters to few centimeters thick. It shows orthocumulate texture having euhedral plagioclase and clinopyroxene having a zonal structure.

High level Gabbro- comprises clinopyroxene gabbro and hornblende bearing gabbro. Contact with overlying intrusive sheeted complex is irregular. It is porphyritic, subhedral, granular and ophitic texture. Rock contains plagioclase and clinopyroxene.

Sheeted Dyke Complex: It overlies High level gabbro or Cumulate sequence. This unit show sheeted planar basalt/andesite dykes of 0.5 to 2m thickness with chilled contact and trend N-S. These rocks show ophitic texture of clinopyroxene and plagioclase.

Samail Volcanic Rocks: They overlie Sheeted dyke complex and are overlain by terrace deposits (wadi sediments). It has been divided into the Lower Volcanic rocks (SV_1), Middle Volcanic rocks (SV_2) and Upper Volcanic rocks (SV_3).

Lower Volcanic Rocks: These rocks overlie sheeted dyke complex. These are composed of basaltic pillows and massive lava flows associated with volcanoclastic rocks. These are intercalated with minor metalliferous sediments. Pillows range in diameter from < 0.5 m to 2.0 m forming elonagated tubes with radial cracks. Pillows are associated with pillow breccia and hyaloclastite. Clinopyroxene phenocrysts are rarely seen and show amygdaoidal and variolitic texture. Massive lavas are marked by columnar joints, chilled margin and occur as sheet flows each 15m thick with basal breccia. Pillow and massive lava are cut by dykes of andesite, basaltic and felsitic dykes and acted as feeders for middle volcanic rocks. Numerous copper occurrences are seen in these rocks.

Metalliferous Sediments (SU_1) - These occur as intercalations in the lower extrusives and are dark brown, reddish brown and grey in colour and 0.5 to 5m thick and extend for 2 to 20 m length. They are cherty and often disseminated with magnetite, pyrite and malachite.

Middle Volcanic Rocks (SV_2) - These overlie lower volcanic rocks and are divided into middle extrusive, phyritic basalt, acidic volcanic rocks and metalliferous sediments. The extrusives comprise basaltic to andesitic pillow lava and massive lavas associated with hyaloclastite and pillow breccia. Pillows range in size from < 0.5 to 2.0 m. Massive lava sheets range in thickness from 1-10m. Rocks show aphyric, subophtic texture and contain plagioclase orthopyroxene, clinopyroxene.

Metalliferous Sediments (SU_2) - These are intercalated with extrusives (SV_2) and are yellow, black and red having several meters thickness with occasionally brown chert range from < 1-15m thickness and composed of chert/shale, rare magnetite, chalcopyrite, malachite and pyrite.

Upper Volcanic Rocks (SV_3) - These are exposed in eastern part overlying SV_2, massive doleritic lavas with subordinate pillow and intercalated with pelagic sediments. Massive lavas are marked with columnar joints. These are doleritic to gabbroic rocks. Pillows are seen in lower part of extrusives in other parts massive flows of non vesicular nature and aphyric type are noticed. In massive lavas flows and each flow is 170 m thick. Composition varies from doleritic to gabbroic and show ophitic texture. Pillows are 50 cm to 1.2 m wide.

Metalliferous Sediments (SU_3) - These are found in lower most part of SV_3 and comprise of greenish grey shale, red chert. They range in thickness from 30 to 50m.

Intrusive Rocks: Peridotite, gabbro and trondhjemite occur as intrusives.

Peridotite range in width from 200-500 m and show layering. These intrude upper part of lower volcanic rocks. These are composed largely of dark coloured plagioclase lherjolite and show adcumulate texture consisting of olivine, orthopyroxene, clinopyroxene and plagioclase.

Trondhjemite are intrusive into lower volcanics and are associated with copper mineralization.

Late Doleritic Dykes – They occur as feeders for lower volcanic rocks and are doleritic-andesitic and basaltic in composition.

Supra-Ophiolite Sediments- Sedimentary rocks of Middle to Late cretaceous age are grouped under it. They comprise pelagic sediments with intercalations of sandstone, limestone, conglomerate and olistotrome.

Post Nappe Autocthonous Units – Late Cretaceous to Tertiary sediments are exposed in the area lying unconformable over supra ophiolite sediments. These autochthonous sediments comprise conglomerate, sandstone, limestone of Maastrichtian age. Late tertiary - Quaternary sediments are forming terrace sediments.

Geological History – First stage of Samail ophiolite sequence is related to spreading ridge magmatism which formed a complete ophiolite succession which is made up of Tectonites, cumulate sequence, High level Gabbro, sheeted dyke complex and Lower Volcanic rocks. The second stage is related to intra-ocean magmatism involving intrusion of peridotite, gabbro, trondhjemite and late dolerite dykes and extrusion of middle volcanic rocks. The third stage is related to within plate magmatism that produced upper volcanic rocks (Lippard et al, 1986).

Copper Mineralization is noticed in the form of veins and gossan in the lower volcanic rocks (SV_1), sheeted dykes, near contact of lower volcanic rocks (SV_1) and upper volcanic rocks (SV_2). Since copper mineralization occurs hosted in the volcanic rocks it is called Volcanic Hosted Massive Sulphide (VHMS).It is also known as Volcanic Massive Sulphides and Volcanic Hosted Massive Sulphides. The veins of copper are narrow and measures few centimeters in width and few meters in length. Gossans are 2 to 15 m wide and 5 to 300m in length. Gossans are composed of hematite, minor limonite, malachite, azurite and clay minerals. These seem to be derived from oxidation of disseminated as well as stockwork mineralization. Extensive old mine workings are seen at several places and strewn dumps of slag witness ancient smelting (3000 yrs B.P). Malachite bearing volcanics have been mined during ancient mining and locally which smelting activities are also witnessed. Ancient mines are in the form of ancient arches may be adits or drives and ancient smelting is evidenced in the form of slag. Over a span of ancient time copper from Oman was supplied to Sumerian and Roman emperors (Griffitts et al, 1972). Minor amount of gold and silver is also reported from the gossan caps.

Origin: Volcanic Hosted Massive Sulphide mineralisation of the region was created by volcanic associated hydrothermal events in submarine environments. Volcanic hosted Massive Sulfide deposits are forming today along mid oceanic ridges by submarine volcanism. Ophiolite hosted VHMS deposits have root zones extending to the base of sheeted dyke section. VHMS are clustered in groups along the entire strike length of the ophiolite. Within these clusters base metals occur from top of the magma chamber to the overlying metalliferous sediments. However, VHMS deposits are found above sheeted dyke complex. Stratiform Massive Sulphides are occurring along the contact of different lava suites. Copper deposits consist of stratified massive lens and a proximal underlying feeder stockwork. These units may occur singly or together. Stockwork may extend over hundreds of meters and equally deep in sheeted dyke complex. Massive sulphides comprise up to 60% pyrite and 10% basemetals. Stockwork zone is quartz and pyrite rich. Sea water rich interface is presumed to be near contact of two volcanics which represent a hiatus in magmatic activity that allowed development of a hydrothermal system. Low grade ore bodies are fossilized roots for copper mineralization. Ophiolites formed in supra obduction zone. Ore bodies are restricted to pillow lava sequence and confined in basal sections. In such lavas ore bodies can be found anywhere.

Characteristic features of these deposits are extensive sea floor oxidation of sulfide debris and formation of gossan on the surface of the deposit (Hannington et al, 1998). Gossans are developed mainly above cherty units. Sea floor oxidation has been limited to the exposed sulfides and penetration of sea water has not produced deep weathering profile. Subsequent effusive volcanism has buried some gossans. These ochres comprise of goethite, limonite to hematite, magnetite bearing sediments and jarosite rich deposits. Ochres do not extend beyond the limit of the ore body. Bedded ochres contain detrital sulfides and jarosite. These gossan caps have been extensively mined for gold and silver. Sea floor weathering might have enriched gold in gossan.

Weathering has caused intense alteration. Distinct red clays are common at the top of the pillow sequence in proximity to the massive sulfides. This alteration has been ascribed to leaching by near surface ground water. Beneath the massive sulfides also red clays have been found. It suggests acid alteration in VHMS near the sea floor where overlying sulfides were exposed to oxidation. Acid leaching due to pyrite and water has caused leaching of basalt sometimes complete conversion of rock to residual quartz and kaolinite. Preservation of potential massive sulfides on the sea floor may account for large no of well preserved massive sulfide lenses in the pillow lava sequence.

At many locations alterations are noticed around VHMS deposits. The main alteration minerals are quartz, chlorite, illite and kaolinite. Pyrite is often associated with clay alterations. Chloritised pillow rim breccias occur closer to sea floor. Beyond this halo basalt is seen in alteration zones. At the margin of the ore zone contact with country rock is abrupt. Weak 10-15m wide chlorite, silicification zone is seen. *Reddish to purple lavas are seen outside chlorite zone.*

Exploration guides: Major exploration guides for VHMS deposits in Batinah coast area are :

1. Deposits occur in volcanic belts of Early to Late Cretaceous age {Cenomanian-early Turonian, 92 ±7 Ma (BEC, 1987) , to Albian 99 Ma (BEC, 1987)}
2. Exploration should be focused up to 3000 meters up section in the comagmatic volcanic suites in the hanging wall of intrusives.
3. Presence of felsic volcanic environment.
4. Presence of synvolcanic dyke swarms and exhalite horizons indicate palaeoheat flow heat zone.
5. Aeromagnetic survey can locate iron formations
6. Alterations zones of VHMS like epidotisation, silicification, chloritisation and sericitisation coupled with pyritisation and presence of magnetite indicate proximity to hydrothermal system. Presence of more aluminous minerals is seen near volcanic pipes.
7. Alteration zones may have discordant sulfide silicate stockwork vein system.
8. Proximity with synvolcanic faults which would have acted as conduits for hydrothermal system.
9. Palaeomagnetic properties of basalt samples from TAG-4 (Trans Atlantic Geotraverse-4) have been reported to be controlled by magnetite, minor amount of maghemite and hematite. Changes in magnetic properties have been interpretated due to hydrothermal fluid system. It resulted in shallowing of inclination (Xiax Zhao et al, 1998).

Conclusion: In Central and Southern Batinah coastal area lower volcanic rocks in Samail Ophiolite sequence are host of VHMS mineralization. Since ancient time these ophiolites have been source of Cu and Au which was supplied to Sumerians and Romans. Sulphide mineralisation was formed by hydrothermal solutions through sheeted dykes along faults or conduits at sea bed oxidation which resulted in the formation of Gossan cap. Volcanic Hosted Massive Sulphide (VHMS) mineralization occurs in Samail Ophiolite sequence and shows evidence of stratigraphic control and occurs at the contact between two lower volcanic units of Samail ophiolite. At the contact of two lavas which are dominated by pillows, wide kaolinitic alterations coupled with chloritisation, epidotisation and silicification are noticed around hydrothermal pipes. Silicified gossans occur as caps sealing fault controlled conduits and metalliferous sediments are exhalatives with profuse malachite, pyrite, epidote and magnetite. Since massive sulphide mineralization is not exposed on the surface for searching copper indirect methods of exploration are useful e.g. landsat imagery, magnetic and EM survey, volcanic rock geochemestry and ground geophysical prospecting. Cover rocks are very thick hence geochemical leakage anomalies may not be present but *geochemistry of volcanic rocks and intercalatory thin metalliferous sediments could be successfully used as guides in exploration for copper*. Wide *alterations zones are found on the footwall and hanging wall side of mineralization consisting epidotisation, chloritisation, silicification and kaolinisation. Massive sulphide mineralization is associated with synvolcanic faults which acted as conduits for passage of hydrothermal solutions*. Metalliferous sediments and zones of alterations like kaolinitic alteration coupled with chloritisation, epidotisation and silicification are noticed around hydrothermal pipes these can be used as guide for search of massive sulphide coupled with pyritisation and presence of magnetite also indicate proximity to hydrothermal system.

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