Mineral potential mapping and exploration for cupriferous sulphide mineralisation, Cyprus

Naden J.[1], Nicolaides S.[2], Jowitt S.M.[3], Bateson L.[1], McEvoy F.M.[1], Gunn A.G.[1] & Rollin K.E.[1]

[1]British Geological Survey, Keyworth, Notts, NG12 5GG, UK, jna@bgs.ac.uk
[2]Geological Survey Department, 1415 Nicosia, Cyprus, director@gsd.moa.gov.cy
[3]Camborne School of Mines, University of Exeter, UK, simonmjowitt@hotmail.com

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Introduction

This paper presents the results of pilot mineral potential mapping project undertaken for cupriferous volcanic-hosted massive sulphide (VHMS) mineralisation in Cyprus. Mineral potential or prospectivity maps are a digital extension to traditional geochemical, geophysical and geological exploration methodologies. They are constructed using statistical modelling techniques (e.g. weights of evidence, fuzzy logic) and use mineral deposit models and spatial digital data. Mineral deposit models can be empirically based, comprising a catalogue of characteristic features, such as host-rock lithology, deposit form (vein, stockwork), alteration, ore mineralogy etc. Deposit models may also be genetic or conceptual. Here, they describe mineralisation in terms of formation processes such as fluid chemistry, temperature and metal precipitation mechanisms. The best are, however, an amalgamation of empirical information and genetic concepts—a typical example would be that developed by Hedenquist *et al.* (1996) for epithermal mineralisation. The mineral deposit model aids in selecting the most appropriate input data themes and the statistical methods are used to integrate the various data layers to produce the mineral potential map. This study focuses on Cu-bearing VHMS mineralisation in one of its type localities - the Troodos ophiolite - and utilises digital geological, structural and geophysical maps, along with mineral alteration maps derived from ASTER satellite data, to produce a prospectivity map that identifies new exploration targets.

Methodology

The mineral deposit model for the Cu mineralisation was created from a literature review of Cyprus and other VHMS deposits. Its essential parameters are:

1. Deposits are associated with obducted mid-ocean ridges and oceanic arcs. They occur in the submarine environment and are controlled by fault systems and grabens. Host rocks are mafic-dominated extrusive lavas of variable age.
2. Deposit form is as massive sulphide lenses, disseminations and stockworks with stratigraphy, feeder structures and alteration envelopes controlling ore distribution.
3. Close to mineralisation alteration comprises pyrite, sericite, chlorite and silica, whilst away from it, alteration is dominantly argillic, propylitic and carbonitic. The gangue minerals comprise quartz, sericite, chlorite, carbonate, smectite, whilst the main ore minerals are pyrite, chalcopyrite and sphalerite.

Digital geology, for the analysis, was provided by the Geological Survey Department, Cyprus. Other available digital data were ASTER satellite imagery, digital elevation models and regional gravity (Gass and Masson Smith, 1963). In addition, legacy map data (1:31,680) were scanned and georeferenced to digitise mineral occurrences, gossan locations and small-scale faults. The satellite data were processed and parameters extracted to highlight alteration intensity (Sabins, 1999).

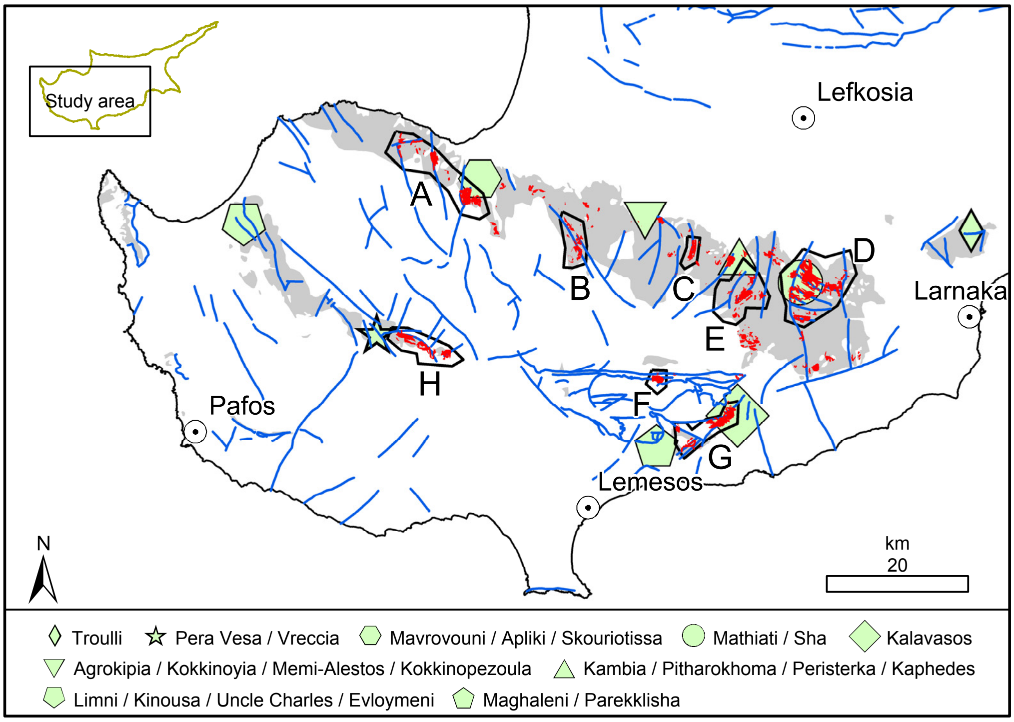

Figure 1. Prospectivity map for VHMS mineralisation in Cyprus, showing mining areas (symbols), the ophiolite crustal sequence (grey) and major faults (blue lines). Lettered areas enclose zones of high mineral potential (red).

Area		A	B	C	D	E	F	G	H
Number of mineral occurrences per area		7	7	6	13	5	7	13	2
1:250 000 digital geology	Alluvium - Colluvium				*				
	Fanglomerate		*			*			
	Pakhna Formation								*
	Lefkara Formation			*					*
	Perapedhi Formation				*				
	Lava and Volcaniclastic Sediments						*	*	
	Lavas and Volcaniclastic Sediments			*			*	*	*
	Upper Pillow Lavas	*	*		*	*			
	Lower Pillow Lavas	*	*	*	*	*	*	*	*
	Basal Group	*	*	*	*	*	*	*	*
	Sheeted Dyke Complex	*		*			*	*	*
	Gabbro						*	*	
	Intrusive Plutonic rocks			*					*
1:250,000 Fault Data		■	■	■	■	■	■	■	■
1:31,680 Fault Data		■	■	■	■	■	■	■	■
Bouguer Gravity Anomaly					M	■	■	■	■
Gossan Occurrence Data		■	■	■	■	■	■	■	■
Lower–Upper Pillow Lava Contact		■	■	■	■				
Lower Pillow Lava–Basal Group Contact		■		■	■	■	■	■	■
Basal Group–Sheeted Dyke Contact		■		■		■	■	■	■
Satellite Lineations	E–W	■			■	■	■		
	NW–SE	■						■	■
Landsat TM Band Ratio Image		■	■				■	■	
ASTER Band Ratio Images	1/3		■			■		■	
	1/5		■			■			
	2/3		■		■		■	■	
	2/5		■	■	■		■	■	
	4/5		■	■	■	■	■	■	
	6/1	■	■		■			■	■

Table 1. Summary of exploration criteria used in the prospectivity analysis and their occurrence in new target areas. ■ = Area prospective according to dataset (M = missing data), * = Formation present in area (italics represent prospective geological units). Refer to Figure 1 for the location of prospective areas.

Generally, mineral deposit models contain features that cannot be resolved at scales suitable for prospectivity mapping. For example, isotopic data, which may define fluid sources and processes of fluid—rock interaction, is not sampled to the same extent as most exploration data and cannot be incorporated into the geographical database. Hence, the following exploration model, which only utilises available data, was developed:

1. Deposits are typically fault-associated and in a number of cases these acted as fluid conduits.
2. Economic deposits can be capped by gossans and associated with umber, gold and ochre deposits.
3. Alteration assemblages identified using a portable infrared mineral analyser were used to ground-truth the ASTER imagery to indicate zones of mineralisation-associated alteration.
4. Deposits are preferentially associated with lithological units and contacts that may represent hiatuses in magmatism.
5. Mineralisation is associated with regional Bouguer anomaly values between 146.7 and 166.7 mGal.

The process of binary weights-of-evidence prospectivity analysis involved converting (generalising) individual data themes (e.g. fault, geological and geophysical maps) into binary maps that indicate prospective and unprospective areas. For the geology, this was done by statistically analysing the spatial association between points of known mineralisation (old and working mines, prospects) and the various rock units depicted on the geological map. This simplifies the map into rocks associated with mineralisation and those that are not. Similarly, the association between faults and mineralisation was examined. Here, because the faults are lines, they are given additional thicknesses—buffers—to increase the likelihood of their spatial association with mineralisation. These are set at increasing steps (e.g. 100-m) and the spatial association examined for each increment. The analysis procedure shows the distance where the spatial association breaks down and is used to help create a binary map of thickened faults. Likewise, binary maps can be created for a variety of other parameters, such as contacts between geological units, geochemistry and satellite lineaments. The procedure of generalisation, as well as simplifying data to a binary map, also calculates how prospective each theme is. When generalisation is complete, the individual binary map themes and their associated prospectivity weightings are integrated to produce the final prospectivity map. For detailed descriptions of the statistical theory behind the methodology and use of the software see Tangestani and Moore (2001) and Kemp *et al*. (2001).

Results

The final prospectivity analysis (Figure 1), using ArcView™ and the Spatial Data Modeller extension (Kemp *et al.*, 2001), was undertaken using seventeen data themes (Table 1). It identified eight areas of high mineral potential, all located within 10-km of the boundary between the Troodos ophiolite and the autochthonous sedimentary cover sequences draping the ophiolite. Key features of the prospectivity analysis are listed in Table 1.

Discussion

Areas with high potential in Figure 1 are all related to clusters of known mineral occurrences. However, areas with large numbers of mineral occurrences may indicate that reserves are already exploited. Also, for areas F and G, associated with the Arakapas transform fault, the mineralisation could be podiform Fe-Ni-Co-Cu rather than VHMS Cu-mineralisation. Area H, and the northern extension of area A, located within the 1:31,680-scale mapping area and with few known mineral occurrences, are more attractive targets with little mining history. Area D is also worthy of note. It is large in size and associated with a number of occurrences. Although some of these have been worked, it may indicate prospectivity in adjacent regions with sedimentary cover. However, the known Troulli and Limni—Kinousa—Uncle Charles—Evloymeni (LKUCE) mining districts are not prospective (Figure 1). The Troulli Inlier is associated with only one mineral occurrence, because it is not covered by the 1:31,680 geological mapping and, therefore, would not be indicated prospective by a weights-of-evidence analysis—here a fuzzy logic analytical approach may be more appropriate. Also, it would be unprospective in the high-resolution fault and gossan themes, as this information is a component of the 1:31,680 geology theme. The LKUCE district is more problematic as it has significant mineral occurrence data (10 points). However, it is also outside the 1:31,680 mapping. In addition, most of the ASTER band ratio images are also unprospective. This last disparity is most likely the result of image processing. The image used comprised three separate passes of the ASTER satellite and the resulting mosaic had significant spectral intensity differences with the westernmost image being of lower overall intensity than both the central and eastern. Overall the prospectivity analysis is consistent with known mineralisation and has identified areas for future exploration, but the two areas discussed above emphasise the need for good data validation procedures, so that anomalous results can be readily identified and explained.

Conclusions and future work

Mineral potential mapping has identified eight separate areas of high mineral potential. The areas are located at or within 10-km of the boundary between the Troodos ophiolite and the autochthonous sedimentary cover sequences. Areas A, C and H, and to a limited extent area D are considered to be the highest priority. These have relatively few mineral deposits, but have comparatively large areas of high mineral potential, indicating areas of unexploited ground with the correct characteristics for massive sulphide and stockwork mineralisation. Though not indicated directly, buried deposits in areas overlain by sediments but adjacent to areas of high mineral potential should also be considered. For the pilot mineral potential analysis, prospectivity mapping was undertaken at the regional scale. To use the methodology at higher resolutions more data (e.g. high resolution geophysics and geochemistry) are required. Also a fuzzy logic methodology, which does not require training data, may be able to identify prospective areas away from known deposits. These approaches will be undertaken in the next phase of the prospectivity analysis.

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