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The environmental impact of mining in the Pontides, Turkey: reconnaissance sampling and GIS-based analysis

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ABSTRACT: The Pontide metallotect is the major producing area in Turkey for base metals and has significant Au producing potential. Two major developments are currently at the feasibility stage and face opposition because of their potential environmental impact. Little information exists to substantiate past impacts.

This study describes reconnaissance water sampling and observations of the impact of some of the major current and disused operations. These are volcanic-hosted massive sulphide (VMS) deposits at Murgul, Kutlular, Lahanos and Çayeli. Smaller vein mines at Gümüski Tepe and Midi Maden were also sampled. The VMS deposits have had considerable impact. At Kutlular and Lahanos acid mine drainage (AMD) is strongly developed and metals are transported into drainages. In contrast, this situation has been avoided at Murgul because tailings have been released into the local river and subsequently into the major Çoruh River resulting in Cu, Zn and Fe contamination that is transported across the border into Georgia and discharged into the Black Sea. Both As and Cd are potential contaminants at Murgul although their areal distribution requires further investigation. Remediation at the three VMS deposits is minimal. In contrast, the relatively modern mine at Çayeli has little impact, partly because tailings are disposed of at depth in the reducing Black Sea.

Limited sampling at the vein mines suggests that AMD is not a major problem. Stream sediment sampling shows that As may, however, be released during ore treatment at Midi Maden. Visual examination at the vein mines shows that surface erosion is a major problem, probably due to the high altitude and thin soils. Surface conditions at the Au prospect at Mastra suggest that AMD and metal release should not be a major problem. However, the use of cyanide presents a more significant public relations issue. Examination of porphyry prospects shows that natural AMD is developed in places. Any development is unlikely as grades are sub-economic.

Regional determination of potential AMD was made using the sulphide content of deposit type established in the local studies and related to measured water pH. The wide variation in rainfall was taken into account with areas of high rainfall on the Black Sea predicted as having high potential for AMD formation. Potential surface degradation was predicted using height information from a digital elevation model and deposit type.

KEYWORDS: *mining, pollution, heavy metals, Turkey, Black Sea*

INTRODUCTION

The debate on the benefits of mining in Turkey took on intensity in 1998 with the suspension of the Ovacik mine in west Turkey by court order, after development but before mining, at an immediate cost to the company of $5.2 million (Normandy Mining Limited 1998). The mine was brought into production in 2001 and is producing after spending close to 50% of the development budget on environmental control (Extractive Industries Review 2003). The reason for the mine suspension was the perceived risk of using cyanide to extract Au in a populated agricultural area. However, cyanide is widely used elsewhere in the country; a more common negative perception may be the image of Turkish mining as having a major impact on the environment, as well as very limited local consultation before development. Little information exists on the present impact of mining in Turkey. This study aims to provide an overview of the impact of mining in the Pontide metallotect which occurs in the Black Sea coastal area of north Turkey (Fig. 1). The Pontide metallotect was chosen as it is the location of most base metal mining in Turkey, as well as being host to at least two potential Au producers (Karayazıcı 1997; Tören 1998). In general, the area is relatively underdeveloped with an average regional gross domestic

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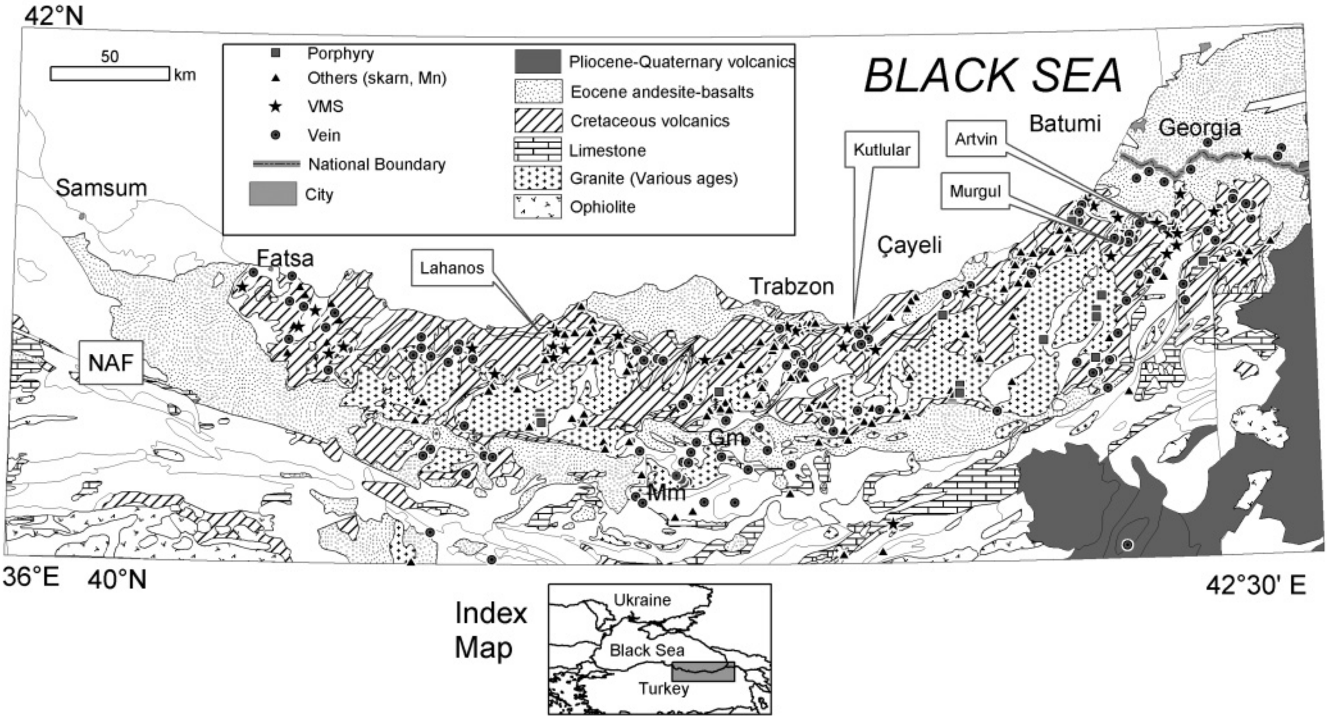

Fig. 1. Location of the area with major mineral deposits. The vertical line near the east of the map represents the eastern limit of the detailed mapping of Güven 1993. All maps use the Turkish Transverse Mercator grid. Mm = Midi Maden, Gm = Gümüşhane

product of 66% of the Turkish average and emigration of more than 50 000 people over the years 1990–1997 (Nippon Koei 2000), so mining is potentially a source of employment.

Geology

The Pontide metallotect is hosted in a late Mesozoic–early Tertiary island arc terrane, that is a continuation of the Mesozoic–Tertiary Arc that is present through Romania and Bulgaria, discussed in detail by Mitchell (1992, 1996). The arc is offset by the major West Crimean Fault in the Black Sea (Banks & Robinson 1997) and is present onshore in Turkey in the area along the Black Sea coast, east of Samsun, and continues in the south of Georgia. In Turkey, the island arc is bounded to the south by the North Anatolian fault. This is a major strike-slip fault that probably takes up the northward motion of the Anatolian microplate, which collided with the island arc in the Palaeocene (Y. Yilmaz *et al.* 1997).

Geologically the Pontide terrane is divided into a volcanic-dominated belt of largely Mesozoic age along the Black Sea coast and a central area of Tertiary intrusives. The evolution of the area is summarized by Okay & Sahintürk (1997). Deposition of sediments began in the early Jurassic on a basement of metasediments and granites of Carboniferous and probable Devonian age. Jurassic sedimentation is dominated by volcanics, limestones and flysch sediments of probable rift origin. A mid-Cretaceous hiatus was followed by deposition of a 2000-m thick volcanic succession in the late Cretaceous. Collision in the Palaeocene resulted in thrusting that was followed by a mid-Eocene sedimentary and volcanic cycle of probable extensional origin. This period also probably coincided with the opening of the Black Sea (Banks & Robinson 1997). The next phase of volcanism is more alkaline, largely of Oligocene age, and unconformably overlies older rocks in the east of the Turkish Pontides. Volcanism continued from the Miocene until the Pliocene–Quaternary with extensive development in the border area between Georgia and Turkey (Yılmaz *et al.* 2000).

The present-day topography reflects the geology with the central part of the terrane forming mountains up to 3937 m in height and the volcanic areas forming highly dissected areas along the coast and in the area immediately north of the North Anatolian Fault (Fig. 2).

Metallogenesis

The Pontide arc (Fig. 1) contains a variety of mineral deposits, typical of island arcs (Sawkins 1990). The most important deposits are volcanic-hosted massive deposits (VMS), vein Au and base metal as well as porphyry Cu deposits (Ersecen 1989; Aslaner *et al.* 1994; Çamur *et al.* 1994; Engin *et al.* 2000). In contrast to the Carpathians and the Sredno–Gorie Zone of Bulgaria, porphyries and vein Au deposits are not important metal producers (Jankovic 1980).

The most important deposit type in the Pontides is VMS hosted in dacitic volcanics of upper Cretaceous age. These deposits show variation from disseminated stockwork-dominated types, as at Murgul, to large polymetallic occurrences, such as the Madenköy deposit, near Çayeli, similar to those of the Kuroko district of Japan (Hobbs 2000). The dominant commodities are pyrite, Cu and Zn but some deposits contain significant precious metals, both in sulphides or, as at Cerattepe, in iron oxide zones (Ciftehan & O'Brien 1998). Volcanic-hosted massive sulphides of early Jurassic age are present in the Kure area, are of the Cyprus type and are economically less significant (Ustaömaer & Robertson 1997).

Manganese deposits have also been worked in places in the Pontides and are associated with upper Cretaceous volcanism.

A variety of vein deposits are known in the area, although few are currently of interest. The major economic deposits are epithermal Au ± base metal deposits. A major adularia–sericite type epithermal Au prospect at Mastra is at the development

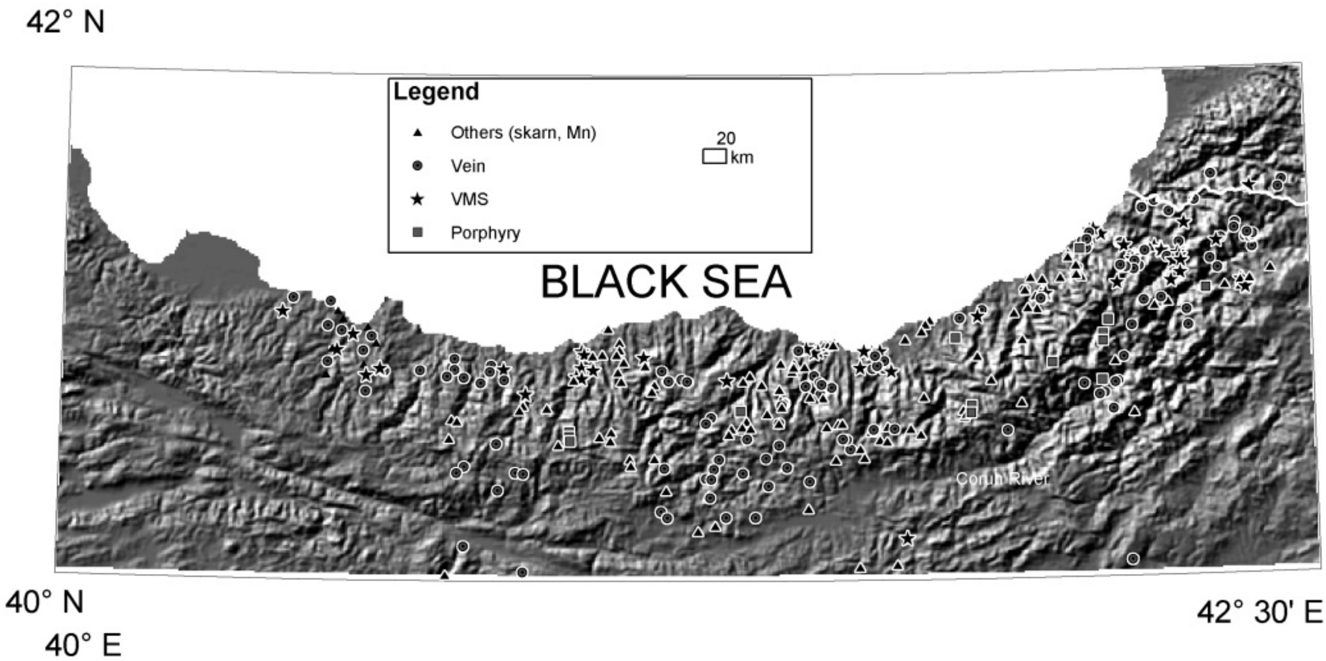

Fig. 2. Digital elevation model of the Pontides overlain with the distribution of mineral deposits. DEM source: Globe Team (2002).

stage and is hosted in Eocene volcanics (Tüysüz *et al.* 1995). Related precious metal deposits include the Eocene limestone-hosted prospect at Kaletas near Gümüshane (Çubukçu & Tüysüz 2000). The stratigraphical location of other prospects is uncertain, for example, Bahcecik (Yigit *et al.* 2000), which could be of either Upper Cretaceous or Eocene age, although Yigit *et al.* (2000) favour the latter. Other significant Au veins occur at Altintepe, near Fatsa, (Curtis 2002) and at Akoluk, Ordu, both in Cretaceous volcanics (Tüysüz & Akçay 2000). Vein and breccia base metal deposits associated with volcanism are known from areas such as Gümüski Tepe and Midi Maden (Ayan & Dora 1994).

Although not economic at present, a number of porphyry deposits of both Cu–Mo and Cu–Au type have been discovered in the Pontides. Çamur *et al.* (1994) suggest that the deposits form a linear belt to the south of the VMS deposits, which form a belt along the coast corresponding to the outcrop of Cretaceous volcanics. However, the true position appears more complex with porphyry prospects also occurring in the NE of the eastern Pontides. The major Cu–Mo deposits at Güzelyayla and Ulutas have been investigated in detail and the host pluton at Ulutas has been dated at 132 ± 5 Ma by Giles in Taylor & Fryer (1980), although determinations on the prospect as well as the Bakircay prospect give *c.* 38 Ma as the probable age of mineralization. Moore *et al.* (1980) suggested a modal age of *c.* 80 Ma for Pontide granitic magmatism with later phases at 45 and 25 Ma. Exploration in the Artvin area has defined an Au-rich porphyry (Gümüshane dated as Eocene (K/Ar: 51–54 Ma; Röckl 1998).

Skarn deposits of various ages are known from the Pontides (Çamur et al. 1994). These are currently of little economic interest.

Mining history

The Pontides have had a long mining history. The various civilizations and traders along the Black Sea prospected and mined deposits, particularly of the coastal VMS deposits. Modern mining at Murgul started in 1945 and was followed by the development of other VMS and vein deposits.

Current status. The major metal producers are the underground operation at Çayeli and the open pits in the Murgul area (Fig. 1). The VMS deposits in the Lahanos area have capacity for production but are currently idle. The VMS deposit at Kutlular was mined out in the 1980 s. Although the vein and breccia base metal deposits appear too small to be of interest for large-scale mining, they are of current interest to small-scale operators.

There has been significant exploration activity in the late 1980s and early 1990s that resulted in the discovery of two important deposits: a VMS deposit at Cerattepe, west of Artvin (Cominco Ltd 1997) and the epithermal Au deposit at Mastra (Tüysüz *et al.* 1995). Both are currently at the feasibility stage. Cominco, the past operators at Cerattepe, have announced that the deposit contains sulphide reserves of a probable 3.5 Mt of 4.9% Cu and 1 g/t Au together with a possible reserve of 0.6 Mt of similar material; oxide reserves are 1.7 Mt of 4.9 g/t Au and 204 g/t Ag together with a further 5.6 Mt of possible reserves (Cominco Ltd 1997). The deposit was the subject of an underground exploration attempt that was stopped when it was realized development permission was unlikely due to the proximity of the Hatila Vadisi National Park. More recently, the deposit is under investigation by Çayeli B.I., the operators of the Çayeli mine. Mastra was also the subject of underground exploration in 1998 by Eurogold (in 2004 held by Newmont). However, any development is likely to depend on the successful operation of the company's deposit at Ovacik. Mastra is relatively small with resources of 1 Mt of 12.3 g/t Au (393 000 oz).

Climate and vegetation

The coastal part of the region has a strong maritime influence with NW winds predominating (Dewdney 1971). Rainfall is high (the city of Rize: annual total 2440 mm) with a maximum in the winter and some in the summer. Precipitation increases with height and there is a pronounced rain shadow so that the interior parts of the area, such as Gümüshane, are semi-arid. Winters on the coast are mild (mean January temperature *c.* 7°C) and the coastal climate is mild and moist, different from that experienced in the rest of Turkey. Inland, temperature contrast is more continental.

High rainfall and mild winters have produced a rich Pontic forest and brushwood cover along the Black Sea coast (Dewdney 1971). Typical species are sweet chestnut, alder, rhododendron, hazel and myrtle. The forest reaches 500–700 m in height, above which coniferous forest is common. Above 2000 m the forests are largely absent and alpine meadows are used for summer grazing. Forest is less dense in the rain shadow area and grass and small bushes are commonly predominant.

DIGITAL AND FIELD DATA COMPILATION

The lack of a comprehensive data set in the public domain and the impact of mining, obvious from a cursory journey through the area, were the impetus for the initiation of this project. A major aim of this study was to build a database (of the deposits, geochemical results from exploration and environmental parameters) in digital form for use in a geographical information system. It is believed that this information will enable better prediction of environmental impact of new discoveries and of problems in areas with existing or disused mines. Key features of the deposits collected are their (1) location, (2) geological host rocks, (3) mineralogy and (4) mining status. Where possible data collected during exploration have been digitized. Although a number of recent studies of the geology have been made, the majority are proprietary to major mining groups active in the area, such as Inmet Mining, Cominco, Inco and Rio Tinto. Only the studies of the Turkish Geological Institute, Maden Tetkik ve Arama (MTA), are partially in the public domain, but many of their studies were made in the 1980s. The key data sets used for mineral deposit location were: (1) the 1:250 000 map of Güven (1993); (2) for the border area between Turkey and Georgia from the database of mineral deposits given as an appendix in A. Yilmaz *et al.* (1997); and (3) the 1:1 000 000 metallogenic map of Engin *et al.* (2000). Geology was taken largely from Güven (1993) as well as MTA 1:500 000 maps and that of Georgia from Vsegei (1982).

In addition to building a database, sampling and field visits were undertaken to the more important deposits in the Turkish Pontides to establish the impact of current mining operations.

RESULTS OF FIELD STUDIES AND SAMPLING

In order to assess the present impact of mining, we visited a number of the more important mines and deposits in the area. In addition to visual assessment, where possible, water and sediment samples of the drainage from these mines were taken from drainages to gauge their quality.

VMS deposits

Volcanic-hosted massive sulphide deposits are the main source of metal in the Pontides and the most important potential source of mining-related pollution.

Murgul. Deposits in the Murgul area (Fig. 1), although the largest in the belt, are also atypical of the VMS deposits in the Pontides as mineralization is disseminated with very little stratiform ore in contrast to the massive sulphides elsewhere. Schneider *et al.* (1988) have compared them to porphyry Cu deposits, although other features indicate VMS stockwork-type deposits. The deposit is hosted in dacitic pyroclastics and overlain by tuffs, mudstone and some limestone, all of upper Cretaceous age.

There are a number of deposits in the vicinity of the town of Murgul town, of which two to the south have been mined on a large scale: Çakmakkaya and Damar (Çamur *et al.* 1994). Mining has been in open pits, with the target commodities Cu and pyrite. Initial resources were estimated at 40 Mt of 1.25% Cu, 0.1% Zn, 0.01% Pb, 25 ppm Ag and 0.2 ppm Au (Schneider et al. 1988). Çamur *et al.* (1994) indicate that the total resource is higher, at *c.* 60 Mt. Mining started *c.* 2000 BC at Damar although modern mining by a subsidiary of the state mining company, Etibank Mining, only commenced in 1945. The sulphides are separated by flotation with an overall capacity for the two mines of 3.85 Mt/a ore and concentrator output to 168,900 t/a of 17% Cu product (Anon. 1988). Production in 1997, when the samples were collected, was *c.* 3 Mt yielding 25 000 t of Cu concentrate 25 000 t of sulphur and 10 000 t of sulphuric acid (Akçay & Tüysüz 1998). No tailings dam was constructed and tailings are directly disposed of into the Murgul River, a tributary of the Çoruh River. Originally ore was smelted at Murgul but, after the building of a smelter at Samsun, Cakmakayya, ore was shipped by pipeline to the coast for onward transport and smelting (Anon. 1982). A by-product of the operation was the generation of sulphuric acid by roasting of sulphide concentrates south of Murgul (Akçay 1998).

Samples were taken in 1997 along the length of the Murgul River over 18.5 km from the open pits input, via the Damar River, to the river's confluence with the Çoruh River, the major river in the area (Fig. 2), repeating in less detail (*c.* 1-km intervals) than the 1996 sampling of Akçay & Tüysüz (1998). The 1997 sampling, carried out by the present authors however, also compared suspended and soluble (<0.45 μm) water samples by on-site filtration. In places, filtration was rendered difficult due to the large amounts of suspended material, which was seen to be raw tailings, either being discharged during sampling or reworked from previously deposited material. All samples were acidified on site, the 1996 samples were analysed by GFAAS in at Black Sea Technical University in Trabzon, the 1997 samples by ICP-ES at the University of Leicester. Typical analytical precision is 10% at the concentrations encountered at Murgul.

The pH of the Murgul River varies between 7.6 and 8.4, slightly more acid than the Çoruh (8.2–8.4), probably as a result of pyrite oxidation in the river (flotation products have a pH of 9.7). Total Cu and Zn in the 1996 survey (Fig. 4) range from 3.7 to 6.2 ppm and 1.4 to 4.7 ppm, respectively. There appears to be a significant Cd enrichment of up to 80 ppb in waters near the tailings disposal but these values require confirmation. Stream sediments taken in the 1996 survey also report up to 6 ppm Cd. Comparison of suspended with dissolved metal content of samples collected in 1997 (Fig. 5) shows that most Cu (average 75%), Fe (85%) and considerable Zn (65%) are transported in suspension in the Murgul River.

The results (Figs. 4, 5) indicate clearly the effect of the discharge of raw tailings on the Murgul River. The Murgul River then discharges into the Çoruh River (Figs. 1, 3), the most important river in NE Turkey. This river flows across the border with Georgia and eventually discharges into the Black Sea near the major port of Batumi. The extent and nature of the contamination and its impact on Georgia is, as far as known, unstudied. Both the 1996 and 1997 sampling surveys examined a short reach of the Çoruh, immediately up- and down-stream of the confluence with the Murgul River. Copper, Fe and probably Zn are detectable in the Çoruh River (Fig. 6). The suspended Fe concentrations are comparable to those near the tailings outfall. Both Cu (400 ppb) and Fe (2100 ppb) exceed Turkish quality standards (20 ppb Cu and 300 ppb Fe) but conform for Zn (80 ppb v. 200 ppb Zn). Compliance for Cd

Fig. 3. Landsat TM scene showing the location of Murgul mines, and route of tailings discharge into the Black Sea near Batumi.

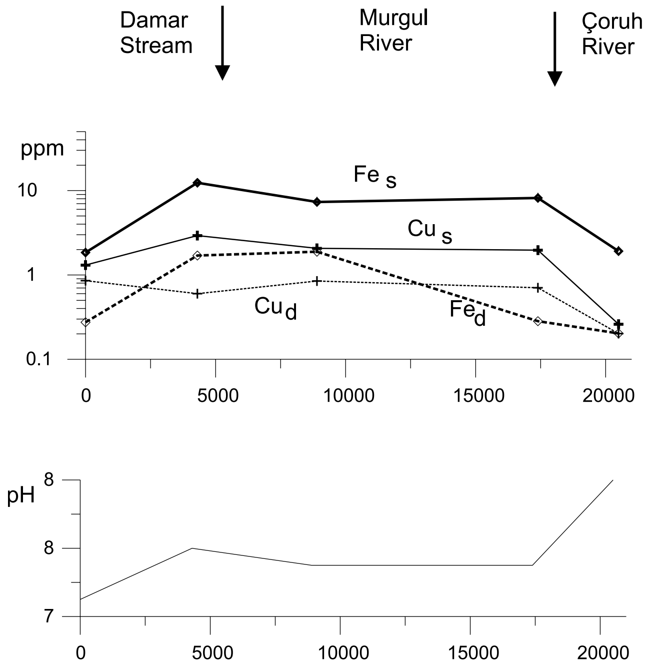

Fig. 5. Comparison of dissolved (d) and suspended (s) metals in the Damar, Murgul and Çoruh Rivers due to tailing discharge.

and As needs further investigation. It was not possible to trace the tailings into Georgia in any detail. However, a brief observation of the Çoruh River near Batumi confirmed the occurrence of tailings-like sand and a water sample reported 90 ppb dissolved Cu. The Landsat image (Fig. 3) indicates that a substantial area (>6 km^2) may be contaminated and the discharge from the Çoruh River, at least partly of tailings, can be clearly seen entering the Black Sea. Since the samples were collected a dam has been constructed on the Çoruh River immediately downstream from its confluence with the Murgul River, impeding any further flow of tailings.

A major output of the Murgul complex has been sulphuric acid, mainly produced by roasting sulphides on site. A small soil survey investigated the impact of this roasting plant (Akçay 1998). This demonstrated that the area immediately downwind (hundreds of metres) is strongly contaminated with Cu and As.

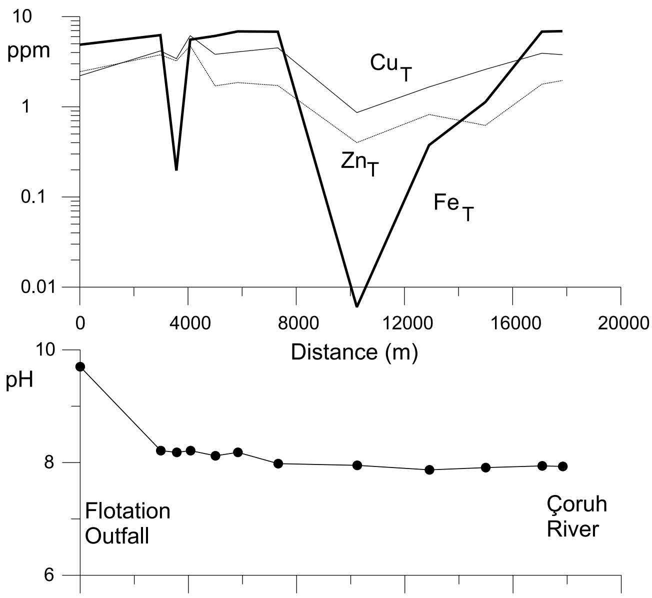

Fig. 4. Plot of downstream water samples from flotation outfall to Çoruh River, 1986 samples. Location of traverse starts downstream from open pits shown on Figure 3. T = total (unfiltered) metal.

Kutlular. Kutlular (Figs. 1, 6) is a small (1.3 Mt at 2.4% Cu and 1.5% Zn of which 0.76 Mt has been mined; Catagay 1993) VMS deposit that was worked in the mid-1980s to early 1990s and abandoned. There has been little attempt at reclamation, apart from the removal of buildings. The open pit has been left as a small shallow lake.

Sampling in 1997 (Figs. 7, 8) showed that AMD is well developed with a pH of *c.* 3 measured in the pit. This is coupled with high concentrations of dissolved Cu, Fe and Zn (Fig. 8). In contrast to Murgul, the suspended Cu and Fe levels are low, indicating the transport of metals in solution in accord with behaviour at AMD sites, such as Wheal Jane, UK (Bowen *et al.* 1998). Acid mine drainage is developed for the whole length of the river until its outfall into the Black Sea and can be visually estimated from precipitation of Fe ochres along the river bank. Measurements of pH of *c.* 4 in the tributary to the main drainage

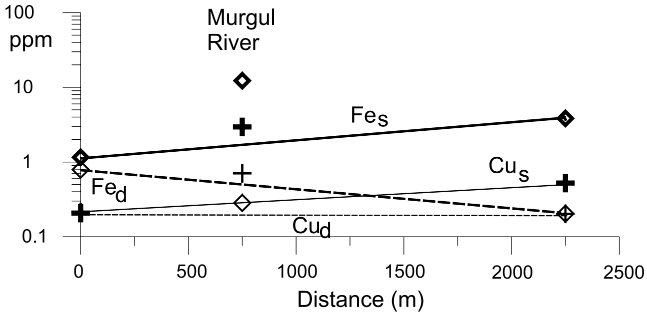

Fig. 6. Downstream dispersion in the Çoruh River. Note the effect of the Murgul River.

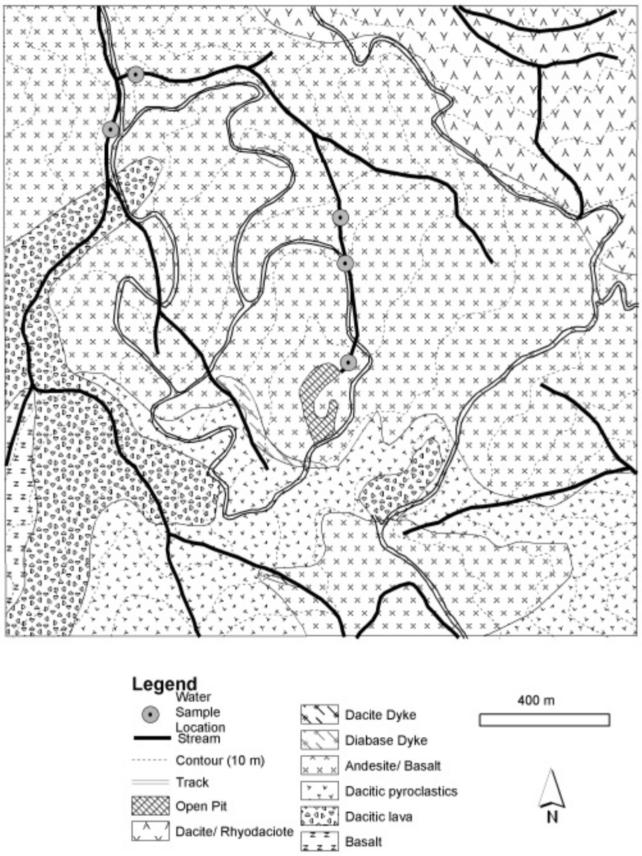

Fig. 7. Kutular: location map of sampling and base geology. Source: MTA (unpublished data).

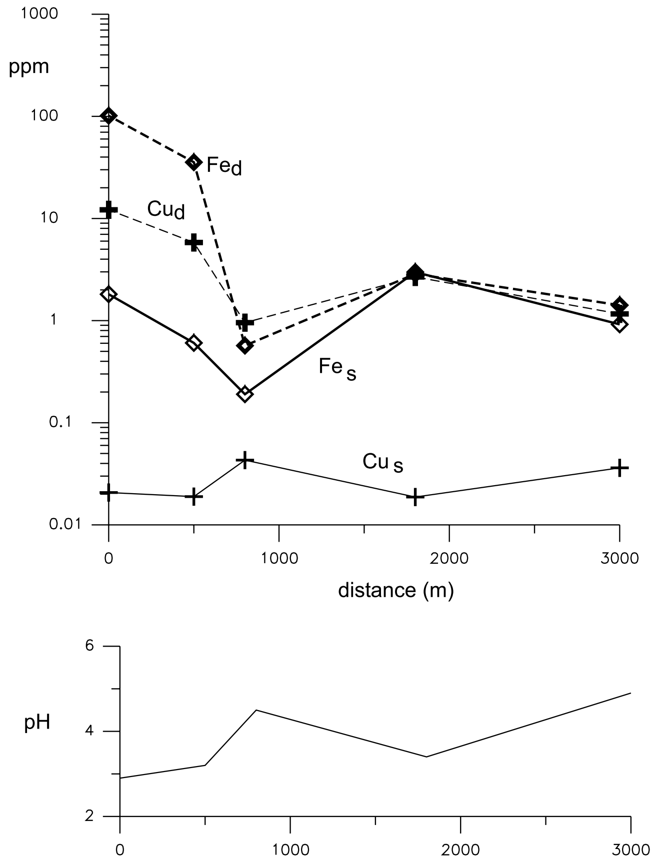

Fig. 8. Downstream movement of metals (d = dissolved, s = suspended) from open pit. Sample locations shown in Figure 7.

suggest that the AMD is not confined to runoff from the open pit and that AMD is generated from spoil or background enrichment in pyrite elsewhere in the area.

At Kutlular, data from MTA exploration were available to provide some measure of metal dispersion in the area around the open pit (Fig. 9). As an example, data for As suggest that the element is not a major problem in the area, with soil samples on the edge of the open pit at about 50 ppm As. Much of the area surrounding the open pit is planted with tea but the impact on these plantations and the flux of As into humans has not, as far as is known, been studied.

Lahanos. Deposits in the Lahanos area form a cluster typical of VMS occurrences (Leitch 1981). Current mining activities concentrate on the Lahanos deposit, although mining was suspended at the time of sampling (July 1998) due to low metal prices. Reserves are put at 1.5 Mt of 3.5% Cu with a capacity of 120 000 t/a. The Lahanos deposit is mined underground and sulphides are separated by flotation. A dam has been constructed to store tailings and overflow from the dam is discharged into the Kizil River (Fig. 10).

Reconnaissance water sampling (Fig. 11) indicated that downstream from the tailings dam pH was *c.* 3 and that this was maintained for at least 3 km downstream. This AMD drainage is transporting significant Cu and Zn (*c.* 40 ppm at source).

Another major potential problem is the location of the tailings dam on a steep slope 160 m above the main valley floor.

Çayeli. The Madenköy deposit near the town of Çayeli is the largest underground operation in the area and is operated by a joint venture between Inmet Mining and Etibank. Large-scale mining began in 1994 after an investment of $155 million, which included provision for environmental monitoring (Fig. 12). This underground Cu–Zn mine was designed with growth in mind, and the mill has a capacity of 600 000 t/a of ore. Capacity is 28 000 t/a of Cu in concentrates while Zn in concentrate is 38 000 t/a (Anon. 1995). As of 2002, 7.35 Mt of ore had been mined and reserves are estimated at 16.9 Mt of 3.8% Cu, 5.8% Zn, 0.5 g/t Au and 47 g/t Ag (Inmet Mining 2003). A further resource of 2.9 Mt is inferred. Çayeli operates a flotation separation, of chalcopyrite from sphalerite, which was initially problematic due to very fine-grained intergrowths of the two minerals (Catgay & Boyle 1980; Anon. 1996). Tailings are disposed of into the Black Sea by means of a pipeline to the coastline and introduction at a depth of 350 m. At this depth the southeastern Black Sea is reducing and oxidation of sulphides is not possible. Backfill has been derived by extracting river gravels and from a surface basalt quarry (Çayeli Bakir Isletmeleri A S 1993). Access to the orebody is by surface declines and a shaft from the edge of the Buyuk Dere River. Although pumping and backfilling minimize the generation of AMD, the position of the mine entrances on the edge of a river suggests that there may be a problem on closure due to flooding. Although the mine uses filters to collect dust at source and washes down regularly, dust is likely to present a problem as the mine is close to a populated area (Extractive Industries Review 2003). No measurements have been made of elemental fluxes during this study.

Vein and breccia deposits

Vein and breccia are attractive targets for small-scale mining in the Pontides, particularly those that have higher precious metal

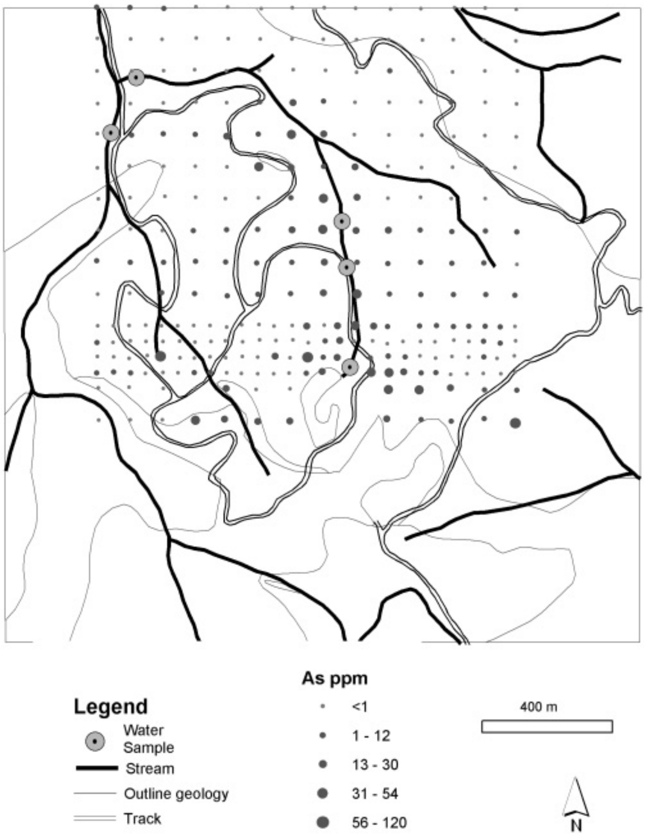

Fig. 9. Arsenic distribution from soil exploration data around Kutlular open pit (data source: MTA).

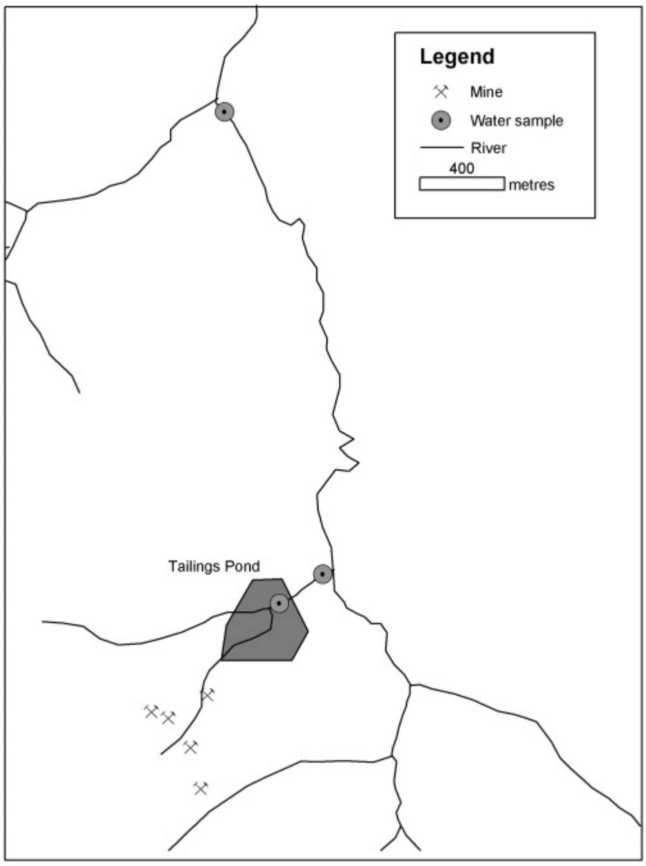

Fig. 10. Lahanos: sketch sample location map.

contents. This study examined two deposits: Midi Maden, 18 km SW of Gümüshane, and Gümüski Tepe in high yayala or summer pasture, 42 km south of Trabzon. Other vein mineralization was also examined in the area to the SW of Artvin and AMD was developed in at least two sites in the area.

Midi Maden. The Midi Maden breccia deposit is a small-scale operation which produced *c.* 50 000 t of ore per year in 1997. The ore is trucked from the underground workings and separated in a central plant, and waste was stored in a small tailings pond (Fig. 13).

Water sampling demonstrated that the pH of the rivers is between 7.1 and 8.2. Metal concentrations are 60 ppb Zn downstream from the mine and 150 ppb Zn downstream from the plant. Stream sediments are enriched in As (up to 400 ppm) and Pb (up to 1300 ppm) suggesting that metals are being released from the tailings disposal areas (Fig. 14). The high pH of the stream water is probably due to the widespread occurrence of limestone in the area.

Gümüski Tepe. Gümüski Tepe is small operation mining high-grade sphalerite–galena veins hosted in silicified tuffs (Hall 1992). The operators, Genç Maden, have stripped the surface to aid access to underground mining. This has resulted in soil erosion and a general barren landscape on the order of >100 m around the main vein. The mine is on the edge of a major scarp and there is no planned waste disposal site. Ores are generally trucked out after separation at a nearby plant. Due to the area's elevation there was little surface drainage during the July visit.

There are a number of other geochemical anomalies in the area, notably at Zerbenos, which is 3–4 km from Gümüski Tepe and enriched in As and base metals. When the area was visited stripping had begun for small-scale production. Vegetation is sparse, of the Alpine meadow type, and it will probably be difficult to re-vegetate the stripped areas. An interesting side-light on the area is the presence of large amounts of ancient slag in the area.

Gold prospects

The Mastra epithermal vein Au prospect contains little sulphide or other metals in addition to Au (Tüysüz *et al.* 1995). Typical concentrations are 200 ppm Cu, 300 ppm Pb and 40 ppm As. The deposit itself is small, *c.* 1 Mt at *c.* 12 g/t Au, and little waste will be generated. The major concern is the extraction of Au by

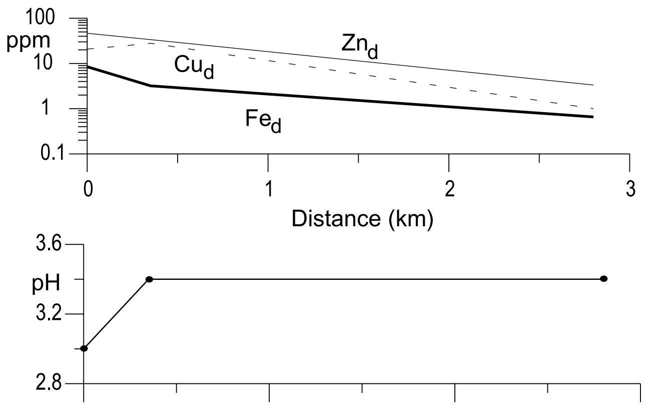

Fig. 11. Downstream dispersion of dissolved metals from Lahanos tailings dam from sample location shown in Figure 10.

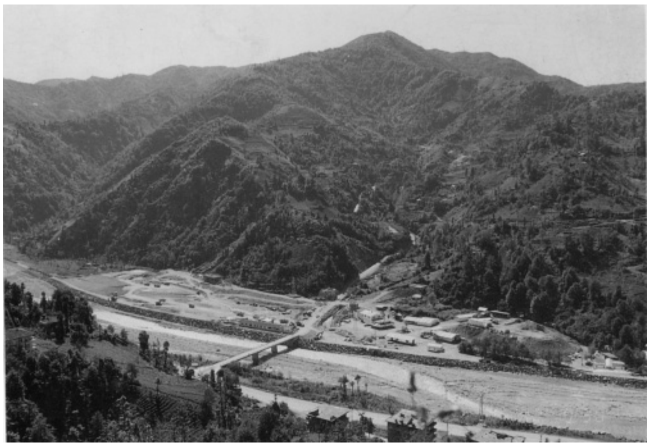

Fig. 12. Photo of Çayeli mine in *c.* 1994. Note the position of the mine on the edge of the river and entry declines. The relief is typical of the coastal area.

cyanide, disposal of cyanide wastes and surface disturbance of thin soils. There seems to be little concern about the leaching of metals because the pH of surface waters is about 8.

Porphyry prospects

One of the most significant porphyry prospects in the Pontides is the Güselyayla deposit *c.* 40 km SW of Trabzon. An overall resource of 300 Mt at 0.3% Cu suggests that it is unlikely to be mined. Reconnaissance water sampling indicated that natural AMD (pH *c.* 4) is developed in a pyritic zone around the deposit. This is accompanied by ferric oxide precipitation. No water analyses are available.

DISCUSSION OF FIELD VISITS AND SAMPLING

The studies provide some indication of the mining impact in the area especially when coupled with similar studies elsewhere in the world (Ripley *et al.* 1996) and generalized models, such as those of the United States Geological Survey (USGS) (Dubray 1995).

VMS deposits

A comparison of the four deposits visited is shown in Table 1. Both at Lahanos, where the tailings have been impounded, and

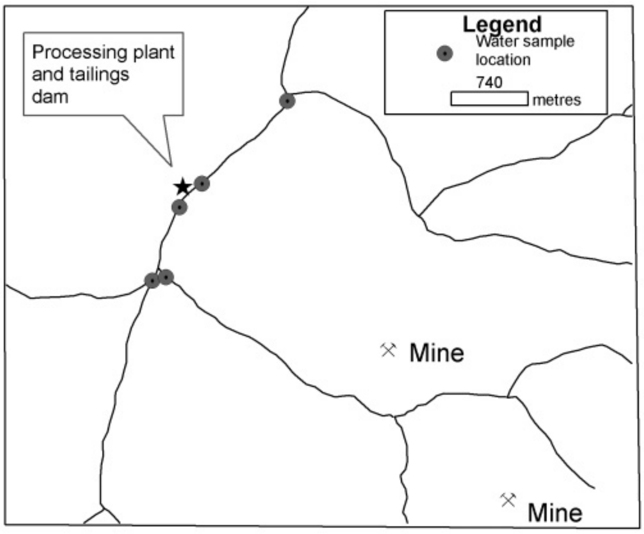

Fig. 13. Midi Maden: sketch location map.

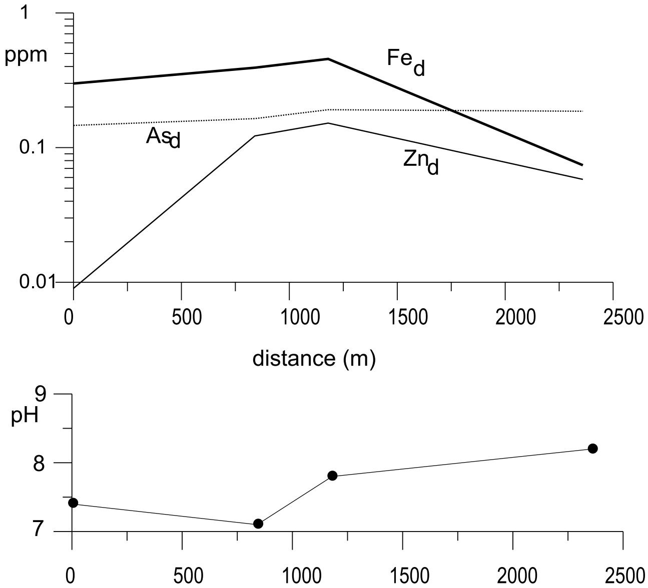

Fig. 14. Downstream dispersion of dissolved (d) metals: Midi Maden. Sample location shown in Figure 14.

at Kutlular, AMD is developed. Metals in any waste, in the unmined wall rocks and any tailings are leached into the drainages. No remediation schemes (National Rivers Authority 1994) have so far been implemented in the Pontides. In contrast, the major deposits at Murgul do not generate AMD but export the problem into the Damkar, Murgul and Çoruh Rivers and finally into Georgia. The potential for AMD generation at Çayeli appears limited during mining as backfilling is used and tailings are disposed of at depth in the Black Sea.

Geochemical studies of deposits at the exploration stage indicated metals that are viable for leaching. Besides Fe, Cu and Zn, which form major metals in the deposit, As and Cd are of concern. Catagay & Boyle (1977) indicated Cd values of 1–5 ppm in volcanics associated with the stratiform deposit and 2 ppm in the stockwork type; they also have concentrations of 20 ppm and 5 ppm As. Sulphide ore at Madenköy has As concentrations of up to 4500 ppm As and 340 ppm Cd. The black ores at the top of the deposit contain the greatest amounts of As and Cd. Yellow ores have much lower concentrations (up to 35 ppm Cd and 850 ppm As). Maximum mercury levels in both types are *c.* 5 ppm Hg.

Vein and breccia deposits

The vein and breccia deposits have considerable sulphide, with sphalerite the main product in the deposits examined. However, at Gümüski Tepe AMD was not observed due to the altitude of the deposit and consequent lack of summer rainfall. At Midi Maden the pH is high and AMD is not generated due to buffering from limestone. Nevertheless, some As is released and incorporated into stream sediments, probably due to high concentrations of sulphosalt minerals. At both locations soil erosion was significant, probably due to a combination of small-scale mining methods and susceptibility of thin alpine soils to erosion.

Gold prospects

Gold deposits are likely candidates for AMD generation due to the removal of buffering by acid alteration of host rocks surrounding the deposit. Water samples from Mastra, however, indicate neutral pH in surface waters, which has moderate

Table 1. . *Various aspects of the impact of VMS deposits in the Pontides.*

	Visual impact	Dust	Acid plant	Tailings dumps	AMD	As and Cd in AMD
Murgul	high	moderate	high	low	low	moderate
Kutlular	moderate	low		low	high	low
Lahanos	low			low	high	
Çayeli	low			low		low?

Blank cell indicates unknown value.

concern for AMD generation. The occurrence of deposits on the high yayala suggests that surface disturbance and soil erosion should be of major concern. Overcoming public concern of cyanide usage is, however, the greatest worry for the operators.

Porphyry prospects

Acid mine drainage is a major potential problem for the development of porphyry deposits and natural development of AMD was observed at Güselyayla. Soil erosion and deforestation are likely to be of major concern due to the general location of these deposits that are hosted in Tertiary granites that form the high areas in the Pontides.

REGIONAL GIS-BASED ANALYSIS

One of the major parts of this study was to assemble a database in geographical information system (GIS) format. This presents a problem in Turkey as there has been a long tradition of governmental classification of map data as secret. As a result very little information is available in digital format and obtaining paper maps to digitize is not easy.

Data and rationale for use

Topographic data. For regional analysis the most useful source of information is the *Digital Chart of the World* (ESRI 1993). Data layers include political boundaries, settlements, drainage and topography. In addition to the digital map of the world, a digital elevation model for the area is also available from the Globe Worldwide web site (Globe Team 2002). Although detailed digital elevation models derived from 1: 25 000 Turkish mapping are available commercially, these data sets are adequate for modelling on a regional basis (Fig. 1).

Rainfall. Local studies have shown the control on AMD generation by rainfall and the variation of vegetation between the high rainfall areas on the north-facing slopes of the Black Sea coast and the rain shadow areas to the south. Accurate rainfall data are therefore an important component of any model. Probably the most recent estimate available is the work of Altinbilek et al. (1997); this was digitized.

Geology. Geology was derived from published and open-file maps kindly provided by MTA. The regional data were taken from the 1: 250 000 map of Güven (1993), the published 1:2 000 000 scale map of Turkey (MTA 1989) and 1:500 000 scale MTA maps (MTA 2002).

Mineral deposits. Information on deposits was collected from published sources as discussed in the 'Digital and field data compilation' section and from site visits. The parameters used were location and deposit type.

Regional analysis

Based on the local studies and more generalized studies, such as those of the group at the USGS (Lee 2002; Wanty *et al.* 2002) it is possible to highlight areas of potential mining impact and areas where future work should be conducted.

Predicting the occurrence of AMD can be undertaken by combining the maps in raster mode in GIS, in this case in the spatial modeller extension to Arcview. No regional geochemical data were available so this analysis used mineral deposit occurrence, geology and rainfall layers. A cell size of 1 km was used for the analysis reflecting the resolution of the data.

A number of approaches have been used to quantify favourability using GIS (O'Sullivan & Unwin 2003). In this study the simple index overlay approach was chosen as the number of test areas with known AMD on which to develop a model was limited and the conditions needed to develop it are understood. In the index overlay method, key decisions are the weights to assign to different layers and how to convert different values within a layer to a value to be used in an overlay. From the local studies it appeared that the two most important factors in AMD generation are the amount of sulphide and the climate, particularly rainfall. The main parameter, as indicated from the local studies, is the amount of sulphide in the different deposit types and ability of pyrite in the deposit to form AMD. Porphyry and VMS deposits were assigned very high (5), whereas veins were assigned medium (3), skarn, because of the likelihood of buffering, low (1), and manganese deposits also low (1) due to their lack of sulphide. A limestone geological layer was used to remove areas in which natural buffering of AMD is likely. A more difficult parameter to evaluate was climate. The local studies indicate that AMD is most easily generated in the areas of high rainfall and therefore of chemical weathering. As the climatic stations are widely spaced in the Pontides only the broadest generalization can be made. Areas of annual precipitation >1500 mm, on the coast and coastal slopes, were assigned high (3), 400–1500 mm medium (2), and < 400 mm, corresponding to the inland rain shadow area, low (1). The climate and sulphide layers were combined with weights of 1 to give an overall index to shade the buffer zones (Fig. 15, Table 2).

The size of the area with potential AMD generation is controlled by the type of mineral occurrence. As VMS deposits tend to occur in clusters coupled with observed sulphides around them, they were given a 5 km buffer (2.5 km radius); porphyries were given similar buffers because of their inherent size, whereas veins, skarns and the less significant Mn deposits were assigned a 1 km buffer.

Examination of Figure 15 shows that the known areas of AMD generation at Lahanos, Kutlular and the potential of the Murgul area are visible. The eastern coastal area with high rainfall and a large number of VMS occurrences should be targeted for further investigation, particularly as the area is responsible for much of Turkey's tea output.

From the localized studies, deposits on the high yayala seem more susceptible to soil erosion. Areas over 2000 m in the

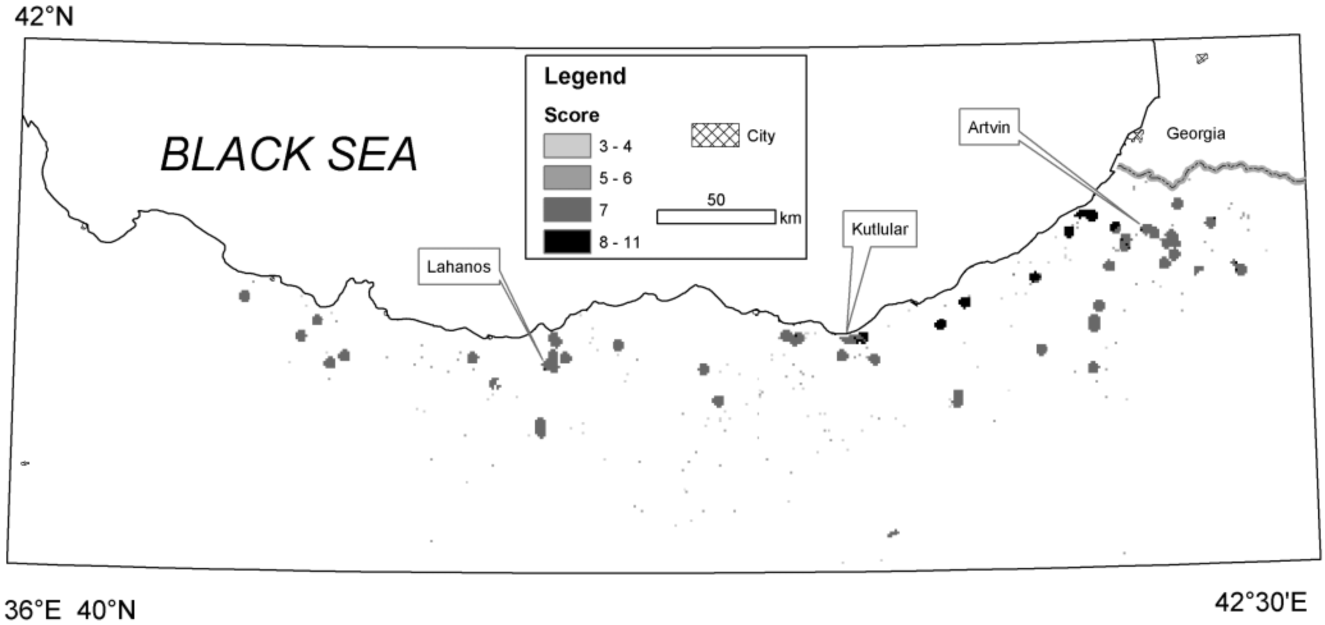

Fig. 15. Potential for AMD based on deposit type and rainfall. Weightings of parameters are discussed in the text. Limestone areas are excluded and the cell size is 1 km.

buffers created in Figure 15 were selected to indicate potential problem areas (Fig. 16). Any development of AMD from features such as pyritic shells around porphyries or acid leaching of rock around Au veins would excaberate the soil erosion. These areas for further investigation are mainly inland from Trabzon towards Artvin.

Table 2. . *Scores used for AMD prediction.*

Deposit Type	Score	Rainfall (mm)	Score
VMS	5	>1500	3
Porphyry Cu	5	400–1500	2
Mn	1	<400	1
Skarn	1		
Vein	3		
Sb and Ba	1		
Epithermal Au	1		

CONCLUSIONS

Mining has had, and is having, considerable impact on the Pontide environment. This is largely as a result of the lack of remediation strategies. The worst example is the transnational problem at Murgul where untreated tailings are disposed of into the main drainage. The scale of the problem is largely unquantified and may have consequences for the population of the southern suburbs of Batumi. Similar discharges at Ok Tedi have provoked much debate (Mines & Minerals Sustainable Development Project 2002). Murgul also has had a problem with acid

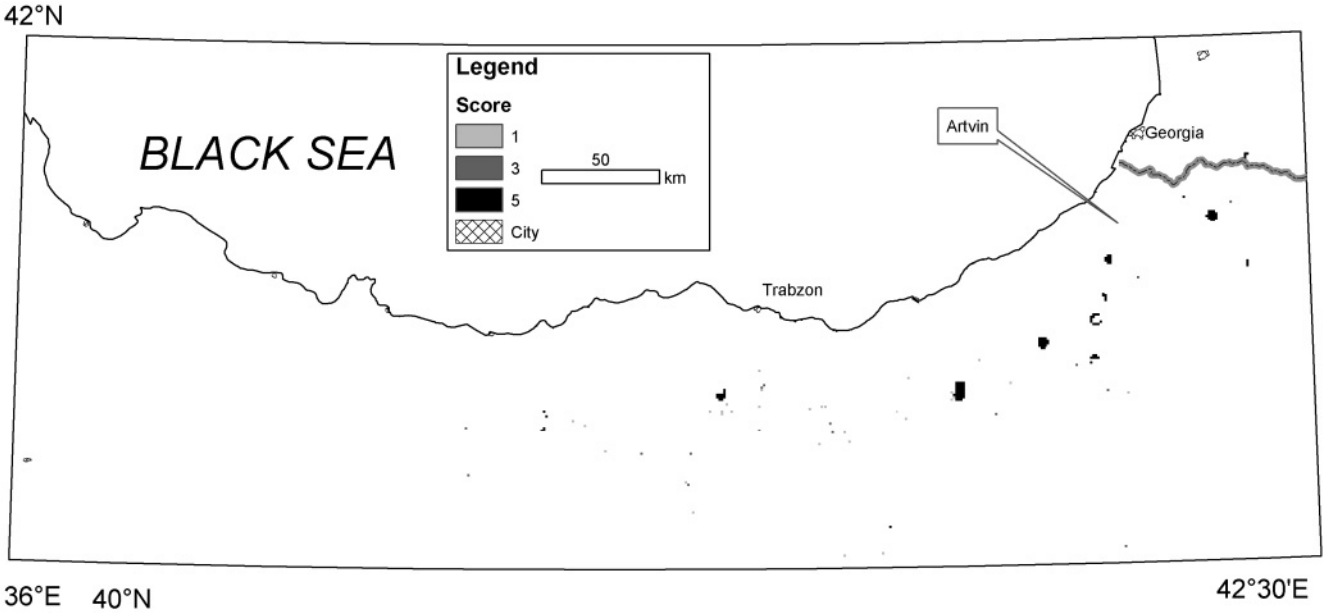

Fig. 16. Potential for surface degradation using weightings discussed in the text and a 2000-m height cut-off. Values are as in Table 2.

rain generation from pyrite roasting as well as large-scale open-pit mining. Acid mine drainage is strongly developed at a number of other VMS deposits, notably Kutlular and Lahanos. In contrast, the operation at Çayeli demonstrates what can be achieved by planning proactive cleaning of dust and off-site disposal of tailings. The location of the Cerattepe prospect is less favourable for tailings disposal and AMD will need to be carefully controlled if and when the deposit's development can be agreed.

Small-scale mining of vein deposits seems to be responsible for surface degradation, particularly in high altitude areas, but is not generally associated with AMD. Most problems result from small-scale operators who have insufficient capital to remediate sites. It is likely that the environmental impact of mining can be minimized at prospects such as Mastra by containment of dust and zero-discharge strategies for cyanide, as implemented at Ovacik. Perhaps more importantly, the full agreement and involvement of the local population is essential.

The localized studies emphasized the importance of climate and amount of sulphide. The GIS compilation highlighted areas for further detailed investigation in the east of the Pontides, particularly in the Artvin and Murgul areas

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