Low-cost geochemical surveys for environmental studies in developing countries: Testing a field portable XRF instrument under quasi-realistic conditions

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A B S T R A C T
Environmental monitoring, as a prerequisite for environmental risk assessment, is crucial in developing nations from Africa, Latin America, South East Asia, or Melanesia, where conspicuously most of the World’s mining activity concentrates. One of the most important environmental problems relates to the disposal of mine concentrates to river systems (e.g., Irian Jaya or Papua New Guinea). However, environmental monitoring is severely restricted in developing countries due to the chronic lack of funds. This paper explores the potential for a wider use of Field Portable X-Ray Fluorescence Spectroscopy instruments (FPXRFs) in fast, real-time, cost-effective environmental surveys for heavy metal dispersal in developing countries, where access to fully equipped geochemical labs is not usually a viable option. We simulated a scenario resembling conditions to be found in a remote region affected by mining-derived metal pollution where no proper laboratory facilities existed. We used an OXFORD X-MET 3000TX XRF analyzer under quasi-realistic conditions, relying solely on the instrument to allow geochemical characterization of a highly polluted Pb-Zn old mining district in the Alcudian Valley of central Spain. Our results for Pb, Zn, Cu, As, and Cd from 12 mine sites showed an excellent performance of the instrument, both under real-time and laboratory conditions. Furthermore, the instrument proved to be fit to endure a variety of field operational conditions and was able to deal with different types of samples, including tailings, soils, and stream sediments. Thus, taking into account the affordability of FPXRFs in relation to bench-top laboratory metal analyzers and their operational simplicity, we suggest that these portable instruments should become the equipment of choice for environmental monitoring in developing countries. In this respect, FPXRFs satisfy the system-independence criterion for sustainable development, i.e., the instrument can stand alone and do its job with few or no other supporting facilities or devices. We go further on these matters providing some hints on how FPXRFs could become widely available via international cooperation, and the technical and social benefits that such equipments could bring to foreign aid recipient countries.

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1. Introduction
Mining, concentration, and smelting of heavy metal ores (e.g., Pb, Zn, Cu, Ni, Co, etc.) are among the most pollutant industrial activities at a global scale. As noted by Ownby et al. (2005), many environmental and human health hazards worldwide can be attributed to past metal mining and smelting activities. In some regions pollution has been a well established phenomenon lasting millennia, either due to natural causes (e.g., the Elqui Basin, northern Chile: Oyarzun et al. 2004) or persistent mining through history (e.g., the Iberian Pyrite Belt in southern Spain, and Almadén in central Spain; Higueras et al., 2006; Leblanc et al., 2000). Not much can be done in these cases. However, a quick response focused on the evaluation of the extent and intensity of metal pollution derived from mine tailing accidents (such as that of Aznalcollar in Spain; Grimalt et al., 1999), can be dealt with in a few days at the most if the proper analytical equipment is available. Kalnicky and Singhvi (2001) showed that one of the critical factors for successfully conducting extent of contamination, removal, and remedial operations at hazardous waste sites is rapid and appropriate analytical support to analyze site samples in a timely fashion. They also contended that Field Portable X-Ray Fluorescence (FPXRF) instruments provide an effective analytical approach for many types of environmental samples. We here explore the potential for a wider use of FPXRF instruments in developing countries, where environmental monitoring is usually restricted due to the scarcity of funds to sustain specialized laboratory facilities and field teams of scientists.

This is not a paper aimed to compare either performance between bench-top and portable XRFs or between different models of portable XRFs. All this has been already discussed in the comprehensive papers of Kalnicky and Singhvi (2001) and that of the USEPA (2006). Our study is
focused on the practicalities of the use of a FPXRF instrument in simple and fast geochemical surveys under quasi-realistic conditions. We use the term ‘quasi-realistic’ for a model that can realistically simulate a sequence of real events (von Storch, 2003). Thus, we mimicked in central Spain a geochemical survey to be carried out in a remote region where no laboratory facilities existed. We run a pilot regional study focused on abandoned mine sites lacking land reclamation. We used an OXFORD X-MET 3000TX, a lightweight XRF analyzer for metals. The mines belong to the so-called Valle de Alcudia (Alcudian Valley from here onwards) district, where Pb, Zn and Ag were extracted during the late 19th, early 20th centuries (Palero-Fernández and Martín-Izard, 2005) (Fig. 1). The density of population of this Spanish realm is very low: 25 inhabitants per km², equivalent for example to that of Somali-land in eastern Africa. Given that Spain has neither an environmental agency in the way the USEPA (United States Environmental Protection Agency) is forged, nor a Superfund program (e.g., USEPA, 2010) the test was thus even more realistic.

This work goes beyond the mere practicalities of field analytical methods. During the last decade we have gained firsthand experience in Latin America (GEMM, 2010) on the difficulties faced by national environmental agencies (or equivalent institutions) regarding mining pollution. Thus, we also wanted to summarize the social and economic framework of some developing countries (e.g., Papua New Guinea, where major environmental disasters have taken place during the last decades), and provide some clues on: 1) how FPXRF instruments could be available for developing nations via international technical assistance and/or monetary aid; and 2) the social and scientific benefits that such equipments could bring to the foreign aid recipient countries.

2. Fully equipped labs versus FPXRFs: a matter of money and affordable state-of-the-art technology

2.1. Unaffordable costs and cost-effective potential solutions

There is always a critical factor regarding fast and efficient sampling-analytical procedures in areas affected by mining activities: money, or worse, the lack of it. Although the access to state-of-the-art laboratory installations is taken for granted in the developed countries, the less favored nations face enormous problems to detect and measure environmental disturbances created by the mining industry. From our experience at the Almadén School of Mines (ASM), a fully equipped laboratory for environmental geochemistry is usually expensive. For example, our new ASM geochemical lab involved a global investment (building and equipment) of about €950,000 (US$ 1,200,000) (UCLM, 2009). On the other hand, the cost of a portable XRF instrument is in the order of US$ 30,000 (e.g., NITON-XL800 and OXFORD X-MET). These instruments do not require expensive installations and cost a bargain compared to a fully equipped geochemical lab (see above). Even single bench-top XRF units are considerably more expensive (e.g., the price of a JEOL JSX instrument is around US$ 100,000), although they can typically detect a wider range of elements at higher sensitivity than portable units (Labcompare, 2010). In this respect, one may argue that US$ 30,000 is still a large sum of money for many environmental agencies from poor countries. However, we must take into account that developing nations are also net recipients of foreign aid, which is aimed to the transfer of capital, goods, or services. This aid is offered in several forms, and one of them is technical assistance and training, usually as grants in the form of human resources and technical equipment (Inaga and Mandah, 2008). Besides, one of the aims of the World Bank and OECD (lenders/fund donors) countries is precisely the reversal of negative environmental trends (Inaga and Mandah, 2008), and conspicuously, the international foreign aid is becoming progressively tied to environmental projects (Roberts et al., 2009).

Having said all this, we must make clear at this point that we are not implying that a portable XRF instrument will fully substitute for a well equipped geochemical lab. All we are saying is: 1) the analytical costs of environmental geochemical surveys can be reduced to a minimum (e.g., CLAIRE, 2008); 2) that field portable XRF instruments cost a fraction of bench-top metal analyzers; and last but not least 3) that environmental monitoring, as a prerequisite for environmental risk assessment, is not just a good idea but “a must” in developing nations from Africa, Latin America, South East Asia, or Melanesia,
where conspicuously most of the World’s mining activity and biodiversity concentrates.

2.2. On the use of FPXRFs: a brief introduction for the non specialist

FPXRF instruments have different configurations (Kalnicky and Singhvi, 2001). An older group incorporated a measurement probe connected to an electronics unit via a flexible cable. The older probes housed the detector and radioisotope source(s), whereas the electronics unit contained the microprocessor and data processing electronics. The upgraded group, to which our instrument (OXFORD X-MET 3000TX) belongs, consists of a single unit. Radiation shielding is provided by the manufacturer in accordance with regulations on manufacturing and licensing of radioactive devices. Besides, the manufacturer provides training in the safe and proper operation of the analyzer. Both groups of instruments have a minimum of 8 h of field use with replacement of batteries. Besides, in our case, the OXFORD X-MET 3000TX is very lightweight (1.8 kg only), having the following dimensions: 9.9 cm (W) × 28.3 cm (L) × 27.8 cm (H). All these specifications confer a truly field portable character to the instrument. Furthermore, modern field portable XRF analyzers enable researchers to determine metal concentrations both rapidly and easily, which provides an ideal approach for the assessment of metal-contaminated soils, sediments, and last but not least, abandoned tailing deposits that usually pervade the mining fields (Carr et al., 2008; Kalnicky and Singhvi, 2001; Oyarzun et al., 2010a). We shall return to this matter in the following sections.

3. The Alcudian Valley abandoned mines: the test sites

3.1. Geology and ore deposits

The Alcudian mining district (Fig. 1) covers an area of some 2500 km², and most of the ore deposits are Pb-Zn veins, with variable contents of Ag, Cu, Sn, W, As and Bi (Palero-Fernández and Martín-Izard, 2005). The mineral deposits are hosted by rock formations of Precambrian to Silurian age (Palero-Fernández and Martín-Izard, 2005). The Precambrian formations comprise very thick units (>8000 m) of greywacke and shale of Riphean age, and shelf facies of Vendian age. The Paleozoic series starts with Lower Ordovician shales, sandstone and quartzite with some conglomerate lenses at the base. The white Armorican Quartzite of Arenigian age is a regional marker. By the end of Ordovician times, sedimentation became more shale-rich. Basaltic diatremes are intercalated in the Ordovician sequence. The Silurian–Devonian series comprises a sequence of quartz-arenites, rhythmically interlayered sandstones and shales, black shales, alkaline basaltic rocks, and diatremes. The ore deposits are emplaced at different levels of the stratigraphic column, from Riphean to Silurian age (Palero-Fernández and Martín-Izard, 2005). Most of the deposits were very small, but some of them such as San Quintín (500,000 t of Pb metal), El Horcaco (300,000 t of Pb metal), and Diógenes (200,000 t of Pb metal) were important producers (Palero-Fernández and Martín-Izard, 2005).

3.2. Environmental disturbances

From a mineralogical and chemical point of view a major problem regarding the Alcudian mine sites relates to the abandoned tailing deposits (Fig. 2A). Tailings, if rich in pyrite, may be an active source of Acid Mine Drainage (AMD). However, given the Mediterranean climate of the region, instead of a permanent flow of AMD, what usually forms are seasonal poolsstreams of deep red to orange colored waters (Fig. 2B,C). In this respect, rainfall events cause both increases and decreases in acid and metal concentrations, and the process does not end until pyrite is fully weathered, which can take hundreds to thousands of years (Nordstrom, 2009). Long dry spells result in gradual increases in heavy metal concentrations, whereas sudden large increases are observed during initiation of rains. However, as precipitations reach their peak, the solutions become diluted (Nordstrom, 2009).

Taking into account that most of the Alcudian tailings were generated before froth flotation became a common concentration technology, the sulfides were gravitationally concentrated with jigs, an inefficient procedure in older times that left metal-rich tailings throughout the Alcudian district (Tables 1,2). Furthermore, some of the dumps are in fact mixed tailings-waste rock (MTWR) deposits, which reveals the absence of good practices even for the late 19th, early 20th century standards.

4. Methods

4.1. Sampling and sample preparation procedures

In order to approach a quasi-realistic scenario we chose to survey a number of abandoned mine sites to test time-efficiency and instrument versatility via two types of procedures: 1) sampling-only visits to the mine sites (2–3/day) (Fig. 3A); and 2) sampling–real-time analysis of soils, stream sediments, and tailings in one of the largest mining sites (San Quintín) (Fig. 3B). Given that the topsoil is the most important part of the soil profile for degradation control (FAO, 1998), we concentrated our efforts on this superior horizon (5 to 30 cm). In the sampling-only case we sampled tailings, waste rock, and mixed tailings-waste rock (MTWR) deposits using either an auger tube kit for up to 50 cm long samples (tailings), or a simple shovel (soils/sediments) and pick (if required) for soils and stream sediments. The latter was also used as a standard procedure during sampling and real-time analysis of samples. The samples from the first group were stored in double density plastic bags (3–5 kg of sample), and latter milled, and ground to a grain size of <150 μm. For the sampling–real-time analysis test we took some 1.5 kg of sample (soil, sediment or tailings materials), we removed the topsoil rock fragments and roots (if present) by hand and stored the sample in double density plastic bags. While the samples from the first group were taken at random, for the second group at San Quintín we used regular grids (Fig. 4A) or followed the stream patterns, both with the aid of a Garmin (Gpsmap 60 CS series) GPS uploaded with a 1:25,000 basemap from TOPO España.

4.2. Analytical procedures

To study different instrumental conditions, we used our FPXRF instrument in two different ways: 1) as a lab integrated instrument (set up for bench-top analysis) to analyze metals at the ASM Geochemical Laboratory (Fig. 3C); we used this procedure for the sampling-only test sites (see above); and 2) as a truly field portable instrument for in-situ measurements (Fig. 3D,E). Our OXFORD X-MET 3000TX is presently certified by OXFORD Instruments to analyze heavy metals in soils following the USEPA method 6020. The certified dynamic ranges for the studied metals are (data in μg g⁻¹): Pb (0, 2342); Zn (4, 6791); Cu (0, 3584); As (0, 754); and Cd (0, 1000). Quality control at the ASM geochemical lab is done by analyzing duplicate samples to check precision, whereas accuracy is obtained by using the certified standards (SRM NIST 2710, (SRM NIST 2711, and BCR 146R. Precision and accuracy for the studied elements are (in %): Pb (0.2, 89.8); Zn (0.5, 99.9); Cu (3.5, 96.7), As (3.5, 98.1), and Cd (6.2, 98.2). Operational metal detection limits for the instrument are (data in μg g⁻¹): Pb: 46, Zn: 9, Cu: 8, As: 1, and Cd: 1. The OXFORD X-MET is a fully portable instrument and can be operated in the hand-held mode at a sampling site with a good overall performance (USEPA, 2006), allowing metal identification and quantitative measurement of concentration. The OXFORD X-MET analyzer uses a Hewlett-Packard (HP) iPAQ personal data assistant (PDA) for data storage of up to
10,000 tests with spectra in its 64 MB memory. Besides, the instrument can analyze elements from sodium to uranium in suites of 25 elements simultaneously (USEPA, 2006). Under laboratory conditions (Fig. 3C), the measurement time is 240 s/sample, and for field, in-situ conditions 40 s/sample (Fig. 3D;E). Although a comparison between field portable and bench-top XRF instruments is beyond the scope of our work, it is worth mentioning here the results from the comprehensive work of Kalnicky and Singhvi (2001) on this matter. They state that field portable instruments are generally less sensitive (they have higher detection limits) than laboratory methods, however the results are sufficient to meet site action level requirements in most cases, in accordance to the strict regulations from the US OSHA (Occupational Safety and Health Administration). Thus, if FPXRF instruments can achieve this level of excellence, then it follows that definition of geochemical anomalies for environmental purposes is well within their range of possibilities. Further results are shown in the comprehensive test of the OXFORD X-MET analyzer ordered by the USEPA (USEPA, 2006). In any case, we are not judging here the instrument in its capacity to finely analyze trace elements for scientific purposes, but to generate rapid, real-time assessments of environmental accidents involving heavy metal dispersal. These will usually result in spilled materials with metal concentrations more in the range of hundreds to thousands μg g⁻¹ than a few ones. In this respect, our tests showed that the OXFORD X-MET analyzer easily
Pinpointed the extreme highs and lows in metal concentrations when dealing with metal-rich and baseline samples respectively (Tables 1,2).

5. Results and discussion

5.1. Geochemistry of mine wastes and formation of AMD in the Alcudian mines

The keys for the understanding of environmental disturbances in the abandoned Alcudian mines, other than visual impacts, are: 1) the chemistry of the tailings and MTWR deposits (Fig. 2D,E), some of them still having almost commercial grades of Pb and Zn, with high concentrations in the range of 10^3 to 10^4 μg g⁻¹ (Tables 1,2); 2) the chemistry of sediments from seasonal AMD streams, with extreme concentrations of Pb and Zn of up to 27,000 and 6150 μg g⁻¹ respectively. (Fig. 2B,C) (Tables 1,2); and 3) the chemistry of anthrosols, with up to 60,000 μg g⁻¹ Pb and 16,000 μg g⁻¹ Zn (Tables 1,2). Cu, As and Cd are also high, with concentrations well above world baselines (Table 2).

For many reasons the Alcudian tailing deposits can be regarded as soil-like materials. For example, vegetation grows on top of some of the tailings of artifical origin, these poorly consolidated materials can be perfectly ascribed to the technosol category of Rossiter (2005). These deposits of artificial origin, these poorly consolidated materials can be perfectly ascribed to the technosol category of Rossiter (2005). The keys for the understanding of environmental disturbances in the abandoned Alcudian mines, other than visual impacts, are: 1) the chemistry of the tailings and MTWR deposits (Fig. 2D,E), some of them still having almost commercial grades of Pb and Zn, with high concentrations in the range of 10^3 to 10^4 μg g⁻¹ (Tables 1,2); 2) the chemistry of sediments from seasonal AMD streams, with extreme concentrations of Pb and Zn of up to 27,000 and 6150 μg g⁻¹ respectively. (Fig. 2B,C) (Tables 1,2); and 3) the chemistry of anthrosols, with up to 60,000 μg g⁻¹ Pb and 16,000 μg g⁻¹ Zn (Tables 1,2). Cu, As and Cd are also high, with concentrations well above world baselines (Table 2).

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All these are unchecked phenomena, and little or nothing has been done to prevent further environmental hazards regarding these matters. A sound policy on land reclamation is urgent for the whole Alcudian district, and in this respect, let us stress that garden-like restoration of a polluted site will not solve the many environmental hazards associated with heavy metals and metalloids, neither at the

<table>
<thead>
<tr>
<th>Element (μg g⁻¹)</th>
<th>Pb</th>
<th>Zn</th>
<th>Cu</th>
<th>As</th>
<th>Cd</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alcudian mining district</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tailings and MTWR deposits¹</td>
<td>15175.3</td>
<td>8175.2</td>
<td>710.4</td>
<td>422.6</td>
<td>233.2</td>
<td>This work and Azañón Fernández-Trejo et al. (2009)</td>
</tr>
<tr>
<td>Soils²</td>
<td>2209.1</td>
<td>2447.9</td>
<td>209.1</td>
<td>36.1</td>
<td>70.8</td>
<td>&quot;</td>
</tr>
<tr>
<td>Baseline soils³</td>
<td>234</td>
<td>113</td>
<td>10</td>
<td>24</td>
<td>&lt;DL</td>
<td>This work and Alvarez Cachafeiro et al. (2010)</td>
</tr>
<tr>
<td>Stream sediments⁴</td>
<td>1783.5</td>
<td>3117.3</td>
<td>201.4</td>
<td>27.8</td>
<td>8.4</td>
<td>This work and Chicharro Alvarez et al. (2010)</td>
</tr>
<tr>
<td>Baseline stream sediments⁵</td>
<td>66</td>
<td>20</td>
<td>&lt;DL</td>
<td>26</td>
<td>&lt;DL</td>
<td>&quot;</td>
</tr>
<tr>
<td>World averages for soils and stream sediments</td>
<td></td>
<td></td>
<td></td>
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<td>Selected average for soils</td>
<td>32</td>
<td>13–24</td>
<td>5.8</td>
<td>0.06–1.1</td>
<td>Alloway (2005)</td>
<td></td>
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<tr>
<td>World soils</td>
<td>30</td>
<td>66</td>
<td>22</td>
<td>0.06</td>
<td>Callender (2004)</td>
<td></td>
</tr>
</tbody>
</table>

Table 2
Mean concentrations of elements for different data sets and baseline samples. ¹: Most mining sites (Table 1). ²: San Quintín East. ³: Topsoil sample away from the San Quintín mining site. ⁴: Stream sediments from San Quintín and Diógenes. ⁵: Stream sediment sample away from the San Quintín mining site. The term baseline is used here to show the local geochemical background of an element, in a sector not directly affected by the mining activity, within a distance of ~0.3–1 km.

Fig. 3. Sampling and analytical instruments. A: Sampling a tailing deposit at Veredilla. B: Sampling soils at San Quintín. C: The OXFORD X-MET 3000TX lightweight XRF analyzer set up for bench-top analysis. D: Analyzing samples in the field with the OXFORD X-MET 3000TX. E: A detail of the instrument depicting the Hewlett-Packard IPAD PDA for real-time data storage and reading.
Alcudian Valley nor anywhere elsewhere equivalent conditions are found (e.g., Martínez-Coronado et al., 2011; Oyarzun et al., 2010b). We may hide the contaminated land with clean topsoil, we may even plant some flowers and trees, but the problem will not fade away. Metals and metalloids will keep contaminating aquifers, and if erosion is not kept at bay, the metals will eventually find their way to the water courses. Given that the region is subjected to strong flash flood phenomena, the latter is likely to happen.

5.2. On the practicalities and benefits of FPXRF instruments

The OXFORD X-MET 3000TX allowed clear identification in San Quintín (Fig. 1) of Pb–Zn anomalies from the older tailing deposits (Fig. 4A–C), remnants from an era when mineral concentration was very inefficient. But far more important, the instrument allowed chemical differentiation between these deposits and a large modern one, from a time (1973–1988) when froth flotation was already a common practice. However, as shown by the instrument, flotation and concentration were far from perfect (Fig. 4C). Sampling-only procedures were also revealing in many aspects. As shown above, this method has the advantage of sampling more than one site per day (Table 3), although no geochemical information is retrieved from the field. Whatever the case, whether one procedure or the other is chosen, one thing is clear: geochemical characterization of several mine sites can indeed be achieved in a few days (Table 3). These time-saving strategies could prove to be crucial under real circumstances, for example, if a remote region becomes affected by a mine tailings accident, with several sectors of a river system becoming polluted by metal-rich wastes. In this respect, FPXRF instruments can prove to be most helpful for decision making on short notice in order to prioritize pollution removal and remediation actions in differently affected areas. We examine a real case scenario in the next sections.

5.3. Training personnel: lessons from San Quintín

We have had a long lasting experience with San Quintín (Fig. 1), a mining-environmental test site from the Alcudian district that proved to be inspirational for this work. Given the level of abandonment of mining waste deposits and seasonal development of AMD (Fig. 2A–C), the site has an extraordinary educational value for both under- and post-graduate students that attend training courses on environmental issues (López García et al., 2010). This is the reason why San Quintín provides important clues regarding field training on geochemical surveys, and more important, how long such training may take. The students are taught on how to design and carry out geochemical surveys (soil and stream sediments), perform measurements of pH and Eh in the waters of nearby streams, measure gaseous mercury in air, and study the mineralogy of mining wastes (Oyarzun et al., 2010a). The last two years have been mostly devoted to students from the UCM (Madrid Complutense University) Master’s degree on Environmental Geology and Mineral Resources (Departamento de Cristalografía y Mineralogía, 2010). Teams of three to four students can complete comprehensive surveys in about 8 h, including field geochemical analyses of soil or stream sediments, within an area of ~500,000 m² (Table 3). Given their initial lack of experience on this type of surveys, including field positioning with the aid of GPS, this is quite an achievement. This experience also provides hints on what the personnel from local environmental agencies from developing countries could do if some basic training is provided on these matters. Besides, one should be reminded that it does not take a university degree to operate a modern technological device. As shown by the work of Blake et al. (2002) in Africa, even semi-literate trackers can operate a computer device to gather complex data on animal behavior providing that the interface is adapted to their skills. In this respect, we are neither implying here that a portable XRF instrument can be properly operated by illiterate people, nor that anyone can design a sound geochemical survey. What matters nonetheless is that the number of people capable of being trained on these matters can be much higher than initially expected, which is crucial in countries having a chronic shortage of technicians and/or university graduates.
in sciences (e.g., Birdsall, 1996). In this respect, one of the authors (R.O.) had firsthand experience in the early 1970s with a system devised by the Anconda Copper Company and later followed in these years by CODELCO (Corporación Nacional del Cobre) at the El Salvador copper mine (northern Chile). Unskilled miners with a potential for more complex tasks were progressively trained up to the level of becoming highly skilled technicians in the fields of ore microscopy and petrography, and X Ray Diffraction at the labs of the Geology Superintendence.

5.4. Tailings and environmental hazards in developing countries: potential scenarios for the use of FPXRF instruments

We focused our test on a district pervaded by old mining waste deposits, because tailing deposits represent one of the most acute environmental problems worldwide. This is a particularly sensitive case in tropical mountainous regions, where some of largest mines of the World are operated. In this respect, one of the most typical examples of the difficult relationships between mining and the environment is provided by the large copper–gold mines operated at Papua New Guinea (Ok Tedi and Porgera) and Irian Jaya (Grasberg) (Fig. 5). Apart from cultural and political conflicts, the single most important problem relates to the disposal of mine concentrates to the river systems (Banks, 2002). These mines are emplaced at high altitude and face enormous problems regarding tailings (and other wastes) disposal within a challenging landscape. This industrial–environmental scenario is aggravated by the existence of rich ecosystems at both high (cold mountainous) and low altitudes (tropical rainforest) (Fig. 5). Moreover, the mining industry in these two countries (Irian Jaya is part of Indonesia) is a central part of their economies. For example, as indicated by Banks (2002), the formal economy of Papua New Guinea is dominated by the mining and oil sector, which has made up approximately 70% of exports and accounted for 25% of the gross domestic product for the last three decades. Besides, according to the Secretariat of the Pacific Regional Environmental Program (SPREP, 2010) only a few Pacific countries and territories have specific environmental acts and associated regulations, and even fewer have laws and regulations that deal with specific aspects of pollution, such as waste management.

The environmental situation is so bad in Papua New Guinea that even the mining company operating the OK Tedi copper mine recognizes that an average of 90 Mt (million tons) per year of tailings, overburden and mine-induced erosion are discharged to the Ok Tedi river from the mine (OK Tedi Mining, 2008). About 50 Mtr of these materials reach the Fly River, having significant impacts on the river system. The question is what can be really done by a country with a GDP per capita of about US$ 2300, ranking 137 in world at GDP purchasing power parity (CIA, 2010). In this respect, one of the main constraints regarding environmental monitoring in Papua New Guinea relates to its limited financial resources. Regarding this matter, the allocation of inadequate resources to the regulatory authorities creates an additional constraint in the form of an imbalance in access to monitoring information between the developers and the regulators (ESCAP Virtual Conference, 2010). The Papua New Guinea case is neither new nor an isolated one, and this is the reason why fast, reliable, cost-efficient, and affordable geochemical monitoring is so important. Given that tailings disposal is also performed underwater at Papua New Guinea (Coumans, 2002), monitoring coastal sediments may also prove to be crucial.

6. Conclusions

We have shown that FPXRF instruments can perform well in environmental surveys for heavy metal pollution in large mining districts. We have also rendered new and updated information regarding FPXRF versatility to operate under both field and laboratory conditions depending of what is required from a time-efficient viewpoint. Thus, the following keywords should be highlighted here, real-time data, cost-effective technology, affordability. Environmental disasters involving heavy metal dispersal require immediate action to
assessment and intensity, and real-time field geochemical data can provide both. Besides, composite samples can be taken from several distant sites at a good rate (Table 3). In this respect, FPXRF instruments can also help with decision making regarding which contaminated areas should be dealt with first. Besides, the instrument would be also helpful to check afterwards whether the cleaning up of the hazardous wastes has been properly carried out or not. Regarding cost-effective technology, few analytical technologies offer so much for so little (e.g., CLAIRE, 2008). Affordability is the complex term here, because the price of FPXRF instruments is still somewhat high for environmental agencies struggling to survive in many developing nations. However, if lending and/or donor institutions are indeed interested in the reversal of negative environmental trends in these nations (e.g., Inaga and Mandah, 2008), then it follows that FPXRF instruments could then become the geochemical analyzer of choice of local environmental agencies. This could prove to be enormously more cost-effective than other, expensive solutions that could shortly fall into oblivion if the international aid runs dry. For example, improved conditions in laboratory facilities in Africa have come at a high price including continued dependence on foreign donors, who presently contribute with 99.9% of the required funding (Nordling, 2010). In this respect, we should here consider the systems-independent criterion for sustainable development, which relates to the ability of a technological device to stand alone, to do its job with few or no other supporting facilities or devices to aid in its function (Wicklein, 2004); otherwise the introduced technology may end up being (as in an old Spanish saying): bread for today, hunger for tomorrow.

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