

6-2012

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Erin M. Delman

Union College - Schenectady, NY

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The History of Mining in Cerro de Pasco and
Heavy Metal Deposition in Lake Junín Peru

By Erin Delman



Submitted in partial fulfillment
of the requirements for
Honors in the Departments of Geology and Latin American and Caribbean Studies
UNION COLLEGE
June, 2012

ABSTRACT

DELMAN, ERIN The History of Mining in Cerro de Pasco and Heavy Metal Deposition in Lake Junín Peru.

Departments of Geology and Latin American and Caribbean Studies, June 2012

ADVISORS: Donald Rodbell, Daniel Mosquera

Lake Junín covers 530-km² and is located at 4,430-m in an intermontane basin between the eastern and western cordillera of the central Peruvian Andes. The lake sits between the large sulfide mining districts of La Oroya and Cerro de Pasco. Designated a National Reserve in 1974, Lake Junín drains northward to the Río San Juan, which joins the Río Mantaro within several kilometers of the lake. Dam construction by the Cerro de Pasco Copper Corporation on the Río Mantaro in 1932 caused the Río San Juan, the principal river draining Cerro de Pasco, to back up into the lake. Using an ICP-MS, this report documents the contamination of Lake Junín with Co, Cu, Zn, Pb, Fe, and Mn; constrains the timing of the heavy metal pollution by correlating the $\delta^{18}\text{O}$ record of a Lake Junín Core with a core from nearby Lake Pumacocha; and quantifies the contribution of heavy metals delivered via surficial runoff by comparing metal concentrations in Lake Junín sediments with those of Lake Pumacocha, which receives heavy metals only through atmospheric deposition and airfall. We analyzed six sediment cores, and the results reveal dramatic peaks in most metal concentrations at depths ranging from 10-55 cm below the sediment surface. Comparison of the sediment record from Lake Junín with Lake Pumacocha indicates that metal laden sediment transported into Lake Junín from the Río San Juan has formed a deposit with concentrations at least one order of magnitude greater than lakes that received only atmospherically transported metals.

INTRODUCTION

It is difficult to conceive life without iron, aluminum, copper, zinc, lead, gold, or silver. These and other metallic resources have been mined from the Earth for centuries, allowing for the rapid advancement of human civilization. Yet as the global population increases and standards of living advance, so does the demand for metals; the United States alone uses more than three times as much copper and four times as much lead and zinc today than 75 years ago (Hudson et al. 1999). Ultimately, society's progress will be limited by its inability to satiate its need for natural resources. Therefore, metal mining – the industry responsible for extracting metals from the Earth – will continue to be necessary (Hudson et al. 1999).

Regardless of our dependence on metal resources, the very nature of the extraction industry renders environmental damage inevitable. The operations and waste products associated with the mining and processing are the principal causes of ecological concern, particularly the physical disturbance of landscapes, the increased acidity of soils, the prevalence of air-borne dust and other emissions, and the degradation of surface and groundwater quality (Hudson et al. 1999). The negative externalities of mineral extraction, however, are not equitably distributed; rather, it is often the impoverished and underrepresented communities of the developing world that are most strongly impacted by mining operations (LAOEC 2007).

One such example is Cerro de Pasco, a city of 70,000 residents in the central highlands of the Peruvian Andes (Figure 1). At 4,430 m elevation, Cerro de Pasco is exceedingly important to the Peruvian economy due to its extensive, multi-century history of metal extraction. Although the Cerro de Pasco mine historically produced

copious amounts of copper, the 1.8 km-long open pit operation – run by the Peruvian-owned Volcan Compañía Minera S.A.A – currently yields substantial quantities of lead, silver, and zinc (Gurmendi 2009).



Figure 1: Shows the location (red box) of Cerro de Pasco in Peru.

Despite the economic vitality of the Cerro de Pasco mine, the processing and smelting raise substantial concerns for local human and environmental health. This report will focus on the latter by studying the impact of Cerro de Pasco mining on the limnology of Lake Junín (530 km²), located in a watershed that includes the mine. Declared in a state of emergency by the Peruvian government in 1999, Lake Junín has been publicly and widely recognized as polluted, and mining activity is the primary suspect (Shoobridge 2006). Still, very little empirical data exists to correlate regional mining activity and contamination of the lake. Analysis of Lake Junín sediments, as well as a comparison with those from the nearby Lake Pumacocha, verifies exorbitantly high concentrations of heavy metals in Lake Junín, elucidates their potential origin and

transportation method, and highlights crucial discrepancies in the relationship between the mine and the town, thus explaining the environmental injustice that ensues.

A MINING HISTORY OF PERU

The South American continent is a major producer of base and ferrous metals, and the Andes represent the largest source of mineral wealth in the Americas. Thus, it logically follows that this mineral-rich region fostered the advent of New World metallurgy (Cooke et al., 2007). When Francisco Pizarro conquered Peru from the Incas in 1553, he found a longstanding legacy of metallurgy and mining activity spanning almost a millennium (Cooke et al., 2008). Prior to the arrival of the Spanish conquistadores, the Wari and then Incan Empires smelted silver, hammered gold, and annealed copper independently of European technologies (Cooke et al., 2008). In 1545, an Indian named Diego Gualpa discovered what was to become “Spain’s great treasure house in South America”: the mineral mines of Potosí (Klarén 2000).

In its first ten years, the Potosí mine, now within the Bolivian borders, produced 127 million pesos for Spain, fueling the Hapsburg war machine and Spanish hegemonic pretensions in Europe (Klarén 2000). Furthermore, the Potosí mines set a precedent that mining would play a pivotal role in Peruvian economy. One Peruvian viceroy was quoted saying, “if there are no mines, there is no Peru.” By 1600, Potosí was producing over half of Spanish American silver (Klarén 2000). Despite continued to grow throughout the 17th and 18th centuries, the silver mines of lower Peru, particularly those at Cerro de Pasco, quickly overshadowed the importance of Potosí.

Like much of southern South America, pre-colonial mining also occurred in Cerro de Pasco, with the earliest evidence for anthropogenic lead (Pb) enrichment at ca. A.D. 600 (Cooke et al., 2009). Discovered by the Spanish in 1630, the Cerro de Pasco district is located 190 km northeast of Lima on the Andean plateau (General Science Collection, 1997). The district lies east of the continental divide and west of the Cordillera Oriental (General Science Collection, 1997). One of the most extensively worked districts in Peru, Cerro de Pasco produced 11.2 million pesos in the last five years of the 1700s, far surpassing the silver output in Potosí (Hunefeldt 2004).

The Peruvian War of Independence (1809-1824) temporarily crippled the silver industry at Cerro de Pasco, with a nadir in production occurring between 1814 and 1818. The patriotic and royalist armies alternatively occupied the region during the war, and the final battles for independence took place amongst the silver mines, symbolic of past colonialism and future prosperity. Following the retreat and withdrawal of the royalist military, the agrarian *hacienda* owners fled the region, allowing for the rapid acquisition of land by mine owners and a general increase in output (Hunefeldt 2004). In the first two decades of the post-independence period, Cerro de Pasco produced 65-percent of Peruvian silver (up from 40-percent), despite the fact that most of the 558 mines and 1,000 excavations were small- to medium-scale operations, scattered over a broad territory, and maintained using rudimentary technology and few indigenous laborers (General Science Collection 1997; Klarén 2000). The success of the Cerro de Pasco silver operation was so vast that without it, Peru would have been unable to engage in international trade. The population of the city circumventing the mine grew to accommodate the rapid development, peaking at approximately 18,000 residents in 1840

(General Science Collection 1997); similarly, outlying areas, including Huanuco, Tarma, Mantaro, and Lima, were integrated into Cerro de Pasco's economic life (Hunefeldt 2004).

To support the mining industry, a central railway was constructed between Lima and La Oroya in the late nineteenth century (Klarén 2000). The railroad allowed for the transition to a new unit of production: copper (Becker 1983). The Cerro de Pasco copper industry began in 1896, when a group of New Jersey investors from the Backus and Johnson Company garnered the title to a small copper mine and smelter at nearby Casapalca. The following year, a North American engineer, William A. McCune, explored the cordillera searching for copper, and he found plenty of it amongst the exhausted silver ores of Cerro de Pasco (Becker 1983). More importantly, however, McCune also found local mine owners willing to sell out. The Cerro residents chose to sell based on the price and different assessments by local and U.S. mining interests of the future prospects of the industry, not through forceful coercion or economic crisis (Klarén 2000). Thus, upon his return from Peru, McCune helped organized a syndicate (1900-1901), composed of J.P. Morgan and James B. Haggin, to finance the Peruvian copper venture. Named the Cerro de Pasco Investment Corporation, a name that changed in 1915 to the Cerro de Pasco Copper Corporation, the company initially capitalized at \$10 million (Becker 1983).

La Compañía, as it came to be known, experienced early strokes of luck that facilitated long-term success. The 1901 Mining Code countered a 350-year old tradition of state ownership of mineral rights, instead appealing to foreign interests by declaring that any resident of Peru was eligible to own titles. The first Cerro copper smelter was

constructed in 1906 near the Cerro de Pasco town, and the corporation purchased Backus and Johnson's mine holdings in 1919 (Becker 1983). Cerro's landholdings, originally totaling about 60 hectares, grew to over a thousand hectares by 1920 (Becker 1983).

The volume of ore production at Cerro de Pasco soon justified the construction of a large central smelter, completed in 1922. By 1931, the Cerro smelter held complete monopoly over the refining of nonferrous metals in Peru (Becker 1983). The following year, the Cerro de Pasco Copper Corporation constructed the Upamayo Dam on the Río Mantaro, which began to generate hydroelectricity for the mine's extraction and processing operations in 1936 (Shoobridge 2006). The acquisition of land and machinery allowed the administration to expand Cerro's operation to include lead and zinc by 1952 (Klarén 2000). The rapid industrial growth turned *la Compañía* into Peru's largest private employer and landowner; by 1908, Cerro employed a third of the country's mine labor force (5,166 people), a value that swiftly grew to 14,816 by 1973 (Becker 1983), and during its peak, the company owned 325,000 hectares of land (Klarén 2000). Although all major decisions occurred in the boardroom of the New York headquarters, 50-60% of profits earned between 1916 and 1937 were returned to the Peruvian state. By 1973, the last year in which the Cerro de Pasco Copper Corporation operated as a private concern, Cerro generated \$228.3 million in exports, and paid \$34.1 million in taxes to the Peruvian state.

Political turmoil again disrupted production in the region during the second half of the 20th century. On October 3, 1968 Juan Velasco Alvarado led a bloodless coup d'état against President Fernando Belaúnde. The military junta lasted until 1975 and was characterized by vast left-leaning policies, including rampant nationalization of private

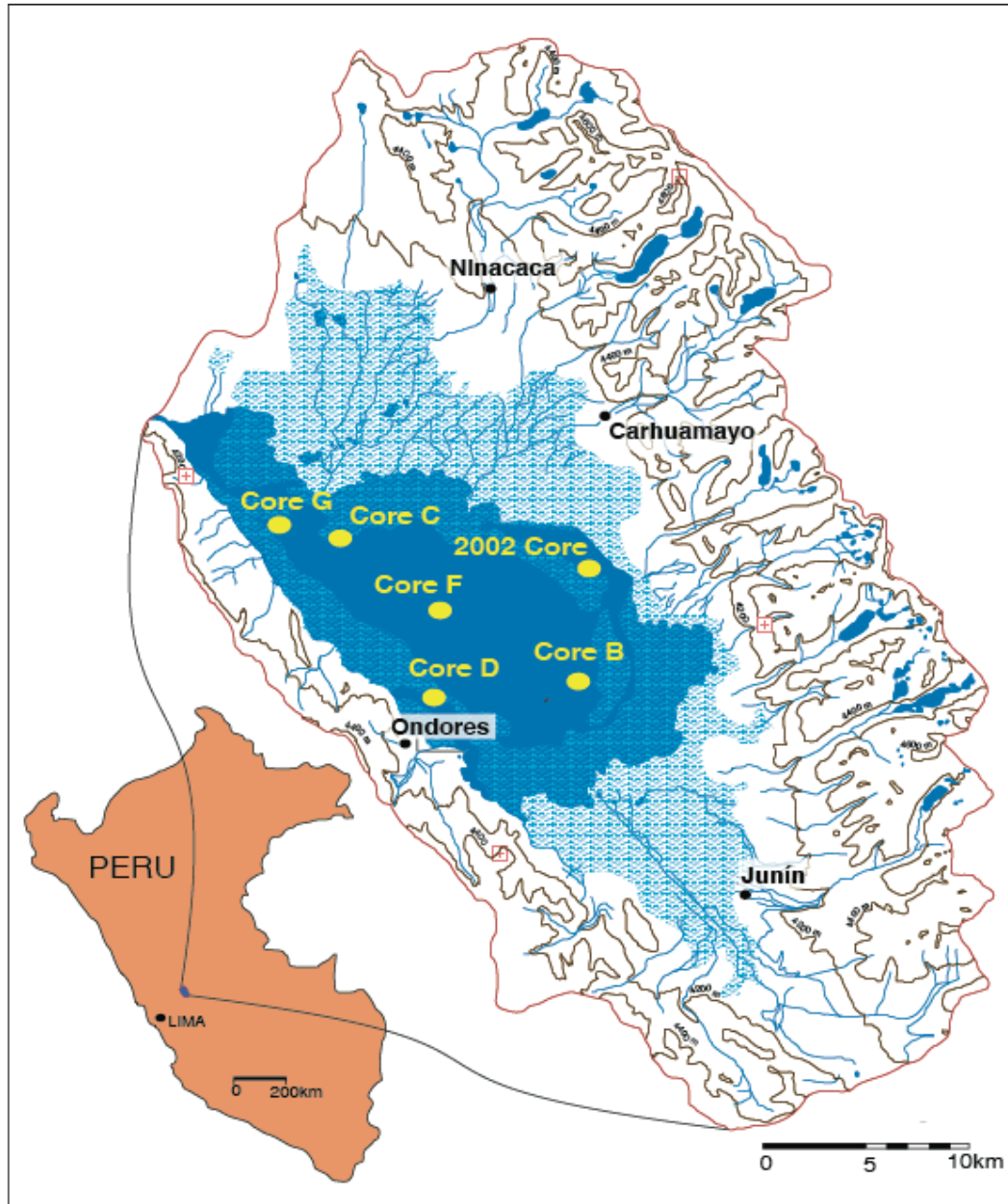
industries; *la Compañía* underwent expropriation between 1971 and 1973 and became the state-owned Centromín (Klarén 2000). Unfortunately, Centromín proved less successful than its privately-owned counterpart, but deregulation measures in the 1990s allowed for the reacquisition of the mine by the private sector, via the Peruvian based company Volcan Compañía Minera S.A.A (Gurmendi 2009). Volcan purchased Cerro de Pasco at public auction for US\$62 million in cash, plus an investment of US\$70 million as per the privatization commitment, in 1999 (Volcan 2010). The company has been economically successful, with US\$973 million in sales and a net profit of \$272 million in 2010. Volcan is currently a leading Peruvian producer of zinc (359,398 MT in 2010), lead (73,106 MT in 2010), and silver (20,083,356 MT in 2010) (Volcan 2010). There are current discussions about expansion of the open pit and further exploration of underground mines.

LAKE JUNÍN

Lake Junín, also known by its Quecha name, Lake Chinchaycocha, is a 530-km² lake located in the far northeastern pampas of Junín (10°S) between the Cordillera Oriental and the Cordillera Occidental (Figure 2) (Shoobridge 2006, Seltzer 2000). The second largest lake in the country, Lake Junín is bordered by the 53,000-hectare Junín National Reserve, which was established in 1974 and lies within both the Junín Province of the Junín Region and the Pasco Province of the Pasco Region (Shoobridge 2006). At an elevation of approximately 4,430-m, Lake Junín drains northeast into the Río Mantaro, one of the principal Andean tributaries of the Amazon Basin. Overall, the hydrologic system of the Mantaro River Basin, which includes Lake Junín, consists of 12 rivers and 20 streams (Shoobridge 2006).



(a)



(b)

Figure 2: (a) Shows the Google Earth image of Lake Junín and Lake Pumacocha, a nearby glacial lake in the highlands of central Peru. The Río San Juan becomes the Río Mantaro at the Upamayo Dam, and the river continues southward, adjacent to the lake. (b) Shows the locations of the six cores – Core G, Core C, Core F, the 2002 Core, Core D, and Core B – taken in 2002 and 2008. Lake Junín used to drain to the Río San Juan toward the northwest, but the construction of the Upamayo Dam on the Río Mantaro in 1932 caused the Río San Juan to back up into the lake, which greatly elevated the water level. The differences in the water level are seen in the different blue shading.

The lake formed when glacial outwash fans and moraines dammed the drainage of the Junín Plain before 40,000 ^{14}C yr B.P. (Seltzer 2000). The climate in the region is

characteristic of the lower puna, with temperatures vacillating between 3 and 7 degrees and an annual rainfall of 940 millimeters, predominantly between December and April (Shoobridge 2006). Lake Junín drains northeastward, initially into the Río San Juan, above the Upamayo Dam, below which marks the beginning of the Río Mantaro. The water depth is relatively shallow, reaching a maximum depth of ~12-m (Shoobridge 2006, Seltzer 2000).

The lake historically supported a substantial level of biodiversity, although the biologic variety has recently declined. The dominant vegetation surrounding the lake includes high, dense puna grasslands and high Andean wetlands. At least 1,460 plant species from 120 families and 560 genera exist within the Mantaro River basin (Shoobridge 2006). Within the lake, submerged aquatic plants such as *Myriophyllum quitense*, *Elodea potamogeton*, *Potamogeton ferrugineus*, *Potamogeton filiformis*, *Utricularia* sp., and algae, such as *Chara fragilis*, *Scytonema* sp. *Zygnema* sp., and *Mougeofia* sp. reside (Shoobridge 2006). Floating plants such as *Lemna* sp., *Spirodela* sp., and *Azolla filiculoides* also are prevalent (Shoobridge 2006). Just offshore, cattails form extensive communities, with two species that reach approximately two meters in height (*Scirpus californicus* var *tatora* and *Juncus articus* var *Andicola* v). The lake is surrounded by high Andean wetlands and puna grasses.

With regards to fauna, no species proves as important to the National Reserve as birds (O'Donnel 1997). The birdlife of Lake Junín is the richest of all high Peruvian wetlands, equaled only by that of Lake Titicaca (O'Donnel 1997). Both endemic and migratory birds frequent the lake. One endemic species, the Junín grebe (*Podiceps taczanowskii*), is on the brink of extinction, and thus proves particularly vulnerable to

changes in the ecosystem (O'Donnel 1997).

Mammals are scarce, although the Andean fox (*Pseudalopex culpaeus*), the long-tailed weasel (*Mustela frenata*), the hog-nosed skunk (*Conepatus chinga*), the vizcacha (*Lagidium peruvianum*), pampas cat (*Onicifelis colocolo*), and the mountain guinea pig (*Cavia tschundii*) all survive within the reserve and rely on the lake for water (Shoobridge 2006). The Junín frog (*Batrachophrynus macrostomus*), valuable to the regional indigenous people, is locally extinct at the lake due to hunting, pollution, and temperature changes (Shoobridge 2006).

CAUSE FOR CONCERN

The Junín National Reserve was founded with the intention to integrate ecosystem conservation with the socioeconomic development in the region, particularly through the extraction of its mineral resources (Shoobridge 2006). Despite a governing body and master plan, the goals of the Reserve – mainly the general policy of restoring the value of the area, protecting the natural scenery, and facilitating its traditional use according to legal regulations – have not been met, and the lake is in a state of disrepair that necessitates exigent action.

The local people have long protested the environmental dilapidation of the lake, although their complaints are founded only in observation. For example, the water remains a brick red year round at the inlet, which increases turbidity and chemical contamination, resulting in the death of aquatic plants and algae (Shoobridge 2006, CMD 2002). Many of the local residents attribute recent fauna decline to the mining contamination; sufficient circumstantial evidence exists that confirms that mining is the

preeminent factor in the recent endangerments and extinctions (Shoobridge 2006). For example, the impact of the pollution is blatant during the dry season, when hundreds of dead birds wash onto shore; although the symptoms these birds exhibit suggest lead poisoning, no study has verified the claim. Also, of the avian populations that do persist, most concentrate within the southern portion of the lake, furthest from the mouth of the Río San Juan. Finally, iron oxide sediments blanket the algae on the bottom of the lake.

The observed effects of pollution in Lake Junín render the question, what instigated this rapid contamination? The historical literature discusses pollution of nearby lakes and streams, yet no mention of Lake Junín emerges until the mid-20th Century. I postulate that the construction of the Upamayo Dam in 1932 on the Río Mantaro directly led to the exorbitant contamination of Lake Junín. Prior to the dam construction, the Río San Juan ran from Cerro de Pasco and past Lake Junín, where it joined the Río Mantaro and continued southward, adjacent to the lake (O'Donnel 1997). The Upamayo Dam, however, altered the hydrologic role played by the Río Mantaro and Río San Juan. The structure caused water from the Río San Juan to backup into Lake Junín, making the river both an inlet and an outlet to the lake. Ultimately, the inflowing river allowed for the incursion of water laden with Cerro de Pasco mining waste into Lake Junín (O'Donnel 1997).

PURPOSE OF THE STUDY

Although limnological studies show high levels of total dissolved metals – particularly copper, lead, zinc, arsenic, cadmium, chromium, mercury, iron, and manganese (CMD 2002) – no empirical data presently exists to tie the construction of the

dam with the contamination of the lake. Thus, the purpose of this study is threefold. Firstly, to verify the contamination, I will show that the concentrations of heavy metals in Lake Junín have increased through time by analyzing six sediment cores. Secondly, I will argue that the construction of the Upamayo Dam caused the pollution by establishing an age-depth correlation between Junín Core B and a core from nearby Lake Pumacocha (Figure 1b). Thirdly, through an analysis of metal flux in Lake Junín and an interlake comparison with Lake Pumacocha, I will demonstrate that the discharge from the Río San Juan, and not other transport mechanisms, is responsible for the contamination. Finally, the report will conclude with suggestions for further study and action.

METHODS

The study included a field, lab, and statistical component. The 54-cm “2002 Core” was collected in 2002 by Donald Rodbell and Mark Besonen, while the other five cores – Core G (60-cm), Core C (57-cm), Core F (118-cm), Core D (127-cm) and Core B (130-cm) – were collected in 2008 using a Verschuren Surface Corer, also by Donald Rodbell and Mark Besonen. The cores were sampled in the field every 0.5-1.0-cm, and subsequently transported back to Union College in Schenectady, New York for further analysis.

In the lab, the cores were dried, sub-sampled, and weighed. Total carbon coulometry was used to acquire total inorganic carbon (TIC) and total organic carbon (TOC). 1.0 mL of high-purity HNO₃ and 9.5 mL of deionized H₂O were added to the sub-samples. All sub-samples were placed in the shaker for 12 hours and then transferred to the refrigerator for 24 hours. After refrigeration, 1.0 mL of the sub-sample fluid was

moved to an ICP-MS tube and mixed with 9.0 mL of diluting solution. Each sub-sample was analyzed by the ICP-MS for Co, Cu, Zn, Ba, Sr, Pb, Fe, and Mn. The ICP-MS data was processed and graphed using Delta Graph and Microsoft Excel.

To establish an age-depth relationship in at least one Lake Junín core, we overlay the $\delta^{18}\text{O}$ record of Junín Core B with the independently-dated $\delta^{18}\text{O}$ record of the Pumacocha Core (dated by Mark Abbott). The $\delta^{18}\text{O}$ record of a lake is dependent on the temperature, as well as the isotopic signature of incoming water, such as that from precipitation, groundwater flow, or overland flow. Since Lake Pumacocha and Lake Junín experience similar climatic forcing, we were able to assume that they would exhibit similar isotopic records, and therefore could be correlated to establish an age-depth relationship for Junín Core B.

To determine the role of the Río San Juan in the recent metal contamination, we calculated the flux of each metal in all six cores, and we compared Zn and Pb levels in Junín Core B and the Lake Pumacocha Core. Changes in cross-lake flux ($\mu\text{g}/\text{cm}/\text{yr}$) were determined by comparing the average flux per core with distance into the lake from the inlet. The flux calculations relied on crucial assumptions. Firstly, flux necessitates age control to determine the sedimentation rate. The sedimentation rate was calculated for each core by assuming that the depth at which metal concentrations started to rise in Pb marked the date of the dam construction. Then, a sedimentation rate is acquired by dividing the aforementioned depth by the time since the dam began operation, or 78 years.

The flux calculations also required the bulk density of the each sub-sample. Bulk density was calculated per sub-sample using an equation derived from the relationship between bulk density (gm/cc) and total organic carbon (%):

$$\text{Bulk Density} = 1.534x^{-0.115}$$

Where x = the total organic content

The flux was ultimately calculated per metal by multiplying the bulk density by the sedimentation rate by the concentration of the metal at each sub-sample depth. These values were then averaged for the entire core. The average flux values for each metal were plotted on DeltaGraph verse distance from inlet into the lake.

Finally, to compare Zn and Pb in the two lakes, data for each was plotted on DeltaGraph and overlain.

RESULTS

The 6 cores were collected at locations that varied in their distance from the inlet (Figure 2; Table 1). The 60-cm Core G is located in the river channel (Figure 2; Table 1) that existed prior to the lake level rise that was associated with the construction of the Upamayo dam. The water depth at the location was 2.88 m (Table 1). The metal concentrations within Core G vary significantly (Figures 3, 4). Co reaches a maximum of 98.7 ppm at 55.5 cm and a minimum of 2.97 ppm at 18.5 cm. The maximum Cu value (6,428 ppm) occurred at 17.5 cm while the minimum concentration (494.74 ppm) occurred at 41.5 cm. The Zn peak of 37,622.07 ppm occurred at 48.5 cm, while the lowest value was recorded at 51.5 cm. The range in Pb is 815.20-3,272.05 ppm with the values being measured at 18.5 and 59.5 cm, respectively. The maximum concentration of Fe in Core G, 218,440 ppm occurs at 26.5 cm and the minimum concentration, 24,162

ppm, occurs at 52.5 cm. Finally, Mn reaches a maximum of 12,342.29 ppm at 55.5 cm and a minimum of 1,323.41 ppm at 16.5 cm.

The 57-cm Core C is located slightly outside the extent of the river at a depth of 4.88 m (Figure 2; Table 1), and it also shows less deviation than Core G (Figures 3, 5). The maximum (100.66 ppm) and minimum (1.14 ppm) Co concentrations occur at 7.5 and 57 cm, respectively. The maximum value of Cu, 6,419 ppm, occurs at 6.5 cm, while the minimum value, 19.71 ppm, occurs at 53 cm. Zn ranges from 314.40 to 49,642 ppm, with the highest concentration at 23.5 cm and the lowest at 57 cm. The maximum concentration of Pb is 2,286.81 ppm at 16.5 cm and its minimum concentration is 24.09 ppm at 57 cm. The concentration of Fe in Core C has a high at 7.5 cm with 595,630.27 ppm and a low at 53 cm with a value of 3,552.16 ppm. Mn varies between 295.51 ppm and 33,910.56 ppm, with the maximum and minimum concentrations measured at 0.5 cm and 57 cm respectively.

At 145-cm, Core F is located 17.8 km from the inlet at a water depth of 10.83 m (Figure 2; Table 1). The Core F metal profiles show much more distinct peaks (Figures 3, 6). Co, Cu, Zn, Pb all have negligible quantities at depth. The minimum for Fe (228.68 ppm) occurs at 113.5 cm; the minimum for Mn (14.48 ppm) occurs at 75.5 cm. The maximum concentrations for Co (46.56 ppm), Zn (48,976.157 ppm), and Mn (33,802.26 ppm) occur at 4.5 cm. The highest values for Cu (1,250.98 ppm) and Pb (917.73 ppm) were measured at 2.5 cm. The maximum concentration of Fe (118,165.21 ppm) occurred at a depth of 5.0 cm.

The 2002 Core is only 54-cm long at a water depth of 2.70 m, and it is located 22.35 km from the inlet near the eastern edge of the lake, about 1 km from the Centromín

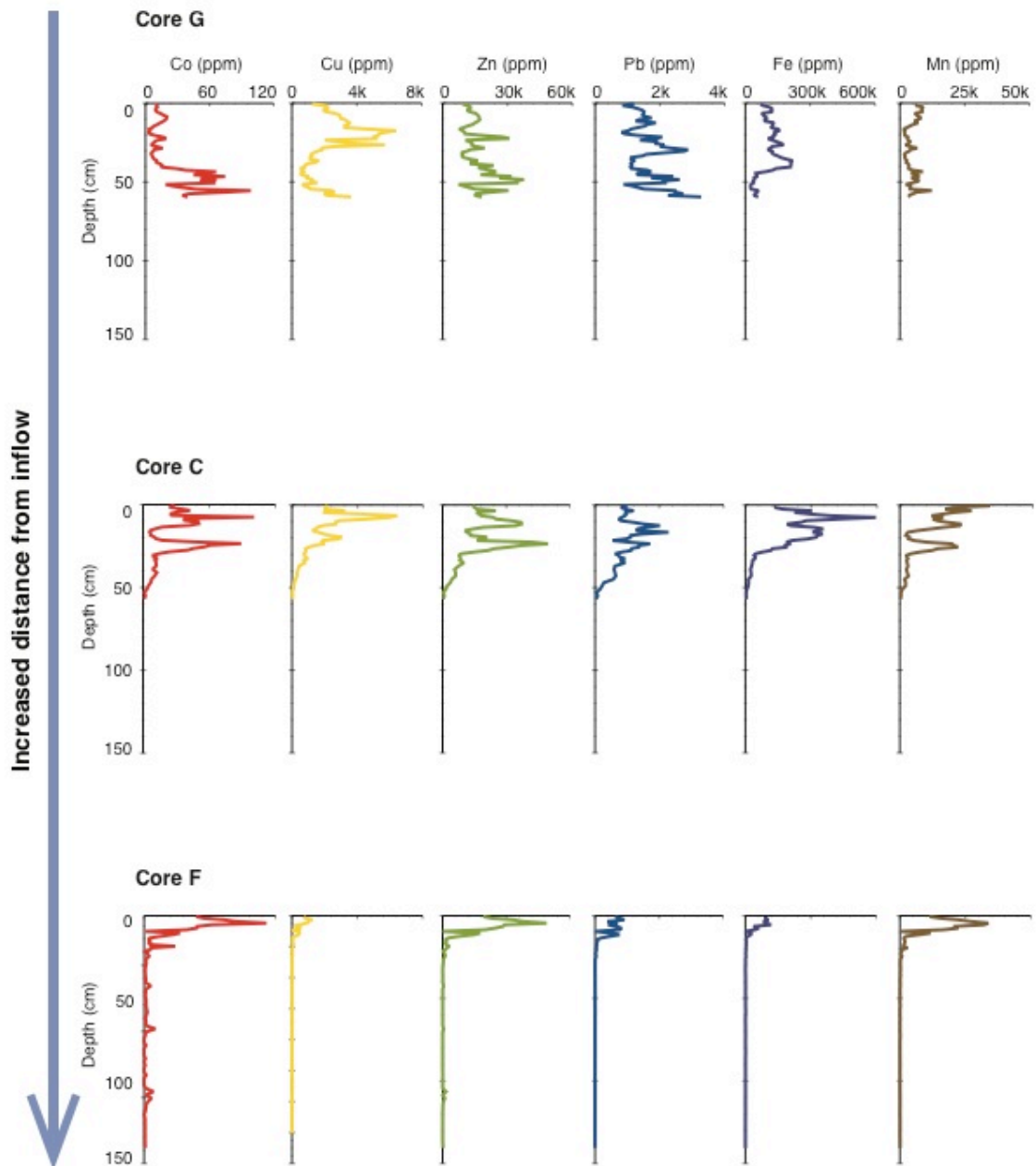
Lodge at Casapato (Figure 2; Table 1). An up-core increase of metal concentrations is very apparent (Figures 3, 7). The concentration of Cu remains steady at 0 ppm up-core until 11 cm where it increases to 10 ppm, eventually maxing at 5 cm with a concentration of 780 ppm. Although Zn concentrations are 10 ppm at 54 cm, the values trend like those of Cu, remaining constant at 0 ppm until 27 cm, when the concentrations increase to 20 ppm. The maximum Zn concentration occurs at 7 cm, with a measurement of 52,000 ppm. Similarly, at 54 cm, the Pb concentrations measure 10 ppm, a value which effectively drop to 0 ppm up-core until an increase to 520 ppm at 9 cm; the maximum Pb value, 710 ppm, occurs at 7 cm.

The 128-cm Core D is located 14.5 km from the inlet and at a depth of 2.20 m, along a portion of the western shore that would not have been submerged prior to the construction of the Upamayo Dam (Figure 2; Table 1). Overall, Core D has less pronounced peaks than the other five cores (Figure 3, 8). The concentration of Co reaches a maximum (5.82 ppm) at 8 cm and a minimum (0.18 ppm) at 73 cm. At cm, Cu hits its maximum of 250.82 ppm at the top subsample of the core, and its nadir occurs at 103 cm, with a value of 0.09 ppm. The maximum (11,582.31 ppm) and minimum (4.04 ppm) concentrations of Zn occur at 10 cm and 103 cm, respectively. The concentrations of Pb reach a maximum of 411.82 ppm at 41 cm and a minimum of 0.65 ppm at 110 cm. The highest recorded concentration of Fe (4,604.65 ppm) occurred at 12 cm, with the lowest value (230.34 ppm) recorded at 73 cm. Finally, the concentration of Mn peaks at 2 cm with a of 2,770.36 ppm, and its minimum of 42.05 ppm occurs at a depth of 63 cm.

Located 25.51 km into the lake from the inlet (Figure 2) and at a water depth of 5.43 m, the metal concentrations in the 130-cm Core B show obvious trends (Figure 3, 9).

Effectively, all metal concentrations remain low in an upcore direction until ~12 cm, when all metals begin to peak. The maximum concentrations of Co (23.48 ppm), Cu (477.10 ppm), Zn (55,089.20 ppm), and Fe (23,525.27 ppm) were recorded at 3.5 cm. The maximum value of Pb (237.66 ppm) occurs at 2.5 cm, and the maximum value of Mn (45,502.75 ppm) was recorded at 9.5 cm. Although the metal concentrations below ~12 cm, and particularly those below ~20 cm, are negligible, it is interesting to note that four metals have minimum concentration values at 81 cm: Cu (0.44 ppm), Pb (0.23 ppm), Fe (313.02 ppm), and Mn (62.44 ppm).

Finally, the TIC and TOC measurements exhibit similar trends in every core (Figure 3). On average, TOC increases , and calcite, or TIC, decreases up-core; the TIC and TOC values effectively mirror one another.



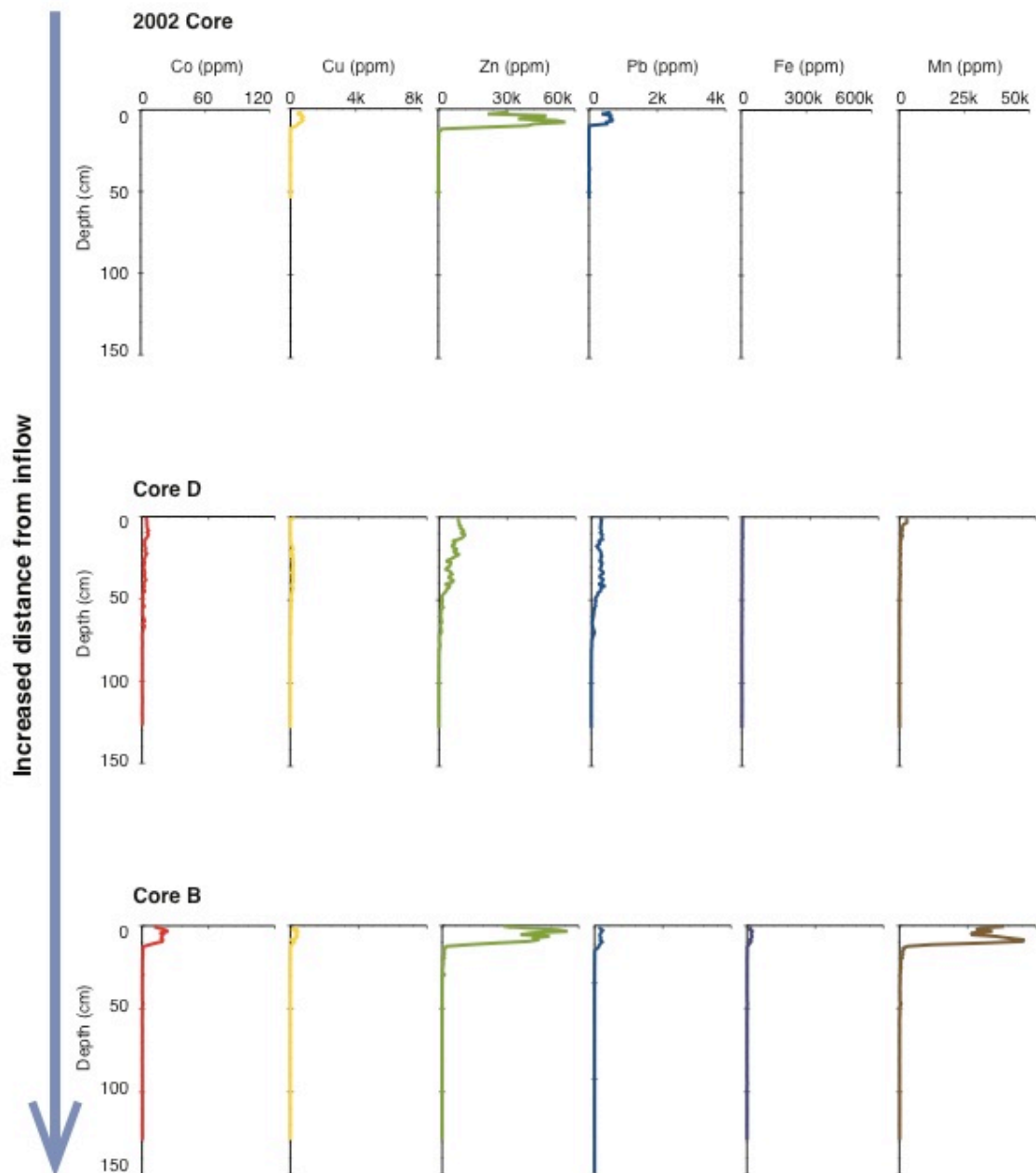


Figure 3: The concentrations (ppm) of Co (red), Cu (yellow), Zn (green), Pb (blue), Fe (purple), and Mn (brown) in Core G, Core C, Core F, the 2002 Core, and Core B in Lake Junín, Peru. All metals, as well as depth, are on a uniform scale. Core G is the most proximal to the Río San Juan inlet while Core B is the most distal. The peaks in metal concentration become more apparent as distance into the lake and from the inlet increases (Figure 2).

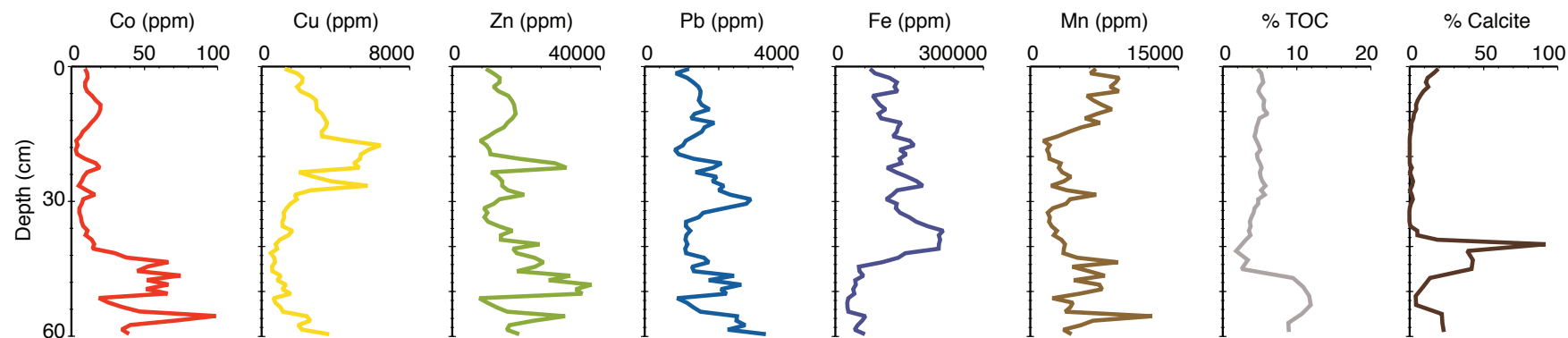


Figure 4: Shows the concentrations (ppm) of Co (red), Cu (yellow), Zn (green), Pb (blue), Fe (purple), Mn (brown), as well as the total organic carbon (%) and calcite (%) of Core G in Lake Junín Peru. There are no discernible peaks in this core.

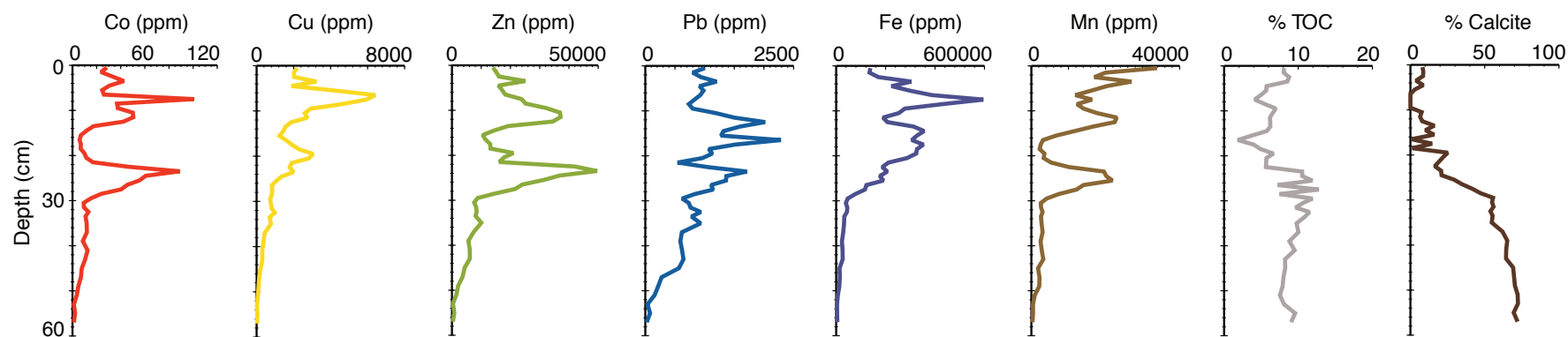


Figure 5: Shows the concentrations (ppm) of Co (red), Cu (yellow), Zn (green), Pb (blue), Fe (purple), Mn (brown), as well as the total organic carbon (%) and calcite (%) of Core C in Lake Junín Peru. Although more pronounced than Core G, there are still no discernible peaks in this core.

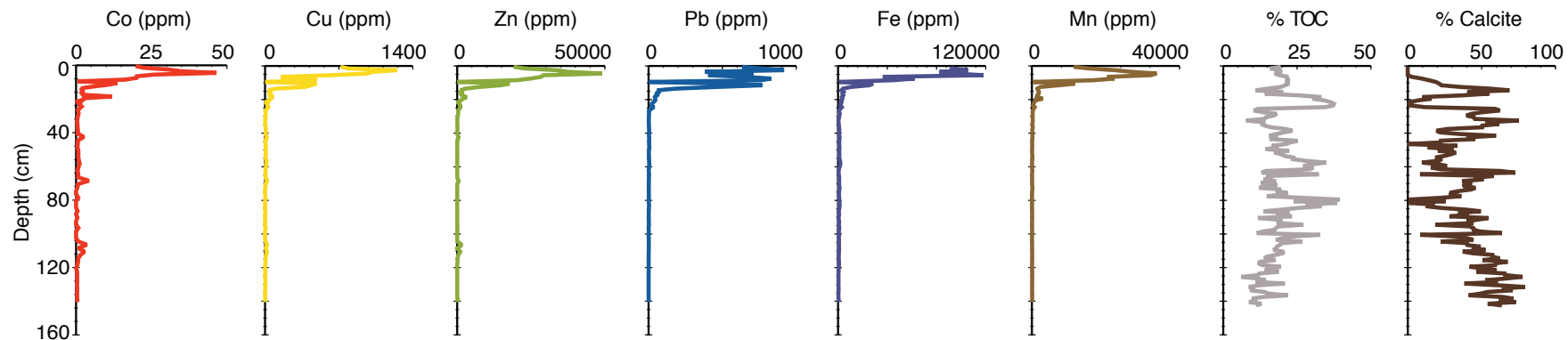


Figure 6: Shows the concentrations (ppm) of Co (red), Cu (yellow), Zn (green), Pb (blue), Fe (purple), Mn (brown), as well as the total organic carbon (%) and calcite (%) of Core F in Lake Junín Peru. The peaks in metals begins around ~20 cm, and this also marks the drastic drop in calcite, which is consistent with the acidification of the lake due to mine drainage.

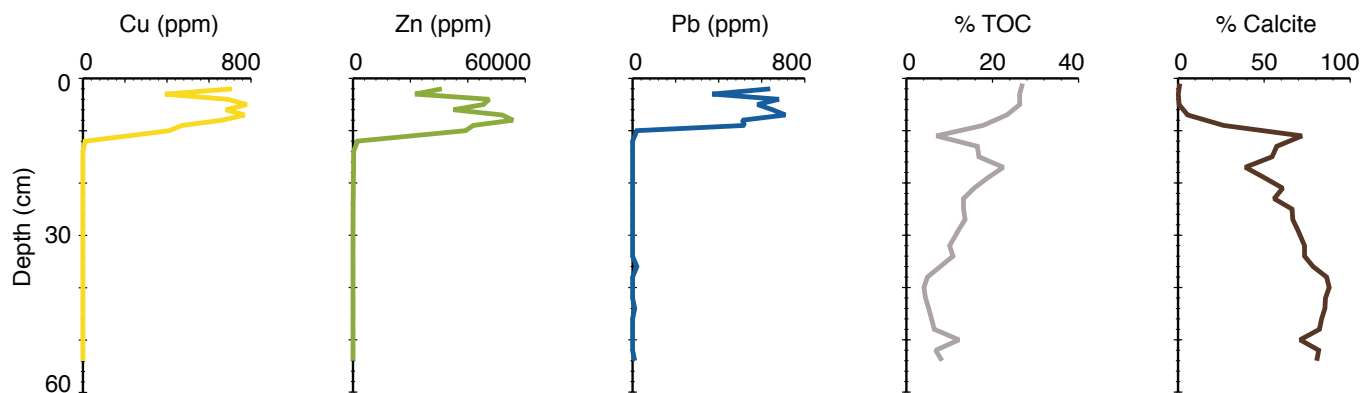


Figure 7: Shows the concentrations (ppm) of Co (red), Cu (yellow), Zn (green), Pb (blue), Fe (purple), Mn (brown), as well as the total organic carbon (%) and calcite (%) of the 2002 Core in Lake Junín Peru. The peaks in metals begin around ~15 cm, and this also marks the drastic drop in calcite, which is consistent with the acidification of the lake due to mine drainage.

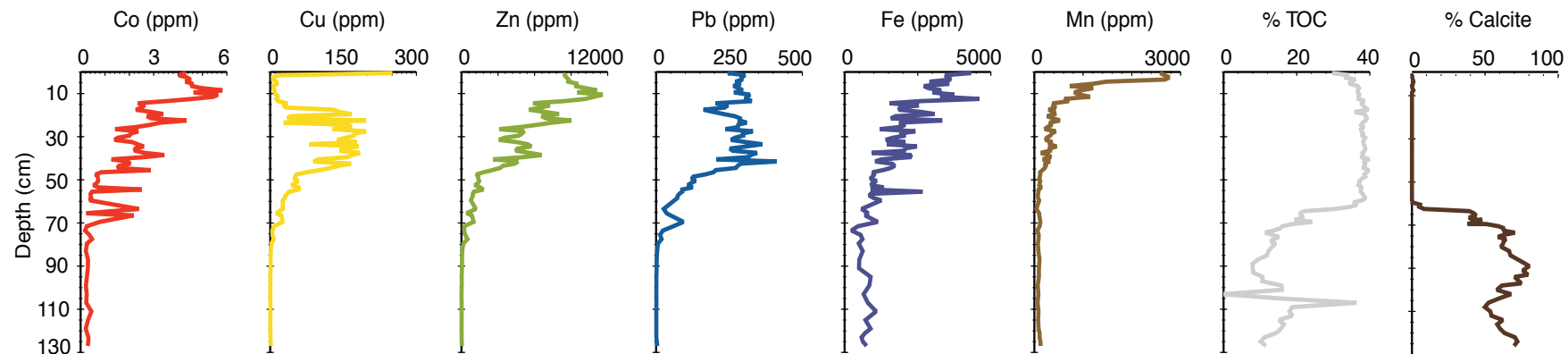


Figure 8: Shows the concentrations (ppm) of Co (red), Cu (yellow), Zn (green), Pb (blue), Fe (purple), Mn (brown), as well as the total organic carbon (%) and calcite (%) of Core D in Lake Junín Peru. The peaks in metals begin around ~15 cm, and this also approximates the drastic drop in calcite, which is consistent with the acidification of the lake due to mine drainage.

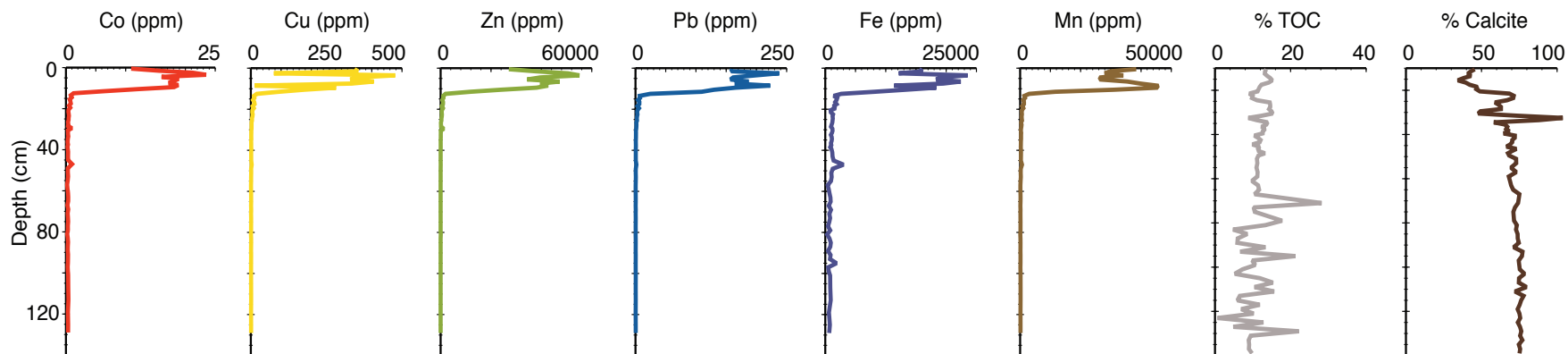


Figure 9: Shows the concentrations (ppm) of Co (red), Cu (yellow), Zn (green), Pb (blue), Fe (purple), Mn (brown), as well as the total organic carbon (%) and calcite (%) of Core B in Lake Junín Peru. The peaks in metals begin around ~12 cm, and this also approximates the drop in calcite, which is consistent with the acidification of the lake due to mine drainage. Core B is the most distal core from the inlet (Figure 2).

DISCUSSION

Although it may be intuitively conjectured that the longstanding mining history of Cerro de Pasco would contaminate the local environment, little empirical evidence exists to support a causal relationship. The overarching goal of this project was to examine changes in Lake Junín heavy metal deposition within the context of historical mining activity in Cerro de Pasco; in particular, I sought to document the impact of the 1932 construction of the Upamayo Dam on the water quality of the lake. Therefore, the fundamental objectives of this study are threefold: to use sediment cores to quantify variations in heavy metal concentrations in Lake Junín through a span of geologic time; to observe and date notable peaks in the data, in an attempt to ultimately correlate their occurrence with the timing of dam construction; and to evaluate the potential existence of alternative conduits of heavy metal contamination into the lake.

Down-core variations in heavy metal concentrations

At the core of my hypothesis is the assumption that metal has increased in recent time in the lake; fundamentally, to prove that the Upamayo Dam polluted Lake Junín, I needed to show that contamination indeed occurred.

The aforementioned numerical and graphical analysis offers conclusive evidence that Lake Junín has been severely polluted in recent time. Granted, the concentrations in Core G vacillate extensively (Figure 4), as would be expected in sediment deposited within an active river channel. The concentrations in Core G reflect fluvial conditions, such as natural and anthropogenic changes in discharge or the reworking and deposition

of sediment variously contaminated with metals, more heavily than the remainder of the lake, and the metal concentrations reflect this mercurial environment.

Although Core C is no longer within the river inlet itself, its proximity renders it likely to be influenced by fluvial processes. Still, a weak pattern emerges in Core C that was absent in Core G: heavy metal concentrations generally increase up-core (Figure 3, 5). The metal concentrations in Core C never drop to zero, as they do in the more distal cores; this suggests that sedimentation rates at Core C may be so high that a 57 cm core length was insufficient to capture the uncontaminated sediment.

However, the remaining four cores show the peak in metals more definitively. The maximum concentration of each metal generally decreases in value with increasing distance into the lake from the inlet, and the maximum concentrations tend to occur at shallower depths (Figure 3). Likewise, the plummeting trend of calcite is consistent with the acidification of the lake due to mine drainage pollution. Thus, the metal profiles of the six cores suggest a recent contamination of Lake Junín.

Core B age-depth correlation with Lake Pumacocha Core

Although the lab analysis unambiguously verified that metal levels have changed in Lake Junín by up to three orders of magnitude, the data is useless without a temporal constraint. Bird et al. (2011) radiocarbon and ^{210}Pb dated and developed a $\delta^{18}\text{O}$ record using calcite for the Lake Pumacocha core. The calcite of Junín Core B had also been previously analyzed for its isotopic signature. As previously mentioned, the $\delta^{18}\text{O}$ record of a lake is dependent on incoming hydrology and temperature, and so we were able to

overlay the Junín Core B and Pumacocha records due to the regional similarities expected between two proximally located lakes; both Lake Junín and Pumacocha experience the same climatic forcing, including temperature and precipitation, and thus one would expect their records to reflect the comparable environmental conditions. By overlaying the dated core on Junín Core B, I was able to generate an age-depth correlation for the latter (Figure 10). Assuming that the date correlation is valid, ~1932, or the time of dam construction on the Río Mantaro, is represented at ~12 cm in Core B.

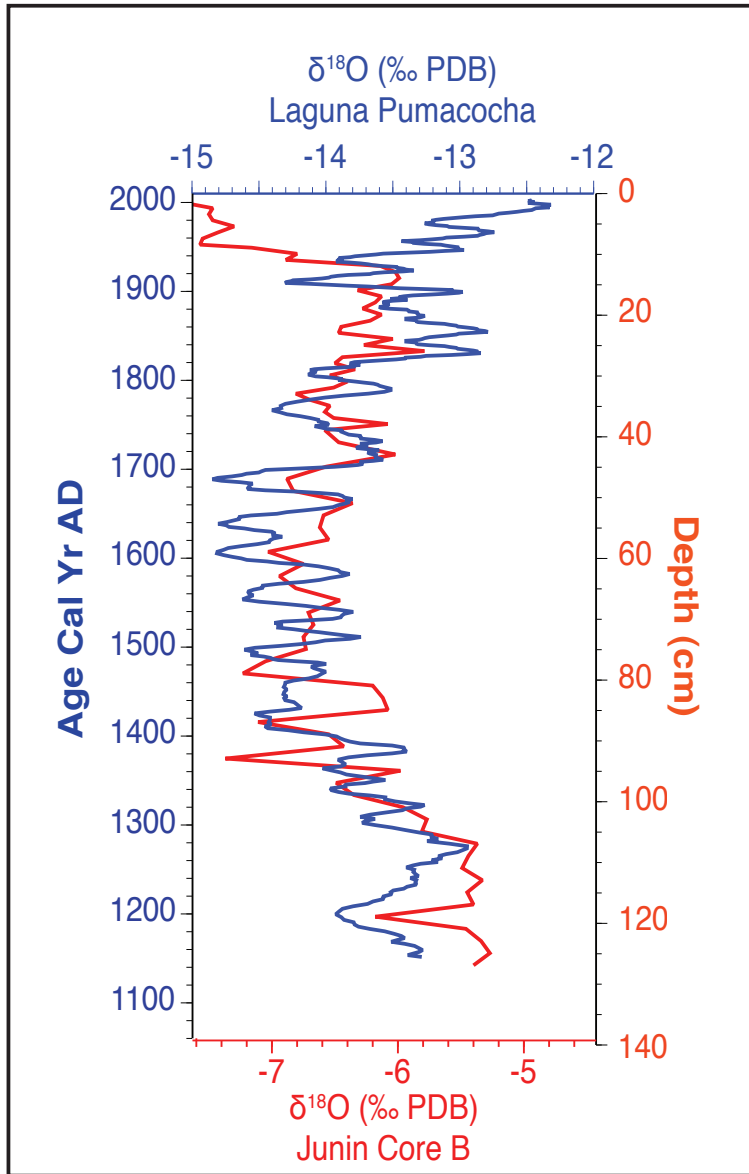


Figure 10: The $\delta^{18}\text{O}$ record for Core B from Lake Junín (red) overlain on the ^{210}Pb -dated and ^{14}C -dated, high-resolution $\delta^{18}\text{O}$ record for Lake Pumacocha (blue) (Bird et al. 2011). Given that the two lakes are located close to one another, we assume that they experience the same relative changes in the $\delta^{18}\text{O}$ value of water. Therefore, the well established chronology from Lake Pumacocha can be transferred to Junín Core B. The correlation between the two cores suggests that sedimentation from 1930 AD occurs at ~2 cm in Core B, which is coincident with the depth at which heavy metal concentrations in the core begin to rise (Figure 9). The marked depletion of $\delta^{18}\text{O}$ values is consistent with a rapid influx of fresh river water.

This correlation offers substantial support to the hypothesis that the Upamayo Dam directly led to the contamination of Lake Junín. The peaks in all metal concentrations occur in Core B at ~12 cm, the depth that corresponds with ~1932. The

$\delta^{18}\text{O}$ record of Junín tracks that of Lake Pumacocha until the early 1900s, when the former becomes less enriched, meaning it exhibits more negative values (Figure 10). The deviation in the isotope records at the top of each sediment core is consistent with a rapid influx of freshwater, such as that from the Río San Juan. Effectively, the input of Río San Juan water into the lake eliminated evaporative enrichment of the water body, and the oxygen isotopic record became more depleted (Figure 10).

The Río San Juan as the point source of the pollution

Placing a temporal constraint on Junín Core B offers substantial evidence suggesting that the Upamayo Dam is indeed culpable for the pollution of Lake Junín. Timing, however, is not the only line of evidence that supports this conclusion. The flux calculations and interlake comparison also support the hypothesis that the Upamayo Dam degraded the nationally protected lake.

If the Río San Juan were depositing pollutant-laden waters into Lake Junín, one would expect to see a decrease in the concentration of heavy metals with more distal locations from the inlet. The flux ($\mu\text{g}/\text{cm}^2\text{yr}$) of each metal decreases with statistical significance (Table 2) as distance from the stream and into the lake increases (Figure 11), indicating that the metals are being diluted during transport through the water body. Since flux measures the amount of a material reaching a specified area, the observed trend makes sense only if the Río San Juan serves as a point source for pollution.

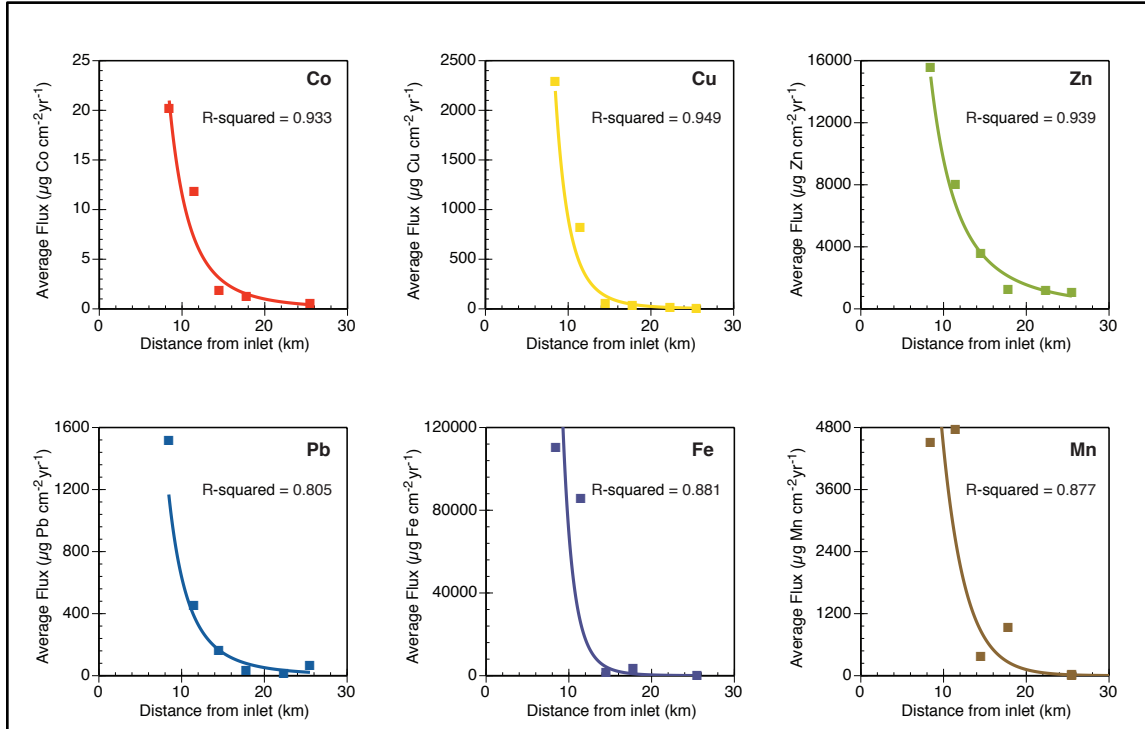


Figure 11: Shows the average flux ($\mu\text{g}/\text{cm}^2\text{yr}$) of Co (red), Cu (yellow), Zn (green), Pb (blue), Fe (purple), and Mn (brown) with distance from the inlet stream (km), as well as their corresponding R^2 values (Table 2). A decreasing flux with distance from the Río San Juan indicates that the heavy metals are entering the lake from the stream and are being diluted with transport, suggesting that the river serves as a point source of the pollution.

While the flux measurements suggest that the Río San Juan is a point source of the acid mine drainage, the data does not preclude other mechanisms of metal transport. To prove that the dam construction was explicitly responsible for the contamination, it is imperative to exclude alternative forms of metal deposition by comparing the paleolimnological concentrations of Zn and Pb in the Lake Pumacocha core with those in Lake Junín Core B. Lake Pumacocha is hydrologically disconnected from Cerro de Pasco, and therefore receives no pollution via hydrologic transport; all metal deposition in Lake Pumacocha comes from atmospheric deposition or airfall. Therefore, if Lake Junín was not impacted by changes along the Río Mantaro or Río San Juan, the trends in its metal concentrations should be mirrored by those at Pumacocha. This assumption holds true

prior to the construction of the dam, when the Zn and Pb levels effectively track one another at negligible concentrations, save a deviation in Pumacocha Pb levels c.a. ~1820 (Figure 12). Both of the metal records from Lake Junín, however, spike at ~1930, while the Pumacocha data remains constant and decreases slightly (Figure 11). The deviation ~1930 suggests that an alternative, more concentrated source of pollution was influencing the water quality of Lake Junín but not Lake Pumacocha; contaminated waters from the Río San Juan are the most likely source.

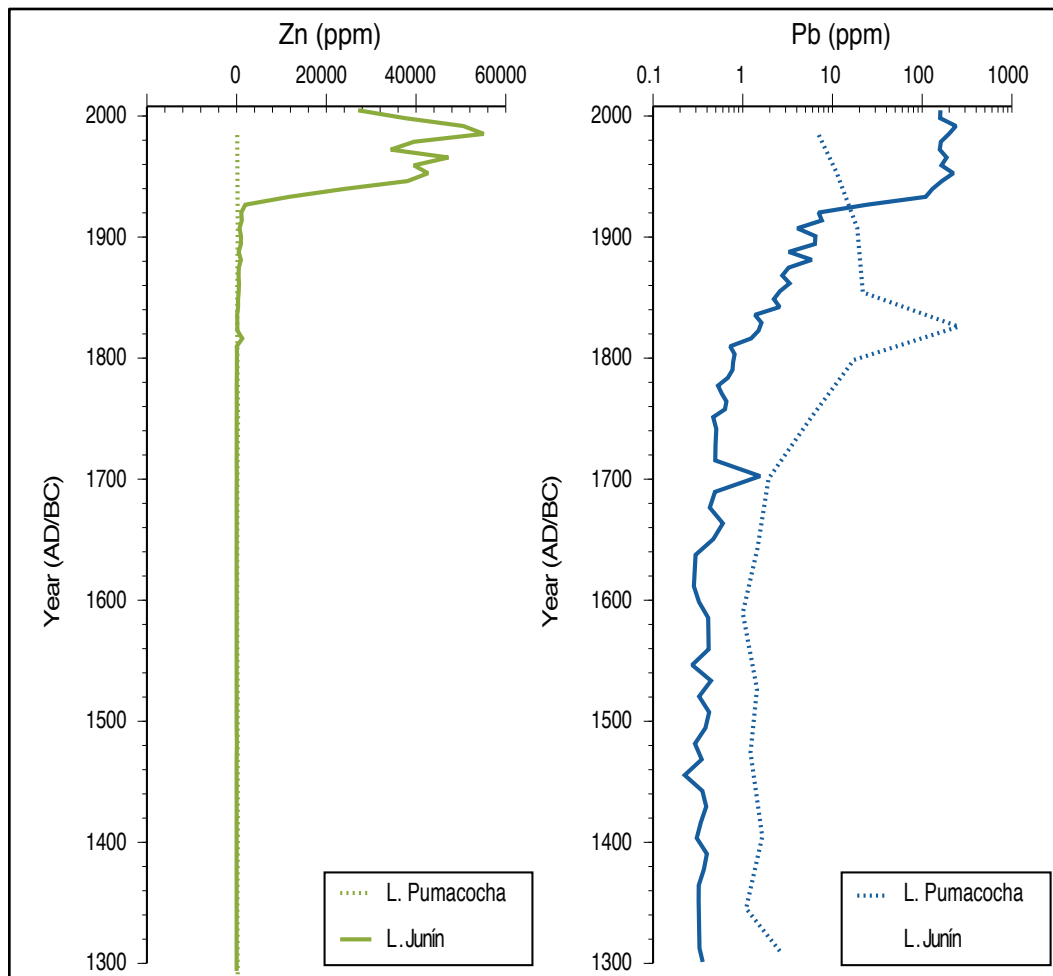


Figure 12: The down-core profile of Pb (ppm) and Zn (ppm) in Lake Junín (solid line) and Lake Pumacocha (dotted line). The records track one another until ~1830 in the Pb profile and ~1930 in the Zn profile. The ~1830 peak is likely due to an increase in smelting activity in Cerro de Pasco in 1832 after a 12-year hiatus due to political turmoil (Waszkis 1993). The latter coincides with the construction of the Upamayo Dam on the Río Mantaro in 1932, and the effect of this construction is seen in the deviation around 1930 in both Zn and Pb concentrations of Lake Junín.

CONCLUSION

In Cerro de Pasco, the relationship between local residents and the mining industry is historically strained. Human health issues place at the forefront of humanitarian concerns. Relocations are common as Volcan expands the open pit into the community (Salazar 2009). A 2005 study by the Pasco regional health agency found that more than 80 percent of children had blood lead levels exceeding 10 micrograms per deciliter of blood, the acceptable limit set by the World Health Organization (Salazar 2009). In May 2007, the Center for Disease Prevention and Control (CDC) tested the local soil and air in the nearby towns of Ayapoto, Chaupimarca, and Paragsha. The report indicated that 91 percent of the children between the ages of one and 12, and 82 percent of women of childbearing age had high blood levels of lead, cesium, and thallium (Salazar 2009). Similarly, living conditions in the community are unbearable. Eighty percent of the available water goes to the mine, and the community expects approximately 6 hours of electricity per day (Whalen 2010). Livestock die due to polluted waters, and the city is seeing mass displacement as citizens flee to the cities in search of higher qualities of life (Whalen 2010). The ecological and human damage has become more apparent in recent years, spurring a call for change.

Fortunately there are agencies that exist to monitor the water quality of the lake, although their effectiveness is debatable. Although the Ministry of Energy and Mining supervises mining operations through the General Director of Environmental Health (DIGESA), there is a lack of public confidence in the results of the evaluations (Shoobridge 2006). Many go as far as to deny their validity, asserting that the mining companies and government overlook crucial ecological issues (Shoobridge 2006). Lake

Junín has been declared in a state of emergency twice since the Reserve was established in 1974, but many residents bemoan the absence of any apparent improvement (Shoobridge 2006).

The local people have known about the contamination of Lake Junín, as well as the impact of the Cerro de Pasco Mine for a long time. Unfortunately, as is the case in most instances where a private, multi-million dollar corporation subjugates impoverished and indigenous people, there is a lack of support for those who need it most. Many independent Peruvian media sources report on the environmental and health crises in the region, yet as of now, the issue persists without national or international attention. Even if remediation is unlikely, a transition to more sustainable mining practices should be pursued. Hopefully, by augmenting the repertoire of scientific research conducted on this issue, Cerro de Pasco and Lake Junín will receive the exigent action that they so desperately need.

TABLES

Table 1: Shows the length, water depth, longitude, latitude, and distance into the lake from the inlet for Core G, Core C, Core F, the 2002 Core, Core D, and Core B.

Core	Length (cm)	Water Depth (m)	Longitude	Latitude	Distance into the lake from the inlet (km)
G	60	2.88	10°59'06.36''S	76°12'19.95''W	8.45
C	57	4.88	10°59'30.29''S	76°10'21.72''W	11.47
F	145	10.83	11°01'07.19''S	76°07'14.42''W	17.8
2002	51	2.70	10°59'47.95''S	76°03'54.14''W	22.35
D	128	2.20	11°03'49.71''S	76°07'36.46''W	14.50
B	133	5.43	11°02'54.25''S	76°03'21.35''W	25.51

Table 2: Shows the nature of the relationship (including the equation and r^2 value) in the average flux ($\mu\text{g/cm/yr}$) of each metal with distance into the lake from the inlet.

Metal	Equation	R²	Type or relationship
Co	$y = 40439x^{-3.544}$	0.93289	Power
Cu	$y = 2\text{E}+08x^{-5.218}$	0.94899	Power
Zn	$y = 4\text{E}+06x^{-2.628}$	0.93885	Power
Pb	$y = 3\text{E}+06x^{-3.611}$	0.80545	Power
Fe	$y = 2\text{E}+12x^{-7.484}$	0.88135	Power
Mn	$y = 164242e^{-0.3616x}$	0.877852	Exponential

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