Colonialism and the environment: the pollution legacy of the Southern Hemisphere's largest copper mine in the 20th century

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Abstract: Mining has been a major contributor to economic development in Australia since British arrival in the late 1700s, with little to no thought about the long-term environmental consequences. This study assesses the metal pollution legacy caused by different smelting methods and mining activities during the British colonialism in western Tasmania. This region was the largest copper producer in the Southern Hemisphere during the 20th century. Lake sediments from Basin Lake and Owen Tarn, 12 and 5 km from Queenstown's mines, respectively, were used to reconstruct historical metal contamination. Temporal changes in metal concentrations (iron, cupper, arsenic, selenium and lead) were assessed in relation to the scale of mining activities and the technologies used. Sedimentation rates and metal influxes increased from 1900, reflecting the beginning of copper mining in Mount Lyell. Observed metal concentrations peaked after 1930, coinciding with the introduction of large-scale open-cut operations and an expansion of the mining machinery. All elements underwent at least minor enrichment (EF 1-3) during the lifespan of the mine, with lead and copper undergoing extremely severe enrichment (EF > 50). Although smelters contributed to metal increases in the lakes, large open-cut large operations in the 1930s contributed most to metal contamination. Local metal deposition from mining-related activities decreased significantly once the operations decreased, with selenium and arsenic falling to almost background values within 50 years. Lead and copper, the elements which underwent major enrichment, have not yet reached background values. The ecological consequences include the current degraded local landscape, poor water quality and disrupted local biota. Knowledge about the environmental impacts of mining in western Tasmania is less known compared to other sites around the world with a similar history. Our results demonstrate the urgent need to develop better policies and remediation programs that can mitigate the consequences of metal pollution from abandoned mines in Australia.

Introduction:

The European colonisation had dramatic environmental consequences (Wood, 2015). Empires sought affluence through the extraction of resources from their colonies, particularly driven by the industrial revolution. While the economic prosperity and development of the colonies relied on exporting resources to the wider empire, the environmental consequences of mineral extraction were not considered (Guerrero, 2016).

Australia was rapidly transformed by mining. The gold rush of the 1850s attracted large immigrant populations to its shores from Europe, North America and Asia, stimulating substantial economic growth in supply industries such as agriculture, timber and manufacturing (Blainey, 1978). The west coast of Tasmania was first explored by the British for mineral mining purposes in 1862 (all dates in this study referred as calendar year AD - Anno Domini).

Mining activities mainly started as artisanal, small-scale activities, and remained so until the establishment of the Mount Lyell Gold Mining Company in 1881 (Figure 1) (Blainey, 1978). This venture proved incredibly successful in 1892, when the Mount Lyell Company began searching for copper (Rae, 1994), and established the largest copper mine in both the British Commonwealth and the Southern Hemisphere (Blainey, 1978; Harle et al., 2002).

Australia currently has more than 50,000 legacy mines. These are former mining sites requiring remediation where no individual or company can be held responsible (Unger, 2014). Mount Lyell is one of them, with activities starting before environmental management and mine rehabilitation regulations that exist today were in place (Unger, 2014). Some of these sites represent a significant contamination threat that may pose health issues for wildlife and human populations, for example from bioaccumulation through local food chains (De Blas, 1994).

In Tasmania, legislation from the *Environment Protection Act 1973* provided environmental protection for air, water and noise pollution, and waste management (Bingham, 1992). However, mining companies were not forced to abide by these restrictions as the government granted exemptions (De Blas, 1994). It was argued that the cost of doing so would be so high that the mines would be forced to close (De Blas, 1994).

Thus, a century of continuous copper mining and processing at the Mount Lyell has resulted in significant environmental impacts both in the mine area and off-site (Augustinus et al., 2010; De Blas, 1994; Harle et al., 2002; Schneider et al., 2019). Although the history of mining at Mount Lyell has been described (Blainey, 1993; Mainwarring, 2020; Rae, 1994), no detailed quantitative description of the temporal metal contamination has been published

This study aims to reconstruct the history of airborne metal pollution surrounding Queenstown western Tasmania. This follows previous work investigating the spatial distribution of metals in the Tasmanian Wilderness World Heritage Area (Schneider et al., 2019), and the environmental effects pollution from mining had on the landscape, vegetation and aquatic ecosystems (Beck et al. 2020) The current study refines our long-term understanding of metal contamination as a result of different mining methods over time.

Sediment records from two isolated high-altitude lakes with small catchments were used to evaluate the contribution of different mining techniques applied by the Mount Lyell Mining and Railway Company on the emission of metal and metalloids (hereafter collectively referred as metals) to the region. Specifically, we assess changes in smelting and mining methods during the late 19th and 20th centuries on the temporal atmospheric deposition of lead, arsenic, and selenium, which are known to have been lost in great quantities (Schneider et al., 2019), along with copper, which is known to be enriched in the local mining ores (Blainey, 1993). The major element iron was analysed as a reference element to evaluate the enrichment factor of the metals, while zinc was used as a chronological marker. In conjunction with these empirical findings, we identify and discuss past governmental decisions and approaches that resulted in the current legacy pollution. Finally, we discuss the case of the Mount Lyell mine in comparison to the Sudbury Mine in Canada, where similar environmental degradation was recorded under the British colonial regime.

2. Material and Methods

2.1. Site description and historical setting

Western Tasmania is a mountainous area predominantly underlain by intensely folded and faulted Cambrian and pre-Cambrian quartzite rocks and conglomerate units, intersected with highly mineralised volcanic belts (Corbett and Solomon, 1989). British occupation began when a convict settlement opened in the region in 1821 (Figure 1), with the Aboriginal population removed by 1832 (Plomley, 1971). The convict settlement was abandoned in January 1834 (Blainey, 1954), and interest in the region remained relatively low until the 1850s, due largely to the difficult terrain and isolation of the area. Geological surveys seeking gold occurred sporadically from the 1850s, with interest in the area culminating in a gold rush in the 1880s. After this early period of small-scale mining, mainly focused on gold until around 1890, several towns associated with mining were established in the region (Mainwarring, 2020). The most notable of these are Queenstown, Rosebery and Zeehan (Figure 1). The largest operations in the area were centred around Queenstown, particularly the copper mines , under the control of the Mount Lyell, North Mount Lyell, and later Mount Lyell Mining and Railway Companies.

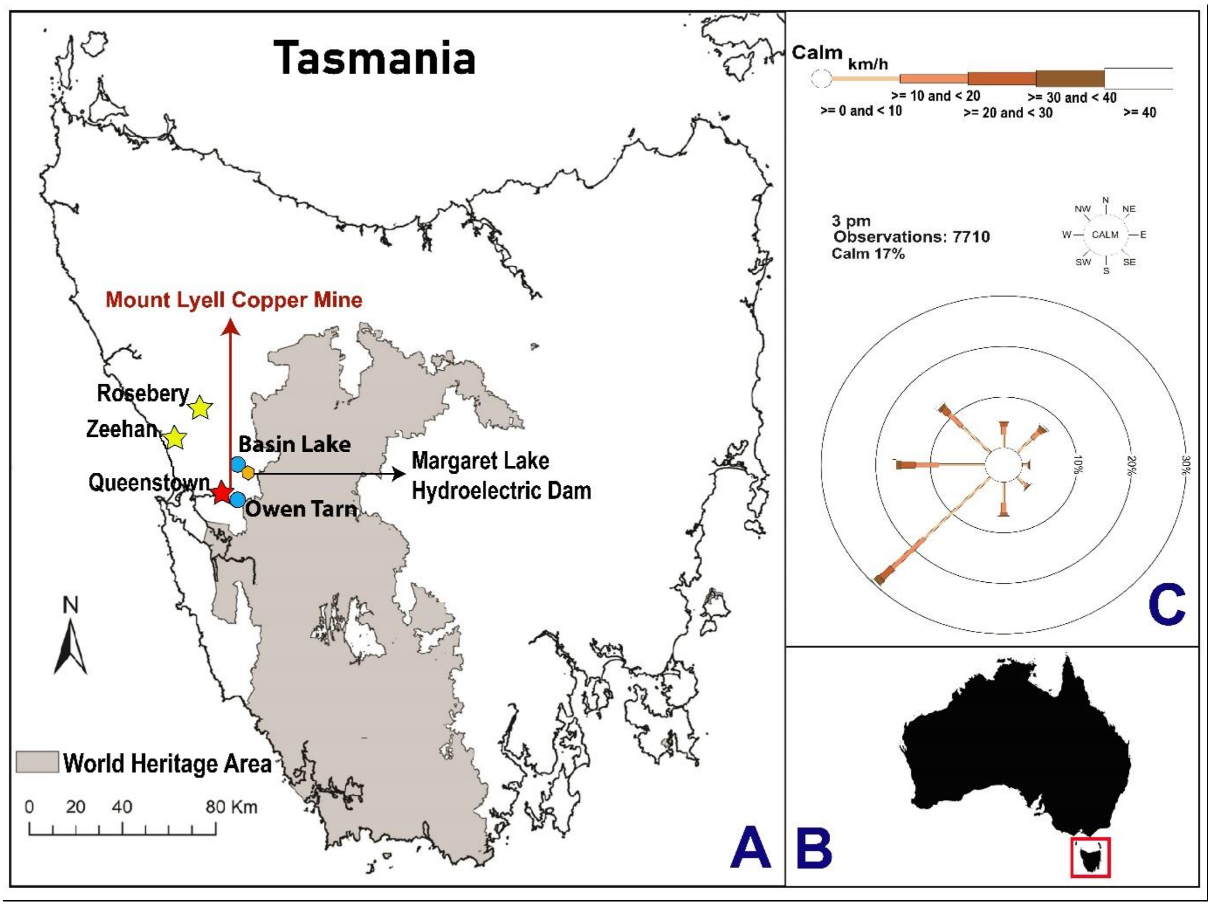

Figure 1 – A) Map of Tasmania with the three main mining towns in western Tasmania: Zeehan, Roseberry and Queenstown. B) Map of Australia and location of Tasmania (red square). C) Wind rose showing the frequency of occurrence of wind speed and direction in Queenstown between 1970 and 2015. The length of each segment within a branch is proportional to the frequency of winds blowing within the corresponding range of speeds from that direction. Wind rose from: Australian Bureau of Meteorology (BOM, 2019).

2.1.1. The exploitation of minerals other than gold and smelting

Although initial interest in the region was sparked by gold, other minerals were mined from the 1880s onwards (Mainwarring, 2020). This study focuses on Queenstown’s mining history as it was the largest mining centre in the region. It is also closest to and upwind from the study sites Basin Lake and Owen Tarn (Figure 1).

Queenstown became a prosperous mining town in the 1890s, with the discovery of the Iron Blow, a rich deposit of copper ore on Mount Lyell (Figure 2; Mainwarring, 2020). Despite the abundance of copper in the area, many attempts to establish smelters for on-site processing were unsuccessful. This was largely due to the remoteness of the region and the high cost of transporting coke (fuel for the smelters) to the area (Blainey, 1993). It was only in 1896, with the introduction of pyritic that smelting became an efficient and affordable method in the area (Blainey, 1993). This is a technique that reduces the amount of coke needed by utilising the heat generated during the combustion of iron and sulphur in the pyritic ore as fuel (Blainey, 1993). With the establishment of the smelter in Queenstown in 1896, Mount Lyell Mining and Railway Company became the largest copper producer in the British Commonwealth and the largest in the Southern Hemisphere (De Blas, 1994).

In 1922, the pyritic smelting method was revised as coke became too expensive and the market price of copper too low. Thus, a flotation system was put in place, in which the ore would be concentrated in the mill prior to smelting (Blainey, 1993). The mill and flotation tank were able to turn 6% ore into a concentration of 15 to 18% copper, and the smelting process would occur without the aid of pyrites, reducing atmospheric metal contamination. In contrast to the 11 large furnaces required for the previous smelting process, the new flotation method only required one small furnace (Blainey, 1993). In 1964, due to low prices of copper and decrease of ore concentrates, the smelter closed down and copper concentrates were shipped to mainland Australian and overseas smelters (McQuade et al., 1995). For most of the twentieth century, the Mount Lyell Mining and Railway Company yielded a total 1.3 million tonnes of copper, 750 tonnes of silver and 45 tonnes of gold in a century of mining (Blainey, 1993).

2.1.2. Mechanisation and the opening of large open-cut mines in Mount Lyell

Exploration at Mount Lyell covered approximately 9 km^2, leading to the establishment of underground and open-cut mines (Figure 2; Newnham, 1993). The periods of operation varied widely between these

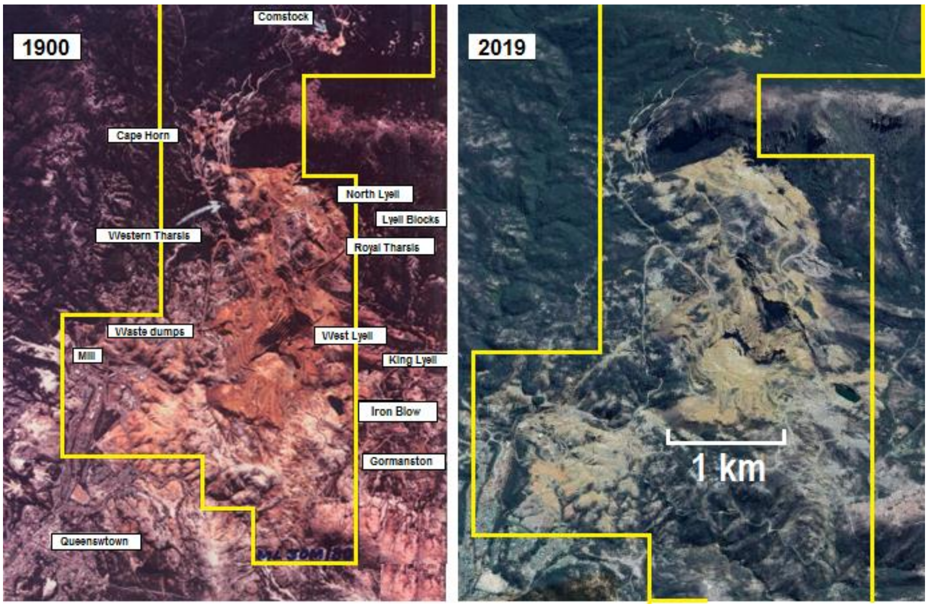

Figure 2: A map of the different mines at Mount Lyell, in 1990 and 2019, demonstrating the long-term legacy of the environmental impacts from mining in the area. From Newnham 1993 and and Google Earth Pro 2019.

Initial excavations in the late 1800s and early 1900s were mainly centred around the Mount Lyell (Iron Blow) and North Lyell mines (Figure 2), both of which were at least partially open-cut (Rae, 2005). The Mount Lyell mine ceased operation in 1929, due to a decline in the quality of the ore. However, in 1934 mining commenced at the West Lyell mine (Figure 2), which was the largest above ground operation in the area (McQuade et al., 1995). The introduction of new machinery and technology resulted in an increase in suspended particulate matter in the air due to drilling, blasting, tailing production and transportation (Blainey, 1993). Furthermore, the increase in tailing heaps and localised deforestation also contributed to dust formation (Blainey, 1993). Dust and aerosol produced by mining operations often contain elevated levels of metal and metalloid contaminants (Csavina et al., 2014; Stinton et al., 2020). This increase in metal emissions has previously been recorded in the sediments of freshwater lakes in western Tasmania, including Basin Lake and Owen Tarn (Schneider et al., 2019).

From 1940, Australian mining faced periods of instability linked to the falling price of copper and increases in processing cost due to decreasing ore concentrations. However, the Mount Lyell Mining and Railway Company was able to dominate local markets during this period, and was initially able to expand its operations accordingly (Rae, 2005). Despite this, production did not reach earlier levels and the North Lyell and West Lyell mines, which began in 1896 and 1934 respectively, ceased operation in 1972. While some sites continued production, most were underground and thus contributed less to atmospheric pollution in the area.

All mining operations by the Mount Lyell Mining and Railway Company ceased in December 1994. In 1995, the site was sold to Copper Mines of Tasmania Pty Ltd (CMOUNT), who continued to work at the site (McQuade et al, 1995). Operations ceased again in 2014 following the deaths of three workers, and the site has not operated since that time (Jarvie, 2019).

2.2. Sediment collection

Sediment samples from Basin Lake and Owen Tarn (Figure 1 and 3) were collected in 2011 and 2015 respectively. Sediment cores were collected using a Universal Gravity Corer from Aquatic Instruments (http://www.aquaticresearch.com/). These lakes are ideal to record historical contamination through atmospheric fallout as they are relatively small: the catchment of Owen Tarn is around 11,950 m^2 and the Basin Lake catchment is around 205,000 m^2, with no inflowing water from the upper catchment. The small catchment size and lack of inflow from the upper catchment suggests minor runoff at these two sites. Owen Tarn and Basin Lake are 5 and 12 km, respectively, from Mount Lyell. Sediment cores were transported to the University of Melbourne and stored at 4º C until they were transported to the University of Canberra for metal analyses.

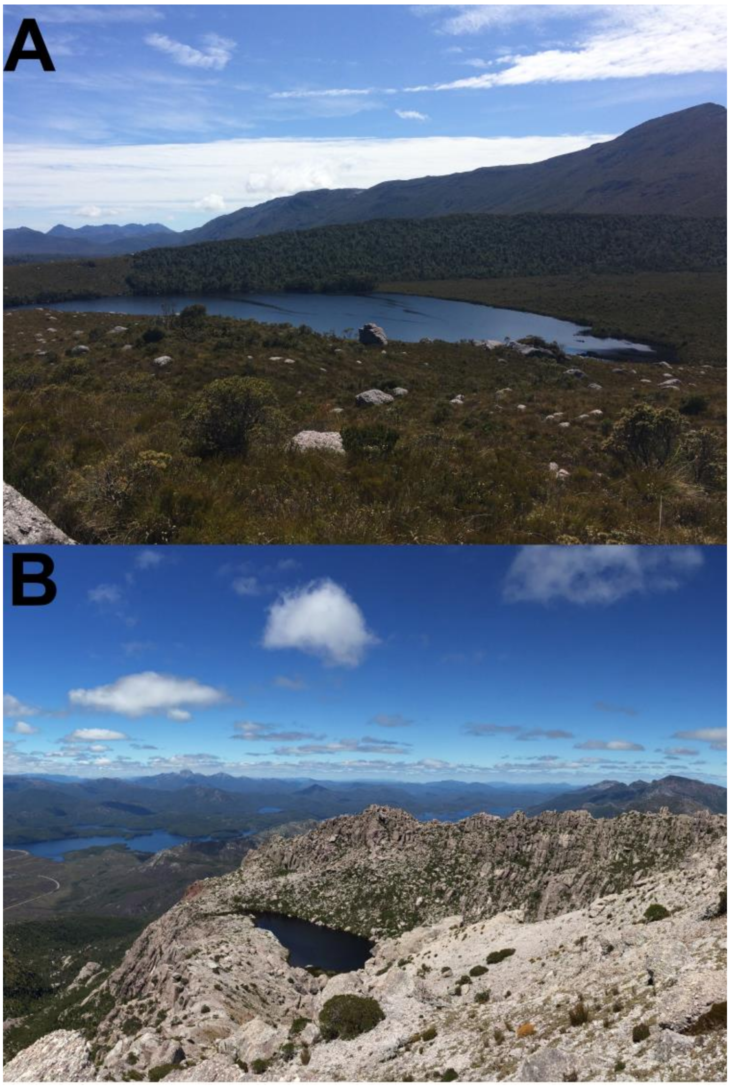

Figure 3 – Photo of: A) Basin Lake and B) Owen Tarn. Credit: Michael-Shawn Fletcher.

The original cores, Basin Lake (TAS1104) and Owen Tarn (TAS1501), were 87 and 70 cm long and span ca. 20,000 and 7,535 years, respectively (Mariani et al., 2019; Mariani and

Fletcher, 2017). In this study, we focused on the upper part of these cores corresponding to the period capturing pre-, during and post-mining activities (last 500 years). For metal background calculations, the period between ~ 1500 and 1700 was considered, while metal concentrations from 1850 to 2014 were used to interpret historical mining activities.

2.3. Dating analyses and age-depth model

Lead-210 (^{210}Pb) dating was processed at the Australian Nuclear Science and Technology Organisation (ANSTO), following standard methods for alpha spectrometry described by Appleby (2002). Details on the method are given in Supplementary Material.

Radiocarbon analyses were processed at ANSTO and at DirectAMS (USA). Radiocarbon ages were calibrated to calendar years before present (cal year BP; 1950) using the Southern Hemisphere calibration curve (SHCal13) (Hogg, 2013).

The age-depth models were created using *Plum* in R (Aquino-López et al., 2018). This approach uses a Statistical-Bayesian framework to obtained sediment chronologies. *Plum* uses an autoregressive gamma process (Blaauw and Christen, 2011) A constant supply of ^{210}Pb to the sediment is assumed to infer an age-depth function. *Plum* differs from other traditional ^{210}Pb dating methods as it uses a forward model of the ^{210}Pb sedimentation system, which allows to supported ^{210}Pb to be inferred together with the rest of the model parameters. Details are given in Supplementary Material.

A chronological marker for mining activity was used within *Plum* to support the age-depth model. Zinc was selected because: (a) it was extracted from the Mount Lyell mines (McQuade et al., 1995); (b) it shows the same depositional trends to other heavy metals mined in the area; and (c) there was no evidence of post-depositional mobility (Andrade et al., 2010; Augustinus et al., 2010; Schneider et al., 2019). For the two sites, the date 1885 (± 2.5 for Owen Tarn and

± 3 for Basin Lake) was assigned to the age-depth models using the first increases in zinc (between 18 and 19 cm in Owen Tarn, and 8 cm in Basin Lake) as the start of commercial mining between 1880 and 1890 (Figure 4). The assigned errors differed slightly between the sites due to the differences in sedimentation and uncertainty.

2.4. Geochemical analyses

The trace elements copper, zinc, cadmium, arsenic, selenium, and lead were analysed to assess the impact of mining activity (Schneider et al., 2019). The major element iron was used to calculate enrichment factors (EFs) and interpret metal changes within the cores. Zinc was excluded from the geochemical interpretation because it was used as an age marker for mining activity in the two age-depth models (see section 2.3). Cadmium was also excluded from historical interpretation in this study as most of the sediment had cadmium concentrations below the confident detection limit of 0.1 mg/kg.

Sediment samples were transported to the Ecochemistry Lab at the University of Canberra, and were analysed using an inductively coupled plasma mass spectrometer (PerkinElmer DRC-e) with an AS-90 autosampler (Maher et al., 2001). The certified reference NIST- 2710 Montana Soil was used as a control to check the quality and traceability of metals. Measured concentrations were in agreement with certified values (Supplementary Table 1). The confidence detection limit applied at the Ecochemistry Laboratory for all metals is 0.1 mg/kg. Details on the geochemical analyses, including digestion, are given in Supplementary Material.

Natural background heavy metal values for the two lakes were based on the average of pre-colonial (1500-1700) trace element concentrations. As this study is interested in assessing atmospheric inputs from mining into the environment, metal fluxes were calculated considering the sedimentation rate, dry bulk density and metal concentrations in sediments, and reported as µg/cm^2/yr.

2.5. Enrichment factors

Estimation of anthropogenic inputs of metals to sediments was calculated by normalising the metal concentrations in contaminated layers to the uncontaminated background levels (Abrahim and Parker, 2008). This method, Enrichment Factor (EF), normalises the measured metal concentration with respect to a sample reference element such as iron (Fe) (Cevik et al., 2009). Natural background metal values for the two lakes were calculated based on the average sediment metal concentration for the period between 1700 and 1800. The EF calculation is detailed in Supplementary Material.

For this study, iron was chosen as the reference element to calculate the EF as this element was the least affected by mining operations (Supplementary Table 2). The EF categories are: EF < 1 = no enrichment, EF 1–3 = minor enrichment, EF 3–5 = moderate enrichment, EF 5–10 = moderately severe enrichment, EF 10–25 = severe enrichment, EF 25–50 = very severe enrichment, and EF > 50 = extremely severe enrichment (Cevik et al., 2009).

2.6. Statistical analyses

All analyses were performed using the R Statistical Software (R Development Core Team, 2008). Stratigraphic plots with metal profiles plotted against age were produced using the R package analogue https://cran.r-project.org/web/packages/analogue/index.html. Principal Component Analysis (PCA) was used to explore the similarity of metal concentrations in the lakes before and after mining began. The PCA plot was produced using the function *prcomp* with the metal scores indicated by *ggbiplot* arrows. (https://www.rdocumentation.org/packages/ggbiplot/versions/0.55). Each of the sediment layers was put into one category, Basin Lake or Owen Tarn, using the groups argument of *ggbiplot.* The ellipse argument was set to be TRUE, and an ellipse is drawn around each lake (group).

3. Results and Discussion

3.1. Chronology and sedimentation rate

Age-depth models from Basin Lake and Owen Tarn are shown in Figure 4 and Supplementary Material Tables S1-S4. The unsupported ^{210}Pb profiles for both cores exhibit decreasing trends with depth and reach background levels by the bottom two ^{210}Pb samples (Supplementary Material Tables S1-S4, Figures S1 and S2). After adjusting for reservoir effects and incorporating the zinc as the chronological anchor, both age-depth models show close agreement to the dating results. The change in sedimentation is consistent with changes in the deposition processes characterised by the impacts of mining. Bottommost sediments had a slow accumulation rate, shifting to fast accumulation at 0-22 cm in Basin Lake and 0-19 cm in Owen Tarn (Figure 4). This shift coincides with the start of mining activities in Queenstown, Tasmania from the 1880s.

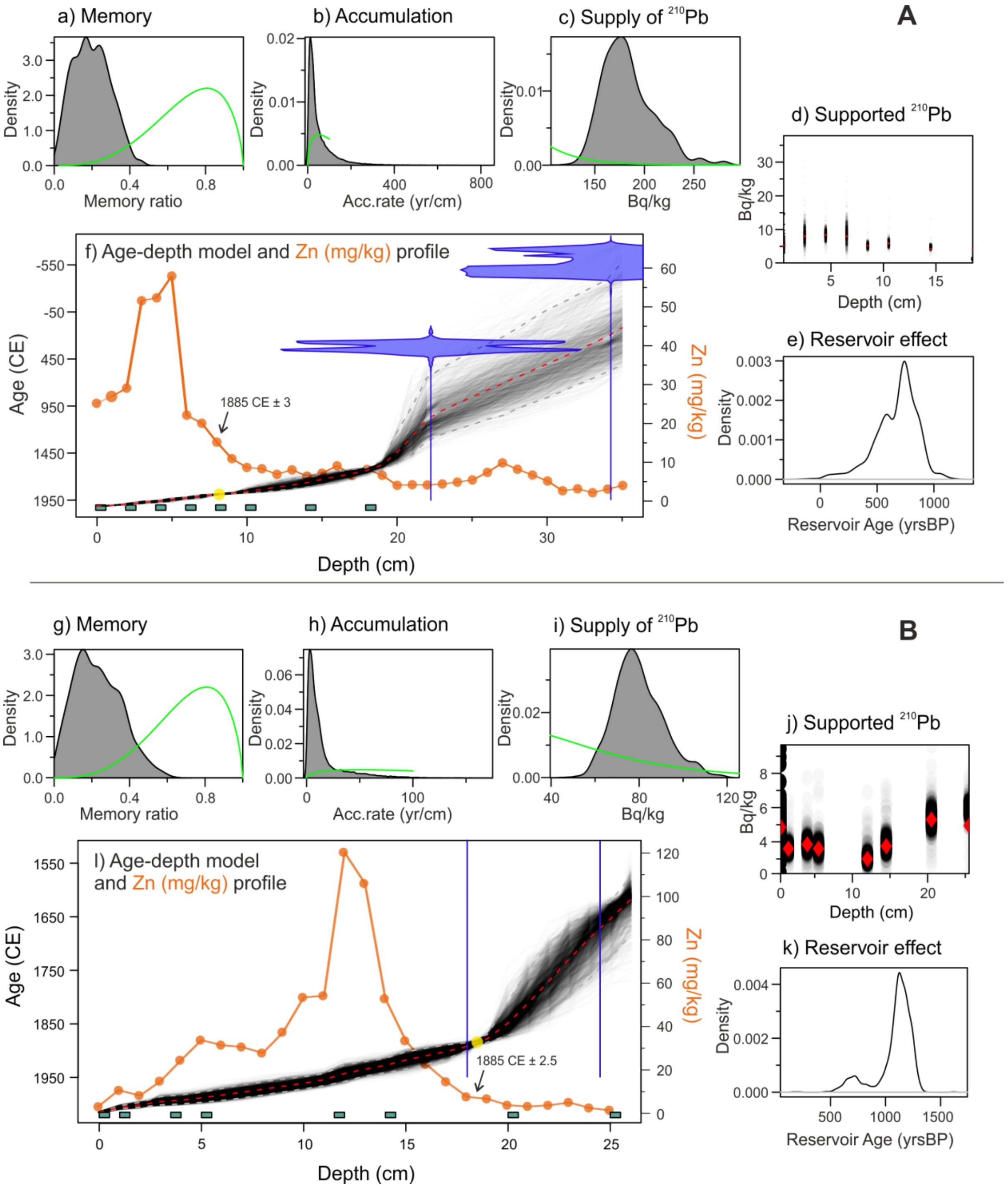

Figure 4 - Age-depth model of Basin Lake (A) and Owen Tarn (Beck et al. 2020) (B) Bayesian ^{210}Pb analyses obtained by *Plum* (Aquino-López et al. 2018). a-g)"Memory" panel (dependence of accumulation rate between neighbouring depths) shows the prior (green) and posterior (grey) distributionsof the memory parameter, b&h)"Accumulation rate" panel shows the prior (green) and posterior (grey) distributions of the accumulation rate, e&j) "Supported ^{210}Pb" panel shows the prior (green) and posterior (grey) distributions of the supported ^{210}Pb obtained from ^{226}Ra measured in red and the mean of the posterior in blue, d&j) "Supply of ^{210}Pb" panel shows the prior (green) and posterior (grey) distributions of the supply of ^{210}Pb to the sediment per year, e&k) "Reservoir" shows the distribution of the calculated reservoir effect between the ^{210}Pb results and the radiocarbon ages. f&l) main panel shows the age-depth model with 95% credible interval and mean as red dashed line. Zinc (Zn) profile is shown in

orange with its associated tie points in the age-depth models in yellow. Green rectangles indicated the depths of ^{210}Pb samples and the blue symbols represent the calibrated radiocarbon dates.

3.2. Catchment and geological differences

The Principal Component Analysis (PCA) demonstrates that these two lakes have distinct geochemical signatures as they cluster separately (Figure 5). The two catchments are unique in terms of geological setting, with Owen Tarn on the upper Cambrian- lower Ordovician Owen conglomerate, and Basin Lake on the central volcanic complex (Corbett and Solomon, 1989). Basin Lake has high iron and selenium background concentrations when compared to other lakes in Tasmania (Schneider et al., 2019).

The spatial distribution of the sediment metal concentrations in the PCA (Figure 5) demonstrates that sediment samples deposited during the copper mine period has the highest metal concentrations. Sediments from before the start of mining (year shown on the PCA plot) are at the beginning of Axis 1 (PC1), in the low metal concentration zone, while samples related to the time after mining activities started are located at the end of Axis 1 (PCA1), in the high metal concentration zone.

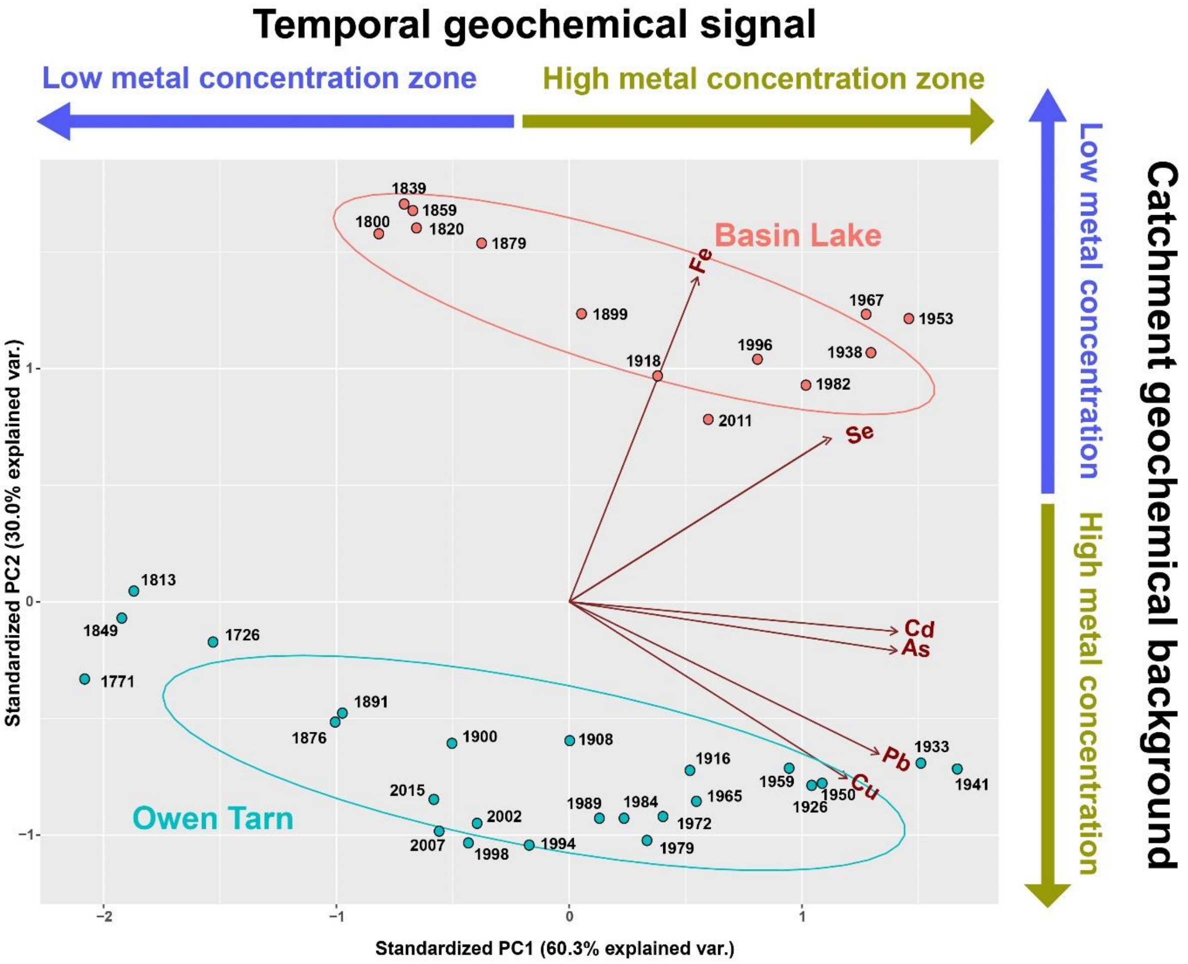

Figure 5: Principal Component Analyses for metal concentrations in Basin Lake and Owen Tarn. Numbers next to dots are the year for a given sediment layer. The ellipses indicate a 0.95 confidence level.

3.3. Historical metal atmospheric fluxes and deposition in lakes

Metal concentrations and fluxes for Basin Lake and Owen Tarn are reported in Supplementary Table 2, with their respective years and sedimentation rates.

3.3.1. Basin Lake

Atmospheric deposition flux and concentrations of copper, arsenic, selenium and lead in Basin Lake significantly increased after 1920, peaking in the late 1960s-early 1970s, and have been declining since then (Figure 6). Gold prospecting in west Tasmania (1850 – 1890) did not result in significant increases in the atmospheric deposition of metals in Basin Lake (Figure 6). Instead, metal deposition increased with the discovery of the Iron Blow, when copper mining and smelting operations started in Queenstown. The major increase in metal deposition in this lake was concurrent with the introduction of new machinery and the commencement of the West Lyell mine in 1934 (McQuade et al., 1995).

The introduction of flotation technology associated with pre-concentration of the ores, and the construction of the Lake Margaret Hydroelectric dam in 1914 (Mathers, 2010), did not cause a major increase in metal deposition in Basin Lake (Figure 6), which means open-cut mining was a larger contributor. Metal deposition decreased at ca. 1970, concurrent with the downturn in mining operations in Mount Lyell, including the closure of the West and North Lyell open-cut mines, and the closure of the smelters in Queenstown in 1969 (Rae 2005).

Selenium concentrations increased in the sediments of Basin Lake in the 1700s, which is earlier than when copper mining activities took place (Figure 6). This could be a result of Se species in this lake being subject to chemically and/or microbiologically mediated oxidation-reduction, which can cause vertical mobilisation of Se within sediment cores (Masscheleyn et al., 1991). Selenium background concentrations were measured as 4.5 mg/kg, which is more than double the background concentrations of other lakes in Tasmania (Schneider et al 2019). The lack of increases in other metals before mining activities commenced, and the unique nature of Se in this lake, suggest that this earlier increase in concentration is unlikely to be linked to mining operations.

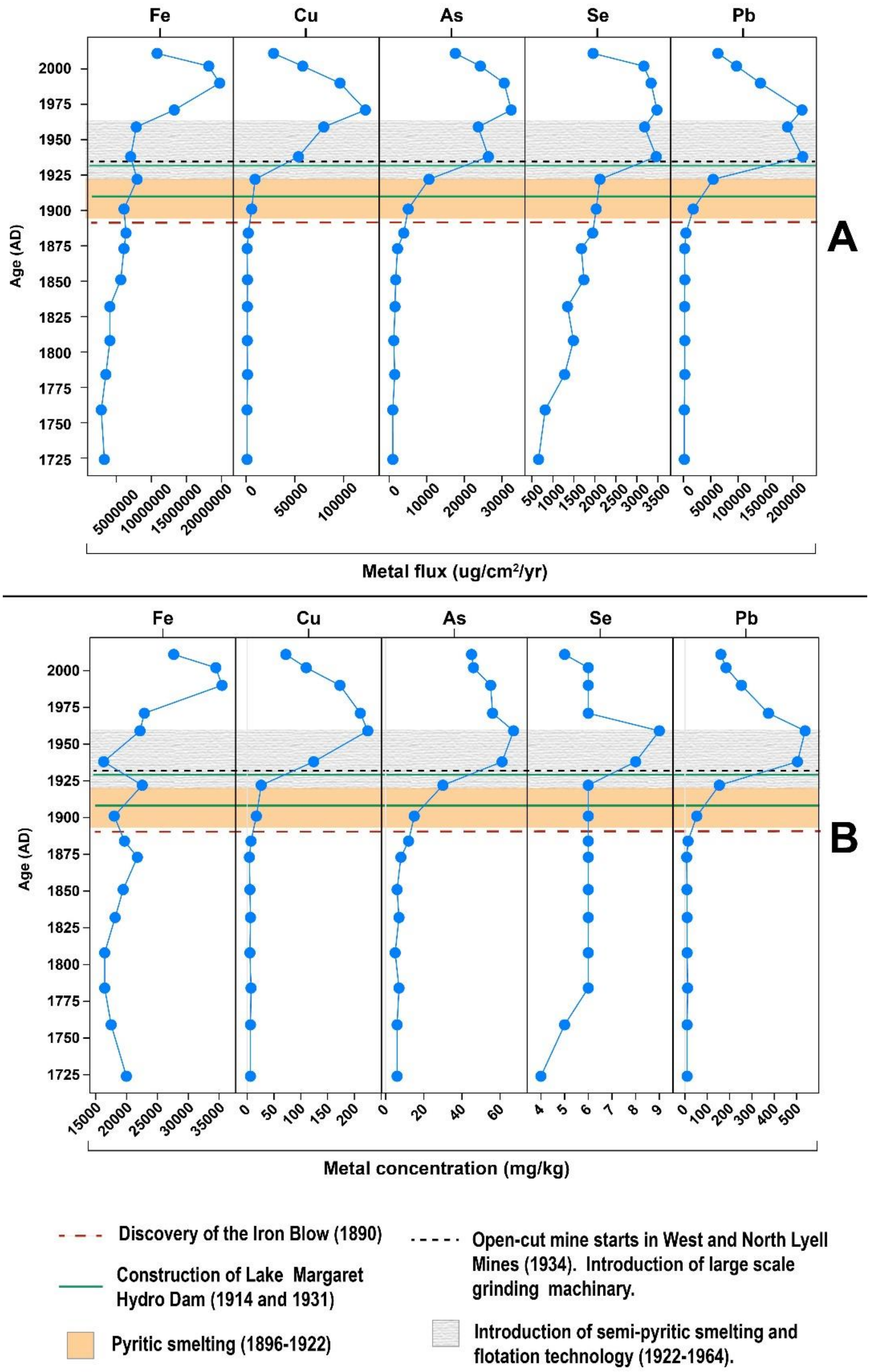

Figure 6 – Metal concentration (mg/kg) (A) and metal deposition flux (µg/cm^2/yr) plotted by year in Basin Lake, with the smelting and mining methods applied indicated.

3.3.2. Owen Tarn

Similar to Basin Lake, the early gold mining exploration in western Tasmania did not result in an increase in metal deposition in Owen Tarn (Figure 7). Metal concentrations and deposition fluxes in this lake increased with the discovery of the Iron Blow in 1890, and with the initial copper mining and smelting activities. With the exception of copper, metal concentrations peaked in the 1930s, when new machinery increased operations and the West Lyell mine commenced open-cut operations in 1934 (Figure 7). Margaret Lake Hydroelectric Dam construction is unlikely to have significantly affected metal deposition in Owen Tarn as this tarn is located opposite to the dominant wind direction relative to Margaret Lake (Figure 1).

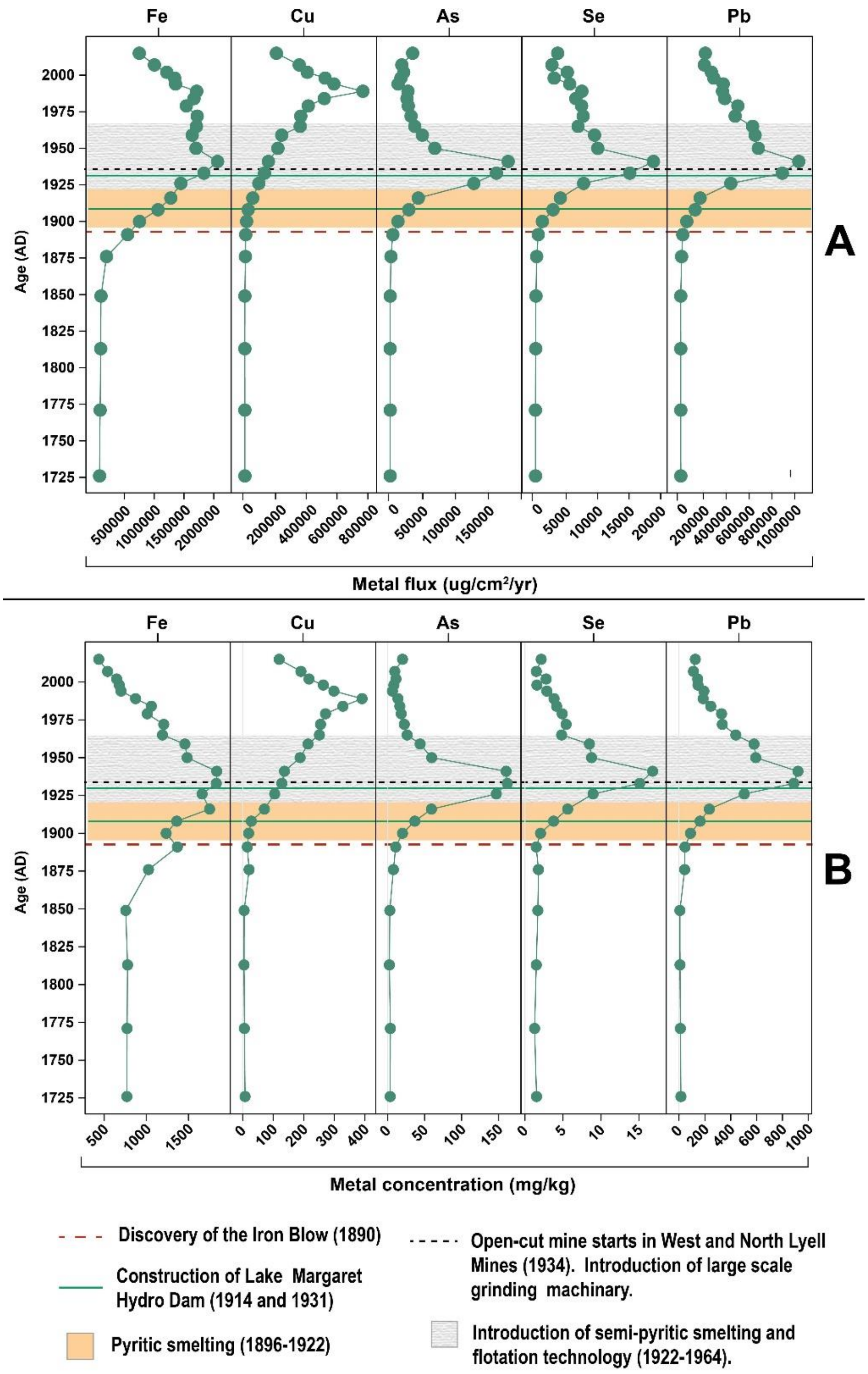

Figure 7 – Metal concentration (mg/kg) (A) and metal deposition flux (µg/cm^2/yr) plotted by year in Owen Tarn, with the smelting and mining methods applied indicated.

Copper in Owen Tarn had a unique deposition history, with concentrations peaking in the 1980s rather than the 1930s, as was the case with the other metals (Figure 7). Given the significantly higher melting point of copper (1083 ºC compared to 817 ºC, 220 ºC and 327 ºC for arsenic, selenium and lead respectively), emissions from the smelter were unlikely to have been a major contributor to airborne copper concentrations in the area. Instead, dust transport from open cut and grinding operations are more likely to have been the major contributor.

The phase and chemical composition of the dust emitted by metallurgical processes is dependent on the nature of the ore and the mining processing (Barcan, 2002). Elements such as lead, zinc and arsenic are mainly emitted from the ore smelting process due to the volatile nature of their compounds (Barcan, 2002). Copper is emitted to a lower extent due to its high melting point. In our study, the time in which copper increases slightly is concurrent with the introduction of automation and new machinery, rather than during the smelting peak. The increase in ore extraction and crushing aligns with the tailing discharge rates during that period (Figure 8). Approximately 97,000,000 t of tailings were produced by Mount Lyell Mining and Railway Company between 1922 and 1994 (McQuade et al., 1995), increasing most notably around 1935- concurrent with both open-cut mining at West Lyell and changes to machinery.

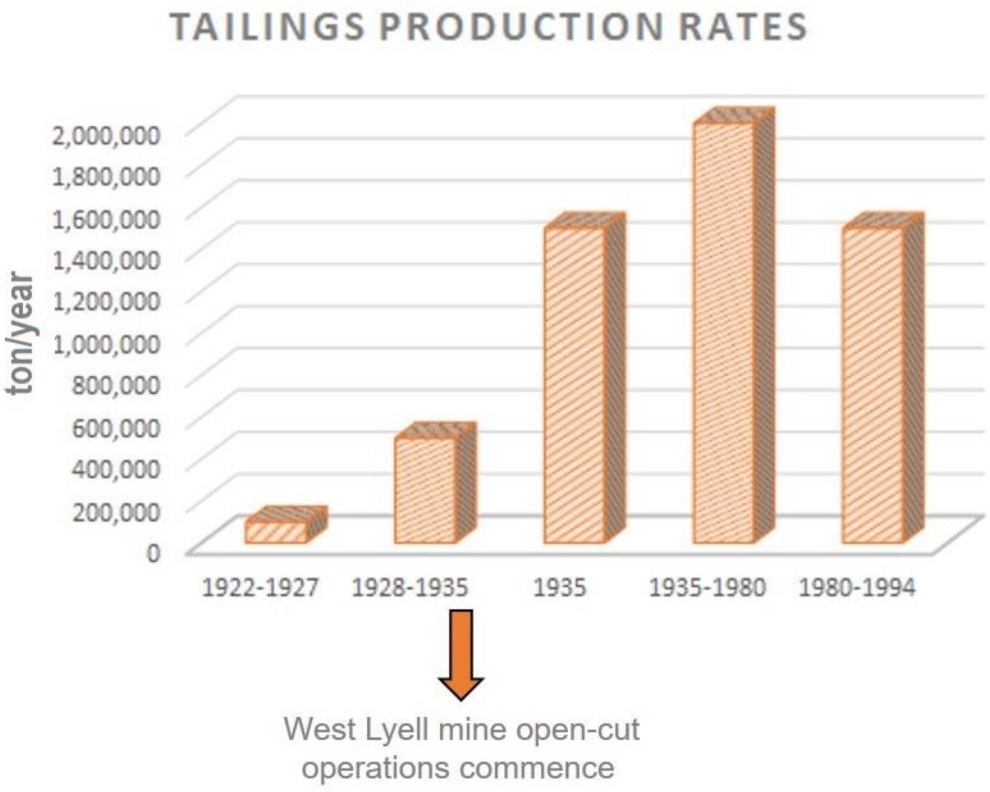

Figure 8- Tailings production rates (ton/year) for mining at Mount Lyell Mining and Railway Company. Data from McQuade, C.V., Johnston, J.F., Innes, S.M., 1995. Mount Lyell remediation. Review of historical literature and data on the sources and quality of effluent from Mount Lyell lease site. (No. 104). Supervising Scientist, Canberra, ACT. Australia.

Comparing the historical deposition of the two lakes, the records show that Owen Tarn metal concentrations increased before Basin Lake. This may be due to the closer proximity of Owen Tarn to Queenstown and the dominant wind direction, placing Owen Tarn in a location more susceptible to receiving metal deposition from smelting and sintering plants (Figure 1). Time lags in metal deposition for lakes further from mining sites have also been observed elsewhere, such as Sudbury mine in Canada (Tropea et al., 2010).

For both lakes, while smelting played a role in metal deposition, the impact of open-cut mining was far greater locally (Figure 6 and 7), especially given the lack of dust control at the site. The scale of mining operations in the 1930s was enormous, to the point that the slag dump was successfully used as an airstrip in 1931. It was even suggested in a 1994 cultural heritage assessment that the area was a “landscape element of high cultural significance” which should be retained (Rae, 1994). Clearly, mining operations during this period were immense, and are reflected in the metal fluxes observed in the sediment cores in this study.

This is not to say that smelting has not emitted as much metal to the atmosphere as mining activities. Queenstown smelters were reported to have processed 4,787 tons of ore in 1898, increasing to 9,787 tons in 1900, and an average of 6,286 tons/year between 1903 and 1922 when a new flotation method was introduced (Blainey, 1993). A number of complaints were issued by local residents about the sulphur fumes emitted during the period of pyritic smelting (between 1896 - 1922), demonstrating the extent of metal emissions during this time (Rae, 1994). However, the metals from smelters are in smaller/lighter forms and have a longer atmospheric transport range (Ghayoraneh and Qishlaqi, 2017; Rasmussen, 1998; Roy et al., 2019; Thuens et al., 2014) while metal emission to the atmosphere from open-cut mining occurs mainly as dust and particulate emissions (Despić and Popov, 1972; Weng et al., 2012), and are more likely to be deposited in the nearby lakes.

3.4. **Enrichment Factors**

The Enrichment Factor (EF) in these lakes showed that they have gone through at least minor enrichment (Figure 9 A-B). In Basin Lake, metals reached their maximum enrichment in the 1930s, corresponding to the peak in mining production and open-cut activities. Arsenic underwent moderately severe enrichment, copper reached very severe enrichment, and lead is under extremely severe enrichment (Figure 9 B).

In Owen Tarn, metal enrichment peaked in the late 1920s and beginning of the 1930s. The earlier peak in metal enrichment is a reflection of its closer location to the source. The elements that underwent major enrichment are copper and arsenic (extremely severe enrichment), and lead (very severe enrichment) (Figure 9B). Copper had a later peak than other metals, as explained above, likely due to its unique chemistry characteristics such as higher melting point.

Enrichment factors declined from the 1940s, concurrent with the downsizing of mining operations due to falling copper prices and increases in processing costs (Mainwarring, 2020). The Basin Lake decline is seen later, again, likely a result of contamination lagging due to its greater distance from Queenstown (Figure 1). These results demonstrate that, while smelters had emitted a significant amount of metals, the commencement of major open-cut mining operations and increased production with the aid of new machinery were the main contributors to metal deposition in the local environment. No dust control methods were in place (Blainey, 1993) and due to the sheer size of the operations (Figure 2), a substantial amount of dust and metal were emitted from open-cut activities.

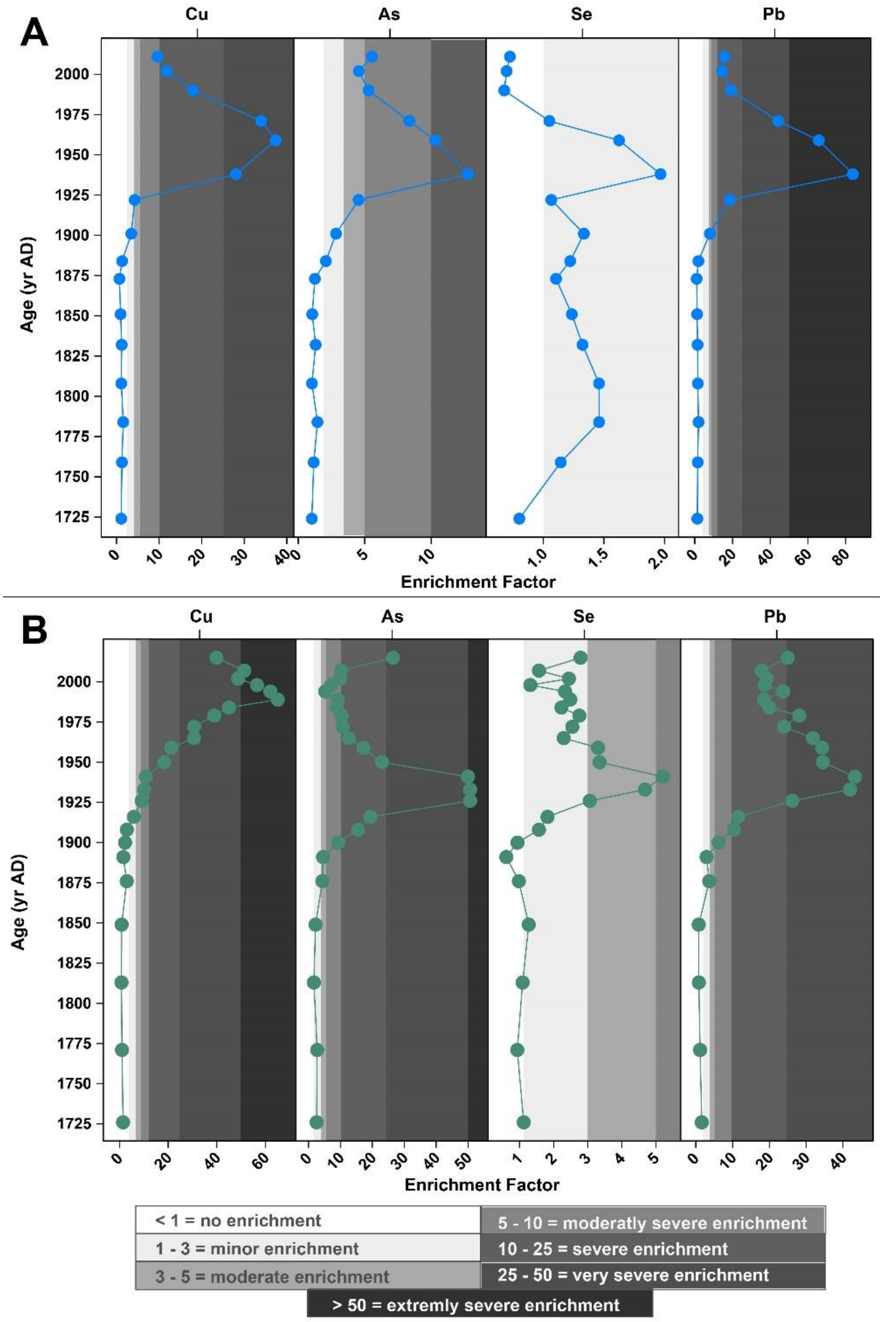

Figure 9 - Enrichment factor of metals plotted against years in sediments of Basin Lake (A) and Owen Tarn (B).

Although previous reports from the Environmental Protection Agency (Tasmania) argued that there are potential sources of metals in the area that are not directly related to mining, many of these sources can also be considered as part of the broader mining-related infrastructure, rather than independent activity. For example, the construction of the Margaret River dam could have contributed to erosion and contamination of nearby catchments such as Basin Lake (Figure 1).

However, the dam was constructed by the Mount Lyell Mining and Railway Company itself, and its primary purpose was to provide electricity for mining work. Similarly, forestry was one of the only other industries active within western Tasmania for an extended period of time, and was at least partially used to provide a source of fuel for the smelter furnaces along with coke (Blainey, 1993). Thus, most activity in the area which was likely to produce metal contaminants was in some way associated with the Mountt Lyell mines, either directly or as a supply industry.

The pollution impacts of colonial mining on local environments has not just been observed in Australia. The history of the Sudbury mine in Canada was, in many ways, similar to the Mount Lyell works: nickel and copper ores were discovered in the late 1800s, with roasting and smelting facilities established in the early 1900s (Tropea et al., 2010). The onset of the Sudbury mine was characterised by displacement and the removal of first nation communities, contamination of the environment through acid mine drainage, toxic effluents and atmospheric pollution (Winterhalder, 1995).

Through research supported and funded by the Ontario Ministry of the Environment, the peak in copper concentrations in the mine was recorded in the mid- 20th Century, at 2400 mg/kg, increasing from a background of 120 mg/kg (Tropea et al., 2010). This increase is larger than the changes observed in this study (225 and 391 mg/kg, respectively, for Basin Lake and Owen Tarn), but the recovery of the area surrounding the Sudbury mine remains a good analogue for changes occurring in the Queenstown/Mount Lyell area. In both historical mines, the recovery of metal concentrations in the sediment of these lentic ecosystems is positive, but the legacy is an on ongoing environmental problem, particularly through the acid drained to downstream water catchments (ANSTO, 1994). It has been estimated that the single West Lyell waste rock dump will continue generating acid leachate for more than 600 years. Approximately 130 tonnes of copper and 1300 tonnes of sulphate per year leach from a single 25 ha dump below the West Lyell open-cut (ANSTO, 1994).

A significant difference between the environmental work at Mount Lyell compared to the Sudbury mine is that the latter has been subject to many more environmental studies. While the Canadian government supported and worked together with academics to generate independent environmental studies (Keller et al., 1986; Molot et al., 1984), the Tasmanian government and other institutions have criticised and actively discouraged independent scientific findings (Atkin, 2016; Baker, 2019). This combined with the lower number of researchers in Australia has resulted in fewer environmental studies and therefore limited understanding of the impact of metal contaminants on human and animal health.

Thus far, there has been no evidence for impacts on human health in the Queenstown region as it has been reported for lakes around Sudbury (Gunn et al., 1988). However, this may be due to a lack of studies. Results from a previous study in Owen Tarn showed that mining pollution resulted in algal assemblages and biological effects, such as deformed diatom valves (Beck et al., 2020). Further independent research assessing the ecological impacts and human health effects caused by Queenstown mines and smelters are needed.

3.5. **Environmental implications and public and governmental perceptions**

The large-scale mining operations at Mount Lyell had a major impact on the surrounding environment and on the local population living in the area. An 1896 report in the *Zeehan and Dundas Herald* claimed that all undergrowth within a mile to the north, east, and south of the works was dead, while the "*forest presents the appearance of having been ring-barked*" (Zeehan & Dundas Herald, 1896, in Rae, 2005, pp. 124). Historical descriptions reported the smelter as the main source of pollution in Queenstown (Blainey, 1993; Mainwarring, 2020; Rae, 1994), likely due to the visible damage caused by the sulphur fumes. Due to these impacts, the Mount Lyell Mining and Railway Company requested, and was granted, an extension of the Noxious Trade Area to a distance of five miles from the smelter (Rae, 2005).

The Company appeared to be aware of the impacts the fumes were causing, and the legal defence was that they were "*carrying on the trade of smelting with the best means known at the day… consisting simply of a high chimney*." (letter from R. Sticht to Mount Lyell Company's Secretary 1897, reproduced in Rae, 2005, pp. 125). Metal emissions from the smelters only decreased in 1922, not driven by better environmental and health guidelines, but by changes to the smelting process required to increase efficiency in copper production (Blainey, 1993).

The local residents were aware of the environmental damage being caused to the environment by the smelting works (Rae, 2005), however, the economic assurance that the smelter provided was seen by both the company and the government as protection against any legal action (Blainey, 1993; Rae, 1994). By the late 1890s, the profits of the Mount Lyell Mining and Railway Company had exceeded the entire revenue of the Tasmanian government (Keele, 2003) and by 1900, the Queenstown smelting works were Tasmania's largest industrial enterprise, employing 1300 people (Blainey, 1993). Attempts to raise awareness of the health issues encountered defence from the mining industry, with a 1901 newspaper report expressing concern about "*the weak and struggling companies being victimised by unwarranted and vexatious claims resulting from the emission of noxious fumes*" (Mount Lyell Standard, 1901, reproduced in Rae, 2005, pp. 129).

Paradoxically, Tasmania was one of the first states in Australia to implement environmental protection legislation, with the *Environment Protection Act 1973* (comprising air, water and noise pollution, and waste management) (Bingham, 1992), yet mining companies were allowed to operate under exemptions by the government of the day (De Blas, 1994). The argument supporting exemptions was that the cost of installing equipment to comply with emission standards would be such that the mine would have to close (De Blas, 1994).

The negative environmental impacts in Tasmania have also been seen as positive by some, who claim that the bare hills are a major tourist attraction and part of the history and cultural heritage of the town (Anderson, 1993). The decrease in copper-rich ores and decline in copper prices allowed for metal concentrations in the sediments to begin returning towards background levels. However, this period also represented an economic downturn for the local economy and was seen as an unfortunate occurrence by many (Blainey et al 1993).

In addition to the damage caused by the mine and smelter activities, the Mount Lyell Mining and Railway frequently went outside of its permits for logging and also discharged waste into river systems (Rae, 1994). The Queenstown Council defended the Company's actions, and the isolation of the site meant that government response was often delayed by months, if it occurred at all (Rae, 1994). Thus, despite awareness surrounding the issues caused by pollution, the Mount Lyell Mining and Railway Company was able to continue operations largely unsupervised (Rae, 1994).

The lack of environmental protection from legacy mines is a widespread problem in Australia. Mining has been one of the main economic activities over the last 200 years, encouraging immigration to the country and generating economic growth (Gregory, 2001). Legacy mines in Australia, such as Mount Lyell, commenced activities before environmental management and mine rehabilitation regulations were in place as they are today. The country currently has more than 50,000 abandoned mines (Unger, 2014) with some representing a significant contamination threat. In the case of Mount Lyell, mining leases or titles no longer exist, and responsibility for rehabilitation cannot be allocated to any individual, company or organisation responsible for the original mining activities.

Understanding the legacy pollution left by mining can provide important lessons for Australia and other countries to make key environmental decisions that ensures ecosystem and human health services for future generations.

4. **Conclusion**

Mineral exploration in western Tasmania began not long after British settlement. Both copper mining and smelting led to enormous amounts of metal pollution in the area that caused serious environmental degradation. The results of this study allowed for the reconstruction of atmospheric metal deposition in two freshwater lakes in close proximity to the mines, providing an understanding of the impact changes in mining and smelting methods had on metal deposition in the local environment over the years of operation. Although smelting released substantial amounts of metals to the atmosphere per year, dust emissions from open-cut mining and the introduction of large-scale machinery were the main source of metal deposition locally. These findings demonstrate the significant dust budget in this region.

Tasmania, as a British colony, faced political, economic and social pressures that had no consideration for environmental systems. This pressure for resource extraction and local calls for development combined to turn the Mount Lyell Mining and Railway Company into the largest copper producer in both the Southern Hemisphere and the British Commonwealth. The impact of these pressures caused environmental damages that will take centuries to return to a state similar to pre-colonial.

Currently, no government body, company or individual can be held directly responsible for the environmental damage, as the first environmental regulations were in place after 1970, and mining companies still remained exempt. The historical mining events and environmental impact assessment here are to be used to identify the impact of historical flaws in environmental protection measures. It is important for Australia to address the damage caused by legacy sites such as Mount Lyell, as well as ensuring that current environmental regulations are sufficient to protect ecosystems for current and future generations.

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