Introduction
Tailings from gold mining are known to be a significant source of mercury emissions world-wide and their management is coming under increasing scrutiny as a result of the UN Environment Program’s Minamata Convention on Mercury. While attention has focussed on the immediate risks posed by mercury use in small-scale artisanal mining (e.g. Esdaile and Chalker, 2018; Gunson and Veiga, 2004; Lacerda, 2003; Schmidt, 2012; Spiegel et al., 2018; Spiegel and Veiga, 2010; Veiga et al., 2006), less is known about risks posed by legacy tailings resulting from historical mercury use in pre-20th-century gold mining. Mercury has been used in gold mining from antiquity (Agricola, 1950) and spread to the New World with European exploitation of Mexican and Central and South American gold and silver deposits from the 16th century (Bakewell 1971; Guerro, 2017; Lacerda and Salomans, 1998; Malm, 1998; Robins, 2011). Gold mining and mercury use spread further in the 19th century, with gold rushes to Pacific Rim countries including the western United States and Canada, Australia and New Zealand, and later to South Africa (May, 1970; Mountford and Tuffnell, 2018). Increasing industrialisation and technological efficiencies during this period resulted in high levels of mercury use. At the same time, environmental regulation was in its infancy, with few or no controls over the discharge of mining wastes, including mercury (Isenberg, 2005; Lawrence and Davies, 2014, 2019).

Previous research indicates that mercury use in mining during this period has contributed to significant increases in global atmospheric mercury emissions (Miller and Gustin, 2015; Nriagu, 1994; Singer et al., 2013; Strode et al., 2009). Miners used mercury to amalgamate gold particles when processing alluvial washdirt and crushing auriferous quartz, with significant portions of the mercury lost in the tailings and discharged as atmospheric emissions when amalgams were retorted and concentrated for gold recovery. Elemental mercury in legacy mine tailings also presents risks to the environment and human health (Ashe, 2012; Kim and Jung, 2012; Martin et al., 2016; Pearce et al., 2010; Slowley et al., 2005), with recent studies focussing on soil and plant bioremediation of mercury contamination (e.g. Alcantara et al., 2017; Chasanah et al., 2018; Opiso et al., 2018). Australia has tens of thousands of legacy mine sites (Unger et al., 2012), many of which are almost certain to include mercury-contaminated tailings. Despite the historical scale of gold mining in Australia, the extensive use of mercury, and the lack of anti-pollution measures, there has been little research to document the extent of mercury contamination from this source. Our paper begins to address this gap by using documentary evidence to estimate historic mercury losses in Victoria, and to model the likely distribution of high mercury concentrations in legacy tailings. The analysis is restricted to the loss of anthropogenic elemental mercury only and does not consider atmospheric emissions from the retorting of mercury amalgams, as no reliable historical data are available for analysis.

Victoria has historically been one of the world’s most productive gold provinces and during the period...
1851–1914 it was the source of more than 2% of all the gold ever recovered to that time (Phillips and Hughes, 1996). The legacy implications of industrial mercury use in the state, however, are poorly understood. In this paper historical research provides crucial context for modelling the distribution of elemental mercury in legacy mine tailings. Fine-grained analysis of historical data published by the former Mines Department from the 1860s—1880s has been used as the basis for understanding the relationships between processing technologies and mercury emissions and for mapping their spatial distribution across the state. This discussion provides a foundation for the further research needed for Victoria to effectively manage mercury emissions from legacy mine tailings.

The analysis here builds on previous research (Davies et al., 2015) that used documentary sources from the Mines Department to estimate total elemental mercury losses from mechanical ore crushing. Sources included annual summaries of mining activity published as Mineral Statistics of Victoria and quarterly reports published as Reports of the Mining Surveyors and Registrars. Several techniques were used in Victoria to separate gold from ore and processing methods changed over time as technologies became more efficient and more highly industrialised. Each method varied in the quantity of mercury used and its potential for loss to the environment. Further, the varying and complex geology and chemistry of ore bodies across the Victorian gold province meant miners used different methods based on the mineralogy of local ores. Thus, it is likely that mercury contamination will be more concentrated in some areas than in others. Spatial mapping of the technologies combined with mercury consumption figures allows the distribution of contamination to be modelled, which will in turn facilitate more targeted testing of mercury in the environment. Mining occurred across a large portion of the state, so improved testing regimes are likely to have considerable benefit.

Most research on mercury losses from historic mining in Victoria has been highly localised. Sample locations in waterways have included the Lorderderg River west of Melbourne (Bycroft et al., 1982), the Gippsland Lakes in eastern Victoria (Fabris, 2012; Glover et al., 1980), Reedy Creek in the north-east (Churchill et al., 2004) and the Goulburn River in central Victoria (McCredie, 1982). Mercury and other heavy metal contamination (especially arsenic) in soils affected by historical mining has also been studied at various locations in central Victoria, including Ballarat, Bendigo, Maldon and Stawell (Abraham et al., 2010; Martin et al., 2016; Noble et al., 2010; Pearce et al., 2010, 2012; Sultan and Dowling, 2006). Victorian data indicate similar patterns of mercury toxicity to those recorded at other centres of 19th-century gold mining, including New Zealand (Moreno et al., 2004), California (Alpers, 2017; Isenberg, 2005) and other locations throughout North and South America (Lacerda and Salomons, 1998; Lacerda, 2003; Nriagu, 1993, 1994; Robins, 2011; Singer et al., 2013).

One of the most detailed surveys of mercury contamination in the state was carried out by the Environment Protection Authority (Victoria) in 2016. The EPA assessed mercury and arsenic contamination levels in a range of aquatic ecosystems that had been exposed to historical gold mining activities (EPA, 2016). This was part of a broader program of monitoring the health of waterways across the state in relation to catchment land use, vegetation and biotic indices. The EPA study used the MINSITE spatial database to identify clusters of historical mining activity that overlapped waterways used and valued for recreational fishing. Ten waterways were targeted for detailed monitoring and analysis, with results showing sediment-bound mercury levels exceeded Interim Sediment Quality Guidelines at four of the ten locations. The EPA noted that while density of historical mining activity can be used to identify sites with elevated mercury, the results show the method does not well predict mercury concentrations as these are likely to vary spatially across a site and across the range of sediment particle sizes present. Our discussion here provides that predictive capacity by offering more nuanced analysis of the likely volume and geographical location of mercury contamination at specific sites that resulted from historical mining in Victoria.

Legacy gold mines in Victoria

Commercial exploitation of gold in Victoria began in 1851, triggering a gold rush that mirrored the contemporary rush to California in scale and effect (Blainey, 1963). The industry declined by the end of the century and continued on a smaller scale until the Second World War. In this period miners found at least 2500 tonnes of gold (Figure 1). Around 40% of the gold came from alluvial (placer) deposits in sands and gravels of stream beds, but nearly half derived from crushing and processing hard rock quartz deposits recovered from deep below the surface (Birrell and Lerk, 2001; Phillips and Hughes, 1996). Throughout this period the environmental regulation of mining was minimal. Mines discharged tailings, contaminants and atmospheric pollution directly into the environment until the first legislation to control tailings emissions was passed in 1904 (Lawrence and Davies, 2019).

The goldfields region covers a substantial portion of central and north-eastern Victoria, extending 500 kilometres from the New South Wales border to the Grampians-Gariwerd ranges in the west. Legacy and abandoned mines are widely distributed and well preserved throughout this area, especially on public land reserves. Mine sites include patches of shallow shafts up to 20 m in depth, substantial voids covering hundreds of hectares created by ground and hydraulic sluicing, machinery installations and building ruins, and deep shafts accompanied by piles of mullock (overburden) and tailings. In-filling of many thousands of mine shafts was undertaken by the Mines Department around Ballarat and Bendigo between the 1930s and 1970s (Condon, 1969). Several municipal councils on the goldfields have also levelled and redistributed mine tailings and mullock heaps for housing and other local development, while in other cases mine tailings were reprocessed using new methods after the Second World War to recover residual gold (Birrell and Lerk, 2001; Lerk, 2005).
Most of these mines, however, are now considered ‘historical’ and are not regulated under the Mineral Resources (Sustainable Development) Act or Regulations (Government of Victoria, 2019), which otherwise manage mine rehabilitation. The Victorian government does not consider them to be ‘legacy’ or ‘abandoned’ mines as generally understood (e.g. Abandoned Mines Working Group, 2010). These sites are managed on a case-by-case basis with emphasis primarily on the risk posed by open shafts. The number of abandoned historical gold mines extant in Victoria is uncertain, although the VicProd and VicMine databases developed by GeoScience Victoria (2002) list more than 3000 sites. This is a significant underestimate, however, as the databases do not include mines worked as small alluvial claims, which was a common practice in the 19th century. In addition, the Bendigo and Ballarat mining districts are poorly represented in the databases, despite being the most active and richest mining regions in Victorian history. A final limitation is that these datasets record extraction locations but are silent on the location of ore processing and concentration, which often occurred elsewhere in specialised treatment plants and which is more relevant for the distribution of mercury.

**Origins of mercury used in Victoria**

Australia is rich in most minerals but not cinnabar (mercuric sulphide, HgS). The Australian continent features similar geological settings to the main historical mercury-producing regions in Spain (Almaden), Slovenia (Idria) and California (New Almaden and New Idria) but known deposits in Australia are small and have generally proved uneconomic to exploit. The historical gold mining industry offered a rich market for mercury but many years of prospecting, mine development and cinnabar processing yielded very limited output. Global mercury demand in the 19th century could be met with a few very large deposits, worked by cheap labour and controlled by a small number of producers. The Rothschild family, for example, maintained a monopoly on production by their hold on mining leases in Spain and contracts in Slovenia (Parra, 2016).

Notwithstanding Australia’s limited mercury deposits, several attempts were made during the 19th and early 20th century to mine and treat known resources. McQueen’s (2011) review of quicksilver production in Australia identified several operations in New South Wales and Queensland established between the 1860s and the First World War. The most significant of these included Kilkivan in south-east Queensland, where the company refined almost 6 tonnes of mercury between 1873 and 1892, and Pulganbar in north-east New South Wales, which produced c.1 tonne in 1915–1916 (McQueen, 2011; Stubbs and Gardiner, 2015). There were also minor deposits near Jamieson in Victoria’s central highlands, at Willunga in South Australia, and at Jane River in south-west Tasmania, while exploration licences were issued to search for mercury in Gippsland in the 1860s (MSV, 1868). These volumes of locally treated mercury, however, were far below the needs of the gold mining industry, which looked to international sources for a secure and economical supply. The local price of mercury in the 19th century was about 2 shillings and sixpence per pound (0.45 kg), at

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**Figure 1: Map of Victoria showing principal goldfields and centres of pyrites processing.**

Gold deposits were mined across the Central and Eastern Highlands of Victoria from 1851. The principal population centres associated with the industry were Ballarat, Bendigo and Castlemaine. DOI: https://doi.org/10.1525/elementa.432.f1
a time when gold traded for 70 shillings per troy ounce (31.1 g). Mercury was normally stored and transported in iron bottles or flasks that contained 76 pounds (34.4 kg) of quicksilver. Glass, porcelain and stoneware ceramic bottles were also used at times as the mercury did not stick to the insides. Victoria imported 675 tonnes of mercury between 1868 and 1888 (MSV, 1868–1889, Davies et al., 2015), the period for which the best figures are available. Annual totals varied but the mean annual quantity imported was 32 tonnes. Out of this total more than 80 tonnes were also re-exported to other Australian colonies, while some was used in non-mining applications such as medical treatments and dental amalgams. Mining companies also stockpiled mercury, which meant that large volumes were available for purchase when companies went out of business. Most of the mercury imported during this period was probably used to replace mercury lost during the processing of auriferous quartz.

Historical sources and methods
A range of historical sources provide important quantitative and qualitative information about rates of mercury use and loss in Victoria’s gold mining industry. These include quarterly reports prepared by district mining surveyors and the annual series *Mineral Statistics of Victoria* (MSV), both published by the Mines Department. Information included ore volumes, the total number of stamp heads used in crushing batteries, the quantity of mercury used per stamp head each week for amalgamation, and the quantity of mercury (in ounces) lost per stamp head each week. In a previous paper (Davies et al., 2015) we used these data to calculate the amount of mercury used by miners to amalgamate gold in stamp batteries and rates of mercury lost in the process. This analysis spanned the years 1868–1888, a period for which consistent and comparable data were available, and covered Victoria’s seven mining districts of Ararat, Ballarat, Beechworth, Bendigo, Castlemaine, Gippsland and Maryborough. We calculated that a minimum of 70 tonnes of elemental mercury were lost from stamp batteries and amalgamating plates and troughs during this period. The mercury was either retained close to mine workings or discharged into nearby waterways as part of semi-liquid waste.

Methods of treating auriferous pyrites and associated rates of mercury use and loss were reported by a government ‘Pyrites Board’ that sat in 1873 (Board, 1874). The board was typical of 19th-century inquiries where government authorities interviewed experienced and expert witnesses, gathered and collated evidence and published the results in the public interest and to promote industrial progress. The Pyrites Board was formed in response to widespread concern that pyritic treatment methods were highly variable, often inefficient and presented a public health risk. These concerns were also expressed by mine managers and engineers in Europe and America during this period (e.g. Collins 1885; Phillips 1887). Board members inspected 14 pyrites treatment works across Victoria and interviewed 58 witnesses. The latter included mine managers, who described the amounts of mercury used and lost in treating pyritic ores. We discuss these rates in more detail in the section ‘Processing Pyritic Ores’.

**Mercury use in Victorian gold processing**
Miners have used mercury to amalgamate gold and silver since at least the Roman period. German metallurgist Georgius Agricola described the mercury amalgamation process in Europe in the mid-16th century, along with its devastating environmental effects (Agricola, 1950:295–300). Mercury remained a crucial component of processing gold-bearing ores in 19th and early 20th-century Australia. Gold miners used mercury to amalgamate small flakes and particles of gold liberated from ore crushed in stamp batteries. Processing pyritic (sulphide) ores also consumed significant amounts of mercury.

Victorian miners appear to have used minimal amounts of mercury for working alluvial placer deposits compared to their contemporaries in California, where it quickly became an integral part of hydraulic mining throughout the region. Coastal California featured substantial ore deposits of mercury sulphide that were widely exploited in the 19th century. One of the largest operations to exploit this resource was the New Almaden Quicksilver Mining Company at San Jose. Annual production by the company between 1850 and 1885 was over 770 tonnes each year. Mercury production was the second largest industry in California after gold mining until the 1890s. Miners typically charged the upper 100 metres or so of long sluice boxes with 100 kg of mercury, with more distributed lower down. Environmental historian Andrew Isenberg (2005:50) reports an 1869 estimate that California’s mines consumed almost 500,000 kg of mercury each year. While much of this mercury was cleaned up and recovered by mining crews, a great deal was washed out of the sluice boxes and into the environment with the mine tailings. Canyons below the largest hydraulic mines may have contained up to 20 tonnes or more of mercury every mile (Greenland, 2001; Isenberg, 2005).

In Victoria, recorded details of the use of mercury in sluice boxes are rare, despite numerous mentions of mercury in other branches of mining, and it was likely to have been used infrequently. The periodic use of mercury in alluvial mining is suggested, however, by reference to ‘quicksilver and compound cradles’, which consisted of a large cradle with three tiers of tables and a ‘quicksilver ripple’ (Smyth, 1980; Figure 2). These may have been like the ‘quicksilver machines’ used in the early gold rush in California (May, 1970). During the 1870s there were generally between 150 and 200 compound cradles used in Victoria, mostly in the Ararat, Castlemaine and Maryborough mining districts, although it remains unclear how much mercury the cradles used and discharged.

The most significant use of mercury was in processing ore from veins of auriferous quartz, which were recognised by the 1860s as the primary source of gold. Recovering the gold meant processing ores via a range of technologies including roasting, crushing and amalgamation with mercury. The most common way of crushing gold-bearing ore was in a stamp battery, which typically consisted of a set of heavy iron stamp heads held in a timber frame, with each head weighing 200 kg or more (Birrell, 2005) (Figure 3). The stamp heads were lifted and dropped by a rotating overhead cam shaft driven by steam engine or water wheel. The ore was pushed into a large cast-iron
Figure 2: Quicksilver cradle from the 1860s. Quicksilver cradles were widely used in Victoria in the 1860s and 1870s to wash gold from alluvial deposits and amalgamate the gold particles with mercury. Source: Smyth 1980, The gold fields and mineral districts of Victoria, p. 619. DOI: https://doi.org/10.1525/elementa.432.f2

Figure 3: Stamp batteries and mercury amalgamation tables at the Port Phillip and Colonial Gold Mining Company. Stamp batteries crushed auriferous quartz to a fine sand, which was mixed with water to form a slurry. The water and sand slurry was forced through fine mesh screens and onto inclined wooden tables covered with copper sheets coated with mercury. The mercury caught and amalgamated the gold, which was periodically scraped off the sheets and retorted to collect the gold and recover the mercury for reuse. Mercury was also placed in troughs at the ends of the tables to capture more gold from the tailings. This engraving was prepared by C.E. Winston in 1869 (source: State Library of Victoria, image IAN19/06/69/132). DOI: https://doi.org/10.1525/elementa.432.f3
battery box, mixed with water and pulverised into sand by the stamp heads. The slurry of water and sand was then forced from the box and onto sloping wooden tables below the stamp heads. The tables were covered with copper sheets coated with mercury, which caught and amalgamated much of the free gold from the battery sand. Some mining companies also installed troughs or ripple boxes at the foot of the battery box and amalgamating tables. The troughs were filled with mercury and caught a further portion of gold particles. The amalgam was regularly scraped off the copper sheets and heated in a furnace to vapourise the mercury and recover the gold. More mercury was added to the sheets each time as significant fractions of the mercury were lost in the agitations of the battery, in poor maintenance of the blanket tables, and in the tailings discharged after processing. The retorting furnaces were designed to recapture the mercury vapour, but some atmospheric mercury would also have been lost through this process.

An alternative process used blanket strakes, which were heavy blankets of woollen felt or cattle hides placed over wooden boards below the stamps. The finely crushed ore was passed over the blankets and the gold particles were caught and held in the blanket fibres. The crushed sand and gold were washed from the blankets and then treated in a ‘berdan’ pan (Woodland, 2001). This was a rotating iron basin up to one metre in diameter containing a heavy steel ball or weight for grinding. Blanket sand was milled in the pan with water and mercury for several hours until the gold amalgamated with the mercury. A charge of 100–150 kg of mercury for each pan was common, much of which was lost when the waste sand was discharged. The amalgam was then squeezed in a canvas or leather bag to extract the free mercury, with the remainder heated in a retort and collected for reuse. The retorted gold was sold to a bank or mint for further refining.

**Processing pyritic ores**

An additional source of anthropogenic elemental mercury loss not captured in the above statistics was tailings associated with processing pyritic ores. Auriferous quartz crushed by miners in the early years of the gold rush came mostly from shallow reefs above the water table. Base metals associated with gold in these ores were largely oxidised by percolating rainwater, leaving large gold particles that were easy to separate by mercury amalgamation. Ore from depths below the water table, however, contained intact base metals including iron, arsenic, lead and zinc. These arsenic-bearing sulphides, referred to as pyrites or refractory ores (also mundic or fool’s gold), represented a major challenge to efficiently and profitably recovering the embedded gold (Phillips and Hughes, 1996; Rae, 2001). Conventional mercury amalgamation of pyritic ores resulted in ‘flouring’ or ‘sickening’, where tiny mercury particles were coated with a film of sulphides, and the gold was washed away with mercury in the tailings. The loss of gold was significant, prompting technological adaptations to resolve the issue.

There were two parts to solving the problem: separating pyrites from the battery tailings without using mercury; and economically extracting gold from the concentrated pyrites. The Port Phillip and Colonial Gold Mining Company experimented successfully during the 1860s with roasting, grinding and mercury amalgamation (Board, 1874). The company published its results to encourage industry innovation, with numerous mining companies adopting and adapting its techniques (Woodland, 2001).

To solve the first problem of separating pyrites, mining companies adapted a process used in Cornwall to concentrate tin and copper ores that relied on gravity instead of mercury (Henderson, 1858). The ore was crushed and passed over blanket strakes as described above. Then the crushed sand and gold were washed from the blankets and further concentrated in buddies, which were large, circular basins with sloping sides (convex or concave), up to 6 metres in diameter. Crushed quartz and pyritic grains were mixed with water and piped to the outer edge of the buddy floor. Sweeper arms separated the heavier pyrites from the lighter quartz grains. The pyrites were cleaned from the outer part of the buddy for subsequent processing, while the quartz tailings were discharged into a retaining dam.

To solve the second problem, the concentrated pyritic sands from the buddies were roasted (or calcined) in a reverberatory furnace, where the heat was reflected onto the contents of the furnace. This process burnt off arsenic oxide and sulphur dioxide in the sands, making them amendable for use with mercury. The roasted sands were then finely crushed in a Chilean mill which consisted of a circular trough around which a heavy, iron-capped stone wheel was rotated by steam engine. The Port Phillip Company added up to 90 kg of mercury to each ‘charge’ of 100 kg of calcined ore in the mill. This ensured that each particle of gold had enough contact with mercury to be amalgamated. The mercury-gold amalgam accumulated in the base of the trough and was cleaned out periodically, before being squeezed in a cloth or leather bag to remove the excess mercury. Residual sands, generally containing significant traces of mercury, were discarded onto tailings heaps nearby. Numerous companies in Bendigo and Ballarat developed variations on this process in the 1870s and developments continued in Victoria until at least the 1890s, when chlorination and cyanidation techniques were applied to pyritic ores (Birrell, 2004; Lawrence et al., 2000; Rae, 2001). Mercury amalgamation persisted in Australia as an effective process of gold separation, however, well into the 20th century (Birrell, 2004:21). As late as 1938, for example, Australia imported 34.7 tonnes of mercury, mostly for gold processing (McQueen, 2011).

Mercury amalgamation of pyritic ores was a highly successful technology on the Victorian goldfields, with 46 pyrites works established by 1881 (MSV, 1882). The mining industry processed 137,000 tonnes of auriferous pyrites between 1869 and 1890, yielding more than 300,000 troy ounces (9.6 tonnes) of gold (Table 1; Secretary for Mines, 1891). This volume of pyritic ores was about 0.7% of all the ore treated by gold mining companies in this period.
Table 1: Annual number of pyrites processors, gross volume of pyritic sands treated in Victoria and minimum mercury loss per year (data source: MSV, 1870–1891). Pyrites were treated both by individual mines and by specialised processors, with the latter tabulated between 1876 and 1888. DOI: https://doi.org/10.1525/elementa.432.t1

| Year | Pyrites processors | Pyritic sands treated (tonnes) | Annual mercury loss (kg) |
|------|--------------------|-------------------------------|--------------------------|
| 1869 | –                  | 1422                          | 634                      |
| 1870 | –                  | 3231                          | 1440                     |
| 1871 | –                  | 3619                          | 1613                     |
| 1872 | –                  | 5088                          | 2269                     |
| 1873 | –                  | 5657                          | 2522                     |
| 1874 | –                  | 6833                          | 3046                     |
| 1875 | –                  | 7619                          | 3397                     |
| 1876 | 34                 | 7170                          | 3197                     |
| 1877 | 37                 | 7477                          | 3334                     |
| 1878 | 45                 | 5461                          | 2435                     |
| 1879 | 43                 | 5389                          | 2403                     |
| 1880 | 41                 | 8167                          | 3641                     |
| 1881 | 46                 | 6063                          | 2703                     |
| 1882 | 47                 | 7070                          | 3152                     |
| 1883 | 38                 | 7798                          | 3477                     |
| 1884 | 32                 | 7201                          | 3210                     |
| 1885 | 33                 | 14,754                        | 6578                     |
| 1886 | 27                 | 6638                          | 2959                     |
| 1887 | 25                 | 4614                          | 2057                     |
| 1888 | 26                 | 4959                          | 2211                     |
| 1889 | –                  | 5364                          | 2391                     |
| 1890 | –                  | 5649                          | 2519                     |
| totals | 137,244 tons | 61,188 kg | |

However, a significant fraction of the mercury used by the mining industry was lost to the environment during pyrites processing. Mine managers responding to a government board of inquiry in 1873 on methods of treating pyrites acknowledged that mercury losses in tailings sands generally ranged between 1 lb (0.45 kg) and 2 lb (0.9 kg) per ton of roasted ore (Board, 1874). Adopting the lower figure of 1 lb as a minimum, the processing of pyritic concentrates over this 22-year period resulted in the discharge of at least 61 tonnes of mercury to the environment (Table 1). These mercury losses were greatest at locations where treatment of pyritic ores was most concentrated, including Bendigo, Ballarat, Castlemaine and Clunes (Table 2; Board, 1874). It was also widely understood that the arsenical fumes from roasting pyrites were highly dangerous to public health and surrounding vegetation (Board, 1874). There are no data for the years after 1884 but the introduction of cyanidation processes to treat pyritic ores from the 1890s likely means that mercury losses from this source declined. The total minimum volume of mercury discharged from mining operations between 1868 and 1888 thus included 70 tonnes from quartz crushing plus 61.2 tonnes from processing arsenical pyrites, with a minimum of 131.2 tonnes during this period.

Spatial distribution of mercury losses

In this section we build on our previous estimates of mercury use and loss in Victoria’s 19th-century gold mining industry (Davies et al., 2015) to understand in more detail the likely concentrations of environmental mercury around several large mines and pyrites processing works. We present brief case studies of two successful and productive mining operations: the Port Phillip and Colonial Gold Mining Company at Clunes, and the Long Tunnel and Long Tunnel Extended Companies at Walhalla. These mines operated for many years and were at the forefront of technological developments to maximise rates of gold recovered from ore bodies. In addition, we review pyrites processing works at Bendigo and elsewhere and the extent of mercury use and loss by the industry in these areas.

The Port Phillip Company commenced mining operations on private land at Clunes in 1857, with ore processing under the leadership of Joseph Robson, a battery manager with 25 years’ experience in Cornwall and South America (Woodland, 2001). The company was at the forefront of mining technology in Australia, including the treatment of pyritic ores by mercury amalgamation. By the time it closed in 1888, the company had processed 7182 tonnes of pyritic sands and recovered 942 kg of gold from this material (Bland, 1890). Pyrites represented 0.5% of the 1.3 Mt of auriferous quartz the company crushed in the same period. The company was highly efficient at treating gold but nevertheless lost on average 0.04 ounces (1.2 g) per ton of crushed ore (Davies et al., 2015). The company lost, in total, approximately 1.45 tonnes of mercury through the stamp batteries and amalgamating tables over its 31 years of operation. In addition, however, the company’s processing of pyritic concentrates resulted in the discharge of further 3.2 tonnes of elemental mercury via tailings into the local environment, including Creswick Creek. Ten other companies operating nearby on the same gold-bearing reefs (Bland, 1890) are likely to have contributed several more tonnes of mercury to the immediate environment as well.

In eastern Victoria, one of the largest mining centres was at the town of Walhalla on Stringers Creek, a tributary of the Thomson River which rises in the Central Highlands and flows into the Gippsland Lakes. Rich gold-bearing reefs were discovered in the area during the early 1860s. The Long Tunnel Company was established at Walhalla in 1865 and produced its first gold in 1867. The company installed a 20-head battery, along with mercury amalgamation tables and a furnace and mills for processing pyrites. The Long Tunnel Extended Company
was formed to work an adjacent claim in 1871 and the two companies cooperated to be among the richest gold producers in 19th-century Victoria. The Long Tunnel Company installed a 40-head stamp battery around 1877, and the Long Tunnel Extended later used four grinding pans to treat battery sands with mercury. The Long Tunnel Extended closed in 1911 and the Long Tunnel Company closed in 1913. The two companies processed 1.15 Mt of ore during the operating period of both mines (Lloyd and Combes, 2010). The companies were far less efficient than the Port Phillip Company and reported minimum losses of 0.54 ounces (15 g) of mercury per tonne of crushed ore (Davies et al., 2015). Over the life of the two mines they discharged at least 610,727 ounces (17.3 tonnes) of mercury.

Table 2: Volumes of pyritic sands processed 1869–1884, recorded by Mines Department and published in the annual series Mineral Statistics of Victoria (minor volumes excluded); minimum mercury loss derived from Board (1874).
DOI: https://doi.org/10.1525/elementa.432.t2

| Mining district & division 1869–1884 | River catchment | Pyrites processed (tons) | Mercury lost (kg) |
|--------------------------------------|-----------------|-------------------------|------------------|
| **Ballarat**                         |                 |                         |                  |
| Central                              | Yarrowee        | 6169                    | 2751             |
| Buninyong                            | Yarrowee        | 194                     | 86               |
| Creswick/Clunes                      | Loddon          | 12,249                  | 5461             |
| Gordon                               | Moorabool       | 216                     | 96               |
| Steiglitz                            | Moorabool       | 4826                    | 2152             |
| Blackwood                            | Werribee        | 635                     | 283              |
| **Beechworth**                       |                 |                         |                  |
| Beechworth                           | Ovens           | 501                     | 223              |
| Yackandandah South                   | Kiewa           | 1193                    | 532              |
| Wandiligong                          | Ovens           | 852                     | 380              |
| Buckland                             | Ovens           | 2224                    | 992              |
| Gaffney’s Creek                      | Goulburn        | 100                     | 44               |
| Wood’s Point                         | Goulburn        | 227                     | 101              |
| Mitta Mitta North                    | Mitta Mitta     | 466                     | 208              |
| Bethanga                             | Murray          | 514                     | 229              |
| **Sandhurst (Bendigo)**              |                 |                         |                  |
| Sandhurst                            | Bendigo Creek   | 48,140                  | 21,463           |
| Eaglehawk                            | Bendigo Creek   | 2915                    | 1300             |
| Heathcote                            | Campaspe        | 268                     | 119              |
| Inglewood                            | Loddon          | 96                      | 42               |
| **Maryborough**                      |                 |                         |                  |
| Maryborough                          | Loddon          | 801                     | 357              |
| Dunolly & Tarnagulla                 | Loddon          | 155                     | 69               |
| Redbank St Arnaud South              | Avoca           | 1922                    | 857              |
| St Arnaud North                      | Avoca           | 1222                    | 545              |
| **Castlemaine**                      |                 |                         |                  |
| Castlemaine                          | Loddon          | 4656                    | 2076             |
| Fryer’s Creek                        | Loddon          | 209                     | 93               |
| Hepburn/Daylesford                   | Loddon          | 1233                    | 550              |
| Tarrangower/Maldon                   | Loddon          | 254                     | 113              |
| Ararat                               |                 | 0                       | 0                |
| **Gippsland**                        |                 |                         |                  |
| Stringer’s Creek                     | Thomson         | 2815                    | 1255             |
mercury into the local environment, including Stringers Creek. An additional 1.2 tonnes of mercury were lost via the processing of auriferous pyrites between 1877–1884 (Table 2).

The major centre for treating auriferous pyrites in colonial Victoria was the central Victorian city of Bendigo (Figure 4). Although gold reefs in the area did not contain large quantities of pyrites below the water line, several companies developed significant expertise in treating pyritic concentrates. These companies installed reverberatory furnaces and mercury-amalgamating equipment to roast and treat pyritic sands from their own crushing plants, while specialised works processed pyrites sent from other mines for a fee. Many small mines from all over Australia sent their pyritic sands to Bendigo (and Ballarat) for treatment (Royal Commission, 1891). In 1862, the Catherine Reef United Claimholders Company became the first mining company in Bendigo to successfully treat pyrites from its own claim (Figure 5). Henry Koch’s Pioneer mill opened in 1869, charging £3 per ton for treating pyrites from other companies (Macartney, 1871), while the Morning Light Company established a pyrites processing plant in 1874 (Bannear, 1993b). Three dedicated pyrites processing companies were established in Bendigo in 1872, with two more in the 1880s (Birrell and Lerk, 2001; Figure 6). A. Victor Leggo established a pyrites treatment plant in 1907.
using the cyanidation process, which continued in business until the 1950s. All these plants were in the northern and western parts of the Bendigo goldfield. During the 20 years between 1869 and 1888 for which good records are available, more than 50,000 tonnes of pyritic sands were treated at Bendigo, with roasting and mercury amalgamation (MSV, 1870–1889; Table 2). This was more than one-third of all the pyrites treated in Victoria during this period. Based on a minimum loss of 1 pound (0.45 kg) of mercury per ton of pyritic ore treated, we estimate that at least 22 tonnes of mercury were discharged to the environment over this period in the immediate vicinity of the treatment works in Bendigo.

Pyritic sands were treated by roasting and mercury amalgamation in other mining areas as well. At Stawell in western Victoria, for example, there were at least four companies processing pyrites by the early 1870s (Board, 1874). During the same period at Maldon, miners were discovering that complex refractory ores required treatment in Chilean mills charged with mercury, after which the sands were also put through quicksilver cradles (Bannear, 1993a; Davey, 1986; Mining Surveyor, 1885). Metallurgical treatment of pyritic ore also occurred on a significant scale at Ballarat during the 1880s, when the Band of Hope and Albion Consols Pyrites Company (1880), the Ballarat Pyrites Works Company (1883) and the Edwards Pyrites Works company (1890) were active. These companies collected pyritic material from other Ballarat mines for processing, with residues, including mercury, discharged into Yarrowee Creek (Ballarat Star, 1880, 1883). Pyrites processing operations along the Maribyrnong River in Melbourne may also have contributed to mercury contamination of sediments in Port Phillip Bay (Rae, 2001).

**Discussion**

This overview of mercury use in historical gold mining in Victoria provides a framework for future research. While total amounts of mercury released for one brief period have now been estimated, much remains unknown about how and where mercury has been emitted to the environment. Of the 594 tonnes of mercury used in Victoria between 1868–1888, archival research has confirmed a minimum of 131 tonnes was discharged as anthropogenic elemental mercury in battery and pyrites tailings. This is a conservative estimate that accounts for only a brief period of mining activity, takes a deliberately minimalist approach to the calculation of reported losses, and includes only those branches of mining for which good records exist. The real quantity lost is likely to be considerably higher. We know that stamp batteries associated with gold mines were widely distributed around Victoria and that pyrites treatment works were spatially concentrated in a few locations. The condition of the associated tailings today and their potential to be ongoing sources of emissions remains unknown.

An important area for further research concerns the location of tailings sands. Some may have been stored on mine sites in dams and tailings piles. It is known from other research, however, that it was common practice for mines to discharge their waste, including battery tailings, directly into local waterways and that this continued after the passage of anti-pollution regulations in 1904 (Lawrence and Davies, 2019). We have calculated elsewhere (Davies et al., 2018a, 2018b) that approximately 800 million m$^3$ of mining waste was discharged into Victorian waterways up to 1914. Some of this volume was almost...
certainly contaminated with mercury and is likely to be the source of some of the mercury identified in waterways by the EPA and other researchers (e.g. Bycroft et al., 1982; Churchill, 2004; Fabris, 2012; Glover, 1980; McCredie, 1982). Much of the discharged mining waste, however, is stored on downstream floodplains and remains a source of potential contamination beyond the mines (Davies et al., 2020). In addition, erosion and widening of stream channels during storm events will continue to be an episodic source of waterway contamination (Singer et al., 2013). Tailings stored on mine sites represent potential additional pathways for contamination, where mercury may leach into both waterways and the atmosphere. This is a major concern as former mines are increasingly incorporated into built-up urban areas. Targeted monitoring of soil, air and water is needed to clarify this issue.

Known losses discussed above account for only 22 per cent of the total quantity of mercury imported to Victoria. It is likely that a considerable portion of the remaining mercury was released as atmospheric mercury during the retorting of amalgams. Again, however, the precise quantities and locations involved remain unknown. Unlike small-scale artisanal gold miners today (e.g. Brooks et al., 2006; Hillson, 2006; Veiga et al., 2006), our impression is that much of the retorting and recovery of mercury in Victoria was done at centralised locations with equipment designed to recapture as much mercury vapour as possible (Birrell, 2005). Further research is needed, however, to determine if this was the case and to determine the efficiency of the recovery methods used. It is highly likely, however, that there were significant losses to the atmosphere and that efficiencies varied between operators. It may be that, as with pyritic ores, it will be possible to identify regions where losses were more concentrated. Atmospheric mercury released through retorting is probably the source of soil contamination around the town of Maldon identified by Abraham et al. (2018). Further testing of soils downwind of mining areas may help to address this issue.

Conclusion

Mercury contamination is part of the wider story of environmental damage caused by historical metals mining. Gold rushes around the Pacific Rim in the 19th century introduced large-scale metals mining to regions where it was previously unknown. The industry rapidly transformed the physical landscape around mines with waste rock piles, tailings heaps and mining voids, while its need for timber resulted in extensive forest clearance (Dasmann, 1999; Frost, 2013; Isenberg, 2005; Lawrence and Davies, 2019; Morse, 2003). Heavy metal contamination of soils and waterways and acid mine drainage at mine sites was also common (Lottermoser, 2003). Many mining operations discharged waste directly into waterways, which altered channel morphology, reduced biodiversity and created new, anthropogenic sediment layers on floodplains. There were few if any laws or regulations to limit or prevent the disposal of wastes and obligate the rehabilitation of mine sites. This resulted in tens of thousands of historical mines with contaminated soils, sediments and water. Mercury discharge was thus one significant factor among a range of environmental changes that resulted from metals mining around the Pacific in the 19th century.

Mercury was an important and widespread component of Victoria’s historical gold mining industry. Local production of mercury was negligible, with industrial needs met with imports from California and Spain. Mining companies used mercury to amalgamate gold particles liberated from crushed quartz and in the treatment of pyritic sands. The use of mercury by alluvial miners, however, was much more limited. Mining companies were generally efficient at retaining and recovering the mercury used in stamp batteries, but significant amounts were still lost to the environment. We estimate this included at least 70 tonnes of mercury across Victoria for the period 1869 to 1888. A further 61 tonnes of mercury were also lost in the processing of pyritic ores over the same period, but this was mostly concentrated in a smaller number of mining centres, including Bendigo, Ballarat, Castlemaine, Clunes, Maldon and Walhalla. While cyanidation became an important new technique for treating pyrites from the 1890s, mercury continued to be used by the gold mining industry, and lost to the environment, until the 1930s and beyond.

Tailings from abandoned mines are widespread and potentially associated with mercury contamination. Historical research provides a valuable tool for improved modelling of the location of contaminated tailings and the extent of contamination. An understanding of the processes that lead to the loss of mercury during the processing of ores can assist with identifying sites and regions for further environmental testing.

Data Accessibility Statement

The data that support the findings of this study are can be found in the supplemental materials file.

Supplemental file

The supplemental file for this article can be found as follows:

· Text S1. Study data. DOI: https://doi.org/10.1525/elementa.432.s1

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Competing interests

The authors have no competing interests to declare.
Author contributions
• Contributed to conception and design: SL, PD
• Contributed to acquisition of data: PD
• Contributed to analysis and interpretation: SL, PD
• Drafted and revised the article: SL, PD
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