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Mining in Papua New Guinea:

A Complex Story of Trends, Impacts and Governance

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Abstract:

Mining is often portrayed as a contributor to sustainable development, especially so in developing countries such as Papua New Guinea (PNG). Since 1970, several large mines have been developed in PNG (e.g. Panguna, Ok Tedi, Porgera, Lihir, Ramu) but always with controversial environmental standards and social impacts often overlooked or ignored. In PNG, mine wastes are approved to be discharged to rivers or oceans on a very large scale, leading to widespread environmental and social impacts – to the point of civil war in the case of Panguna. The intimate links between indigenous communities and their environment have invariably been under-estimated or ignored, leading many to question mining's role in PNG's development. Here, we review the geology of PNG, its mineral resources, mining history, key trends for grades and resources, environmental metrics (water, energy, carbon), mine waste management, and regulatory and governance issues. The study provides a unique and comprehensive insight into the sustainable development contribution of the mining industry in PNG – especially the controversial practices of riverine and marine mine waste disposal. The history of mining is a complex story of the links between the anthroposphere, biosphere, hydrosphere and geosphere. Ultimately, this study demonstrates that the scale of environmental and social impacts and risks are clearly related to the vast scale of mine wastes – a fact which remains been poorly recognised. For PNG, the promise of mining-led development remains elusive to many communities and they

are invariably left with significant social and environmental legacies which will last for decades to centuries (e.g. mine waste impacts on water resources). Most recently, the PNG government has moved to ban riverine tailings disposal for future projects and encourage greater transparency and accountability by the mining sector, including its interactions with communities. There remains hope for better outcomes in the future.

Journal Pre-proof

1. Introduction

There is no perhaps other country in the world that has such a complex story to tell about mining than Papua New Guinea (PNG) (e.g. Connell, 1997) – despite the often geologically young nature of PNG mineral deposits and an abundance of mineral and other natural resources, it remains contentious as to whether mining's promise has been fulfilled. In the age of sustainable development, especially considering the United Nations' Sustainable Development Goals (or 'SDGs')[1], it is critical to understand and evaluate the links between mining and SDGs that relate to environmental pollution (especially water), energy and carbon footprints, social issues and especially regulatory and mine waste management practices (e.g. Franks et al., 2011; Mudd, 2010; Nickless, 2018; Spitz and Trudinger, 2008).

In light of recent catastrophic tailings dam failures in Brazil (and elsewhere; see Roche et al., 2017; Robertson,et al, 2019), there is considerably greater focus on the potential impacts of tailings spills on the environment – and yet PNG has allowed direct discharge of tailings to its rivers and seas for decades. This suggests that there is much to learn from PNG about the impacts of tailings getting into the environment, especially as the mining industry, governments and communities alike are hoping to reduce these impacts and improve the sustainability performance of mines. In other words, PNG provides a clear case study demonstrating that direct tailings discharge to the environment are not a viable alternative to tailings dams, and this paper will explore and justify this position.

In this paper, we review the geology of PNG and briefly explore its history of gold (Au), copper (Cu), silver (Ag) and more recent nickel (Ni)-cobalt (Co) mining. We then examine currently reported mineral resources and mineral deposit types sa well as synthesize mining trends over time such as metal production, grades, tailings and waste rock. We also explore mine waste management practices and their associated environmental and social impacts. Finally, we compile statistics and trends on the energy, water and carbon intensities of mine production. This paper is

[1] These are a list of 17 major categories of development goals which the international community will work towards achieving by 2030; see www.un.org/sustainabledevelopment/sustainable-development-goals/.

reliant on the author's direct knowledge of PNG mining issues and the information derived from this experience, especially from numerous community visits to many of PNG's mining districts. The primary purpose of this paper is to examine key projects such as Ok Tedi, Porgera, Lihir and Hidden Valley, with uniquely synthesized datasets for each project. These data are combined to present a comprehensive synthesis of the links between the lithosphere (i.e. mineral resources), hydrosphere (i.e. water resources), atmosphere (i.e. greenhouse gas emissions), biosphere (i.e. ecological impacts and biodiversity) and the anthroposphere (i.e. humans and associated activities such as mining). For an industry such as mining, it is clear that impacts cut across all of these critical themes that underpin sustainable development and the SDGs. In essence, this paper explores the hypothesis that mining contributes to sustainable development in Papua New Guinea.

Overall, the paper provides a unique national level assessment of PNG's mining industry and the complex environmental and social challenges faced by communities, governments and companies as they all work towards achieving better sustainable development outcomes for a socially-, environmentally- and resource-rich but financially-poor country.

2. Geology of Papua New Guinea

Despite recent research, the details of the geology of PNG remain relatively poorly known, primarily as a result of the combination of very complex geology and a lack of detailed geological mapping, the logistical challenges presented by the rugged mountain terrain, dense rainforest, the lack of modern infrastructure, and the tropical climate present across much of PNG. This also reflects a lack of published geochronological, geochemical, and kinematic data for a significant proportion of the units and structures hitherto identified on PNG (Sheppard and Cranfield, 2012). In general, the geological history of PNG is dominated by its location within the collision zone between the northward moving continental Australian Plate and the oceanic Pacific Plate, with the majority of the Cenozoic geological processes recorded on PNG related to terrane collisional events associated with this collision (e.g. Sheppard and Cranfield, 2012; Williamson and Hancock, 2005). This makes PNG highly prospective for a variety of mineral deposit types, including porphyry, high- and low-sulfidation epithermal, skarn, onland and offshore volcanogenic massive

sulfide (VMS) and lateritic Ni-Co deposits. Interestingly, although the geological history of PNG extends at least as far back as the Permian and possibly the Archean (e.g. Baldwin and Ireland, 1995; Sheppard and Cranfield, 2012), the majority of the known mineralisation only dates from the latest Miocene to the Pleistocene, indicating a clear relationship between more recent tectonism and magmatism and the majority of the metallogenesis recorded across PNG (e.g. Hill et al., 2002; Sillitoe, 1997). This relationship continued beyond the cessation of subduction in this area to <7 Ma, with ploughing of the Australian lithosphere into the mantle in this area potentially related to the genesis of the more recent (and world-class) porphyry systems on New Guinea, including PNG (van Hinsbergen et al., 2020).

In broad terms, the geology of PNG is dominated by three major components, namely the Australian Craton that underlies western PNG (including the Fly Platform) and the Torres Strait, the mountainous New Guinea Orogen that records the folding, thrusting and metamorphism of sedimentary, volcanic and igneous rocks in central PNG, and the Melanesian Arc, a series of island arcs and associated mountain ranges to the east of the New Guinea Orogen. These components are further split into a number of tectonic provinces that are generally poorly defined and are bounded by major faults or shear zones (Sheppard and Cranfield, 2012). Each of these tectonic provinces has a unique geological history that in turn has yielded differing metallogenic prospectivities and endowments; here we focus on the provinces that host the majority of the mineralisation in PNG, namely (from south to north) the Fly Platform, the Papuan Fold Belt, and the New Guinea Thrust Belt, all of which form east-west trending belts within western PNG, the East Papuan Composite Terrane that dominates the Papuan Peninsula in eastern PNG, and offshore islands of the Melanesian Arc and the Tabar–Lihir–Tanga–Feni island chain.

The broad and low-lying Fly Platform is located in southwest PNG and is underlain by continental crust of the Australian Craton (Sheppard and Cranfield, 2012). This region hosts alluvial Au mineralisation in the Ningerum region to the south of the Ok Tedi mine as well as streams further to the east. Weathering of rocks in this region has also generated soils and beach sands that may

be prospective for bauxite and heavy mineral sands resources, respectively, but no economic mineralisation has been found to date (Sheppard and Cranfield, 2012).

The Papuan Fold Belt lies to the north of the Fly Platform and to the southeast of the Aure Fold Belt and host a significant proportion of the mineral resources identified to date on PNG. These include the porphyry-type Porgera Au and Ok Tedi Cu-Au-Ag mines, as well as the Mount Kare epithermal and Bolivip Cu-Au prospects (Sheppard and Cranfield, 2012) and hydrocarbon resources in the form of the Kutubu oil and Hides gas fields.

The major New Guinea Thrust Belt lies to the north of the Papuan Fold Belt, to the north of the Torricelli and Finisterre terranes, and to the west of the Aure Fold Belt (Sheppard and Cranfield, 2012). This region hosts significant amounts of intrusion-related porphyry Cu and epithermal Au mineralisation, the lateritic Ramu Ni-Co deposit, alluvial Au resources, and some minor VMS mineralisation. This area also remains relatively under-explored, meaning that it should be considered highly prospective for exploration for all of these styles of mineralisation (Sheppard and Cranfield, 2012).

The East Papuan Composite Terrane dominates the Papuan Peninsula in eastern PNG and contains two major units, the ophiolites of the Papuan Ultramafic Belts to the northeast and the Owen Stanley metamorphics to the southwest, with the latter overlain in places by the Wau Basin and other units (Sheppard and Cranfield, 2012). The Papuan Ultramafic Belts host minor amounts of Au mineralisation as well as the Wowo Gap lateritic Ni-Co deposit and other laterite Ni-Co prospects. In comparison, the Owen Stanley metamorphics and cross-cutting magmatic units are associated with world-class porphyry and epithermal type deposits, including the Wafi-Golpu Cu-Au-Ag-molybdenum (Mo) and Hidden Valley-Hamata Au-Ag deposits.

The offshore geology of the New Guinea Islands is split into the Melanesian Arc, which consists of Manus, New Britain, New Hanover, New Ireland, Bougainville and the Solomon Islands, and the Tabar–Lihir–Tanga–Feni island chain that lies to the NE of New Ireland (Sheppard and Cranfield,

2012). The Melanesian Arc is an Eocene island arc formed by magmatism associated with the subduction of the Pacific Plate beneath the Australian Plate, a process that ceased as a result of the arrival of the Ontong-Java Plateau at the trench (Ernst and Jowitt, 2013; Petterson, 2004). The arc hosts porphyry and epithermal mineralisation, including the Metawarei, Panguna, and Simuku deposits, as well as seafloor massive sulfide mineralisation within the Bismark Sea. In comparison, the Tabar–Lihir–Tanga–Feni island chain hosts epithermal mineralisation that includes the Ladolam (Lihir) and Simberi Au deposits as well as presently forming seafloor VMS type mineralisation at Solwara within the Manus Basin (Yang and Scott, 2002).

3. Brief Historical Review of Mining in PNG

Mining has been occurring in PNG for just over a century in Au fields such as Misima Island, Wau-Bulolo, Woodlark Island and Mount Kare. Despite rich grades and promise, these fields were largely very modest in nature, with only the Edie Creek mines and Bulolo dredges achieving any lasting scale and economic returns (e.g. Nye and Fisher, 1954; Grainger and Grainger, 1974). The tyranny of distance, often mountainous tropical jungles and lack of infrastructure meant high risk and typically high costs. The arrival of World War 2 in PNG shut down the entire Au mining industry, only getting re-established in the late 1940's a few years after hostilities formally ceased – but it never reached the same heights (averaging ~9.3 t Au./year in the 5 years before the war but peaked at 4.0 t Au in 1952 and then gradually declined; Grainger and Grainger, 1974). The rich geological promise, however, remained enticing for mining companies and governments alike.

In the 1960's global mining companies targeted PNG for modern exploration – with rewards quickly following in the form of the discovery of world-class and giant porphyry Cu-Au and epithermal Au deposits. This led to the 1972 development of the Panguna porphyry Cu-Au-Ag mine on Bougainville Island, the 1984 development of the Ok Tedi porphyry Cu-Au-Ag mine in Western Province, the small Mount Victor Au mine in 1987 in the Eastern Highlands, the Porgera epithermal Au mine in the Central Highlands in 1990, the Lihir epithermal Au mine in New Ireland in 1997 and more recently the Hidden Valley epithermal Au-Ag mine in 2009. Smaller mines from the 1990s

include Tolukuma, Kainantu, Simberi and Sinivit, as well as major deposits being explored and considered for development at Frieda River, Wafi-Golpu and Yandera. The Rami Ni-Co project (near Madang) was built in the late 2000's and began production in late 2012. A mining map of PNG is shown in Figure S1 (Supplementary Information).

Mining at the Panguna mine involved the direct discharge of tailings into tributaries of the Jaba River, a practice known as riverine tailings disposal, whereas the majority of waste rock was placed on easily erodible dumps. The substantive scale of social and environmental impacts from the Panguna mine led to a civil war breaking out in May 1989[2] that lasted for more than a decade (Havini and John, 2001), before peace was finally negotiated in 2002. Riverine mine waste disposal (RMWD) is still being used at Ok Tedi, Porgera and Tolukuma, which are all associated with severe environmental and social impacts along their respective river systems (especially the Fly River system downstream from Ok Tedi; see Bolton, 2009; Tingay, 2007).

An alternative method of disposal was used at the former Misima Au-Ag mine on Misima Island and is currently used at the operating Au mines of Simberi and Lihir, where tailings are discharged into the sea at water depths of >100 m. At Lihir, most waste rock is emplaced in shallow marine waters of the adjacent Luise Harbour, effectively forming a new land mass. The Ramu Ni-Co refinery at Basamuk Bay also now uses marine tailings disposal and began production in late 2012 after a lengthy court case failed to stop this practice. Collectively, we refer to disposal of mine wastes into the marine environment as 'marine mine waste disposal' (MMWD). Major concerns with MMWD include the unknown but potentially significant impacts on shallow and deep marine biodiversity and ecosystem processes, the lack of transparency, the difficulties of independent monitoring and enforcement (especially in a developing nation context) as well as arguable flaws in predicting potential impacts during the environmental approvals process (e.g. Vare et al., 2018) – which are absolutely critical in the face of weak or minimal baseline studies. Ongoing concerns about MMWD impacts at Basamuk Bay are regularly reported in PNG's formal and social media

[2] The genesis of the Bougainville conflict is complex and outside the scope of this paper but is broadly agreed to be related to income inequality, different conditions between expat and local workers, significant cultural conflicts, severe social impacts as well as the extensive environmental impacts. For further reading, see Connell (1997), Lasslett (2012), Regan (1998), amongst others.

(e.g. see the many stories in PNGMW, 2020) – with reports of a major tailings spill into Basamuk Bay in October 2019 leading to a temporary shut-down of the Ni-Co refinery and new litigation cases being lodged in February 2020 based on scientific investigations of the potential impacts on marine ecosystems and local communities (PNGMW, 2020).

By the start of the new millennium, there was yet to be a major PNG mine that used conventional engineered mine waste management, such as a tailings storage facility (or dam) and careful waste rock dump designs to minimise erosion, seepage and environmental impacts. Typically, the justification for RMWD or MMWD was the strong seismic risk, high rainfall, rugged topography and intense weathering and erosion rates which made engineering conventional tailings dams and waste rock facilities difficult and expensive (e.g. Stead, 1990). Conventional approaches are required by law in major mining countries such as Australia or Canada (the most common countries with mining companies active in PNG), as well as other high seismic risk countries such as Chile, and are considered minimum mining practice (we explore mine waste management in detail later). Although the Mount Victor Au mine used a tailings dam in the late 1980s, it was extremely small (~0.2 Mt of tailings) and not a reasonable analogue for projects some thousands of times larger such as Ok Tedi and others – and community concerns remain regarding ongoing metal and chemical leaching risks from this former Au mine.

In the past decade (Ramu being the exception), it appeared that the PNG mining industry had begun to genuinely evolve with the Hidden Valley Au-Ag mine incorporating a conventional engineered tailings dam, shown in Figure 1 (see Mudd and Roche, 2014) for more background), as well as a continuing commitment for an integrated waste rock-tailings dam facility at the proposed giant Frieda River Cu-Au project (see Coffey, 2018; PanAust, 2016; PanAust, 2017; PanAust, 2018; XFR, 2009). Although the Golpu Cu-Au project had previously proposed a tailings dam (e.g. Moorhead, 2012; Moorhead and Cantrell, 2011), in early 2018 this was changed to favour marine disposal (WGJV, 2018). We explore tailings disposal and management later in this paper.

Overall, despite an extended history of Au and Cu mining and recent Ni-Co mining, it is arguable and highly contentious as to the nature of the contribution that mining has made to PNG's evolution as a nation. That is, questions remain about the ability to transform economic wealth from mining projects to support social, governance and environmental progress across PNG (e.g. Connell, 1997). The rich geological terrain promises so much but the navigation of complex social, environmental, economic and political issues associated with mining remain as difficult as ever – all intimately linked with perceived and actual impacts of mine waste management practices.

4. Mineral Resources

Here, we classify all known mineral resources by their reported mineral deposit type (based on the work of Jowitt et al., 2013; Mudd and Jowitt, 2014; Mudd et al., 2013a; Mudd et al., 2013b). Most data are drawn from company financial reporting (e.g. quarterly, annual or technical reports) or relevant technical papers, synthesized into a comprehensive database which is regularly updated.

There are a variety of mineral deposit types in PNG, closely related to its geology and tropical climatic setting, but dominated (to date) by porphyry Cu-Au, epithermal Au and Ni laterite deposits. The most recent resources for all projects are compiled in Tables S1 to S3 (Supp. Info.) for Cu, Au and Ni. Many of these resources are giants, such as the Frieda River group, Porgera and Lihir, whilst others have above average grades compared to industry averages (e.g. Golpu is 0.87% Cu compared to a global average mine grade of 0.65% Cu; see Mudd and Jowitt, 2018).

Some limited data are available for grades over time and, although they do not include all resources known at that time, they are indicative and provide insight into the changes in the grades of resources over time. In the 1910s-30s, Au resources were typically ~10-100 kt, with Edie Creek being up to ~0.5 Mt, and grades mostly 10-30 g/t Au; whilst Cu resources were also somewhat small at ~5-270 kt and ~1.7-4.6% Cu (see Supplementary Information).

The grade of reported mineral resources for currently and recently operating Au mines (including Lihir, Hidden Valley, Simberi, Porgera, Tolukuma) are given in Figure S2 (we exclude other mineral resources due to the lack of equivalent data over time). Between 1984 to 2017 the average grade has declined by about one third from 3.6 to 2.3 g/t Au, despite the emergence of the good grades at Lihir and Porgera. This is reflective of the gradually declining grades at these projects as they move from high grades in their early years (i.e. to earn a quick return on the capital invested) to larger scales and lower grades as they expand and mature, as well as the real increase in the price of Au over this time allowing for lower grades to be mined and processed (e.g. Mudd, 2010).

Although detailed compiled data over time for Cu resources are not available, it appears that overall grades are similar since the emergence of the various porphyry deposits from the 1970s. For example, in 1981, a compilation of all PNG Cu resources by Rogerson et al. (1986) shows 2,635 Mt at 0.44% Cu, 0.32 g/t Au to contain 11.7 Mt Cu, 850 t Au (this includes Panguna, Ok Tedi, Arie, Yandera, Laloki and the Horse-Ivaal-Koki deposits at Frieda River) – identical grades to those in Table S1. Curiously the resource given for the main zone of Ok Tedi also includes 0.011% Mo, although, despite this being in the normal range for Mo extraction at many porphyry Cu mines, Mo has never been reported in mineral resources after this date and is not extracted (see Mudd et al, 2020).

For some deposits (or projects), there can be more than one mineral deposit type present – and unless detailed reserves-resources are reported, this leaves assigning a principal deposit type a difficult task. For example, although Ok Tedi is broadly considered to be a porphyry deposit, there is also considerable skarn mineralisation; similarly, the Ertsberg-Grasberg field in Indonesia contains both porphyry and skarn deposits (see Jowitt et al., 2013).

An unusual mineral resource is the chromite-rich sands of the river deltas draining coastal mountains of the Morobe Province, reported to be 103 Mt at 2.83% chromite (Lole, 2015). Recently, the Ramu Ni-Co laterite project began extracting chromite but it is not reported in resources (nor in company production data). There also continues to be significant discoveries,

such as the Star Mountains-Olgal porphyry Cu-Au prospect ~20 km north of Ok Tedi (450 Mt at 0.3% Cu, 0.3 g/t Au), the Townsville Au prospect ~5 km north of Ok Tedi (19.0 Mt at 4.3 g/t Au) and the Kili Teke porphyry Cu-Au prospect in the central highlands (221.5 Mt at 0.35% Cu, 0.25 g/t Au).

5. Mining Production Trends

The dominant metals in PNG's mining history are Au and Cu, with Ni being a more recent addition. Although the early years and up to the 1960s were typically very small to modest scales (the Bulolo dredging operations being the main exception), the 1970s introduced large scale mining to PNG – led by Panguna on Bougainville Island and later joined by Ok Tedi, Misima, Porgera and Lihir. Very minor quantities of platinum group elements and manganese ore have also been produced but these are negligible in global terms (see Grainger and Grainger, 1974; Nye and Fisher, 1954).

5.1 Gold

The available production statistics for Au in PNG are reasonably complete for hard rock mining and dredging (except perhaps the very early years up to about the 1920's), but there is a lack of historical data on small scale (or artisanal) mining and prospecting. Historical Au production in PNG is shown in Figure 2 – clearly showing the rise and dominance of major mines such as Panguna, Ok Tedi, Misima, Porgera and Lihir. Another important aspect of Figure 2 is the severe interruption caused by World War 2, which shut down all production from mid-1942 until 1947, emphasizing the critical role of social (or political) situations in understanding mineral production trends.

The mining of Au by artisanal miners is difficult to quantify, due to the informal nature of the industry, lack of oversight and the unknown level of illegal Au sales (e.g. Banks, 2001; Susapu and Crispin, 2001). In the year 2000, it was estimated that 50,000 to 100,000 people were active miners with approximately ~1.86 t Au exported by artisanal miners (Susapu and Crispin, 2001). For the year 2015, world Au mine production statistics show ~60.0 t Au for PNG (BGS, var.), with major mines producing 54.6 t Au – suggesting some 5.4 t Au from artisanal sources. In March

2020, the PNG Mineral Resources Authority reported that 2019 artisanal Au mining produced ~3.7 t Au (PNGMW, 2020). It is clear that artisanal Au mining is important for local economies and communities, supporting semi and subsistence lifestyles – especially given the fact that almost all artisanal mining is in rivers, meaning deep personal and cultural interactions between Au mining and river lifestyles.

Based on a detailed compilation of data by individual mines, the average Au grade over time is included in Figure 2. This shows that typically high grades (>5 g/t Au) persisted until the early 1960's, with the advent of large scale Cu-Au mines from the 1970's leading to a shift to ~0.5 g/t Au. The start of Porgera, with initial grades of 60 g/t Au over its first two years (although grades rapidly declined to ~6 g/t Au within several years), lifts average grades to ~2.1 g/t across PNG. The initial high grades at Lihir also show a similar effect in the late 1990's as the mine entered production. Based on reported Cu-Au and Au mineral resources, average grades are likely to stay in the range of 1-2 g/t Au for the foreseeable future based on reported reserves and resources (see Supplementary Information). In general, after allowing for alluvial Au production, the compiled production data accounts for 80-90% of reported PNG Au production until 1971, after which it is mostly 95% or higher; demonstrating that the grade trends shown are a realistic reflection of the Au industry across this time. A compilation of available cumulative Au mine production data to 2018 is given in Table S4 (Supp. Info.) for various Au fields and major projects.

An interesting example of a new Au mining project is Kainantu. In 2005, just before commercial development by Highlands Pacific Ltd, it had reported grades in ore reserves and mineral resources of 21.8 and 24 g/t Au, respectively, with mineral resources of 55.7 t Au (or 1.79 Moz Au) (HP, 2006). Over 2006 to 2007, despite a design production target of ~3.58 t Au/year, the mine only achieved annual production of ~0.8 t Au/year – with the mine subsequently shut down and sold, and, after a period of being owned by Barrick Gold, Kainantu is now owned by the new company K92 Mining. Although there is little published on the reasons for such a poor project outcome, it appears that Kainantu faced the difficult 'nugget effect' (see Woodward, 2015) – whereby most of the Au is contained in a small fraction of the vein structures, making mineral

resources assessments, planning and mining more challenging and risky (e.g. central Au fields of Victoria, Australia; see Dominy et al., 2003). Kainantu was re-opened in late 2017 as a new Au-Cu mine.

5.2 Copper

Although there was minor Cu mining and production in the early 1900's from the Laloki and Sapphire-Moresby King mines, just east of Port Moresby, PNG began large scale Cu mining with the 1972 development of the Panguna project on Bougainville Island. The Ok Tedi project, after a few years of Au mining, began Cu production in 1987. Production over time and trends in grades are shown in Figure 3. The high grades of the Laloki field effectively show the selective nature of mining but also the extremely small scale of production. After the closure of Panguna in May 1989 (see later), this left Ok Tedi as the only Cu mine in PNG – although the recent efforts to develop the Solwara deep sea mineral resources could see this becoming the next Cu producer (albeit with extensive project delays due to a variety of complex social, environmental, political, technical and economic issues; see Baker and Beaudoin, 2013). A small amount of Cu-Au ore was mined from the Kora mine in the Kainantu region in the 1960's, but this was only of the order of several tonnes (Williamson and Hancock, 2005). A compilation of available cumulative Cu mine production data to 2016 is given in Table S5 (Supp. Info.), with the giant size of Panguna and Ok Tedi made very clear (especially when combined with remaining mineral resources which are still larger albeit at lower grades than production to date). In visits to Panguna, there is clear evidence of artisanal Cu mining from the waste rock, tailings and AMD-derived Cu precipitates.

5.3 Nickel

The development of Ni laterite resources is the most recent addition to PNG's modern mining industry. The Ramu project consists of the Kurumbukari mine in the highlands (~60 km southwest of Madang) and the Basamuk Bay refinery (~75 km southeast of Madang), and began production in late 2012 after extended (but failed) court cases from local Madang-Bismarck Bay communities to prevent the use of marine tailings disposal. The refinery uses the high pressure acid leach (HPAL) process to produce a mixed hydroxide product containing Ni and Co. Production has been

ramping up, and is now near design capacity, with total production to 2018 of 16.54 Mt at ~1.0 %Ni, 0.1 %Co for 155.5 kt Ni, 14.9 kt Co. Chromite recently began to be extracted at the beneficiation plant at the Kurumbukari mine, but no data has been reported by the joint venture to date.

5.4 Resource-Reserve-Production Case Studies

We compiled detailed datasets over time to assess the long-term trends in remaining mineral resources and ore reserves as well as cumulative production for the Ok Tedi, Porgera, Lihir, Simberi and Hidden Valley projects, given in Figure S3 (Supp. Info.). All five cases show strong conversion of mineral resources through ore reserves to cumulative production combined with a growing endowment over time.

An interesting case is the Misima project, operated by Placer Dome Ltd from 1989 to 2004. Reported mineral resources in 1987, just before development, were 56 Mt at 1.37 g/t Au, 20.9 g/t Ag and containing 76.8 t Au, 1,171 t Ag. By the completion of milling in 2004, total production was 87.47 Mt at 1.45 g/t Au, 13.2 g/t Ag for production of 115.9 t Au, 563.0 t Ag – delivering a greater Au endowment than the original resource but with a low Ag recovery (from a similar endowment of 1,155 t Ag).

For Tolukuma (although the data is not shown due to the limited number of years of production), there also appears to be a common pattern of mineral resources growth and conversion through to ore reserves and mine production. The Kainantu project appears to be the only project where there were difficulties in converting resources to reserves and production – most likely due to the nugget effect (as noted previously).

6. Environmental and Social Issues and Sustainable Development

In this section, we explore the dominant environmental issues and highlight some of the complex links to social and governance issues. First, we review mine waste disposal and management

practices (i.e. riverine / marine mine waste disposal or RMWD / MMWD), including recent improvements at new projects such as Hidden Valley. Second, we compile data on the energy, carbon (i.e. greenhouse gas emissions) and water intensity of PNG mines. Finally, we make some brief comments on proposed PNG mining projects and note the current commitments by their respective companies.

In identifying some links between environmental and social issues, we recognise that for mining affected local and indigenous communities, the issues are always interrelated – a merging of multiple spheres of impact from intentional and immanent forms of extractive-led development (Banks et al, 2013; Roche et al, 2019). The separation of environmental and social spheres is an arbitrary, western and scientific practice built on a reductionist approach (conceptual or lived), rather than a daily integration with the surrounding environment more akin to indigenous culture. Not discussed here are the numerous social and cultural issues associated with mining (e.g. gender, education, power dynamics, etc.), that have been well documented by a plethora of studies in PNG (see Burton, 2013; Cueva, 2016; Jacka, 2015; Kirsch, 2014). More recently, articles on the potential impact of mining at the proposed Wafi-Golpu site illustrate the predictability of mining's detrimental effects on human well-being (*gutpela sindaun*) and the complex, detrimental, intersecting and overlapping impacts on local communities that remain poorly understood and undervalued in risk assessment processes (Roche et al., 2019a; Roche et al., 2019b).

6.1 Mine Waste Disposal and Management Practices

PNG is one of the exceedingly few countries where mine wastes, specifically tailings and waste rock, are allowed to be discharged into rivers or oceans – the only other countries which allow such practices are Indonesia (at Ertsberg-Grasberg and Batu Hijau), Turkey (at Çayeli), several small mines in Norway, and single small mines each in England, Greece, Finland, France and Chile (Cardiff et al., 2012; Vogt, 2014). Mine wastes are also often deposited into freshwater lakes by numerous projects in Canada as well as at Lower Slate Lake in Alaska, USA (Cardiff et al., 2012). Although most of these projects are of the order of millions of tonnes of tailings (or less), sites such

as Ok Tedi, Lihir, Ertsberg-Grasberg and Batu Hijau represent billions of tonnes of tailings and waste rock each (see Tables S4 and S5) – which invariably represents a considerable change in the sediment and contaminant loads and geomorphology of these rivers or marine areas.

For PNG projects (and elsewhere), the main arguments used to support tailings and waste rock disposal into rivers or marine areas were the perceived high risks and costs of engineering tailings dams (or waste rock dumps) to address high rainfall, difficult topography, weathering and geology and/or significant seismicity (as discussed by Stead, 1990; Murray et al., 2003). Although this could be easily confused with meaning that tailings dams were 'technically impossible', it is more accurate to describe these factors as leading to high capital and/or operating costs (especially allowing for post-mining and rehabilitation monitoring and maintenance costs decades or millennia into the future) – meaning that the use of riverine or marine disposal of mine wastes, with its low upfront costs (Franks et al., 2011), was the only way to profitably develop the mines at the time. This effectively externalises costs to the environment and local communities. Typically, decisions to prioritise cost reduction over environmental and social impact are made early in the project design phase and are rarely subject to public scrutiny or detailed independent critique. More positively, and countering the costs argument, is the recent development of an engineered tailings dam at the Hidden Valley Au-Ag mine in Wau-Bulolo Au field of the highlands of Morobe Province (Murray et al., 2010; Rynhoud et al., 2017) as well as the continuing commitment of the Frieda River project to build a combined waste rock-tailings dam facility (Coffey, 2018). This proves that it is indeed possible to plan and design a robustly engineered tailings dam in PNG – similar in concept and nature to many hydro-electric projects and tailings dams in similar terrains or contexts around the world (see discussion in Section 3, Supplementary Information).

In the early years of PNG mining, the size of mines was very small (even for their time period) and PNG's high energy rivers could, theoretically at least, accommodate very minor quantities of mine wastes relative to natural sediment loads with low risks (except perhaps near points of discharge and accumulation). A tailings dam of ~0.2 Mt capacity was built for the Mount Victor Au mine in the late 1980's, whilst the Kainantu Au mine, operated from 2006-2008, also built a tailings dam with a

capacity of ~1.2 Mt – both very small in comparison to the scale of Panguna or Ok Tedi (i.e. ~1,000 Mt). During the construction of the Kainantu tailings dam a major storm led the dam to fill with water – necessitating the engineers to develop a breach in the dam wall to drain the water and maintain dam safety[3]. There remain concerns from local communities about the environmental stability of both of these dams, although technical studies on seepage rates and monitoring of these dams are not available (and in reality most likely not completed in any case; e.g. the Kainantu site claims their tailings dam is achieving regulatory compliance but presents no data, see Woodward et al., 2017).

However, the development of giant projects such as Panguna and Ok Tedi changed everything as the additional loads from tailings and waste rock simply dwarfed the natural (or pre-mining) sediment loads flowing down rivers such as the Jaba River for Panguna or the Fly River for Ok Tedi. Based on the mine waste data from all Cu-Au-Ag and Au mines (Tables S4 and S5), the total disposal by 2017 includes ~1,536 Mt of tailings into rivers, ~230 Mt of tailings into oceans and direct disposal or indirect erosion of up to ~3,670 Mt of waste rock; shown in Figure 4. This scale is equal to that of the Ertsberg-Grasberg Cu-Au-Ag project in Papua Province of Indonesia (the western side of the island of New Guinea), where ~1,690 Mt of tailings and ~4,665 Mt of waste rock have been disposed (or will erode) into the Ajkwa River system (see Table S5).

In brief, the main environmental impacts of tailings and waste rock disposal into rivers are (e.g. Baumgardt, 2006; Da Rosa et al., 1997; Dold, 2008; Hettler et al., 1997; Hudson-Edwards, 2016; Lottermoser, 2010; Vogt, 2014):

1. increased sedimentation, leading to changes in river hydrology and often greater flooding of adjacent floodplains;
2. heavy metal loads to these aquatic ecosystems, including uptake through the food chains and potential exposure of subsistence communities living along these rivers;

[3] This risk was identified prior to site construction in a review of the environmental impact statement for Kainantu and was exacerbated by a lack of local climate monitoring data (see Mudd, 2004).

3. uptake of heavy metals by biodiversity – especially those which can biooaccumulate up trophic levels in an aquatic ecosystem (e.g. mercury);
4. effects on biodiversity, driven by lower dissolved oxygen due to greater suspended sediment;
5. impacts on water quality, especially if sulfides are present in the tailings or waste rock and undergo oxidation and release high levels of acids, salts and heavy metals (a process often known as acid and metalliferous drainage or acid mine drainage; aka 'AMD').

The social aspects of mine waste disposal are, like environmental impacts, complex, interrelated and multi-generational. With hundreds of affected communities, it is impossible to even list all the issues here. What follows is a brief overview of several examples of RMWD, MMWD or poor mine waste management to illustrate the seriousness and breadth of impact and the asymmetric relations apparent in them.

At Panguna, the impact of mine waste and RMWD was quickly identified by locals and researchers alike, with Brown (1974) describing "… a profound effect on the river system, the vegetation, and the people living within the tailings lease area" (page 23). Village relocations, sediment choked rivers, damage to ecological processes and existing systems of agricultural and subsistence production were all seen by Bougainville Copper Ltd (or BCL) and the colonial administrator, Australia, as acceptable externalities that could be addressed through minor financial payments. Over time, the significant environmental impacts from riverine tailings and waste rock disposal, combined with other socio-economic impacts and issues (see Connell, 1997; Dove et al., 1974), led to entrenched – and in the end violent – opposition from indigenous communities. In May 1989 a group of landowners used explosives from the mine to destroy the powerline into the mine, causing a complete loss of electricity and the mine was shut down and workers evacuated. The Bougainville Crisis ensued, whereby the local landowners fought as the Bougainville Revolutionary Army to protect their land and human rights. The civil war between Bougainvilleans and PNG's Government and military lasted more than a decade, reportedly leading directly and indirectly to between 16-20,000 deaths (Havini and John, 2001). The Bougainville case challenged and changed the way international mining companies approached mining on indigenous and

communally owned lands through its contribution to the MMSD Project[4] and subsequent formation of the global industry lobby group the International Council on Mining and Metals (ICMM) (Filer et al., 2008). Panguna remains deeply mired in political, economic and environmental controversy, and, despite desires from selective minority interests to reopen the mine, its future remains deeply contentious – with the consequences of war still very fresh and raw in the minds of local people (Roche, 2009). Some photographs of Panguna are shown in Figure 5, showing the extent of damage to mine trucks and infrastructure as well as the significant impacts on the Jaba River and its ecosystems and communities.

For the Ok Tedi project, a tailings dam was under construction during project development but the site was destroyed in a landslide on 7 January 1984 less than a year before before production began (Zorn, 2018) – triggering the joint venture (JV) led by Australia's BHP Ltd to seek and win permission for riverine tailings disposal in less than three weeks (see Bolton, 2009; Connell, 1997; Zorn, 2018). Although this was supposed to be temporary, within a few years it was made permanent by the PNG Government to allow Ok Tedi to remain profitable within a global market of lower prices (Connell, 1997). Waste rock was never explicitly acknowledged as another major source of mine waste to the Fly River system at this time. Within a decade the increasing social and environmental impacts from the Ok Tedi project were becoming an infamous case study of poorly regulated mining in developing countries. The BHP-led JV faced a major Australian court case in 1994, which the local Fly River communities won in 1996 through settlement out of court. This forced a massive increase in compensation arrangements along the entire Fly River system and not merely the mine area only. BHP left its involvement in Ok Tedi in 2001 in highly controversial circumstances whereby the PNG Parliament passed special legislation to prevent any future liability to BHP from the project, leaving their 52% majority shareholding in a trust company operating from Singapore (the PNG Sustainable Development Program). Other minority partners at this time were Canada's Inmet Mining Ltd (18%) and the PNG Government (30%). After again

[4] The MMSD Project was the "Mining, Minerals and Sustainable Development" Project, run through the Global Mining Initiative, in order to explore the contribution mining can make to sustainable development. The Final Report for the MMSD Project was launched at the Earth Summit in Johannesburg, South Africa, in 2002 (see (IIED and WBCSD, 2002); plus (Franks, 2015) for a 10 year follow-up of the success of the MMSD in changing the way mining approaches sustainability issues.

passing special legislation in 2013, the PNG Government completely nationalised and gained 100% control of the Ok Tedi project. Some photographs of Ok Tedi are shown in Figure 6, showing the scale of impacts on the Fly River and its ecosystems and communities. Despite significant flows of money to mine landholders and affected downstream communities, the negative social impacts of Ok Tedi's mine waste are difficult to overstate. The Western Province of PNG – despite the presence of Ok Tedi now for more than three decades – arguably remains the poorest and least developed of PNG's provinces. While far from supplicant to the process of RMWD, the vulnerability and powerlessness of local communities in the face of environmental destruction, direct human health impacts and cultural dislocation is widespread and long lasting (Kirsch, 2014).

At the Porgera Au mine, tailings are discharged to the Porgera River, a tributary to the Lagaip and then Strickland Rivers (which then enters the lower Fly River). Waste rock is distinguished as competent or erodible, with the latter allowed to discharge sediments to rivers. By 2018, based on monitoring and assessment over nearly 30 years, the mine estimates that the total amount of tailings discharged has been 131.5 Mt while erodible waste rock was 479.3 Mt (Table 4-3, page 44, PJV, 2019). From 2011, a small fraction of tailings are now used as paste backfill in former underground mine workings, rising from 1.4% in 2011 to 13.3% in 2017 (PJV, 2018) but declining to 9.4% in 2018 (PJV, 2019). Like Panguna and Ok Tedi, there remains significant controversy over the extent of environmental, social and economic impacts associated with RMWD downstream from Porgera (see Burton, 2014; Coumans, 2011; Filer and Macintyre, 2006; Kirsch, 2014).

An alternative to a local tailings dam is to build a long-distance pipeline and pump the tailings to another suitable location which can be engineered to store tailings safely. For sites such as Ok Tedi and Ertsberg-Grasberg, this is typically discounted as expensive and impractical[5] (e.g. Rusdinar et al., 2013) – despite both sites having ~130 and ~100 km pipelines, respectively, for the transport of Cu concentrate through the very terrain they say is impractical for the same type of

[5] Curiously, the Panguna mine on Bougainville Island in PNG was in the middle of building a tailings pipeline to the sea when civil unrest caused the closure of the mine – showing that such pipelines are indeed recognised as practicable when companies deem them necessary (for their own reasons or interests).

pipeline to carry tailings to an engineered dam. Similarly, the Ramu Ni-Co project operates a 135 km pipeline to transport beneficiated ore slurry from the Kurumbukari mine to the refinery site at Basamuk Bay on the coast east of Madang.

It is also worth noting that since the late 1990s, as part of the settlement of litigation, Ok Tedi began dredging in the lower Ok Tedi, emplacing sediments in engineered storage facilities which are similar to engineer as tailings dams in any case.

A contrary argument is that it might be better to allow tailings and waste rock to be dispersed gradually in the environment through RMWD rather than risk a catastrophic dam failure (e.g. Samarco's severe tailings dam failure in Brazil in November 2015; do Carmo et al., 2017). However, such a case is never put forward in jurisdictions of major mining countries such as Australia, Chile, Canada, South Africa or the USA (etc.) – only in developing countries such as PNG or Indonesia. Furthermore, to the authors' collective knowledge, rarely is a comprehensive comparative analysis of relative risks and benefits put forward as part of justifying RMWD or MMWD.

The use of MMWD is also a feature of mining in PNG. Historically used at the Misima Au-Ag mine (1989-2004), MMWD is currently used at the Lihir and Simberi Au mines, at Basumuk Bay for the Ramu Ni-Co refinery, was recently approved for a proposed Au mine on Woodlark Island and most recently proposed for the Wafi-Golpu project in Morobe Province (near Lae; see later discussion also). While seen as less polluting by industry (or, in reality, simply lower cost, like RMWD), the practice has attracted signification opposition from communities living near or dependent on marine ecosystems and services for food, economic or cultural activity (Ramirez-Llodra et al., 2015). It is contentious as to whether the direct and indirect social impacts of MMWD are less than RTD, or even conventional mine waste management practices, but there remains a lack of research to identify impacts that engages with local concerns and is available to communities. There is clearly a strong argument for applying the precautionary principle to MMWD on environmental grounds (Franks et al., 2011), which is further supported by the connections between mining, water and

human rights (Kemp et al., 2010). Nowhere is this more important than in PNG, where incommensurable values and clash of cultures can lead to poor local outcomes (Jacka, 2015; Leach, 2014).

For the Lihir Au project, which sits on a very small (~21 by 12 km), mountainous and populated island, there is very little land available for disposal of large volumes of mine waste – and given the steep oceanic sides of the island, this led to a proposal for deep sea disposal of tailings and shallow bay disposal of waste rock. Here the economic preference for a large open pit operation was mainly determinant in arriving at justifying MMWD. Again, it is arguable and controversial as to whether the sum total of environmental impacts and risks of land-based tailings and waste rock management are greater in this context than those from MMWD. It is clear, however, that the use of deep sea tailings disposal at Lihir has greatly reduced species abundance and caused changes in higher-taxon composition (Haywood et al., 2016). While the full effects of Lihir's mine waste disposal are evident 20 km from the discharge point and at 2000 m in depth, further studies are required to determine the extent and nature of impacts beyond this distance (Hughes et al., 2015). It is apparent that the effects on marine biodiversity cover a greater sea floor area than originally expected and that ecological recovery from deposited tailings is slower than expected (an outcome also observed at the former Misima Au-Ag mine, which also used deep sea tailings disposal; see Fallon et al., 2002). Furthermore, the disposal of waste rock into the shallow waters of Luise Harbour is often overlooked in comparison to deep sea tailings disposal – but this also causes significant impacts on water quality, the coral reefs and shallow marine ecosystem (e.g. Haywood et al., 2016). Despite being regarded by many as PNG's mining success story, social impacts from Lihir are equally contentious, with direct benefits being offset by social fragmentation and the inability of technical decision-making processes to see, value or protect local well-being (Cueva, 2016).

The Hidden Valley project with its engineered tailings dam was clearly a positive step forward for tailings management in PNG – although it was not able to prevent all mine waste impacts (Mudd and Roche, 2014). There, incorrect environmental impact assessment and poor mine management

lead to a massive sedimentation event, due mainly to the dumping of waste rock over the sides of steep mountain slopes during site construction and early operations (~2006-2010), with ~20-30 Mt of mine-derived sediment entering the Watut River (and not mostly the Bulolo River as predicted during the assessment and approvals process, as discussed further below). Based on best estimates, this approximately doubled the sediment load of the Watut River, with immediate impacts on water quality, biota and riverbed morphology affecting the many communities living along and dependent on the river. These errors were then compounded by poor management response and a lack of transparency with multiple breaches of international standards in the OECD Guidelines and Equator Principles (Roche et al., 2017). Site practices were changed from ~2010, such as detailed waste rock planning, design and implementation, including triple handling at times, as well as careful separation and management of mine site waters. This has clearly reduced erosion reaching off-site and this is evident in environmental monitoring of the Watut River, such as lower total suspended sediment, copper and zinc levels (see review by Mudd and Roche, 2014). The social and economic impacts persist, however, especially where the river shifted near Tsile Tsile, effectively moving the village from the main channel, increasing their isolation and making river navigation and commerce difficult (Burton, 2013). The lived experience illustrates the two-speed nature of mining and the Anthroposphere. The Hidden Valley mine was initiated by Harmony Gold Ltd from South Africa in 2006, with Australia's Newcrest Mining joining in mid-2010 to form the 50-50% 'Morobe Mining Joint Venture' (which includes the Wafi-Golpu project). With high unit production costs that often-exceeded market prices, Newcrest were keen to forget, selling their half share in the underperforming Hidden Valley mine in September 2016 for just one dollar, along with paying US$22.5 million dollar for the resulting mine legacies and eventual site rehabilitation (see Newcrest, 2016b). The community, however, live with the consequences, affected by environmental decline and troubled by their loss of agency and autonomy. The former joint venture operators of Hidden Valley are now proposing the much larger Wafi-Golpu project (see Tables S1 and S2) between the mid- and lower sections of the Watut River – and it is these affected communities which they now need to seek permission from for Wafi-Golpu. It is therefore in the best interests of Harmony and Newcrest (through the MMJV) to understand and address the communities grievances.

To describe RMWD and MMWD practices as highly controversial is perhaps obvious, but they are clearly far from simple. Aerial images of each of the major mines are shown in Figures S7 to S12 in Supplementary Information. In many countries, the discharge of tailings and waste rock to rivers or marine waters is simply not allowed (e.g. Australia, Canada[6], USA, New Zealand, South Africa, etc; see Lottermoser, 2010; Franks et al, 2011; Cardiff et al., 2012) – but countries such as PNG or Indonesia are seeking to promote economic development and view the risks and impacts from mines such as Ok Tedi and others as worth the benefits (implying that more expensive mine waste management regimes would make these projects more marginal in their economics). In reality, the benefits are almost always concentrated far from the mine (e.g. Port Moresby or shareholders in the projects in Australia, Canada, Japan, South Africa, Europe, etc) whereas the often-high impacts are local to the project, its river system and adjacent communities (Cardiff et al., 2012). Mine waste represents a wicked sustainability conundrum with complex interactions across natural and human spheres. Less well captured is the complexities of the Anthroposphere, with colonial pasts and asymmetric relations at the heart of inequalities between proponents, governments and communities – let alone the complexities of intra-community inequalities and outcomes (e.g. community heterogeneity, coastal versus lowland versus highland peoples; rural versus urban; technocrat, bureaucrat or agrarian; etc.). There is clearly a strong case for a more ethical, principled approach to managing mine waste in PNG. A future where the global mining industry needs to implement consistent standards for mine waste management practices (see Franks et al., 2011) and be transparent and accountable – especially in a post-Samarco / Brumadinho mining industry.

The issues of mine closure, rehabilitation and remediation are rarely addressed in PNG, in large part due to the fact that so few mines have actually closed and reached this phase of mining. Rehabilitation works were completed at the Mount Victor Au mine, although no long-term assessment of its effectiveness is known – with community concerns remaining about ongoing pollution risks from the tailings dam in particular (see PNGMW, 2020). The Sinivit Au mine near the

[6] Canada does allow the use of freshwater lakes for disposal of tailings at some sites.

north-east corner of New Britain operated briefly (2008 to 2013; see Table S4), but the bankruptcy of the company has left the PNG Government with the cost of remediation of the cyanide-impacted soils and waters at the site (PNGMW, 2020). Given the pending closure of Ok Tedi in the next several years and the current status of Porgera (see later), this makes mine closure, rehabilitation and remediation key issues to urgently address.

Despite the often easily justified pessimism for mine waste management in PNG, in early 2020 there have been developments which can rightly be labelled as seismic. In late 2019, PNG's Constitutional and Law Reform Commission released their review of environmental and mining laws – with PNG Prime Minister James Marape announcing on 19 March 2020 that they have accepted the numerous recommendations (DPM-NEC, 2020). Specifically – and most importantly – the use of RMWD will be banned for all future mining projects to protect the environment and livelihood of communities. Whilst this will not change the use of RMWD at Ok Tedi, Porgera or Tolukuma (nor address cumulative impacts to date and their potential remediation), it is a very welcome change in policy. Another recommendation was to incorporate health impact assessments during the approvals process for new mining projects. Finally, PNG has refused to approve a renewal of the mining lease for Porgera (which expired in August 2019 but was extended to 29 April 2020) – whilst it could ostensibly be viewed as a battle over revenue flows, the significant environmental and social impacts of RMWD at Porgera are certainly being used as part of the moral justification for refusing the extension[7]. Porgera's future at present clearly remains in political and legal limbo. It seems there may be significant changes occurring in PNG's approach to regulating and approving mine waste management in the very near future.

6.2 Environmental Metrics

Over the past two decades there has been strong growth in mining companies reporting annually on their sustainability performance – often in conjunction with statutory financial reporting. The most common framework which is used for such reporting is the Global Reporting Initiative (GRI, 2016), which has many indicators covering economic, environmental, labour and human rights –

[7] Based on various media commentary and related sources.

whilst earlier GRI editions included a specific mining sector supplement for additional reporting tailored to the mining industry (GRI, 2013). The growing wealth of data allows detailed analyses of energy requirements, greenhouse gas emissions (aka carbon intensity), water use and impacts on water resources, and when this is linked to basic mining production aspects such as scale (e.g. tonnes milled per year), grades (e.g. g/t Au, %Cu) or products (e.g. Cu, Au), this facilitates a clear comparison between various mines and their respective outputs. All data has been sourced from corporate and sustainability reporting from the operating companies (e.g. Newcrest Mining, Ok Tedi Mining, Placer Dome, Barrick Gold, Inmet, Harmony Gold, etc). All results are presented in Tables 1 and 2.

6.2.1 Energy

Energy is often a major cost factor in mining (see Leveque et al., 2014), especially for remote mines which also have to generate their own electricity. Four different metrics for energy intensity over time are shown in Figure S4 (Supp. Info.) for the various PNG mines. For total energy consumption per tonne of ore processed (GJ/t ore), the four Au mines show a declining trend over time (albeit with some variability at times), although the Ok Tedi Cu-Au-Ag mine shows a gradual increasing trend. At Au mines, this result would most likely be a result of energy efficiency efforts, but for Ok Tedi it is probably related to the increasing size and depth of the pit as well as growing electrical energy needs for ore processing (Figure S4b). For electrical energy inputs, Misima was relatively stable, Hidden Valley shows a significant decline and then stability, and Porgera, being significantly higher relative to Misima and Hidden Valley, shows a gradual decline. In terms of diesel intensity, all mines (except Hidden Valley, which only has 2 years of data reported) show a clear increasing trend over time (despite some variability). This suggests that as pits enlarge in area, get deeper and have longer haul roads, this drives up the diesel required to shift a tonne of rock (i.e. ore plus waste rock) and that these factors are outstripping the improvements in haul truck technology, size and efficiency. Another interesting observation is that despite the variations in grades (i.e. ~6 g/t in the earlier days of Porgera and Lihir), the energy intensity for all Au mines

is somewhat similar – all being of the order of 300 to 600 GJ/kg Au, suggesting that grade alone is not always the driving factor in energy intensity.

A unique aspect of Lihir is that it is mining within a waning volcanic caldera – and there is still significant residual heat in the geology (Melaku, 2005). Initially, this heat was simply vented via steam, but in 2003 a successful 6 MW pilot project was built to convert the geothermal heat to steam for electricity production, followed by a 30 MW expansion in 2004 and another 20 MW in 2008 (Moorhead, 2014). The reductions in greenhouse gas emissions achieved from the geothermal power plant (i.e. through reductions in diesel use for electricity) were certified under the Clean Development Mechanism of the Kyoto Protocol and then traded as carbon credits. In recent years there have been some issues with steam productivity from some wells, with the system only supplying at an average capacity of 21 MW in 2016 – and seems to average between 30 to 60% of electricity consumption for the project. Although the lack of consistent reporting of electricity consumption data limits further insight, it is clear that the project has been highly beneficial in terms of lowering diesel inputs and greenhouse gas emissions.

Another interesting aspect of energy consumption is the recent four years of data reported by Ok Tedi which includes energy used in their logistics and supply chain (i.e. the barge used to transport concentrates down the Fly River and to international marine vessels). Between 2013 to 2016, transport-related energy ranged from 1.6 and 3.2 million GJ, which adds to total onsite energy consumption of between 3.3 to 5.5 million GJ, respectively – a clearly significant addition of ~52% in energy requirements. These have been excluded from the tables and graphs, as the transport and supply chain is unique to every mining project (especially Ok Tedi); however, on a global basis, it would be important to analyse total supply chain transport distances (perhaps weighted by mine production by region).

6.2.2 Greenhouse Gas (Carbon) Emissions

Similarly to energy, unit carbon intensities for ore processed are typically declining over time for all Au mines, although Ok Tedi is gradually increasing, shown in Figure S5 (Supp. Info.). In terms of

unit carbon intensities per metal produced, there is often significant variability in all Au mines with no discernible trend over time, with Ok Tedi again showing a subtle increasing trend over time. Furthermore, despite the variations in grades between all Au mines, the carbon intensities for Au produced are all somewhat similar except for Hidden Valley, which also has a low grade (~1.9 g/t Au; Table S4), but not as low as Misima (1.45 g/t Au; Table S4). Given that Misima was solely reliant on diesel for electricity, a carbon intensive electricity source, and Hidden Valley now enjoys a majority hydroelectric supply with minority diesel, this highlights the potential role that the greater scale plays at Misima – since it had a greater throughput than Hidden Valley (i.e. ~5.9 versus ~3.6 Mt/year). For Lihir, although there are significant reductions in greenhouse gas emissions arising from the use of geothermal steam for electricity supply, it still maintains an average carbon intensity similar to other PNG mines such as Porgera or Misima which are (or were) entirely reliant on fossil fuel-derived electricity.

6.2.3 Water

Figure S6 (Supp. Info.) and Table 2 show summarised water use data for PNG mine sites. In wet climates there is typically lower incentive for mining operations to conserve water and so the water efficiency of PNG mine sites is considerably poorer than comparable mine sites in dryer regions when measured in terms of total water used per tonne of ore processed or metal produced (see examples provided by Mudd (2008) and Northey et al. (2013)). Unlike energy consumption and greenhouse gas emissions, the general trend at PNG mine sites has been towards an increase in water use intensity over time – regardless of whether measured on an ore or metal product basis. A variety of factors may be contributing to this increase overtime (e.g. processing changes, increases in water discharged with tailings, etc.). However, a lack of transparency and inconsistency from year-to-year in water use reporting at the various mines limits the ability to fully understand the causal reasons for these changes. There has been some limited progress towards more consistent water use reporting, with Newcrest adopting the Water Accounting Framework for the Minerals Industry (SMI and MCA, 2012) to report water use information for Lihir, which is gradually being adopted more widely through the global mining industry (Northey et al., 2019).

The Lihir Au mine is particularly interesting from a water management perspective. Extensive dewatering is required to prevent groundwater flow into the open pit mine. There has been evidence of significant seawater intrusion into the dewatered aquifers from the adjacent Luise Harbour, resulting in reduced dewatering efficiency and increasing the corrosion rates of pumps (Vogwill et al., 2009). As part of Newcrest's Lihir pit optimisation project, the 2013 prefeasibility study proposed a cofferdam be constructed to mitigate long-term seepage risks at an estimated cost of US$1,290 million (Newcrest, 2016a). However, the subsequent 2016 feasibility study identified an alternative strategy through the use of a near shore cut-off wall and harbour infill, at a much reduced estimated cost of US$215 million (Newcrest, 2016a). Beyond the management of seepage, dewatering efforts are also complicated by the hot groundwater temperatures associated with the active geothermal system. Some aquifer reinjection also occurs on-site to improve the sustainability of power supply from the geothermal resource. The highly saline groundwater from pit dewatering is discharged directly into the ocean rather than used on-site due to the sensitivity of the production processes to the presence of chlorides (Berry and Moorhead, 2011; Corp, 2013; Moorhead, 2014). Therefore, the raw water requirements of ore processing are fulfilled by freshwater sourced from the Londolovit and Wurtol rivers located 8 km and 22 km respectively from the plant. Variability in local rainfall has impacted production at the Lihir mine site. In early 2011, extremely low rainfall reduced the freshwater available for the flotation circuit and resulted in 40,000 oz Au lower production (Newcrest, 2011b). The site was also impacted by extremely high rainfall in September 2011, which limited production from high grade sections of the pit until mid-November 2011 and required an immediate doubling of pit water pumping capacity with expectations of more in early 2012 (Newcrest, 2011a).

The issue of water quality is a vexed one, and, in the authors' experience, GRI-style reporting still fails to adequately address this critical area (Mudd, 2008; Northey et al., 2016). An intriguing example, however, is older reporting by Inmet Mining Ltd, a former minority owner of Ok Tedi. For 2003 to 2005, Inmet reported metal loads[8] discharged to rivers at Ok Tedi of ~95,000 t Cu and

[8] The reporting is similar to pollutant release inventory systems, such as Canada's National Pollutant Release Inventory (NPRI), with similar statutory systems in Australia, USA and Europe.

~21,000 t zinc (Zn) (Inmet, 2006). These metals would be contained in both tailings and waste rock, meaning the average grade of mine waste discharged to the Fly River (based on tailings+waste rock data) is ~0.12 and ~0.03% Cu and Zn, respectively. Ok Tedi also began direct reporting of the quantities of tailings and waste rock with Cu grades in recent annual environmental reports, shown in Figure S7. The Cu grades have gone down over time but ranged from a high of 0.25 and 0.14% Cu in waste rock and tailings, respectively, to 0.08 and 0.05% Cu, respectively, in 2016. For comparison, these Cu grades can represent economic ore at other mines (e.g. Morenci, USA; Aitik, Sweden; Cadia, Australia; subject to various modifying factors in resource assessments; see data in Mudd and Jowitt, 2018). Although the heavy metal concentrations of discharged mine wastes are important, it is also the metal concentrations in mixed sediment down the Fly River system as well as dissolved concentrations in river waters which are crucial in assessing ecosystem and human health (see Bolton, 2009). The reporting by Inmet and Ok Tedi shows the value in being transparent about such monitoring. Furthermore, Hidden Valley has released two annual environmental monitoring reports for the years 2011 and 2012, but nothing more recent. It should also be noted that Ok Tedi conducts and reports annually on its extensive environmental monitoring, although these are more statutory-style technical reports to regulators and not GRI-style sustainability reports. A fundamental issue for water quality is establishing the impacts due to mining – which ideally requires extensive baseline studies prior to project development as well as upstream and downstream monitoring. We explore the regulation of water further in the discussion.

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6.2.4 Reagents and Consumables

The consumption of process reagents, explosives and other consumables (e.g. tyres) at mining operations results in a range of impacts being generated throughout the supply chains of these products. Often the indirect impacts associated with producing and supplying these consumables go unrecognised when assessing the benefits or detriments of mining. Currently the reporting of consumable use by mining operations is not widespread, however there are some data available

for consumables at PNG mine sites. Values are presented as mean (M) plus / minus one standard deviation (SD) with the number of years of data (N) in brackets; i.e. M ± SD (N).

The consumption of explosives varies between mine sites due to ore hardness, density, particle size distributions, mine design and also processing requirements. Explosive consumption averaged 0.14 ± 0.06 (10) kg/t rock at Porgera, 0.16 ± 0.07 (6) kg/t rock at Lihir, 0.08 ± 0.02 (4) kg/t rock at Misima, and 0.12 (1) kg/t rock at Hidden Valley.

Cyanide is the most common lixiviant used for extracting Au from ores. Cyanide consumption varies substantially between PNG's Au mines due to differences in ore mineralogy and processing design requirements. Cyanide consumption averaged 30.5 ± 15 (19) kg/kg Au at Porgera, 141 ± 12 (8) kg/kg Au at Lihir, 458 ± 119 (7) kg/kg Au at Misima, and 524 ± 176 (5) kg/kg Au at Hidden Valley. The management and containment of cyanide affected mine wastes is heavily regulated at Au mines in developed countries due to the potential for large impacts to ecosystems when these wastes are released into waterways. Consequently, the tailings disposal methods practiced by PNG Au mines would be considered sub-standard when compared to the global industry. Cyanide accidents such as the one on the Wampet section of the Bulolo Highway on the 31st January 2012 (to supply Hidden Valley) have heightened community awareness with testing failing to alleviate concerns about fish deaths and wider eco-system and human impacts (Sawaraba and Rao, 2014).

Another aspect of cyanide use is whether a mine is certified under the International Cyanide Management Code (ICMI)[9]. Under the code, a mine is certified if it meets compliance for the transport, use and disposal of cyanide in a safe manner. The code was developed mainly in response to the Baia Mare tailings overflow incident in eastern Europe in January 2000, whereby cyanide-laiden water flowed into the Tsiza and Danube River systems and caused extensive ecological, social and economic impacts (Baia Mare occurred shortly after the April 1998 Los Frailes-Aznalcollar tailings dam failure in southern Spain) (Rico et al., 2008). Following Baia Mare, a helicopter carrying cyanide to the Tolukuma mine accidentally dumped its cargo into the Auger River in March 2000, also causing significant ecological, social and economic impacts (see

Macdonald, 2004). At present, only Porgera (May 2016) and Lihir (Nov 2019)[9] are fully code compliant and certified, while Hidden Valley is intending to gain certification but is not yet compliant and certified (Edie Creek and Simberi are not considering code certification).

Only limited data is available for other mine site consumables (e.g. grinding balls, flocculant, cyanide, lime, etc.). The average process requirements for Lihir and Ok Tedi are provided in Supplementary Information. Relating the use of these consumables to metrics for indirect impact, such as embodied energy or greenhouse gas emissions, would provide more insight into the impacts occurring in the supply chains that feed PNG mine sites. These indirect impacts can be assessed using life cycle assessment, which remains an important area for future research to ensure accurate inventory databases for life cycle assessment studies. Existing life cycle inventory databases have very limited data for PNG production systems, meaning that the PNG mining industry is currently being implicitly accounted for using generic datasets for 'rest of world' mineral production. Due to this, the significant waste and toxicity impacts associated PNG mining are likely to be under-represented within existing life cycle inventory datasets. The data provided in Table 1, Table 2 and the supporting information may provide an initial basis for development of life cycle inventory datasets that can accurately represent the environmental impacts of PNG mining processes.

6.3 Discussion: Existing and Future Environmental Standards for PNG Mining Projects

There are many complex and interrelated aspects of the environmental standards for mining projects in PNG, as noted already. Here we focus on the key underlying issues, specifically the environmental impact assessment (EIA) process, followed by regulatory and governance processes, mining and the SDGs, and finally discuss future projects and their current proposed approach. The large scale of PNG mining projects, especially the use of RMWD and MMWD, leads to significant community concerns for water pollution, land disturbance, biodiversity, socioeconomic changes and risks for subsistence and semi-traditional livelihoods.

[9] List of current mining companies who are signatories to the International Cyanide Management Code https://www.cyanidecode.org/signatory-companies/directory-of-signatory-companies (Accessed 7 March 2020).

6.3.1 Environmental Impact Assessment (EIA) and Project Configuration and Scale

Before a large industrial project is allowed to proceed, PNG, like almost every other country in the world, requires that it be considered using an environmental impact assessment (EIA) process (e.g. Harvey & Clark, 2012; Elliott, 2014). Through an EIA, a projects' configuration, risks and proposed management measures can be examined, and, if acceptable, approval can be given by government. In theory, the process should allow a detailed comparison of impacts and benefits, especially across environmental, social and economic spheres. In the case of mining in PNG, however, the EIA process is proving to be flawed for a few critical reasons. Below, we present our synthesis and analysis of key issues which we believe substantiate this claim.

It is widely understood that the scale of mining projects invariably grows over time (e.g. Mudd & Jowitt, 2018). The project scale and configuration presented during an EIA process is only sufficient for the company's business case to justify project development – despite the mineral resources often being recognised as substantially bigger. To explore this, we compile the initial pre-mining mineral resources of most PNG mining projects and contrast this with cumulative production by 2017 and remaining resources, shown in Table S6. These data show that projects always end up much bigger in scale than the EIA process ever envisaged – which also means much greater risks and impacts as well as potential benefits (see Banks, 2013). The EIA process, however, never goes back and revisits this fundamental mismatch – with projects often continuing or expanding simply as a variation of approval conditions, meaning the public consultation component of an EIA process is bypassed. Based on the authors' collective experience, this outcome is also common across Australia, Canada and many mining-dependent nations.

The Ok Tedi project is a classic case of a poor EIA process, with specific points including:

1. The project was approved for construction in August 1981 yet the full environmental impact statement (EIS) was not released until June 1982 (Townsend and Townsend, 2004) – effectively showing that the PNG Government wanted the project to proceed and that the EIS was constrained to assuming the project would proceed and excluded the alternative of no

project, which is a fundamental aspect of a fair and balanced EIS and EIA process (e.g. Elliott, 2014; Harvey and Clarke, 2012);

2. Assumed use of a tailings dam – yet the initial dam site was destroyed by a landslide during construction and the project was subsequently approved to use riverine tailings (and later waste rock) disposal (see Jenkins, 2016; Townsend and Townsend, 2004);
3. Impacts assumed to be very local to the mine area only (e.g. Jenkins, 2016; Salomons and Eagle, 1990) and not reaching down the entire Fly River system – yet the onset of RMWD ensured extensive impacts, with the estimate of floodplains affected always being under-estimated; specifically:
   a) within the first decade of operations, sediment loads reaching the Fly River estuary increased from 85 to 120 million tonnes per year (Mt/year) (Salomons and Eagle, 1990, cited by Apte and Day, 1998) – led by a nearly ten-fold increase in tailings and waste rock leaving the Ok Tedi site over that originally expected (Zorn, 2018);
   b) between 1985-2000, sediment loads in the Ok Tedi at D'Albertis Junction[10], more than 100 km downstream from the mine, increased from pre-mining loads of 3-5 to ~45 Mt/year (Pickup and Marshall, 2009);
   c) by the early 1990s, widespread community concerns were being expressed at the rapidly growing extent of impacts on the downstream Fly River environment and communities, especially greater overbank flooding due to increased sediment loads and associated forest dieback – leading to international protests and eventually a successful litigation case in Australia which forced the mine to pay extensive compensation to affected communities along the entire Fly River system (e.g. Jenkins, 2016; Kirsch, 2003; Pickup and Cui, 2009);
   d) by 2000, the estimate of affected floodplains was 1,347.7 km^2 (2002 Edition, OTML, var.);
   e) by 2016, the estimate of affected floodplains was 1,954.1 km^2 and was predicted to reach 2,395 km^2 – noting that 313 km^2 was demonstrating "some form of recovery" (page 2, 2016 Edition, OTML, var.) (the assessments of affected floodplain area over time is given in Figure S14). Although it appears as though the area of affected floodplain has started to plateau, the area under recovery has declined from a peak of 527 km^2 in 2005, suggesting a

[10] This is the confluence of the Ok Tedi with the Fly River system (i.e. between Atkamba and Nukumba on Figure S15).

long-lasting impact on the Fly River floodplain ecosystems and the communities that depend on them;

4. Scale of project now far exceeds original expectations (see Table S6) – which could be viewed as a blessing (i.e. economically) or a curse (i.e. environmentally), but it certainly means that the scale of environmental and social risks continues to grow as mine waste continues to enter the Ok Tedi-Fly River system;
5. Assumed trickle-down economics would deliver substantial development progress in the region – yet Western Province remains PNG's least developed despite Ok Tedi;

As stated eloquently by Townsend and Townsend (2004) (page 19):

"The most obvious weakness is a vast underestimate of the volume of waste rock and tailings that would enter the river system. The project for which the EIS was written was not the project that was built …"

It should be noted that in 2000 the Ok Tedi mine life was planned until 2010, and in order to extend beyond this, legislation was passed in the PNG Parliament in 2001 to facilitate BHP's exit from Ok Tedi, establish new environmental monitoring requirements as well as community consultation along the entire Fly River system (essentially all communities impacted by Ok Tedi's operations) (see Kirsch, 2014; OTML, various). By 2006, as community engagement continued along the Fly River, mine life had been extended to 2013, and in 2011 extended to 2015, with further community agreements being signed in 2012 and PNG legislation passed in 2014 to extend mine life to 2025 (OTML, various). In reality, although the project extensions are often presented as economic saviours (especially by Ok Tedi Mining Ltd and the PNG Government), for many Fly River communities it means greater impacts and for longer – based on Table S6, total mine waste will now be some four times larger than the original proposed project (if not even greater). Despite the impending deadline of 2025, Ok Tedi is still investigating new possible projects, including the Townsville Au prospect ~5 km north and several near-mine targets, albeit noting the "environmental constraints due to riverine tailings disposal and waste disposal" (page 35, 2019 Edition, OTML, various).

It is hard to understate the complexity and scale of impacts and issues with Ok Tedi, but it clearly highlights the challenges in proposing large mining projects in remote areas on indigenous lands in a developing country – especially projects that inevitably get much bigger over time. From a sustainable development perspective, the Ok Tedi case continues to shine as a poor example of global mining standards but also a crystal-clear example of the intimate connections between the lithosphere, hydrosphere, biosphere, atmosphere and anthroposphere.

For the Hidden Valley project, although a well-engineered tailings dam was built (see Murray et al., 2010), the early years of construction and operation saw significant erosion of waste rock into the Watut River system. The 2004 EIS, however, predicted minor erosion and that this would drain equally to both the Bulolo and Watut Rivers (see Figure 16b) – yet in reality some 90% of the erosion entered the Upper Watut River (Mudd and Roche, 2014). At the Lihir project, Corp (2013) noted that there was active consideration to building a coffer dam in Luise Harbour to mitigate saline intrusion through groundwater into the active pits – suggesting the engineering is possible to build such large dam structures at sites like Lihir.

Although the significant controversies at other PNG mines are not reviewed in detail herein (namely Misima, Porgera, Lihir and Ramu), it is our view that the EIA process has not delivered a robust view of likely project scales and risks – which is a major part of the reason that communities remained concerned over the extent of impacts from such mines. In other words, communities have expected a certain range of impacts but perceive the actual impacts to be much bigger and arguably worse – an issue which, in the authors' collective experience, is also observed in Australia, Canada, New Zealand and other mining-dependent countries.

Finally, it is worth noting that the EIS's for Wafi-Golpu and Frieda River were released in late 2018, both remain in the public consultation and engagement phase and with approvals expected in 2020/21. The proposed method of tailings management for Wafi-Golpu is MMWD into the Huon Gulf, though concerns about impacts and opposition from local communities and the Evangelical

Lutheran Church of PNG challenge the acceptability and viability of the concept. Although the Freida River project is proposing to construct an integrated tailings and waste rock storage facility (Coffey, 2018), this approach remains controversial amongst host communities and civil society groups[11].

6.3.2 Regulatory Issues for Water Quality

Although there are a range of regulatory issues concerning mining and the environment in PNG, we will focus here on water quality since this is a fundamental risk factor for ecosystem and public health impacts (plus water quantity issues are typically not an issue given PNG's high rainfall). Typically, water quality has been regulated by the selection of a compliance point downstream of a mine with set statutory criteria after allowing for a 'mixing zone'. Initially, criteria set in the 1980s to 1990s were somewhat arbitrary (especially given the lack of cohesive PNG standards or guidelines), but after the new Australian guidelines for freshwater quality protection were released in 2000 (ANZECC and ARMCANZ, 2000), these have been progressively adopted and supplemented with other national or international guidelines for ecosystems or drinking water (compiled in Table S7, Supplementary Information). Some notes on each mine (based on their respective reporting):

- **Porgera** (PJV, 2019)– trigger values are used to guide risk assessment for ecosystem protection and drinking water for human health, based mostly on Australian guidelines with some international sources. A mixing zone is applied down the Porgera and Lagaip rivers to just past the confluence of the Ok Om and Strickland River, a site called SG3 (~180 km downstream from the mine). The monitoring map is shown in Figure S15. Although the criteria are close to the ANZECC guidelines, this is after substantial dilution and mixing down the Porgera and Lagaip Rivers – also meaning that impacts along the mixing zone are not given strict criteria such as the ANZECC guidelines (especially close to the mine and direct discharges). For tailings discharge, the annual volumetric limit is set at 56.35 Mm^3; based on ~5.5 Mt being discharged, a particle specific gravity of 2.7 t/m^3 and an average slurry density of 20% (based on PJV, 2018), this means ~10.2 Mm^3 per year – showing that the limit is very generous and

[11] For example, see https://savethesepik.org/

provides no incentive to minimise discharge volumes or metal loads dispersed into the freshwater environment.

- **Hidden Valley** (MMJV, 2013) – the Nauti compliance point in the Watut River is ~20 km downstream from the mine (e.g. MMJV, 2013). Only treated water was expected to be discharged to the Watut River, plus there were supposedly no villages along the river between the mine and the nearest village at Nauti. The compliance monitoring maps are shown Figure S16a and S16b. There are, however, two villages in between the mine and Nauti, namely Heyu and Hikinangowe. Furthermore, the cyanide detoxification treatment plant was not performing to the required standard in late 2011 (residual cyanide levels were higher than desired), which, combined with high rainfall, caused a rapid build-up of water in the TSF. The mine sought and received approval to discharge at a greater rate with slightly elevated cyanide concentrations (MMJV, 2013), which caused significant concern in the Wau-Bulolo region – although it was clearly not RMWD nor was it highly contaminated waters (i.e. heavy metal-rich AMD waters), the community was clearly worried that the mine could be heading towards this.
- **Ok Tedi** (OTML, various) – the mine used to have a compliance point ~175 km downstream for Total Suspended Solids (TSS, or particulate matter) of 940 mg/L (Townsend & Townsend, 2004), but after 2000 a new regime was adopted based on drinking water guidelines since the Ok Tedi itself was severely impacted above ecosystem protection values. This was soon realised as inappropriate to protect the water quality and uses of the Middle and Lower Fly River sections, and from 2006 a new regime was adopted whereby monitoring along the entire Ok Tedi-Fly River system would be compared against the 95% ecosystem protection levels from the ANZECC guidelines (see Table S6). The compliance monitoring map is shown Figure S17. Whilst it is acknowledged that these values may be exceeded, even regularly (page 22, OTML, 2017), this is a more progressive approach – but it still ignores the long-term issues of bioaccumulation in the aquatic ecosystem, the complex interplay with floodplain geomorphology, acid mine drainage risks from exposed iron sulfides and related metal mobilisation.
- **Lihir** (LGL, 2008) – concentration limits are set for the tailings slurry (see Table S6) but there are no specific regulatory criteria for marine water quality. An extensive range of monitoring is

undertaken to assess any dispersion or mobilisation of sediment and metals, including marine water quality, biodiversity and seafloor sedimentology, but this body of work is not publicly reported.

There are no details available for the regulatory criteria applied for the Simberi Au mine, the Ramu Ni-Co refinery at Basamuk Bay nor the recent approvals for Woodlark Island. The approach to regulatory criteria has certainly improved over the past two decades in PNG, moving from a single, distant compliance point which allows for very generous dilution to adopting Australia's modern ecotoxicological approach to deriving freshwater quality criteria (e.g. Table S6). This does not absolve the fact that the way compliance is assessed is still very distant down-river – effectively still allowing major impacts on river systems and the ecosystems and communities that depend on the river, especially within the 'mixing zones'. After all, PNG's young geology and high energy rivers naturally carry substantial sediment loads, meaning the modern regulatory approach is still reliant on dilution to mitigate risks and impacts. Our synthesis of the regulatory criteria for water quality compliance is shown in Table 3, including relevant information and strengths and weaknesses, highlighting especially the importance of transparency and public reporting.

6.3.3 Governance Issues

The role of governance is absolutely crucial in ensuring the role that mining can play in helping or hindering a country such as PNG in working towards the SDGs. There are several key governance issues which stand out with respect to mining:

- **Resourcing** – government agencies, in reality, are not resourced sufficiently to achieve the expectations of communities in their scrutiny of mines and companies. Statutory groups are seen to be the protector of public interest and are expected to be independent of industry, but without sufficient resourcing they cannot perform their duties. This leaves companies as effectively self-regulating, and given the history of mining in PNG, this often leaves a deep sense of mistrust of both mining companies and government agencies – which affects all involved and not just communities.

- **Enforcement** – there is a widespread perception, and indeed reality, that mines are poorly regulated since the PNG government rarely enforces environmental conditions. For example, although the Hidden Valley project clearly operated outside its approved environmental management program in its early years, there was no penalty applied to the mine at all. Even though the mine has publicly acknowledged it was the cause of the extra sediment loads in the Watut River, there was no legal or other action by the Department of Environment and Conservation nor the Mineral Resources Authority (except perhaps to trust the mine to address the issues, including compensation to some communities).
- **Ramu Ni-Co Refinery, Basamuk Bay** – as part of the community-led court case to stop the use of MMWD by the Ramu project, a series of conditions were set, including public reporting of the monitoring of tailings disposal impacts on the marine environment. As of the date of this paper, there is still no such public reporting – and no action by PNG statutory agencies to enforce such conditions and reporting either.
- **Public Environmental Reporting** – since 2000 there has been a strong uptake of public reporting of statutory environmental monitoring and management, such as annual environment reports, but almost entirely by Ok Tedi and Porgera and not many others. For example, annual reports have been released since ~2001 for Ok Tedi and since 2009 for Porgera, but only 2011 and 2012 for Hidden Valley and only 2005 to 2007 for Lihir, whilst other mines have not done this. These reports are crucial in many ways; firstly because mines claim to be in compliance and such reporting allows an assessment of these claims; secondly because they allow a much more sophisticated understanding of the actual extent of monitoring and impacts at each mine, especially long-term trends over time; and finally they allow independent assessment of the environmental reality for each mine – moving beyond perception only to allow review of actual data. It is interesting to note that for Newcrest's mine at Cadia Au-Cu-Ag in New South Wales, Australia, they are required by law to release such reports annually on their website but not for their Telfer Au-Cu mine in Western Australia – nor do Newcrest practice this for the Lihir mine. In the modern age, public access to compliance monitoring is crucial and a key test of corporate transparency.

- **Extractive Industries Transparency Initiative (EITI)** – the EITI began shortly after the 2002 Earth Summit in Johannesburg, South Africa (Harmony Gold's home country), and aimed to facilitate better transparency around the governance of revenue flows from resource extraction. PNG officially joined the EITI in 2014, with annual EITI reports available from 2013 to 2016. These reports give clarity to the production of various resources (despite some missing data and minor variances between company and EITI data), their export value and revenues to government – although significant data gaps and inconsistencies clearly remain to ensure accurate and responsible governance. It also remains unclear to what extent the EITI can assess the effects of special tax credits and development deals and the potential revenue loss this may have led to for the PNG government. Although the EITI can track revenue flows to and within government, it cannot address the way that payments are distributed within communities. For example, royalties may be paid to a village chief as per a development agreement, but this is then shared mostly with sons while daughters receive very little – meaning poor gender equity (a critical SDG).

There remain many strands of the governance of the extractive resources sector in PNG which still need substantial improvement. Although some mines are clearly adopting more transparent governance (e.g. Ok Tedi, Porgera), many others remain behind (e.g. Hidden Valley last released an annual environmental report for the year 2012). The role of the PNG Government and its statutory agencies remains crucial, but they are collectively perceived to be poorly resourced and ineffective.

6.3.4 Mining in PNG and the Sustainable Development Goals (SDGs)

The history and status of mining in PNG raises serious questions about the role that mining can or should play in broader national development through to local community development. For PNG, these issues deserve considerable research and analysis which are clearly beyond the scope or ability of this paper. However, we include some succinct points to provide some context for the oft-repeated mantra that 'mining brings development'.

The UN Development Program (UNDP) has been reporting their 'Human Development Index' (HDI) assessment of countries now since 1990. Whilst there are issues with the data underpinning HDI and contention about its utility in assessing human development status (including the impacts on human development from a severely degraded environment), it is at least a continuing and independent assessment. For PNG, it scored a HDI value of 0.471 in 1990 and 0.543 in 2018 – both years placing it in the 'low human development' category (UNDP, var.). This marginal improvement suggests that PNG's long-term focus on the extractive industries as the means of economic development since independence in 1975 has failed to deliver the anticipated improvements in human development outcomes at the national level (Banks, 2014). Significant reforms are therefore required to ensure that extractive industries make a greater contribution to human well-being in PNG

In recent years, the SDGs have become an important lens to assess development priorities, especially in developing countries such as PNG and for large-scale industrial sectors such as mining (e.g. Nickless, 2017, 2018; Reis Monteiro et al., 2019; Yakovleva et al., 2017). Many of the 17 SDGs relate directly to the role that mining projects can contribute to (e.g. clean water supplies, jobs, education), whilst others are more indirect or perhaps nebulous (e.g. gender equity, peace) (e.g. CCSI, 2016; Fraser, 2019) – but in PNG, mining can also strongly hinder SDG progress (e.g. polluted rivers, loss of land, fractured communities, unequal wealth distribution, etc), as clearly evidenced at mines sites such as Panguna, Ok Tedi, Porgera and others. A positive example is the Hidden Valley mine which, after the recognition of excessive waste rock erosion into and sedimentation of the Watut River, funded new water supplies for a variety of villages along the river as part of compensation and, perhaps more importantly, acknowledgement of the mines' impacts (SDG 6 Water, plus others to a lesser extent). Though, as discussed above, better practices, more accurate impact assessments and effective regulation could have avoided the water contamination issues in the first instance.

The global mining industry is increasingly using SDG-style thinking to underpin its approach to sustainable development and the way that mines and mining companies can contribute to the

achieving the SDGs in many developing countries – such as the 'Ten Mining Principles' promoted by International Council on Mining and Metals (ICMM, the industry's representative body) (ICMM, 2020). The principles build on previous work in this area by the ICMM, and importantly, all member companies are bound to implement these principles in their mines and activities. It is worth noting, of course, that the approved standards for PNG mines could be seen to contravene most (if not all) of these principles, depending on whether the perspective is from community, industry or government.

Finally, a major issue in assessing the actual contribution of mining to human development in PNG is the lack of detailed socioeconomic data (e.g. health, education, wages, demographics) – including assessments prior to mining projects proceeding, appropriate monitoring during operations and assessments again after mining has been completed (see Banks, 2014). For example, the Misima Au-Ag mine operated for 15 years but there has been no follow-up study to assess the development effects of mining (similar could also be said for environmental issues). At present, there are no such detailed studies known to the authors.

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7. Summary

Despite the wealth of mineral resources and opportunity present in PNG, the mining industry has played a controversial role in development of the country over the past century. The complex geologic provinces that underlie PNG (Australian Craton, New Guinea Orogen and the Melanesian Arc) have been shown to host world-class mineral deposits, with potential for further discoveries into the future. However, the processes used to exploit these deposits in PNG have fostered economic inequalities, damaged social cohesion and caused considerable environmental degradation and complex social and environmental mining legacies that will remain into the decades and centuries to come. The approaches taken to managing and regulating large-scale mines – especially their wastes and tailings – in PNG are sub-par by global standards, and this has been compounded by an under appreciation during approvals processes of how the scale of mining projects and the magnitude of waste volumes may change through the life of a mine. Many of the social and environmental impacts arising from these projects are associated with the magnitude of mining wastes as well as a lack of recognition and consideration of the immanent impacts from extractive-led development. Through outlining the history of mining in PNG and highlighting the key factors that have led to the emergence of these issues, we hope that new approaches to governance and management of resource projects in PNG will emerge. Shifting the balance for mining being a force for sustainable development, rather than its' bane, will require PNG regulators and mining operations to significantly improve the governance of mineral resource projects, adopt international best practices for mine waste management and to genuinely respond to the diverse needs and concerns of communities and stakeholders.

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6. Acknowledgements

This paper is the result of involvement in PNG mining issues over many years. We would like to particularly acknowledge the numerous communities which have supported and hosted visits, engaged in the issues and worked hard to ensure sustainable development for their region. In particular, we acknowledge the many funders of the Mineral Policy Institute over the past ~25 years, especially the funding for recent work in the Morobe Province. The Bismark-Ramu Group

(BRG) also deserve special thanks and recognition for their tireless work towards a truly sustainable Papua New Guinea. Whilst some companies have responded to requests for information and previous site visits (thank you), most chose not to release the reports sought – we hope our work helps to improve the recognition of the need for greater transparency across the PNG mining sector and its governance. We also thank reviewers for their clear, honest and constructive comments.

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7. Figures

Figure 1: The tailings dam at the Hidden Valley Au-Ag project, Wau-Bulolo gold field, Papua New Guinea (February 2012)

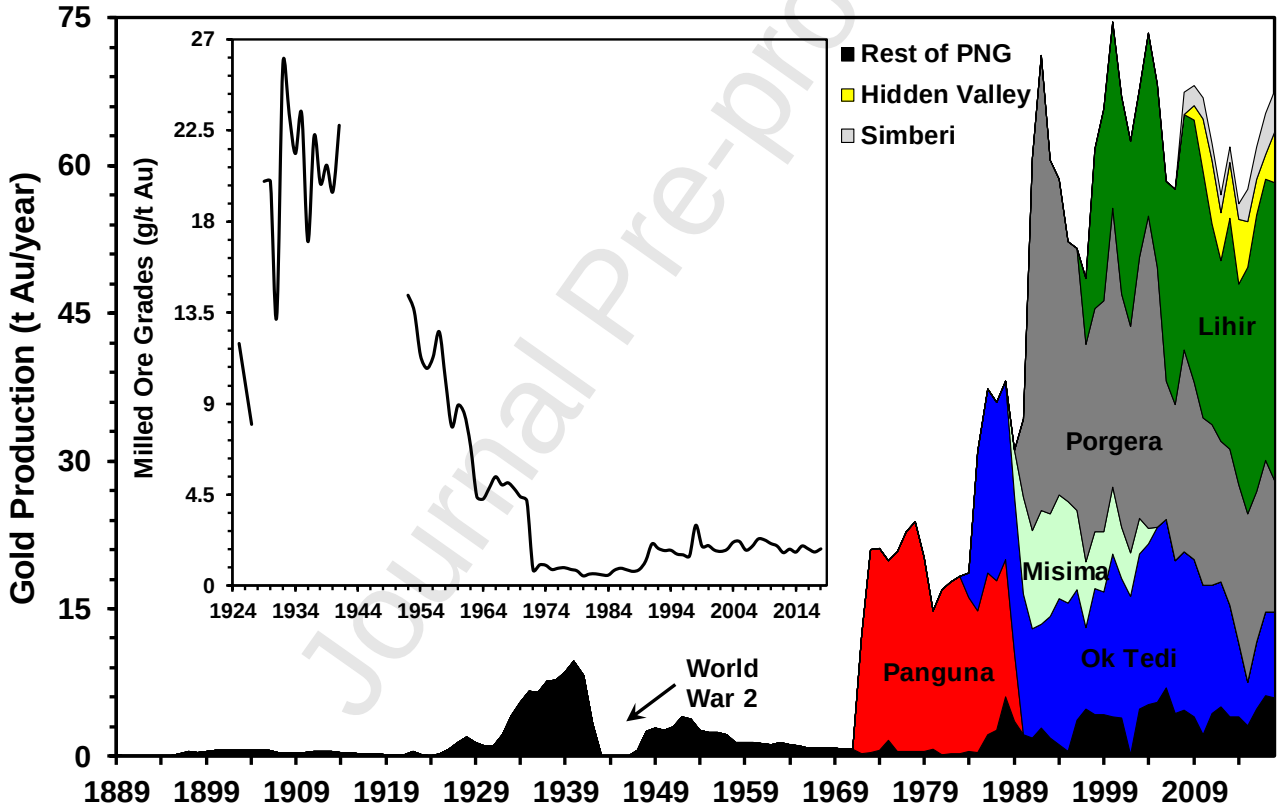

Figure 2: Historical gold production in Papua New Guinea (data to 2018)

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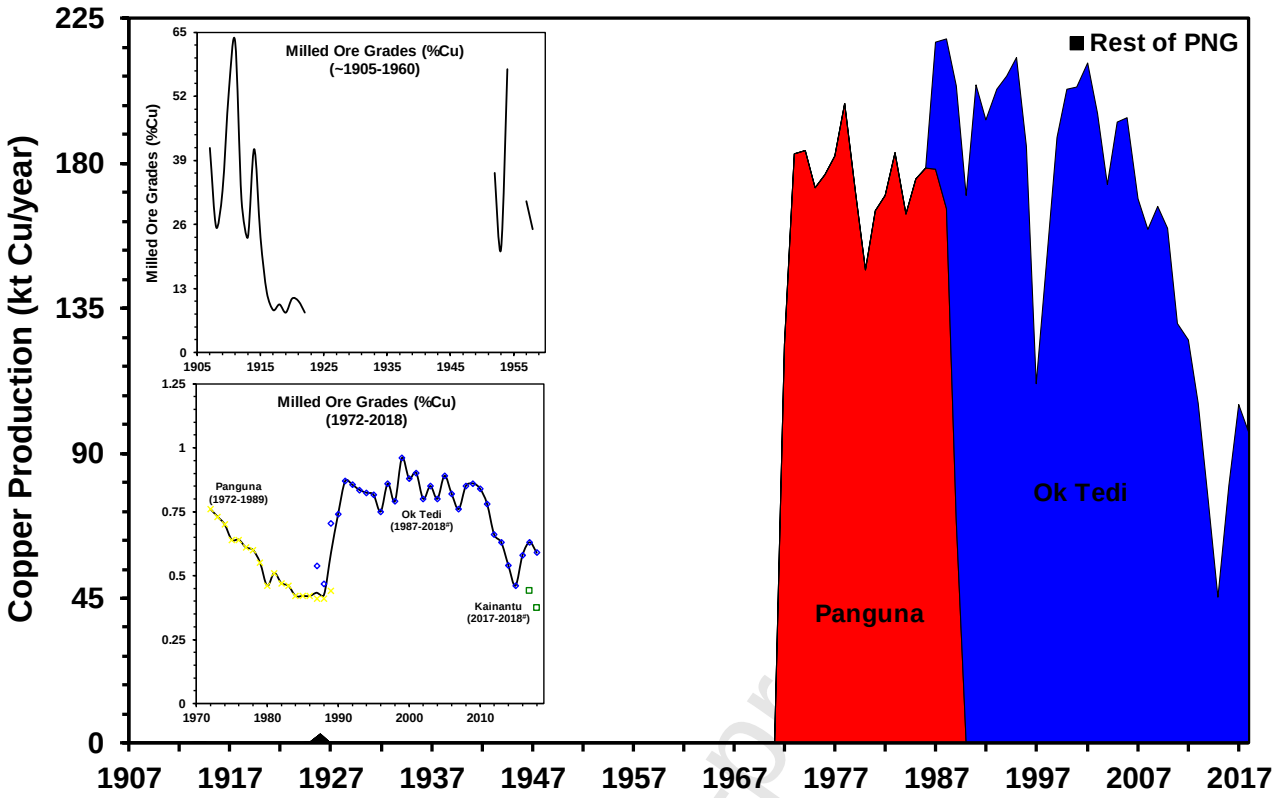

Figure 3: Historical copper production and grades in Papua New Guinea (note: both y-axes have a different scale for %Cu; data to 2018)

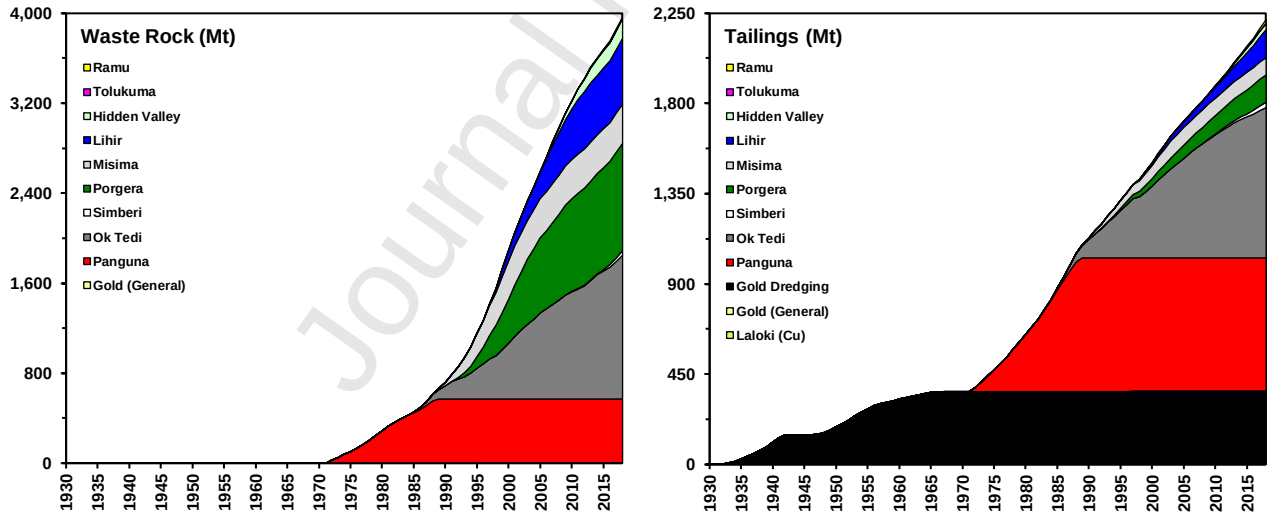

Figure 4: Estimated cumulative waste rock (left) and tailings (right) for Papua New Guinea (data to 2018)

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Figure 5: Images of the Panguna Cu-Au-Ag mine, Bougainville Island, Papua New Guinea: the main open cut, including the line of destroyed haul trucks (top left); the delta of tailings and waste rock downstream of Panguna, including local people left to cope with the ongoing impacts (top right); close up of the line of destroyed haul trucks (bottom left); rock excavator surrounded by Cu-laden acidic drainage (bottom right) (photographs: Mineral Policy Institute, November 2009).

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Figure 6: Images of the Ok Tedi Cu-Au-Ag mine, Papua New Guinea, showing open cut mine (top left; 2016 edition, OTML, var.); adjacent town of Tabubil and Ok Tedi river with tailings and waste rock (top right); tailings in the Fly River floodplain (middle); vegetation dieback on the Fly River floodplain (bottom) (all photographs: Mineral Policy Institute, variable years, unless noted).

8. Tables

Table 1: Energy intensity for PNG Cu and Au mines (mean ± standard deviation, data count in brackets)

Project (operating years)	Electricity	Total Energy		Electricity		Mining	Metal (Cu or Au)
	Source	GJ/t ore	%renewable	kWh/t ore	%renewable	L diesel/t rock	GJ/t metal[a]
Ok Tedi (2003-2018)[b]	Hydro+Diesel	0.26±0.04 (15)	23.5±2.2 (15)	21.9±3.4 (15)	75.4±4.1 (15)	1.01±0.16 (15)	41.3±15.3 (15)[c]
Porgera (1997-2015)[b]	Gas	1.64±0.35 (19)	0 (19)	81.6±3.8 (7)	0 (19)	0.90±0.12 (7)	434±109 (19)
Lihir (2002-2018)[b]	Diesel +Geothermal	1.39±0.59 (14)	ID[d] (~27.3)	160.3±65.6 (6)	32.9±11.9 (5)	0.99±0.31 (10)	415±150 (14)
Simberi (2016-2017) [b]	Diesel	0.33 (3)	NR	NR	NR	NR	311 (3)
Hidden Valley (2011-2018)[b]	Hydro+Diesel	0.67±0.35 (4)	7.9±5.2 (4)	23.0±10.1 (9)	47.0±2.82 (9)	1.14 (2)	412±179 (4)
Misima (1997-2004)	Diesel	0.33±0.06 (8)	0 (8)	19.4±0.9 (7)	0 (8)	0.35±0.15 (7)	342±41 (8)

Notes: ID – insufficient data; NR – not reported; [a]this GJ/t Cu or GJ/kg Au; [b]still operating; [c]this is Cu only and does not allocate any value for Au or Ag; [d]due to lack of specific electricity generation reporting, it is not possible to reliably estimate the proportion of energy and electricity derived from geothermal energy at Lihir.

Table 2: Greenhouse gas and water use intensity for PNG Cu and Au mines (mean ± standard deviation, data count in brackets)

Project	Greenhouse Gas Emissions		Water Use or Withdrawals			Discharged Water (DW)		
	Total	Metal (Cu or Au)	Total	Recycled	Metal (Cu or Au)	Volume	Rate	Intensity
	kg CO_2/t ore	kg CO_2/t metal[a]	m^3/t ore	%	m^3/t metal	ML/year	m^3 DW/t ore	m^3 DW/t metal
Ok Tedi[b]	14.6±2.5 (15)	2.34±0.66 (15)[c]	2.31±0.86 (16)	72.2±10.1 (16)	367±232 (16)[c]	NR	NR	NR
Porgera	89.2±14.7 (21)	24.4±4.7 (21)	5.11±0.76 (21)	NR	1,397±467 (21)	42,404±17,320 (11)	7.79±2.92 (11)	2,435±1,202 (11)
Lihir	12.5±21.2 (14)	20.5±4.6 (14)	3.93±1.57 (13)	NR	1,213±665 (13)	149,222±47,652 (11)	27.5±6.3 (11)	7,049±1,808 (11)
Simberi	20.6 (3)	19.4 (3)	NR	NR	NR	NR	NR	NR
Hidden Valley	41.6±15.0 (7)	28.2±6.3 (7)	1.52±0.56 (4)	50.8±28.9 (4)	746±368 (6)	468±488 (5)	0.14±0.14 (5)	84.6±88.8 (5)
Misima	21.1±4.3 (8)	22.2±3.8 (8)	0.90±0.25 (7)	NR	935±411 (7)	NR	NR	NR

Notes: DW – discharged water; NR – not reported; [a]units are t CO_2/t Cu or t CO_2/kg Au; [b]still operating; [c]no allocation given to Au or Ag; years of data give in Table 1.

Table 3: Water quality regulation for PNG mines - key criteria, strengths and weaknesses

	Water Resources	Compliance Location(s)	Water Quality Basis	Transparency[#]	Strengths	Weaknesses
Ok Tedi[b]	Fresh	Along entire river system	ANZECC 95% Values	High	• Extensive monitoring • Annual public reporting • Ecotoxicological basis • Clarity on compliance	• Fails to address bioaccumulation of metals and long-term acid drainage risks • Still allows significant impacts along river system
Porgera	Fresh	~180 km downstream (SG3)	ANZECC 95% Values (mostly)	High	• Extensive monitoring • Annual public reporting • Ecotoxicological basis • Clarity on compliance	• Fails to address bioaccumulation of metals and long-term acid drainage risks • Still allows significant impacts along river system
Hidden Valley	Fresh	~20 km downstream (Nauti)	Unclear	Medium	• Extensive monitoring • Some historic public reporting • Unclear scientific basis • Some clarity on compliance	• Fails to address bioaccumulation of metals and long-term acid drainage risks
Lihir	Marine	Tailings discharge point	Unclear	Low	• None identified	• No public transparency • Uncertain compliance • Unclear scientific basis
Simberi	Marine	Unclear	Unclear	Low	• None identified	• No public transparency • Uncertain compliance • Unclear scientific basis
Ramu	Marine	Unclear	Unclear	Low	• None identified	• No public transparency • Uncertain compliance • Unclear scientific basis

Notes: [#]Based on public reporting and scientific justification of compliance regime (Low = no public reporting or explanation; Medium = infrequent public reporting and explanation; High = frequent public reporting (e.g. annual), clear scientific explanation and regular review and improvement in regime criteria).

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Mining in Papua New Guinea:

A Complex Story of Trends, Impacts and Governance

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Visualization	All Authors
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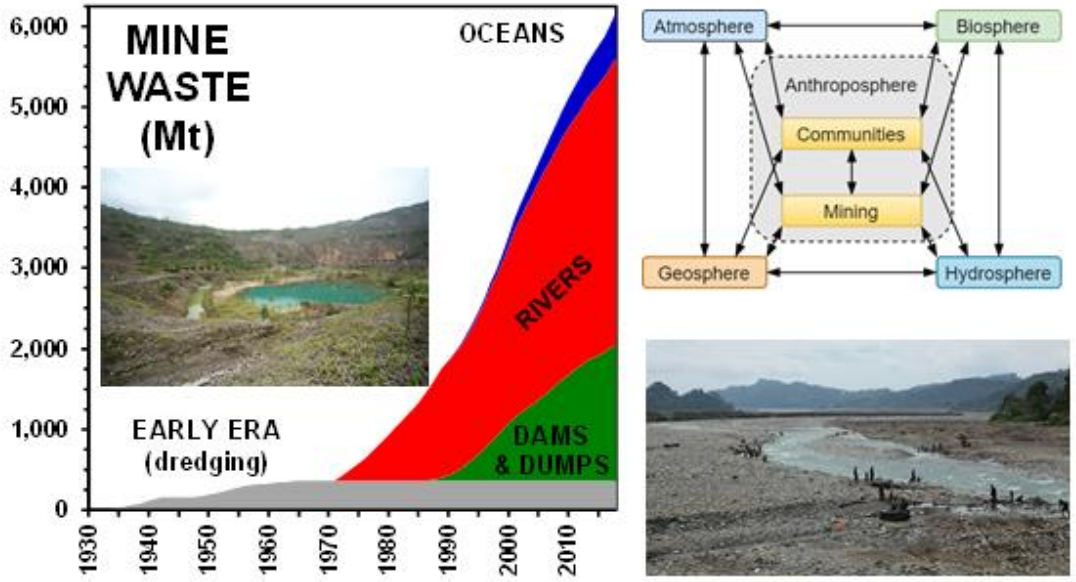

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Highlights:

- PNG has large metal mines but major controversies over environmental-social impacts
- Mine waste management includes extensive use of riverine and marine disposal
- Environmental and social impacts are determined by the growing scale of mine wastes
- Regulatory governance needs considerable improvement for sustainable development

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