Mapping to explore the challenges and opportunities for reconciling artisanal gem mining and biodiversity conservation

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Supplementary Information

1. Further details on the formation of gems and Madagascar's geology

1.1 Geological conditions for the formation of ruby and sapphire

Ruby and sapphire are gem-quality variants of the mineral corundum (Al_2O_3). Corundum typically occurs in rocks that are aluminium-rich and silica-poor, and have been metamorphosed at moderate pressures and relatively high temperatures (Simonet, Fritsch and Lasnier, 2008; Giuliani *et al.*, 2020). Metamorphism at these pressure and temperature (*P-T)* conditions falls within the amphibolite to granulite facies and is most commonly indicative of regional metamorphism in zones of continental collision or contact metamorphism (whereby intruding magma heats the surrounding rocks). Corundum formation under these P-T conditions commonly requires the circulation of a fluid to supply Al or other trace elements and remove silica from the host rock (Simonet, Fritsch and Lasnier, 2008). A desilicated environment is critical for corundum formation, as where silica is available aluminium will preferentially react with it to form other minerals such as feldspar or mica.

Giuliani *et al* (2020) reviewed corundum deposits from around the world to produce a classification of the geology and formation of deposits. Primary deposits are classed as magmatic (Type I) or metamorphic (Type II) based on the geological environment in which they are found.
Type I magmatic deposits include two sub-types:

A) gems as xenocrysts or in xenoliths within erupted volcanic rocks, such as alkali basalts.
B) gems in intrusive igneous rocks, such as kimberlite, lamprophyre or syenite

Gems within magmatic deposits were formed at depth within the Earth's crust and then transported to shallower levels by rising magma. As such, other authors classify these types of magmatic deposits as secondary as they have been moved from where they were originally formed (Simonet, Fritsch and Lasnier, 2008).
Type II metamorphic deposits can be divided into:

A) strictly metamorphic, where the chemistry of the rocks is such that gem corundum could form during metamorphism with no introduction or removal of elements by fluids.
B) Metamorphic-metasomatic, where the introduction of fluids has led to the formation of gem corundum.

Host rocks for metamorphic gem corundum deposits typically have relatively low silica content but moderately high Al contents. These may include mafic-ultramafic igneous rocks, which typically also contain chromium, and metasedimentary rocks. In some cases, deposits considered to be metamorphic are found in marble; however marble is depleted in both silica and aluminium so requires aluminium and trace elements to be supplied from impurities, or layers of other sediments, within the limestone protolith (Dzikowski *et al.*, 2014).

Metamorphic-metasomatic deposits are formed through fluid-rock interactions which result in chemical alteration of the host rock and the formation of new minerals (metasomatism) (Putnis and Austrheim, 2010). During periods of regional metamorphism, fluids circulate through thrusts, veins and shear zones, reacting with wall rocks and facilitating the diffusion of elements between rocks of contrasting lithologies along geochemical gradients (Putnis and Austrheim, 2010). Fluid can also be supplied by the intrusion of magma, with metasomatized zones typically focused along the contact of the intrusion (Simonet, Fritsch and Lasnier, 2008). Typically, metasomatic corundum deposits are formed through the interaction of a silica and alumina-rich rock or fluid, with a silica-poor rock. Silica diffuses from the former into the latter, leaving an environment relatively enriched in aluminium where corundum can crystallise, given the required trace elements are present (Simonet, Fritsch and Lasnier, 2008). Metasomatic corundum deposits are associated with desilicated pegmatites intruding mafic-ultramafic rocks or marbles (to form skarns), and desilicated gneiss (Giuliani *et al.*, 2020)

Both types of magmatic and metamorphic deposits have been documented in Madagascar (Rakotondrazafy *et al.*, 2008; Rakotosamizanany *et al.*, 2014; Giuliani *et al.*, 2020).

1.2 Formation of emerald

Emerald is green gem-quality beryl ($Be_2Al_2Si_6O^{18}$). Trace amounts of chromium and/or vanadium produce the green colour. Beryllium is rare in the upper continental crust and is typically supplied through the intrusion of magma, or fluid migration along thrusts, veins and shear zones. Deposits formed through the intrusion of magma are classed as tectonic-magmatic and typically occur where granites and pegmatites have intruded mafic-ultramafic or sedimentary rocks (Groat *et al.*, 2008). An example of this occurs at the Ianapera deposit, Madagascar; (Andrianjakavah *et al.*, 2009). As the intruding magma cools beryllium and other incompatible elements become concentrated in late-stage melts and fluids, which can react with mafic-ultramafic or sedimentary wall rocks to form emeralds at the contact zone. Emeralds formed through fluid-rock interactions in the absence of magmatism are termed tectonic-metamorphic and are associated with fluid pathways such as shear zones cross-cutting mafic-ultramafic rocks, black shale and metamorphic rocks (Giuliani *et al.*, 2019). The known emerald deposits of Madagascar are associated with desilicified pegmatites and metasomatism within shear zones cutting mafic-ultramafic host rocks (BGS-USGS-GLW, 2008; Giuliani *et al.*, 2019)

1.3 The geology of Madagascar and relevance to the formation of gemstones

Madagascar has a long and dynamic geological history, featuring the formation and break-up of supercontinents. The East African and Kuungan orogenies, 650 – 500 Ma (Fritz *et al.*, 2013), in which much of Madagascar collided with East Africa and subsequently with India during the assembly of Gondwana, provided the conditions for the formation of many of Madagascar's mineral deposits, including gemstones (Giuliani *et al.*, 2007, 2020; Rakotondrazafy *et al.*, 2008). In fact, gemstones are found across the Neoproterozoic Mozambique belt which extends through Kenya, Tanzania, Mozambique and into Madagascar, and defines a major part of the East African Orogen (Giuliani *et al.*, 2020).

The island of Madagascar can be divided into the Precambrian basement rocks that occupy the eastern two-thirds of the island, and the late-Palaeozoic to recent sedimentary sequences of the western third. The younger sedimentary sequences have not experienced the metamorphic conditions required for the formation of gems, nor alkaline volcanism and are therefore not prospective for primary deposits. The Precambrian basement comprises nine tectonic domains of different ages, origins, and dominant lithologies. From north to south these are; the Bemarivo, Anaboriana-Manampotsy, Antongil-Masora, Tsaratanana, Antananarivo, Ikalamavony, Anosyen, Androyen and Vohibory domains (Figure S1; Boger et al, 2019; Key et al, 2011).The Antananarivo, Tsaratanana and Antongil-Masora domains are fragments of older continental crust, termed cratons, dating from the Archaean (Schofield *et al.*, 2010; Key *et al.*, 2011). These domains constitute the oldest core of Madagascar to which the other domains were accreted between 1.6 Ga and 530 Ma (Thomas *et al.*, 2009; Tucker *et al.*, 2014). Debate is ongoing regarding the exact timing and location of this amalgamation. Tucker et al (2014) propose that the Antananarivo and Antongil-Masora domains formed part of the Greater Dharwar Craton of India, to which the Southern domains (Androyen, Anosyen and Vohibory) and the northern Bemarivo domain were accreted in the Neoproterozoic to Cambrian. According to this interpretation, the Malagasy basement amalgamated at the Western margin of the Greater Dharwar Craton before a combined India and Madagascar collided with East Africa in the Neoproterozoic. In contrast, Collins and Pisarevsky (2005) argue that only the Antongil-Masora domain was joined to the Greater Dharwar Craton during the Archaean, and that the Antananarivo domain, which comprises most of Central Madagascar, was part of the island micro-continent of Azania. In this model, Azania collided with East Africa c. 630 Ma, whilst collision with India only occurred during the late stages of assembly after 550 Ma (Armistead *et al.*, 2020). However, this argument is complicated by the presence of the extensive c. 850-750 Ma Imorona-Itsindro igneous suite intruding the Antananarivo, Ikalamavony, and (possibly) Antongil-Masora domains, which suggests the likelihood of an earlier Proterozoic collision (Key *et al.*, 2011; Archibald *et al.*, 2016; Zhou *et al.*, 2018).

Regardless of the exact sequence of events, evidence of high-grade metamorphism recorded across south-west, central and northern Madagascar suggests that much of the Malagasy basement was substantially reworked during the East African and Kuungan orogenies of the Neoproterozoic (Thomas *et al.*, 2009; Fritz *et al.*, 2013; Tucker *et al.*, 2014; Boger *et al.*, 2019). Continental convergence led to regional metamorphism and magmatism which produced the high temperatures, pressures, and fluids necessary for the formation of gems. Shear zones were formed or re-activated in areas of high strain and acted as conduits for fluid circulation and metasomatism (Wit *et al.*, 2001). Continental arc-magmatism related to oceanic subduction led to the emplacement of the 560 – 520 Ma Ambalavao – Kiangara – Maevarano granites (Goodenough *et al.*, 2010; Tucker *et al.*, 2014).

More recent volcanism during the Cenozoic provided the second, and final, period of gem emplacement in Madagascar. The eruption of alkali basalts across parts of northern and central Madagascar 23 – 2.6Ma transported gems formed at greater crustal depths to the surface, forming the magmatic-type ruby deposits discovered at Soamiakatra and Ambondromifey (Rakotondrazafy *et al.*, 2008; Rakotosamizanany *et al.*, 2014).

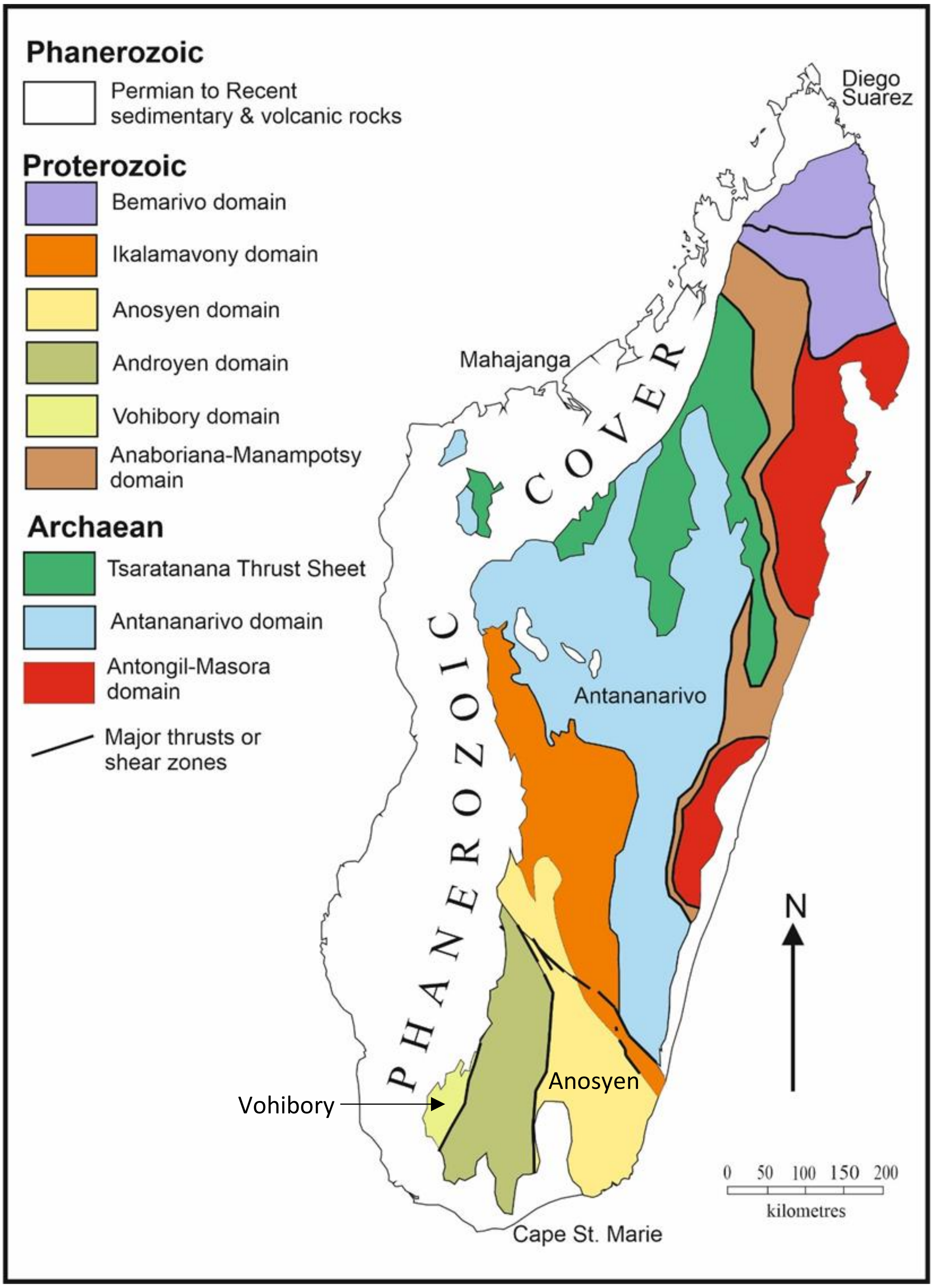

Figure S1: Map of the tectonic domains of Madagascar derived from Key *et al* (2011)

2. Supplementary Methods

2.1 Identifying potentially prospective units

Table S1: Lithologies identified as potentially prospective for ruby, sapphire or emerald from the Geological Map of Madagascar (Roig *et al.*, 2012)

Geological unit code on map	Domain/Group or Suite	Description	Notes	Type of potential deposit
Ad8	Androyen	Impure marble with calc-silicate minerals		Metamorphic
Ad9	Androyen	Graphitic basic gneiss with pyroxene		Metamorphic
An1	Anosyen – Tranomaro Group	Calc-silicate paragneiss	Tranomaro group prospective for skarns where marble intruded by granite	Metamorphic
An2	Anosyen – Tranomaro Group	Banded metapelitic paragneiss with Mag, Crd and Opx	Tranomaro group prospective for skarns where marble intruded by granite	Metamorphic
An6	Anosyen	Basic orthogneiss (metagabbro)		Metamorphic
At11	Antananarivo	Marble and calc-silicate paragneiss		Metamorphic
At17	Antananarivo	Orthogneiss basique		Metamorphic
At3	Antananarivo – Manampotsy group	Quartzite and Ampasary paragneiss with relics of ultramafic rock		Metamorphic
At4	Antananarivo – Manampotsy group	Andasibe paragneiss and schist		Metamorphic

At5	Antananarivo – Manampotsy group	Ranomafana paragneiss		Metamorphic
At7	Antananarivo	Calc-silicate paragneiss and marble		Metamorphic
At9	Antananarivo	Ultramafic rock		Metamorphic
Atn3	Bemarivo – Antsirabe North suite	Undifferentiated ultramafic rock		Metamorphic
Bm11	Bemarivo	Marble and calc-silicate paragneiss		Metamorphic
Bm12		Amphibolite		Metamorphic
Ik2	Ikalamavony	Calc-silicate paragneiss, Mag + Cpx		Metamorphic
Ik4		Calc-silicate marble with intercalcated amphibolite		Metamorphic
Ik5		Basic paragneiss with amphibolite		Metamorphic
Il2	Imorona - Itsindro	Granite and basic orthogneiss of Itsindro type	Includes metagabbro	Metamorphic
Il4	Imorona - Itsindro	Hazburgite, pyroxenite and periodotite		Metamorphic
It1	Itremo	Dolomitic marble		Metamorphic
Ma1	Masora	Pelitic schist and amphibolite		Metamorphic
Pea	Cenozoic volcanism	Syenite and granite		Magmatic
Pem		Gabbro		Magmatic
Vmpa		Rhyolite, trachyte, phonolite, ignimbrite		Magmatic
Vmpa + Pea		Basalt, Ankaratrite basanite with syenite and granite		Magmatic

Vmpm		Basalt, Ankaratrite basanite		Magmatic
Vo3	Vohibory	Amphibolitised metabasalt		Metamorphic
Vo5		Calc-silicate marble		Metamorphic
Akm1	Ambalavao – Kiangara – Maevarano suite	Charnockitic granite		Metamorphic
Akm2		Granite, monzonite and undifferentiated syenite		Metamorphic
Akm3		Granite and syenite stratoids		Metamorphic
Akm4		Gabbro and diorite		Metamorphic
Akm5		Pyroxenite		Metamorphic
Akm6		Granitic and monzonitic orthogneiss		Metamorphic

N.B – Several units were identified as prospective but not found on the map (Ad3, Ma3)

2.2 Biodiversity data

Table S2: Summary of the datasets capturing conservation priorities which were used in this analysis, including changes to the original data layers (excluding raster to polygon conversion and vice-versa). All data layers were reprojected to WGS 1984 UTM Zone 38S projected co-ordinate system.

Biodiversity indicator layer	**Original format**	**Raster resolution**	**Edits**	**Source**
Key Biodiversity Areas (KBA)	Polygon	100m (when converted)	Removed KBA polygons with a marine portion > 80% of the polygon area and clipped the remaining data to the boundary of Madagascar	Birdlife International (2021)
Conservation Priority Areas	Raster	918m	We use the version unconstrained to the existing protected area	Kremen *et al* (2008)

			network. No edits except reprojection.	
Protected Areas	Polygon	100m (when converted)	Amended by Jorge Llopis to remove PAs classified as Marine Protected Areas and PAs where no supporting evidence of existence could be found (i.e no evidence of legal definition). The resulting dataset was verified by an expert (Dimby Razafimpahanana). We further amended the dataset to remove PAs with a marine portion > 80% and clipped the remaining data to the boundary of Madagascar	Rebioma (2017) edited by Jorge Llopis
Forests 2020	Raster	30m	We created this layer by merging a forest cover map of Madagascar for the Year 2000 (Harper *et al.*, 2007; updated by Vieilledent *et al.*, 2018) with the Global Forest Change data.	Harper *et al,* (2007); Vieilledent *et al,* (2018)*;* Hansen *et al,* (2013)

2.3 Our database of known gem deposits

Table S3**:** Database of 69 known ruby, sapphire and emerald deposits in Madagascar compiled from a literature search.

Name	Stone	Primary	Source	Notes
Ambalavihy Village	Sapphire	No	Site visited by Vincent Pardieu (VP), location provided.	
Ambalavihy mines	Sapphire	No	Site visited by VP, location provided.	
Ambalmasi	Sapphire	No	Site visited by VP, location provided.	
Ambarinakoho	Sapphire	No	Site visited by VP, location provided.	
Ambarinakoho	Sapphire	No	Site visited by VP, location provided.	
Ambatomianty	Sapphire	No	Site visited by VP, location provided.	
Ambodibakoly	Emerald	Yes	https://www.mindat.org/loc-27840.html	
Ambodipaiso	Sapphire	No	Perkins (2016, 2017)	
Ampandamisivaly	Sapphire	No	Site visited by VP, location provided.	
Ampasimamitaka	Sapphire	No	Site visited by VP, location provided.	
Anakondro	Sapphire	No	Site visited by VP, location provided.	
Analalava Village	Sapphire	No	Site visited by VP, location provided.	
Analasoa Village	Sapphire	No	Site visited by VP, location provided.	
Anavoha	Ruby	Yes	Rakotondrazafy *et al* (2008)*;* Mercier *et al* (1999)*;* https://www.mindat.org/loc-264252.html;	Compared location between 3 sources. Likely correct within 5km
Andilamena	Ruby	Yes	Site visited by VP, location provided. Leuenberger (2001); Hughes, Pardieu and Schorr (2005); Pardieu and Wise (2008)	
Andohasilaka	Sapphire	No	Site visited by VP, location provided.	
Andranondambo	Sapphire	Yes	Schwarz (1996)	
Andrebabe	Sapphire	No	Hughes, Pardieu and Schorr (2005); Pardieu and Rakotosaona (2012); https://www.mindat.org/loc-304128.html.	

Anduharano	Sapphire	No	Site visited by VP, location provided.	
Anena	Sapphire	No	Site visited by VP, location provided.	This is highly likely to be Soabiby mentioned in Baker-Médard (2012).
Ankadilalana	Emerald	Yes	Schwarz (1994); https://www.mindat.org/loc-26409.html	
Ankaranduha (Antsoa)	Sapphire	No	Site visited by VP, location provided.	
Ankazoabo	Sapphire	Yes	https://www.mindat.org/loc-226853.html. Also shown in Figure 2 Pardieu *et al* (2016)	
Ankilimasy	Sapphire	No	Site visited by VP, location provided.	
Ankilitelo	Sapphire	No	Site visited by VP, location provided.	
Ankotika (Andampy)	Sapphire	No	Cook and Healy (2012); https://www.mindat.org/loc-232739.html	
Antaralava	Sapphire	No	Site visited by VP, location provided.	
Antsimobohitra	Sapphire	No	Site visited by VP, location provided.	
Antsirabe	Sapphire	No	Cook and Healy (2012); https://www.mindat.org/loc-232904.html.	
Antsoa village	Sapphire	No	Site visited by VP, location provided.	
Banque Suisse	Sapphire	No	Site visited by VP, location provided.	
Beforona	Sapphire	Yes	Rakotondrazafy et al (2008). https://www.mindat.org/loc-191486.html.	
Befotaka, Nosy Be	Sapphire	No	Ramdohr and Millisenda (2006)	
Bekily	Sapphire	No	Cook and Healey (2012)	Next to Zombitse-Vohibasia National Park. Located using Figure 13 in Cook and Healy (2012)
Belamoty (Rush 2018)	Sapphire	No	Site visited by VP, location provided.	
Bepeha	Sapphire	No	Site visited by VP, location provided.	
Betsingaly	Sapphire	No	Site visited by VP, location provided.	
Bevilany	Sapphire	No	Site visited by VP, location provided.	

Ambondromifey	Sapphire	No	Schwartz et al (2000)	
Antsiermene	Sapphire	Yes	Schwartz et al (1996)	Around 11km north of Andranondambo. Several mining spots within 4km radius.
Didy	Ruby & Sapphire	No	Pardieu and Rakotosaona (2012)	Placer deposits (Giuliani *et al,* 2020)
Esoki	Sapphire	No	Site visited by VP, location provided.	
Ianapera	Emerald	Yes	Mercier *et al* (1999), Andrianjakavah *et al* (2009)*;* https://www.mindat.org/loc-27838.html;	Ruby also found at this locality
Ilakaka	Sapphire	No	Pardieu (2013), Rakotondrazafy *et al,* (2008); https://www.mindat.org/loc-27802.html,	There are many mine sites in the immediate vicinity of Ilakaka.
Limit	Sapphire	No	Site visited by VP, location provided.	
Lovakadabo	Sapphire	No	Site visited by VP, location provided.	
Madama Pauline (Vohimena)	Sapphire	No	Site visited by VP, location provided.	
Mahasoa village	Sapphire	No	Site visited by VP, location provided.	
Manamboay	Sapphire	No	Cook and Healy (2012)	Cross-referenced Figure 13 in Cook and Healy (2012) with Google Earth to visually identify mine site.
Mangatuka (Antsoa)	Sapphire	No	Site visited by VP, location provided.	
Maniry	Ruby	Yes	Mercier *et al* (1999)	Map in Mercier *et al* (1999) shows deposits are next to large anorthosite block. Cross-referenced with the location of this block in the Geological Map of Madagascar to locate deposits.
Manombo – Misereno	Sapphire	No	Site visited by VP, location provided.	
Manombo Kel	Sapphire	No	Site visited by VP, location provided.	
Manombo Voavoa	Sapphire	No	Pardieu (2013); https://www.mindat.org/loc-45926.html,	

Maromiandry	Sapphire	No	Cook and Healey (2012); https://www.mindat.org/loc-157486.html	Near border of Zombitse-Vohibasia National Park
Morafeno	Emerald	Yes	Schwarz (1994); https://www.mindat.org/loc-27842.html.	
Old Thai sapphire Mine Ankaboka Ambinany	Sapphire	No	Site visited by VP, location provided.	
Sakabe	Sapphire	No	Site visited by VP, location provided.	
Sakalama	Sapphire	No	Site visited by VP, location provided.	
Sakameloka village	Sapphire	No	Site visited by VP, location provided.	
Sakaraha	Sapphire	No	Pardieu (2013)	Location of town. Evidence of mining visible on Google Earth
Soamiakatra	Ruby	Yes	Rakotosamizanany (2009); https://www.mindat.org/loc-191507.html	Co-ordinates from Mindat, near village of Soamiakatra. Figure IV-4 in Rakotosamizanany (2009) suggests primary Morarano deposit is located to East, but within 5km of village.
Tananarive	Sapphire	No	Pardieu *et al* (2017); Perkins (2017)	
Vatomandry	Ruby	No	Rakotosamizanany *et al* (2014), Rakotosamizanany (2009)	Identified based on map in Rakotosamizanany (2009)
Vohimena Mahafala	Sapphire	No	Site visited by VP, location provided.	
Vohimena Vovo Village	Sapphire	No	Site visited by VP, location provided.	
Zahamena NP 1	Ruby	No	Pardieu *et al* (2015); Giuliani *et al* (2020)	
Zahamena NP 2	Ruby	No	Pardieu *et al* (2015); Giuliani *et al* (2020)	
Zazafotsy Quarry	Sapphire	Yes	Rakotondrazafy et al (2008), https://www.mindat.org/loc-27844.html	

2.4 Spatial overlay analysis

To enable the raster overlay analysis, we converted our polygon layer of gem potential to a raster with cell size 100m x 100m. Our polygon biodiversity data (KBAs and PAs) were converted to raster layers of the same resolution and snapped to the gem potential raster to align cells, resulting in a maximum spatial error of 50m. Biodiversity data originally in raster form (forests and priority areas) were not resampled to the same resolution to avoid unnecessary error.

We then used raster overlay to combine each biodiversity raster with the gem potential layer to produce a new raster showing the area of overlap, with a resolution equal to the finest resolution input data. This was used to calculate what percentage of the total area of KBAs, Priority Areas, PAs and forests is potentially prospective for gems. Following Eklund et al (2022) we disaggregated the results for forest by forest type (using the biome classification from the Resolve Ecoregions project (Dinerstein *et al.*, 2017)), to evaluate whether certain types of forest (humid, dry or spiny) are more likely to be threatened by gemstone mining than others.

We also calculated the percentage of each individual locality (PA/KBA/Priority Area or forest block) which is potentially prospective for gems using Tabulate Intersection on the polygon data. To do so, the raster biodiversity layers (Priority Areas and forests) were converted to polygon. This produced > 900,000 forest polygons. To speed processing we removed forest polygons smaller than 84ha (the size of the smallest polygon in the other biodiversity datasets), which are too small be visible in the resulting maps and whose inclusion could locate prospective sites at too fine a scale.

3. Supplementary Results

3.1 Validating our map of gem potential against the locations of gem deposits

Table S4: Distance of known gem deposits from nearest potentially prospective zone

Name	Distance (km)	Deposit type
Morafeno	0	Primary Emerald
Ambodibakoly	0	Primary Emerald
Ianapera	0	Primary Emerald
Zahamena NP 1	0	Secondary Ruby
Maniry	0	Primary Ruby
Vatomandry	0	Secondary Ruby
Ampasimamitaka	0	Secondary Sapphire
Lovakadabo	0	Secondary Sapphire
Antsiermene	0	Primary Sapphire
Beforona	0	Primary Sapphire
Zazafotsy Quarry	0	Primary Sapphire
Befotaka, Nosy Be	0	Secondary Sapphire
Andrebabe	0	Secondary Sapphire
Ankazoabo	0	Primary Sapphire
Andranondambo	0	Primary Sapphire
Ankadilalana	0	Primary Emerald
Didy	0	Secondary Ruby and Sapphire
Ambondromifey	0.31	Secondary Sapphire
Sakabe	0.49	Secondary Sapphire
Anavoha	0.60	Primary Ruby
Antsirabe	0.77	Secondary Sapphire
Zahamena NP 2	0.80	Secondary Ruby
Anakondro	0.83	Secondary Sapphire
Sakalama	1.00	Secondary Sapphire
Soamiakatra	1.45	Primary Ruby
Andilamena	1.58	Primary Ruby
Tananarive	1.79	Secondary Sapphire
Ambodipaiso	4.33	Secondary Sapphire
Ankotika (Andampy)	7.15	Secondary Sapphire
Belamoty (Rush 2018)	8.74	Secondary Sapphire
Antsimobohitra	9.48	Secondary Sapphire
Ilakaka	14.88	Secondary Sapphire
Banque Suisse	17.63	Secondary Sapphire
Ampandamisivaly	20.86	Secondary Sapphire
Vohimena Mahafala	22.43	Secondary Sapphire
Madama Pauline (Vohimena)	25.10	Secondary Sapphire
Bepeha	26.13	Secondary Sapphire
Andohasilaka	27.01	Secondary Sapphire
Manombo Voavoa	27.43	Secondary Sapphire
VOHIMENA Vovo Village	27.62	Secondary Sapphire

Anduharano	27.71	Secondary Sapphire
Manombo – Misereno	27.90	Secondary Sapphire
Manombo Kel	28.98	Secondary Sapphire
Sakameloka	30.44	Secondary Sapphire
Limit	31.77	Secondary Sapphire
Ankilitelo	39.28	Secondary Sapphire
Ankilimasy	40.01	Secondary Sapphire
Ambalmasi	42.49	Secondary Sapphire
Ambarinakoho	43.05	Secondary Sapphire
Analalava Village	45.40	Secondary Sapphire
Betsingaly	47.17	Secondary Sapphire
Analasoa Village	48.92	Secondary Sapphire
Bekily	53.96	Secondary Sapphire
Mahasoa village	54.13	Secondary Sapphire
Ambatomianty	55.75	Secondary Sapphire
Ambalavihy mines	55.78	Secondary Sapphire
Ambalavihy (Village)	55.82	Secondary Sapphire
Ankaranduha (Antsoa)	56.51	Secondary Sapphire
Mangatuka (Antsoa)	56.55	Secondary Sapphire
Bevilany	58.55	Secondary Sapphire
Antsoa village	60.60	Secondary Sapphire
Anena	61.51	Secondary Sapphire
Maromiandry	61.62	Secondary Sapphire
Ambarinakoho (Rush 2018)	62.48	Secondary Sapphire
Esoki	62.63	Secondary Sapphire
Old Thai sapphire Mine Ankaboka Ambinany	68.46	Secondary Sapphire
Manamboay ZV	76.20	Secondary Sapphire
Sakaraha	81.69	Secondary Sapphire
Antaralava	87.75	Secondary Sapphire

3.2. Raw results from the raster overlay

Table S5: The area and percentage of each biodiversity layer which is potentially prospective for primary ruby, sapphire, or emerald deposits. The area and percentage of non-protected parts of Key Biodiversity Areas (KBAs), Priority Areas, and forests which are potentially prospective is also reported. Non-protected refers to the areas outside the formal protected area network.

	Area with gem potential (ha)	**Total area (ha)**	**Percentage with gem potential (%)**	**Non-protected area with gem potential (ha)**	**Total non-protected area (ha)**	**Percentage of non-protected area with gem potential (%)**	**Percentage of potentially prospective land unprotected (%)**
Protected Areas	742,000	6,758,000	11.0	-	-	-	-
KBAs	1,018,000	9,134,000	11.1	414,086	4,096,458	10.1	40.7
Priority Areas	839,000	5,927,000	14.2	559,928	3,810,900	14.7	66.7
Forest cover (2020)	992,000	8,163,000	12.1	466,479	4,557,603	10.2	47.0
Humid forest	709,000	4,028,000	17.6	-	-	-	-
Dry forest	45,000	1,428,000	3.1	-	-	-	-
Spiny forest	237,000	2,578,000	9.2	-	-	-	-
Mangroves	1,000	123,000	1.0	-	-	-	-

3.3 Additional results disaggregating forest by forest type

Disaggregating forest by type (using the biome classification from the Resolve Ecoregions project (Dinerstein *et al.*, 2017)) shows that humid and sub-humid forests are the most potentially prospective forest type in terms of area (18% have gem potential) and are consequently more likely to host gem mining in future than other forest types (Figure S3). Only 9% of spiny forests, 3% of dry forests and 1% of mangrove forests are potentially prospective. This is not surprising as dry forests and mangroves are mostly found in Western Madagascar where the underlying geology comprises relatively recent sedimentary sequences. In contrast, humid and spiny forests are concentrated in the northern, southern, and eastern parts of the island which experienced regional metamorphism and magmatism during the East African and Kuungan Orogenies. In certain areas, with the right lithologies, these large-scale processes provided the required temperature and pressure conditions to enable the formation of gemstones.

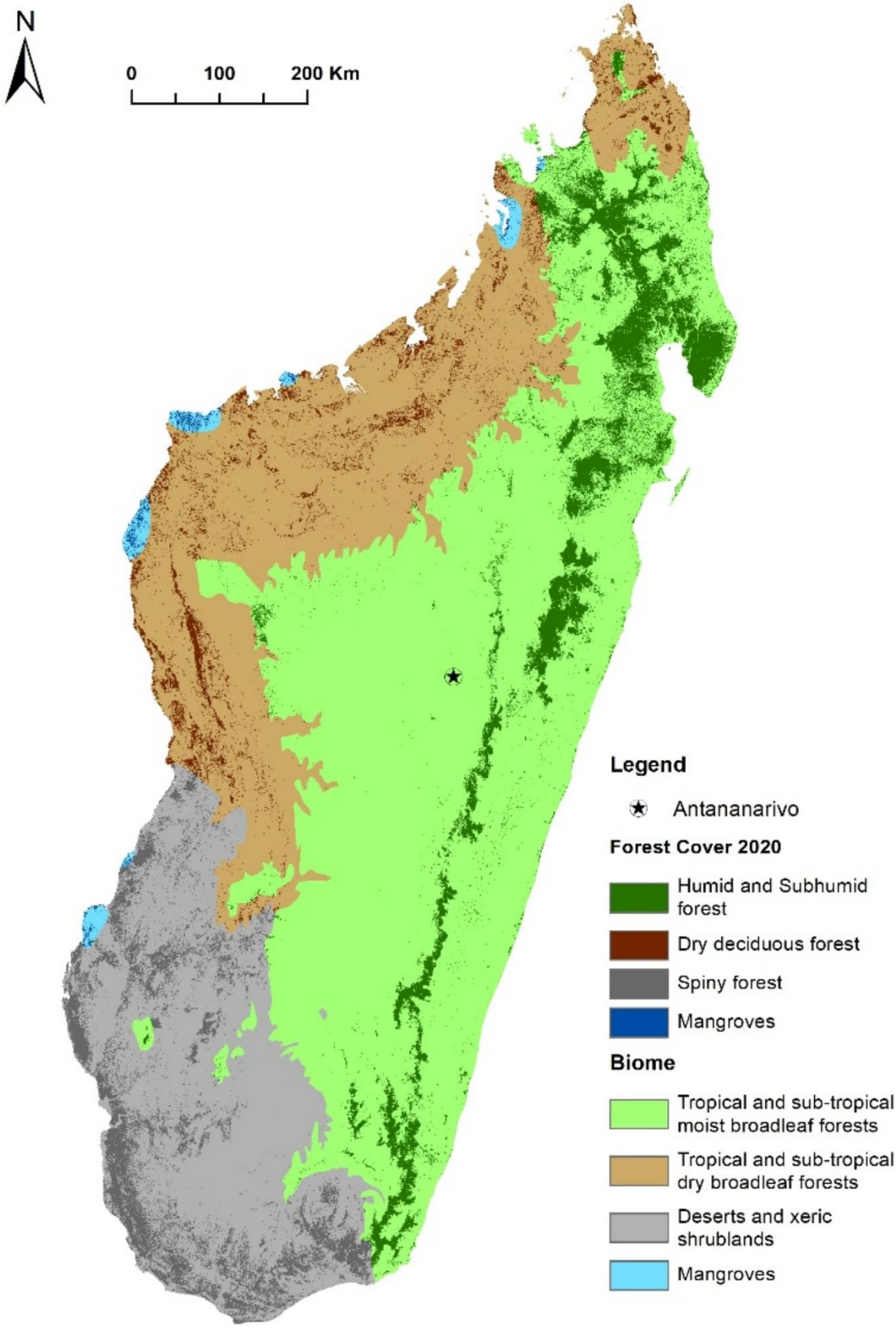

Figure S2: Map of forest cover in 2020 categorised by forest type. The four biomes of Madagascar are also shown (Dinerstein *et al.*, 2017).

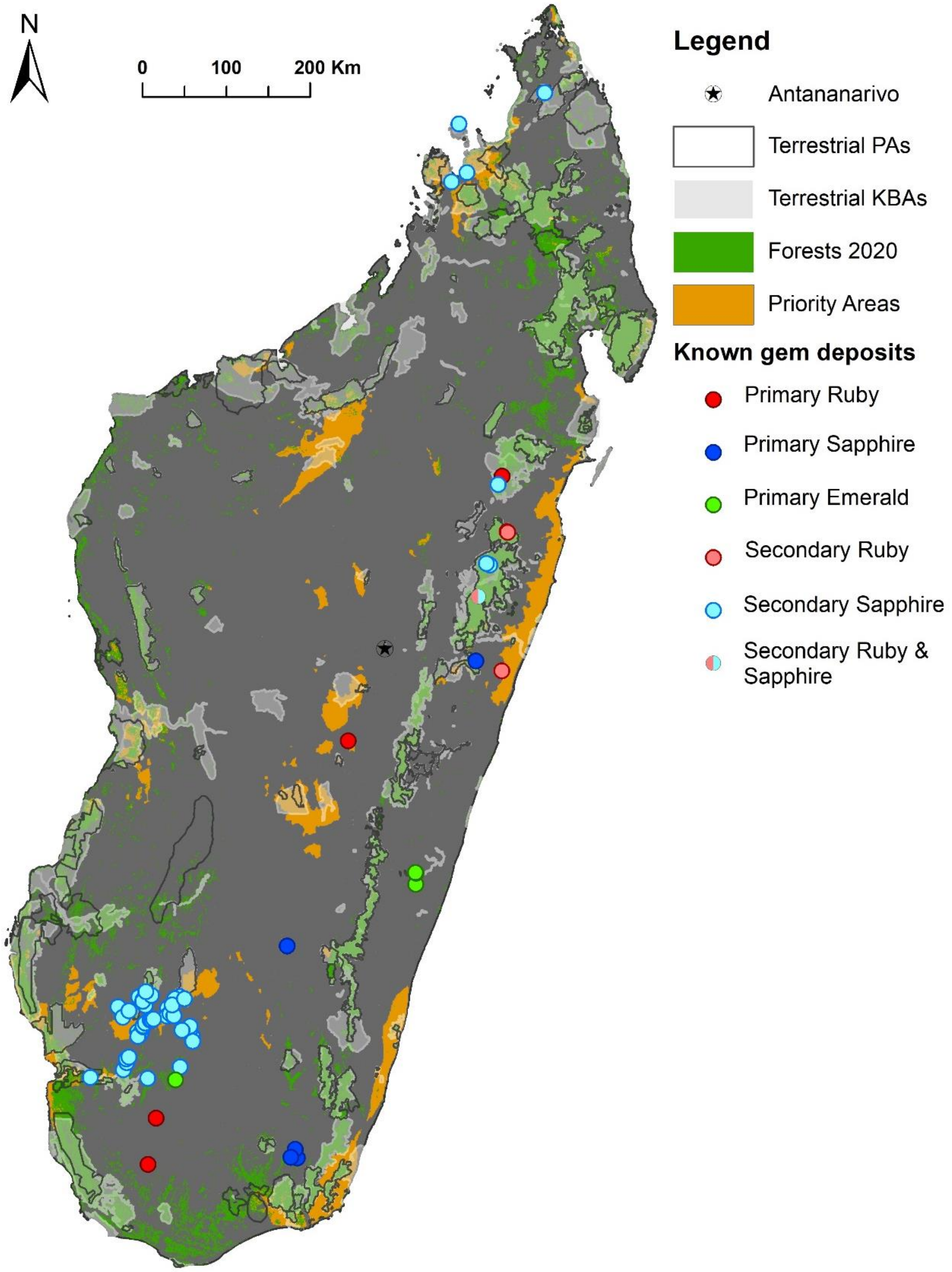

Figure S3: Location of known gem deposits in relation to important areas for biodiversity (Terrestrial Protected Areas [PAs], Key Biodiversity Areas [KBAs], Forest cover in 2020, and Priority Areas).

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