FIELD GUIDE

TO THE GEOLOGY OF

MADAGASCAR

IGCP 648 Field Symposium 2019

22nd June – 6th July

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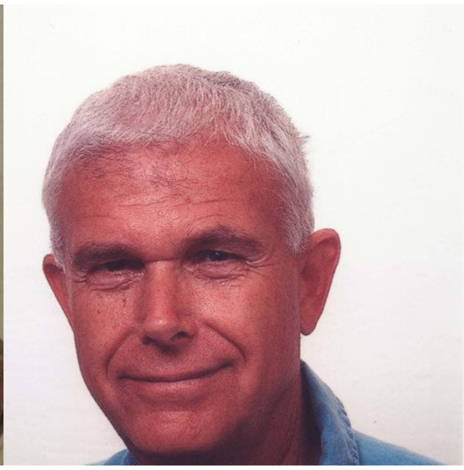
United Nations Educational, Scientific and Cultural Organization

IUGS UNESCO

In appreciative memory of two wonderful geologists,
lost to the community in 2019

Prof Svetlana Bogdanova
&
Prof Alfred Kröner

IGCP 648 Field Symposium 2019

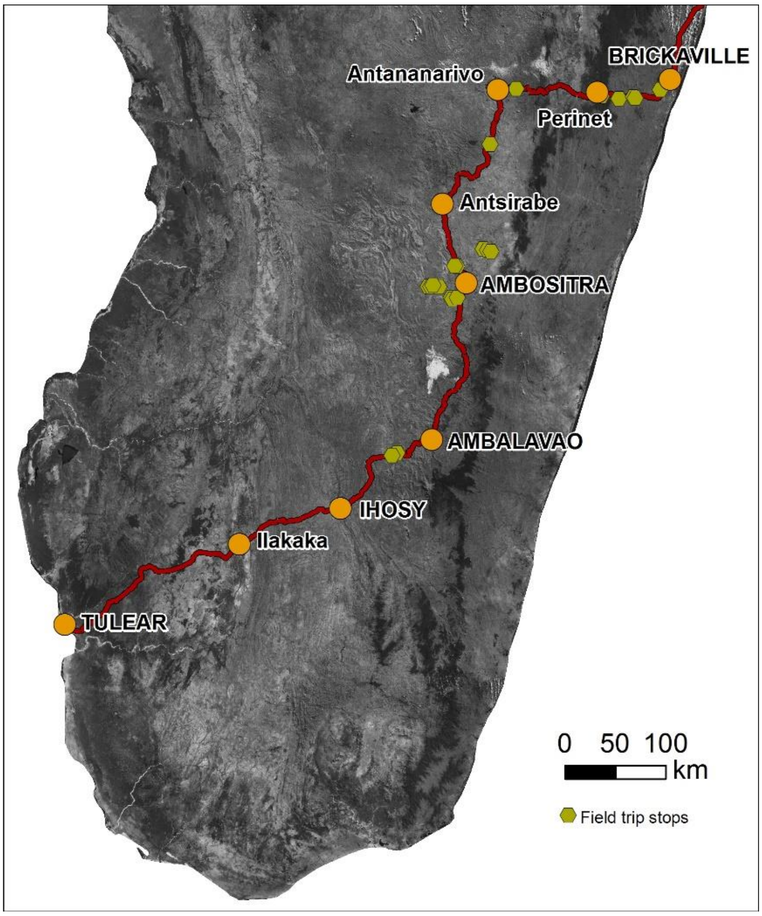
Madagascar

Itinerary

Day/Date	Activity	Details	Accommodation
Saturday 22nd June	Welcome and introduction	Meet at Hotel Tana Jacaranda 5pm for welcome, introduction, distribution of field guides.	Tana Jacaranda, Antananarivo
Sunday 23rd June	Field day 1	Outcrops around Antananarivo, relationship between the Archean Betsiboka Suite and Neoproterozoic intrusive rocks.	Tana Jacaranda, Antananarivo
Monday 24th June	Field day 2	Antananarivo to Andasibe National Park (Perinet), explore rocks of the eastern Antananarivo Domain. Examine outcrops of Ambalavao Suite granites and Manampotsy Group.	Feon'ny ala, Andasibe
Tuesday 25th June	Field day 3	Andasibe to Brickaville return, explore the eastern transect through eastern Tana Block, the Tsaratanana Complex and towards the controversial Betsimisaraka Suture	Feon'ny ala, Andasibe
Wednesday 26th June	Field day 4	Andasibe to Antsirabe, via Antananarivo, more outcrops of the Antananarivo Block	Hasina Hotel, Antsirabe
Thursday 27th June	Field day 5	Antsirabe to Ambositra, walk through the Ilaka granite to the boundary with the Itremo sub-domain at the Betsileo Shear Zone	Grand Hotel, Ambositra
Friday 28th June	Field day 6	Outcrops around Ambositra, look at parts of the Itremo Subdomain including the gabbros of the Imorona-Itsindro Suite	Grand Hotel, Ambositra
Saturday 29th June	Field day 7	Ambositra to Ambalavao, examine outcrops along and down the Ranomafana escarpment	Aux Bougainvilliers, Ambalavao
Sunday 30th June	Field day 8	Ambalavao to Ihosy, examine Betsileo shear zone, Ikalamavony Domain and Anosyen Domains	Tamana Hotell, Ihosy
Monday 1st July	Field day 9	Ihosy to Ifaty, via Ilakaka (sapphire mining town, in the Permian Morondava Basin)	La Mira Madiorano, Ifaty
Tuesday 2nd July	Day off ☺		La Mira Madiorano, Ifaty
Wednesday 3rd July	Conference	Conference Day 1	La Mira Madiorano, Ifaty
Thursday 4th July	Conference	Conference Day 2	La Mira Madiorano, Ifaty
Friday 5th July	Drive to Finar		Mahamanina Hotel, Fianarantsoa
Saturday 6th July	Drive to Antananarivo		Tana Jacaranda, Antananarivo

Field Trip overview

Antananarivo to Brickaville



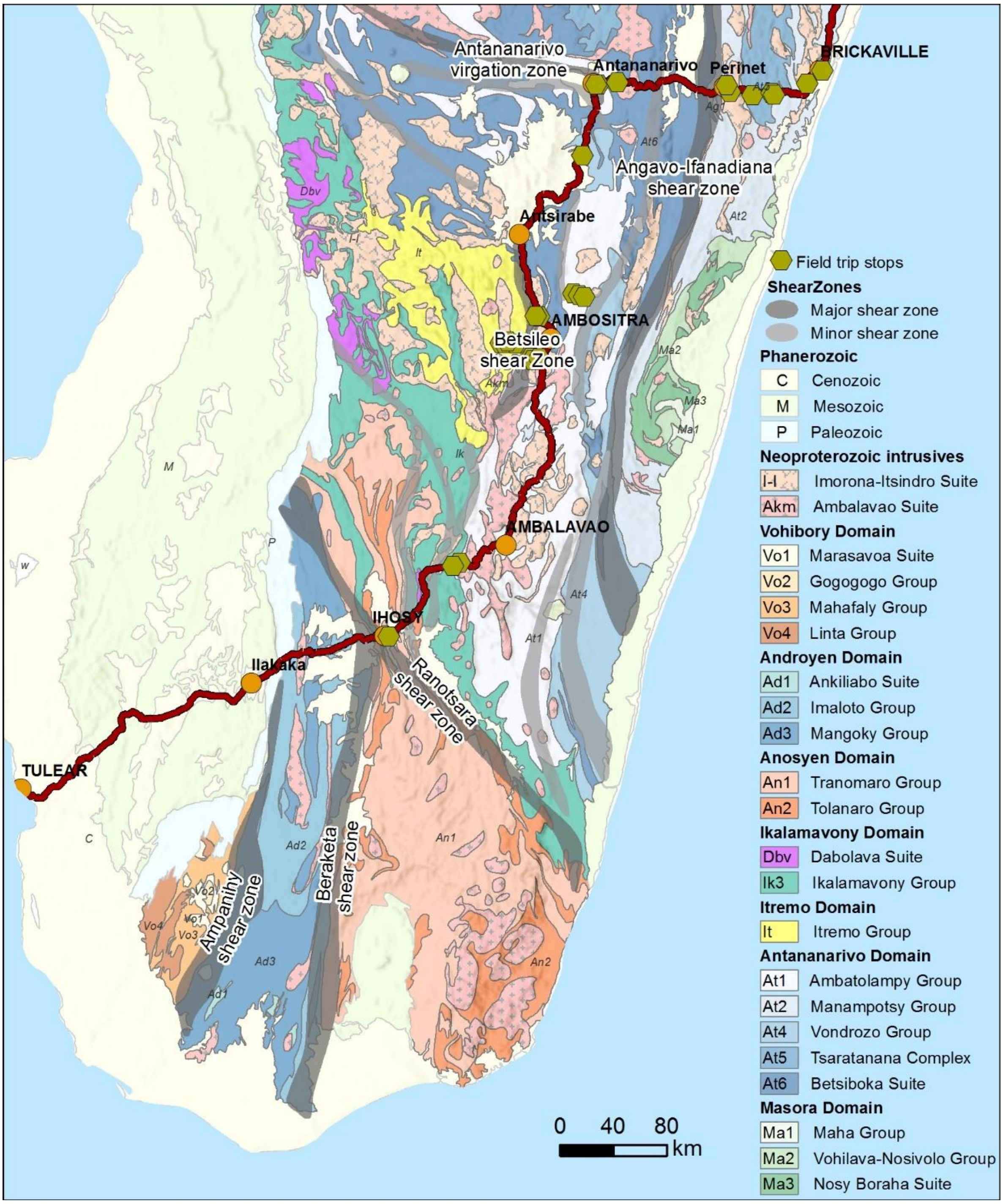
On field trip days 1, 2 and 3 we will explore the region from Antananarivo (Tana) to Brickaville. Along the east-west road between Antananarivo and Brickaville, we will go through the section of the controversial 'Betsimisaraka Suture'. We will see outcrops of Ediacaran–Cambrian post-tectonic granites (the Ambalavao Suite), most notably the Carion Granite.

Antananarivo to Ambalavao

Field trip days 4 to 7 we will explore the region south of Antananarivo to Ambalavao. The north-south road between Antananarivo and Ambalavao contains exposure of Cenozoic volcanics, which obscure much of the underlying Precambrian geology. Nevertheless, we will see some outcrops of the Paleoproterozoic Ambatolampy Group and Itremo Group quartzites. We will also see more outcrops of the Ambalavao Suite as well as the ca. 850–750 Ma Imorona-Itsindro Suite.

Ambalavao to Ilakaka

On field trip days 8 and 9, we will make our way from Ambalavao towards Tulear on the southwest coast. In this section we drive through the southern domains of Madagascar, which contain several high-strain shear zones and spectacular metamorphic assemblages. We will traverse through the southern extent of the Ikalamavony Domain, the Anosyen Domain and Androyen Domain.



Geological map of the field trip region in central and southern Madagascar. Modified from Roig et al., 2012

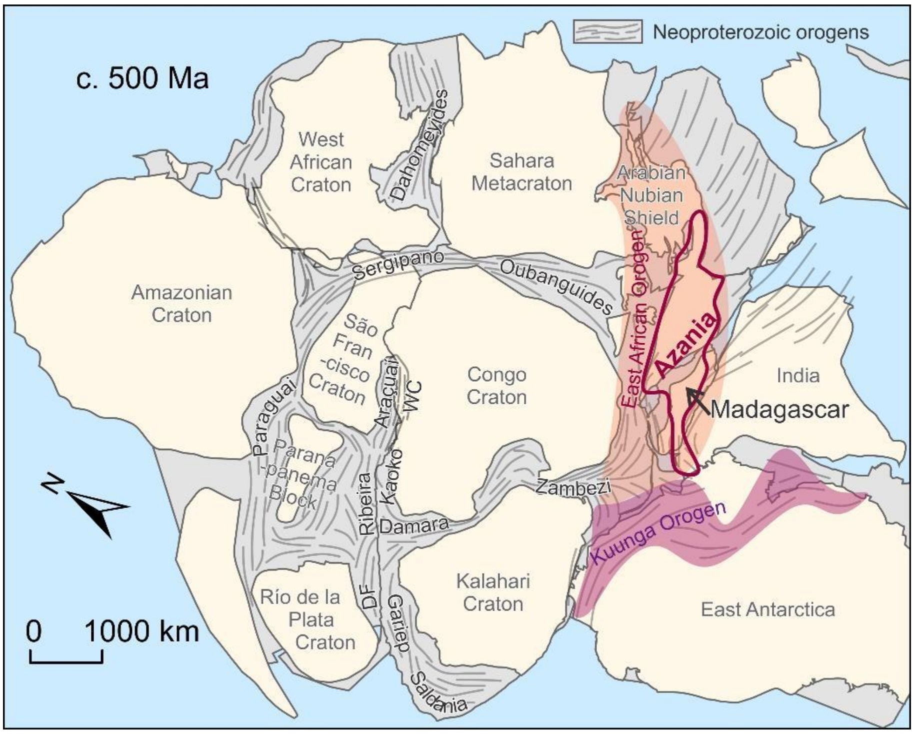
Introduction to the geology of Madagascar

Gondwana formed when the continents of eastern Gondwana including Australia, India and East Antarctica amalgamated with the Precambrian blocks of western Gondwana including Madagascar, Africa and South America (e.g. Fritz et al., 2013; Johnson et al., 2011). On this field trip we will see evidence of the largest Gondwana-forming collisional belt—the East African Orogen—and its expression into Madagascar and Madagascar's paleo-neighbours. The East African Orogen was comparable in scale to the modern Himalaya System (>5000 km length) and formed during closure of the Mozambique Ocean that separated India, Madagascar and Africa (Collins and Pisarevsky, 2005; Fritz et al., 2013; Johnson et al., 2011; Meert, 2003; Merdith et al., 2017; Merdith et al., 2019).

The timing and duration of magmatic arc assembly along the length of the East African Orogen is still an emerging area of research. Originally, it was thought that the East African Orogen was a product of a single-stage collision between East and West Gondwana (Stern, 1994). However, with the abundance of isotopic data that now exist for the East African Orogen, we know that the age distribution does not reflect a simple single-stage collision. Considerable research has shown that smaller continental fragments came together over a protracted period of time during the Neoproterozoic and early Cambrian (e.g. Boger et al., 2015; Collins, 2006; Collins and Pisarevsky, 2005; de Wit et al., 2001; Kusky et al., 2003).

The microcontinent 'Azania' was proposed by Collins and Windley (2002), which comprised fragments of Madagascar, Somalia, eastern Ethiopia and Arabia. It was suggested that Azania collided with the Congo Craton, Tanzania Craton, Bangweulu Block and the western Arabian Nubian Shield at c. 650 Ma. In Madagascar this suture is termed the Vohibory Suture, which separates the Vohibory Domain and Androyen Domain of southern Madagascar. The location of a Gondwana suture in southwestern Madagascar is contentious however. The boundary between the Androyen and Anosyen domains has alternatively been interpreted as the major Gondwana-forming collision zone in Madagascar that sutured at c. 580–520 Ma (Boger et al., 2015; Boger et al., 2014; Boger et al., 2019).

A younger orogeny marked by the Betsimisaraka Suture in eastern Madagascar has also been proposed, which sutured Madagascar and India at c. 550 Ma (Collins and Pisarevsky, 2005). In Madagascar, this suture separates the Antananarivo Domain from the Antongil and Masora domains of Indian origin. The Betsimisaraka Suture is controversial however, with some researchers maintaining that Madagascar and India have been contiguous since c. 2500 Ma (Tucker et al., 2011; Tucker et al., 2014; Zhou et al., 2018). Other authors have suggested that the Betsimisaraka Suture is more like c. 700 Ma (Fitzsimons and Hulscher, 2005).



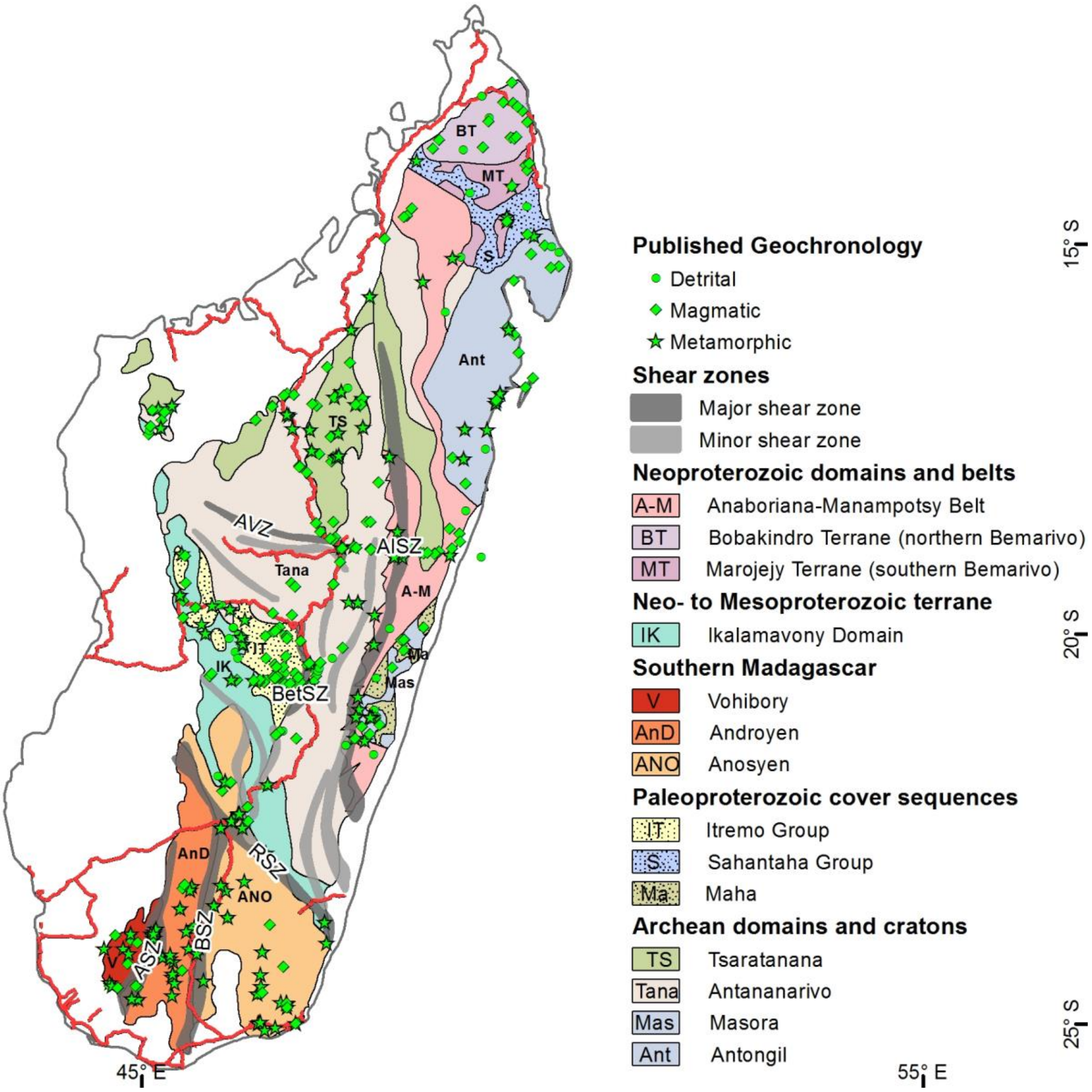
Tectonic map of Gondwana made using GPlates exported geometries from Merdith et al. (2017) in ArcGIS; projected in Hotine Oblique Mercator with Madagascar in the centre (reconstructed position, longitude=-75 and latitude=+40). DF=Dom Feliciano Belt, WC=West Congo.

Geological domains of Madagascar

Considerable advances in the understanding of the mapped geology of Madagascar were gained through the collection of isotopic, structural and mapping data of a major World Bank Project in Madagascar (BGS-USGS-GLW, 2008). This resulted in several publications (e.g. De Waele et al., 2011; Goodenough et al., 2010; Schofield et al., 2010; Thomas et al., 2009; Tucker et al., 2014) and an updated 1:1,000,000 map for the entire country (Roig et al., 2012) that have provided a good foundation to understanding the age and composition of the major domains in Madagascar. Madagascar is made up of several domains spanning from Archean to Neoproterozoic. Central Madagascar contains the Antananarivo Domain, which is composed of magmatic gneisses of the c. 2500 Ma Betsiboka Suite (Collins and Windley, 2002; Kröner et al., 2000). In eastern Madagascar are the Antongil and Masora domains, which contain c. 3100 Ma rocks and are likely a continuation of the Dharwar Craton of India (Armistead et al., 2017; Schofield et al., 2010; Tucker et al., 1999). To the southwest of, and overlying the Antananarivo Craton, is the Itremo Group, composed of quartzites, schists and marbles with a maximum depositional age of c. 1700 Ma (Cox et al., 1998; Fernandez et al., 2003). To the southwest of the Itremo Group, is the Ikalamavony Group, similarly made up of quartzites, schists and marbles, but with a maximum depositional age of c. 1000 Ma. To the south of these metasedimentary domains are the Proterozoic Anosyen, Androyen and Vohibory domains (Boger et al., 2014; Emmel et al., 2008; Jöns and Schenk, 2008). In northern Madagascar is the c. 800–700 Ma Bemarivo Domain, which likely formed as an exotic juvenile arc terrane that amalgamated with Madagascar at c. 520 Ma (Armistead et al., 2019; Jöns et al., 2009; Thomas et al., 2009).

A series of Neoproterozoic sedimentary sequences overly these major domains, and a suite of Neoproterozoic magmatic rocks intrude the domains. Overlying the Ikalamavony and Itremo domains is the Molo Group, which has a maximum depositional age of c. 620 Ma and a minimum depositional age of c. 560 Ma defined by metamorphic overgrowths (Cox et al., 2004). The c. 1000 Ma Dabolava Suite (Archibald et al., 2017) is restricted to the Ikalamavony Domain while the c. 850–750 Ma Imorona-Itsindro Suite (Archibald et al., 2016; Moine et al., 2014; Zhou et al., 2018) is widespread throughout much of central and eastern Madagascar. In the Vohibory Domain, the Linta group contains sedimentary rocks with maximum depositional ages of c. 620 Ma that closely reflect the ages of the intrusive Marasavoa and Vohitany suites.

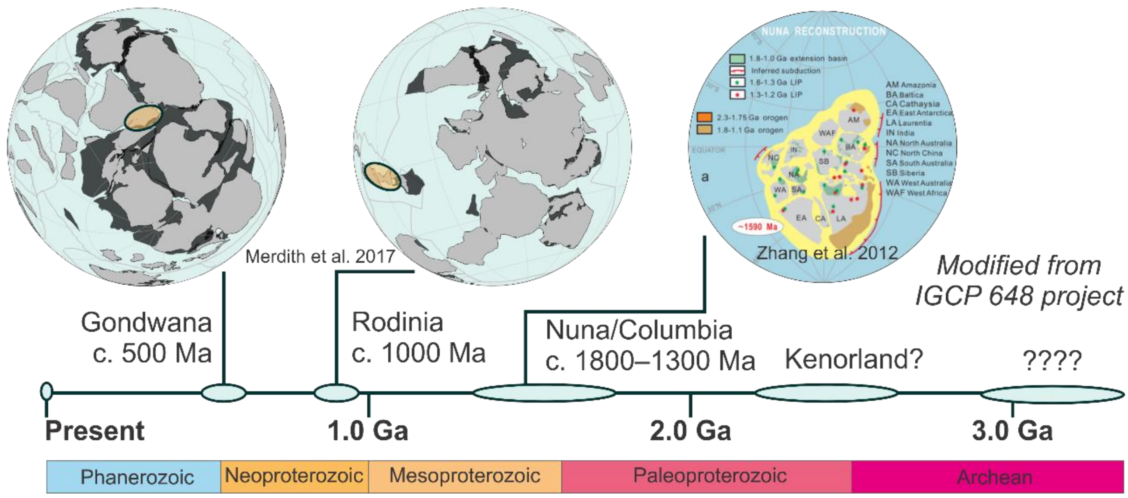
All of these domains have been deformed and metamorphosed during the late Neoproterozoic and early Cambrian (e.g. Armistead et al., In Review; Collins et al., 2003a; Collins et al., 2003b; Tucker et al., 2007) in response to the East African Orogen.



Tectonic Domains of Madagascar. Locations for published geochronology data shown; updated from the compilation of Tucker et al. (2014). AISZ=Angavo-Ifanadiana shear zone, AVZ=Antananarivo virgation zone, BetSZ=Betsileo shear zone, RSZ=Ranotsara shear zone, BSZ=Beraketa shear zone, ASZ=Ampanihy shear zone.

Supercontinents

Madagascar records suites of rocks that formed during all of the known supercontinents that Earth has experienced. These include Gondwana (c. 0.5 Ga), Rodinia (c. 1.0 Ga), Nuna/Columbia (c. 1.8–1.3 Ga) and Kenorland (c. 2.5 Ga). This makes Madagascar an important place to understand the evolution of its geology, its correlation with other terranes and understanding supercontinent cycles more broadly. In particular, Madagascar occupied an important place in the centre of Gondwana during the East African Orogeny. The timing and nature of how the terranes of Madagascar assembled with neighbouring blocks in Africa and India during Gondwana assembly—and indeed during other supercontinents—remains contentious.



Reconstructions of Earth's major supercontinents, with Madagascar's position circled in Gondwana and Rodinia. Gondwana and Rodinia reconstructions from Merdith et al. (2017) and Nuna Reconstruction from Zhang et al. (2012).

Saturday June 22nd – Welcome and Introduction

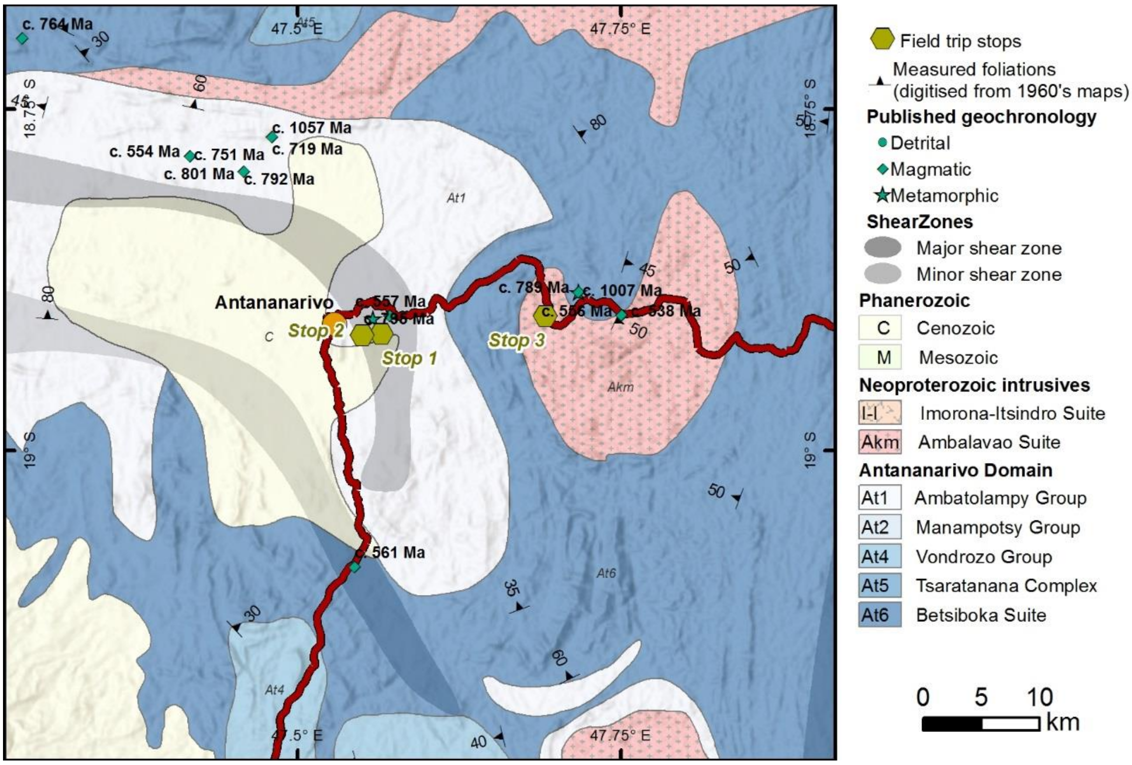
Accommodation: Tana Jacaranda, Antananarivo

Meet at Hotel Tana Jacaranda 5pm for welcome, introduction, distribution of field guides.

Field day 1: Sunday June 23rd – Antananarivo

Accommodation: Tana Jacaranda, Antananarivo

Aim: Explore the Antananarivo Block

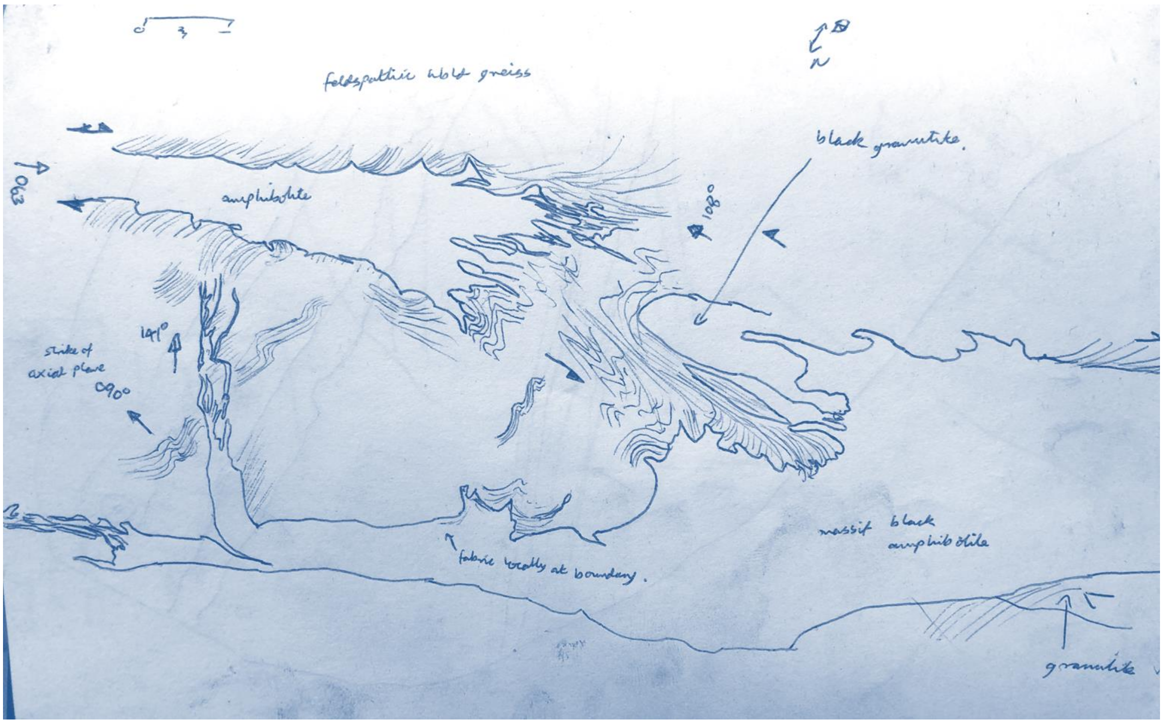


Geological map of the region around Antananarivo.

Stop 1

Ambatomaro Quarry 18°54’52.8”S, 47°33’53.0”E

A vast, mad, and impressive quarry in the east of Antananarivo. The country rock is cm-foliated garnet orthogneiss of the Imorona-Itsindro Suite (sample DA13-83, 795 ± 13 Ma, Archibald et al. 2016) with fine trondjemitic leucosomes. It hosts disseminated pods of pyritiferous amphibole and biotite rich gneiss with margins rich in pale red garnet (these may be relics of the Neoarchaean Betsiboka Suite?). The outcrop is cut by distinct fine to medium grained mesocratic to melanocratic dykes (striking 165°) with cuspate margins with fine K-spar leucogranite (sample 108, 517.8 ± 1.0 Ma, Kröner et al. 2000, Ambalavao Suite) that appears to be formed by in-situ melting of the gneiss. The dykes, and the host gneiss are cut by a mesh of K-spar leucogranite that grades into coarse biotite pegmatite.

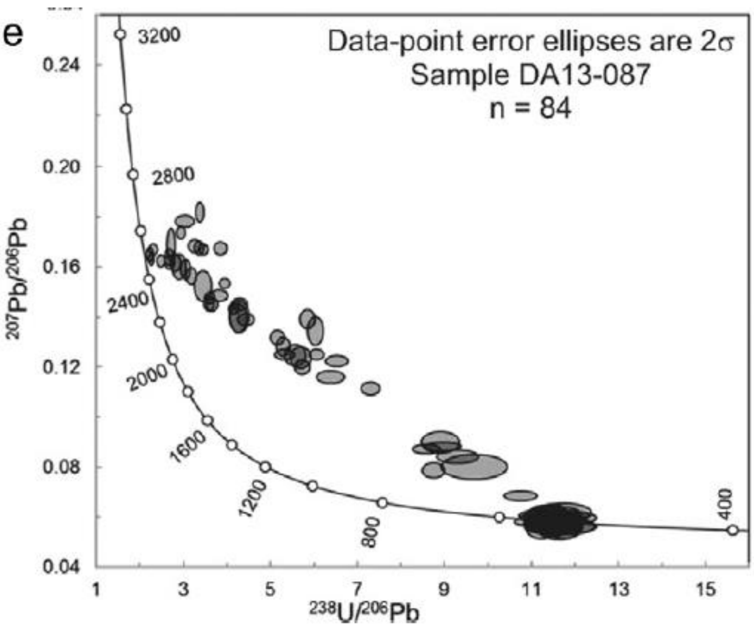


Sketch of Rock relationships in Ambatomaro Quarry

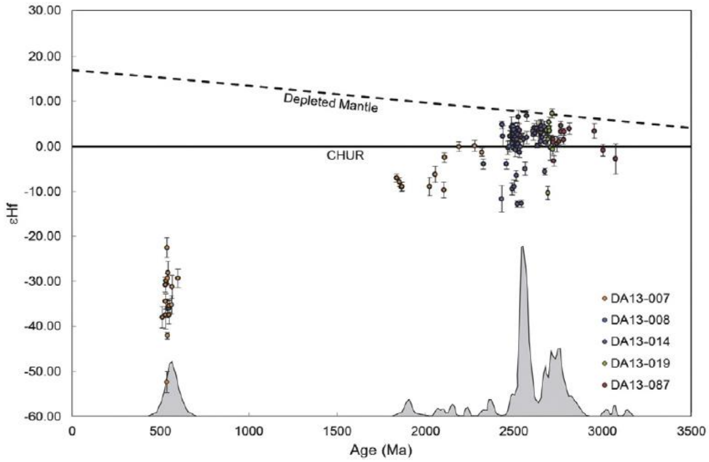
Stop 2

Ankatso 18°54’56.0”S, 47°32’57.9”E

Roadside outcrop of Ambatolampy Group quartzite at the entrance to the University of Antananarivo. The Ambatolampy Group has become somewhat controversial as most of the samples from it yield detrital zircons that appear very similar to the zircons in the Mesoproterozoic Itremo Group and Archibald et al. (2015) and Armistead et al (submitted) supported the view that these were just a high-grade version of the Itremo Group. A couple of samples have yielded much younger zircons and distinct detrital zircon profiles that appear to show a completely different source. Some argue that these then show that all the high-grade quartzites in the Antananarivo Domain are Neoproterozoic (Tucker et al. 2014). Whilst others argue that there are more than one sequence of quartzites in the Antananarivo Domain, and that the younger zircons belong to the equivalent of the Manampotsy Group that are focussed in the east of the island (Archibald et al. 2015).



Sample from this locality demonstrating the exclusive Neoarchaean source for these protoliths (Archibald et al. 2015).



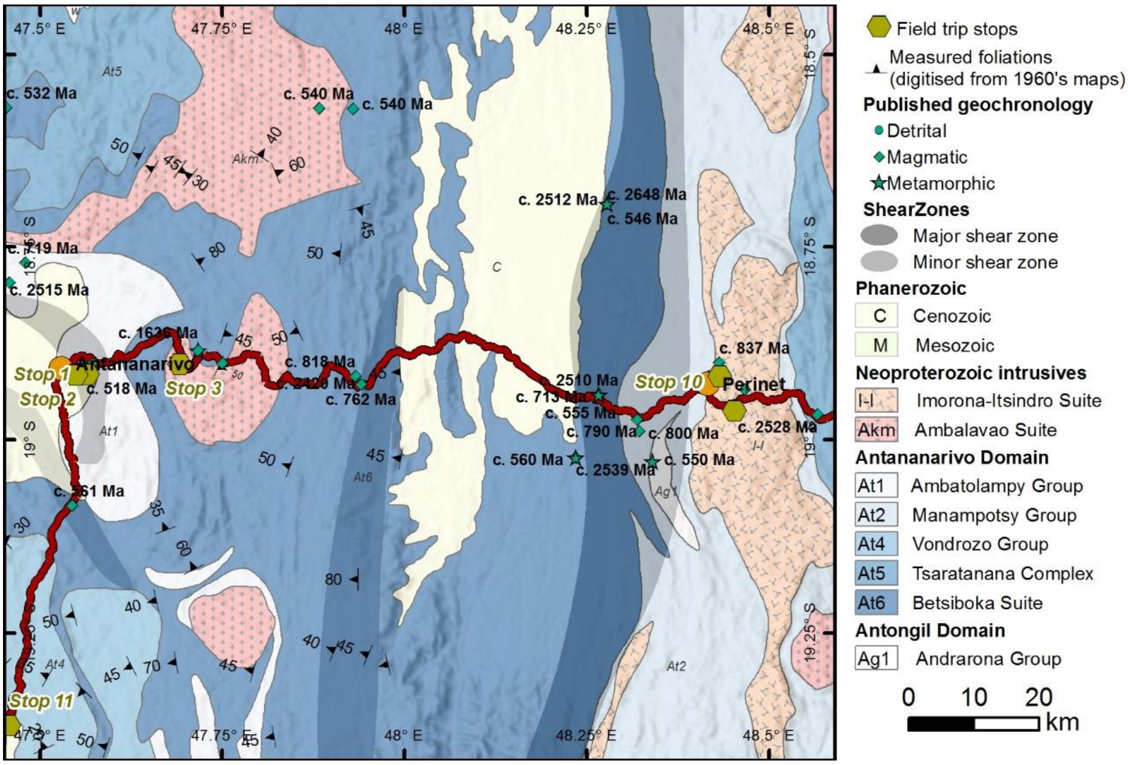
Detrital profile and Hf isotopes from 5 samples of Ambatolampy quartzite (Archibald et al. 2015).

Field day 2: Monday June 24th – Antananarivo to Andasibe (Perinet)

Driving time: 159 km; 4 h 1 min

Aim: Drive to Andasibe and explore rocks of the eastern Antananarivo Domain. Examine outcrops of Ambalavao Suite granites and Manampotsy Group

Accommodation: Feon'ny ala, Andasibe (Perinet)

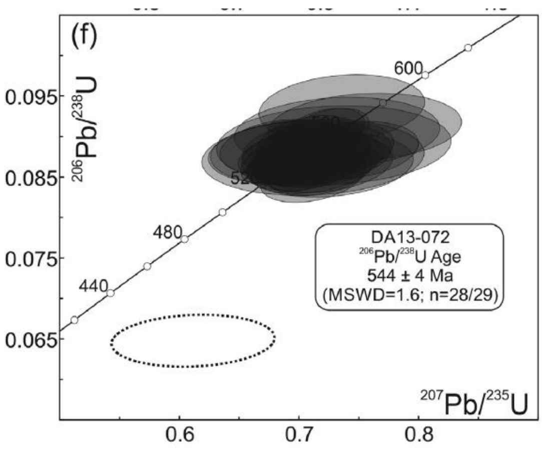


Geological map of the region visited for Day 2.

Stop 3

Carion Granite 18°54'05.9"S 47°41'28.6"E

Late to post-tectonic granite pluton in apex of Antananarivo Virgation zone. Dated by Meert et al. (2001) at crystallizing at ca. 532 Ma (544 ± 4 Ma; Archibald et al. in press) and had cooled below the Ar closure temperature for amphibole (~550°C) by ca. 515 Ma. Between here and the Angavo escarpment foliations in the Neoarchean/Palaeoproterozoic Betsiboka Suite bend dramatically to strike approximately N–S in the Angavo Shear Zone (Nédélec et al. 2000).



U–Pb data of the Carion Granite from Archibald et al. in press.

Visit Réserve Peyrieras to see their spectacular collection of moths, chameleons and other Malagasy creatures.

Stop 4

Maromizaha Quarry 18°57'43.1"S, 48°27'09.9"E

Foliated K-feldspar+biotite orthogneiss with rare garnet and allanite. Shallow W-dipping foliation. These lie in structural Domain 2 of Collins et al. (2003a) where shallow foliations are matched with W-plunging mineral aggregate lineations.

Visit the wonderful Perinét national park to look for the magnificent Indri amongst a host of other lemurs and Malagasy endemic creatures. There will be an opportunity for a night tour as well, which is highly recommended.

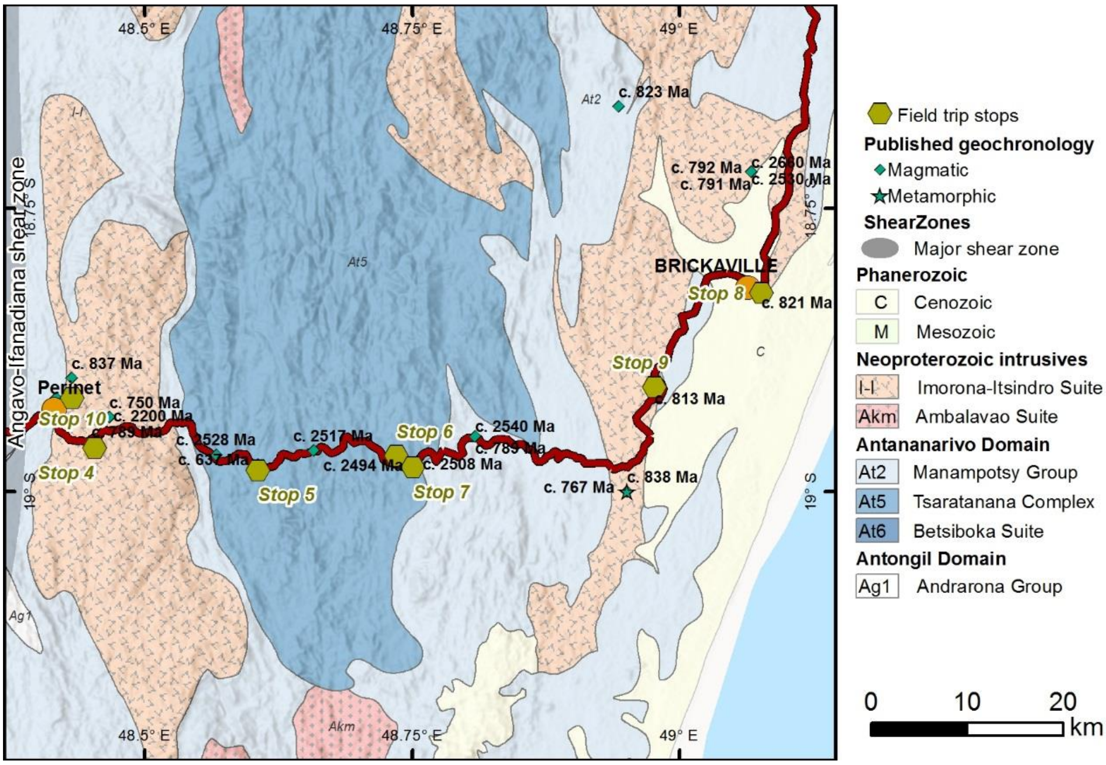
Field day 3: Tuesday June 25th – Andasibe to Brickaville rtn

Driving time: 132 km; 2 h 54 min x2

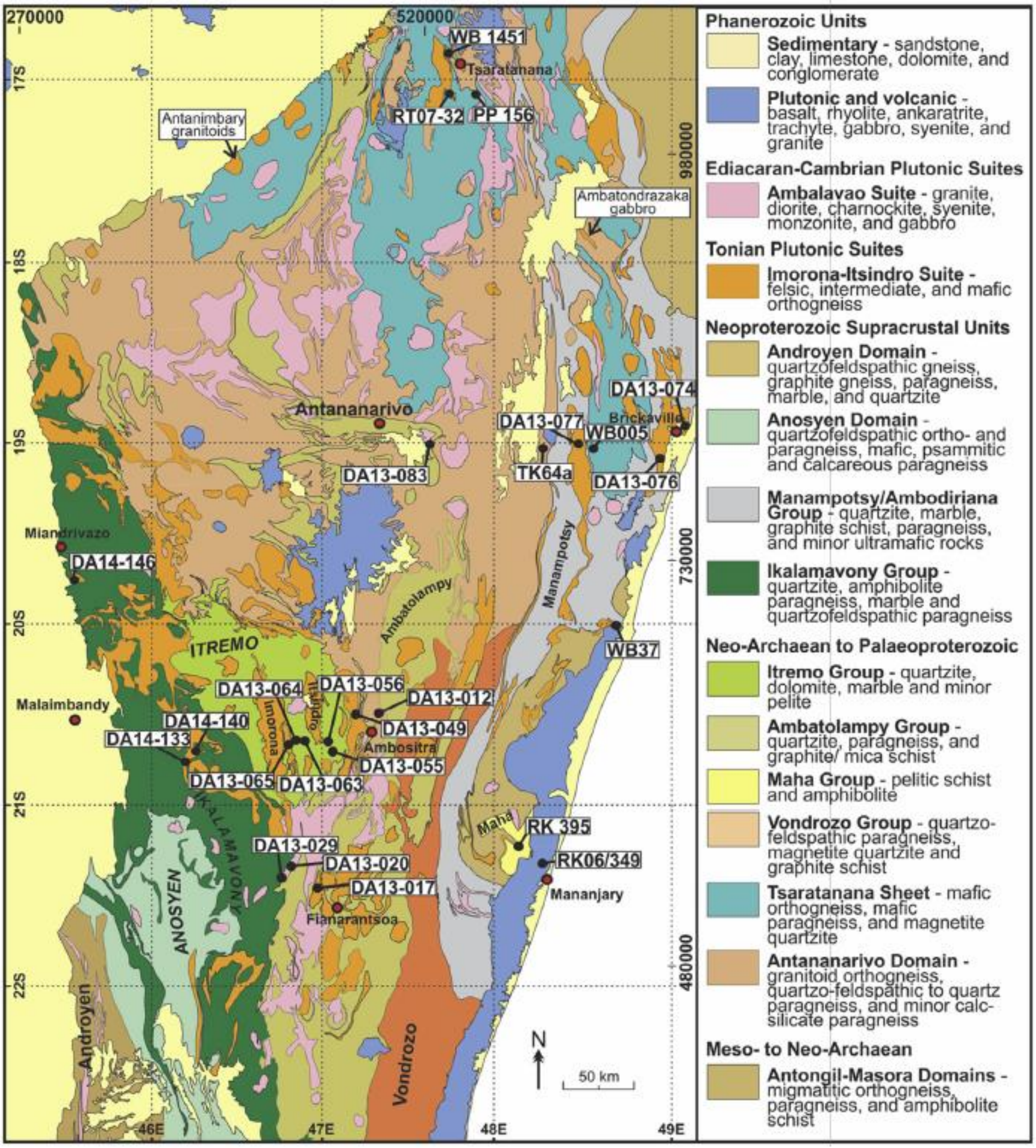
Accommodation: Feon'ny ala, Andasibe

Aim: Explore the eastern transect through eastern Tana Block, the Tsaratanana Complex and towards the controversial Betsimisaraka Suture

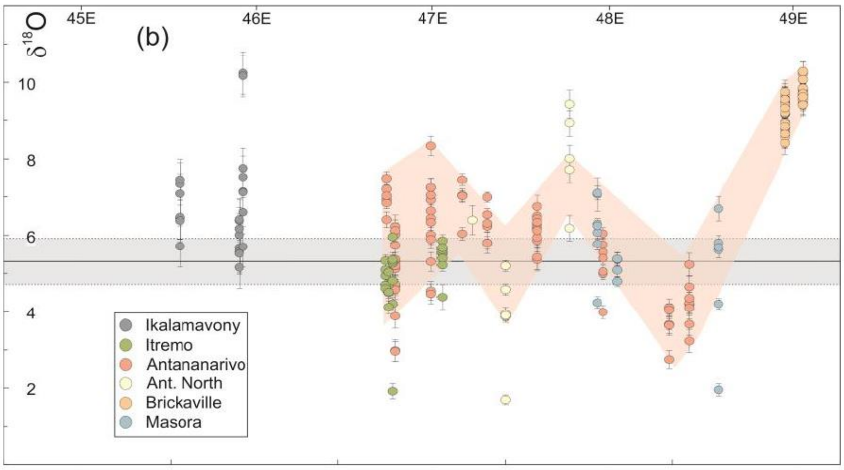
This section largely follows the transect published in Collins et al. (2003a), through the Neoproterozoic metasedimentary rocks of the Manampotsy Group and traversing the Tsaratanana Complex either side of the town of Beforona. This complex forms three broad synclinoriums throughout northern central Madagascar, with mylonite zones at the base of their outcrop. The Tsaratanana Complex is structurally above the rest of the Antananarivo Domain, yet has the highest grade rocks reported from the region and also the oldest rocks within the Antananarivo Domain. It has been interpreted as an allochthonous unit, thrust over the Antananarivo Domain (Windley et al. 1993; Collins and Windley 2002; Collins 2006) and also as an autochthonous component of the Antananarivo Domain (Tucker et al. 2011). As Tucker et al. (2011) pointed out, if these are allochthonous, they must have been emplaced pre ca. 800 Ma as they are intruded by the Imorona-Itsindro Suite (Handke et al. 1999; Tucker et al. 1999; Archibald et al. 2016).



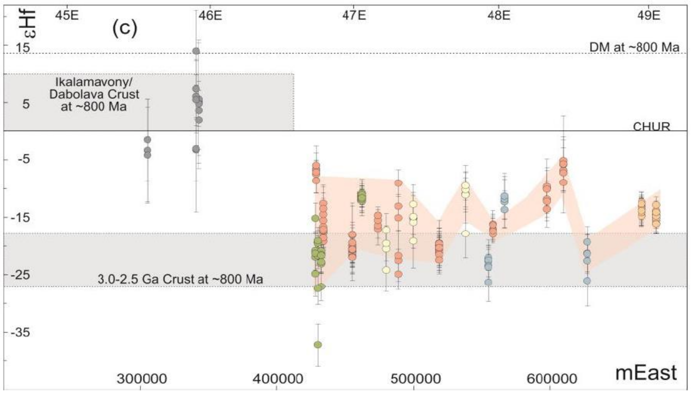
Geological Map of the region between Andasibe and Brickaville.

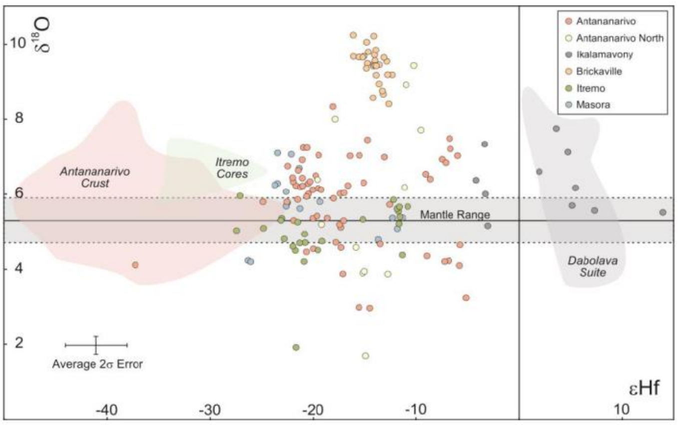


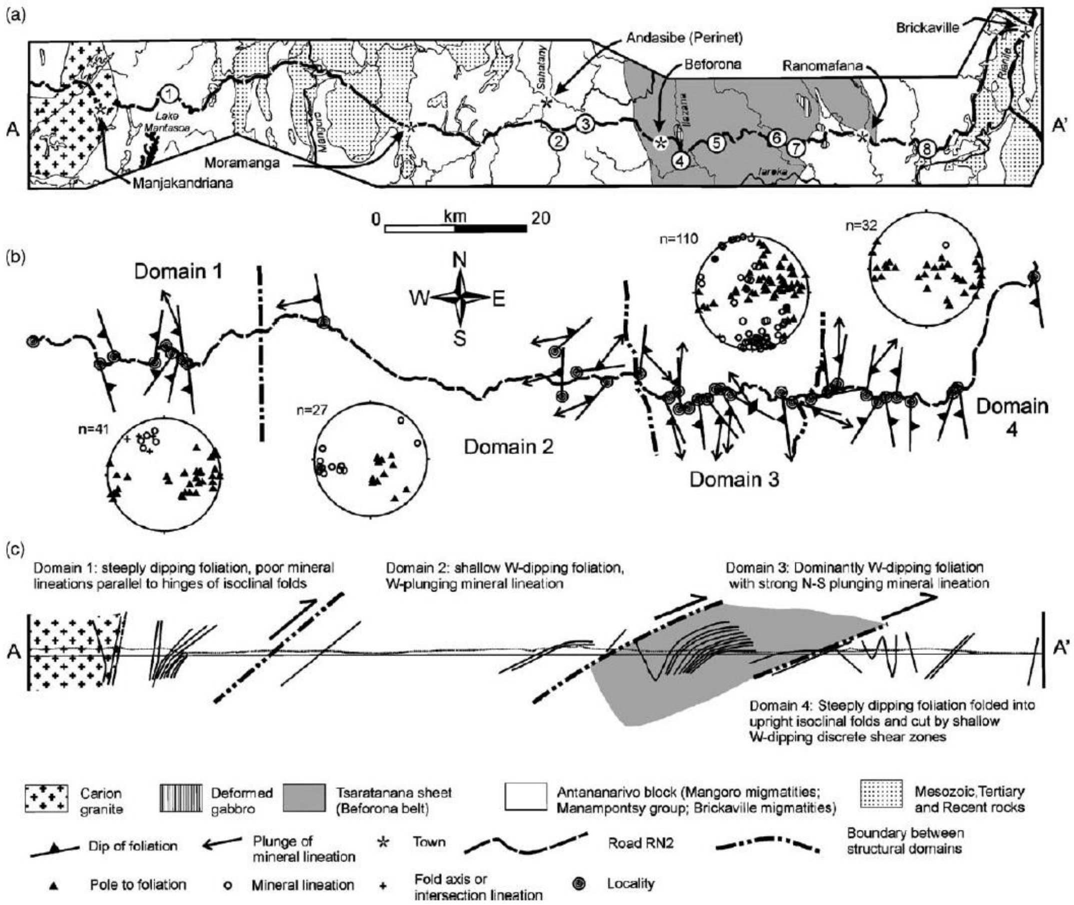
Geological Map of central Madagascar (from Roig et al. 2012) showing the extent of Tonian magmatism sampled in Archibald et al. (2016) as well as the locations of the Ambatondrazaka Gabbro (Zhou et al. 2015) and Antanimbary Granitoid (Yang et al. 2014).



Above are oxygen isotope data along a west–east traverse (Archibald et al. 2016). Below are the Hf isotope data along the same transect. Note that the Brickaville Granties are unusual and have different profiles from both the Antananarivo Block basement, the Itremo zircon xenocrysts and the Stenian-Tonian Dabolava Suite (see two below). This is interpreted to reflect that the magmatic source was contaminated with Manampotsy Group Neoproterozoic metasedimentary sources.





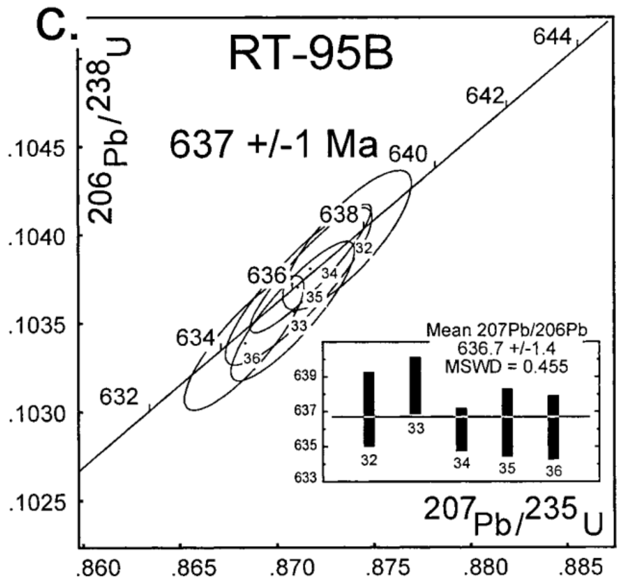


Map, cross-section and equal-area lower hemisphere projections of structural data from Manjakandriana to the coast along the Route National 2. Numbers refer to locations not otherwise on map: 1) Angavo escarpment; 2) Maromizaha Quarry; 3) Ihasy River; 4) Soakambana Quarry; 5) Sandrakatrana River; 6) Farimbona River; 7) Antongobatu Quarry; 8) Iamborano. From Collins et al. (2003a).

Stop 5

Soakambana Quarry 18°58'53.9"S, 48°36'20.9"E

L-tectonite granite with fabric cut by discrete steeply dipping shear zones. The crystallization age of the protolith to this gneiss was dated as 637 ± 1 Ma (Tucker et al. 1999). Ca. 630 Ma magmatism has been reported through central Madagascar (Paquette & Nédélec 1998), and were termed the ‘Kiangara Suite’. Recently, Nédélec et al. (2016) suggested that these were misdated and that ca. 630 Ma magmatism was missing in Madagascar. This really demonstrates that there is still much work to be done in the island.



The granite intrudes through steeply dipping grossular-bearing calc-silicates exposed at the E side of the quarry. Mafic dykes cut the L-Tectonite, but are deformed in steep shear zones. This forms part of Domain 3 of Collins et al. (2003a), which is restricted to the Beforona-Alaotra Belt, where prominent extensional lineations gently plunge N-S. The high strain in ca. 630 Ma granites demonstrates the youth of the deformation here in the east of the country.

U-Pb TIMS dating of main phase in Soakambana Quarry (Tucker et al. 1999).

Stop 6

River Farimbona 18°58'6.70"S, 48°44'5.40"E

Foliated and lineated hornblende gneiss with many E-verging asymmetric folds, fabric boudins with necks infilled with leucosome. Fabric folded into large steep shear zones and fabric converted into L-tectonite. Coarse pegmatite cuts outcrop as do mafic dykes.

Stop 7

Antongobato Quarry 18°58'44.1"S, 48°45'2.0"E

Highly deformed hornblende gabbro gneiss dated at 2494 +4/-3 Ma with a Neoproterozoic lower intercept (Tucker et al. 1999). These show liquid-liquid textures with a more felsic magma and both are mylonitized. The outcrop is cut by basaltic dykes with top-to-the-SE discrete shear zones deforming these. The rocks are then deformed into asymmetric folds.

Stop 8

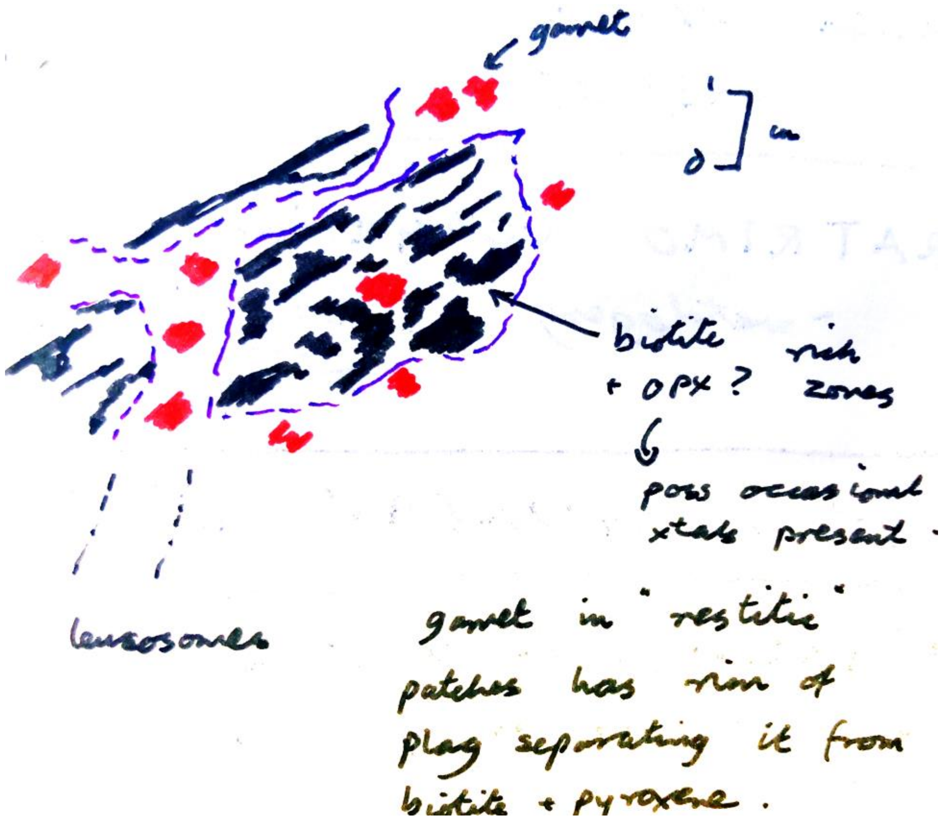
Brickaville Quarry 18°49'29.00"S, 49° 4'35.00"E

Migmatitic garnet-bearing granite of the Imorona-Itsindro Suite. Occasional large graphite crystals. A large Jurassic (?) dolerite dyke cuts the outcrop. Archibald et al. (2016) dated the protolith as crystallizing at 821 ± 11 Ma, with possible metamorphism at 657 ± 11 Ma and 545 ± 23 Ma. Kröner et al. (2000) obtained Pb-Pb evaporation ages of ca. 790 Ma from the same rocks. $\delta^{18}O$ values are ~8-10 demonstrating the supracrustal mature of the source (Archibald et al. 2016).

Stop 9

Loharano Quarry 18°54'27.7"S, 48° 58'34.2"E

Outcrops on way towards GRAP-MADA graphite mine. Migmatitic garnet granite. Biotite-rich blebs are foliated and possibly contain OPX. Non-foliated garnet-bearing leucosomes makes up 60-70% of rock. Graphite is present in the restite. Archibald et al. (2016) dated the crystallization of the protolith of this sample at 813 ± 10 Ma and the metamorphism/partial melting at 540 ± 10 Ma.



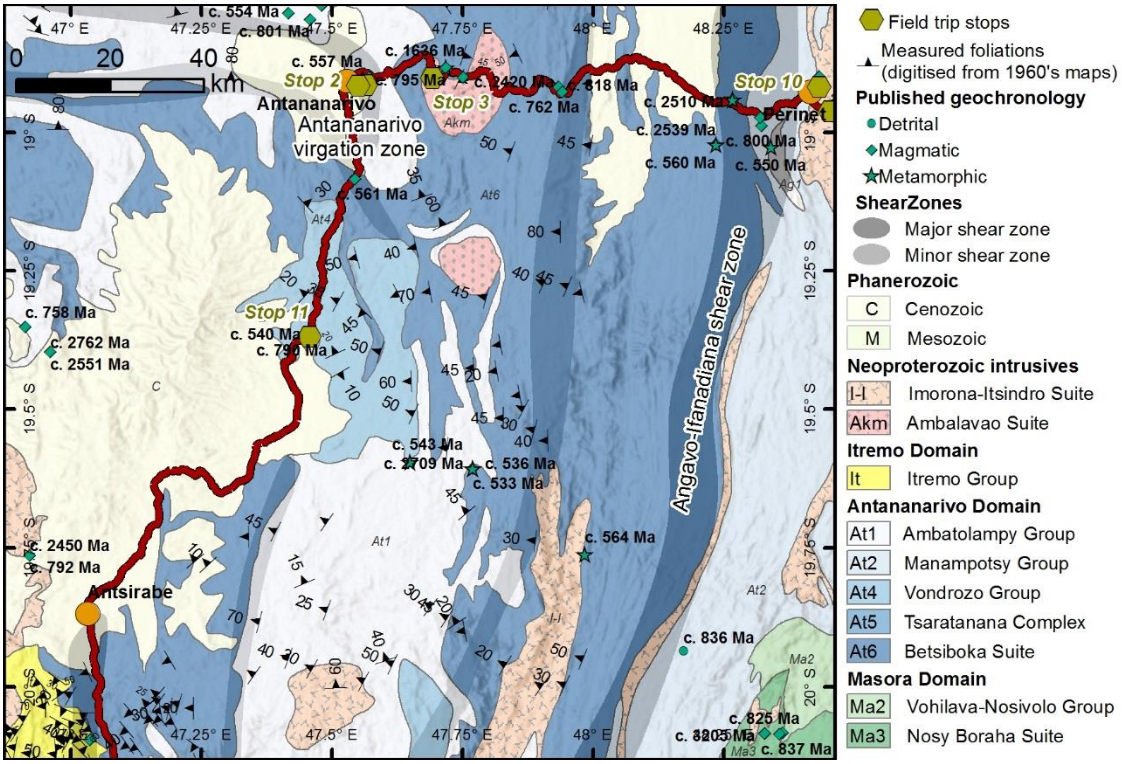
Sketch of relationship between garnet rimmed with plagioclase in foliated biotite restite (Tonian) and network of garnet leucosomes (Cambrian)

Field day 4: Wednesday June 26th – Andasibe (Perinet) to Antsirabe

Driving time: 312 km; 6 h 38 min

Accommodation: Hasina Hotel, Antsirabe

Aim: Drive to Antsirabe with stop in Tana Block

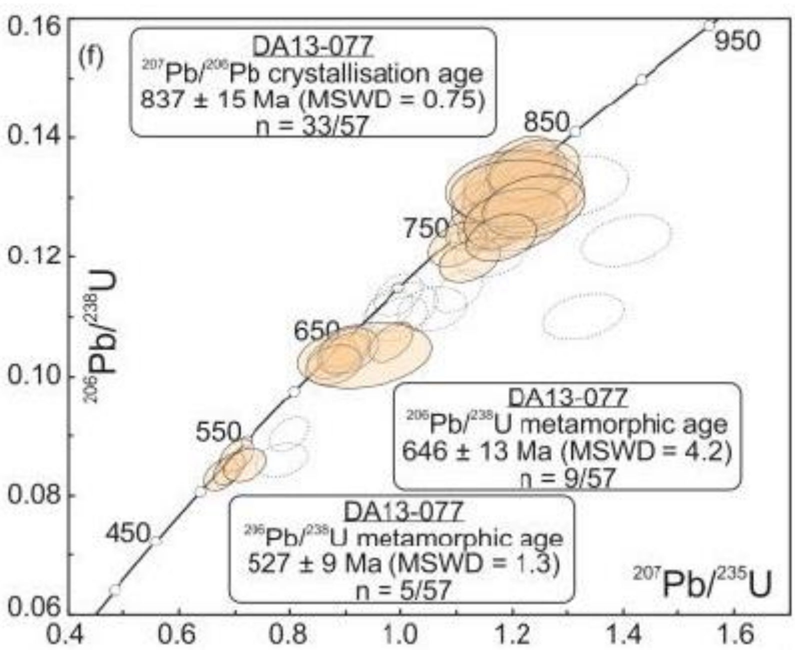


Geological map of the region around Andasibe to Antsirabe.

Stop 10

Andasifahtelo Graphite Mine (Sahatany Falls) 18°55'04.1"S, 48°25'54.5"E

Highly strained gar+bio felsic gneiss. Shallow foliation and pronounced mineral aggregate lineation and foliation. Relic K-feldspar phenocrysts locally preserve sigma-type geometries. Protolith is part of the Imorona-Itsindro Suite and crystallized at 837 ± 15 Ma, with possible ages of metamorphism at both 646 ± 13 Ma and 527 ± 9 Ma (Archibald et al. 2016). Kröner et al. (2000) obtained a Pb-evaporation age of 774.0 ± 0.9 Ma from a rock from this locality. These, along with zones of C/S fabrics, suggest top-to-east non-coaxial shear. Strain Domain 2 of Collins et al (2003a). Coarse pegmatite veins cut the outcrop.

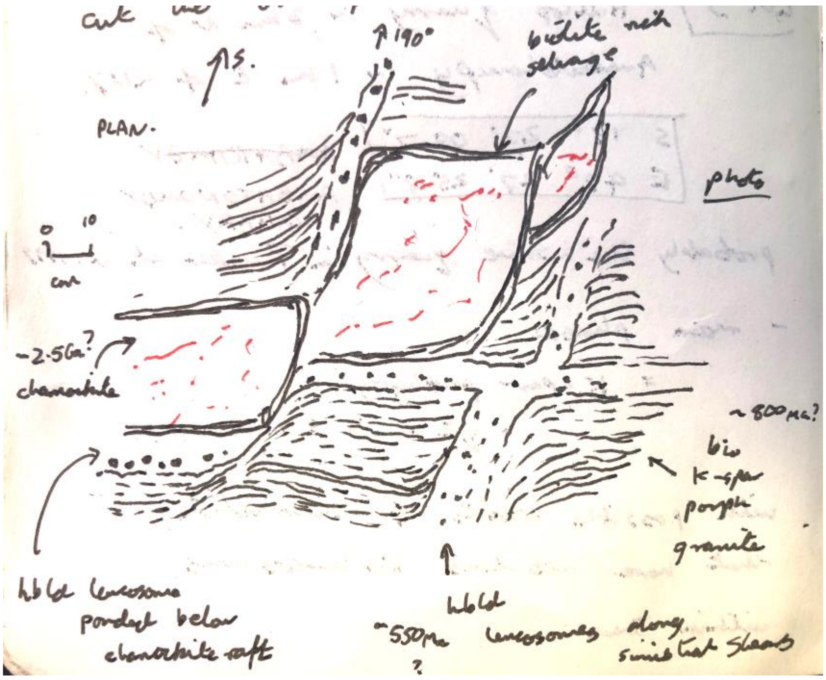


Concordia plot of U-Pb zircon data from Sahantany Falls. Are there really two metamorphic ages???

Stop 11

Ambatonomby Quarry 19°22'08.7"S, 47° 27'25.8"E

Folitated Itremo-Itsindro Suite K-feldspar porphyritic granite (790 ± 2 Ma, Tucker et al. 1999) enveloping zones of Betsiboka Suite (2515 ± 2, 2505 +6/-3 Ma, Tucker et al. 1999) charnockite that are cut by shear zones coeval with hornblende-bearing leucosomes. Late homogenous Ambalavao Suite pink granites (540 ± 3 Ma, Tucker et al. 1999, 531 ± 6 Ma, Archibald et al. in press) cut the outcrop.



Field sketch of rock relationships in the Ambatonomby Quarry

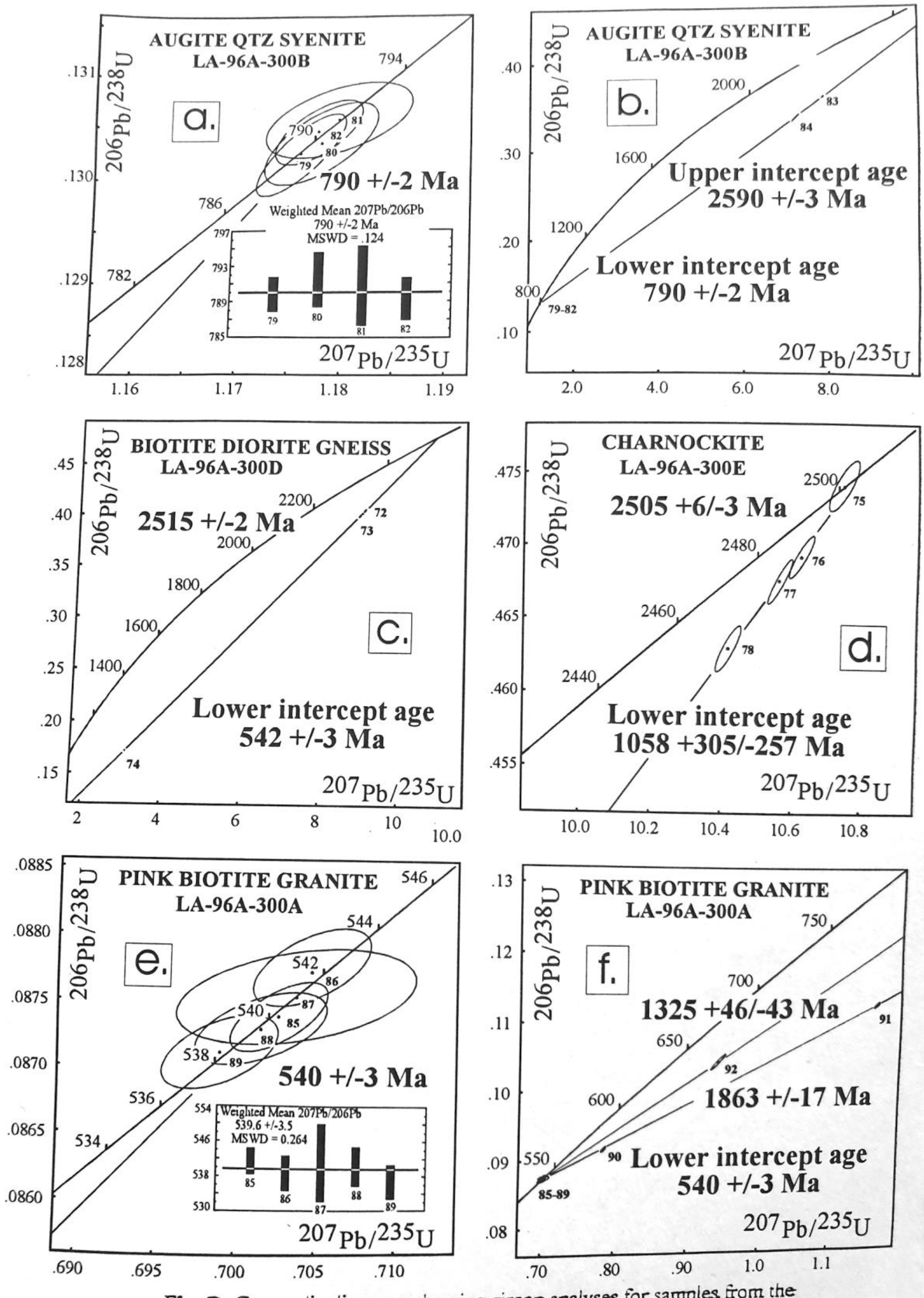


Fig. 7. Concordia diagrams showing zircon analyses for samples from the Ambatonomby quarry (Stop 2-1).

U-Pb data from Tucker et al. 1999 - data collected from Ambatonomby Quarry

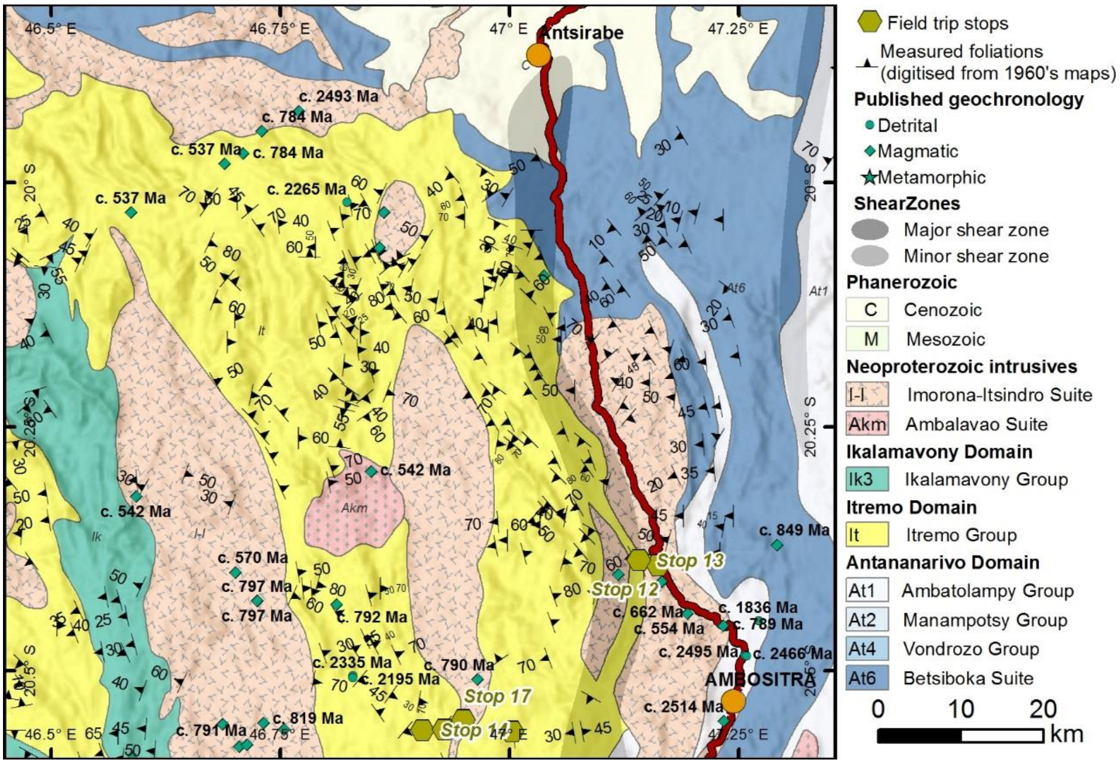
Afternoon to explore Antsirabe and especially the gem and rock market

Field day 5: Thursday June 27th – Antsirabe to Ambositra

Driving time: 93 km; 1 h 54 min

Accommodation: Grand Hotel, Ambositra

Aim: Walk through the Ilaka granite to the boundary with the Itremo sub-domain at the Betsileo Shear Zone

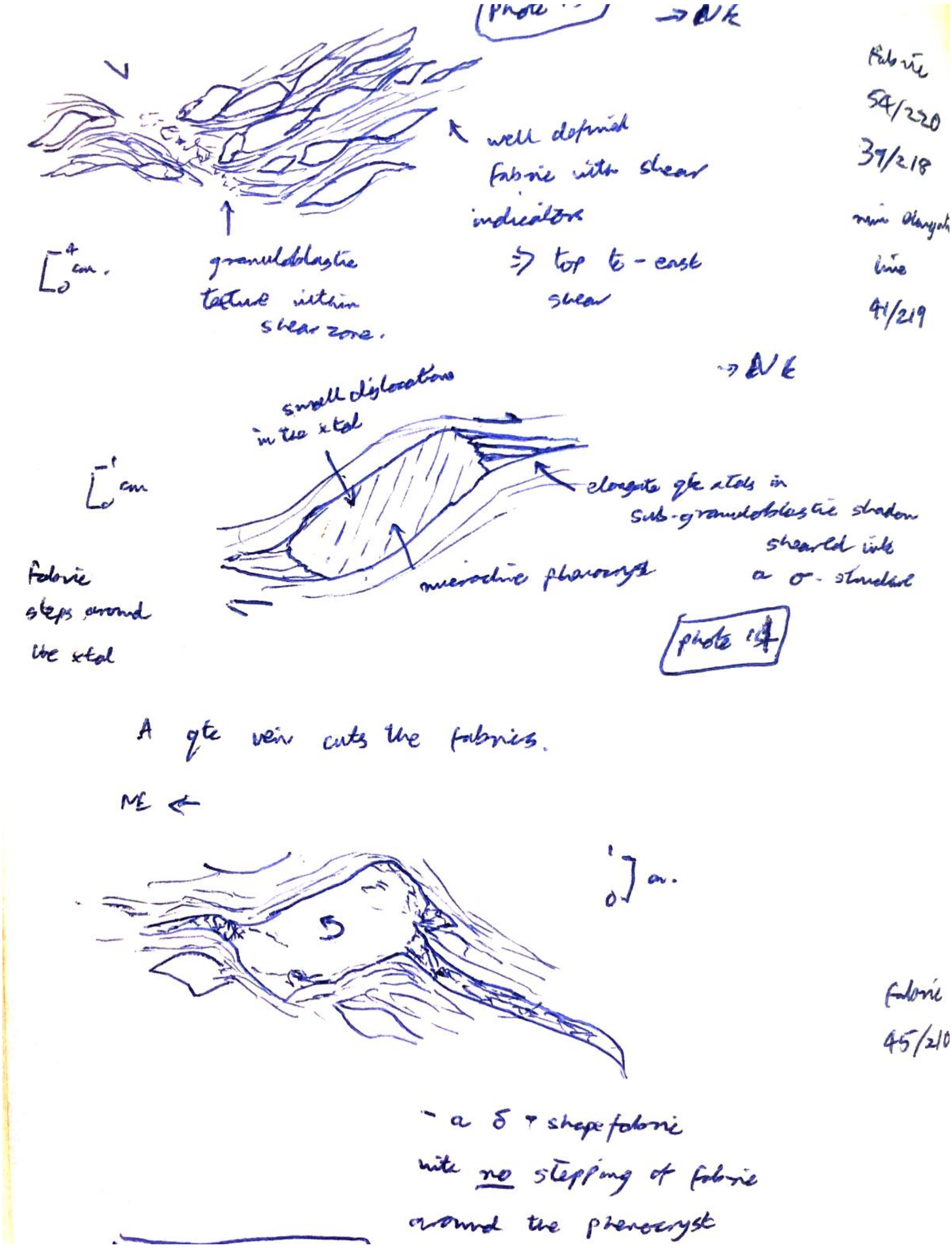


Geological map of the Imorona-Itsindro Suite intruding the Itremo Group.

Stop 12 & Stop 13

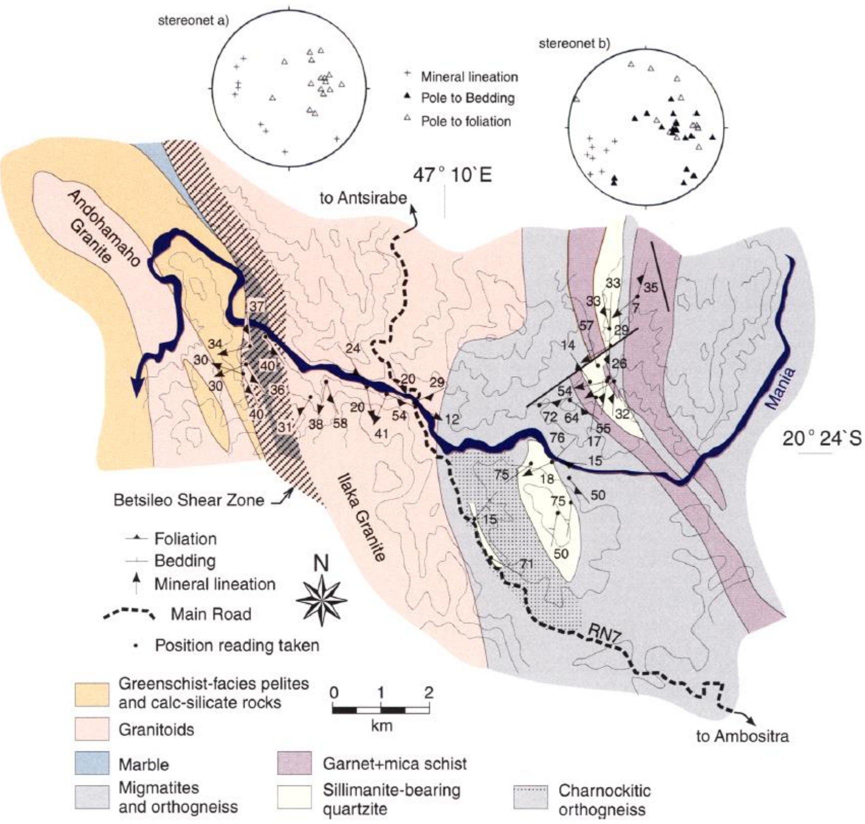
Mania River transect downstream of RN7 bridge. Start at Mania River bridge 20°23'30.0"S, 47° 09'42.0"E and head west to Andranomody Village 20°23'11.8"S, 47° 08'25.7"E

The beautiful K-spar porphyritic Ilaka Granite of the Imorona-Itsindro Suite gets progressively deformed by non-coaxial strain as we walk west along the river. Initial C' fabrics and sigma clasts around the microcline phenocrysts suggest top-to-NE sense of shear (thrust). See sketches below.

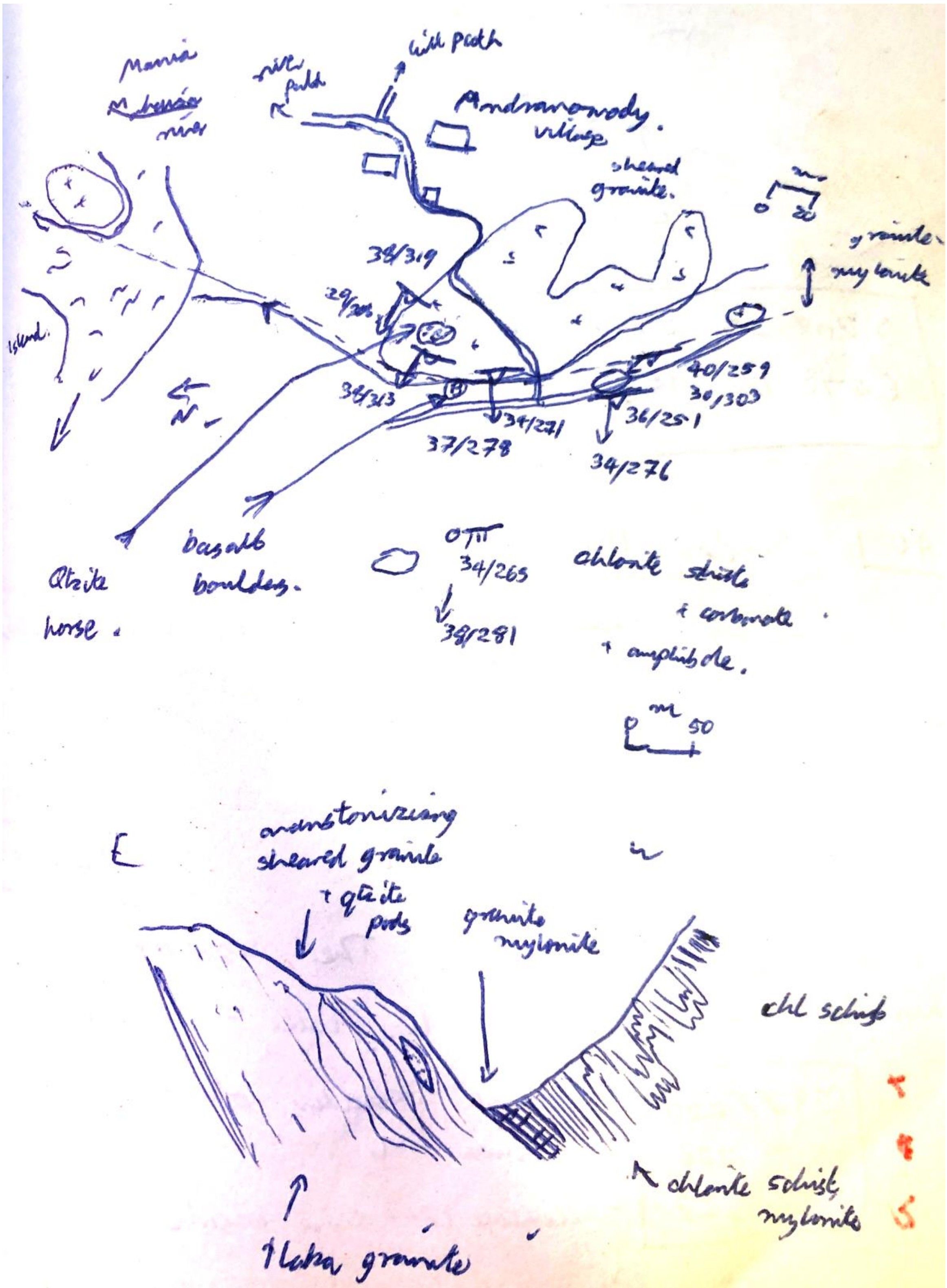


Higher strain C-S fabrics and highly attenuated sigma type fabrics developed in Ilaka granite mylonite near to the boundary with the greenschist-facies rocks of the Itremo Sub-domain suggest top-to-SW 'normal' shear sense of the Betsileo Shear Zone (Collins et al. 2000). See Below.

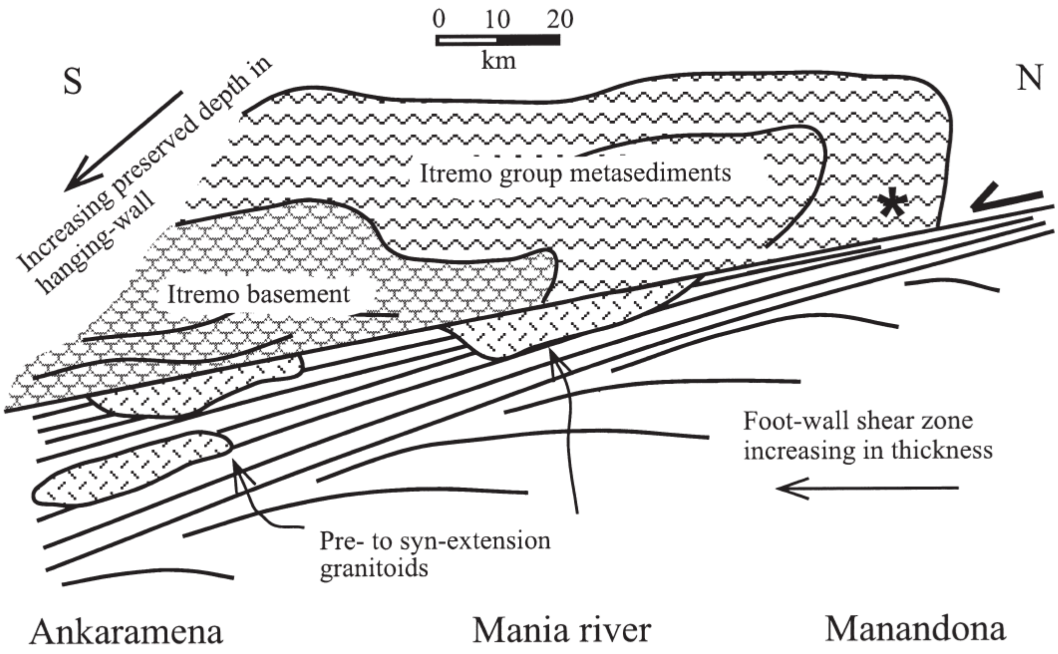
When mapped out the sillimanite-bearing quartzites of the Ambatolampy Group occur within 10km of the greenschist facies Itremo Group (see below). Archibald et al. (2015) suggested that these were equivalent (likely) Mesoproterozoic sedimentary packages. This supported the argument of Collins et al. (2000) that the Betsileo Shear Zone represented a major extensional detachment late in the Malagasy Orogeny that juxtaposed granulite/upper amphibolite grade rocks of the footwall with greenschist-facies rocks of the hangingwall.



Upper Mania River region with RN7 from Collins et al. (2003b). We aim to walk the section downstream of the RN7 bridge through the Ilaka Granite to the protomylonites and mylonites of the Betsileo Shear Zone (Collins et al. 2000). Note the Ambatolampy Group sillimanite-bearing quartzites in the footwall of the Betsileo Shear Zone and low-grade pelites of the Itremo Group in the hanging-wall.



Field map of Andranomody Village and boundary between the Ilaka Granite of the Antananarivo Domain and the greenschist-facies pelites of the Itremo Sub-domain along the Betsileo Shear Zone of Collins et al. (2000).

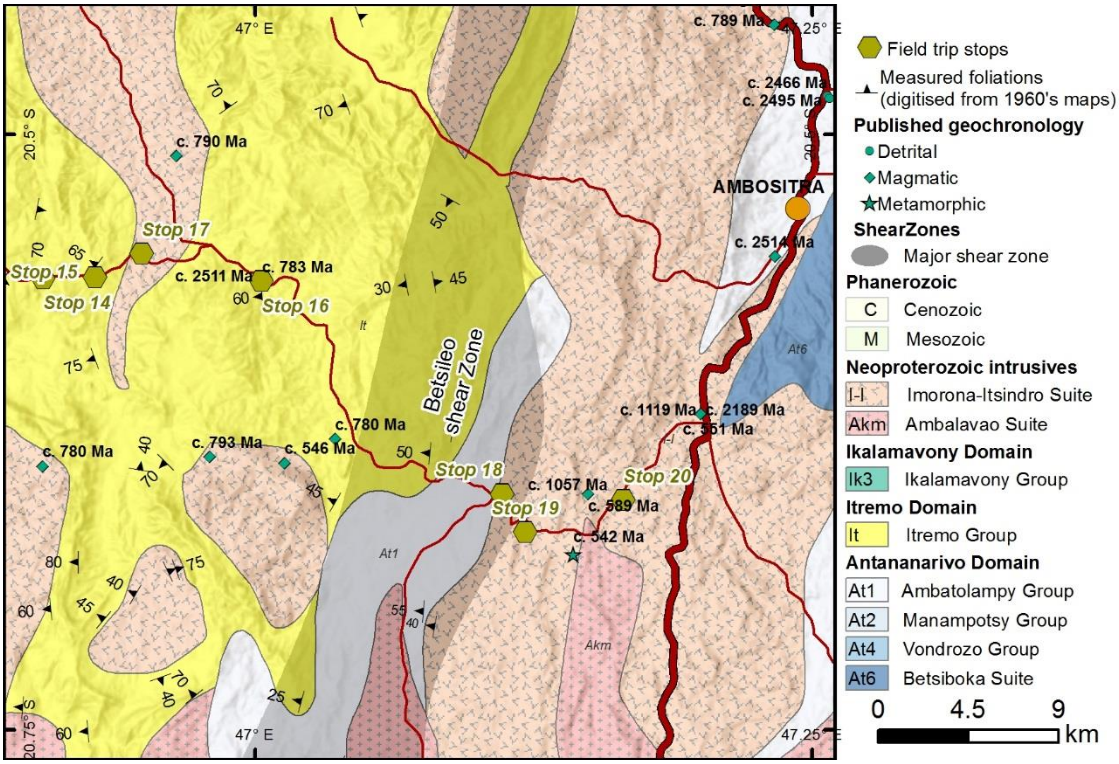


Cartoon of the Betsileo Shear Zone from Collins et al. (2000).

Field day 6: Friday June 28th – Ambositra to Ambositra

Accommodation: Grand Hotel, Ambositra

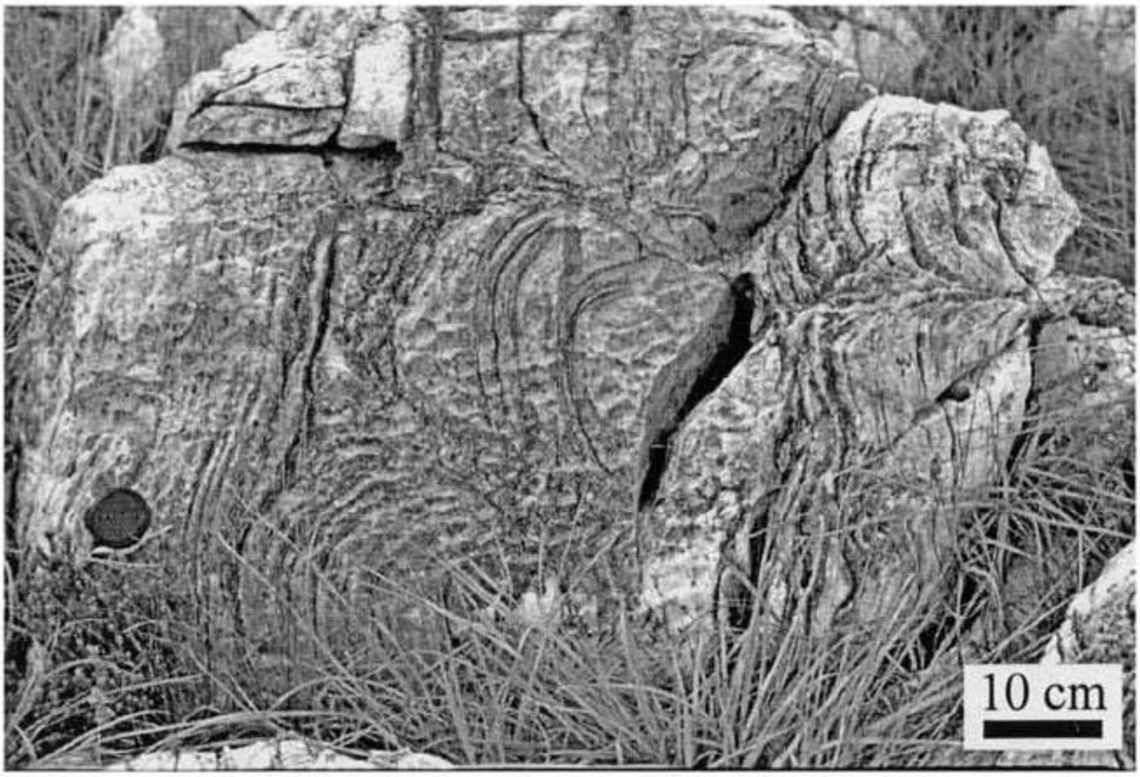
Aim: Look at parts of the Itremo Subdomain including the gabbros of the Imorona-Itsindro Suite



Stop 14

Antsahakely to Ambatofinadrahana road   20°33'37.1"S, 46° 54'16.7"E

Marbles of the Itremo Group, recrystallized and folded into upright folds. Elsewhere in the Itremo Subdomain strain and metamorphic grade are extremely low and good stromatolite structures are preserved in the carbonates. These carbonates preserve carbon isotope values consistent with late Palaeoproterozoic-Mesoproterozoic values ($\delta^{13}C$ between -1.4 and 1.2, Cox et al. 2004).



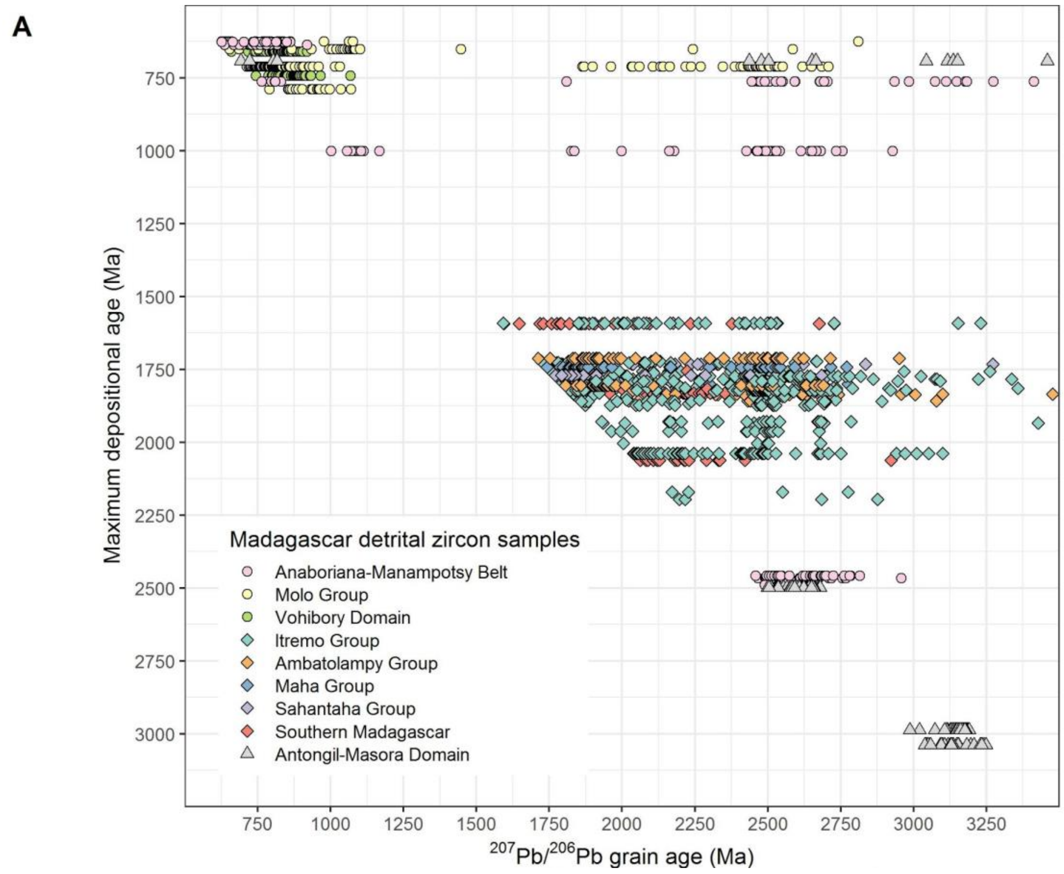
A stromatolite in less deformed correlatives of these Itremo Group carbonates. These exhibit simple, non-branching, Palaeoproterozoic-like forms (Cox et al. 2004).

Stop 15

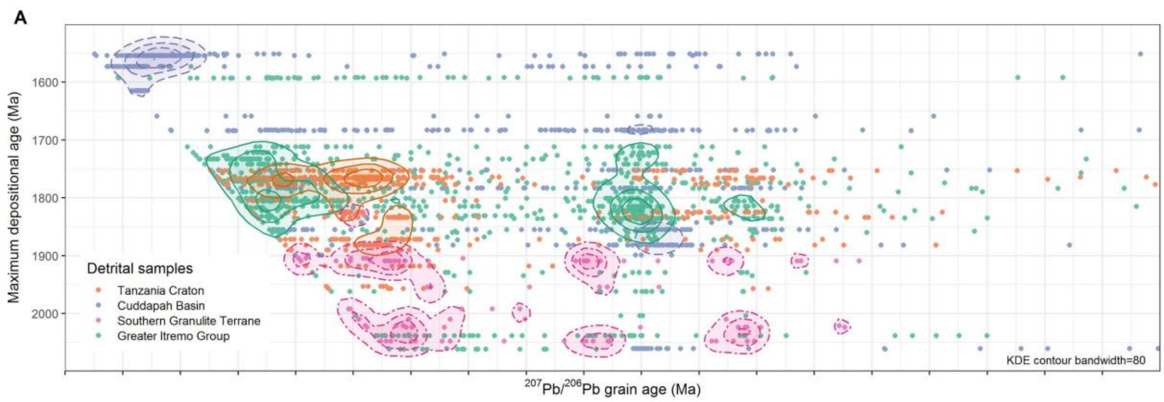
KM 47 from Ambositra 20°33'35.4"S, 46° 55'40.3"E

Siliciclastic sediments of the Itremo Group. Dark weathered foliated fine micaceous sandstone interbedded with dm-thick quartzites. Foliated and with mineral aggregate lineation.

These were the subject of an incredible map by Moine (1968), who delineated these metasedimentary units and mapped a series of metamorphic isograds through the Itremo Subdomain. Cox et al. (1998; 2004) and Fernandez & Scheurs (2003) specifically studied the sedimentology, isotopic geochemistry and detrital zircon chronology of the Itremo Group. Cox et al. (2004) demonstrated that the detritus ages are similar to the Muva Group in Zambia and postulated an earliest Mesoproterozoic link between central Madagascar and central Africa. De Waele et al. (2011) demonstrated that the Sahantaha Group of northern MAdagascar and the Maha Group of the central east coast are likely equivalents. Archibald et al. (2014) argued that the high-grade Ambatolampy Group of the Antananarivo Domain was also a correlative and Plavsa et al. (2014) argued that high-grade metasedimentary protoliths from the Madurai Block of India also correlate. Armistead et al. (in prep.) U-Pb zircon from the Itremo Group samples (as well as Hf isotopes), and from other putative corelatable groups (including sediments from the Purana Basins of India - the Cuddapah Basin - Collins et al. 2014). She demonstrated the similarities in age and isotopic composition of detrital zircons from a wide region of Madagascar, East Africa and southern India--and a contrast with coeval detritus from the Purana basins of India.



Comparison of detrital zircon samples from Madagascar, symbolised by Group/Region plotted as maximum depositional age vs. grain age (Armistead et al., in prep).



Detrital samples from the Tanzania Craton, Cuddapah Basin, Southern Granulite Terrane and greater Itremo Group plotted and contoured using KDE (bandwidth=80). Only data within 10% concordance is plotted (Armistead et al., in prep).

Stop 16

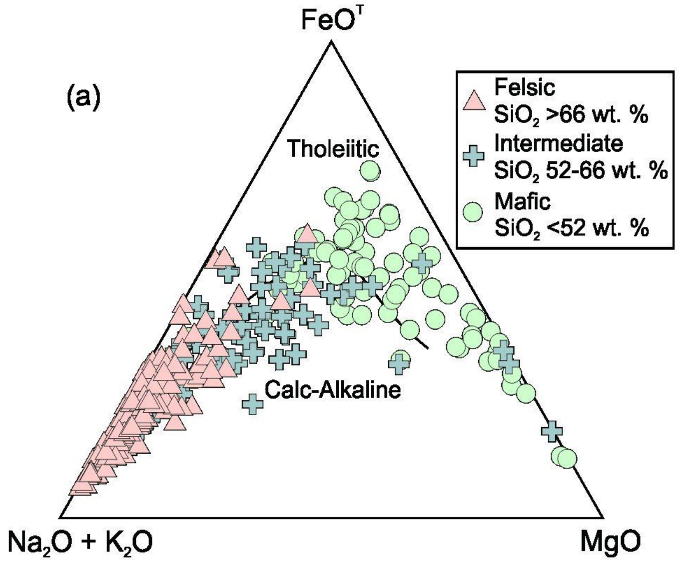
Andriana River, 5km W of Ambatomarina 20°33'41.9"S, 47° 00'09.2"E

Archaean tonalitic gneiss of the Betsiboka Suite--basement to the Itremo Group. Dated by Tucker et al. (1999) at 2511 +3/-2 Ma, with a lower intercept at 809 ± 30 Ma. This is intruded by a K-feldspar porphyritic granite that was dated by Archibald et al. (2016) at 822 ± 28 Ma. Gneiss has a strong foliation that grades into a linear fabric with boudinaged pegmatites, aligned parallel to the foliation.

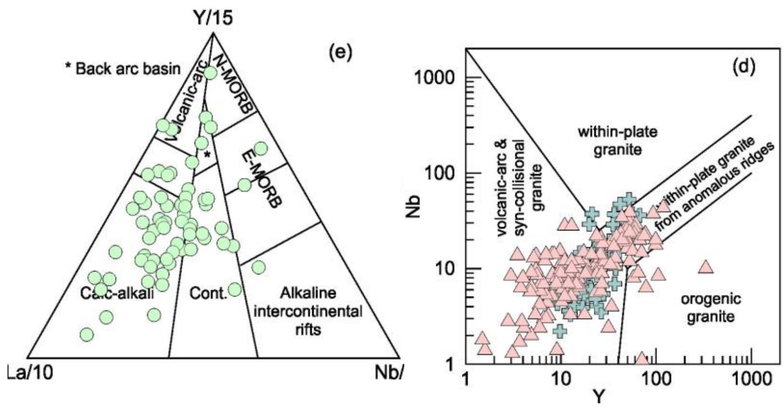
Stop 17

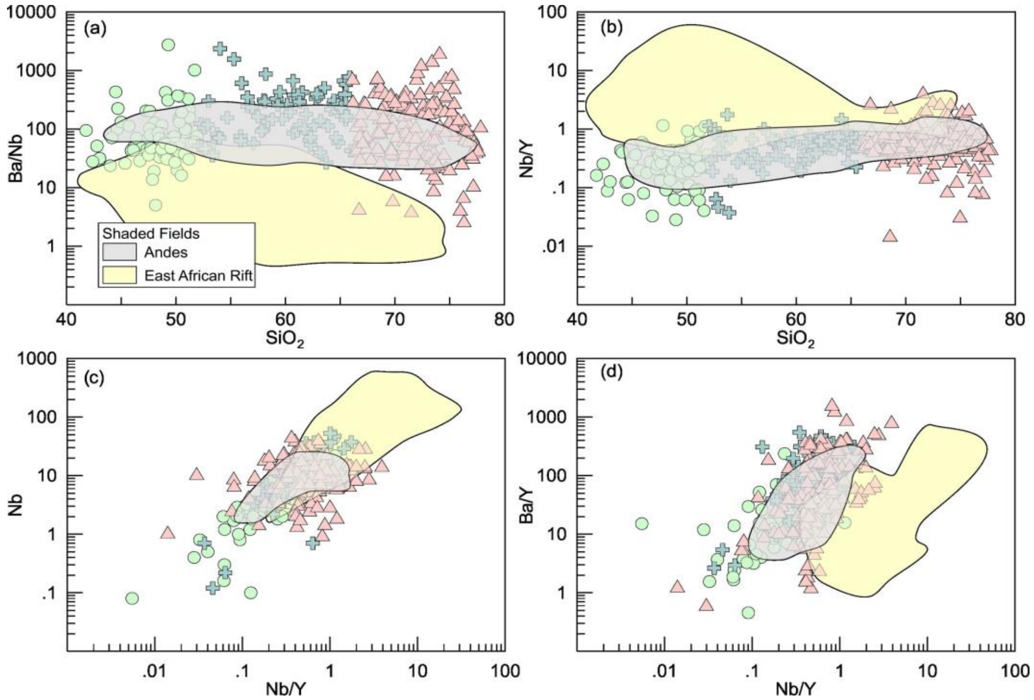
Ambatomainty Gabbro 20°33'00.0"S, 46° 56'56.5"E

This is similar to the Itsindro gabbro, the type mafic endmember of the Itsindro-Imorona suite, which has a 45 x 10km outcrop elongate in a N-S direction a few kms to the west. The suite extends across the whole calc-alkaline spectrum from mafic to felsic. The chemistry is strongly related to an arc as is the longevity (Handke et al. 1999; Archibald et al. 2017). Some researchers have suggested that the suite is more related to a plume-related rift model (Yang et al. 2014; Zhao et al. 2015), although the chemistry of the suite, when taken together, does not seem to support this.



Geochemistry of the Imorona-Itsindro Suite (Archibald et al. 2017).





Comparison of the Imorona Suite geochemistry with the Andes and the East African Rift.

Stop 18

Tsarafandry Quarry   20°39'3.50"S,   47° 6'39.00"E

Small quarry exposing quartzites, biotite psammites and muscovite schists folded into assymetric fold. Rosettes of sillimanite occur in the quartzite. The outcrop is cut by a pegmatite. This location is directly on the hanging wall of the Betsileo Shear Zone, which is poorly exposed in the valley to the east. The Ilaka Granite is exposed on the wooded hills to the east.

Stop 19

Girder Bridge 20°40'1.30"S, 47° 7'16.30"E

The boundary between the Itremo Subdomain (hangingwall) and the Antananarivo Domain (footwall). Relatively homogenous K-Feldspar porphyritic granites of the Ilaka Granite lie to the west of the creek. The top of the granite is marked with a weak C/S fabric in the granite with some stretching lineations developed. Directly overlying these is a sheared conglomerate with clasts of quartzite, vein quartz and biotite tonalite. These are sheared into top-to-SW shear indicators. Pegmatites also cut the boundary. Overlying these are sheared quartzites of the Itremo Group.

Boundary between Ilaka Granite and overlying Itremo Group metasedimentary rocks.

Stop 20

Ilaka River 20°39'13.1"S, 47° 9'54.7"E

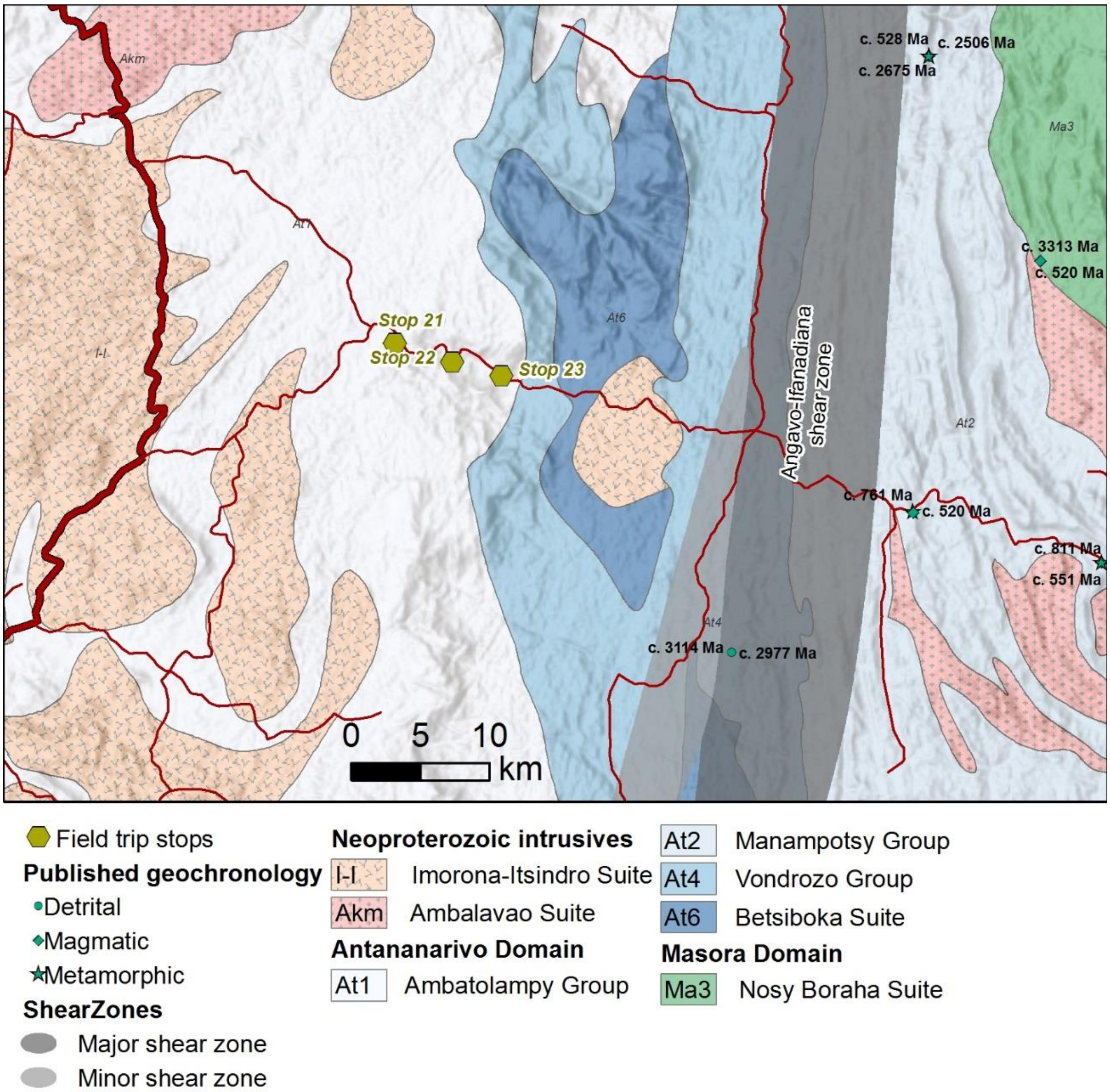
C-S fabric developed in highly strained granitic mylonite. Mafic pods within the granite are sheared into top-to-the-SW shear indicators.

Field day 7: Saturday June 29th – Ambositra to Ambalavao

Driving time: 205 km; 4 h 21 min

Accommodation: Aux Bougainvilliers, Ambalavao

Aim: Examine outcrops along and down the Ranomafana escarpment



Stop 21

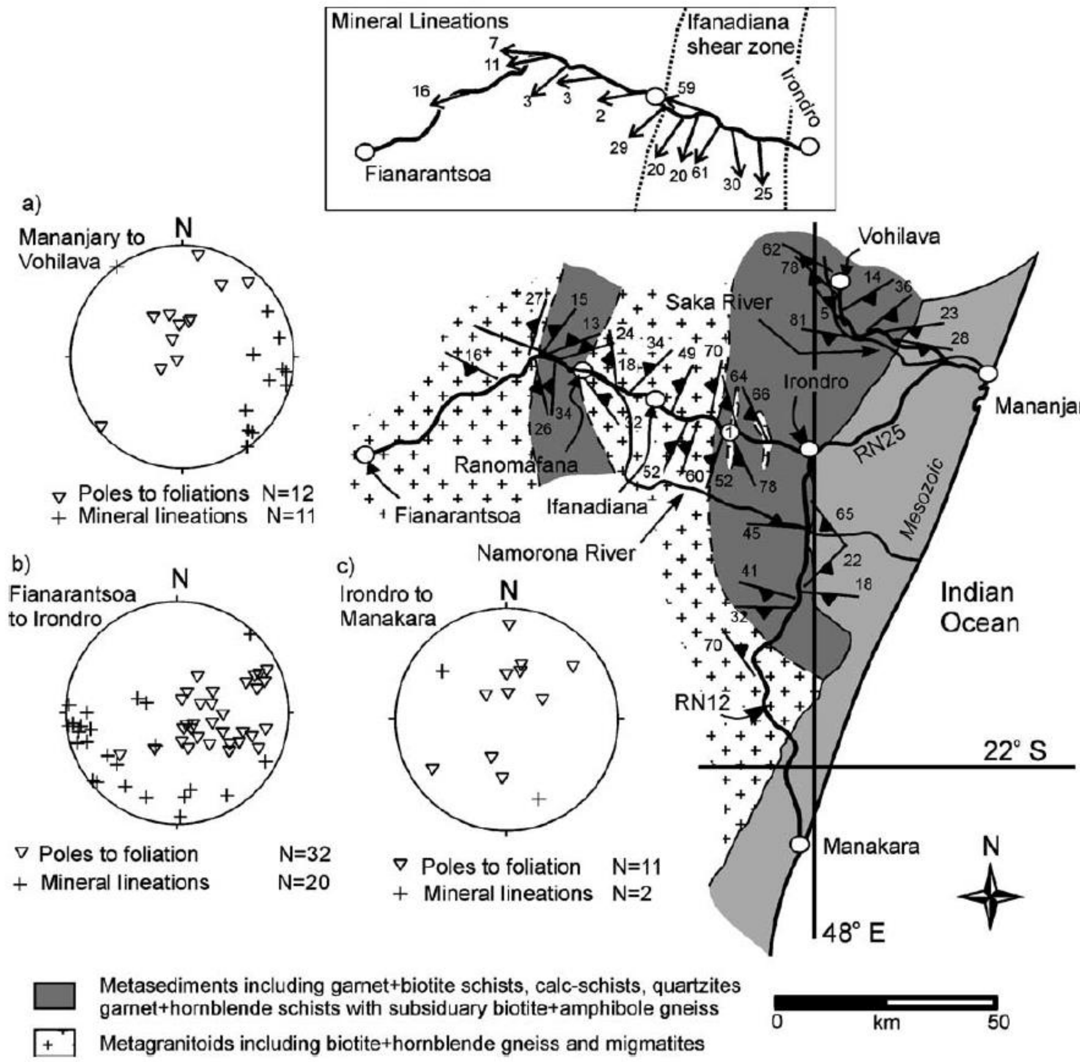
Top of Namorona River waterfall 21°14'44.4"S, 47°23'50.4"E

Well foliated and lineated garnet bearing amphibole and biotite gneiss. Garnet-bearing leucosomes concordant with foliation as well 10m-wide granite sills.

Stop 22

Jirama Dam, Namorona River 21°15'25.3"S, 47°26'04.5"E

Well foliated biotite+amphibole gneiss with many leucosomes. Strain suggests top-to-the-NE shear zonse. Calc-silicate horizons occur interlayered with the felsic gneisses, consisting of diopside, phlogopite, grossular and calcite with possible scapolite. The diopside+phlogopite layers form boudins. These rocks are undated, but may be either part of the probably Mesoproterozoic Ambatolampy Group or Neoproterozoic Manampotsy Group. Similar calc-silicate-bearing rocks ~35km east (and east of the Ifanadiana Shear Zone) have yielded Tonian detrital zircons (Collins et al. 2003c).



Structure along Fianarantsoa to Mananjary section (Collins et al. 2003b).

Stop 23

Ranomafana Quarry 21°15'54,7"S, 47°27'59.5"E

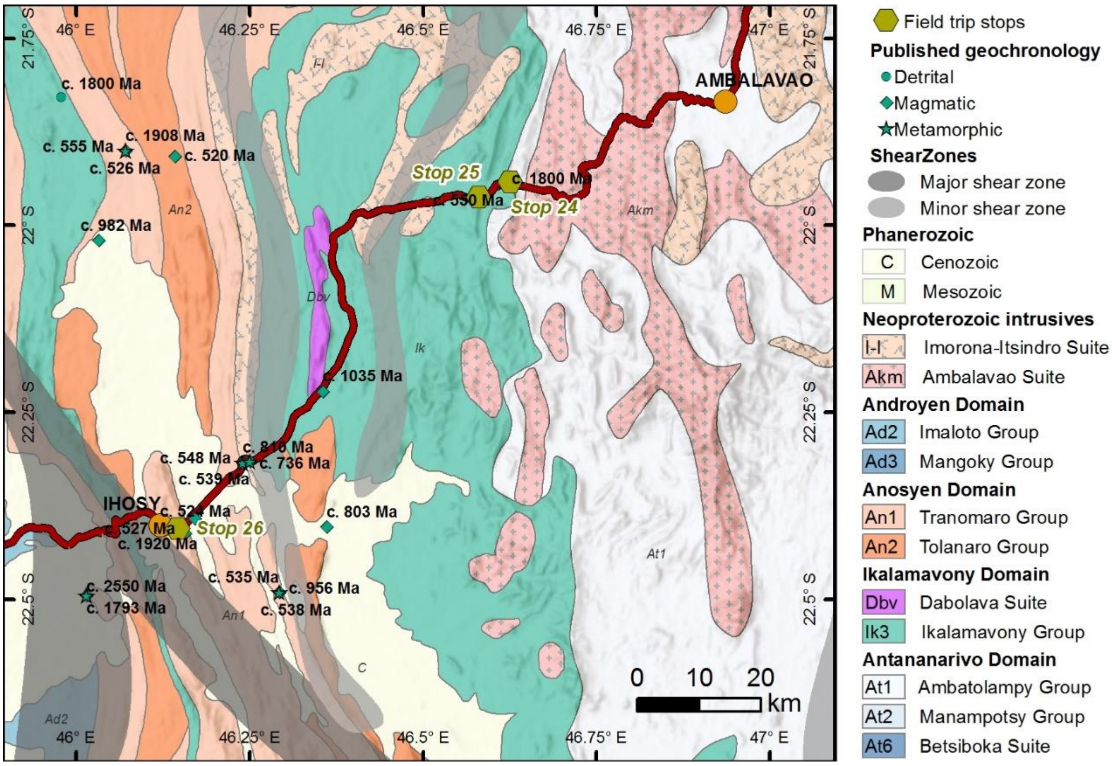
Migmatitic gneiss with mafic restite pods in felsic leucosome complexly deformed but with broadly aligned fold hinges suggesting coaxial deformation during partial melt generation.

Field day 8: Sunday June 30th – Ambalavao to Ihosy

Driving time: 137 km; 1 h 50 min

Accommodation: Tamana Hotell, Ihosy

Aim: Examine Betsileo shear zone, Ikalamavony Domain and Anosyen Domains



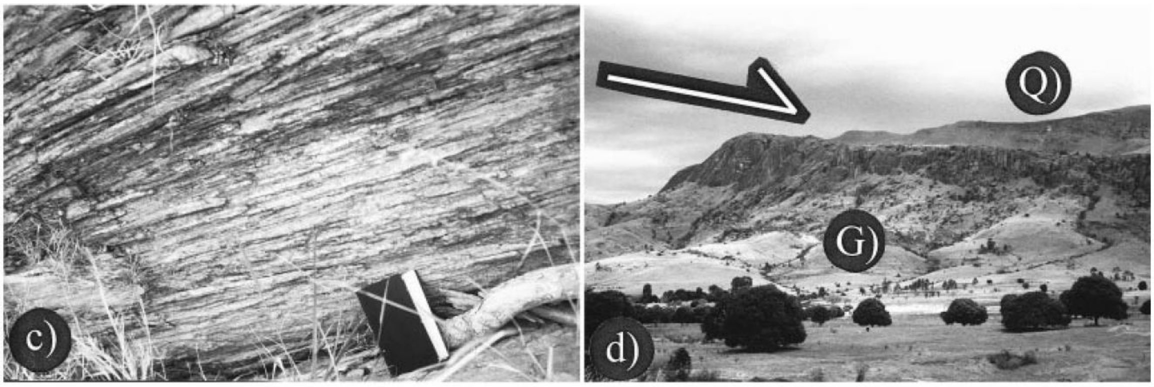
Geological map of the southern extent of the Ikalamavony Domain in contact with the Anosyen Domain.

Visit the Anja Community Reserve for spectacular scenery and lemurs

Stop 24

Ankaramena, Zamondoa River 21°56'31.8"S, 46°37'36.3"E

View north over the boundary between sheared granites of the Antananarivo Domain (east and below), becoming progressively more mylonitized up section to the Betsileo Shear Zone contact with the Itremo Subdomain and structurally overlying quartzites.

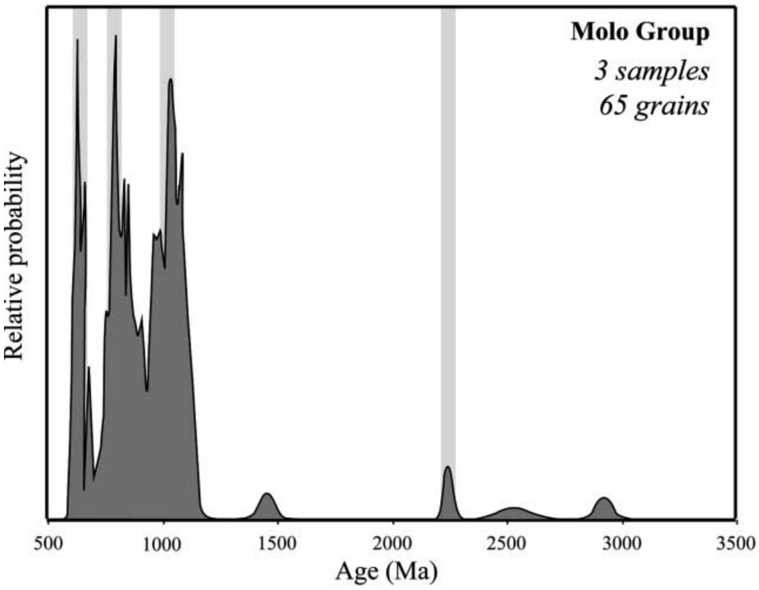


Highly strained quartzites at the base of the Itremo Subgroup and the contact, both from Ankaramena (Collins et al. 2000).

Stop 25

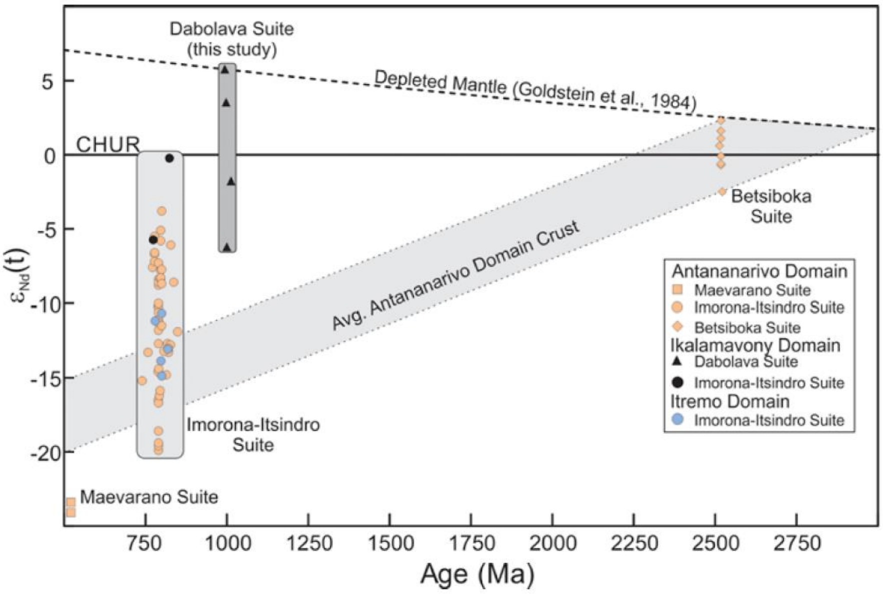
Mafaitra Quarry 21°57'46.2"S, 46°34'52.0"E

Fine-medium grained psammitic gneisses of the Ikalamavony Domain with hornblende-bearing leucosomes crosscutting the intense fabric. Detrital zircons from a sample of the psammite here was dated and included within the Cryogenian/Ediacaran Molo Group of Cox et al. (2004) as it contained many Neoproterozoic zircons. These are interlayered with diopside+titanite+plag+qtz calc silicate rocks. Between these outcrops are highly deformed conglomerates with clasts of granite and quartzite.



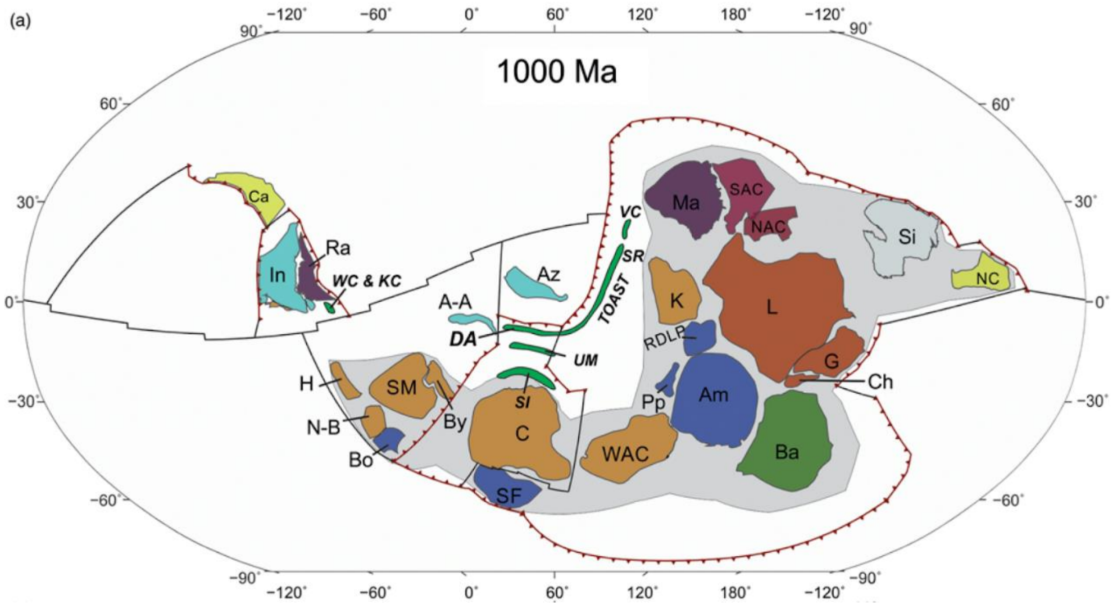
U-Pb zircon data from Cox et al. (2004). Maximum depositional age interpreted to be 654 ± 5 Ma.

The Ikalamavony Domain is unusual in Madagascar in that it appears to have no pre-Mesoproterozoic basement, but is made of a ca. 1080-980 Ma suite of gabbros to granitoids called the Dabolava Suite, that crop out in the north of the domain (Tucker et al. 2014; Archibald et al. 2017) and Mesoproterozoic to Tonian metasedimentary and metavolcanic rocks known as the Ikalamavony Group (Roig et al. 2012).



Neodymium isotopes of the Dabolava Suite in comparison to the Neoarchean Betsiboka and Tonian Imorona-Itsindro, and Ediacaran/Cambrian Ambalavao/Maevarano Suites (Archibald et al. 2017).

Archibald et al. (2017) suggested that the Ikalamavony Domain is a part of an extensive island arc system in the Mozambique Ocean that includes the TOAST terrane in Antarctica (Jacobs et al. 2015; Elburg et al. 2015).



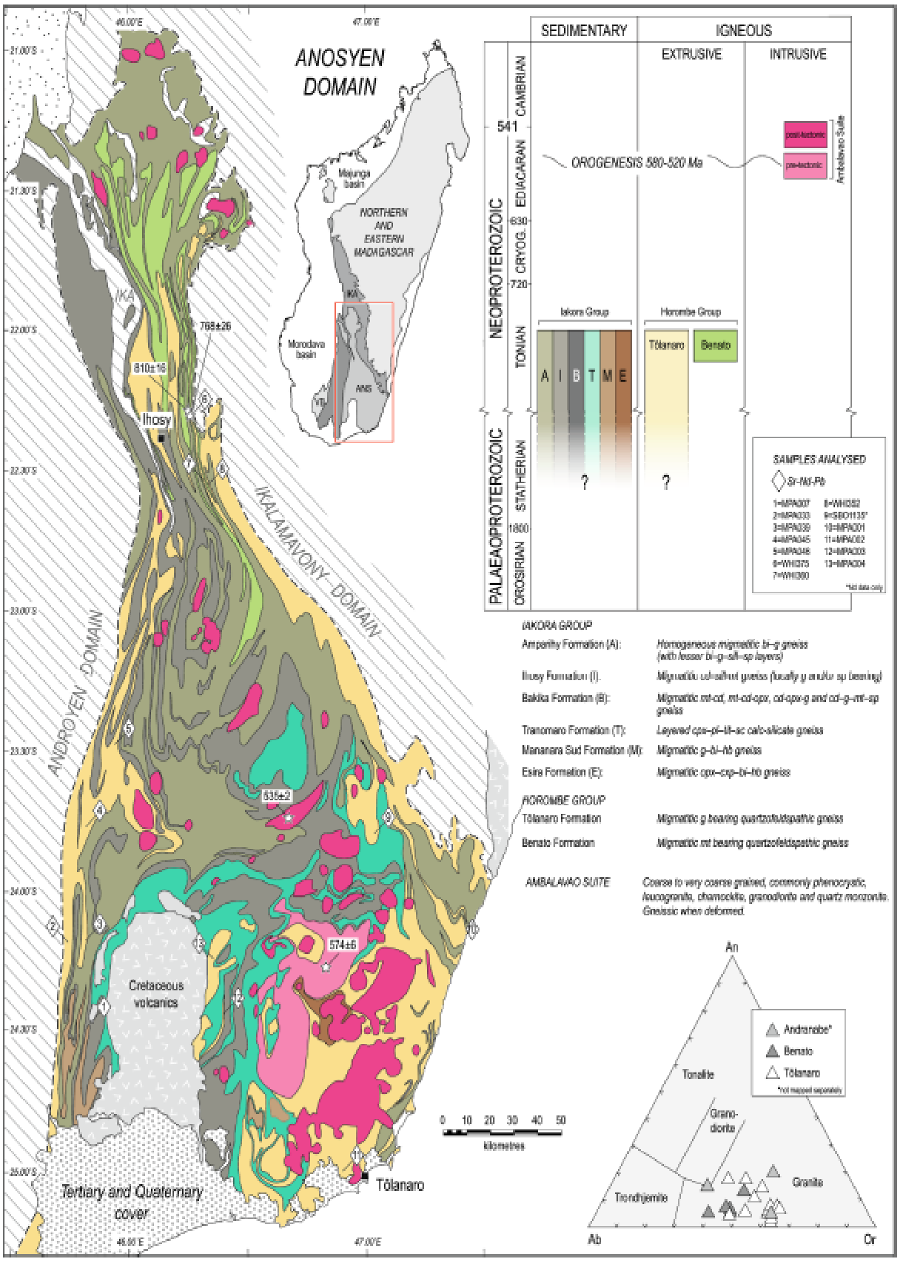
Suggested location of the Ikalamavony Domain (DA), connected to TOAST and possibly the Vijayan Complex of Sri Lanka (VC) (Archibald et al. 2017).

Stop 26

Ihosy Quarry 22° 24' 18.3''S, 46° 8' 47.8”E

Foliated cordierite+sillimanite paragneiss of the Ihosy Formation. The main rock is a blue pelitic gneiss with qtz+plag+K-spar+bio+cordierite+sill+Fe-Ti oxides+garnet+spinel. Kornerupine, sapphirine and grandidierite have been reported here (Nicollet 1990). Abundant coarse grained leucosomes were generated by dehydration melting and are cordierite bearing.

Kröner et al. (1996) obtained Pb evaporation ages of ca. 720 and 1855 Ma that were interpreted as detrital. This would suggest that these protoliths were part of the Molo Group. However, Tang et al. (in press) report detrital zircon U-Pb ages between 2030 and 1784 Ma, which are more consistent with the Ioraka Group of the Anoysen Domain (Boger et al. 2014) and similar to the Itremo Group detritus. Metamorphic zircons from leucosomes and restites yield ages of ca. 550 Ma and a U-Pb monazite age also has been reported at 561 ± 12 Ma (Andriamarofahatra 1989, quoted in Nicollet 1990). These rocks have been correlated with the Anyosen Domain of southern Madagascar (Roig et al. 2012; Boger et al. 2014). Tang et al. (in press) argues that the peak metamorphic conditions achieved here are ~ 7.7-6.9 kbar and 960-850 °C and experienced a clockwise metamorphic path. Unlike domains further southwest (Androyen and Vohibory), the Anyosen Domain does not preserve evidence for high-grade metamorphism at ca. 650 Ma (Jöns and Schenk 2008; Boger et al. 2014).



The Anosyen Domain after Boger et al. (2019)

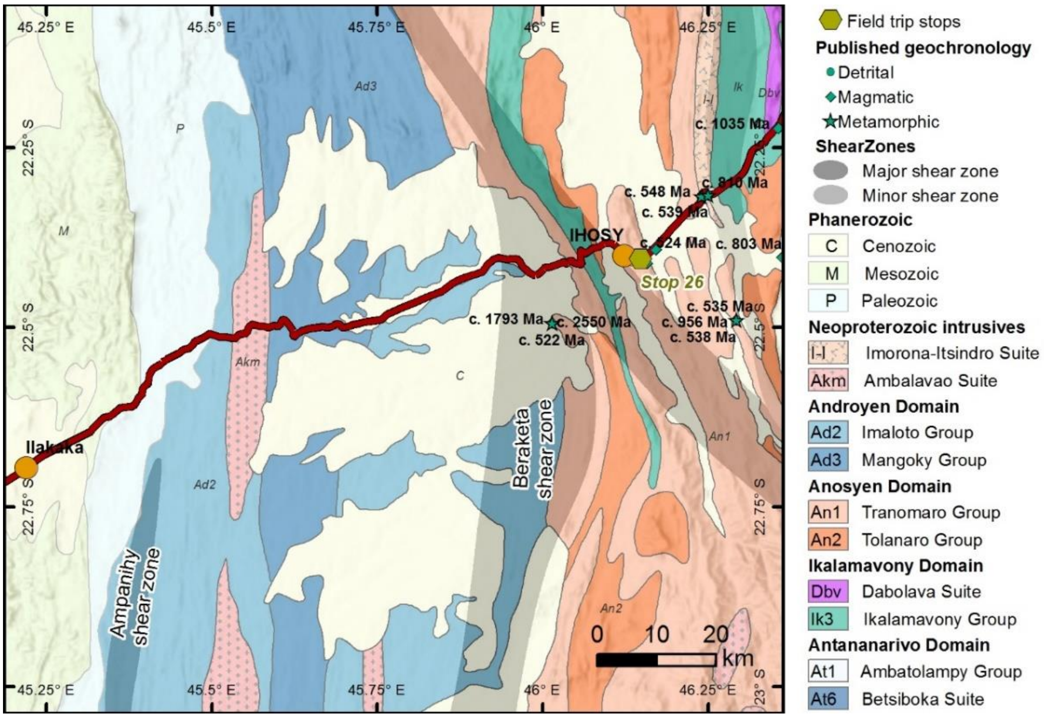
Field trip day 9: Monday July 1st – Ihosy to Ifaty

Driving time: 353 km; 5 h 12 min

Accommodation: La Mira Madioriano, Ifaty

Aim: Drive to Ifaty via Ilakaka

Stop at Ilakaka to explore sapphire mines and gems at Color Line



Geological map of the Mesozoic Morondava Basin, Androyen Domain and Anosyen Domain.

Tuesday July 2nd – day off

Accommodation: La Mira Madioriano, Ifaty

Wednesday + Thursday July 3-4 – conference

Accommodation: La Mira Madioriano, Ifaty

Friday + Saturday July 5-6 Drive back to Tana with a night in Fianarantsoa

Accommodation 5th: Mahamanina Hotel, Fianarantsoa

Accommodation 6th: Tana Jacaranda, Antananarivo

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