

## Precambrian crustal architecture of Malawi: a keystone in SE Africa<sup>☆</sup>

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### ABSTRACT

The results of a major geological mapping project in Malawi have produced a new model of the Precambrian structural architecture of this small country, with major implications for the whole of central-eastern Africa. In the north, the oldest rocks of the Palaeoproterozoic Ubendian Domain (c. 2150–1950 Ma), the traditional division into the Mbozi, Ufipa and Nyika “terranes” (here termed “subdomains - SD”) is confirmed, but with one important proviso. Geophysical data indicate that the Nyika SD extends westwards without break into the “Bangweulu Block” in northern Zambia, suggesting that they are one and the same and the name “Bangweulu-Nyika block” (BaNy) is proposed for the combined entity. The extended Nyika SD is considered to be the central zone of the orogen, with the other two being the steeply dipping root zones of nappes that were transported NE over the Tanzanian Craton during the Ubendian collision phase. The Ubendian Domain returns Neoproterozoic Nd model ages. It is unconformably overlain by the low-grade Mafingi Group metasedimentary rocks, seen as equivalents of parts of the Muva Supergroup in Zambia.

The Irumide Domain in central Malawi is separated into the Mzimba, Kasungu and Mchinji subdomains. They are characterized by Nd model ages between 1.5 and 2.7 Ga, no Ubendian magmatism, voluminous collision-related granitoid magmatism between 1070 and 1030 Ma and medium to high-grade metamorphism. The South Irumide Domain in southern Malawi is subdivided into the Lilongwe, Unango and Nampula subdomains, characterized by Nd model ages between 1.1 and 1.5 Ga, indicating generation in a juvenile island arc geodynamic setting with little evidence of older crustal involvement. The Irumide orogeny is marked by tectonic stacking at ~1070 Ma with polyphase reactivation at the end of the main collision at ~1020 Ma and overprinting during the Pan-African event at ~560 Ma. Structural younging of the Irumide thrust stack implies subduction of the South Irumide Domain to the north below the Irumide Domain, with the latter constituting an active continental margin SE of the Congo-BaNy craton. The main collision phase and prograde metamorphism between 1050 and 1020 Ma are interpreted as evidence of collision between the Congo-BaNy-Tanzania Craton (upper plate), and the subducting Proto-Kalahari Craton margin.

The three fundamental Proterozoic domains of Malawi were intruded by several polyphase Neoproterozoic (Tonian) alkaline igneous plutons (Nyassa Suite) between ~850 and 700 Ma, implying that the domains formed a contiguous block of continental crust in Rodinia at c. 1000 Ma. The Nyassa Suite represents a failed continental rift associated with Rodinia break-up between c. 700–640 Ma. To the west of Malawi, this event was manifested in a confined oceanic basin between the Kalahari and Congo cratons and represented by the Zambezi-Lufilian-Damara belts. This basin closed between 590 and 520 Ma resulting in the re-amalgamation of Congo and

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Kalahari during the later phases of the Pan-African orogeny and variable tectonic (shear zones), magmatic (Blantyre Suite) and metamorphic effects in Malawi increasing in intensity towards the south.

## 1. Introduction

The papers in the Special Issue of JAES on the Geology of Malawi cover the main aspects of the country's crustal evolution in SE Africa, based on the recently completed Geological Mapping and Mineral Assessment Project (GEMMAP; 2016 to 2022; [Appendix 1](#)), where the entire country was mapped at 1: 100,000 scale. Malawi may be a small country, but it occupies a central and critical position straddling important Precambrian blocks and mobile belts between the Archaean nuclei of the Congo, Tanzania, and Zimbabwe cratons, and bears critically on the subsequent evolution of the Kalahari Craton, the assembly and fragmentation of Rodinia and the growth of Gondwana. Before GEMMAP, the distribution of the major tectonic blocks in this part of Africa was projected as extrapolations of data from the surrounding countries (e.g. [Fritz et al., 2013](#)). Knowledge of Malawi itself was largely based on the most recent countrywide mapping conducted by the British Geological Survey (BGS) between the 1950s and 1970s (e.g. [Bloomfield, 1966, 1968](#)). In these surveys the older crystalline rocks of Malawi were referred to as the singular "Malawi Basement Complex", but little was known about the ranges of ages of the component rocks.

Over subsequent decades, with the advent in particular of detailed geochronology, the Precambrian crustal components of the countries surrounding Malawi became elucidated and compiled, for example, in review papers such as [Fritz et al. \(2013\)](#) and references therein). The crustal blocks extrapolated into Malawi comprise the Paleoproterozoic Bangweulu-Ubendian-Usagaran system in the north, the Mesoproterozoic Irumide Belt in central Malawi and the South(ern) Irumide Belt in the south. This complex early to mid-Proterozoic crustal collage was variably, but locally intensely, re-worked during the often cryptic Neoproterozoic to lower Palaeozoic ("Pan-African") orogeny. In the literature, the latter includes the older (~600 Ma), generally N-S oriented East African Orogeny and the younger E-W oriented Kuunga Orogeny ([Meert, 2003](#)).

In view of this lack of direct knowledge of the crustal architecture of Malawi, GEMMAP faced the problem of the precise location, geometry and nature of the boundaries between the constituent blocks, along with any internal subdivisions. Apart from a few individual studies very little was known about the overall metamorphic and structural histories of the Malawi crustal blocks, nor the distribution, age and compositions of the various igneous suites present.

Consequently, GEMMAP aimed to fill the knowledge gap in Malawi through an extensive field mapping and sampling program, interpretation of a new high-resolution airborne geophysical survey, analysis of

remote sensing data, traditional petrographic studies, and modern laboratory analytical methods (major and trace element whole-rock geochemistry, U-Pb zircon dating, radiogenic isotope analysis, microprobe analyses etc., as outlined in [Table 1](#)).

In this overview we present the main findings of the geological mapping module of GEMMAP which resulted in revised geological maps at 1:100K, 1: 250K and 1:1 million scales. In addition, geochronological data are presented on critical samples taken from the boundaries between major crustal blocks in order to determine the precise timing of the structures seen. Approximately 100 Sm-Nd radiogenic isotope data are presented on samples from the major intrusive rock units, which are critical in defining the major geological domains. The GEMMAP results indicate that the basement rocks represent a highly complex and intricate system of older crustal blocks, younger accretionary tectonic entities, a long and complex magmatic history, and later polyphase rejuvenation. In a reverse of the former paradigm, the crustal architecture of Malawi can be extended back into the neighbouring countries, providing a significant contribution to the geological evolution of the wider southeast African area. It is evident that GEMMAP generated a significant amount of data, presented through numerous maps (at the three scales mentioned earlier), sheet explanations, and thematic memoirs. The details are too many to mention in this paper, but the entire dataset is accessible through the Geological Survey Department and listed in [Appendix 1](#).

## 2. Major crustal blocks in Malawi

### 2.1. Definitions

Before discussing the crustal entities identified in Malawi, it is important to define the nomenclatural scheme employed for the various lithostratigraphic and lithodemic units. The highest-level term used is **Domain**, which refers to the rocks of the three main Precambrian crustal blocks that make up the Malawi basement. These are the Palaeoproterozoic **Ubendian Domain (UBD)** in the north, the Mesoproterozoic **Irumide Domain (IRD)** in the centre, and the Mesoproterozoic **South Irumide Domain (SID)** in the south. The non-genetic term "Domain" is preferred over other terms of similar rank, such as "Orogen", "Belt", "Complex" or "Province". Each domain is bounded by tectonic contacts and subdivided into two or more tectonically-bounded **Subdomains** ("SD" for short) These SD share the main definition of the over-arching domain, including age and origin, but may differ significantly in term of lithology, composition, structure, metamorphism,

**Table 1**

Main activities, analytical methods employed and products of the geological mapping module of GEMMAP.

Phase	Module	Activity	Amount	
<b>Main Phase (2017–2020)</b>	Field Mapping	7 main campaigns of 5–7 weeks each, by 4–5 teams	About 95 % coverage of the land surface c. 9500 field observation points c. 2850 samples c. 1200 thin sections	
	Analytical Program	Petrography U-Pb zircon isotope analysis Whole rock Sm-Nd isotope analysis Whole rock geochemistry (ME, TE, REE) Ar-Ar muscovite isotope analysis P/T studies Palynology (Karoo age rocks)	165 samples 101 samples 638 samples 2 samples 10 studies 40 samples	
<b>Final phase (2020–2021)</b>	Production of geological maps and sheet explanations	Scale	geological	structural
		1:100k	40	none
		1:250k	10	10
		1:1M	1	1

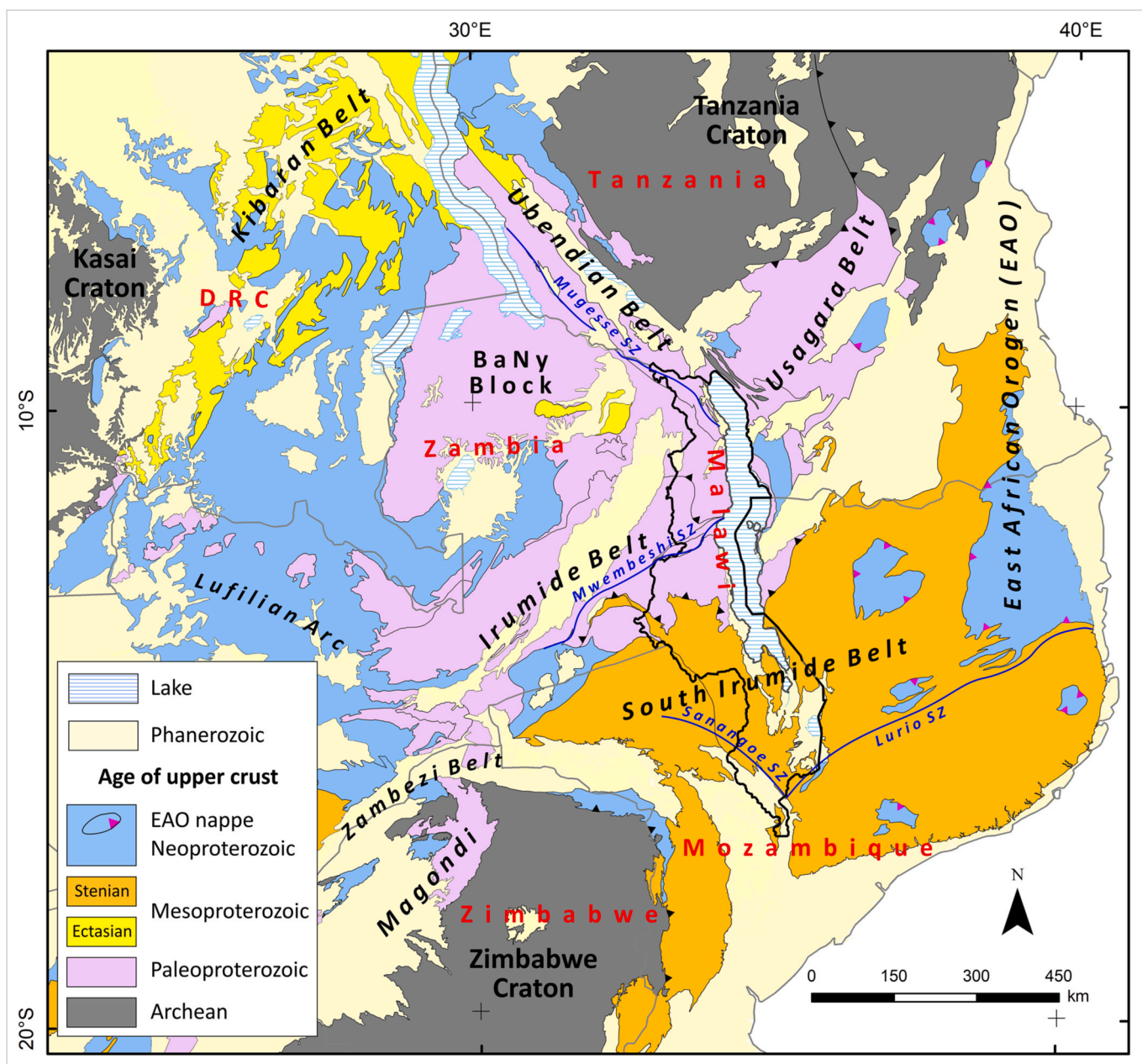


Fig. 1. Precambrian geology of SE Africa illustrating the crustal formation ages and the main structural entities (modified from Fritz et al., 2013 and integrating results of GEMMAP).

timing and intrusive history. The term SD is considered to be more geologically neutral than other genetic terms, such as “Terrane”. The lower-level lithostratigraphic rock packages in the SDs are subdivided into lithodemic **Groups**, **Subgroups**, **Formations** and **Members** based on their observed lithological characteristics, which are spatially defined by their geophysical characteristics. The plutonic rocks of various ages and origins are typically grouped into **Suites**.

## 2.2. Gross crustal protolith composition of SE Africa

Fig. 1 shows the major Proterozoic crustal blocks and belts of central and south-eastern Africa according to their published protolith ages. The map integrates previous work from numerous sources, combined into the BRGM map of Africa and summarised in Fritz et al. (2013); it also takes into account the new GEMMAP data from Malawi. The map shows that Malawi comprises crustal entities with just two protolith ages,

Palaeo- and Mesoproterozoic. The north is underlain by Palaeoproterozoic rocks (~2.1–1.9 Ga) rocks of the Ubendian Domain, with little or no Mesoproterozoic reworking. South of this lies the Irumide Domain with Ubendian protolith ages, but with extensive high-grade Mesoproterozoic reworking in line with the general concept of De Waele et al. (2006a-b) in Zambia.

The southern half of the country is made up of the SID which is characterised by juvenile Mesoproterozoic crust (1.1 Ga), as reported in SE Zambia (Johnson et al., 2004). Fig. 1 does not indicate zones of later Neoproterozoic (“Pan-African”) reworking (no new crust generation) which is variable, but locally intense throughout the area, especially in the south. This event will be discussed specifically for Malawi in later sections of this paper.



**Table 2**

Summary of geological data characterising the Precambrian domains, subdomains and Pan-African structures in Malawi from GEMMAP data and (1) Karmakar and Schenk (2016), (2) Sakuwaha and Tsunogae (2024). The geodynamic setting of the orthogneisses is based on classifications by Debon and Le Fort (1983, 1988), Frost et al. (2001), Pearce (1996), and Streckeisen and Le Maitre (1979).

Domain	Subdomain/ Structure	Surface [km <sup>2</sup> ]	Key lithologies	Sm-Nd Tdm [Ga]*	Magmatism				Metamorphism					Tectonic style					
					Ubendian	Irumide	Tonian	PanAf	P [kb]	T [C°]	Facies	Ubendian	Irumide	PanAf	Planar	Linear	Kinematics	Interpretation	Age(s)
<b>Pan-African Shear Zones</b>	Mugesse	131	bt-chl schist, mylonite						5–7	350–475	MP grs		1054–1056	526–596	moderate- steep, NW- SE trend	shallow NW-SE	sinistral	shear zone	Ubendian + PanAf
	Nthalire	125	bt-chl-gt schist, mylonite								grs/ amp		989–1034	500–510 (?)	steep, conjugate N, NNE trend			shear zone	Tonian (?) + PanAf
	Mwembeshi	2528	st-gt-ms schist, mylonite						6.5–9	570–620	MP amp		1047–1051	563 ± 17	moderate- steep, NE- SW trend	shallow NE-SW	dextral	shear zone	PanAf
	Ntcheu	?	sil-bt-gt mylonite								amp			575–586	moderate NE-dip	down- dip	reverse/ normal	shear zone	
	Sânangoè SZ	?	mylonite										>1008	550–571	steep SW- dip			shear zone	Irumide (?) + PanAf
<b>South Irumide</b>	Lurio Lilongwe	? 18309	ky-ga-bt schist, (ky)-gr schist, marble, aegirine- leucogneiss	1.14–1.55 (11)		1039–1079 (IAG, COL)	767–773		9–10.5	620–692	MP amp		? >1045 ± 13	474–504 527–592	shallow, unoriented	shallow, NNW- SSE		shear zone nappe	Irumide + variable PanAf
	Unango	34445	2 px granulite, leucogneiss, marble, gt-bt gneiss	1.13–1.61 (8)		1022–1084 (IAG, COL)	771–789	499–586 (alkaline)	9–11	840–930	MP gra		1028 ± 15	515–565	moderate- steep, N-S to NNW- SSE trend			metamorphic dome	Irumide + PanAf
	Nampula	1147	marble, 2 px granulite	0.98–2.24 (10)		1007–1065 (IAG, COL)	667–718	472–704 (alkaline)	6–9	750–800	amp/ gra		>1030 ± 13	494–548	moderate- steep, WSW-ENE trend	various		microterranne	
	Nampula- Ocuca	?	metagabbro						16–18	880–930	HP gra/ ecl			557 ± 16					
<b>Irumide</b>	Mzimba	3985	sp-gt-sil-bt gneiss	1.95–3.18 (8)	1989–2001 (CAG, COL)	1019–1086 (CAG, COL)	not dated		8 6–9 (2)	950 (900–1000 (2))	MP amp/ gra		1035–1040		shallow- moderate, NNW- N-S trend	shallow, NNW- SSE	NE- directed	nappe, metamorphic dome ?	Irumide, minor PanAf
	Kasungu	15785	gt-bt-sil gneiss, amphibolite, sil-quartzite	1.45–2.73 (15)		1037–1152 (CAG, COL)	Kasungu IC (not dated)		6–8	660–670	MP amp/ gra		>1037?		shallow, unoriented	shallow, NNW- SSE	NE- directed	nappe	
	Mchinji	793	sp-px-crd-gt- sil-bt gneiss, ferruginous gneiss, BIF, quartzite	2.01–2.65 (2)		1042–1054 (CAG, COL)			5–7 (1)	800–950 (1)	MP gra		>1053 ± 4	500–556	moderate- steep			metamorphic dome ?	
<b>Ubendian</b>	Mbozi	732	amphibolite	1.81–2.76 (12)	back arc							HP amp/ gra	1974–1985	500–596	moderate- steep/NW- SE trend	shallow NW-SE		microterranne	Ubendian + PanAf
	Ufipa	4646	sil-bt gneiss		1975–2147 (CAG, COL)	1400, 1137–1151 (rift?)	728–734		13–14	730–840	HP gra/ ecl	1951–1964		moderate- steep/NW- SE trend	shallow NW-SE			microterranne	

(continued on next page)

Table 2 (continued)

Domain	Subdomain/ Structure	Surface [km <sup>2</sup> ]	Key lithologies	Sm-Nd T <sub>DM</sub> [Ga]*	Magmatism			Metamorphism			Tectonic style				
					Ubendian	Tonian	PanAf	P [Kb]	T [C°]	Facies	Ubendian	Irumide	PanAf	Planar	Linear
	Nyika	12375	gt-sil-crd gneiss		1987-2162 (CAG, COL)	860-969	6	770-780	MP amp/ gra	1977-1984		steep, weak E-W trend	steep down dip	pop-down?	Ubendian
			<b>Minerals:</b> bt = biotite chl = chlorite crd = cordierite gr = graphite gt = garnet * felsic rocks, (number of analyses)		<b>Magmatism:</b> CAG = continental arc granitoids IAG = island arc granitoids COL = collision-related magmatism				<b>Metamorphism:</b> amp = amphibolite facies ecl = eclogite facies gra = granulite facies grs = greenschist facies			MP = medium pressure HP = high pressure			

### 2.3. Distribution and constitution of the major tectonostratigraphic units in Malawi

GEMMAP delineated the precise spatial distribution of the three major tectonostratigraphic crustal entities (Fig. 1). Fig. 2 shows that each of the tectonic domains are further subdivided into three sub-domains. The map also shows the distribution of the major Pan-African shear zones, which locally form the inter-domain/subdomain tectonic boundaries. The cross section of Fig. 2 illustrates schematically the characteristic tectonic style of each domain and the orientation of the main boundaries, together with the main kinematic movements and plutonic suites.

Table 2 shows the characteristic parameters of the individual sub-domains and regional Pan-African shear zone systems, such as the key lithologies, range of NdT<sub>DM</sub> whole rock model ages, the age, composition and geodynamic setting of magmatism etc. It should be noted that one subdomain can record several phases of magmatism, deformation and metamorphism related to the three major orogenies affecting the basement rocks in Malawi. The data are presented in the following chapters.

### 2.4. Structural geology

In order to illustrate the main structural characteristics of each domain/subdomain, representative stereograms of regional gneissic foliations and linear elements are presented in Fig. 3 and Table 3. The diagrams show about 10,000 structural readings from the entire dataset of 30,000, which comprises about 12,000 readings obtained during GEMMAP fieldwork and about 18,000 digitized from the previously published 1:100,000 scale geological maps (BGS). The structures are described in the section devoted to the relevant subdomain later in this paper.

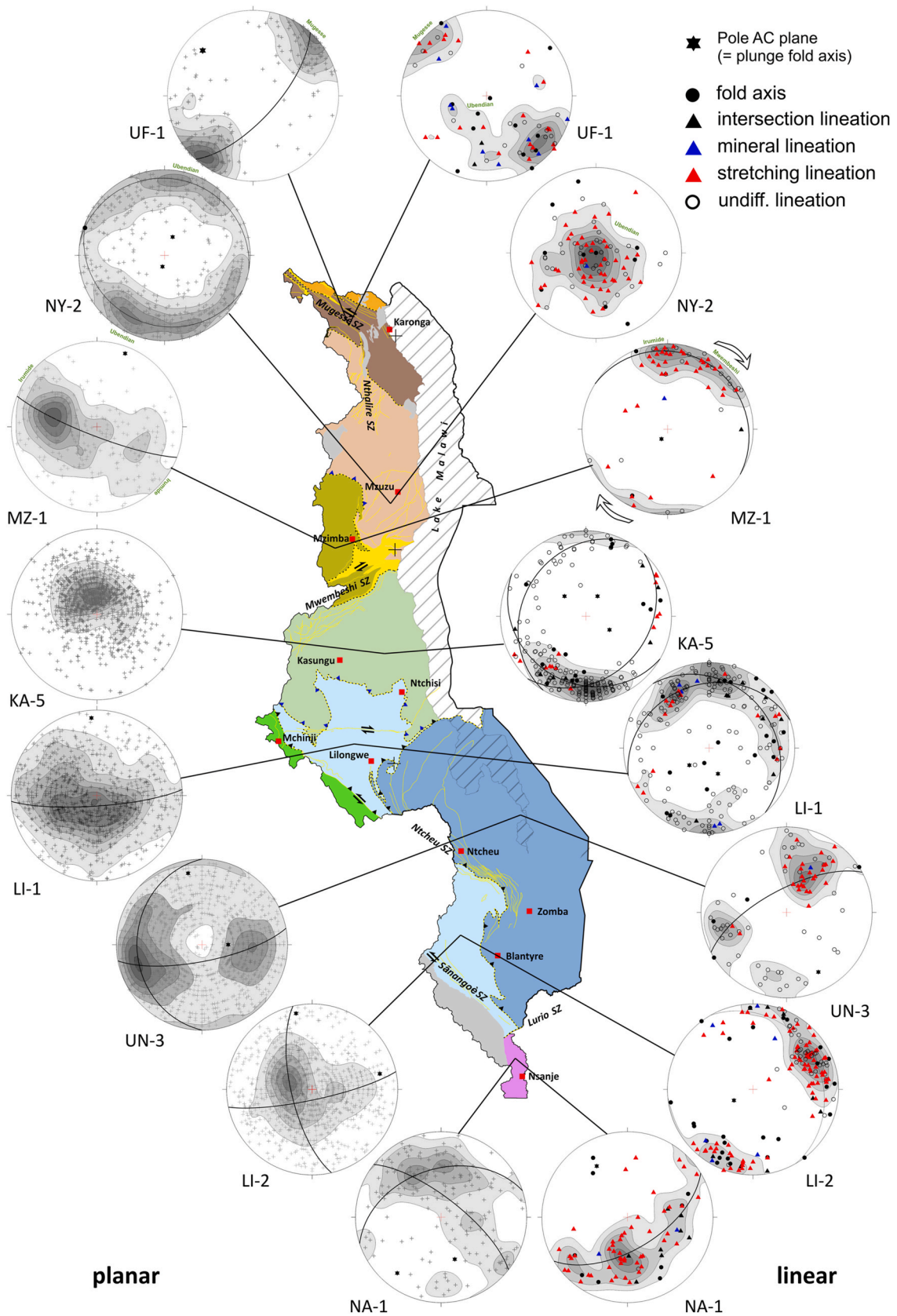
### 2.5. Sm-Nd whole rock analysis

101 samples were analysed for their Sm-Nd (and Rb-Sr) isotopic compositions in order to characterise the various tectonostratigraphic domains and subdomains of Malawi isotopically (Methods and data in Appendix 2). The sampled rocks include mafic and felsic meta-igneous rocks as well as paragneiss. Sampling along a specific traverse from the Mwembeshi Shear Zone (MwSZ) to Kasungu served to confirm the Irumide (reworked Palaeoproterozoic crust)/South Irumide (juvenile Mesoproterozoic crust) domain contact that was derived from airborne geophysics interpretation.

The distribution of the Sm-Nd samples of these samples, together with their T<sub>DM2</sub> ages is given in Fig. 4.

A) T<sub>DM2</sub> model ages of felsic orthogneiss, granitoids and paragneiss (65), anorthosite (4) and syenite (2) show the following geographical distribution (south to north):

- Model ages between 1.0 and 1.6 Ga occur almost exclusively in the SID documenting the juvenile crust of a Mesoproterozoic island arc system;
- Model ages between 1.6 and 2.0 Ga were determined in 9/25 samples of the IRD, indicating mixing of sedimentary/volcanic rocks derived from continental lithosphere with those from juvenile mantle above a subducting slab and suggesting the interpretation of the domain as active continental margin. This is supported by old detrital zircon ages up to 3025 Ma determined in paragneisses and quartzite of the Kasungu and Mchinji groups (GEMMAP).
- Model ages between 2.0 and 2.5 Ga were determined in 11/25 samples of the IRD, demonstrating increasing influence of continental lithosphere in these samples. One sample from the otherwise juvenile Nampula SD in the far south of Malawi suggests a limited contribution from older, Palaeoproterozoic continental crust;



**Fig. 3.** Representative stereograms of structural data for the domains/subdomains (colours as in Fig. 2). Left: Poles to gneissic foliations, right: linear structures. Density contours represent multiples of random distribution and step width that vary between 0.5 and 2 %. Solid lines represent the traces of AC planes through the majority of data. The statistics of the structural data are given in Table 3. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

**Table 3**  
Statistics of selected structural datasets of the Precambrian subdomains of Malawi used in the stereogram plots (except Mchinji SD).

Subdomain		Ufipa	Nyika	Mzimba	Kasungu	Lilongwe N	Lilongwe S	Unango	Nampula
Area		UF-1	NY-2	MZ-1	KA-5	LI-1	LI-2	UN-3	NA-1
<b>Gneissic foliations</b>	number	201	588	321	1097	1073	1474	2049	186
	max 1	6.6 at 218/09 (=038/81)	2.6 at 210/18 (=030/72)	4.9 at 284/45 (=104/45)	8.7 at 350/72 (=170/18)	2.9 at 249/51 (069/39)	5.5 at 283/69 (=103/21)	3.1 at 254/24 (=074/66)	3.8 at 326/42 (=146/48)
	max 2			1.9 at 118/46 (=298/44)		2.9 at 195/83 (=015/07)		2.0 at 093/40 (=273/50)	
	pole AC 1	312/22	190/79	021/09	none	356/10	077/20	090/65	218/18
	pole AC 2		024/81				344/07	349/16	162/47
	<b>Lineations</b>	number	62	97	60	226	201	162	76
	max 1	5.3 at 133/18	6.9 at 240/87	6.8 at 358/09	8.1 at 178/15	4.2 at 329/27	6.9 at 060/24	5.4 at 030/54	5.7 at 189/51
	max 2			5.2 at 028/10		4.1 at 006/20		4.1 at 255/26	
	pole AC 1				038/68	161/64	240/69	152/22	329/31
	pole AC 2				313/62	229/65			
	pole AC 3				120/64				
	f-axis	11	10	2	15	17	26	3	9
	s-lin	21	48	37	14	15	83	27	49
	m-lin	10	1	1		5	6	1	2
	d-lin	2		1	7	9	8		8
	undiff	18	38	19	189	155	39	45	1

Max = maximum density as compared to random distribution; AC plane = plane orthogonal to fold axis, more than one AC plane indicates non-coaxial deformation or interference folding; f-axis = fold axis, m-lin = mineral lineation, s-lin = stretching lineation, d-lin = intersection lineation.

- Model ages older than 2.5 Ga predominate in the UBD (9/13 samples) whereas in the IRD these form a minor group (6/25 samples), documenting an increase in the proportion of Archaean source rocks in the UBD (closer to the Archaean Tanzania Craton).

B) The  $T_{DM2}$  model ages of mafic rocks show the following geographical distribution (Fig. 4b):

- Model ages between 1.0 and 1.6 Ga are limited to the SID, documenting juvenile magmas of an island arc system.
- Model ages between 1.6 and 2.0 Ga occur mainly in the UBD suggesting mixing of Mesoproterozoic magmas with the country rock.
- Model age between 2.0 and >2.5 Ga in the UBD may record juvenile Palaeoproterozoic magmatism.

The isotopic evolution of Nd in the igneous rocks of Malawi is shown in Fig. 5, together with the evolution of depleted mantle and CHUR. The age of most felsic samples has been determined by U-Pb zircon geochronology (GEMMAP; see Appendix 1).

The regression line through Palaeoproterozoic granitoids of the UBD constrains the present  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio of 0.5119 and the  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio of 0.15125 and is interpreted to represent the bulk lithosphere composition of the local ~2 Ga crust. The intersection with the DM and CHUR lines suggest fractionation from the mantle at around 2.5 Ga during a crust-forming event. The trajectories of individual samples of Ubendian granitoids are combined into the grey field in Fig. 5. It implies that the bulk lithosphere of the Palaeoproterozoic crust comprises a considerable proportion of mafic crust resulting in a steeper gradient and the shift of the evolution line out of this field.

Mesoproterozoic Irumide granitoids plot from the CHUR trajectory into the Ubendian granitoid field suggesting recycling of Ubendian crust and mixing with variable amounts of asthenospheric or lithospheric mantle. This is in contrast to broadly coeval South Irumide granitoids, which scatter mainly between the CHUR and DM trajectories, indicating their origin as juvenile mantle magmas and a second crust forming event in this domain.

Rift-related Tonian alkaline granitoids of the Nyassa Suite were emplaced into Palaeoproterozoic to Mesoproterozoic rocks. Their

position between CHUR and DM shows suggests origin of the parent magma from a fertile to depleted mantle with little contamination during ascent.

The Mesoproterozoic Tengani (anorthosite) and Neoproterozoic Blantyre (granitoid) suites also plot largely between the evolution lines of DM and CHUR. However, assimilation of the host rock in the SID would not shift the points out of field of juvenile Mesoproterozoic crust, so it is possible that Blantyre Suite resulted from anataxis of SID crust. The mantle origin is indicated by minor amounts of gabbro and pyroxenite that in some of the plutons are associated with the alkaline felsic rocks.

### 3. Palaeoproterozoic Ubendian Domain

The NW-SE trending, Palaeoproterozoic Ubendian Domain ("Ubendian belt"; McConnell, 1950) runs some 600 km along the SW margin of the Tanzania Craton from eastern Congo, through western Tanzania and Malawi to its SE termination in NE Mozambique. It is considered to be contiguous with the coeval Usagaran belt to the east (e.g. Priem et al., 1979), which together form an orogen wrapping around the southern half of the Tanzania Craton. In this model, the Usagaran belt constitutes the more orthogonal, frontal part of the orogen, with the UBD being a deep-seated lateral, dextral strike-slip segment (Daly, 1986a, 1986b, 1988; Daly et al., 1984). The rocks are characterized by sequences of medium-to high-grade metamorphic supracrustal gneisses and schists, intruded by various plutonic igneous rocks including granitoids, meta-diorites, and gabbros, eclogites and massif anorthosite complexes (e.g. Boniface, 2009). Granitoids are especially common near the margins with the cratonic blocks on either side (Lenoir et al., 1994). The intrusive history is complex and polyphase, with multiple pulses of igneous rocks emplaced in Palaeo, Meso- and Neoproterozoic times. The UBD is unconformably overlain by the low grade Mafingi Group meta-sedimentary rocks (Fig. 6), which are probable correlates of the c. 1800 Ma old Muva Supergroup (Thomas et al., 2022a and references therein; this volume).

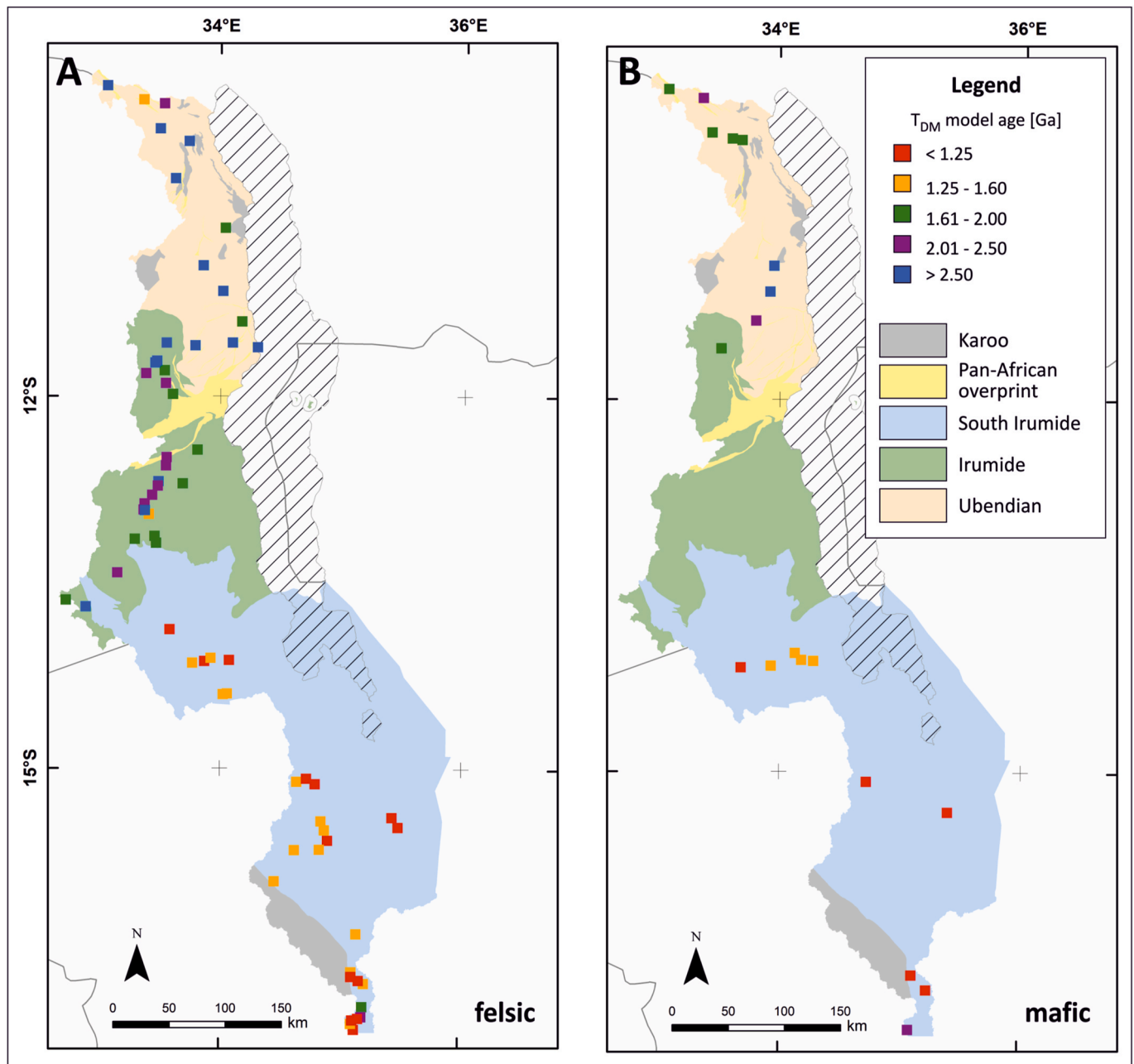


Fig. 4. Location of Sm-Nd whole-rock  $T_{DM2}$  model ages.

### 3.1. General features

The UBD underlies 17,750 km<sup>2</sup> of northern Malawi where it is subdivided into the northern Mbozi, the central Ufipa and the southern Nyika subdomains (Figs. 2 and 6). These three domains were extrapolated into northern Malawi by Daly (1988), who identified eight “terranes” for the Ubendian belt in SW Tanzania, separated by major NW–SE trending, generally dextral strike-slip, ductile shear zones. Our work supports that view and precisely delineates the three subdomains in Malawi for the first time, which together represent about 30 % of the exposed surface area of the entire belt.  $Nd_{Tdm}$  ages vary from 1.8 to 2.8 Ga and together with detrital zircon ages are indicative of Palaeoproterozoic to Archaean sources for the sediments and variable crustal contributions to the igneous rocks (Table 2)

In Malawi, the Mbozi SD (c. 730 km<sup>2</sup>) is predominantly comprised of mafic gneisses (Mbozi Group), with rare intercalations of quartzite and

garnet-biotite-sillimanite gneiss, with no Palaeoproterozoic granitoids (Table 2, Appendix 1). It is tectonically bound with the Ufipa SD to the south by SE-trending branches of the Mugesse Shear Zone (MuSZ). Ubendian prograde metamorphism reached amphibolite to high-pressure granulite grade (Lenoir et al., 1994) and has been dated in Malawi at 1885–1974 Ma (GEMMAP, Table 2), similar to monazite ages between 1816 ± 48 Ma and 1831 ± 81 Ma from paragneiss in Tanzania (Boniface, 2009).

The Ufipa SD (c. 4650 km<sup>2</sup>) comprises several units of high grade supracrustal gneisses (Ufipa Group), with a maximum depositional age of ~2040 Ma, deposited upon a “cryptic” tonalite-granodiorite orthogneiss basement dated at ~2150 Ma, occurring as scattered bodies within the paragneisses (Thomas et al., in prep, this volume). It is tectonically juxtaposed against the Nyika SD in the south by steep Pan-African shear zones. The typical rock-types are (migmatitic) biotite ± sillimanite ± garnet paragneisses, and hornblende-bearing, probably metavolcanic,

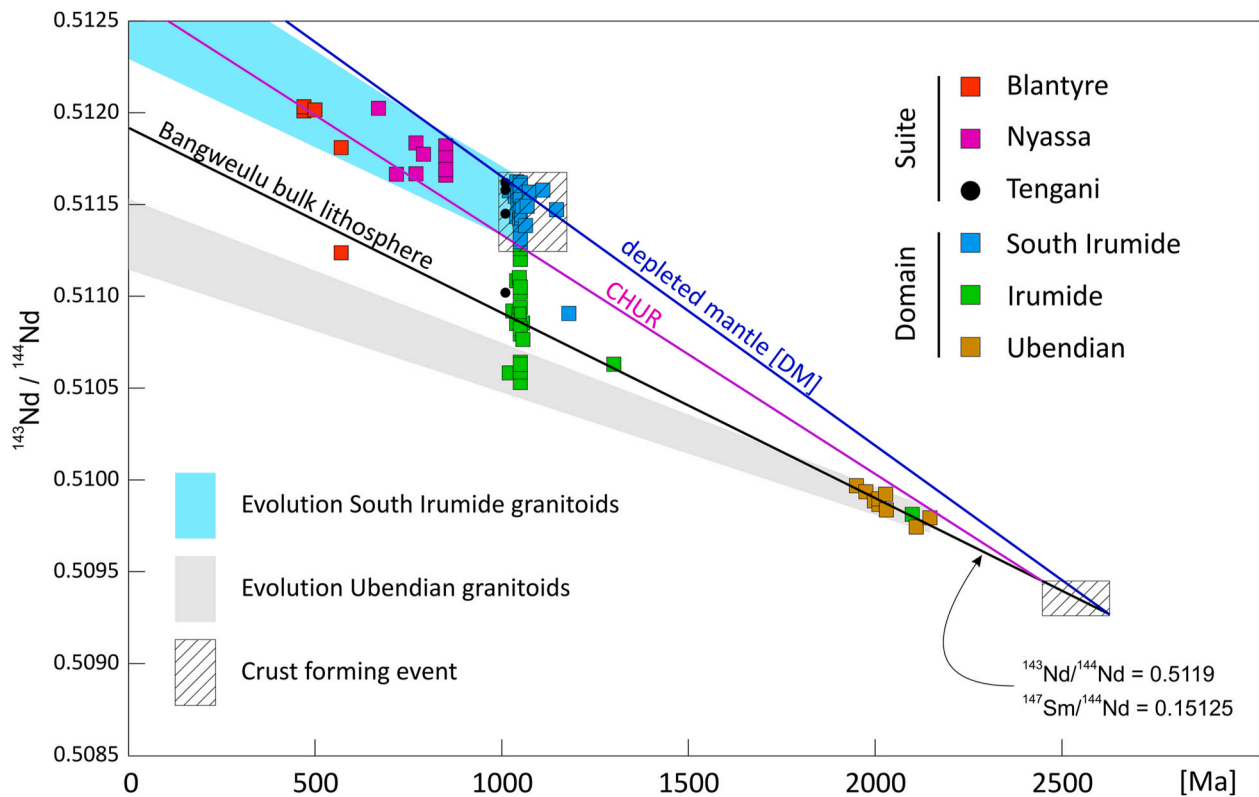


Fig. 5. Isotopic evolution of neodymium in magmatic rocks of Malawi. The emplacement age of most granitoids has been determined by U-Pb zircon geochronology (for localisation of Tengani, Nyassa, and Blantyre suites, see Figs. 12, 16 and 18).

gneisses. Regional prograde HP amphibolite to granulite (or eclogite) facies metamorphism of 730–840<sup>o</sup>, 13–14 kb is probably Ubendian in age even though it was interpreted as Pan-African event (Ring et al., 2002; Boniface and Schenk, 2012; Morita et al., 2022; Gremmel et al., 2023, this volume).

Small volumes of post-Ufipa Group granitoid were emplaced at ~1975 Ma followed by the emplacement of Mesoproterozoic augen gneisses (Mwamikome gneiss) at ~1400 Ma and A-Type granites (Mwenga Suite) at ~1150 Ma (Thomas et al., 2023a, this volume). Polyphase retrograde Pan-African greenschist facies metamorphism, dated at 500–596 Ma, overprints all rocks of the subdomain (Table 2) and is especially apparent along steep shear zones such as the MuSZ, with P/T conditions determined at 5–7 kb and 350–475 °C (Gremmel et al., 2023, this volume).

The Nyika SD (c. 12,400 km<sup>2</sup>) is typified by sequences of high grade supracrustal gneiss (Nyika Group) deposited at ~2000 to 1980 Ma (Le Bayon et al., 2024; this volume). It tectonically overlies the Mzimba SD of the Irumide Domain in the SW and in the south it is juxtaposed along the MwsZ against the Kasungu SD. The contact with the Irumide Domain remains poorly mapped due to limited outcrop but marks a major break in tectonic style and magmatism. The most typical rock type of the Nyika SD is garnet-sillimanite-cordierite gneiss forming numerous extensive bodies intercalated with biotite gneiss. Prograde medium-pressure granulite facies conditions reached 770–780<sup>o</sup>C and 6 kb in the north (Le Bayon et al., 2024; this volume). The supracrustal gneisses were intruded by a number of Palaeoproterozoic granite plutons of varying age up to ~1946, with the emplacement of often porphyritic granites of the post-tectonic Nyika Suite (Le Bayon et al., 2024; this volume)

### 3.2. Ubendian tectonics

The Ubendian belt is considered to represent rocks generated at an active margin along the SW margin of the Archaean Tanzania Craton

(Kazimoto et al., 2015). It has been proposed that it represents a zone of collision and suturing between the Tanzania Craton and the Palaeoproterozoic “Bangweulu Block” in the SW (e.g. Ganbat et al., 2021). However, airborne magnetic data from Zambia, combined with the new high-resolution data in Malawi demonstrate the continuation of the Nyika SD of Malawi into the Bangweulu Block of Zambia, suggesting that they are a coeval, contiguous crustal unit (Bangweulu-Nyika Block – “BaNy”; Fig. 7; Thomas et al., 2023b) forming the central zone of the Ubendian orogen. The other microterranes of the Ubendian-Usagaran belt constitute the root zone of nappes that during the BaNy- Tanzania Craton collision were transported into northern directions over the craton.

In Malawi, the southern margin of the UBD is structurally juxtaposed against rocks with similar Palaeoproterozoic protolith ages, but which have been pervasively overprinted by the SSW to SW-trending Mesoproterozoic Irumide orogen.

The regional NW-SE Ubendian trend is only seen in the NW part of Malawi in the Mbozi and Ufipa Domains, with the pervasive regional metamorphic fabrics being generally near-vertical in orientation and predominantly shallow NW and SE plunging lineations (stretching, intersection and fold axes) (Fig. 3). This trend, however, is predominantly a Pan-African effect, along the wide anastomosing Mugesse set of shear zones. Older Ubendian lineations with steeper plunge are only locally preserved. South of Karonga (for location see Fig. 6), the regional fabrics are less transposed and characterised by interference fold patterns and low-angle NNE-SSW lineations, though close to the contact with the Nyika SD the NW-SE Mugesse trend prevails.

Discounting the Pan-African effects, the Nyika SD is typified by relatively weak regional pervasive fabrics. The northern part shows little or no common structural trend but steep lineations. Further south the gneissic fabrics define a broadly east-west trend that continues without break into Zambia with lineations remaining subvertical (Fig. 3, Ny-2). In the SW corner of the Nyika SD the progressive impact of Irumide

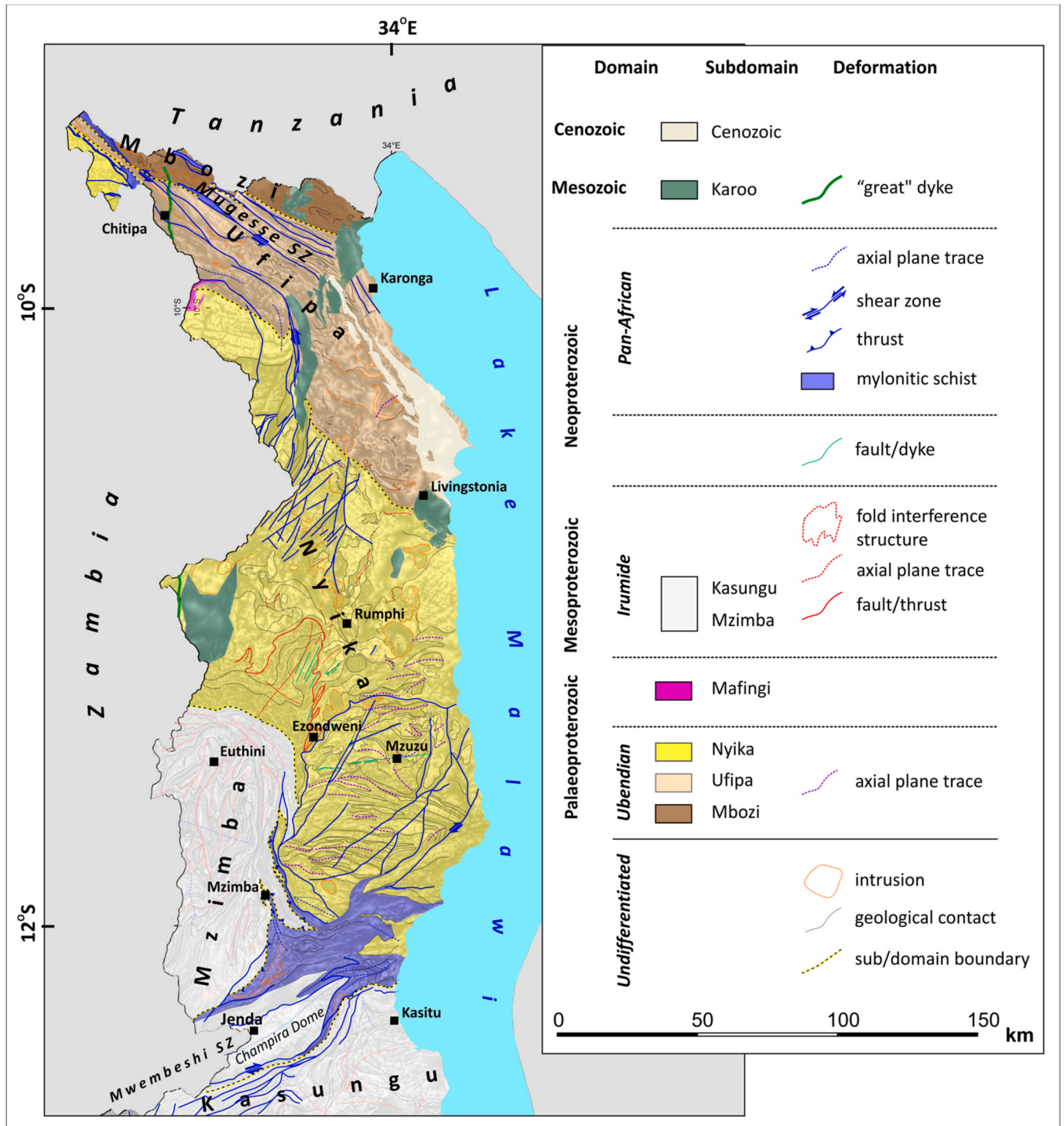


Fig. 6. Main features of the Ubendian Domain in Malawi showing the three subdomains and the main Precambrian structures.

deformation is illustrated by geophysics data, which reveal regional interference fold structures of open the gentle geometry, which are absent elsewhere and a regional structural unconformity interpreted as thrust or detachment (Figs. 2, 6 and 8).

#### 4. Mesoproterozoic Irumide Domain

The Irumide Domain in central Malawi represents the eastern part of a major, generally SW to SSW-trending Mesoproterozoic orogeny, which is mainly exposed in Zambia south of the Palaeoproterozoic BuNy Block

(Fig. 1; Daly, 1986b; Johns et al., 1989; De Waele and Mapani, 2002; De Waele et al., 2003, 2006a, 2006b).

##### 4.1. General features

The Irumide Domain in northern and central Malawi covers an area of c. 20,500 km<sup>2</sup> and is subdivided by crustal-scale shear zones and thrusts into the Mzimba (NW), Kasungu (SE) and Mchinji (SW) subdomains (Figs. 2 and 8). The rocks have Palaeoproterozoic (BuNy and Ubendian) protolith ages, but were pervasively overprinted by

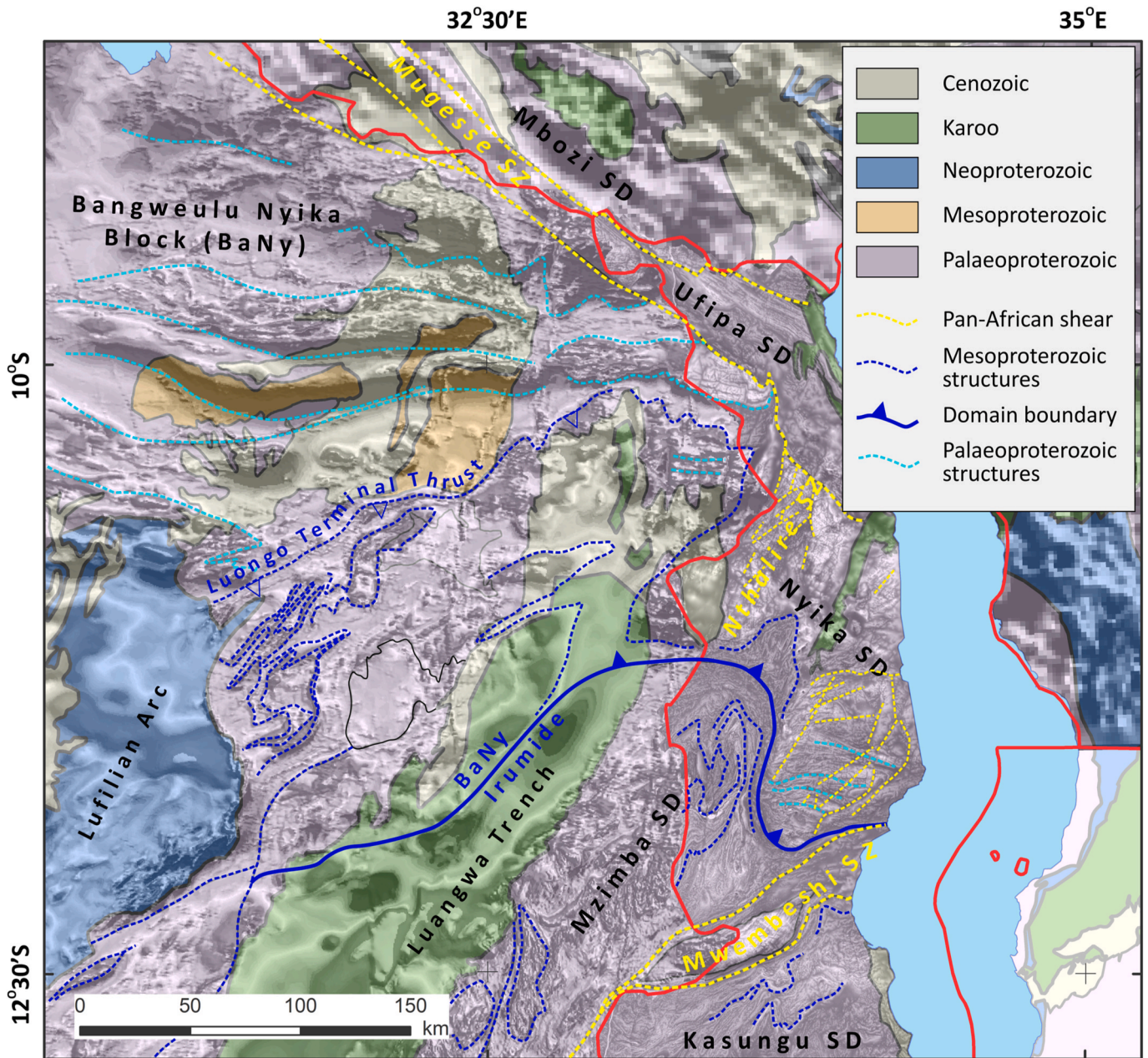


Fig. 7. Regional aeromagnetic image of northern Malawi and surrounding countries, showing NW-SW Ubendian trend in the north, associated with the MuSZ and the contiguous nature of the Nyika SD westwards into Zambia and the joint “BaNy Block” (modified from Thomas et al., 2023b). The Irumides are limited in Zambia by the Luongo Terminal Thrust representing the orogenic front (Daly et al., 1984).

Mesoproterozoic high-grade metamorphism and ductile deformation. The Mzimba (c. 4000 km<sup>2</sup>) and Kasungu (c. 15,800 km<sup>2</sup>) subdomains are separated by the ~30 km wide, NW-trending, Pan-African Mwembeshi SZ. In the south, the Mchinji and Kasungu Subdomains are separated by a sliver of SID rocks in a complex thrust zone.

The Mzimba and Kasungu subdomains have similar geological histories and may have once been contiguous. They share similar rock types, tectonic styles and structures, as well as mainly Archaean to Palaeoproterozoic (Ubendian) Nd<sub>Tdm</sub> protolith ages (Table 2). The absence of Palaeoproterozoic orthogneiss and a systematic southward younging of Nd<sub>Tdm</sub> model ages in the Kasungu SD, up to 1.45 Ga is noteworthy, indicating post-Ubendian deposition for the precursor sediments of the paragneisses and increasing influence of Mesoproterozoic juvenile sources. Detrital zircon ages constrain deposition younger than 1080 Ma for some of the sediments. It implies the Irumide and/or

Pan-African age of metamorphism and deformation in these subdomains.

The characteristic rock type for the poorly exposed Mzimba SD is garnet-sillimanite-biotite gneiss (±spinel), indicating Mesoproterozoic granulite facies peak metamorphic conditions. P/T conditions of 6–9.5 kb/900–1000°C were determined in cordierite gneiss of the Champira Dome; a rhomboidal remnant of Mzimba SD rocks surrounded by the MsSZ (Fig. 8; Hieber, 2021; Sakuwaha and Tsunogae, 2024). Monazite geochronology dates the metamorphism to 1047 ± 47, 1003 ± 8 and 975 ± 7 Ma. The continuation of these rocks westwards is shown on the metamorphic map of Zambia, where lenses of cordierite gneiss follow the international border to the south.

The Kasungu SD is typified by garnet-biotite-sillimanite gneiss and sillimanite-bearing quartzite. In addition, both subdomains contain layered leucogneiss, amphibolite and quartzite besides the

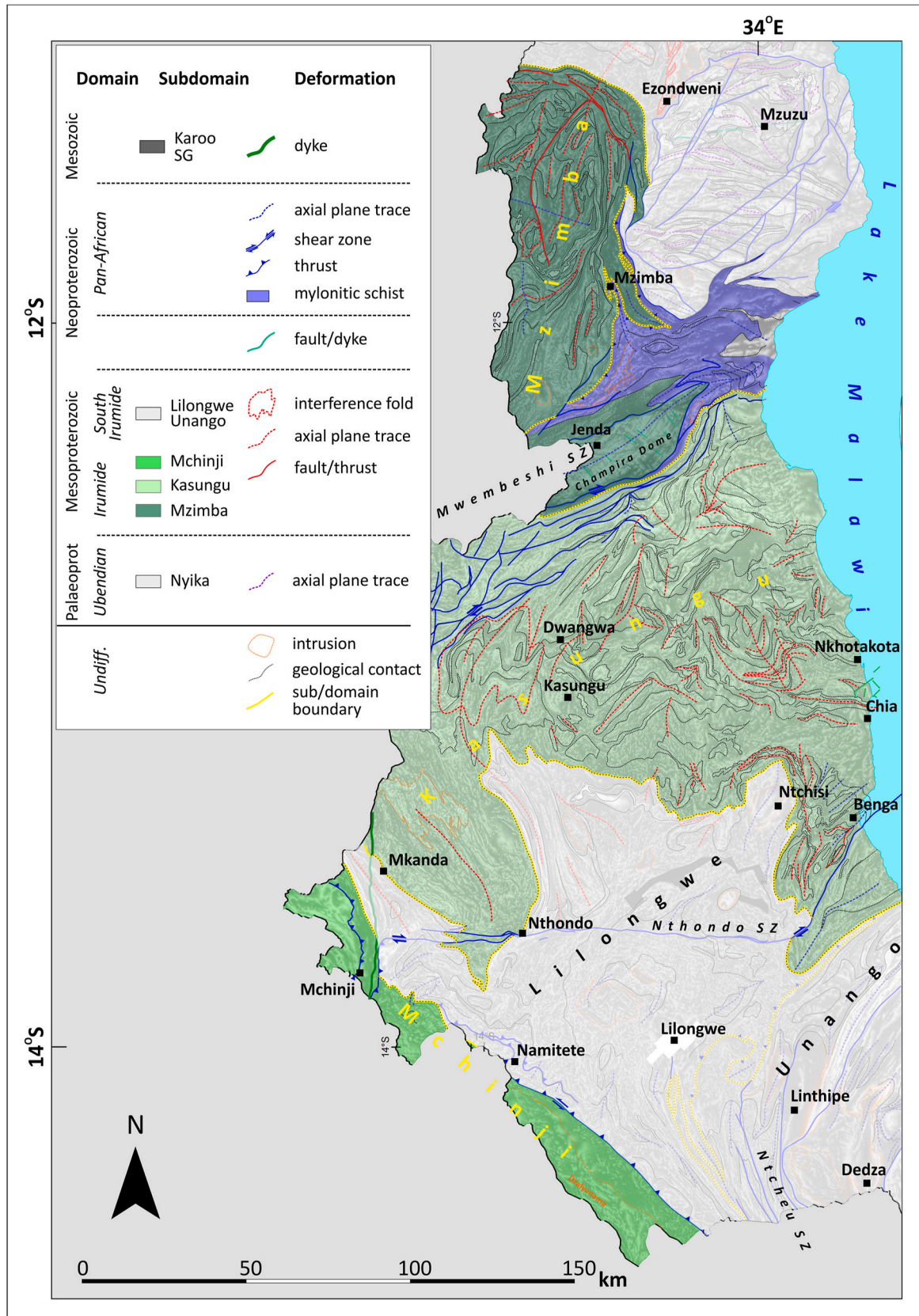


Fig. 8. Structural map of central Malawi illustrating the main geological units and Precambrian structural elements. The three IRD Subdomains are shown in different shades of green. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

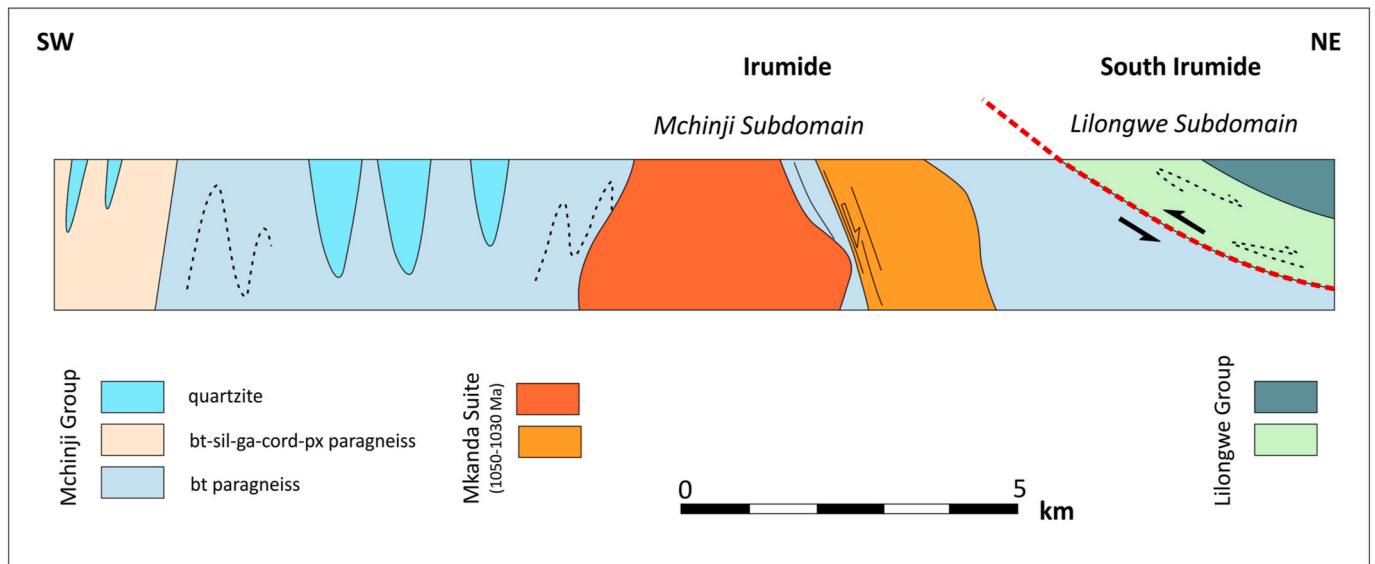


Fig. 9. Geological cross-section across the Mchinji/Lilongwe SD (SID) thrust contact.

predominating biotite gneiss. Medium-pressure granulite facies peak conditions of 5.1–7.2 kb and 730–770°C at 1038 ± 36 Ma were determined in the NE part of the Kasungu SD (Böhme, 2021).

The Mchinji SD occupies a small area along the border with Zambia in the SW and has a distinctly different lithological character. It probably represents the northernmost part of a tectonically-stacked array of microterranes of Palaeo- to Mesoproterozoic provenance that in Zambia and NW Mozambique constitute the “Tete-Chipata Belt” that were assembled between ~1083 and 1066 Ma (Mapani et al., 2004; Johnson and Oliver, 2004; Johnson et al., 2004, 2005; Westerhof et al., 2008a). Ferruginous quartzite, banded iron formation and massive quartzite of the Mchinji Group can be correlated with the basal part of the 1.86 Ga Muva Supergroup in Zambia (De Waele et al., 2006b). However, rocks of the Mchinji SD underwent granulite facies metamorphism of 800–950°C/5–7 kb (Karmakar and Schenk, 2016), predating late- to post-tectonic enderbite and granite intrusion dated at 1053 ± Ma and 1045 ± 4 Ma, respectively (see Appendix 1).

The Irumide subdomains were intruded between 1086 and 1019 Ma by voluminous calc-alkaline granitoids whose composition suggest active continental margin and collision-related geodynamic settings (Table 2). The intrusions have been grouped into the Mkanda Suite, dated between 1050 and 1030 Ma, coinciding with the main phase of Irumide metamorphism and deformation. Vestiges of the 1990–2000 Ma Ubendian plutonism were detected only in two samples from the Mzimba SD.

A late to post-tectonic meta-mafic dyke swarm in the Kasungu, Mchinji and northern Lilongwe SDs (Bua Suite) is dated at 1040 ± 9 Ma, constraining the minimum age of SIB arc accretion and maximum age of regional high-grade metamorphism (Fullgraf et al. subm., this volume).

#### 4.2. Irumide tectonics

The arcuate tectonic boundary between the Mzimba (Irumide) and Nyika (Ubendian) subdomains in the NW (north of the Pan-African MwSZ) swings from E-W in the north, to N-S in the south (Fig. 8). A major change in tectonic style takes place across the contact. E-W-trending foliations and lineations (stretching, fold axes, intersection) in the SW Nyika SD are steep (Fig. 3, NY-3), whereas in the Mzimba SD foliations are folded around shallow north plunging axes that, in vicinity of the MwSZ, are dextrally sheared into a NE direction (Fig. 3, MZ-1, Fig. 8). Within the Mzimba SD, the foliation trends show at least three phases of complex regional-scale deformation into large-scale coupled

antiforms and synforms, mainly evident in the geophysical data due to generally very poor outcrop.

The Kasungu SD similarly shows no evidence of Ubendian effects and the structures and metamorphism are Irumide in age, but with the northern part affected by the dextral Pan-African MwSZ. Foliations in the south-central part of the subdomain are shallow to moderately dipping, with S- to SE plunging lineations (Fig. 3, KA-5). These features are interpreted as recording a phase of Irumide low-angle north- and south-directed nappe-style tectonics. Regional fold interference structures are indicated by the interpreted airborne magnetic data and the great variation in the orientation of linear and planar structures over the entire area (Fig. 8).

In the south, the Kasungu SD is thrust over the Lilongwe SD of the SID (Fig. 10). The very sharp, low-angle contact is parallel to the regional gneissic fabric and refolded at regional scale. It is marked lithologically by the sudden appearance of graphitic and sulphidic schists, which are characteristic of the Lilongwe SD (see below).

The Mchinji SD is overthrust to the east by the Lilongwe SD (Fig. 9). The age of the thrust is unclear, it could be either Mesoproterozoic or Pan-African or both, but at the northern part of the contact 1054 Ma granite is sheared. To the SE the contact links with oblique shear zones of the Pan-African Ntcheu Shear Zone (Figs. 2 and 8).

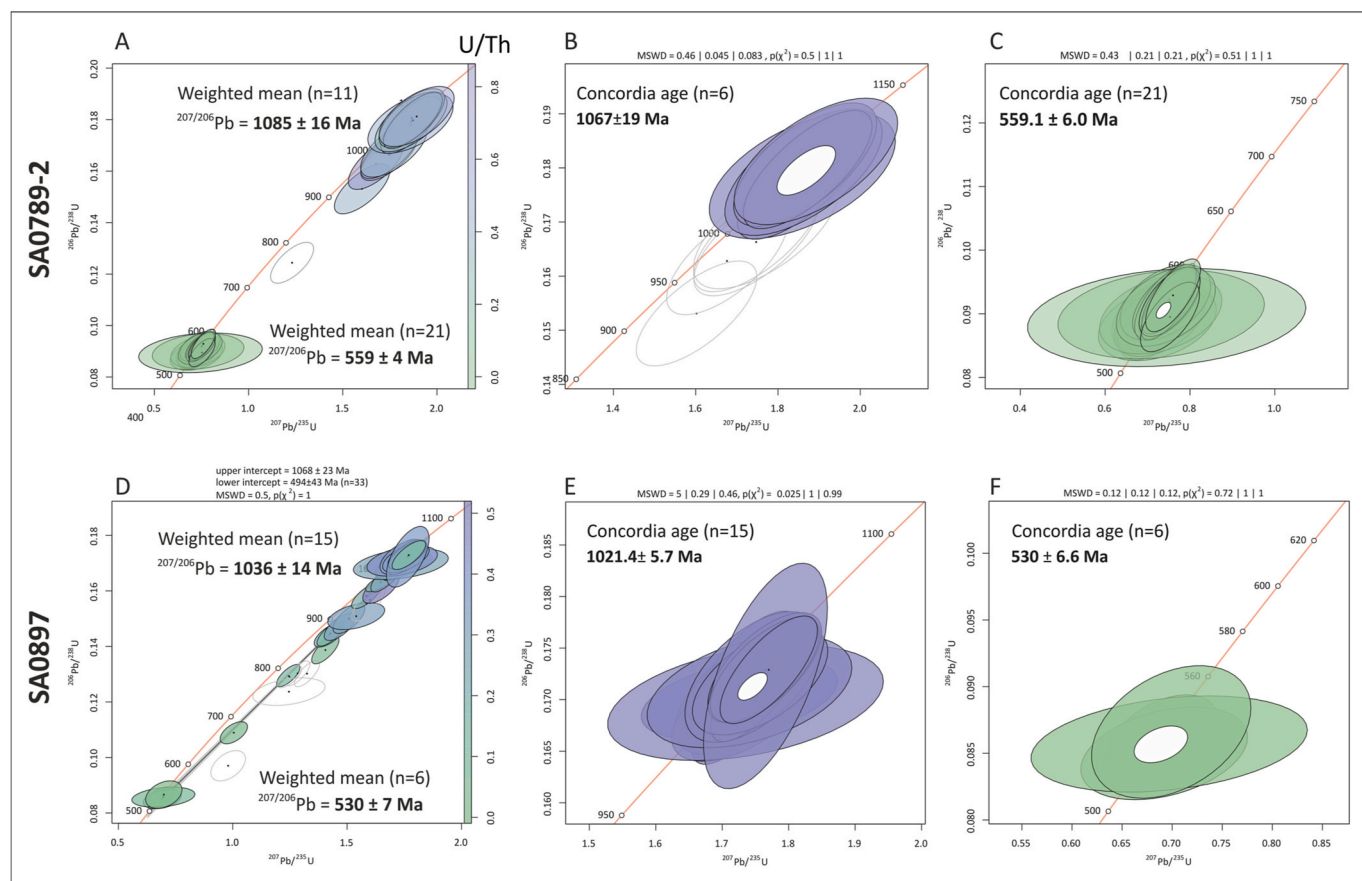
#### 4.3. Geochronology of the Irumide-South Irumide suture

In order to constrain the age of the sharp tectonic contact zone between the Irumide and South Irumide Domains, two samples of syntectonic anatectic melts were taken at the contact zone. This in turn should date the suture between the SID juvenile arc domain and the active margin of the BuNy Block (Figs. 8, 10 and 11; methods and data given in Appendix 2).

Sample SA0789–2 is a leucosome in a syntectonic stromatic migmatite from the contact zone (Fig. 10). Thin leucosome veinlets are transposed into the main shear foliation. 33 analyses of 21 zircon spots identified two distinct zircon age populations (Fig. 11a). The older group comprises 11 analyses from zircon cores having Th/U ratios between 0.26 and 0.83 indicative for their magmatic origin (Rubatto, 2002). The weighted mean  $Pb^{207}/^{206}$  age of this group is 1085 ± 16, with the 6 most concordant zircons yielding a concordia age of 1067 ± 9 Ma (Fig. 11b). The second group of 21 analyses came from low-CL cores and high-CL rims. Both sets yielded low Th/U of <0.02, indicative for their metamorphic origin, and weighted mean  $Pb^{207}/^{206}$  and concordia ages of



**Fig. 10.** a) Geological map of the contact between Kasungu (green) and Lilongwe (light blue) around Ntchisi. b) Photograph of locality SA0789, showing disrupted podiform leucosomes from the tectonic contact zone, the age of which will constrain thrusting and juxtaposition; c) Photograph of locality SA0897; layer-parallel pale anatectic leucogranite sheets hosted in amphibolitic paragneisses. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



**Fig. 11.** Sample SA0789-2: a) Wetherill plot of all data; b) older, most concordant data (6); c) younger, most concordant data (21). Sample SA0897: d) plot of all data; e) older, most concordant data (15); f) younger, most concordant data (6).

559  $\pm$  4 Ma and 559  $\pm$  6 Ma (Fig. 11a–c). The data is taken to reflect formation of the syntectonic leucosome at  $\sim$ 1067 Ma and subsequent metamorphism at  $\sim$ 560 Ma, recording Mesoproterozoic thrusting of the Kasungu over the Lilongwe Subdomain and subsequent Pan-African reactivation.

**Sample SA0897** is a biotite-bearing leucocratic granitoid orthogneiss invading the contact zone between the Kasungu and Lilongwe Subdomains from about 10 km SE of Ntchisi. It forms thin (generally sub-metre-scale) intrusive sheets interlayered with the country rock paragneisses (Fig. 10).

40 analyses from 24 zircon grains show two age populations linked by a well-defined discordia line (Fig. 11d). 25 analyses plot on concordia or along a discordia line that projects toward c. 530 Ma, with an upper intercept age of  $1070 \pm 22$  Ma. 17 of the most concordant of these grains yield a weighted mean  $Pb^{207}/^{206}$  age of  $1036 \pm 14$  Ma, whereas the 16 most concordant zircons yielded an age of  $1021 \pm 6$  Ma (Fig. 11e). The latter is considered to date the crystallisation of the anatectic melt. The youngest six analyses from thin high-CL zircon rims with Th/U < 0.08 group to yield a weighted mean  $Pb^{206}/U^{238}$  age of  $530 \pm 7$  Ma, taken to date Pan-African metamorphism (Fig. 11f).

The two date samples are interpreted to date the suture between the Irumide and South Irumide domains and nappe transport at  $1067 \pm 9$  Ma, coinciding with the stacking of microterranes of the Tete-Chipata Belt in NW Mozambique (Westerhof et al., 2008a). A second phase of anatectic melt emplaced into the contact is dated at 1036–1020 Ma and corresponds to the main and late phases of Irumide collision and orogenic magmatism. Zircon rim ages of  $559 \pm 4$  Ma (SA0789) and  $530 \pm 13$  Ma (SA0897) document Pan-African reactivation of the Mesoproterozoic suture.

## 5. Mesoproterozoic South Irumide Domain

### 5.1. General features

The Mesoproterozoic Southern Irumide Domain covers about 54,000 km<sup>2</sup>, more than half of Malawi's surface area. It comprises three subdomains (Lilongwe, Unango and Nampula; Fig. 2) made up of juvenile  $\sim$ 1.1–1.5 Ga crust, with little evidence of Palaeoproterozoic crustal involvement (Fig. 4).

The funnel-shaped Lilongwe SD (c. 18,300 km<sup>2</sup>) extends south from central Malawi through NW Mozambique and back into southern Malawi (Fig. 12). In the NE it is in contact with the underlying Unango SD (c. 34,450 km<sup>2</sup>) along a sharp NW-dipping ductile extensional detachment of late Mesoproterozoic or early Pan-African age. To the south, the boundary swings into a SE direction under the influence of the Pan-African Ntcheu SZ (NtSZ). This structure accommodated W-directed thrusting associated with the East African orogeny resulting in local transport of the Unango SD over the Lilongwe SD. Field observation also shows evidence for reactivation of the NtSZ as a detachment during a late stage of E-directed extension. In southern Malawi, the Lilongwe SD is bounded in the SW by the SE trending Sanangòè Shear Zone (SaSZ) with the microterranes of the Tête-Chipata Belt further SW (Figs. 2, 3 and 12). In the far south of Malawi, the Unango SD is juxtaposed against the Nampula SD along the ENE trending Lurio Shear Zone that truncates the SaSZ.

The characteristic rock types of the Lilongwe SD are predominantly biotite  $\pm$  kyanite  $\pm$  sillimanite gneiss, graphite-biotite gneiss/schist, dolomitic marble, amphibolite and, in the northern part, migmatitic aegirine-bearing leucogneiss. Metamorphic conditions in the northern and central Lilongwe SD were determined at 760–820  $^{\circ}$ C at 8–10 kb

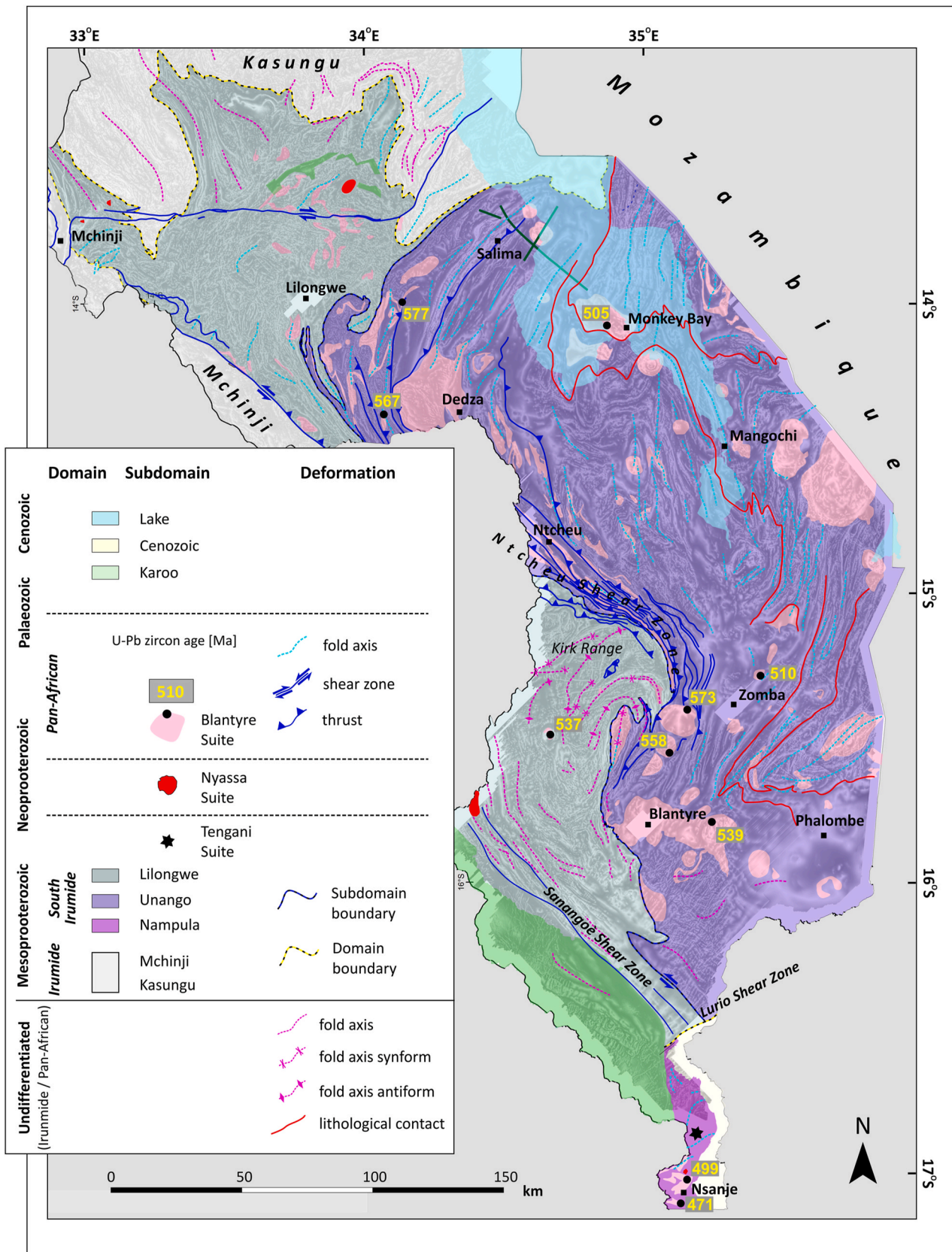


Fig. 12. SID showing the subdomains and main Precambrian structural elements. The Nyassa and Blantyre Suite provide important strain markers for the Pan-African tectonic overprint.

(Goscombe et al., 2020) and in the south at 620–690 °C at 9–10.5 kb (Chirwa, 2021, Table 2).

Typical rock types of the Unango SD are 2-pyroxene “charnockitic” gneiss, amphibolite, leucogneiss, dolomitic marble and garnet-biotite gneiss (Unango Group). Peak P-T granulite conditions of 15 kb at 850 °C and 11.5 kb/875 °C in the northwestern and central parts have been attributed to the Irumide event whereas a second granulite metamorphism during the Pan-African reached 9.9 kb at  $738 \pm 84$  °C (Bingen et al., 2009; Engvik and Bingen, 2017). Two other studies in Malawi yielded similar peak P-T conditions of 9–11 kb at 840–930 °C (Goscombe et al., 2020; Tsunogae et al., 2021), which were interpreted as being of Pan-African age (see below).

The Unango and Lilongwe subdomains were intruded between 1147 and 1028 Ma by voluminous calc-alkaline granitoids whose composition suggest island arc and collision-related geodynamic settings (Table 2). The intrusions have been grouped into the pre-to syntectonic, migmatitic Mwanza (c. 1090–1040) and late-to post-tectonic Tedzani suites (c. 1060–1030). On a major element basis the Mwanza-Tedzani Suite shows a wide range of compositions but is on average less silicic than the temporally equivalent rocks of the Mkanda Suite in the Irumide Domain.

The Nampula SD resembles the Unango SD with 2-pyroxene granulite, marble, garnet-biotite gneiss, and marble as characterising lithotypes, but with large volumes of garnet leucogneiss (Mamala Gneiss), along with 1180–1040 Ma of tonalitic orthogneiss (Mocuba Suite), granitic augen gneiss (Culicui Suite) and post-tectonic anorthosite (Tangani Suite), dated at  $1008 \pm 39$  Ma (Thomas et al., 2022b, this volume). Polyphase metamorphism includes an early phase of locally preserved eclogite facies modelled at 16–18 kb at 880–930 °C and subsequent regional medium-P granulite facies conditions of 8–9 kb at 740–750 °C, overlapping with the two Mesoproterozoic and Pan-African high-grade events recorded in the Unango SD.

## 5.2. South Irumide tectonics

The Irumide age of the regional gneissic fabric in the northern Irumide SD is demonstrated by two weakly deformed stocks of Nyassa Suite syeno-granite emplaced into the gneisses (Fig. 12). The regional aeromagnetic data show two phases of regional folding (Fig. 12). An early generation of NW trending, 10 km-scale folds refolds the Kasungu-Lilongwe SD boundary in the NW. The axial plane of this structure is rotated in the dextral Pan-African MwSZ, which constrains the age of folding between  $1067 \pm 9$  Ma (i.e. Irumide) and the MwSZ dated by the syntectonic Hook granite at 559–566 Ma in central Zambia (Hanson et al., 1993).

A younger generation of NE-striking folds in the east refolds the Lilongwe-Kasungu contact and increases in intensity and frequency towards the SE. Close to the contact with the Unango SD, moderately NW-dipping foliations, axial planes and down-dip stretching lineations indicate NW-directed transports, away from the Unango SD. Combined with the normal geothermal gradient, this suggests the interpretation of the Unango SD as rising gneissic dome in an extensional setting and the Unango-Lilongwe contact as a detachment. Extension and updoming preceded the NtSZ and can be both of Irumide or early Pan-African age.

In the southern Lilongwe SD numerous interference folds of 3–10 km width are developed in the Kirk Range area (Fig. 12, Appendix 3). NNE to NE striking fold axial planes in the central part are progressively overfolded towards the NtSZ. In the southern part, fold axes are rotated anticlockwise into the SaSZ suggesting sinistral strike slip movements (Fig. 12).

Stereograms of structural data from the northern and southern Lilongwe SD are given in diagrams LI-1 and LI-2 of Fig. 3, respectively. Poles to foliations scatter in both areas over the whole stereogram with the majority representing moderate to shallow dips documenting poly-phase folding and predominantly sub-horizontal transports (i.e. nappe style tectonics).

Lineations (stretching, fold axes, intersection) in the northern

subdomain plunge at low angles in all directions with local maxima in northern and NE directions. In the southern subdomain the orientations change from moderate NE plunges in the vicinity of the NtSZ through shallow SSW plunge in the central part into shallow SE plunge when approaching the SaSZ (Fig. 12). The variations are interpreted to reflect Pan-African overprint of NE-SW trending Mesoproterozoic structures by SaSZ shearing and NtSZ thrusting.

The tectonic style in the Unango SD differs significantly from that of the Lilongwe SD, being characterised by moderate to steep foliations and highly variable fold interference patterns (Fig. 3, UN-5). Folds with NE-trending axial planes in the eastern part, outlined by the red lines in Fig. 12, vary from few hundred meters to more than 75 km size. Variably deformed plutons of the 570–480 Ma Pan-African Blantyre Suite are mostly limited to this subdomain and vary from undeformed ring complexes in the central part to sheeted plutons in the NtSZ.

The Nampula SD underlies the southernmost part of Malawi (Fig. 12, Appendix 3). It is juxtaposed along the ENE-trending Lurio SZ with the Unango SD to the north, where it truncates the NW-SE trending SaSZ. The tectonic style in the northern and southern parts the Nampula SD is characterised by moderate to subvertical gneissic foliations, tightly folded and NW-verging on all scales, parallel to the Lurio SZ. Lineations plunge from NE to SW thereby defining a plane whose pole indicates a NW plunging fold axis (Fig. 3, NA-1), suggesting non-coaxial deformation during NW-directed tectonics. In the central part, numerous discrete ENE striking steep oblique dextral mylonitic to ultramylonitic shear zones are considered to be splays of the Lurio SZ. The rather limited impact of Pan-African tectonics on the Mzimba, Kasungu and northern Lilongwe subdomains implies that the regional tectonic stacking resulted from collision of the Zimbabwe Craton and BuNy Block (considered as part of the Congo Craton) during the Irumide orogeny. The structural younging to the north implies the subduction of the Zimbabwe Craton below the BuNy Block (Fig. 13). Continuation of the Nampula SD into the Barue Complex east of the Zimbabwe Craton implies accretion after the main collision stage.

## 5.3. Age of South Irumide Domain (SID) metamorphism and deformation

The relative impact of the Mesoproterozoic Irumide and Neoproterozoic East African (Pan-African) orogenies in the SID of southern Malawi is unclear. In the Unango SD, the characteristic rocks are charnockitic gneisses and variably retrogressed granulite-facies paragneisses. In NE Mozambique Unango SD rocks yielded average metamorphic U-Pb zircon rim ages of  $955 \pm 9$  Ma (Bingen et al., 2009). In contrast, published studies of gneisses from the Unango SD in Malawi have only reported Pan African ages between 594 and 515 Ma, associated with granulite facies metamorphism of  $900 \pm 70$  °C and pressures of 9–12 kb (Kröner et al., 2001; Manda et al., 2019; Goscombe et al., 2020; Tsunogae et al., 2021; GEMMAP).

To try resolving this problem, U-Pb zircon geochronology was carried out on three samples from two key outcrops in the Lilongwe Subdomain to illustrate the problem and provide a possible solution (Fig. 14, Appendix 2). Sample Z00085 was collected from an anatectic granodiorite that crops out near the Unango-Lilongwe subdomain boundary. The intrusion shows a diffuse intrusive contact into paragneissic country rocks and contains layers and schlieren of migmatitic segregations that broadly parallel the regional gneissic foliation.

47 spot analyses were made, 43 of which group to give a weighted mean  $Pb^{207/206}$  age  $1028 \pm 15$  Ma (Fig. 15a) and an identical concordia age of  $1026 \pm 15$  Ma the crystallisation age of the granodiorite and the timing of peak Irumide metamorphism (Fig. 15b). 3 analyses were somewhat older with  $Pb^{207/206}$  ages of  $1407 \pm 46$ ,  $1273 \pm 47$  and  $1179 \pm 27$  Ma, and probably represent inherited xenocrysts.

20m from Z00085, the gneisses are crosscut by a low-angle shear zone, which was locally intruded by a sheet of coeval migmatitised, isoclinally folded tonalitic orthogneiss (Sample Z00769). The migmatitic layers are parallel to the shear zone but oriented at a high angle to the

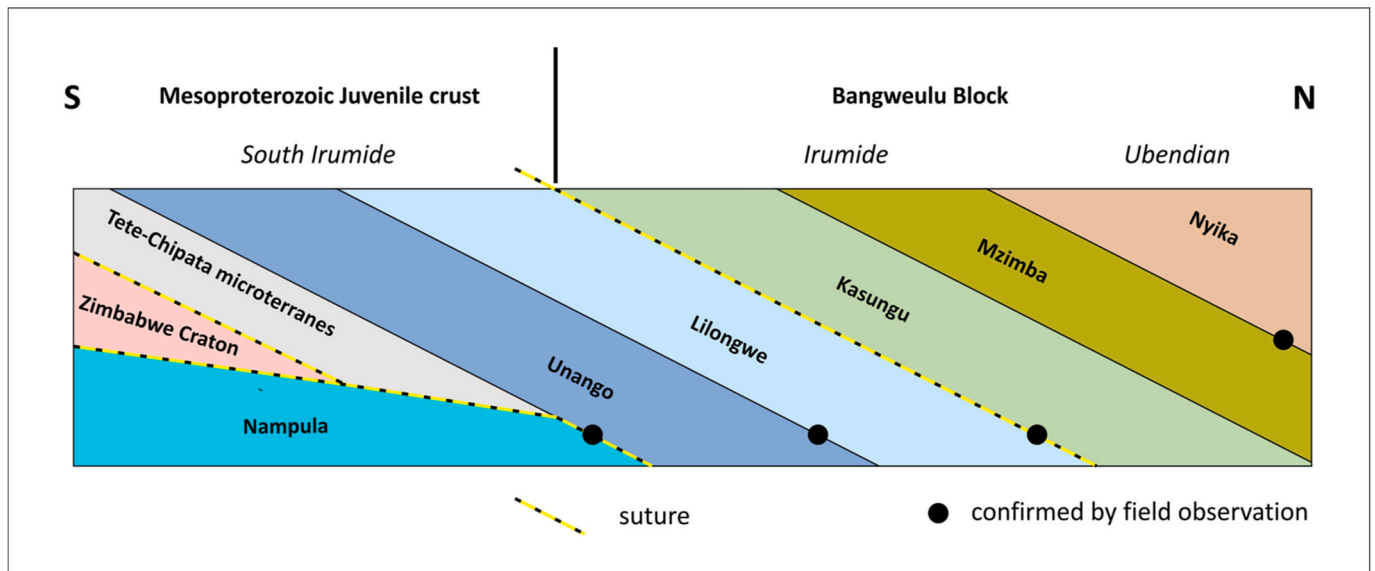


Fig. 13. Schematic structural pile resulting from the Irumide orogeny.

regional gneissic layering, showing that the tonalite sheet was intruded during shearing. Consequently its age will constrain that of intrusion, ductile shearing and the minimum age of the main regional fabric.

29 zircon analyses were made, the majority of which yielded a spread of  $Pb^{207}/Pb^{206}$  ages between 697 and 454 Ma and  $Pb^{206}/U^{238}$  ages between 669 and 513 Ma. Of the most concordant analyses (<15 % discordant), 17 analyses group to yield a weighted mean  $Pb^{207}/Pb^{206}$  age of  $582 \pm 14$  Ma and 22 analyses group to yield an identical concordant age of  $571 \pm 13$  Ma (Fig. 15c). The former is taken to date the emplacement of the cross-cutting granitoid sheet and to provide a maximum age for its gneissic foliation and the shearing during the Pan-African. Two additional grains yielded  $Pb^{207}/Pb^{206}$  ages near 1080 Ma, taken to represent an inherited component.

From the northern part of the contact, **Sample ZO0645** is a syn-thrusting leucosome in highly migmatitic, mesocratic, medium-to coarse-grained (garnet)-biotite-hornblende gneiss with abundant amphibolite boudins developed in the sole thrust of the NtSZ. 43 zircon spot analyses yielded  $Pb^{206}/U^{238}$  ages between 631 and 557 Ma (not shown) with Th/U between 0.05 and 0.12 suggesting a metamorphic origin. For the former there is a clear step in the data with 7 analysis giving an age of  $638 \pm 20$  Ma and the remaining 37 analyses giving  $563 \pm 9$  Ma. In the  $Pb^{206}/U^{238}$  data there is no bimodality and the youngest 35 analyses yielded a  $Pb^{206}/U^{238}$  age of  $583 \pm 5$  Ma from the middle of the group yielded an age of  $586 \pm 6$  Ma. The excluded data are slightly reversely discordant. The 38 most concordant zircons yielded an age of  $583.5 \pm 4$  Ma (Fig. 15d) which is interpreted as the age of the leucosome, and thus anatexis and thrusting.

In conclusion, the combination of structural field observation and geochronology indicate a first phase of regional high-grade metamorphism, deformation and collision-related magmatism dated at  $1028 \pm 15$  Ma, during which the two Irumide domains were juxtaposed, followed by updoming of the Unango SD prior to c. 590-570 Ma, where discrete high-temperature Pan-African African shear systems developed.

## 6. Mid-Neoproterozoic (Tonian-Cryogenian) extension (Nyassa Suite)

Following the end of the Irumide orogeny at  $\sim 1000$  Ma, the Nyassa Suite, a series of alkaline igneous plutons, were emplaced throughout Malawi (Fig. 16). The suite ranges from saturated granitoids through undersaturated feldspathoidal syenite complexes to dolerite dykes, minor gabbro and pyroxenite stocks. The rocks were emplaced during

two main intrusive episodes from c. 890-860 (mainly granitoids) and 790-715 Ma (mainly syenitoids, see Appendix 1). Coeval-bimodal mafic and felsic magmatism is demonstrated in the Rumpi area by cross-cutting relationships between dolerite dykes and granite stocks (Fig. 16, inset). In the Champira dome the mafic dykes are transposed by the MwsZ and further south overprinted progressively by Pan-African metamorphism.

The geotectonic importance of the Nyassa Suite is twofold:

- The c. 10 larger intrusions are distributed over the whole of Malawi (Fig. 16), demonstrating that the present-day crustal configuration already assembled by then, regardless of subsequent (Pan-African) crustal movements.
- The suite was emplaced in an extensional (rift) setting, probably a manifestation of Rodinia break-up.

## 7. Late Neoproterozoic to lower Palaeozoic (Pan-African) orogeny

### 7.1. The Pan-African problem

The precise nature and importance of the late Neoproterozoic “Pan-African” event in this part of Africa remains a thorny issue, due to its largely “overprint” status. Fig. 17 illustrates the principal effects of Pan-African overprint in Malawi, showing areas with pervasive tectono-metamorphic overprint, thermal overprint, and/or discrete shear zone systems, along with the c. 580-470 Ma granitoids of the Blantyre Suite in the southern part of Malawi.

The Pan-African tectonic effects generally intensify towards the south, ranging from discrete shears in the Ubendian and Irumide domains, variable in the Lilongwe SD, and pervasive in the Unango and Nampula subdomains. In similar fashion, metamorphic conditions increase from greenschist facies in the north through amphibolite facies in the centre to granulite facies in the south. The marked jump in metamorphic grade and deformation style across the Unango-Lilongwe SD boundary suggests that contact is a detachment, but other contacts are less clear. Zircon rims in granulite facies rocks of the Unango and Nampula SDs in Malawi indicate a Pan-African pervasive overprint that occurred between 569 and 557 Ma, reaching peak conditions of 9–11 kb and 840-93 °C (Goscombe et al., 2020; Tsunogae et al., 2021; Thomas et al., 2022a, Table 4).

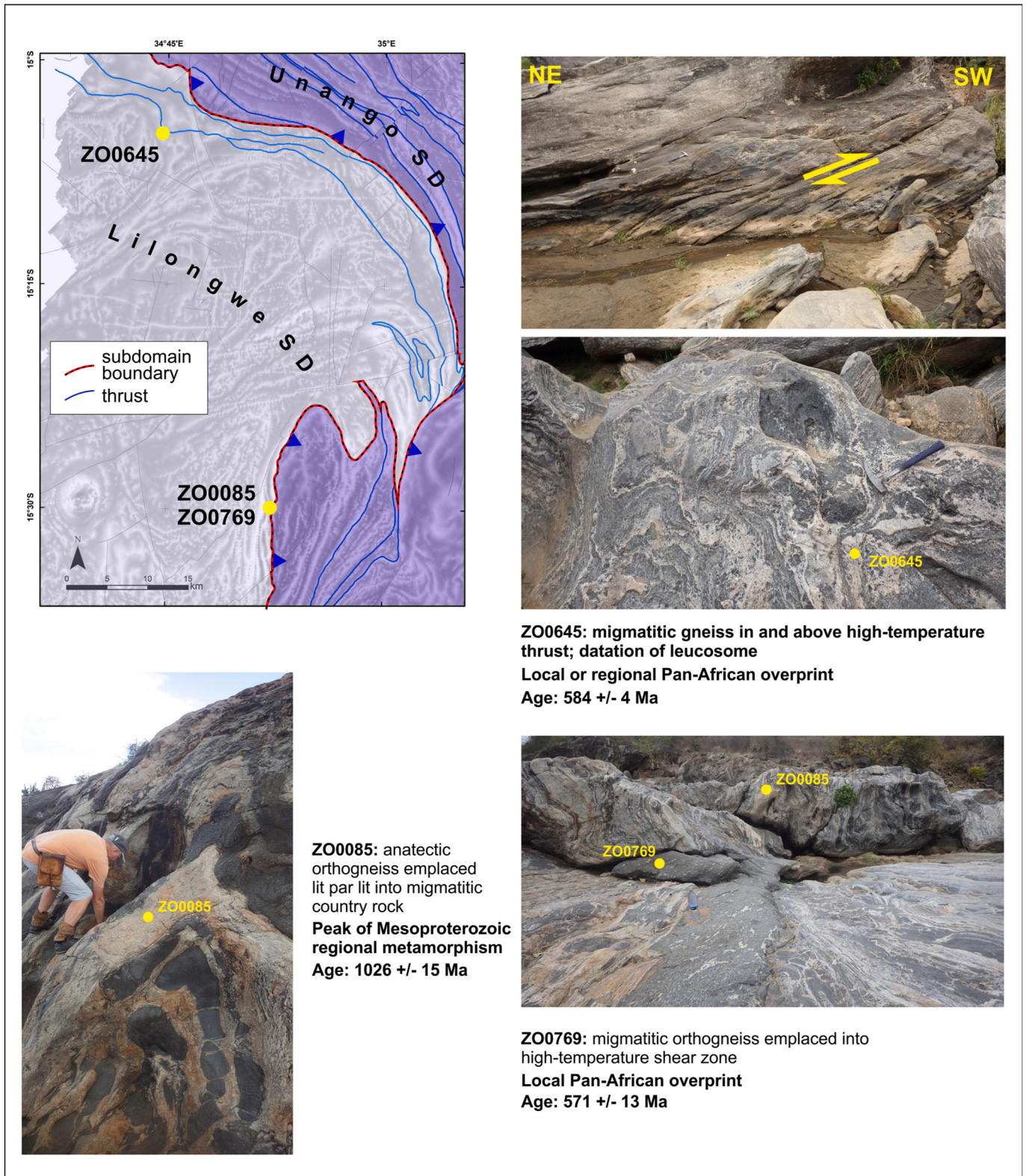


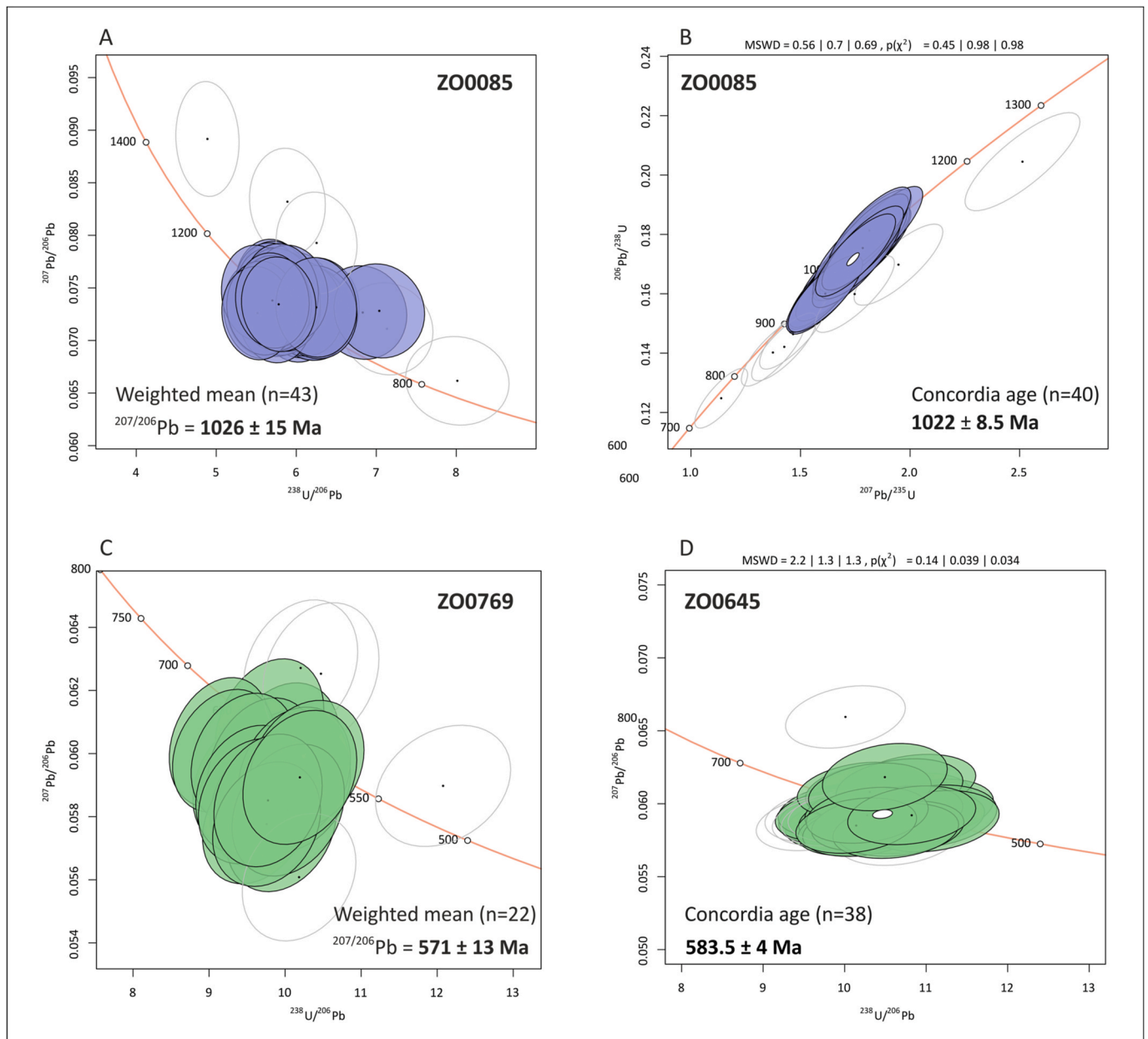
Fig. 14. Key outcrops in the Lilongwe and Unango subdomains document Mesoproterozoic high-grade regional metamorphism by massive intrusions of anatectic granite (ZO0085) and Pan-African magmatism and low-angle thrusting.

7.2. Pan-African shear zones

Short descriptions of these important structures are presented from north to south:

The **Mugesse Shear Zone (MuSZ)** in northern Malawi is a major

regional NW-SE sinistral strike-slip system several tens of km wide with a polyphase Pan-African deformation history. It is likely a reactivated Palaeoproterozoic structure that separates Ubendian subdomains from the Tanzania-Congo Craton (including BaNy). Individual, sub-vertical anastomosing shear zones are up to 2–3 km wide and transformed



**Fig. 15.** Sample ZO0085: a) Tera-Wasserburg (TW) plot of all data; b) Wetherill plot of the most concordant data (40). ZO0769: c) TW plot of the most concordant data (22). Sample ZO0645: d) TW plot of the most concordant data (38).

gneisses of the Ufipa and Mbozi subdomains into mylonite, blastomylonite and schist. The rocks within the shear zones are Palaeoproterozoic in origin, but their current distribution is due to superimposed Neoproterozoic deformation. The shearing occurred under greenschist facies conditions (Gremmel et al., 2023, Table 4).

The N-S striking **Nthalire Shear Zone (NthSZ)** connects the MuSZ in the north to the MwSZ in the south across the Nyika SD. In the north, the NthSZ is truncated by the MuSZ along the Ufipa-Nyika SD boundary, whereas in the south, the system merges with the MwSZ. The aeromagnetic data highlight the up to 50 km long curvilinear structures due to their low magnetic field. Individual branches can be up to 1500 m wide and consist of discrete 5–10 m wide mylonites and schists within the host gneisses. The schists indicate formation under middle amphibolite facies conditions as indicated by staurolite-garnet-muscovite-biotite parageneses.

The **Mwembeshi Shear Zone (MwSZ)** is a major continental structure that runs SW from Lake Malawi through Zambia into Namibia. In

Zambia it forms the boundary between the Lufilian arc and the Zambesi Belt. Extension east may be represented by the Macaloge Shear Zone (see below) in NE Mozambique. It has been interpreted as a Pan-African suture between the Irumide and South Irumide domains or Kalahari and Congo cratons, respectively (Unrug, 1983; Hartnady et al., 1985; Kampunzu and Cailteux, 1997; De Waele et al., 2006b, 2009) or as a reactivated Palaeoproterozoic zone of lithospheric weakness with no evidence of Neoproterozoic collision in the Lufilian/Zambezi Belt domain (Porada and Berhorst, 2000). The principal movements in the MwSZ are described as sinistral (De Swardt and Drysdall, 1964; Porada and Berhorst, 2000) or as a combination of early dextral and subsequent sinistral shear (Goscombe et al., 2020).

In Malawi, similar Irumide Domain rocks and structures occur on both sides of the ~30 km wide MwSZ (Mzimba and Kasungu subdomains) excluding the interpretation of the SZ here as a suture. The shear sense is dextral in Malawi, evidenced by the clockwise rotation of adjacent older gneissic fabrics and fold axial traces, and the dextral

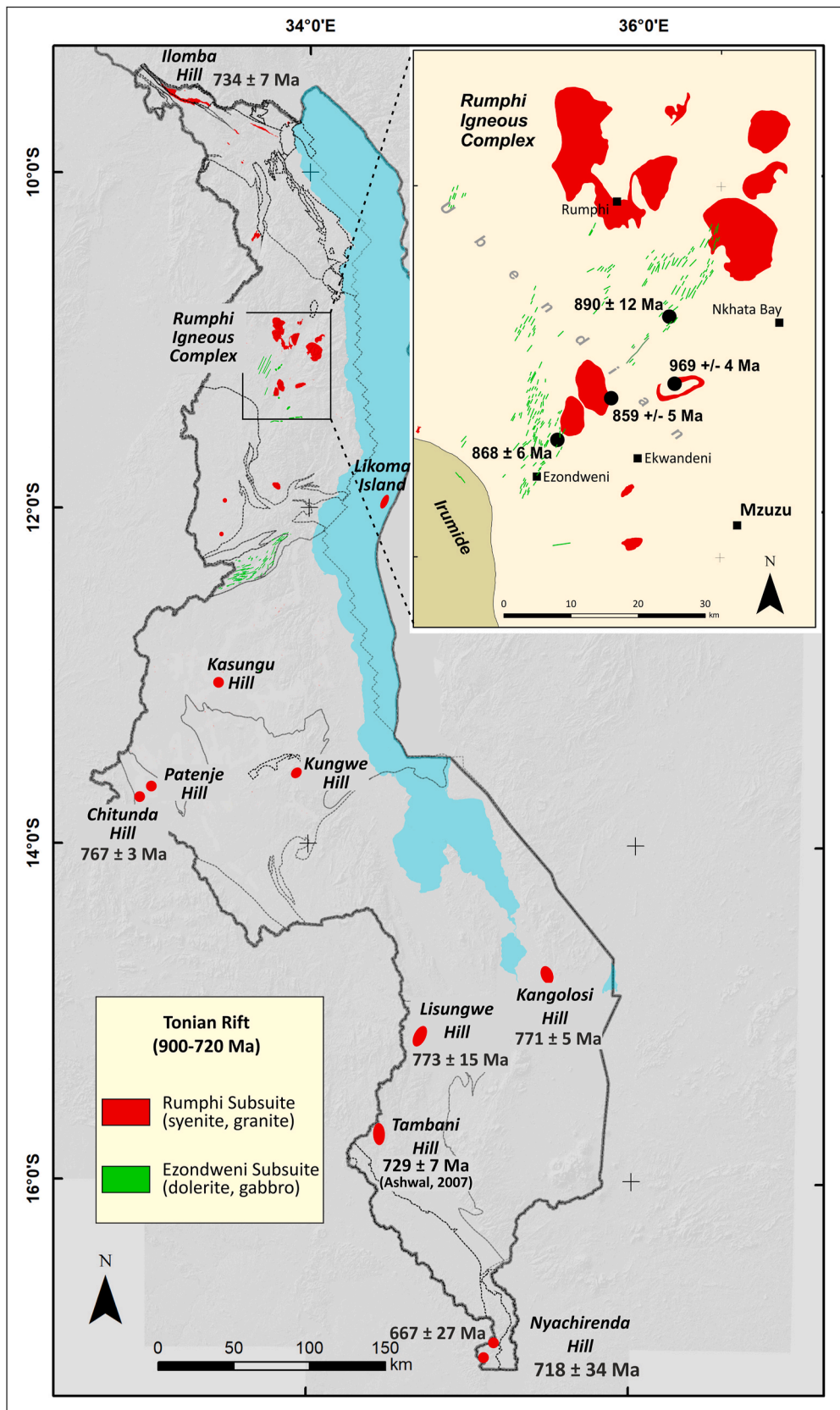


Fig. 16. Distribution of the Nyassa Suite in Malawi with the inset focus on complexes and bimodal magmatism of the Rumphi area. The Tambani Hill intrusion was dated by Ashwal et al. (2006), the rest from GEMMAP.

**Table 4**

Selected P/T/t data constraining Pan-African metamorphism and age in Malawi and northern Mozambique.

Domain	Subdomain/shear zone	Pan-African paragenesis	P [kb]	T [°C]	Age [Ma]	Reference
Ubendian	MuSZ	chl-bt	1–7	330–480	547 ± 5	Gremmel et al. (2023)
Irumide	MwSZ	st-gt-bt-ms-pl-qz	6.5–9	540–645	563 ± 17	Hieber (2021)
	Kasungu	ky-st-gt-bt-ms-pl-qz	6–8	660–670	542 ± 32	Huang (2017)
South Irumide	Lilongwe	bt-gt-ms-pl-qz	9–10.5	620–692		Chirwa (2021)
		gt-opx-cpx-pl	8.6–11.2	654–822	557 ± 16	Engvik and Bingen, 2017
	Unango	gt-opx-cpx-pl	10–13.6	875		
		sp-px-gt-bt	9–11	840–930	569–557	Tsunogae et al., 2021
		gt-2px-pl-qz	7.9 ± 1.3	760 ± 98		Engvik et al. (2019)
	Lurio SZ (Ocua Complex)	sp-2px-gt-bt	10.8	949 ± 92		Engvik et al. (2007); Thomas et al. (2022a)
		Nampula	sp-2px-gt-bt	15.1 ± 1.4	949 ± 92	557 ± 16

rhombohedral shape of the Champitra Dome (Fig. 8). Complex deformation up to 30 km north of the main shear zone is recorded by Ubendian gneisses, which have been transformed pervasively into folded garnet-biotite-muscovite schist (Fig. 17). Staurolite-garnet-muscovite-biotite parageneses in the schist indicates shearing under medium-pressure amphibolite facies conditions of 6.5–9 kb/540–650°C (Hieber, 2021, Table 4). Geochronology of monazite from these rocks yielded three age groups of 1047 ± 47, 748 ± 32 and 563 ± 17 Ma, documenting their Irumide heritage, Tonian rifting (Nyassa Suite) and the final Pan-African overprint (Hieber, 2021). Similar and related reactivation of Mesoproterozoic structures by Tonian rifting is also shown in northern Mozambique by the 714 ± 17 Ma rhyolite of the Txitonga Group immediately north of the MwSZ, locally referred to as Macaloge Shear Zone (Fig. 17, Bjerkgard et al., 2009). These rocks, deposited on Ubendian high-grade gneisses of the Ponta Messuli Complex in turn underwent Pan-African lower greenschist facies metamorphism.

The **Nthonda SZ** is an east-west striking shear zone in central Malawi identified from the airborne geophysics (Fig. 8). The adjacent gneissic foliations were dextrally rotated into the structure. Several small magnetic anomalies along the shear zone are interpreted as syn-tectonic mafic rocks. To the west, near the contact with the Mchinji SD, the shear zone turns south and becomes a west-directed thrust.

The NW-SE trending, NE-dipping **Ntcheu SZ (NtSZ)** extends from Dedza approximately 200 km to the southeast, where it ends in a series of blind thrusts within the Unango Subdomain. The mylonitic gneisses in the NtSZ exhibit prominent down-dip stretching lineations that record SW-directed thrusting of the Unango SD over the Lilongwe SD. While few localities showed kinematic evidence for the thrusting, most places show superimposed normal, NE-directed extensional inversion that also affected c. 550 Ma syenites of the Blantyre Suite and probably associated with orogenic collapse. The regional scale of this stage is suggested by a similar detachment at the base of the Monapo Klippe in NW Mozambique (Miller et al., 2013)

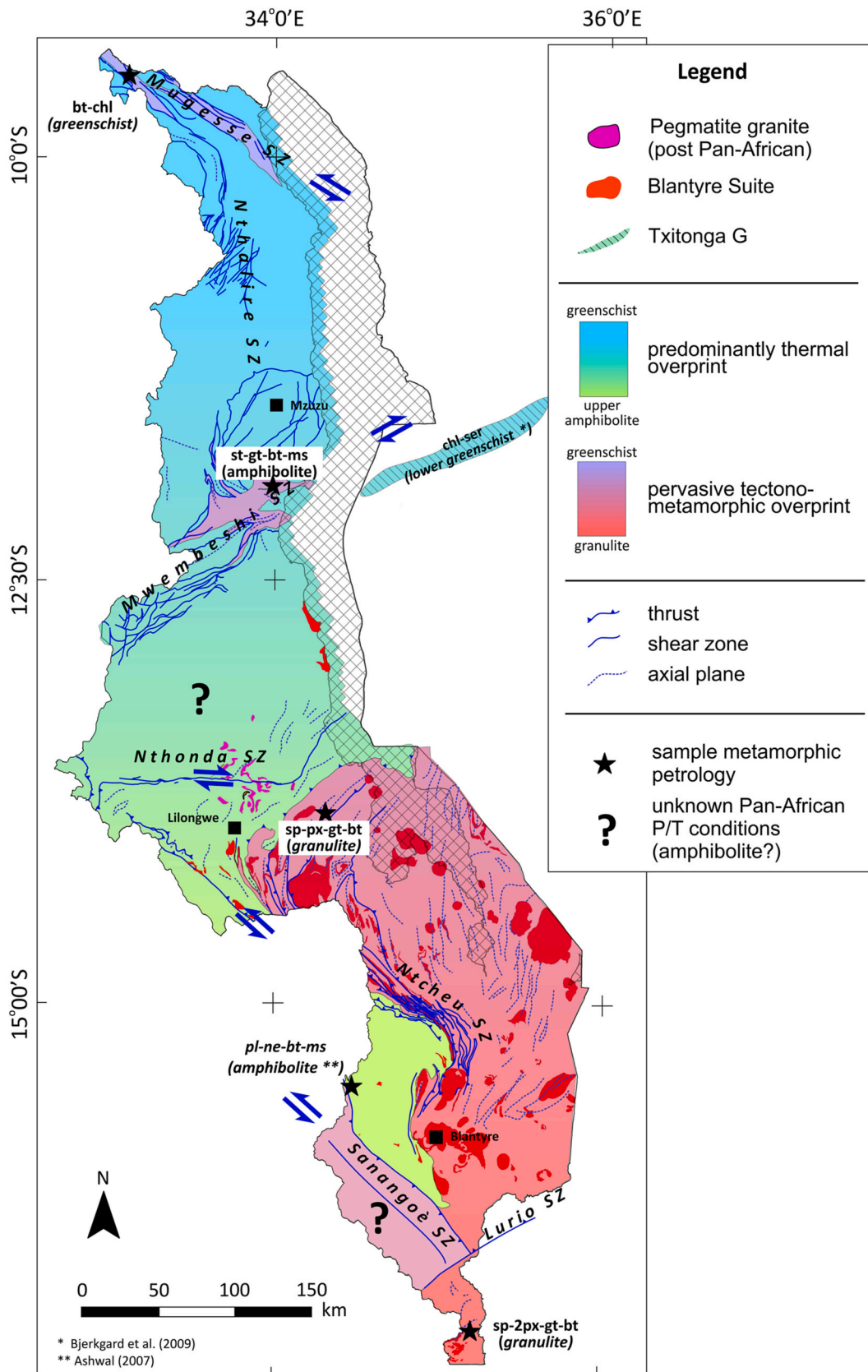
The **Sanangòe Shear Zone (SaSZ)** is a crustal-scale, c. 10 km wide, Pan-African regional transpression zone interpreted as part of the suture between South and West Gondwana (Westerhof et al., 2008a; Goscombe et al., 2020). In Zambia, it merges with the coeval MwSZ (Daly, 1986a-b, 1988). However, post-tectonic Mesoproterozoic granitoids and Tete Suite rocks on both sides of the SaSZ (Pinna et al., 1993; Evans et al., 1999) suggests the Mesoproterozoic origin and Pan-African re-activation.

The SaSZ is oriented E-W in the Zambesi Valley in NW Mozambique, but swings SE near the Malawi border. Airborne geophysical data suggest that the SaSZ is truncated by the NE trending Lurio SZ, although the contact is concealed beneath the younger deposits of the Middle Shire Rift Valley. Anticlockwise rotation of gneissic foliations of the Lilongwe SD into the SaSZ indicates principal sinistral strike-slip movements. These affect the Neoproterozoic Tambani pluton (Nyassa Suite), demonstrating the Pan-African age. However, the consistently steep SW-dip and shallow S-plunging lineations in (mylonitic) gneisses of the eastern graben shoulder of the Shire Valley imply a late phase of dextral strike-slip under a transpressional regime.

The ENE-WSW trending **Lurio Shear Zone (LuSZ)** is an important structure which separates the Lilongwe and Unango subdomains from the southern Nampula SD and may connect with the Umkondo Belt further south. In Malawi, it is concealed below younger deposits. The LuSZ changes along strike from steep in the west to shallow-north dipping in eastern Mozambique. In general it is poorly exposed, but is clearly visible in the geophysics data, where it appears to fan out within the Nampula SD of Malawi into a series of small-scale thrusts and shear zones. These features indicate a polyphase history of deformation at various scales and magnitudes (e.g. Thomas et al., 2022b). The LuSZ contains slivers of high-pressure granulites of the 557 ± 16 Ma Ocua Complex (Boyd et al., 2009; Engvik et al., 2019; Thomas et al., 2022), occurring on both sides of, and within it, resulting in a tectonic mélange of rocks with different metamorphic grades and lithology (Macey et al., 2010). The LuSZ is therefore regarded as a Pan-African suture, but it was probably initiated during Mesoproterozoic (Stenian) times during accretion of juvenile arcs and so may have been the site of Irumide collision, followed by Neoproterozoic extension and (limited?) re-opening and subsequent Pan-African re-collision (e.g. Thomas et al., 2022).

### 7.3. Pan-African magmatism in Malawi - Blantyre Suite

The Blantyre Suite comprises voluminous potassic granitoids and syenites with minor mafic and ultramafic rocks that intrude Malawi south of the MwSZ and are particularly ubiquitous in the Unango Subdomain (Figs. 12, 17 and 18). They range in size from large polyphase nested plutonic complexes up to 40 km across to thin dykes and sills on the metre scale. They show an enormous range of compositions and textural lithotypes with variably developed tectonic fabrics. On a major element basis, the rocks can be subdivided into (i) alkali-feldspar granite-syenogranite monzogranite, (ii) alkali-feldspar syenite-syenite-nepheline syenite, (iii) alkali gabbro and, (iv) lamproite (Boger, 2022). Ten samples were dated by U-Pb zircon during GEMMAP which shows an extremely long period of magmatism from 590 to 470 Ma (Fig. 12). The rocks were emplaced in an extensional geodynamic setting. It is noteworthy that the Blantyre Suite is most widespread in the highest grade Unango SD, with its high geothermal gradient associated with extension and lithospheric uprise. Because of their similar age, Nd-isotope signatures cannot distinguish between a mantle and crustal origin (Fig. 5). High absolute trace element abundances observed for the mafic and ultra-mafic rocks from the Blantyre Suite, together with the enrichment of LREE compared to HREE, implies that these rocks were derived from a non-depleted mantle source, which excludes both a plate margin and collision setting. The persistent negative Nb-Ta anomaly, which commonly is interpreted to reflect either arc or crustal influences, is perhaps best explained via melting within a subduction zone of sub-continental lithospheric mantle, possibly with metasomatism potentially reflecting the convergent margin events associated with the formation of the South Irumide island arc and/or its accretion to the southern margin of the Congo-Tanzania Craton (Boger, 2022). Late magmatism is represented by pegmatite and pegmatite granite swarms in the Mzimba and northern Lilongwe SD, the former of which was dated



**Fig. 17.** Simplified tectono-metamorphic map of Malawi illustrating the main Pan-African structures, intrusions and variation in metamorphic grade and tectonic overprint. Karoo and younger rocks were stripped from the basement. Pan-African P/T conditions in Lilongwe SD and Sanangoe SZ are undetermined but probably reached amphibolite facies.

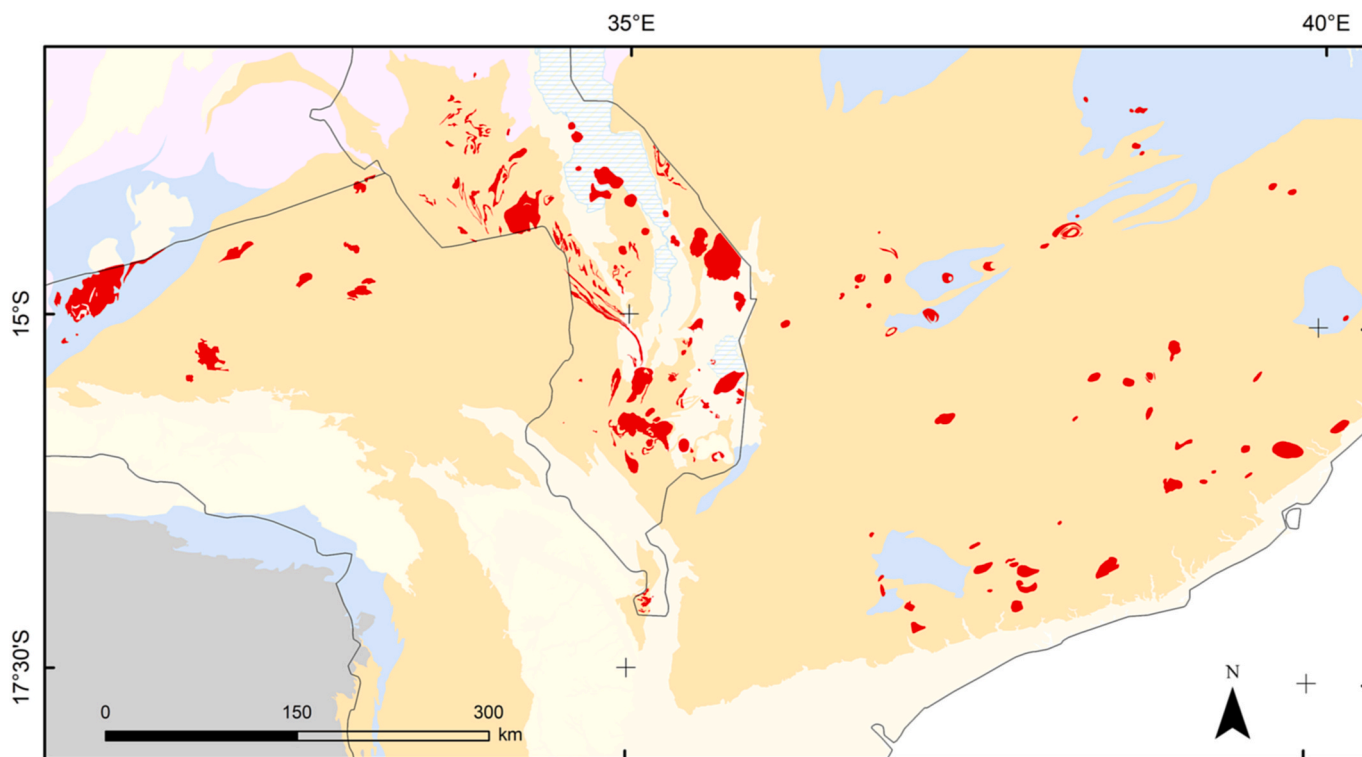


Fig. 18. Blantyre Suite magmatism in northern Mozambique and Malawi (modified from BRGM SIG-Afrique-2016; unpublished).

by Ar-Ar muscovite at  $480.7 \pm 0.9$  and  $475 \pm 1.0$  Ma (Thomas et al., 2022c).

## 8. Precambrian crustal evolution of Malawi

Malawi can be subdivided into three fundamental crustal blocks comprising (from north to south): the Ubendian, Irumide and South Irumide domains. Subsequent Neoproterozoic events affected them all to varying degrees.

### 8.1. Ubendian Domain

The 2150–1800 Ma Ubendian orogen is commonly viewed as an NW-striking linear belt made up of eight separate terranes (e.g. Daly, 1988), variably reworked during the Kibaran (c. 1400 Ma), Irumide (c. 1100 Ma) and (more intensely) Pan-African orogenies (see review in Boniface and Appel, 2017). GEMMAP confirmed extrapolation of three of Daly's (1988) "terranes" into northern Malawi (Mbozi, Ufipa and Nyika subdomains). Each subdomain is characterised by distinct supracrustal rock assemblages, plutonism and prograde medium to high-pressure upper amphibolite to granulite facies metamorphism at c. 2030 Ma (e.g. Le Bayon et al., 2024; see Table 2). In the Ufipa Subdomain isolated remnants of a cryptic ~2150 Ma orthogneissic basement are exposed, upon which supracrustal rocks were deposited at c. 2000–1900 Ma and metamorphosed soon thereafter.

The largest, Nyika Subdomain, contains traces of the older ca 2150 Ma basement in inherited zircon grains in the oldest magmatic rocks emplaced at c. 2030 Ma (Le Bayon et al., 2024). Magmatism at c. 1980 Ma was synchronous with the main Ubendian regional medium-pressure granulite facies metamorphism of c. 780 °C and 6 kb dated between  $1977 \pm 14$  Ma and  $1984 \pm 13$  (Ring et al., 1997; Le Bayon et al., 2024). The geochemistry of the magmatic pulses suggests that they occurred in active continental margin setting above a south-directed subduction zone (Table 2).

Structural data suggests the UBD evolved during an early phase of N-S shortening and thrust-related vertical thickening in a convergent,

Andean-type tectonic setting. The Ufipa and Mbozi SD are part of the steeply dipping root zone for nappes transported during collision to the north over the Tanzania Craton. Post orogenic magmatism is only seen in the Nyika SD, with the emplacement of weakly deformed, typically feldspar porphyritic granites (Nyika Suite) at c. 1945 Ma (Le Bayon et al., 2024).

The Ufipa SD was intruded during the Mesoproterozoic by the c.1410 Ma Mwakikome orthogneiss and the 1110–1150 Ma Mwenga Suite (Thomas et al., 2023a), and subsequently overprinted by widespread Pan-African shear zones (such as the Mugesse SZ) and low-grade metamorphism at 350–475 °C/5–7 kb (Gremmel et al., 2023).

Our study suggests that the Nyika SD extends westwards into the Palaeoproterozoic "Bangweulu Block", without break, implying that they are one and the same forming the internal zone of the Ubendian orogen (Thomas et al., 2023b) and we introduce the term "Bangweulu-Nyika Block" or "BaNy". Docking of BaNy with the Congo-Tanzania craton occurred during the Ubendian orogeny. This is consistent with the tectonic evolution of Africa proposed by Begg et al. (2009). BaNy strikes broadly E-W, as opposed to the general NW-SE trend of the UBD. The latter is interpreted as a Pan-African trend superimposed on the Palaeoproterozoic microterranes of the UBD, reflecting that of the Neoproterozoic shear zone systems (e.g. the Mugesse SZ), which re-aligned and juxtaposed the older crustal subdomains (the Ubendian "terranes" of Daly, 1988).

### 8.2. Irumide and South Irumide Domains

The Mesoproterozoic NE-trending Irumide Belt shows a rapid increase in metamorphic grade over only c. 100 km from sub-greenschist facies in the NW foreland in Zambia (the BaNy Block) to granulite facies in the internal zone of the orogen in Malawi. Here it comprises the IRD and SID with slightly different ages. The former in the north is made up of reworked Palaeoproterozoic crust, while the latter consists of stacked juvenile subdomains (terrane; De Waele et al., 2006a, b; Johnson et al., 2004, 2005; Westerhof et al., 2008a; Boyd et al., 2009; Macey et al., 2010).

A continental margin setting for the Irumide Belt between c. 1150 and 1040 Ma has been proposed in Zambia (De Waele, 2005, 2006 a-b, 2008, 2009; Johnson et al., 2004, 2005; Westerhof et al., 2008a; Alessio et al., 2019a-b). This margin was either passive (De Waele, 2005, 2006a-b; Debruyne et al., 2014) or active (Johnson et al., 2005, 2007a), and was followed by the accretion of the SID between 1040 and 1020 Ma (Westerhof et al., 2008a). Alternatively, the SID was considered an integral part of the Congo Craton margin with different timing of magmatism in the two Irumide subdomains ascribed to an advancing magmatic front in response to a shallowing subduction zone located south of the SID (Bingen et al., 2009; Alessio et al., 2019a-b). The collision phase is characterised by high-temperature, low-pressure metamorphism and voluminous syn-collisional magmatism. Syn-orogenic emplacement of the c. 1040 Ma Tete Anorthosite-Gabbro Suite is associated with melting of dehydrated lower crust (Westerhof et al., 2008b).

Our results enable the definition of the distinct Irumide and South Irumide domains in Malawi, based on their lithostratigraphy, structure, metamorphism, intrusive history and Nd isotopic composition; findings which have significant implications in understanding the Irumide orogeny in central-eastern Africa.

The Nd isotope data indicate that the IRD is characterised by Archaean to Palaeoproterozoic (Ubendian)  $Nd_{Tdm}$  protolith ages, but no Palaeoproterozoic orthogneiss intrusions. The systematic southward younging of  $Nd_{Tdm}$  model ages in the Kasungu SD from >2.5 Ga to 1.45 Ga, suggests post-Ubendian deposition of the (probably once contiguous) Mzimba and Kasungu domain paragneisses and increasing influence of Mesoproterozoic juvenile sources. Detrital zircon geochronology of two samples indicates in some of the supracrustal rocks maximum deposition of <1080 Ma, with Mesoproterozoic igneous activity from 1190 Ma onwards. The Mchinji SG consists of intercalations of high-grade ferruginous quartzite and BIF within a sequence of alternating white quartzite and metapelite, suggesting correlation with the (lower grade) basal part of the Muva Supergroup in Zambia as outlined in De Waele and Mapani, 2002; De Waele et al., 2006b. Shallow foliations and N to NE plunging lineations in the IRD are typical of nappe tectonic style. Together with the structurally overlying position of the UBD, they suggest SE-directed movements resulting in the observed inverse tectonic stacking. Our mapping shows that termination of the folded northern orogenic front of Irumide Domain envelops the NW foreland in Zambia and continues into the folded contact between the Mzimba and Nyika subdomains in Malawi; the MuSZ traverses this foreland and does not terminate the Irumide Belt, nor is it a suture (c.f. Ring, 1993; Vrána et al., 2004; Westerhof et al., 2008a).

The geochemistry of the voluminous pre- to post-tectonic intrusions in the IRD suggests generation in a continental arc, collision-related geodynamic setting. U-Pb zircon ages of the vast majority of granitoid samples range between 1019 and 1086 Ma, peaking between 1030 and 1058 Ma and coinciding with the main phase of collision, deformation and metamorphism (GEMMAP).

The SID records  $Nd_{Tdm}$  protolith ages mainly between 1.1 and 1.5 Ga, indicating the predominance of Mesoproterozoic juvenile, arc-derived rocks. Two samples in the Nampula SG yielded Palaeoproterozoic model ages, demonstrating a greater influence of older continental crust. U-Pb zircon ages of 26 orthogneiss samples from the SID range from 1020 to 1180 Ma, a maximum between 1039 and 1055 Ma. The composition of these rocks suggests generation in an island arc accretionary geodynamic settings.

Field observations show that the SID underlies the Lilongwe SD along a sharp, shallow-dipping contact which was dated at  $1067 \pm 9$  Ma, with reactivation at  $1020 \pm 5$  Ma and again at  $559 \pm 4$  Ma (see above). Metamorphic conditions in the IRD vary from medium-pressure UHT granulite in the Mzimba (6–9.5 kb/900–1000°C; Sakuwaha and Tsunogae, 2024) and Mchinji (5–7 kb/800–950°C; Karmakar and Schenk, 2016) subdomains to upper amphibolite in the Kasungu (and probably the Lilongwe) SD (5.1–7.2 kb/730–770°C; Huang, 2017; Böhme, 2021).

The Irumide metamorphic ages range from  $1053 \pm 4$  Ma to  $1036 \pm 36$  Ma in the IRD and from  $1028 \pm 15$  Ma to  $1031 \pm 5$  Ma in the SID, coinciding with the peak of magmatism in each domains. The emplacement of the Tengani anorthosite at  $1008 \pm 39$  Ma suggests late Irumide emplacement associated with orogenic collapse and lithospheric delamination.

In summary, the evolution of the Irumide belt in Malawi can be divided into five main stages (Table 5) within the geodynamic setting at 1100 to 1070 Ma shown schematically in Fig. 19.

### 8.3. Neoproterozoic rifting

The Nyassa Suite represents extensional rift-related bimodal, partly alkaline plutonism between 850 and 720 Ma across Malawi, which forms an important time-marker for distinguishing Pan-African and Mesoproterozoic deformation and metamorphism. The intrusions cross-cut all Mesoproterozoic (Irumide) features, in turn refuting cross sections developed for Malawi, where the regional tectonic style has been related to the ~500 Ma “Kuunga orogeny” (e.g. Goscombe et al., 2020).

Rocks of similar age and composition occur in eastern and southern Africa for over 1500 km (Kampunzu et al., 1997), extending from Burundi (Decrée et al., 2019) through Tanzania (Brock, 1968), to Zambia (Johnson et al., 2007b, Zimbabwe (Koistinen et al., 2008; Chaúque et al., 2017; Kuribara et al., 2019), and northern Namibia (Hoffman et al., 1996; De Kock et al., 2000) and suggest again connection of the Kalahari-Zimbabwe/Congo-Tanzania cratons following the Irumide orogeny. The rift-related Mutare-Fingeren mafic dyke swarm dated at 724–712 Ma in NE Zimbabwe and East Antarctica (Gumsley et al., 2023) and the bimodal Ocua Complex in NW Mozambique dated at 740–644 Ma may also be part of this event.

### 8.4. Was Malawi's foundation laid by the Irumide or Pan-African orogenies?

There is a continuing debate about whether the basic foundation blocks of this part of SE Africa were put together during the Irumide orogeny and subsequently jostled about during the various stages of the Pan-African orogeny, or whether the juxtaposition happened for the first time during the latter.

The Pan-African event spans the period from c. 660–470 Ma and comprises a series of successive collisional orogens leading to the assembly of Gondwana (Goscombe et al., 2020 and references therein). These orogens have been termed the East African Orogen (650–635 Ma; EAO), the West Antarctica Orogen (605–635 Ma; WAO), the Kuunga Orogen (550–585 Ma; KUO) and the East Gondwana Orogen (530–515 Ma; EGO). Each has had a significant impact on the Precambrian crustal architecture of southern and eastern Africa, resulting an apparent EW-NS “crossroads” configuration in the area south of Malawi between the older N-S trending EAO-WAO and the younger E-W trending KUO. Two models have been postulated to explain this “crossroads” configuration:

- 1) The Kalahari craton formed an independent plate surrounded by large oceanic basins (e.g. Sawyer, 1981; Kröner, 1982; John et al., 2003; John and Schenk, 2003; Collins and Pisarevsky, 2005; De Waele et al., 2008; Grantham et al., 2008; Jacobs et al., 2008a; Bingen et al., 2009; Goscombe et al., 2020). In this “wide-ocean” setting, the LuSZ is interpreted as a Pan-African suture extending through the SaSZ into the Zambezi-Damara Belt in the west and separating the Azania-Dhawar and Dronning-Maud-Land-Mawson plates in the east (Goscombe et al., 2020). The Kuunga orogeny is characterised by N-directed subduction of the Kalahari Craton beneath the Congo-Tanzania Craton) resulting in a pervasive tectonic overprint of all rocks south of the MWSZ (upper amphibolite to granulite conditions in Malawi). In this model, the juxtaposed Unango-Lilongwe-Kasungu crust forms a lithosphere-scale positive

**Table 5**

Reconstruction of the Irumide event in five stages. Left: Westerhof et al., 2008a, b, right: This work (GEMMAP).

Stage	Period [Ma]	Event		Period [Ma]
		Westerhof et al., 2008	This work (GEMMAP)	
	765–800	juvenile Neoproterozoic crust	Neoproterozoic rifting	720–850
Stage 5			Tete anorthosite: late -to post-Irumide (orogenic uplift and collapse, lithospheric delamination)	1000 ± 28
Stage 4			accretion Nampula (?)	1020–1030
Stage 3	1047 ± 29	Tete anorthosite syn-Irumide associated with melting of dehydrated lower crust		
	1020–1040	main orogenic event	continental collision	1030–1050
	1070	collision (subduction ceases)	island arc accretion (subduction ceases)	1067 ± 8
Stage 2	1070–1200	Congo/Bangweulu turns into an active margin		1067–1100
Stage 1	1200–1300	Congo/Bangweulu passive margin/island arcs and back arcs to the south		1100–1180

flower structure that transported rocks to both the north and south over the reactivated basement of the Congo-Tanzania and Kalahari cratons.

- 2) The Kalahari and Congo-Tanzania Cratons were already juxtaposed in the Mesoproterozoic during the Irumide orogeny. Consequently, the Damara-Zambezi Belt/Lufilian Arc formed narrow marine basins in the “aulacogen model”, as proposed by Martin and Porada (1977),

Kasch (1983), Miller (1983, 2008), Hanson et al. (1993), Milani et al. (2015) and Salminen et al. (2018). In this model, the LuSZ is a Mesoproterozoic suture that was reactivated as a rift in the Neoproterozoic and then closed again during the Pan-African event (Thomas et al., 2022b and references therein).

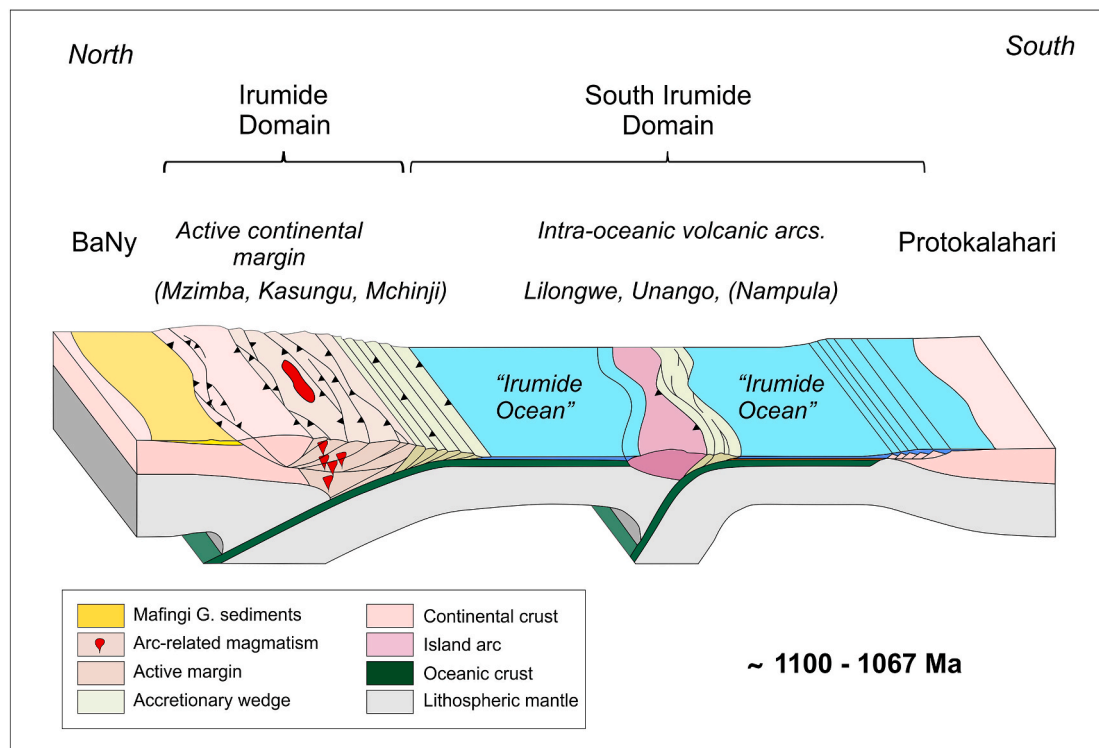
The GEMMAP results favour Model 2, the “aulocogen”, based on the following:

1. The Tonian-Cryogenian (c. 850 to 700 Ma) Nyassa Suite occur throughout Malawi, showing that all three domains must have been juxtaposed by then (i.e. during the Irumide orogeny).
2. The c. 1000 Ma Tete Suite and other Mesoproterozoic granitoids occur on both sides of the SaSZ (Pinna et al., 1993; Evans et al., 1999) suggesting it was initiated in the Mesoproterozoic and does not form a Pan-African suture.
3. The continuation of the Nampula SD into the Barue Complex of eastern Malawi (Chauque et al., 2019) implies the accretion of these terranes on the SE side of the Kalahari Craton and in combination with the Tete Suite the Mesoproterozoic age of Kalahari-Congo collision.

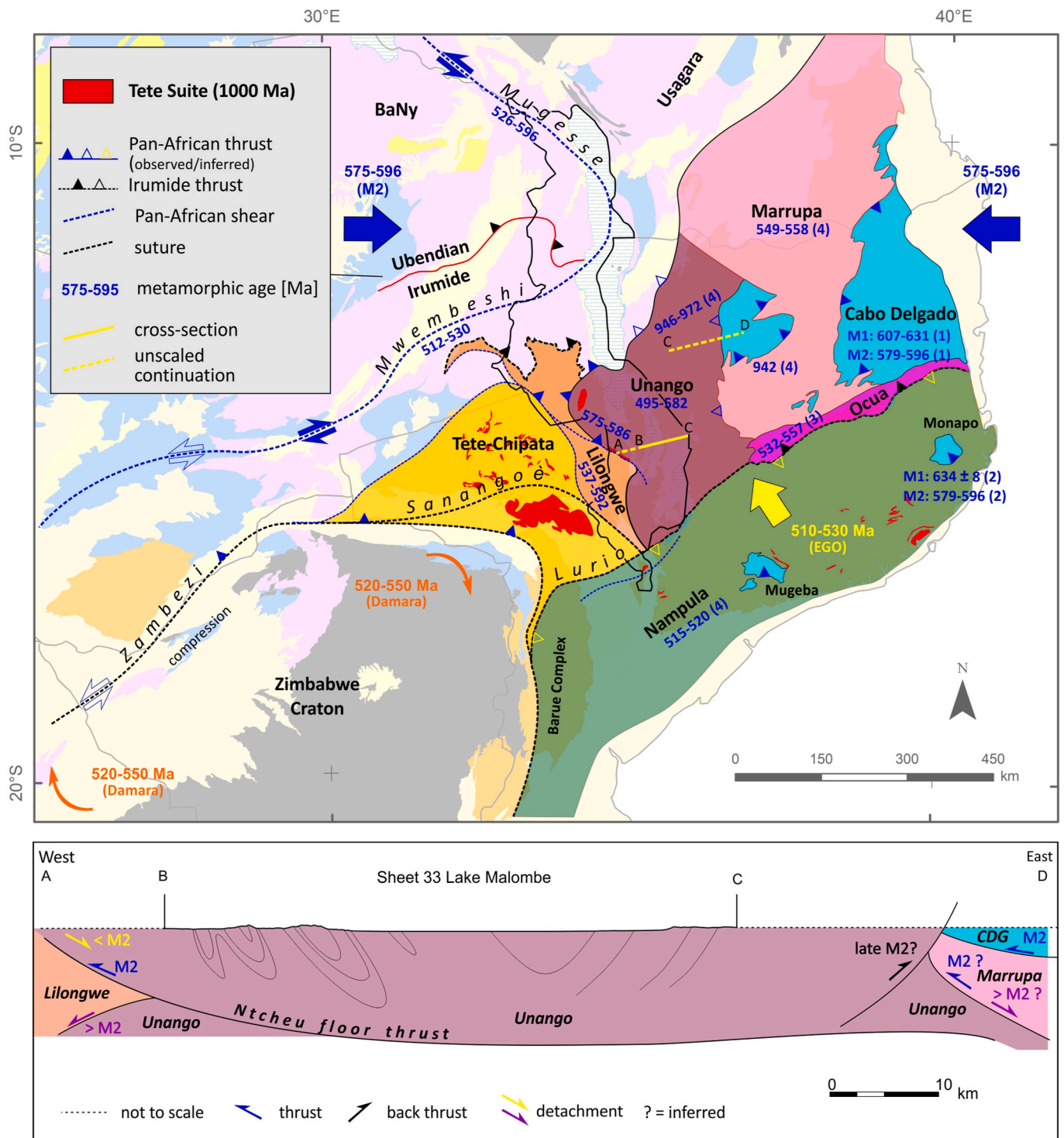
### 8.5. The Pan-African orogeny in Malawi

Assuming Irumide construction of Malawi, our model of the poly-phase Pan-African overprint in Malawi includes four regional stages (Fig. 20):

**Stage 1:** 630-600 Ma (EAO I): accretion of island arcs and micro-terranes at the eastern margin of the Tanzania Craton (Fritz et al., 2013; Fitzsimons, 2016). An early phase of high-grade metamorphism is preserved in the Eastern Granulite-Cabo Delgado Nappe Complex (EGCD) that records NW movements at around 630–610 Ma (Viola et al., 2008). This stage is not directly recorded in Malawi in our data, but it is likely that the Nampula SD was tectono-thermally affected by the Stage 1 accretion event.



**Fig. 19.** Geodynamic setting of the Irumide and South Irumide domains from c. 1100-1067 Ma.



**Fig. 20.** Tectonic map of central-eastern Africa illustrating the main crustal blocks and movements during the Pan-African event. Metamorphic zircon and monazite ages in blue (1: Viola et al., 2008, Boyd et al., 2009; 2: Macey et al., 2013; 3: Engvik et al., 2007; Viola et al., 2008; 4: Bingen et al., 2009), others GEMMAP). Blantyre Suite not shown for clarity (for the Malawian part, see Fig. 12). Simplified synthetic W-E cross section of Sheet 33 (Lake Malombe) demonstrating Pan-African large-scale folding and thrusting. The positive flower structure resulted from W-directed thrusting of the Unango SD, which is probably caused by the emplacement of the Cabo Delgado NC. Extensional settings prior and after this phase resulting in rise of the Unango metamorphic dome, reactivation of the NtcSZ thrusts by normal movements and emplacement of the mantle-derived Blantyre Suite. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

**Stage 2:** 600-570 Ma (EAO II): Final closure of the Mozambique Ocean and continent collision of the Dharwar/Azania with the Congo-Tanzania cratons (Fritz et al., 2013). In our model, this stage is separated from the KUO in Namibia and Zambia and it constitutes

the main Pan-African tectonic event in Malawi, marked by overall E-W compression, and producing all the major Pan-African tectono-metamorphic features described in this paper and summarised in Fig. 20.

**Stage 3:** 550-530 Ma (KUO): Closure of the Khomas Ocean resulted in the main Damara collision in Namibia far to the west, but had little impact in Malawi. Eastward detachments along reactivated thrusts are recorded at the Mchinji/Lilongwe SD boundary and the NtSZ (GEMMAP) may be of this age and may represent far-field effects of the Damara-Lufilian-Sambesi (Kuunga) orogeny, which terminated during this period.

**Stage 4:** 520-515 (EGO). Docking of East Gondwana (Antarctica) with Kalahari pervasively overprinted the Nampula SD and transposed all former structures into the final NE-SW structural trend. Reactivation of the LuSZ in Malawi truncated the SaSZ and resulted in the high-angle structural discordance outlined by airborne magnetic data.

Blantyre Suite magmatism from 580 to 490 Ma indicates a long-lived or repeated extensional tectonic setting(s) in central to southern Malawi with an intermittent phase of east-west compression at c. 570 Ma (see before). It may be related to the clockwise rotation of the Kalahari towards the Congo Plate around a hinge point in the Zimbabwe craton (Fig. 20). The origin of the Blantyre Suite by lithospheric delamination (Jacobs et al., 2008b; Thomas et al., 2010; Ueda et al., 2012) can be excluded due to the longevity of magmatism.

#### CRedit authorship contribution statement

**Thomas Fullgraf:** Writing – original draft, Project administration, Investigation. **Robert J. Thomas:** Writing – review & editing, Writing – original draft, Investigation. **Steven D. Boger:** Writing – review & editing, Investigation. **Olivier Blein:** Investigation. **Nicolas Charles:** Investigation. **Kondwani Dombola:** Project administration. **Dirk Frei:** Investigation. **Eija Hyvönen:** Investigation. **Philippe Lach:** Investigation. **Yann Lahaye:** Investigation. **Benjamin Le Bayon:** Investigation. **Alexis Plunder:** Investigation. **Petrus Le Roux:** Investigation.

#### Declaration of competing interest

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.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jafrearsci.2025.105857>.

#### Data availability

Data will be made available on request.

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