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The Palaeoproterozoic Ubendian shear belt in Tanzania: geochronology and structure

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Abstract - The Ubendian belt is a linear, NW-SE trending orogenic belt in western Tanzania. It is part of a larger Palaeoproterozoic orogen, developed around the west and south-western margin of the Archaean Tanzanian craton. The Ubendian Belt has experienced several periods of reactivation since the Palaeoproterozoic, acting as a zone of displacement during successive orogenic and rift-forming events.

The Ubendian Belt is characterized by an early deformation and granulite-facies metamorphism, isotopically dated at 2100-2025 Ma, and marked by an E-W to ESE-WNW trending foliation. This phase also affected the adjacent Usagaran (and Bangweulu?) Belt and is interpreted as a product of collisional orogeny along the SW margin of the Tanzanian, and possibly Congo, cratons.

A second phase of deformation, apparently restricted to the Ubendian Belt, is characterized by large, NW-SE trending, dextral shear zones. This phase is responsible for the creation of the eight crustal blocks developed throughout the belt and overprints much of the earlier deformation fabric. This second deformation phase is terminated by late- to post-kinematic calc-alkaline granitic batholiths (*ca* 1860 Ma). A phase of tectonic reactivation occurred locally at *ca* 1725 Ma.

Notable by its absence, is any evidence of Kibaran isotopic ages in the Ubendian Belt. Major Kibaran orogenic belts occur to the north (Burundi) and south (Zambia) of the Ubendian Belt, although they are apparently not isotopically recorded within it.

A third phase of deformation is characterized by Neoproterozoic (*ca* 750 Ma) reactivations of the Ubendian shear zones. This deformation is marked by the development of sinistral, brittle-ductile shear zones, displaying retrograde metamorphic mineral assemblages, and intruded by alkaline plutons. These late shear zones were the preferential locus for the brittle rift faults of the western branch of the East African Rift.

Résumé - La chaîne ubendienne, d'orientation générale NO-SE, forme une chaîne linéaire en Tanzanie occidentale. Elle fait partie d'un vaste domaine modelé au Paléoprotérozoïque autour du craton archéen de Tanzanie. La ceinture a été réactivée à de multiples reprises durant le Protérozoïque, en relayant les contraintes induites par les différentes orogénèses qui se sont succédées dans la région.

Une phase précoce (2100-2025 Ma) s'est déroulée en faciès granulite, induisant une foliation orientée E-O à ESE-ONO. Cette phase a également affecté la ceinture usagarienne (et le Bangweulu bloc?) et correspondrait à une collision avec les cratons archéens de Tanzanie et du Congo.

Une seconde déformation, apparemment limitée à la chaîne ubendienne, est caractérisée par des zones de cisaillement majeures dextres NO-SE, responsable de la création des huit blocs crustaux formant la chaîne. Cette phase se termine par la mise en place de batholites calco-alcalins granitiques tardi- à post-cinématiques (*ca* 1860 Ma). Une tectonique de réactivation locale a été datée à *ca* 1725 Ma.

Il est à noter que, contrairement au Burundi au nord et à la Zambie au sud, aucun âge radiométrique kibarien n'est connu dans la chaîne ubendienne.

Une troisième phase de déformation est marquée, au Néoprotérozoïque (*ca* 750 Ma), par le développement de décrochements sénestres cassants-ductiles aux assemblages de faible degré métamorphique, intrudés par des plutons alcalins. Le réseau de failles cassantes de la branche occidentale du Rift Est Africain suit précisément ces couloirs mylonitiques.

INTRODUCTION

The Ubendian Belt (McConnell 1950) forms, together with the Usagaran Belt, a large Palaeoproterozoic metamorphic domain that borders the Archaean Tanzanian craton (Fig. 1): the Usagaran bounds the craton to the S and SE and the Ubendian to the W and SW. The belts have similar high-grade metamorphic lithologies but differ in structural trends: the Ubendian Belt strikes NW to NNW, whereas the Usagaran Belt trends NE-SW to E-W in its southern portion.

The Ubendian Belt is characterized by a consistent NW trending fabric and by the presence of large shear zones persisting along the whole belt. As a consequence, this belt has been regarded as a NW lateral shear belt (Daly *et al.*, 1985; Daly 1988). Episodic reactivations since the Palaeoproterozoic

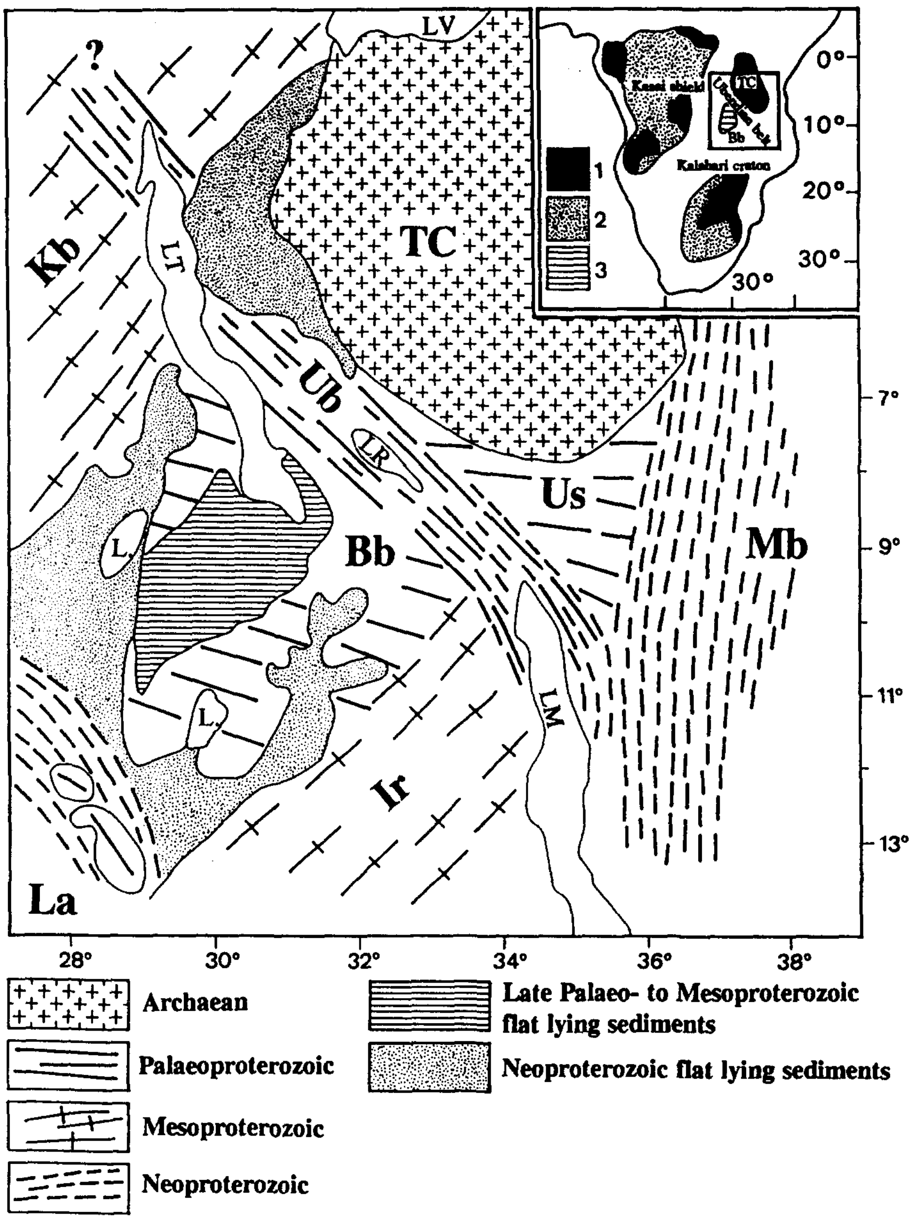

Figure 1. Geological outline of eastern central Africa (modified after Cahen and Snelling 1966; Andersen and Unrug 1984) showing the major geotectonic units and structural trends. TC = Archaean Tanzanian craton; Palaeoproterozoic domains: Ub = Ubendian Belt, Us = Usagaran Belt, Bb = Bangweulu block; Mesoproterozoic belts: Kb = Kibaran Belt, Ir = Irumide Belt; Neoproterozoic belts: Mb = Mozambique Belt, La = Lufilian arc. LT = Lake Tanganyika, LV = Lake Victoria, LR = Lake Rukwa, LM = Lake Malawi, L.= other lakes. The inset represents the main cratonic areas within the southern portion of the African continent: 1. Archaean; 2. Stable since 1750 Ma, including possible hidden Archaean; 3. Bangweulu block, stable since 1750 Ma but post-Archaean.

(Theunissen 1988; Theunissen *et al.*, 1992; Ring 1993), coupled with the obvious parallelism between the Precambrian structures and the Cenozoic rift faults, led to considering the belt as a resurgent taphrogenic lineament (McConnell 1980) or as a perennial structural weakness zone (Sutton and Watson 1986). The belt acted as a zone of lateral stress transfer (Daly 1986; Klerkx *et al.*, 1987) during the succeeding Meso- and Neoproterozoic orogenies before being reactivated during the Phanerozoic rifting.

The aim of this paper is to characterize and to date the major magmatic and metamorphic events that are recorded in the Proterozoic evolution of the Ubendian Belt and to propose a general synthesis, taking into account most of the genetical and geometrical relationships shared by the belt with the adjacent Proterozoic belts and Archaean cratons.

REGIONAL SETTING OF THE UBENDIAN SHEAR BELT

The Ubendian Belt, 500 km long and 150 km wide, runs from northern Mozambique to Zaire through Tanzania (Fig. 1). Its possible extension to the NW or to the S in Malawi (Ray 1974) is still a matter of debate and is beyond the scope of the paper.

The belt, consistently orientated NW-SE, is bounded to the NE by the Archaean Tanzanian craton, to the SE by the E-W trending Usagaran Belt and to the W by the Bangweulu block.

The Ubendian Belt is composed of blocks or terranes which are strongly elongated in a NW-SE direction and which are bounded by fault or shear zones (Fig. 2; Mc Connell 1972; Daly 1988; Daly *et al.*, 1989). Miocene to Recent rifting episodes, by

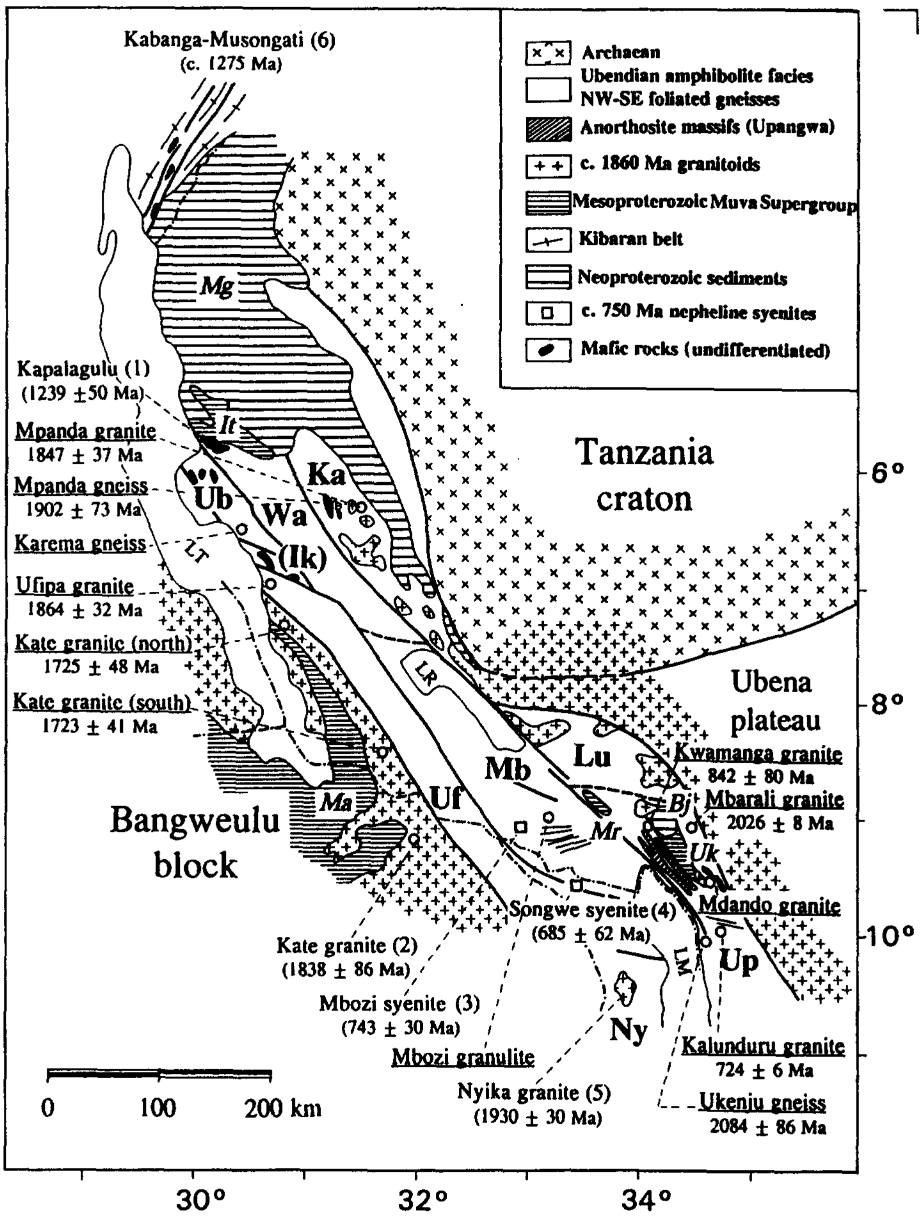

Figure 2. Simplified geological map of western Tanzania. The shear zones represented in this figure delineate the main Ubendian terranes (according to Daly 1988): Ub = Ubende, Wa = Wakole, Ka = Katuma, Uf = Ufipa, Mb = Mbozi, Lu = Lupa, Ny = Nyika and Up = Upangwa). Ikulu basic and eclogitic associations are also indicated (Ik). LT = Lake Tanganyika, LR = Lake Rukwa, LM = Lake Malawi. Main Proterozoic sedimentary basins: Muva Supergroup related basins (Ma = Mbala, Uk = Ukinga, Mr = Mbeya range, It = Itiaso) and Bukoban basins (Mg = Malagarazian, Bj = Buanji). Geochronological data comprise new data (this study) or, within brackets and attached reference number, available data from the literature (open squares for alkaline associations). (1) Cahen and Snelling (1966), (2) Schandelmeier (1983), (3) Brock (1963), (4) Ray (1974), (5) Dodson *et al.* (1975), (6) Tack *et al.* (1994).

differential exhumation and denudation, enhance the terrane boundaries. The terranes are distinct on both a lithological and a structural basis. Shear zones are markedly linear and abundant and they typically exhibit a mixture of ductile and brittle fault rocks. A dominantly NW-SE dextral strike-slip displacement along these zones has been suggested (Mc Connell 1972; Daly 1988).

The ductile shear zones limiting the blocks have been repeatedly reactivated since the Proterozoic until Recent. It has been proposed that the present rift structures have been inherited from the Palaeoproterozoic shears (Wheeler and Karson 1989; Theunissen *et al.*, *submitted*). Sedimentary basins formed during the reactivation episodes from 2 Ga until the present and appear to have been controlled by the NW trending fault zones. Meso- and Neoproterozoic basins are concentrated at the outer margins of the belt (Fig. 2).

The Usagaran Belt is regarded as being equivalent in age with the Ubendian Belt. Although there is a marked difference in orogenic strike, a genetical link between the two belts has been proposed (Gabert and Wendt 1974; Daly 1988). In contrast with the Ubendian assemblages, the Usagaran rocks are more homogeneous in composition throughout the belt and are NE-SW to E-W trending. The Usagaran rocks are mainly metasediments of medium- to high-grade metamorphism (granulites, gneisses, micaschists and amphibolites). Similarly, as in the Ubendian, Daly (Daly *et al.*, 1985; Daly 1988) suggested that both the Ubendian and the Usagaran Belts resulted from collision and accretion onto the Archaean Tanzanian craton during the Eburnian tectonogenesis. In this model, the Usagaran was thrust onto the Tanzanian craton, whereas the Ubendian terranes were accreted laterally on the craton margin owing to major strike-slip movements.

The contact zone between the Tanzanian craton and the Ubendian Belt is invaded by numerous granitic intrusions (Fig. 2). This type of granitic intrusion is also present to the west at the contact of and in the Bangweulu block (Schandelmeier 1983). Along the eastern shore of lake Tanganyika (Fig. 2), the Ubendian-Bangweulu contact is clearly tectonic. A major fault zone separates the undeformed shallow-level plutono-volcanic complexes characteristic of the Bangweulu block (Kate-Kipili complex in the area) from high-grade rock assemblages typical of the Ubendian. NW-SE trending shear zones are absent in the Bangweulu block, which basically consists of a basement of schist belts, metavolcanics and granitoids (Drysdall *et al.*, 1972) and is covered by a weakly deformed late Palaeoproterozoic to early Mesoproterozoic sedimentary sequence (Muva Supergroup; Andersen and Unrug 1984).

INTERNAL STRUCTURE: THE LITHOTECTONIC TERRANES

Within the Ubendian Belt, eight lithotectonic terranes, oriented along the NW-SE trending mega-shear zones, have been defined (Daly *et al.*, 1985): Ubende, Wakole, Katuma, Ufipa, Mbozi, Lupa, Nyika, Upangwa (Fig. 2). All terranes exhibit a dominant NW-SE trending tectonic fabric (Theunissen *et al.*, *submitted*), therefore, it is thought that their structural pattern is in keeping with a single, broad evolution scheme (Sutton *et al.*, 1954).

Within these terranes, the predominantly NW-striking gneissic layering and foliation show variable dips: over large areas the gneissic fabric is shallow dipping, although it systematically steepens near the terrane boundaries. The planar fabric predominates but it is accompanied in the steeply dipping sections by a strong linear fabric parallel with the moderately plunging axes of the asymmetric, tight folds. The gneissic layering and the linear fabric define a NW-orientated ductile fold style with weakly-dipping fold axes along the trend. A dextral sense of lateral shear has been demonstrated (Daly *et al.*, 1985; Daly 1988; Theunissen *et al.*, *submitted*).

Other parts of the Ubendian Belt have their gneissic fabric striking at a high or moderate angle to the regional structure. These transverse structures are best observed in the Mbozi block (Fig. 2) and in the northern Ubende terrane. In these areas, the gneissic layering trends roughly WNW to E-W and relics of isoclinal folds with E-W trending axes are found. Granulite-facies metamorphism is associated with the E-W structures, whereas the common regional metamorphic assemblages, linked to the NW trending shear structures, belong to the amphibolite-facies (Sklyarov *et al.*, *submitted*). The high metamorphic grade, the peculiar orientation of these E-W structures and their apparent truncation by the NW-orientated structures, suggest that they represent the oldest event within the Ubendian Belt. Their orientation is comparable to the Usagaran associations, where similar granulitic complexes are found (Coolen 1980).

After its formation, the NW-orientated Ubendian Belt underwent important ductile-brittle shear sinistral reactivations, mostly effective along the intense sheared structures at the limits of the terranes (Theunissen *et al.*, *submitted*). The effects of these reactivations are marked by the development of thick mylonite and blastomylonite zones with low-grade assemblages (Fig. 2). Reactivations occurred particularly during the Neoproterozoic with the emplacement of granitic and mafic alkaline associations (Theunissen *et al.*, 1992).

Amphibole-bearing orthogneiss, ranging in composition from diorite to granite, is the most frequent Ubendian lithology. Rare metasediments consist of micaschists, aluminous gneisses, marbles and ferruginous quartzites. In the Ikulu series and in the Upangwa block, high pressure rocks, such as blue schists or eclogites, have been described and interpreted as possible disrupted ophiolites (Sklyarov *et al., submitted*). Eclogites are also found in the Usagaran Belt (Appel *et al.*, 1993). Concordant massif-type anorthosites made up of leucogabbro, leuconorite, gabbro and norite with rare ultramafics (pyroxenites, dunites and serpentinites) form huge masses, especially in the Upangwa block.

The terranes are defined by their predominant lithology (Smirnov *et al.*, 1973; Daly 1988):

i) the Ubende terrane is essentially composed of amphibole gneisses with rare quartzites. It includes the Ikulu series which is composed of amphibolites, micaschists and meta-calcareous rocks with remnants of high P-T rock associations.

ii) the Wakole terrane is composed of various schists with abundant kyanite, garnet and micas

iii) the Katuma terrane is essentially made up of biotite gneisses

iv) the Ufipa terrane is characterized by abundant granitic gneisses

v) the Mbozi terrane is dominantly composed of metabasites with rare, interlayered quartzites and preserved granulitic assemblages

vi) the Lupa terrane consists of meta-volcanics intruded by a huge volume of granites with associated gold mineralizations

vii) the Nyika terrane is composed of cordierite granulites, but mostly extends into Malawi

viii) the Upangwa terrane is made up of characteristic meta-anorthosite massifs

MAGMATISM

Granitoids

Granitoids principally occur along both the eastern (Ubena plateau, close to the Tanzanian craton, Fig. 2) and western marginal zones of the Ubendian Belt. These granitoids can be strongly foliated and concordant with the regional foliation or form elongated but weakly deformed batholiths. In the Mpanda area, these granites are associated with gold and base metal mineralizations (Harris 1961; Orlov *et al.*, 1974; Nanyaro 1989). They are late- to post-kinematic. The Kate granite, which extends along the western border of the belt, is probably equivalent to the large granitic batholiths in the Bangweulu block and appears to intrude into the acid volcanics (Kipili volcanites) which discordantly overly the Ubendian gneisses. It is consequently posterior to the Ubendian deformation.

Another older group seems to be associated with the migmatitization which followed the granulitic metamorphism. Granitic in composition, this kind of magmatism occurs in large masses only in the easternmost part of the belt at the junction of the Tanzanian craton, the Usagaran and the Ubendian Belts (Mbarali area, Fig. 2).

The Pan-African late-shear granitoids form narrow intrusions, NW-SE to N-S orientated, that are confined to zones of brittle-ductile shear. These granitoids show little evidence of penetrative deformation but are intensely fractured. Evidence of late stage sodic and potassic enrichment suggests that there was a large amount of fluid circulation along these shear zones. The contacts with the country rocks are generally sharp and of a tectonic nature. Chemically, these granitoids have alkaline affinities, however, due to the possible effects of late fluids, more work is needed to precisely ascertain their petrogenesis. Locally, the association of granites and mafic rocks suggests that they can form a bimodal suite. They are confined to the southern part of the belt.

At the limit between the Bangweulu block and the Ubendian Belt, some silica-undersaturated or mixed complexes intrude at *ca* 750 Ma (Tack *et al.*, 1984). They are subcontemporaneous to the Pan-African late shear granitoids.

Mafic intrusives.

Mafic intrusions are common at the contact between the Ubendian Belt and the Tanzanian craton, in particular in the complex zone of Lupa. More to the west, meta-mafic rocks are found along the contact between the Ufipa and the Ikulu-Ubende blocks. These rocks are gabbro-diorite gneisses and occur as pods or lenses, expressing a foliation which is often concordant with the surrounding gneisses (Theunissen 1988).

Less deformed mafic-ultramafic complexes occur infrequently in the north (e.g. Kapalagulu intrusion, Fig. 2). They could represent the southern extension of the late-kinematic, 350 km long alignment of mafic-ultramafic complexes (*ca* 1275 Ma) described in the Kibaran Belt in Burundi and northern Tanzania (Tack *et al.*, 1994).

In the south-eastern part of the belt (Liganga-Kipengere area, close to the Ukinga basin, Fig. 2), intrusions have been emplaced in the inferred contact between the Ubendian and the Usagaran Belt.

Table 1: U-Pb isotopic data. Bracketed numbers correspond to: (1) Magnetic properties: NM = non magnetic, M = magnetic at the indicated degree of tilt of the Frantz isodynamic separator (1.5 A - 25° slope), negative sign characterizes the diamagnetic fractions. (2) Error on U/Pb ratio <1%. (3) Corrected for common lead (Stacey and Kramers 1975) and contamination (blanks <200 pg). (4) Ratios corrected for isotopic fractionation only (0.13% per a.m.u.). (5) Ratios corrected for fractionation, blank and initial common Pb (error on $^{207}Pb/^{206}Pb$ <0.1%). * - radiogenic lead.

Fraction Number	Size (μ)	Magn. prop. (1)	Weight (mg)	Concentrations U (ppm) (2)	Pb (ppm) (2)	Pb rad (%) (3)	Atomic ratios $^{206}Pb/^{204}Pb$ (4)	$^{208}Pb/^{206}Pb$ (4)	$^{207}Pb^*/^{235}U$ (5)	$^{206}Pb^*/^{238}U$ (5)	$^{207}Pb^*/^{206}Pb^*$ (5)	Ages (Ma) $^{207}Pb^*/^{235}U$	$^{206}Pb^*/^{238}U$	$^{207}Pb^*/^{260}Pb^*$
Mbarali granite														
1	63-106	+1°M	2.40	847	194	88	425±1	0.1655	3.1301	0.1944	0.11680	1440	1145	1907
2	63-106	-1°M	2.80	710	177	91	565±3	0.1521	3.5624	0.2179	0.11856	1541	1271	1934
3	63-106	-3°M	2.75	542	151	94	852±4	0.1366	4.1303	0.2503	0.11968	1660	1440	1951
4	63-106	-3°NM	1.40	428	129	95	1062±8	0.1350	4.5652	0.2713	0.12206	1743	1547	1986
Ufipa granite														
1	63-106	-1°M	3.47	411	119	98	3185±9	0.2014	3.9371	0.2534	0.11268	1621	1456	1843
2	63-106	-3°M	3.43	397	121	99	4272±20	0.1970	4.1629	0.2678	0.11275	1667	1529	1844
3	63-106	-4°M	3.06	364	112	99	4414±26	0.1979	4.2144	0.2706	0.11296	1677	1544	1848
4	63-106	-5°M	3.20	311	96	99	4493±26	0.1958	4.2349	0.2714	0.11316	1681	1548	1851
Kwamanga granite														
1	63-150	-3°M	6.05	263	22	91	588±6	0.2116	0.6065	0.0711	0.06186	481	443	669
2	63-150	-5°M	6.88	239	20	93	768±10	0.2058	0.6548	0.0746	0.06365	511	464	730
3	63-150	-7°M	7.18	221	19	97	1956±61	0.1752	0.6969	0.0802	0.06303	537	497	709
4	63-150	-8°M	3.66	219	17	96	1970±40	0.1740	0.7090	0.0815	0.06310	544	505	711
Kalunduru granite														
1	106-150	-1°M	3.83	143	16	97	2084±55	0.1478	0.9367	0.1068	0.06362	671	654	729
2	106-150	-3°M	4.32	103	13	97	1848±33	0.1559	0.9905	0.1142	0.06288	699	697	704
3	106-150	-5°M	5.04	93	11	97	1883±64	0.1712	0.9812	0.1119	0.06360	694	684	728
4	106-150	-7°M	4.60	83	10	98	2657±220	0.1741	1.0224	0.1161	0.06387	715	708	737
Mbozi granulite														
1	63-106	-4°M	1.88	33	11	93	766±17	0.1269	4.2658	0.3111	0.09948	1687	1746	1614
2	63-106	-5°M	2.41	26	9	90	543±10	0.1241	4.0532	0.3155	0.09302	1645	1768	1491
3	63-106	-6°M	2.54	23	8	93	754±13	0.1277	4.6132	0.3086	0.10827	1752	1734	1773
4	63-106	-7°NM	3.90	15	6	96	1200±11	0.1217	5.2165	0.3551	0.10656	1855	1959	1741
Ukenju gneiss														
1	63-106	-3°M	5.00	212	61	99	14918±1725	0.1834	4.0036	0.2582	0.11247	1635	1481	1839
2	63-106	-5°M	4.52	202	57	99	9369±731	0.1904	3.8704	0.2516	0.11158	1608	1447	1825
3	63-106	-6°M	3.80	176	49	99	5130±300	0.2102	3.6915	0.2438	0.10980	1570	1407	1796
4	63-106	-6°NM	3.70	167	47	98	2746±145	0.2167	3.6808	0.2440	0.10939	1567	1402	1789

Table 2: Rb-Sr on whole rock data.

Sample	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr \pm 2\sigma$
Mpanda granite				
N 55	130	451	0.8356	0.72510 ± 4
N 59	157	332	1.373	0.73972 ± 7
N 62	232	329	2.050	0.75418 ± 11
N 63	210	292	2.091	0.75718 ± 5
N 67*	136	588	0.6702	0.72217 ± 5
N 68	157	3783	0.1201	0.70572 ± 5
N 74B	208	337	1.794	0.75161 ± 6
Kate granite (north)				
UB 140	143	374	1.109	0.73064 ± 4
UB 141A	157	327	1.393	0.73820 ± 4
UB 141B	112	446	0.7277	0.72208 ± 3
UB 144	136	467	0.8441	0.72463 ± 9
UB 145	111	560	0.5741	0.71823 ± 9
UB 148A	202	198	2.971	0.77414 ± 5
UB 148B	200	153	3.817	0.80057 ± 3
UB 151	174	190	2.667	0.77244 ± 3
Kate granite (south)				
IS 190-1	237	285	2.416	0.76622 ± 1
IS 191-3	319	58	16.462	1.10202 ± 2
IS 191-4	193	340	1.649	0.74785 ± 1
IS 192-7	373	27	44.241	1.82983 ± 3
IS 193-8	303	145	6.153	0.86023 ± 1
IS 194-9	385	132	8.625	0.91984 ± 1
Mpanda gneiss				
N 60A	130	900	0.4183	0.71596 ± 7
N 60B	137	840	0.4724	0.71738 ± 4
N 60C	152	590	0.7467	0.72421 ± 5
N 60D	83	682	0.3524	0.71479 ± 4
N 64A	117	248	1.370	0.74348 ± 5
N 64B*	132	376	1.018	0.72706 ± 4
N 66A	134	657	0.5910	0.72128 ± 8
N 66B*	126	322	1.136	0.74239 ± 6
N 66C*	126	289	1.266	0.74254 ± 5
N 76	181	458	1.146	0.73596 ± 8
Ubende gneiss (Karema area)				
UB 87B	18.4	146	0.3648	0.71108 ± 4
UB 94D	214	108	5.775	0.78025 ± 4
UB 94E	201	89.4	6.582	0.82582 ± 4
UB 94F	1.1	123	0.0259	0.70873 ± 5
UB 104A	32.9	978	0.0973	0.70589 ± 2
UB 110	101	113	2.601	0.76677 ± 4
UB 120B	87.4	482	0.5254	0.72200 ± 6
Mdando forest granite				
TG 129	69.2	470	0.4263	0.71375 ± 2
TG 130	226	18.57(ID)	37.81	1.45408 ± 6
TG 132	229	97.8	6.865	0.84139 ± 4
TG 133B	220	10.3	68.34	1.77911 ± 21
TG 133D	192	11.9	50.49	1.53219 ± 42
TG 141	233	13.6	54.56	1.72793 ± 6

(ID) - isotopic dilution, others are XRF. * not used in the age calculation.

U-Pb AND Rb-Sr GEOCHRONOLOGY

Only a few age determinations relative to the evolution of the Ubendian Belt are available in the literature. Most of the data are K-Ar ages on minerals and ill-defined Rb-Sr whole-rock isochrons. However, the best results show the age of the Ubendian orogeny to be in the 2100-1800 Ma range and provide evidence of the polyphase character of the belt (Dodson *et al.*, 1975; Gabert and Wendt 1974; Cahen *et al.*, 1984).

New zircon U-Pb and whole-rock Rb-Sr age determinations have been carried out. Sample locations are reported in Fig. 2 with the attached geochronological results. Additional geochronological data from the literature are reported in the same figure. U-Pb on zircon and Rb-Sr on whole rock results are given, respectively, in Tables 1 and 2.

Analytical techniques

Isotopic measurements have been carried out on a Finnigan MAT 260 and on a Fisons VG sector 54 thermal ionization mass spectrometer at the Belgian Center for Geochronology (MRAC-ULB).

Rb-Sr

After acid dissolution of the sample and Sr separation on the ion-exchange resin, the Sr isotopic composition was measured on a Re double filament (MAT 260) or a Ta simple filament (Sector 54). The $^{87}Sr/^{86}Sr$ of NBS987 standard (normalized to $^{86}Sr/^{88}Sr = 0.1198$) during the course of this study was 0.710221±0.000019 (2σ). Rb and Sr concentrations have been measured by X-ray fluorescence or by isotope dilution for concentrations below 30 ppm. The attached error on the Rb/Sr ratio is <2%. The ages have been calculated following Williamson (1968) and all the errors are given at the 2σ level. The adopted disintegration constant for ^{87}Rb is 1.42×10^{-11} a^{-1} (Steiger and Jäger 1977).

U-Pb

After the dissolution of 2 to 7 mg of pure zircon fractions, the U and Pb were separated on ion exchange resin (Dowex 100-200) micro-columns following the method of Krogh (1973) modified by Lancelot (1975). Pb and U were measured on a Re single filament with the H_3PO_4 - silica gel technique. The error on the U/Pb ratio is assumed to be less than 1%. All the results were corrected for mass fractionation (0.13% per a.m.u) on the basis of the NBS 981 Pb standard. The following disintegrations constants were used (Steiger and Jäger 1977): ^{235}U =

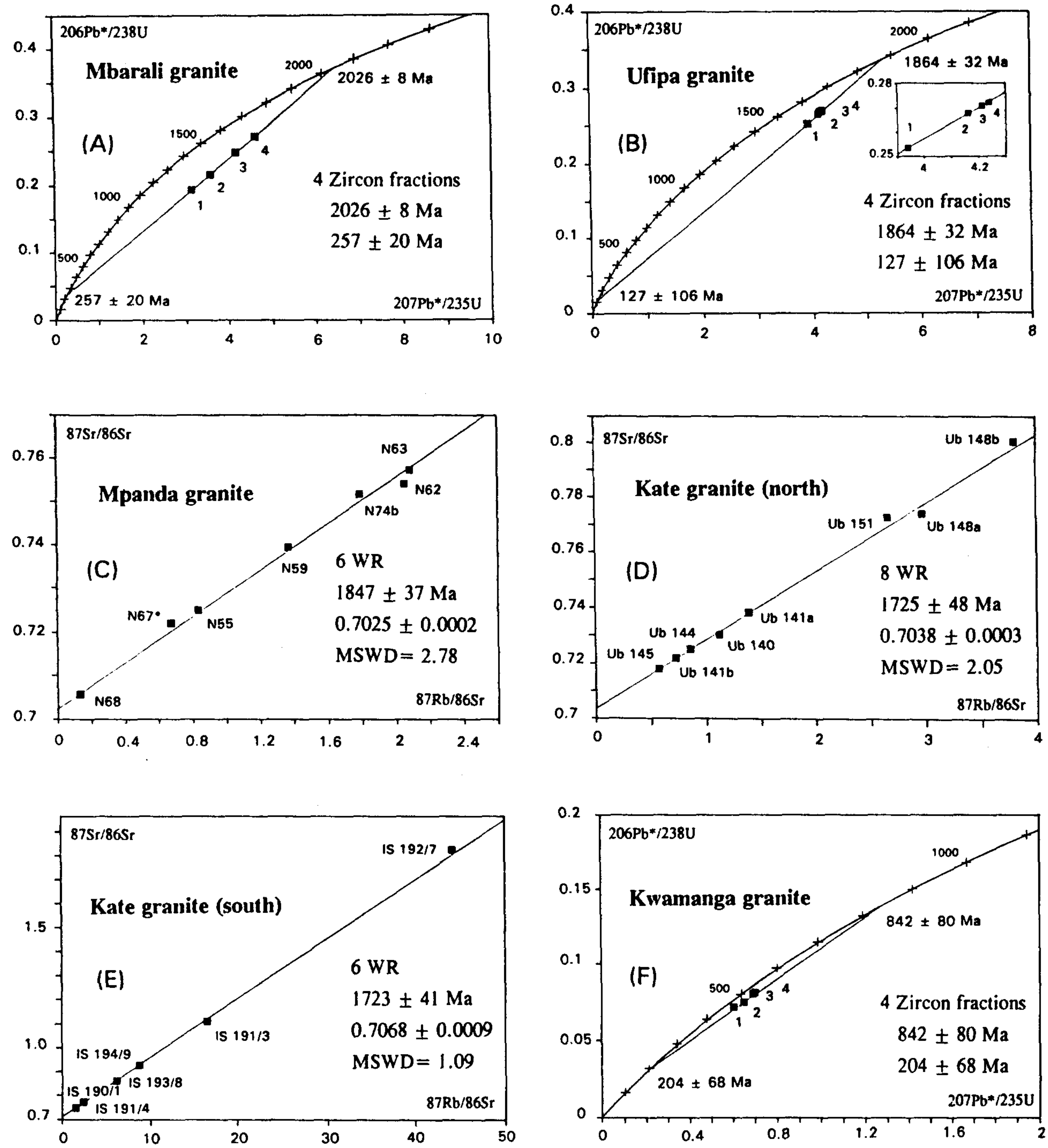

Figure 3 Geochronological data from characteristic Ubendian granite phases. (a) U-Pb on zircon discordia for the Mbarali granite. (b) U-Pb on zircon discordia for the Ufipa granite. (c) Rb-Sr data for the Mpanda granite (* - not included in the calculation). (d) Rb-Sr data for the northern section of the Kate granite. (e) Rb-Sr data for the southern section of the Kate granite. (f) U-Pb on zircon discordia for the Kwamanga granite.

9.8485 x 10^{-10} a^{-1}; ^{238}U = 1.55125 x 10^{-10} a^{-1}. Age calculations and attached errors have been calculated following Ludwig (1980).

Results

Granitoid

The Mbarali granite

Four zircon fractions from a two-mica granite sample (W of the Ubena plateau along the Mbarali river, Upangwa terrane) define an upper intercept of 2026±8 Ma and a lower intercept of 257±20 Ma (Concordia diagram, Fig. 3a). Their degree of discordance is correlated with the U and Pb contents and the $^{204}Pb/^{206}Pb$ ratio. The lower intercept is probably meaningless (continuous lead loss), although a thermal Karoo perturbation (Late Carboniferous; Wopfner 1990) cannot be definetely ruled out. The upper intercept dates the age of the intrusion.

The Ufipa sheared granite

Four zircon fractions from a sheared granite, emplaced in prevailing amphibolite facies conditions (Ufipa terrane, near Karema), define a discordia with an upper intercept of 1864±32 Ma and a lower intercept of 127±107 Ma (Fig. 3b). The degree of discordance (20-25%) is correlated with the U and Pb contents. The lower intercept probably corresponds to a continuous lead loss. The upper intercept dates the intrusion of the granite and the related Ubendian ductile shear deformation.

The Mpanda granite

In the Mpanda area (Katuma terrane), a late-kinematic pluton defines a Rb-Sr isochron: 1847±37 Ma (Sr IR = 0.7025±0.0002, MSWD = 2.78, 6WR on 7; Fig. 3c). This age corresponds to the intrusion age of this granite and to the end of the ductile shear phase.

The Kate granite

This granite corresponds to the eastern edge of the Bangweulu block, although it is affected by late shears. Two areas have been studied at 150 km apart. Granite samples include undeformed magmatic and mylonitic facies. To the north, the samples were collected along the Kipili-Namanyere road (UNESCO geotraverse; Nanyaro *et al.*, 1983) whereas the samples from the south were collected in the Mwimbi area (Lenoir *et al.*, 1993). The results are: northern Kate granite - 1725±48 Ma (Sr IR = 0.7038±0.0003, MSWD = 2.05, 8WR; Fig. 3d); southern Kate granite - 1723±41 Ma (Sr IR= 0.7068±0.0009, MSWD = 1.09; 6WR; Fig. 3e). Petrographical observations (Lenoir *et al.*, 1993) indicate that the deformation affecting this granite occurred in low-grade greenschist facies and rather brittle conditions, conditions which differ from those prevailing for the ductile Ubendian shear phase. The two ages obtained correspond to the brittle tectonic overprint whereas the emplacement of the granite is thought to have occurred some 100 Ma earlier (Lenoir *et al.*, 1993). This is confirmed by the fact that the initial Sr ratios for the northern and southern outcrops of the Kate granite are significantly higher than the one of the Mpanda granite and that they correlate with their mean Rb/Sr ratios. Another conclusive element is the age and initial ratio obtained by Schandelmeier (1983) on this granite more to the west in Zambia and further away from the mega-shear (1838±86 Ma, Sr IR = 0.7016). These ages at *ca* 1725 Ma are then believed to represent a distinct, even if local, tectonic event.

The Kwamanga Neoproterozoic granite

This granite occurs as an elongated body along the main shear zone that bounds the Ukinga-Buanji basin (Fig. 2), in the Upangwa terrane. The main plutonic body is a syenogranite, although it is locally associated with the alkali feldspar granites. The presence of blue Na-amphibole and the abundance of accessory phases, such as zircon or apatite, attest for the alkaline affinity of this granite. The four selected zircon fractions group translucent, core-free, yellowish crystals with high temperature and high alkalinity characteristics, following the criteria of Pupin (1980). They define an upper intercept of 842±80 Ma and a lower intercept of 204±68 Ma (Fig. 3f). The high degree of discordance suggests that the isotopic system has been severely disturbed since the zircon crystallization. The lower intercept can be linked to a thermal or tectonic overprint, in relation to the post-Karoo activity, comprising a carbonatite emplacement. The upper intercept, though unprecise, dates the age of the intrusion.

The Kalunduru granite

The granite crops out more to the south, near the Livingstone mountains. Less alkaline than the Kwamanga granite, this granite lies at the junction of two differently structured domains respectively NW-SE orientated and E-W orientated (Theunissen *et al.*, 1992). The granite is weakly foliated, but well elongated, and was emplaced late in the Pan-African tectonic phase. The four zircon fractions (Fig. 4a; Theunissen *et al.*, 1992) define an upper intercept of 724±6 Ma and a lower intercept of -5±46 Ma (recent Pb loss). The upper intercept dates the emplacement of this granite as being at the end of the Pan-African tectonic phase.

Gneissic sequences

The Mbozi granulite

The Mbozi granulite complex (Mbozi terrane, Fig. 2) displays a well developed E-W trending foliation. Four zircon fractions from a two-pyroxene metagabbro, only very slightly retrogressed in the amphibolite-facies, have been treated. They are composed of core and inclusion free, squatted, colourless and unzoned crystals, in general rounded or oval in shape, the lack of well developed pyramids being an indication of their growth in a dry environment (Caruba 1975). The fractions are very scattered with three of them lying above the Concordia (Fig. 4b; Table 2). Coupled with the very low U content of these zircons (15-33 ppm for 6-11 ppm of Pb), this position suggests an U loss since the time of their crystallization. Individual $^{207}Pb/^{206}Pb$ model ages range between 1491 Ma and 1773 Ma. The last value constitutes a minimum age for the metamorphic event. Although this value is not very useful for the determination of the exact age of the granulitic event, it indicates that this event is likely to be Palaeoproterozoic and not Archaean.

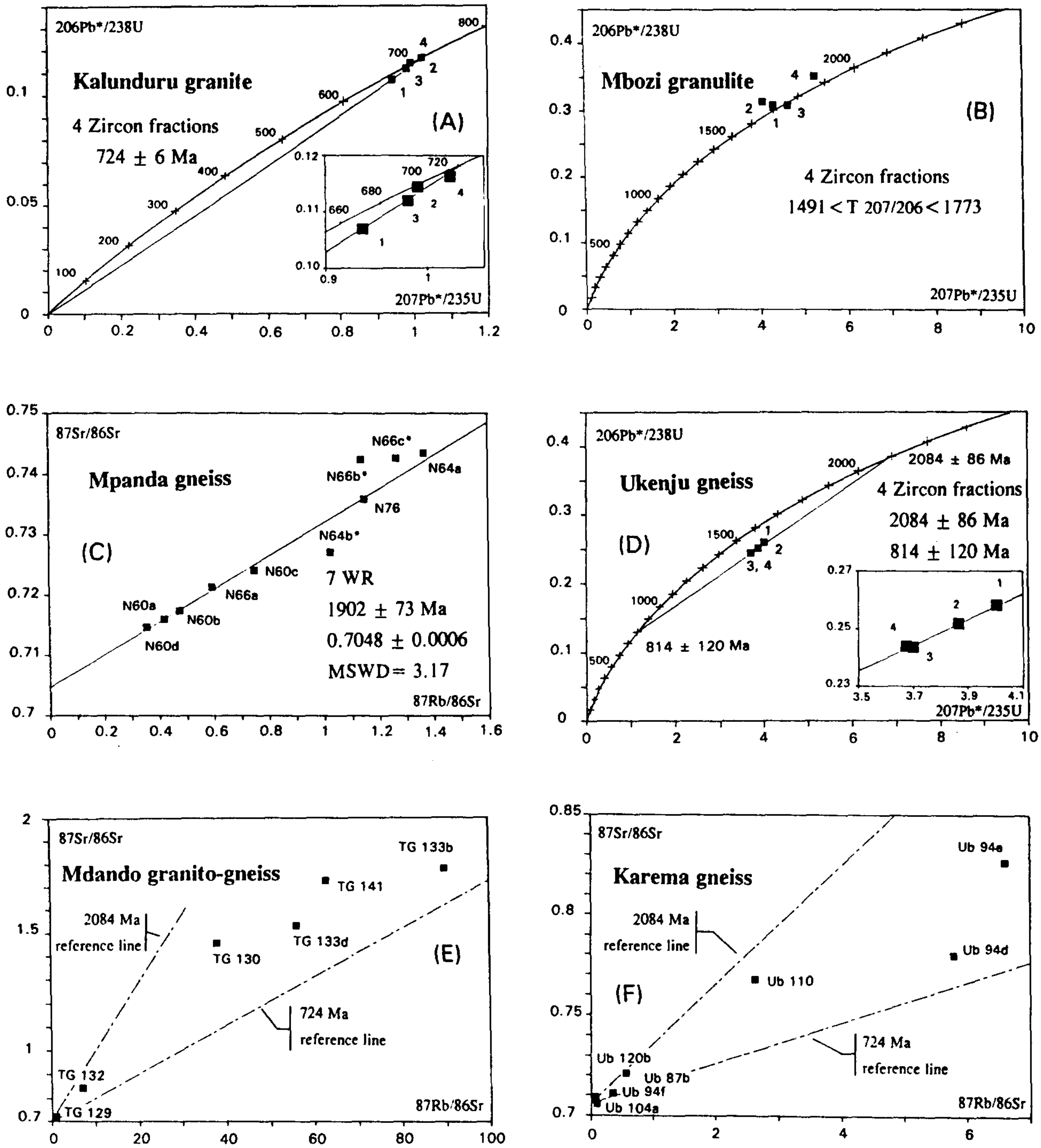

Figure 4 Geochronological data from characteristic Ubendian gneissic associations and granite phases. (a) U-Pb on zircon discordia for the Kalunduru granite. (b) Layout of the Mbozi granulite zircon fractions. (c) Rb-Sr data for the Mpanda gneiss. (d) U-Pb on zircon discordia for the Ukenju gneiss. (e) Rb-Sr data for the Mdando forest granite-gneiss with two reference lines (2084 and 724 Ma). (f) Rb-Sr data for the Karema gneiss with two reference lines (2084 and 724 Ma).

The Mpanda gneiss

In the Mpanda area (Katuma terrane), a series of biotite gneisses determine an isochron of 1902±73 Ma (Sr IR = 0.7048±0.0006, MSWD = 3.17, 7WR; Fig. 4c). Three samples (more fractured) do not plot on this isochron. This value is the age of the closing of the Rb-Sr system, corresponding either to the end of the late Ubendian amphibolite-facies metamorphism or to the Mpanda granite emplacement. These two events may be almost contemporaneous.

The Ukenju gneiss

In the lesser Livingstone mountains (Upangwa terrane), near the Ukenju village, a tonalitic gneiss was sampled in the same area as the Kalunduru granite (Theunissen *et al.*, 1992). The regional basement structure is controlled by the main Ubendian pattern, but the gneissic sequence is locally intensely deformed by Pan-African sinistral shear zones. Four zircon fractions define a discordia with an upper intercept of 2084±86 Ma and a lower

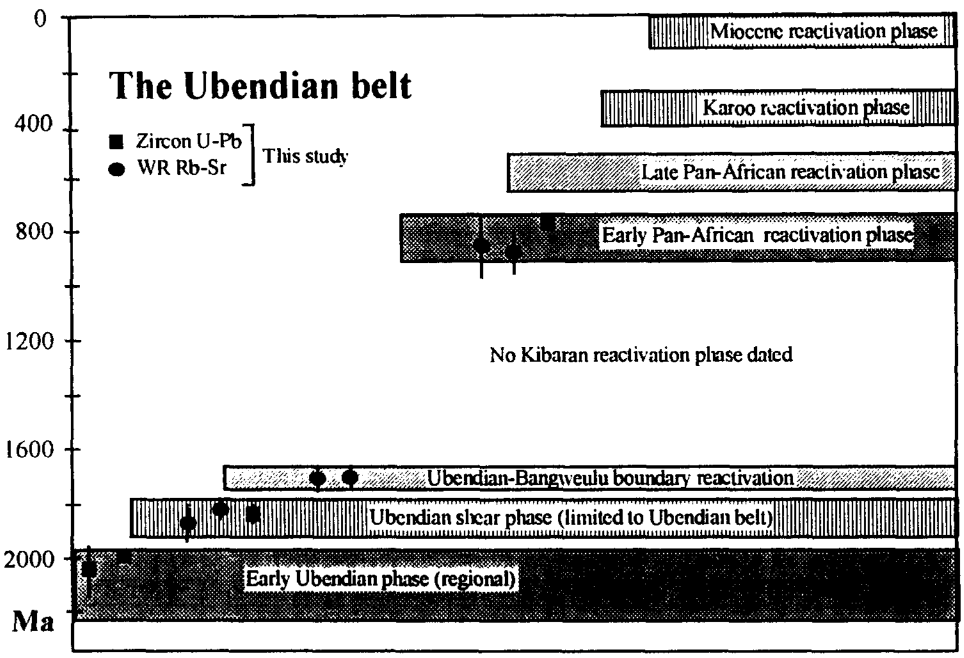

Figure 5 Sequence of dated events that have affected the polyphased Ubendian Belt.

intercept of 814±120 Ma (Fig. 4d; Theunissen *et al.*, 1992). The upper intercept indicates an age for the protolith in the early Ubendian phase range (ending at 2026±8 Ma) while the lower intercept marks the Pan-African overprint (ending at 724±6 Ma).

Karema gneiss and Mdando forest gneiss

Two other gneissic sequences have been analyzed for the Rb-Sr method in the Karema (Ubende terrane) and Mdando Forest (Upangwa terrane) areas. Both sample sets give rise to a cloudy pattern in the $^{87}Rb/^{86}Sr$ versus $^{87}Sr/^{86}Sr$ diagram, which can be interpreted as an interference between the Ubendian and Pan-African effects (Figs. 4e and 4f)

THE UBENDIAN BELT: TIMING AND METAMORPHIC CONDITIONS

The Ubendian Belt has been, since its formation, subjected to repeated reactivations along its characteristic NW-SE trend until recent times. It has been difficult to ascribe an age to these deformation phases. In the light of these new geochronological data, coupled with a metamorphic description, a sequence of events can be proposed. All the ages obtained in this study are reported in Fig. 5.

The early Ubendian deformation is related to the granulitic facies metamorphism. The foliation, associated with the isoclinal folds, is generally E-W to WNW-ESE orientated and is cut by the regional NW-SE foliation. Metamorphic assemblages, characteristic of the granulites, point to medium to high pressure conditions (clinopyroxene+ orthopyroxene+ilmenite). Very high pressure associations are expressed by local eclogitic parageneses with P-T conditions up to 17 kbars and 900°C (Sklyarov *et al., submitted*). Similar P-T estimates in the Usagaran counterpart yield pressures of 12-14 Kb for temperatures in the range 670-740°C (Appel *et al.*, 1993). The oldest ages obtained in this study are two zircon ages (2084±86 Ma and 2026±8 Ma) which agree within the error limits. The latter corresponds to a phase of granitic magmatism at the limit between the Usagaran and the Ubendian. This event is accompanied by complex and highly contorted structures, indicating a high degree of plasticity. This age range is compatible with that of the metamorphic granulitic climax in the Usagaran, which has been dated at *ca* 2100 Ma (U-Pb zircon data; A. Möller *pers. comm.*). Zircon U-Pb data on the Mbozi granulite do not give an accurate age but indicate that this metamorphism is probably related to the Ubendian orogeny and not to an Archaean event.

The major Ubendian tectonic phase is characterized by the development of major, steep NW-SE shear zones. Atthe beginning of this phase, amphibolite-facies metamorphic conditions prevailed. The age is mainly constrained by the late-kinematic granitoids (1847±37 Ma and 1864±32 Ma) with both the zircon U-Pb and the WR Rb-Sr methods being in agreement. The Rb-Sr method, applied to the enclosing gneisses, gives a similar age (1902±73 Ma). The mean, weighted by the errors, of these ages is 1860±23 Ma. If this shear phase is effectively responsible for the large horizontal movements of the Ubendian terranes (Daly 1988), this age would correspond to the end of the process. No constraints exist so far on the period of the functioning of these shear zones. This major period, or at least its effects, is, however, also recorded in the Usagaran by the K-Ar and Rb-Sr methods on granites, which have given values of between 1900 and 1800 Ma (Wendt *et al.*, 1972; Gabert and Wendt 1974; Priem *et al.*, 1979). In northern Malawi, the Nyika granite also fall into this age range (1930±30 Ma (Fig. 2); Dodson *et al.*, 1975; recalculated in Andersen and Unrug 1984). An upper time limit for the Ubendian shear belt is inferred from the age of the Kate granite. This shallow-level granite, which is associated with volcanites unconformably overlying the Ubendian gneisses, postdates the Ubendian shear event. The age of emplacement of the Kate granite is believed to be around 1825 Ma (Schandelmeier 1983). In the Bangweulu block of Zambia and Zaire, ages on late-kinematic granites are in the same age range (1900-1800 Ma; Brewer *et al.*, 1979; Schandelmeier 1983; Kabengele *et al.*, 1990)

Rb-Sr data on the Kate granite also suggest that the main border fault between the Bangweulu block and the Ubendian shear belt was reactivated 100 Ma after its emplacement (at 1724±31 Ma; Lenoir *et al.*, 1993). However, the regional significance of this event can not be determined.

No reliable Kibaran radiometric ages, except two K-Ar data (Cahen and Snelling 1966), are known in the Ubendian Belt. This suggests that if the Kibaran reactivation existed, its intensity was too weak to be marked by Rb-Sr or U-Pb isotopic resetting. The regional cross-cutting character of the Ubendian Belt (Fig. 1) relative to the Mesoproterozoic Zambian Irumides (Daly 1986) and Burundian Kibarides (Tack *et al.*, 1994) is connected to movements along the Ubendian Belt. Whether this reactivation occurred during the Kibaran or Pan-African periods remains unsolved.

The early Pan-African tectonic phase (*ca* 725 Ma) is related to a major E-W compression across the belt and corresponds to the pervasive reactivation of the NW-SE orientated steep shear zones in a sinistral regime and under upper greenschist to lower amphibolite-facies conditions (Theunissen *et al.*, *submitted*). This deformation is interpreted as controlling the development of the Neoproterozoic Buanji sedimentary basin (Klerkx and Nanyaro 1988). This shear event created thick mylonitic sequences and is associated, in the southern part of the belt, with the early Pan-African late-shear granitoids (*ca* 725 Ma; Theunissen *et al.*, 1992). The mylonitic schistosity frequently exhibits a mineral elongation accompanied by rare sheath folds, pointing to a subhorizontal direction. The strain intensity of this phase varied considerably and sometimes obliterated pre-existing structures. These mylonitic alignments are probably at the origin of the localization of the major faults associated with the recent rift network (Theunissen *et al.*, *submitted*).

Several alkaline silica-undersaturated or mixed complexes intruded along the north-eastern boundary of the Bangweulu block in the Ubendian Belt (Fig. 2). The Mbozi gabbro-syenite complex in Tanzania has yielded an age of 743±30 Ma (K-Ar on biotite; Brock 1963) and in Malawi, the Songwe syenite has yielded an age of 685±62 Ma (Ray 1974). These complexes (Fig. 2) are part of a series of Neoproterozoic alkaline complexes outcropping along the recent western rift structure (Tack *et al.*, 1984).

The late Pan-African tectonic phase is restricted to the southern part of the belt and is differentially developed in the basement sequence and its Proterozoic cover. Ubendian gneisses, granitoids and mylonites are crosscut at a high angle by a regional system of prominent NE-striking subvertical joints (Delvaux 1990), often filled by felsic veins or mafic pods. This phase is probably correlated with the thermal effect dated by many Rb-Sr and K-Ar analyses on minerals ages at *ca* 500 Ma (Cahen *et al.*, 1984). These closing ages correspond to the late effects of the nearby Pan-African belts (Mozambiquian, Lufilian arc, Zambezi Belt; Cahen *et al.*, 1984) and to the initial definition of the Pan-African by Kennedy (1964).

Phanerozoic reactivations of Ubendian structures are also important, especially during the Karoo (Delvaux 1990; Wopfner 1990) and recent rift periods (Wheeler and Karson 1989).

THE UBENDIAN BELT: THE EVOLUTION

The age results show a two-phase Palaeoproterozoic evolution for the Ubendian Belt, with a first phase of the deformation in the granulitic facies in the range 2100-2025 Ma and a second phase, mainly NW-trending, whose climax occurred at *ca* 1860 Ma (Fig. 5). The granulite facies first deformation is only found in relics in the Ubendian shear belt. The original structural trends are mostly obliterated, except in major inliers, such as the Mbozi block, where the characteristic E-W trend is well preserved. As the Usagaran Belt possesses a similar E-W trend and metamorphic grade in the same age range, a correspondance between the major structural deformation of the Usagaran and the first phase of deformation of the Ubendian is proposed. Moreover, it is suggested that the E-W granulitic phase of the Ubendian Belt, the E-W orientated main deformation of the Usagaran Belt (Gabert and Wendt 1974) and the ESE-WNW trending foliation of the Bangweulu block (Andersen and Unrug 1984) are all linked to a collision process with a northern craton. For the Usagaran this is obviously the Tanzanian craton (Daly 1988), for the Ubendian and Bangweulu this may be the Archaean Congo craton (Fig. 6).

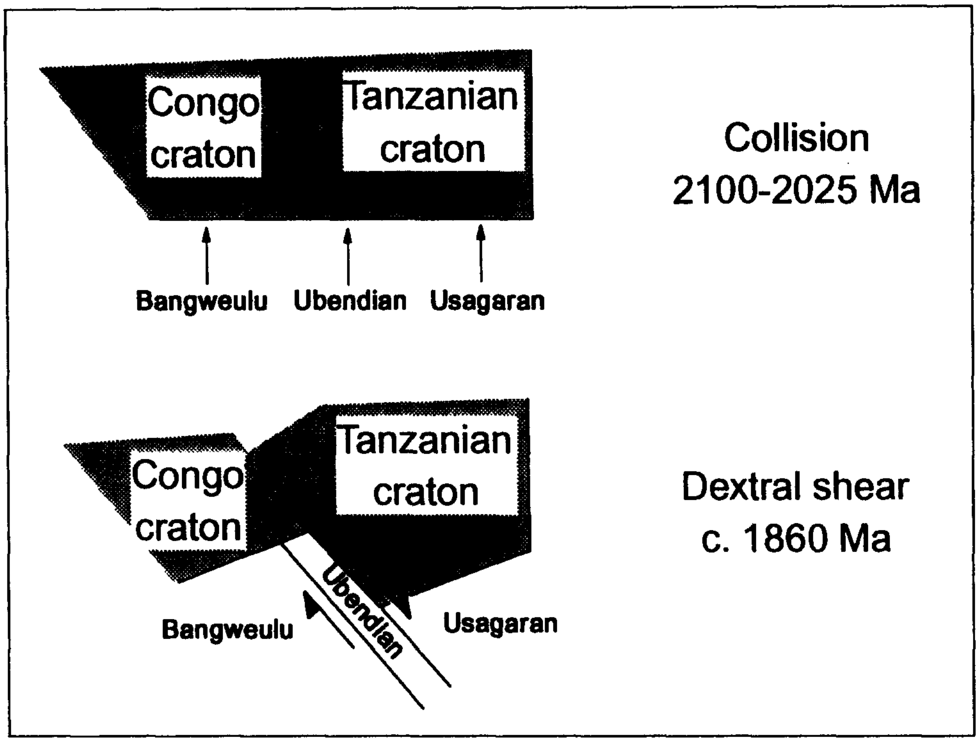

Figure 6 Schematic model of the Palaeoproterozoic evolution of the Ubendian Belt following two orogenic phases. The first phase (2100-2025 Ma) concerns the whole orogenic domain (Ubendian, Bangweulu, Usagaran), which collided with a northern cratonic domain, while the second one (*ca* 1860 Ma) is a shear event affecting only the orogenic domain close to the western border of the Tanzanian craton, *i.e.* the Ubendian Belt.

A NW linear trending shear domain formed at *ca* 1860 Ma along the western side of the rigid Tanzanian craton and marks the Ubendian Belt (Fig. 6). This phase has probably affected the whole Palaeoproterozoic domain, but to a much lower extent. A multi-phase structural evolution has also been recorded in the Usagaran Belt. The Konse series and the Ndembera volcanics, which unconformably overly the Usagaran high-grade sequence between the Usagaran and the Tanzanian craton (Gabert and Wendt 1974) are structurally less evolved and of a lower metamorphic grade (Meinhold 1970; Mruma 1989). It is thought that the northwards directed thrusting of these series onto the Tanzanian craton is related to the *ca* 1860 Ma phase.

NW dextral shear movements then defined a penetrative shear imprint on the Palaeoproterozoic terranes, only in the Ubendian Belt along the western side of the craton (Fig. 6). This transpressive shear ended by rapid uplift, as marked by late undeformed volcanics, of the deep-seated shear terranes, which allowed the preservation of very high pressure metamorphic assemblages in the mafic and ultramafic rocks, possibly of ophiolitic type (Sklyarov *et al., submitted*).

Reactivation of the NW-SE shear zones occurred during the Neoproterozoic (Fig. 5), particularly in the southern Ubendian Belt, near the Mozambiquian Belt, where the Pan-African orogeny was strong by comparison to the Mesoproterozoic reactivations, which have not been recorded. Early events were accompanied in the south-east by alkaline granites (*ca* 725 Ma) and greenschist to lower amphibolite metamorphic overprints, while more to the north-west deformation seems to be weaker and intrusions are characterized by silica-undersaturated syenites. This deformation, which reactivated the NW-SE shear zones by creating brittle to brittle-ductile mylonites, corresponds to a sinistral transpression regime. The alkaline magmatism present in the shear zones (Fig. 2) indicates that the latter are of a lithospheric scale. This mantle magmatism could have been provoked by pressure release in the underlying mantle (Sykes 1978; Black *et al.*, 1985; Black and Liégeois 1993). The Bangweulu block has not been affected by this phase and constituted a rigid block on which was partly thrust the Lufilian arc (Fig. 1; Coward and Daly 1984; Ngoyi *et al.*, 1991). Lastly, a brittle deformation is at the base of a NE-orientated joints network in response to a ENE-WSW compressive stress field. All these Neoproterozoic events are intracontinental. They are a consequence of the events which occurred at distant plate boundaries all around (Lufilian, Mozambiquian, Zambezian).

CONCLUSIONS

The Ubendian Belt represents a shear belt with a tectonic and magmatic evolution extending over more than 2 Ga including 1.5 Ga of Proterozoic activity (Fig. 5). The creation of the belt resulted from the regional 2100-2025 Ma orogeny and to the peculiar position of the Ubendian segment along an edge of the rigid Tanzanian craton. The early granulitic/upper amphibolite phase (*ca* 2100-2025 Ma) can be interpreted as a collisional process against a rigid cratonic block. This rigid block is partly the Tanzanian craton and possibly the Archaean part of the Congo craton.

The Ubendian shear phase (climax at *ca* 1860 Ma) is probably a protracted stage marked by the functionning of NW-SE striking dextral shear zones and the coeval emplacement of calc-alkaline batholiths. These horizontal movements are probably at the origin of the eight crustal blocks (or displaced terranes) constituting the Ubendian Belt. This phase is poorly represented in the other parts of the Palaeoproterozoic domain, but is probably the origin of a new thrusting phase in the Usagaran.

The situation of the Ubendian Belt was so favourable to reactivations that they occurred episodically from 1860 Ma until the present with a maximum reached during the early Pan-African (*ca* 750 Ma). This important reactivation phase was accompanied by upper greenschist to lower amphibolite-facies metamorphic overprint and the intrusion of alkaline magmatic bodies. The cause of these effects can be found in nearby Pan-African belts - the Mozambiquian and the Lufilian. By opposition, adjacent Kibaran Belts (Kibarides, Irumides) seem to have induced only weak reactivations within the Ubendian Belt. The Bangweulu block became rigid relatively early due to quiet conditions (Black and Liégeois 1993) as shown by its nearly undeformed Palaeo- to Mesoproterozoic sedimentary cover.

The mobility of the Ubendian Belt, situated along the western edge of the Tanzanian craton, can be compared to those of the major suture zones, separating major crustal entities of different rheology: the constraints applied at plate boundaries will be expressed as such zones of weakness. This situation also induced the localization of the present East African rift.

Acknowledgments

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