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The Konse Group on the SE margin of the Tanzania Craton – a Paleoproterozoic passive margin succession of the Usagaran Orogen: Constraints from metamorphic monazite ages and isotopically heavy carbon in marbles

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ABSTRACT

The Konse Group is a 2–3 km thick succession of quartzites, metaconglomerates, micaschists, marbles, Mn-rich metasediments and mafic metavolcanics deposited over >200 km in a narrow basin along the SE margin of the Archean Tanzania Craton. The timing of basin formation with respect to the Paleoproterozoic Usagaran orogeny is controversial: it is interpreted either as post-orogenic, overlying folded Usagaran gneisses, or as pre-orogenic, developed on the craton margin. In the latter case, the Konse Group is regarded as a lower-grade, time equivalent of the tectonically overlying Usagaran gneisses, which represent the deeper part of the same basin. Nearly U-free monazite from oxidized Mn^{3+}-rich Konse Group micaschists yielded a Th-Pb age of 2028 ± 15 Ma (95 % confidence) for metamorphism, which argues against a post-orogenic depositional age. The low U content and Mn^{3+}-enrichment are attributed to oxidizing conditions in the precursor sediment. The pre-Usagaran depositional age is supported by highly positive $\delta^{13}C$ values, +12.6 and +9.3 ‰, for marbles of the Konse Group and correlative Mpwapwa Group to the northeast, respectively, indicating sedimentation during the ca. 2.22–2.06 Ga Lomagundi Event. Both groups share a similar depositional age and tectonic setting with marginal successions of other southeastern African cratons, which were deposited at early stages during the assembly of the Paleoproterozoic Columbia/Nuna supercontinent. The Konse and Mpwapwa groups represent cratonic passive margin successions, which belong to the Usagaran Orogen. The latter contains essential lithological members of a Wilson cycle, suggesting that modern-style plate tectonics operated during the Paleoproterozoic.

1. Introduction

The Proterozoic Konse Group (KG) of central Tanzania is a volcano-sedimentary succession, which occurs in a narrow basin developed over more than 200 km along the SE border of the Neoarchean Tanzania Craton (Grantham, 1927; Whittingham, 1959; Meinhold, 1970; Meinhold and Frisch; 1970; Mruma, 1989, 1995). It consists of a 2–3 km thick succession of quartzites, metaconglomerates, greenschists, amphibolites, micaschists, graphite-muscovite schists, iron-rich quartzites, some minor, oxidized Mn^{3+}-silicate bearing micaschists and Mn-rich quartzites, besides some dolomite and calcite marbles (Meinhold, 1970). The succession shows a W-E metamorphic zonation with (sub-) greenschist-facies grade in the west, near the craton, and lower amphibolite facies (Hbl ± Grt; mineral abbreviations after Whitney and Evans, 2010) further east (cf. Meinhold, 1970), and, like many other early Precambrian sedimentary basins, the KG lacks biostratigraphic age information. The Group's assumed age and basin-type, which are based on stratigraphic correlations with adjoining units, are therefore ambiguous and resulted in contrasting interpretations.

Indirect age constraints are based on the observation that the KG on its eastern side is bordered by high-grade gneisses of the Paleoproterozoic Usagaran Orogen. These gneisses of the Lower Isimani Group have been thrust during the Paleoproterozoic and Neoproterozoic orogenic events towards the Tanzania Craton and now overlie the low-grade

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metasediments of the KG. Near the southern termination of the KG basin (Fig. 1), the extensive intermediate to felsic volcanic rocks unconformably overlie the steeply plunging, folded Usagaran gneisses. These volcanics have been dated by Wendt et al. (1972) and Gabert and Wendt (1974) at 1895 ± 27 Ma (Rb-Sr whole rock isochron age; recalculated with the decay constant of Steiger and Jäger, 1977), an age that later was confirmed by SHRIMP U-Pb dating of zircon (Sommer et al., 2005b; Bahame et al., 2016). By correlating the KG metasedimentary rocks with the post-orogenic Ndembera volcanic rocks, Grantham (1927), Whittingham (1959) and Mruma (1989, 1995) inferred a post-orogenic age for the KG, since also the KG metasedimentary rocks were thought to overlie older, folded Usagaran gneisses. Nevertheless, Mruma (1995) interpreted that the KG was deposited in a peripheral foreland basin. Most subsequent workers followed this post-orogenic interpretation (Reddy et al., 2003; Collins et al., 2004; Thomas et al., 2013; Brown et al., 2020; Tamblyn et al., 2021). However, when Reddy et al. (2004) confirmed the Neoproterozoic reworking of the Usagaran Belt rocks by Ar-Ar mica dating (ca. 540 Ma; Wendt et al., 1972; Möller et al., 1995), they also considered a Neoproterozoic deposition and metamorphism for the 'greenschist-facies' KG. In contrast, Meinhold (1970), Meinhold and Frisch (1970) and Meinhold and Ott (1993, unpubl. BGR report) inferred a gradational lateral transition between the Lower Isimani Group and the KG. They regarded the well-preserved volcano-sedimentary KG succession as a pre-orogenic temporal equivalent to the Lower Isimani Group. In their view, the KG represents continental margin sediments, whereas the Lower Isimani Group was deposited in a deeper, more distal part of the same Usagaran basin. These contrasting interpretations described above resulted from correlations of the KG with different adjoining units (Ndembera volcanic rocks vs. Lower Isimani Group).

In the present study, we establish direct age constraints for the KG, based on monazite geochronology and on C-isotope chemostratigraphy that allows interbasinal correlations and an interpretation of the tectonic setting of the Konse Group as a passive margin succession. In order to constrain the age of the KG metamorphism we determine metamorphic monazite ages of spessartine-Mn^{3+}-andalusite micaschists from Mhumbirisa Hill (Figs. 2 and 3), which are regarded as typical members of the KG (Meinhold, 1970; Mruma, 1995). We apply carbon isotopic chemostratigraphy on the widespread marbles of the KG (Figs. 2 and 3a) to further confine its possible depositional age. Since the proposed pre-orogenic depositonal age falls into the time interval between 2.5 Ga (craton stabilization) and 2.0 Ga (Usagaran orogeny), it includes the time of the distinctly positive Lomagundi Carbon Isotope Excursion (LCIE), which is preserved in marine and terrestrial carbonates. The LCIE has long been used as a global chemostratigraphic marker for the time interval between ca. 2.22 and 2.06 Ga (Karhu and Holland, 1996; Bekker et al., 2006) and has been applied for dating and stratigraphic correlations of otherwise poorly dated Paleoproterozoic (meta) sedimentary successions (e.g., Buick et al., 2003; Master et al., 2010, 2013; Hansen et al., 2023). The carbon and oxygen isotopic compositions of the Konse marbles can resolve if the group was deposited during the 'Lomagundi Event'.

Metasedimentary rocks of the Mpwapwa Group, which are exposed to the north and east of the Konse Group in the Kiboriani Mountains and at Mautia Hill (Fig. 1; Thomas et al., 2013; Temperley et al., 1953), show many lithological similarities with those of the Konse Group. In particular, the unusual rock association at the Mautia Hill, which consists of oxidized Mn-rich schists, marbles, quartzites and piemontite quartzites (Jöns and Schenk, 2004) resemble that of the Paleoproterozoic Konse Group at the Mhumbirisa Hill. However, the Mpwapwa Group is regarded as part of the so-called 'Western Granulites' of the Neoproterozoic Mozambique Belt (e.g., Fritz et al., 2005; Fritz et al., 2013; Sommer et al., 2003, 2005a); their depositional age is unconstrained. The striking similarities of the unusual lithologies in combination with new metamorphic ages, which revealed a Paleoproterozoic metamorphism besides a weak Neoproterozoic overprint (Thomas et al., 2013), suggests that the Mpwapwa Group might be correlative with the Konse Group of the Usagaran Orogen. Thus, we included the marbles of the Mpwapwa Group from the Mautia Hill in our investigation to resolve their depositional age and to further constrain the extent of the Paleoproterozoic basin that surrounded the Tanzania Craton along its eastern margin.

Marbles are also abundant in the Eastern Granulites of the Neoproterozoic Mozambique Belt, which border the Western Granulites and the Paleoproterozoic Usagaran Orogen to the east (Fig. 1). They were metamorphosed 50–100 Ma earlier (at 650–600 Ma) than the so-called 'Western Granulites' (at ca. 550 Ma) and are associated with basement rocks that revealed Archean to Neoproterozoic protolith ages (Möller et al., 1998, 2000; Johnson et al., 2003; Sommer et al., 2003, 2005a). With the analyses of the isotopic compositions of these marbles, we explore whether they are correlative with the Paleoproterozoic marbles of the Usagaran Orogen.

2. Geological setting of Paleoproterozoic orogenic belts in Tanzania

The Paleoproterozoic orogenic belts of Tanzania surround the Archean Tanzania Craton on its southwestern (Ubendian Belt) and southeastern (Usagaran Belt) sides (Fig. 1). The crust of the Tanzania Craton has mainly grown during the Neoarchean (ca. 2.72–2.61 Ga) but older rocks with formation ages >2.82 Ga and ca. 3.2 Ga have also been found (Thomas et al., 2013, 2016; Kabete et al., 2012). Both Paleoproterozoic orogenic belts contain eclogites that formed from ocean-floor basalts during metamorphic events dated at ca. 2.0 Ga in the Usagaran Belt (Möller et al., 1995; Collins et al. 2004; Tamblyn et al., 2021) and at 1.88–1.86 Ga in the Ubendian Belt (Boniface et al., 2012). These eclogites are spatially and timely associated with belts containing garnet-cordierite-sillimanite gneisses (Meinhold, 1970; Kazimoto et al., 2014; Loose and Schenk, 2018). Thus, these linear orogenic belts are among the oldest known to preserve metamorphic evidence for subduction and exhumation of oceanic lithosphere in connection with collisional orogeny (Loose and Schenk, 2018). Both belts experienced several tectono-metamorphic events in the Paleoproterozoic (between ca. 2.1 and 1.82 Ga; Kazimoto et al., 2014; Möller et al., 1995; Reddy et al., 2003; Tamblyn et al., 2021), pointing to the similar evolution even though the dated eclogite-facies events of the two belts differ in age by about 140 Ma. The recognized tectono-metamorphic events in the Usagaran and Ubendian belts were associated with calc-alkaline magmatism between ca. 2.1 and 1.8 Ga, reflecting different episodes of Paleoproterozoic crustal growth at the craton margins (Fig. 1; Wendt et al., 1972; Gabert and Wendt, 1974; Priem et al., 1979; Möller et al., 1998, 2000; Reddy et al., 2003; Thomas et al., 2013; Kazimoto et al. 2014; Tulibonywa et al., 2015; Sommer and Kröner, 2019). However, both Paleoproterozoic belts also contain considerable amounts of reworked Archean crust separated from the craton margins (Möller et al., 1998; Johnson et al., 2003; Collins et al., 2004; Kazimoto et al. 2015). Kazimoto et al. (2015) and Loose and Schenk (2018) proposed, based on the presence of paired metamorphic belts, that the Paleoproterozoic subduction in the Ubendian Belt was directed towards the northeast below the craton, whereas the subduction in the Usagaran Belt was east-directed below an Archean crustal block further east (subsequently reworked in the Neoproterozoic Mozambique Belt; Möller et al., 1995; Loose and Schenk, 2018). Other views (Brown et al., 2020; Tamblyn et al., 2021), not aware of the existence and position of a low-P belt in the Usagaran belt (Meinhold, 1970; Meinhold and Frisch, 1970) and inferring that the KG metasediments are a post-orogenic rather than a passive continental margin succession of the Usagaran Orogen, left the direction of subduction open and discussed both possibilities.

In the Usagaran Orogen, the best-preserved Paleoproterozoic metamorphic rocks that were not or only weakly affected by Neoproterozoic reworking occur in a narrow wedge-shaped area along the SE border of the Tanzania Craton (Fig. 1). A compilation map showing the inferred

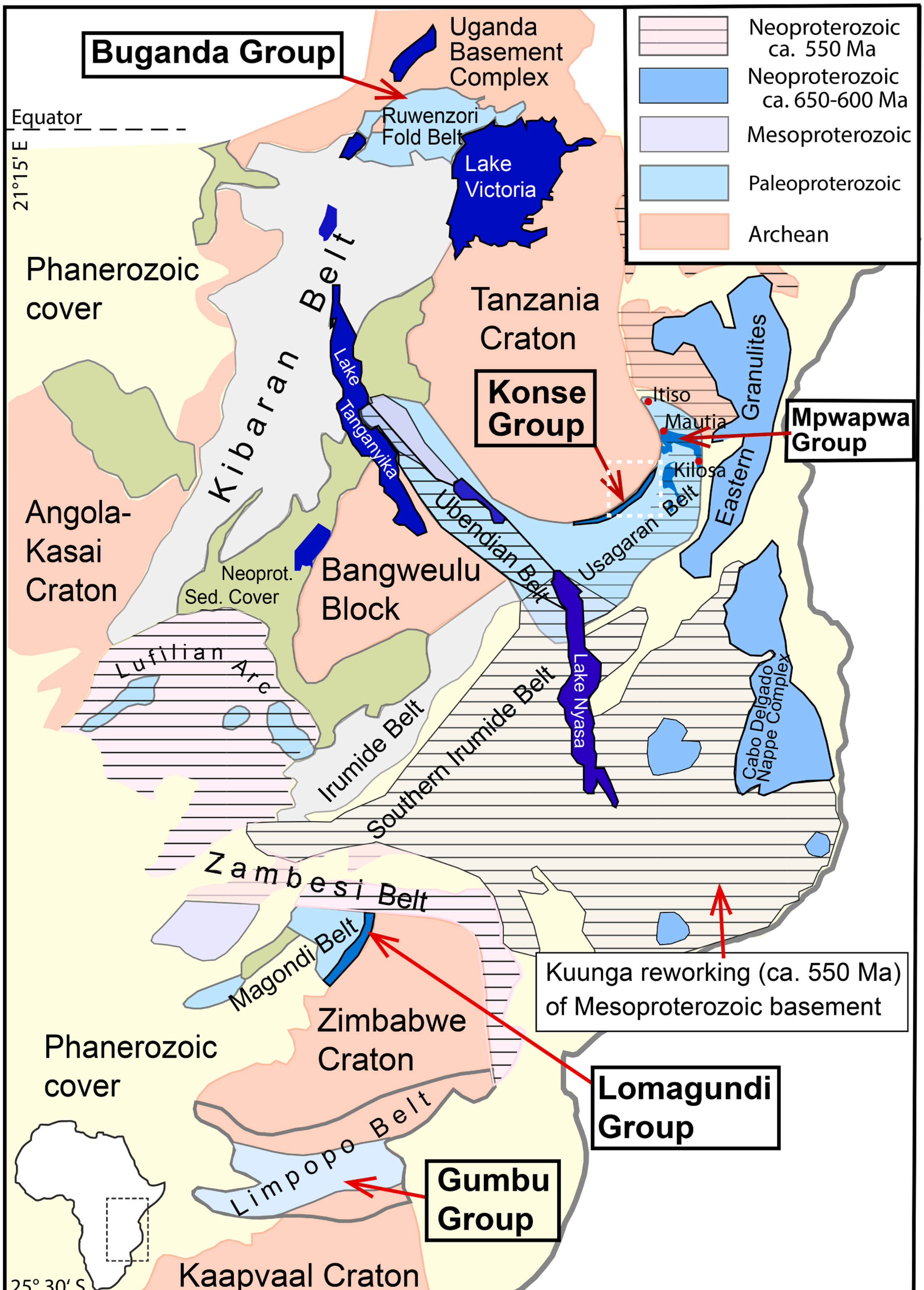

Fig. 1. Geology of southeast Africa highlighting the Paleoproterozoic mobile belts around Archaean cratons that host Paleoprotereozoic passive margin sequences deposited during the Lomagundi carbon isotope excursion at ca. 2.22–2.06 Ga: the Lomagundi Group of the Magondi Supergroup (Magondi Belt), the Gumbu Group of the Limpopo Belt, the Konse Group (Usagaran Orogen) and the Buganda Group (Ruwenzori Fold Belt). The Mpwapwa Group metasediments are correlative to those of the Konse Group. Close to the craton they were mainly metamorphosed during the Usagaran orogeny, further east at the Mautia Hill by the Kuunga collisional event at ca. 550 Ma, and in the south (Kilosa) during both events. Most areas between the Archean cratons were reworked by the Neoproterozoic Kuunga collisional events. Modified after Hanson (2003). The area of Fig. 2 is marked with a white dashed rectangle.

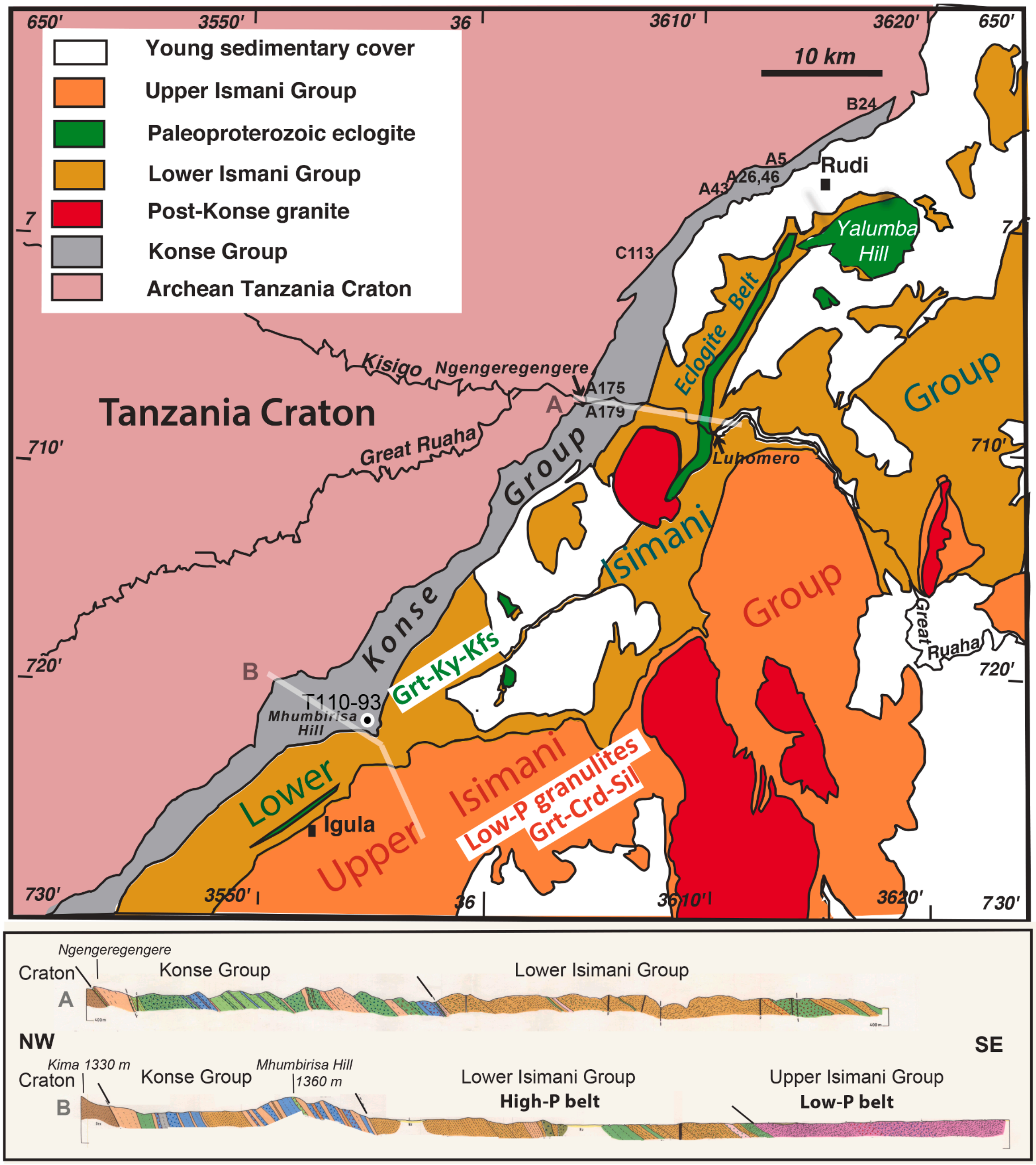

Fig. 2. Geological map of the SE margin of the Tanzania Craton (area marked in Fig. 1) and the adjoining Usagaran Orogen with sample locations (numbers), modified after Meinhold (1970). NW-SE geological cross-sections along the Great Ruaha River (A) and across the Mhumbirisa Hill (B) are shown below the map (for color coding in sections see Fig. 3a). The Konse Group of the Usagaran orogen was deposited during the Lomagundi carbon isotope excursion at ca. 2.22–2.06 Ga at the margin of the Archean Tanzania Craton and was metamorphosed during the Usagaran orogeny at ca. 2.0 Ga. The group is overlain by a Paleoproterozoic nappe pile: The Lower Isimani Group (accretionary wedge sediments) envelopes a belt of subduction-related retrogressed eclogites and is overlain by a nappe of the ca. 2.06 Ga low-pressure granulites (Upper Isimani Group) interpreted to be derived from a 50–60 Myr older low-P/high-T paired metamorphic belt to the east. It was emplaced by NW-directed transport (in today's coordinates) during the Usagaran orogeny at ca. 2.0 Ga.

extent of Usagaran rocks along the SE corner of the Tanzania Craton (Fritz et al., 2005; Fritz et al., 2013) is based on 56 Quarter Degree Sheets (QDS) published by the Tanzanian Geological Survey. However, the indicated regional extent of the wedge-shaped Usagaran Belt in this map is biased by a systematic increase of mica cooling ages towards the craton, from ca. 430 to 1960 Ma, pointing to a gradually decreasing influence of the Pan-African orogeny towards the craton (Wendt et al., 1972; Gabert and Wendt, 1974). The full extent of the belt with dated Paleoproterozoic magmatism and metamorphism is much larger towards north and east (Fig. 1). The Paleoproterozoic Usagaran Belt is bordered by the Archean craton to the NW, and by Neoproterozoic belts to the east. These belts were grouped together under the umbrella of the Mozambique Belt (MB; Holmes, 1951; Hepworth, 1972) or East African Orogen (EAO; Stern, 1994), not discriminating between two separate Neoproterozoic events and belts that have only later been recognized. The ca. 650–600 Ma Eastern Granulites of the MB (Appel et al., 1998; Möller et al., 2000) are thought to form a nappe (Fritz et al., 2005; Fritz et al., 2013), resting on the Tanzanian Kuunga Belt that stretches along the eastern border of the Tanzania Craton. The basement of the Tanzanian Kuunga Belt yielded Archean and Paleoproterozoic formation ages in the southern part (eastern part of Usagaran Belt in Fig. 1), but only Archean ages in the north (Fig. 1). Both parts of the basement are called

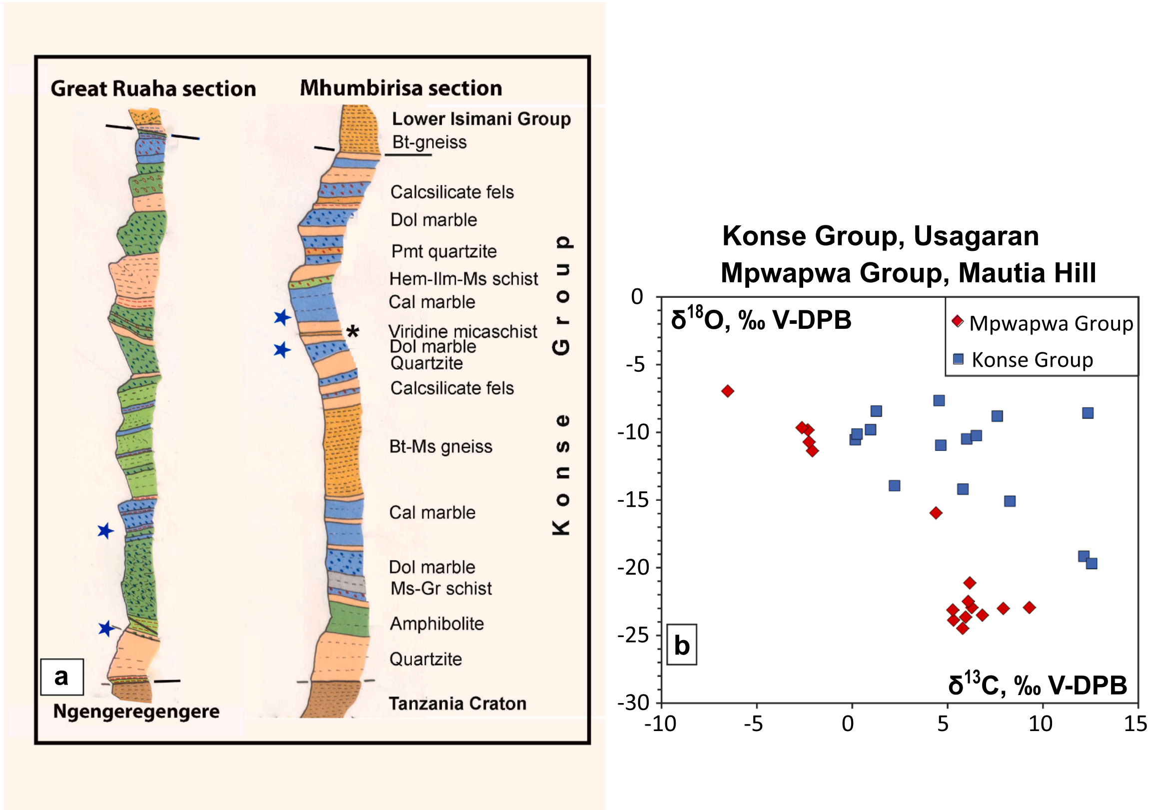

Fig. 3. (a) Two stratigraphic columns of the Konse Group of the Usagaran Orogen drawn after geological sections published by Meinhold (1970): the Great Ruaha River section in the NE and the Mhumbirisa Hill section in the SW (see Fig. 2). The thickness of the Konse Group was estimated by Meinhold (1970) at 2–3 km. The metamorphism of the marked horizon of Mn-rich micaschist (Mhumbirisa Hill; black star) was dated with monazite and the marked marble horizons (blue stars) were analyzed for C and O isotope ratios. (b) Plot of $\delta^{18}O_{carb}$ vs. $\delta^{13}C_{carb}$ for the Konse Group marbles of the Usagaran Orogen, Tanzania. Sample locations are shown in Fig. 2. The Mautia Hill marbles of the Mpwapwa Group, associated with oxidized whiteschists, experienced a high-P amphibolite-facies metamorphism during the ca. 550 Ma Kunnga collisional event. A Paleoproterozoic metamorphism has not been recognised so far at the Mautia Hill. However, the highly oxidized Mn-rich rock association resembles that of the Konse Group at the Mhumbirisa Hill. The herein reported carbon isotope data support this correlation and point to a Paleoproterozoic depositional age during the Lomagundi carbon isotope excursion at ca. 2.22–2.06 Ga.

by many authors ‘Western Granulites’ (e.g., Sommer et al., 2003, 2005a, 2017; Pinna et al., 1993; Fritz, et al., 2005; Fritz et al., 2013; Tenczer et al., 2013; Thomas et al., 2013, 2016; Hauzenberger et al., 2014), which are thought to have been affected by a Neoproterozoic (Kuunga) granulite-facies metamorphism. However, a granulite-facies metamorphism of the Kuunga age (ca. 550 Ma) has so far not been demonstrated. Instead, the study of whiteschist metamorphism of the Mpwapwa Group in the ‘Western Granulites’ at the Mautia Hill resulted in a P-T path pointing to a substantial Neoproterozoic tectonic crustal thickening at ca. 550 Ma. The peak of metamorphism was at high-P amphibolite-facies conditions (Jöns and Schenk, 2004). The eastern boundary of the Paleoproterozoic Usagaran Belt within the Neoproterozoic Mozambique Belt is obscured (and thus uncertain) due to the strong Neoproterozoic reworking of pre-existing older crust. However, taking the distribution of published Paleoproterozoic formation ages as evidence for the extent of the Paleoproterozoic orogeny in the Mozambique Belt and adding new metamorphic monazite ages, we considerably expanded the hitherto assumed regional extent of the Usagaran Orogen towards N and NE as shown in Fig. 1 (up to Itiso in the north and including the Mpwapwa Group exposed in the Kiboriani Mountains). Monazite grains included in garnet porphyroblasts of the Mpwapwa Group metapelites at the Kiboriani Mountains (e.g. at Kilosa in Fig. 1) yielded Paleoproterozoic ages (1956 ± 13 Ma), whereas ages of monazite grains in the matrix reflect the Neoproterozoic reworking (583 ± 10 Ma). This can be taken as evidence that the main metamorphic event that affected these rocks (resulting in growth of garnet porphyroblasts) is of Paleoproterozoic age, whereas the Neoproterozoic re-working was of minor importance. The new Paleoproterozoic monazite ages for the Mpwapwa Group metasediments from near Mautia, Itiso and Kilosa agree with the zircon U-Pb data obtained for metasediments mapped by Temperley (1938) and Temperley et al. (1953) at the eastern craton margin along and south of the Dodoma–Daressalam road (Thomas et al., 2013), in an area that is outside of the formerly assumed extent of the Usagaran Belt (Fritz et al., 2005; Fritz et al., 2013). The main metamorphism (amphibolite facies) of these Mpwapwa Group metasediments is dated as Paleoproterozoic (metamorphic zircon and titanite U-Pb ages of ca. 1993 and 1999 Ma, respectively; Thomas et al., 2013). In contrast, the Neoproterozoic reworking at ca. 550 Ma only weakly affected these Mpwapwa Group metasediments. The only known exception is at the Mautia Hill, where the Neoproterozoic metamorphism (ca. 550 Ma) was of high-P amphibolite-facies grade (720 °C/10–11 kbar; Jöns and Schenk, 2004).

In summary, the new geochronological data reveal that the Mpwapwa Group metasediments, which occur along the eastern margin of the Tanzania Craton between Itiso and the Great Ruaha River (southern area of the so-called ‘Western Granulites’), are part of the Usagaran Belt (Fig. 1). They were affected by an upper amphibolite-facies metamorphism in the Paleoproterozoic, at ca. 2.0–1.96 Ga, and can be regarded as a time equivalent to the metasediments of the Konse and Lower Isimani groups further south. In addition, the data demonstrates that the Paleoproterozoic Usagaran orogeny has left a metamorphic imprint in the Neoproterozoic Mozambique Belt.

3. Geological setting of the Konse Group marbles

The wedge shaped area of the Paleoproterozoic Usagaran Belt at the SE corner of the Tanzania Craton (Fig. 1) was mapped and subdivided by earlier authors (Fig. 2; Meinhold, 1968, 1970; Meinhold and Frisch, 1970; Meinhold and Ott, 1993; Whittingham, 1959; Temperley, 1938; Mruma, 1989, 1995; Fritz et al., 2005 and references therein). Meinhold (1970) distinguished the high-grade Isimani Group ('Usagaran highly metamorphic rocks' of Whittingham, 1959) and the lower-grade KG metasediments, which unconformably overlie migmatitic gneisses of the Archean Tanzania Craton (Fig. 2). The KG is overlain by the Lower Isimani Group, which consists of various types of metasediments (including Grt-Ky-Bt metapelites) and interbedded metabasites (amphibolites, mafic granulites and eclogites) as well as some tectonic slivers of the Archean felsic basement (Meinhold, 1970; Möller et al., 1998; Collins et al., 2004). Geochemical data indicate that the eclogites were formed from subducted oceanic crust (Möller et al., 1995), whereas the associated Lower Isimani Group gneisses, which experienced an interrelated clockwise P-T path with the eclogites during a coeval, short-lived high-P amphibolite-facies metamorphism at ca. 2.0 Ga, are interpreted as accretionary wedge sediments. The low-P granulites (Grt-Crd-Sil) of the Upper Isimani Group rest on the top of the Lower Isimani Group (Fig. 2; Meinhold, 1970) and are restricted to the southern part of the map area (Fig. 2). They are regarded as a nappe, due to the different

Table 1
Secondary ionization mass spectrometry in situ monazite analyses for Konse Group andalusite-spessartine micaschists with data for reference monazite.

Sample Sample	Grain	Spot	Age (Ma) ^{208}Pb*/^{232}Th	Age (Ma) ^{208}Pb*/^{232}Th 2 s.e.	^{208}Pb*/^{232}Th	^{208}Pb*/^{232}Th 2 s.e.	% ^{208}Pb*	Th/U	Th O_2/Th
T110-14	1	1	2010	92	0.105	0.005	99.9	77,900	0.173
T110-14	1	2	2049	93	0.107	0.005	99.9	193,000	0.179
T110-14	1	3	2010	100	0.105	0.005	99.9	767,000	0.176
T110-14	2	1	2023	96	0.105	0.005	99.9	101,000	0.178
T110-14	3	1	2010	98	0.105	0.005	100.0	176,000	0.177
T110-14	3	2	1999	99	0.104	0.005	100.0	445,000	0.172
T110-14	4	1	1835	89	0.0951	0.0048	99.9	302,000	0.178
T110-14	4	2	2068	99	0.108	0.005	99.9	384,000	0.177
T110-14	6	1	2030	92	0.106	0.005	99.9	252,000	0.177
T110-15	3	1	2047	101	0.107	0.006	100.0	107,000	0.181
T110-15	1	1	2031	102	0.106	0.006	99.9	344,000	0.180
References									
44,069	1	1	416	26	0.0208	0.0013	99.9	7.81	0.165
44,069	1	2	431	26	0.0216	0.0013	99.9	6.39	0.154
44,069	2	1	429	23	0.0214	0.0012	99.9	5.86	0.158
44,069	2	2	425	27	0.0213	0.0014	99.9	4.57	0.160
44,069	3	1	427	24	0.0213	0.0012	99.9	9.61	0.161
44,069	4	1	433	24	0.0216	0.0012	99.9	7.16	0.157
44,069	5	1	420	28	0.0210	0.0014	99.9	9.99	0.166
44,069	5	2	430	27	0.0215	0.0014	100.0	11.8	0.163
44,069	1	1	416	22	0.0208	0.0011	99.9	11.7	0.167
44,069	1	2	421	27	0.0210	0.0014	99.9	9.68	0.162
44,069	1	3	419	24	0.0210	0.0012	99.9	9.52	0.164
44,069	2	1	416	28	0.0208	0.0014	99.9	13.1	0.166
44,069	2	2	441	34	0.0220	0.0017	99.9	13.1	0.158
44,069	3	1	440	29	0.0220	0.0015	99.9	10.5	0.151
44,069	4	1	421	24	0.0210	0.0012	99.9	9.45	0.157
44,069	5	1	425	26	0.0212	0.0013	99.9	9.54	0.169
44,069	5	2	438	30	0.0219	0.0015	99.9	9.65	0.162
44,069	5	3	411	23	0.0205	0.0011	99.9	17.1	0.164
44,069	5	4	416	25	0.0208	0.0013	99.9	13.0	0.171
44,069	5	5	429	23	0.0214	0.0012	99.9	9.89	0.163
554	1	1	48.1	4.0	0.00238	0.00020	99.2	416	0.160
554	1	2	44.8	3.5	0.00222	0.00017	99.5	402	0.175
554	2	1	44.7	4.1	0.00221	0.00020	99.3	347	0.167
554	2	2	45.1	3.9	0.00223	0.00019	99.4	245	0.173
554	3	1	46.7	4.9	0.00231	0.00024	99.3	409	0.174
554	4	1	47.1	3.9	0.00233	0.00020	99.5	340	0.171
554	5	1	43.6	5.3	0.00216	0.00027	99.5	325	0.173
554	5	2	46.1	3.9	0.00228	0.00020	99.4	146	0.169
554	5	3	45.1	4.2	0.00223	0.00021	99.4	360	0.169
554	5	4	47.3	4.2	0.00234	0.00021	99.4	142	0.170
Amelia	1	1	269	16	0.0134	0.0008	99.6	494	0.137
Amelia	1	2	278	17	0.0138	0.0009	99.7	504	0.134
Amelia	1	3	276	17	0.0138	0.0008	98.9	529	0.139
Amelia	1	4	276	16	0.0138	0.0008	99.7	518	0.137
Amelia	1	5	278	19	0.0138	0.0009	99.4	497	0.132
Amelia	1	6	273	16	0.0136	0.0008	99.6	492	0.139
Amelia	1	7	278	17	0.0138	0.0008	99.7	515	0.140
Amelia	1	8	278	17	0.0139	0.0009	99.3	511	0.135
Amelia	1	9	273	16	0.0136	0.0008	99.6	496	0.141
Amelia	1	10	265	18	0.0132	0.0009	99.6	498	0.141
Amelia	1	11	272	18	0.0136	0.0009	99.6	496	0.135
Amelia	1	12	276	16	0.0138	0.0008	99.7	506	0.137

*Radiogenic with common Pb correction uses Stacey-Kramer composition for corresponding age.
Reference ages: 424.9 Ma (44069; Aleinikoff et al., 2006), 45 Ma (554; Harrison et al., 1999), 274.6 Ma (Amelia; Peterman et al., 2012).

style and age of their metamorphism. Nappe emplacement likely occurred in the course of the continent–continent collision during the Usagaran orogeny at ca. 2.0 Ga.

The KG pinches out north of the prominent Yalumba Hill that represents the main outcrop of the eclogites (Fig. 2). From there towards southwest, Meinhold (1970) has mapped the area in great detail and has drawn several geological cross-sections, which show the lateral variability in the lithological content of the KG. Along the strike, the volcano-sedimentary succession of the KG varies as quartzites and metavolcanic intercalations change in thickness. The intercalated greenschists/amphibolites might be related to initial rifting in the Konse basin. However, near the base of the Great Ruha River section (Ngengeregengere Gorge) pillow lavas were described (Mruma 1989, 1995) with geochemical signatures of supra-subduction basalts (Boniface and Tsujimori, 2019). The two stratigraphic columns of the KG (Fig. 3a) have been drawn on the basis of the NW–SE section of Meinhold (1970) that crosses the Mhumbirisa Hill (at loc. T110 in Fig. 2) and the section along the Great Ruaha River (Fig. 2).

The KG succession consists of quartzites, metaconglomerates, metabasites, micaschists, graphite-muscovite schists, iron-rich quartzites and marbles with some minor, oxidized Mn^{3+}-rich micaschists, piemontite quartzites, and piemontite-Mn-cummingtonite felses, which are regarded as members of a single sedimentary group (Fig. 3a; Meinhold, 1970; Mruma, 1995). The basal, finely-laminated quartzite that reaches locally a thickness of up to 200 m contains several horizons of coarse-grained conglomerates and is, locally, also overlain by conglomerates. These horizons pinch and swell, but some of them are mappable for several kilometers along strike (Meinhold, 1970; Mruma, 1995). Furthermore, the basal quartzite contains beds with preserved flute structures and ripple marks as well as cross-bedding. The mafic rocks, immediately overlying the quartzites, are only weakly affected by metamorphism, less than the overlying KG members further east.

4. Sampling strategy and sample description

For monazite dating of the Konse Group metamorphism, two samples of Mn^{3+}-rich-andalusite-spessartine micaschists of lower amphibolite-facies grade (T110-14-93; T110-15-93; Table 1) were taken from beds intercalated with marbles at the Mhumbirisa Hill (Figs. 2 and 3a). Mhumbirisa Hill is the location where Mruma (1989, 1995) deduced the stratigraphic and structural relationships between the two groups: here, the assumed stratigraphically 'underlying Isimani Suite' was thought to have been thrust over the 'overlying KG'. These porphyroblastic micaschists have the assemblage of Mn^{3+}-rich andalusite, spessartine (Sps90/Prp8), Mn-bearing biotite, white mica, quartz, plagioclase (An15), piemontite, hematite, rutile, tourmaline, apatite, monazite and zircon. Spessartine forms inclusions in and reaction rims surrounding the 1–2 cm large porphyroblasts of Mn-andalusite (Fig. 4b). The high Mn_2O_3 content (up to 8.5 wt%) of andalusite may have stabilized andalusite relative to kyanite (Abs-Wurmbach et al., 1983), which is the aluminosilicate found in the overlying Lower Isimani Group. The metamorphic grade at this location is of lower amphibolite facies as

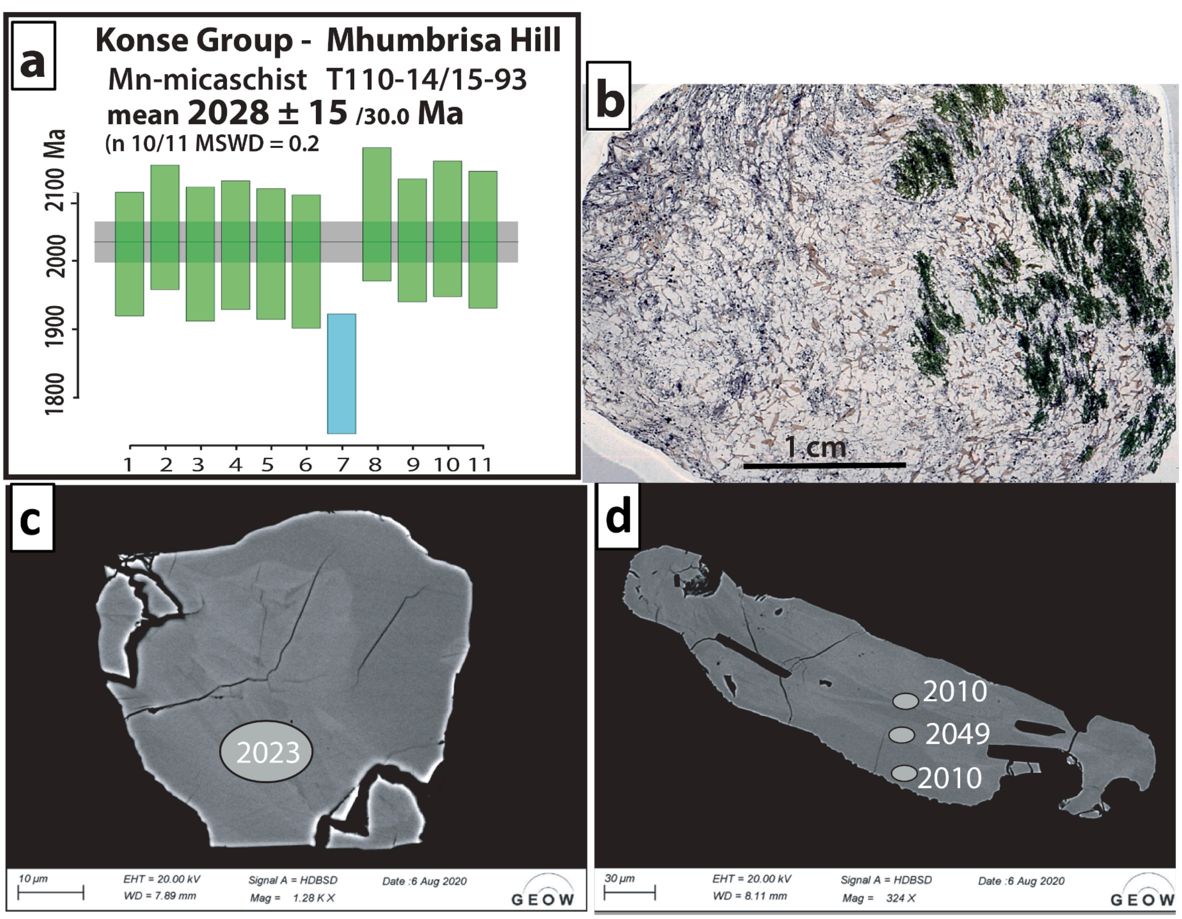

Fig. 4. **(a)** SIMS Th-Pb age of monazite analyzed *in-situ* using thin sections of Mn-micaschists from the Mhumbirisa Hill (loc. T110-93 in Fig. 2). The weighted average age of 2028 ± 15 Ma dates the lower amphibolite-facies metamorphism related to the Usagaran orogeny (ca. 2.0 Ga), and precludes deposition of the Konse Group after the Usagaran orogeny. **(b)** Scan of a thin section (~ 4.5 × 2.5 cm) of porphyroblastic Sps-Mn^{3+}-rich andalusite micaschist T110-15–93. Mn^{3+}-rich andalusite forms porphyroblasts (green) up to several cm in diameter. **(c-d)** BSE images of selected monazite grains in sample T110-14–93; ages in Ma. Monazite grains display patchy or concentrical zoning due to varying Th contents. Due to oxidizing depositional conditions, monazite is nearly U-free (Th/U ratios are between ~ 1 and 8 × 10^5).

indicated by the assemblage of magnesiohornblende and piemontite in associated Mn^{3+}-rich calcsilicates and mafic rocks (Meinhold and Frisch, 1970).

For carbon isotopic analyses of the Konse Group marbles, 15 samples were selected (Table S2; Fig. 2). These marbles come from the Mhumbirisa Hill (n = 6), the Great Ruaha section (n = 3) and from the area west of the Rudi-Yalumba Hill area further north (n = 6) (Fig. 2). The metamorphic grade at the Mhumbirisa Hill is of lower amphibolite facies and at the two other localities likely of (sub-) greenschist facies. The marbles from the Mhumbirisa Hill and the Great Ruaha section are from both stratigraphic levels of the KG that contain marble horizons (Fig. 3a): the marble samples of the Ruaha section are from the lower part of the KG, while the marbles from the Mhumbirisa Hill are from the upper part (Fig. 3a). Additional samples, also attributed to both the lower and upper marble horizons of the KG, were made available through a mapping project carried out W of Rudi/Yalumba (cooperation between BGR (Hannover) and Tanzanian Geological Survey; Meinhold and Ott, 1993, BGR unpublished report; Table S2; Fig. 2).

The Mpwapwa Group samples (n = 16) were collected from the small area that forms the Mautia Hill, although the Mpwapwa Group metasediments are mainly exposed in the Kiboriani Mountains north of the Yalumba Hill and south of the Dar es Salaam–Dodoma road (Figs. 1 and 2). The Mn-silicate-bearing schists of the Mpwapwa Group on the Mautia Hill are well known for their oxidized Mn^{3+}-bearing minerals (piemontite, yoderite, Mn-andalusite, haematite; Jöns and Schenk, 2004). They are associated with marbles and were possibly deposited in the same Paleoproterozoic sedimentary basin as the KG of the Usagaran Belt. The Mpwapwa Group metasediments have been regarded as part of the so-called 'Western Granulites' of the Neoproterozoic Mozambique Belt (e.g., Fritz et al., 2005, 2013; Sommer et al., 2003, 2005a). However, Thomas et al. (2013), Temperley (1938) and Temperley et al. (1953) described a lithological W-E zonation of the Mpwapwa Group that resembles that of the Konse and Lower Isimani groups mapped by Meinhold (1970) further south: low-grade siliciclastic metasediments (including quartzites) and some marbles are dominant in the west, next to the craton, and higher-grade micaschists intercalated with mafic rocks occur further east. In addition, recent zircon and monazite ages revealed that these metasedimentary rocks of the Mpwapwa Group in the Kiboriani Mountains have also been metamorphosed during the Usagaran orogeny (Thomas et al., 2013). Hence, the lithological similarities between the two groups have prompted us to extend our stable isotope study to the Mpwapwa Group marbles to test the suggested correlation. The Neoproterozoic high-P amphibolite-facies metamorphism at the Mautia Hill is of higher grade than that of the KG samples (Jöns and Schenk, 2004).

The granulite-grade marble samples (n = 30) of the Neoproterozoic Eastern Granulites (Fig. 1) were collected in widely separated areas of the Mozambique Belt of Tanzania: in the Uluguru and Pare Mountains, in the Umba Steppe and at the Wami River. They were metamorphosed at peak conditions of 800–850 °C and 8–9 kbar at ca. 650–600 Ma (Appel et al., 1998; Möller et al., 2000). Peak-metamorphism was followed by prolonged near-isobaric cooling in the deep crust, prior to the Kuunga collisional event at ca. 550 Ma.

5. Methods

5.1. Monazite dating

Monazite geochronology by SIMS using the CAMECA IMS 1280-HR at the Heidelberg University followed procedures described in Catlos et al. (2020). In brief, high-energy secondary ions were selectively analyzed by applying a −40 V offset to the 10 kV extraction potential. This mitigates matrix-dependent bias in relative sensitivities of the geochronologically relevant ion species. The mass table (with offsets indicated) included $^{143}Nd^{232}Th^{16}O_2$, ^{204}Pb, ^{206}Pb (−40 V), ^{207}Pb (−40 V), ^{208}Pb (−40 V), ^{208}Pb (0 V), ^{232}Th (−40 V), ^{238}U (−40 V), ^{238}UO (−40 V), $^{232}ThO_2$ (−40 V), and $^{232}ThO_2$ (0 V). Primary ions ($^{16}O^-$) were generated in a duoplasmatron source and shaped by the primary beam mass filter aperture to a ~3 nA oval spot with ~10 × 15 μm diameter and a total impact energy of 23 keV. The secondary column was tuned for high transmission using a 400 μm contrast aperture, a 3000 μm field aperture, a transfer magnification of 60×, and the XY-mode to achieve a mass resolving power (M/ΔM = 5000). After a 30 s presputter with a 15 × 15 μm raster, secondary ion intensities were detected on the axial electron multiplier in peak-hopping mode (waiting and counting times are in Supplementary Data Table S1) and corrected for dead-time. Interfering counts from $^{144}Nd^{232}Th^{16}O_2$ on ^{204}Pb used for the common-Pb correction were subtracted using the measured ^{143}Nd-isotopologue and multiplied with a factor to adjust them to the intensities for Pb ions detected with the −40 V offset, which were calculated from the ^{208}Pb intensities measured with and without offset. Relative sensitivities for Pb and Th were calibrated using a linear regression against ThO_2/Th for repeated analysis of reference monazites 554, Amelia, and 44,069 with input ages of 45, 274.6, and 424.9 Ma, respectively (Harrison et al., 1999; Aleinikoff et al., 2006; Peterman et al. 2012). These reference monazites fall on a single calibration line despite highly variable ThO_2 (~4 to 15 wt% ThO_2; Peterman et al. 2012), underscoring the successful mitigation of matrix effects by analyzing high-energy secondary ions. The standard deviations for repeated $^{208}Pb/^{232}Th$ age determinations for these reference monazites are 1.5 % (Amelia), 2.0 % (4406), and 3.2 % (554); calibration uncertainties are propagated into the stated analytical uncertainties of single spot analyses. All age uncertainties are stated at 95 % confidence (Table 1 and Supplementary Table S1).

5.2. Carbon and oxygen isotope analysis of carbonate samples

Outcrop samples were cut with a diamond saw and polished to obtain fresh surfaces. Based on the three-step staining method (Dickson, 1965), using 1.5 % HCl, alizarine red S and potassium ferricyanide, marble mineralogy (calcite vs. dolomite) was determined. After rinsing the polished surfaces with deionized-H_2O, least-altered portions were micro-drilled with a diamond drill-bit. Carbonate carbon ($\delta^{13}C_{carb}$) and oxygen ($\delta^{18}O_{carb}$) isotope analysis was carried out at the Stable Isotope Geochemistry Laboratory at the University of California, Riverside, USA, using a GasBench II device connected to a Thermo Scientific Delta V Advantage isotope-ratio mass-spectrometer (IRMS) in a continuous-flow mode. The micro-drilled powders were reacted with phosphoric acid in a glass tube at 50 °C for 24 h before the analysis. Two international standards, NBS 18 and NBS 19, and one calibrated internal dolomite standard (Tytyri, $\delta^{13}C$ = +0.78 ‰ V-PDB and $\delta^{18}O$ = −7.07 ‰ V-PDB; Karhu, 1993) were analyzed along with the unknown samples to calibrate isotope data and correct oxygen isotope values for dolomitic marble samples. $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ values are reported in standard delta notation relative to the Vienna Pee Dee Belemnite (V-PDB). Analytical precision was 0.1 ‰ (1σ) for $\delta^{13}C_{carb}$ and 0.2 ‰ (1σ) for $\delta^{18}O_{carb}$ based on repeated analyses of standards.

6. Results

6.1. Monazite ages

The age of metamorphism of the KG was determined by analyzing 7 monazite grains from two samples of Mn^{3+}-rich-andalusite-spessartine micaschists (T110-14-93; T110-15-93). The rare monazite grains (2–11 grains per thin section) were analyzed *in situ* in the two samples (i.e., in petrographic context of thin sections) from the same locality (T110-93 in Figs. 2 and 3a). The grains are concentrically or patchy zoned, which is visible as brighter and darker zones in backscattered electron (BSE) images (Fig. 4c and d). The monazite SIMS analyses determined that all grains of the two samples are essentially free of U (Th/U of 1–8 x 10^5; Tables 1 and S1) and only $^{208}Pb/^{232}Th$ ages are therefore reported. The obtained age of 2028 ± 15 Ma (MSWD = 0.2; n = 10, with one slightly younger spot omitted; Fig. 4a; Tables 1 and S1) clearly attributes the metamorphism of the KG to the Usagaran orogeny and invalidates former interpretations of the KG as deposited in a post-Usagaran basin. We attribute the near-absence of U in all 7 analyzed metamorphic monazite grains of the Mn^{3+}-rich schists to the oxidizing depositional conditions for the sedimentary precursor under which U remains in the water column as uranyl tetracarbonate ($UO_2(CO_3)_3^{4-}$; Partin et al., 2013). The metamorphic assemblage of this rock with hematite, Mn^{3+}-rich andalusite, piemontite, and nearly almandine-free spessartine-pyrope garnets points to its high oxidation state.

6.2. Stable isotope compositions of marbles

The KG marbles are both calcitic and dolomitic and show a spread of $\delta^{13}C_{carb}$ values (Table S2) from +0.3 to +12.6 ‰ V-PDB and a range of $\delta^{18}O$ values from −19.7 to −7.7 ‰ V-PDB. Eight Konse samples out of 15 yielded highly positive $\delta^{13}C_{carb}$ values above +5 ‰ V-PDB (Fig. 3b).

The Mpwapwa Group samples from the Mautia Hill show a spread of $\delta^{13}C_{carb}$ values from −6.5 to +9.3 ‰ V-PDB (Table 2; Fig. 3b) and a range of $\delta^{18}O$ values from −25.1 to −7.0 ‰ V-PDB. Both $\delta^{13}C_{carb}$ and $\delta^{18}O$ values of the Mpwapwa Group marbles show a wider spread than the KG samples, although 9 out of 16 samples cluster together within a very narrow range around +6.7 ‰ V-PDB for $\delta^{13}C_{carb}$ and −23.2 ‰ V-PDB for $\delta^{18}O$ (Fig. 3b). The more negative $\delta^{18}O$ values of the higher-grade Mpwapwa Group marbles from the Mautia Hill compared to KG marbles are in agreement with metamorphic devolatilization reactions in impure marbles that release CO_2 and lead to a depletion in ^{18}O in the residual carbonate (e.g., Rumble, 1982; Valley, 1986). The same pattern holds true for carbon isotope values, but it is less pronounced in the data for the high-grade Mautia Hill marbles. Furthermore, C and O isotope values show a strong negative co-variation for the Mpwapwa Group marbles (R^2 = 0.91), but only weak negative correlation for marbles from the KG (R^2 = 0.28; Fig. 3b), indicating that while O isotope values were strongly affected by post-depositional alteration, highly positive carbon isotope values likely retained their near-to-primary signature. Therefore, the highly positive $\delta^{13}C_{carb}$ values measured for many marble samples of the Konse and Mpwapwa groups cannot be explained by metamorphic processes, but are regarded as a primary sedimentary signature of the metamorphosed carbonates.

The analyses of marbles from the Eastern Granulites show a range in $\delta^{13}C_{carb}$ values from −5.0 to +5.3 ‰ V-PDB and a spread of $\delta^{18}O$ values from −16.9 to −2.7 ‰ (Table S2; Fig. 5). In contrast to the Paleoproterozoic marbles of the Konse and Mpwapwa groups, this sample set includes only a single sample with a $\delta^{13}C_{carb}$ value of >+5.0 ‰ (+5.3 ‰), but all other samples have either near-to-zero or negative (5 samples) carbon isotope values. There is again no significant co-variation between C and O isotope values on the scatter diagram for marbles from the Neoproterozoic Eastern Granulites (Fig. 5), suggesting that C isotope values retained near-to-primary values. Importantly, in contrast to marbles from the Konse and Mpwapwa groups, marbles from the Neoproterozoic Eastern Granulites lack highly positive C isotope values.

7. Discussion

The highly positive $\delta^{13}C_{carb}$ values between +5.0 and +12.6 ‰ V-PDB of many marble samples of the low-grade KG, as well as those of the high-grade Mpwapwa Group, are interpreted as a primary sedimentary signature because metamorphic devolatilization would have resulted in lighter carbon isotope values instead of the highly positive values observed. An interpretation of the highly positive $\delta^{13}C_{carb}$ values as a paleo-seawater signature, reflecting sedimentation during the Paleoproterozoic (ca. 2.22–2.06 Ga) Lomagundi Carbon Isotope Excursion (Karhu and Holland, 1996; Bekker et al., 2006; Bekker, 2022a) agrees with the metamorphic monazite age for a lower amphibolite-facies Mn-

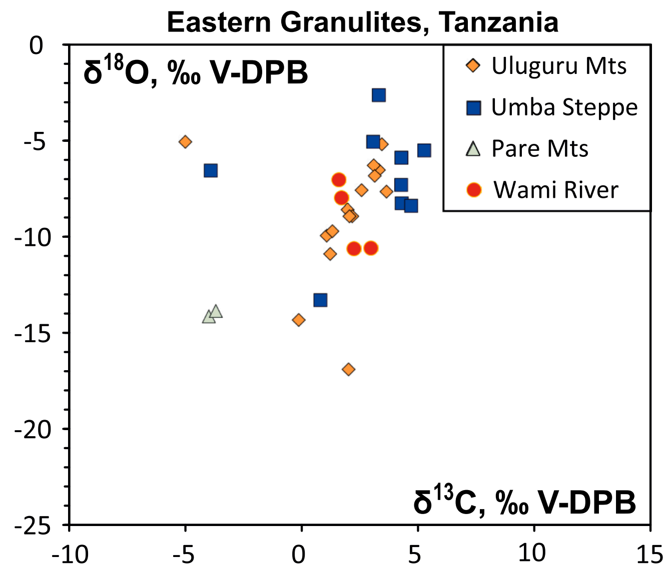

Fig. 5. Plot of $\delta^{18}O_{carb}$ vs. $\delta^{13}C_{carb}$ values for marbles of the Neoproterozoic Eastern Granulites of the Mozambique Belt of Tanzania (Uluguru Mountains, Pare Mountains, Umba Steppe, and Wami River).

rich micaschist of the KG at the Mhumbirisa Hill. The metamorphic age of the KG (2028 ± 15 Ma) constrains its depositional age to between ca. 2.5 Ga (craton stabilization) and ca. 2.0 Ga (Usagaran orogeny/metamorphism) and clearly identifies the KG as a passive continental margin succession on the Tanzania Craton deposited prior to the Usagaran orogeny. The age of the LCIE (ca. 2.22–2.06 Ga) squarely falls into this time interval. As both the lower and upper marble intervals of the KG yielded highly positive $\delta^{13}C_{carb}$ values, the whole KG must have been deposited during the LCIE. The highest carbon isotope values of the Konse and Mpwapwa Group marbles are similar to those typical for the peak of the Lomagundi carbon isotope excursion (Table 2 in Bekker et al., 2003a); we therefore tentatively infer that deposition of the Konse and Mpwapwa groups started in the middle of the LCIE (see Fig. 6).

The Lomagundi Carbon Isotope Excursion has first been recognized during early carbon isotope studies of the Lomagundi Group dolostones of the Magondi Belt on the northwestern margin of the Zimbabwe Craton. This study revealed a distinct carbon isotope excursion in marine carbonates with a mean $\delta^{13}C_{carb}$ value of about +8 ‰ V-PDB (Schidlowski et al., 1975, 1976) that was later recognized as a worldwide chemostratigraphic marker, characteristic for the LCIE (Karhu and Holland, 1996; Bekker et al., 2006; Bekker, 2022a). The Lomagundi carbon isotopic excursion followed its footsteps and is therefore regarded as related to the 'Great Oxidation Episode' (Fig. 6; GOE; ca. 2.45–2.06 Ga; Farquhar et al., 2000; Holland, 2002; Bekker et al., 2004, 2020; Bekker, 2022b). The GOE led to oxygenation of the atmosphere and the shallow parts of the oceans. A high burial rate of isotopically light organic carbon is thought to have been responsible for the Lomagundi positive excursion in carbon isotope ratios in seawater and thus of marine carbonates. Since $\delta^{13}C_{carb}$ values higher than +9 ‰ V-PDB in Paleoproterozoic carbonates are unique to the Lomagundi carbon isotope excursion, this signature can be used as a chemostratigraphic marker for carbonate deposition between ca. 2.22 and 2.06 Ga (Karhu and Holland, 1996; Bekker et al., 2006; Bekker, 2022a).

Passive continental margin sedimentary successions of similar age as that of the Konse and Mpwapwa groups on the eastern margin of the Tanzania Craton include the Lomagundi Group of the Paleoproterozoic Magondi Belt on the western margin, the Gumbu Group of the Limpopo Belt to the south of the Archean Zimbabwe Craton (Fig. 1; Schidlowski et al 1976; Buick et al., 2003; Master et al., 2010) and the Buganda Group of the Ruwenzori Fold Belt in Uganda on the northern margin of the Tanzania Craton (Tanner, 1970, Tanner, 1971; Master et al., 2013). The

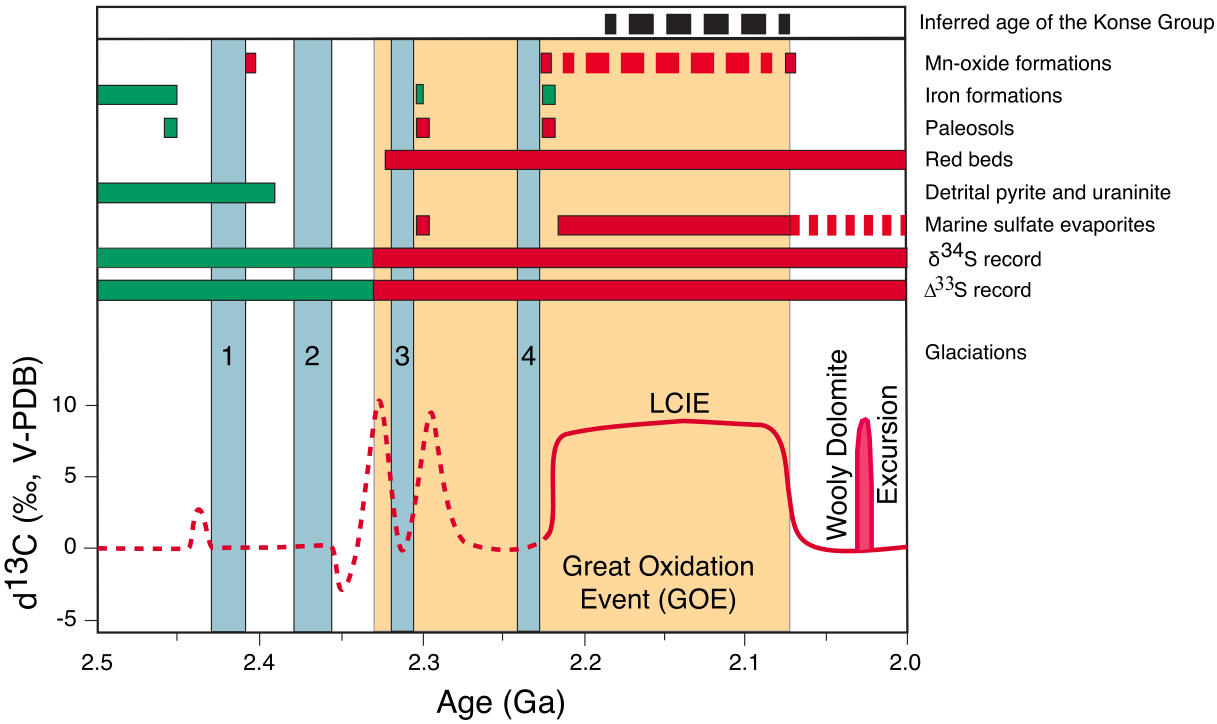

Fig. 6. Secular carbon isotope variations in seawater and redox indicators for the oxidation state of the early Paleoproterozoic atmosphere–ocean system (modified from Bekker, 2022a). Four blue vertical bars mark Paleoproterozoic glacial events; the dashed secular carbon isotope curve between 2.5 and 2.22 Ga emphasizes the uncertainty in this part of the curve; red-filled shape is the Wooly Dolomite excursion; the dashed bar for marine sulfate evaporites after ~ 2.06 Ga indicates that sulfate evaporites again became rare in the Paleoproterozoic and Mesoproterozoic records after that time. Deposition of iron formations and Mn-rich deposits indicates anoxic conditions in deep waters. While deposition of iron formations does not necessary require atmospheric oxygen and can be mediated by anoxygenic photosynthetic bacteria, Mn oxidation requires significant levels of atmospheric oxygen. Mn deposition largely decoupled from iron deposition, started at the beginning of the GOE and continued at least until the aftermath of the LCIE. Within this framework, the likely depositional age of the Konse Group sediments falls into the interval of ca. 2.22–2.0 Ga defined by the beginning of the LCIE and the Usagaran Orogeny. These 220 Ma represent a maiximum estimate for the duration of the sedimentation, but most likely the Konse Group deposition took much less time. The higly positive carbon isotope values for the Konse and Mpwapwa groups potentially indicate deposition during the peak of the Lomagundi carbon isotope excursion at ca. 2.15 Ga and its duration was less than the mean lifetime of Phanerozoic passive margins of ~ 134 million years (Bradley, 2008).

orogenies of the Magondi and Limpopo belts of Zimbabwe are of the same age as the Usagaran orogeny (ca. 2.0 Ga; Treloar, 1988; Buick et al., 2003; Kramers and Mouri, 2011; Glynn, 2017; Glynn et al., 2020). Although the age of the orogeny in the Ruwenzori Fold Belt is poorly constrained, zircon ages for granulite and granite also point to this time span of 2.1–1.9 Ga (Mänttäri et al., 2011). The Ruwenzori Fold Belt includes large volumes of mafic rocks, which are in part pillow basalts of MORB geochemical affinity and are associated with marbles and metasiliciclastic units of the Buganda Group. These mafic rocks indicate an extensive Paleoproterozoic ocean that separated the Tanzania Craton from the Archean basement of northern Uganda (Tanner, 1970; Barth and Meinhold, 1974). However, the occurrence of eclogites, like those in the Usagaran Orogen, has not been reported so far. Other well-known, comparable Paleoproterozoic passive continental margin successions developed around Archean cratons are the Coronation Supergroup in the Wopmay Orogen (Slave Craton, NW Canada; Hoffman, 1973; Hoffman and Bowring, 1984) and the lower Minas Supergroup of the São Francisco Craton (Bekker et al., 2003b; Alkmim and Teixeira, 2017). However, none of these Paleoproterozoic passive continental margin successions are associated with MORB-derived eclogites and paired metamorphic belt, which is unique for the KG. By identifying the Konse and Mpwapwa groups as passive continental margin successions deposited on the Tanzania Craton, the Usagaran Orogen stands out by uniquely preserving lithological vestiges of a complete Wilson cycle. The beginning of the Usagaran Wilson cycle is currently unconstrained because a corresponding rift succession has neither been described nor dated. Only the age span of the LCIE (ca. 2.22–2.06 Ga) places an age constraint for the beginning of the Usagaran Wilson cycle, pointing to a maximum duration of ca. 220 Ma for the sedimentation of the KG prior to the Usagaran orogeny. The mean lifespan of Phanerozoic passive margins, ca. 134 Ma (Bradley, 2008), is on the same time scale as the minimum duration of 60 Ma, based on the time difference between the end of the LCIE and the Usagaran orogeny, or 150 Ma, if the highest carbon isotope values of the Konse and Mpwapwa groups correspond to the peak of the LCIE (Bekker et al., 2003a).

The uniquely high $\delta^{13}C_{carb}$ values of the LCIE found in marbles of the Buganda Group of the Ruwenzori Fold Belt have been used to infer the carbonate depositional age between ca. 2.22 and 2.06 Ga (Master et al., 2013), in accordance with the age of dolostones at the type locality of the LCIE in the Magondi Belt of northwestern Zimbabwe (Schidlowski et al., 1976; Master et al., 2010), and the global age constraints for the LCIE (Karhu and Holland, 1996; Bekker et al., 2006; Bekker, 2022a). In agreement with the passive continental margin setting for the Lomagundi and Buganda groups, we conclude that the Konse and Mpwapwa groups were also deposited during the LCIE on a passive continental margin immediately prior to the assembly of the Columbia/Nuna supercontinent (Fig. 1). Furthermore, since these passive continental margin successions were affected by the ca. 2.1–2.0 Ga orogenies (Magondi, Usagaran, Limpopo, and Ruwenzori), these cratons (Zimbabwe, Tanzania, and Kaapvaal) as well as others that experienced similar-age orogenic events (e.g., Amazonia, Congo, North China, Pilbara, São Francisco, Sarmatia, Slave, Volgo-Uralia, and West Africa) likely formed the core/s of the Columbia/Nuna supercontinent that fully assembled only much later (Li et al., 2023; Zhao et al., 2002, 2011;

Evans, 2013; Bogdanova et al., 2016). Intriguingly, these orogenic events at ca. 2.1–2.0 Ga that assembled the core/s of the Columbia/Nuna supercontinent coincided in age with the ultimate breakup of the Superia supercraton (e.g., Aspler and Chiarenzelli, 1998; Bleeker, 2003; Mammone et al., 2022).

The marbles of the KG are associated with highly oxidized metasediments (Mn-rich andalusite-spessartine micaschists, piemontite-quartzites; Fig. 3a) containing Mn^{3+}-bearing minerals such as Mn^{3+}-rich-andalusite and piemontite. All monazite grains of the two dated Mn-rich micaschist samples lack significant U abundances (Tables 1 and S1), which points to oxidizing conditions in the precursor sediments, at least since the growth of monazite grains during metamorphism, but most likely already since its sedimentation. This interpretation is in agreement with deposition after the beginning of the GOE and during the LCIE. Similarly, the Mn-silicate-bearing schists and marbles of the Mautia Hill that are known for their oxidized Mn-minerals (piemontite, yoderite, Mn-haematite and Mn^{3+}-rich andalusite; Jöns and Schenk, 2004) were also deposited during the LCIE under highly oxidizing conditions in the foreland basin that developed between the Tanzania Craton and the approaching Mozambique Belt Metacraton prior to the Usagaran orogeny. Both Paleoproterozoic groups (KG and Mpwapwa Group in the Kiboriani Mountains) experienced their main metamorphism during the Usagaran orogeny and were thrust towards the Tanzania Craton (Meinhold, 1970; Temperley et al., 1953; Reddy et al., 2003; Thomas et al., 2013). In contrast, at the Mautia Hill (at a distance of ~20 km to the east from the craton border) no trace of a Paleoproterozoic metamorphism has been found in the oxidized metasediments. There, significant crustal thickening during the late Neoproterozoic Kuunga event caused its high-P amphibolite-facies metamorphism at ca. 550 Ma (Jöns and Schenk, 2004; Cutten et al., 2006). High submarine hydrothermal and volcanic activity has been proposed to explain the Mn-enrichment in sediments of the broadly correlative Paleoproterozoic Francevillian basin (Gabon) on the western margin of the Congo Craton (e.g. Gauthier-Lafaye and Weber, 2003; Ossa Ossa et al., 2018). Similar interpretations might also apply to the eastern margin of the Tanzania Craton, where the Mn-rich sediments might have been related to the pre-orogenic submarine volcanism linked to the formation of the basaltic crust of the Usagaran ocean, the oceanic crust that became later, prior to the Usagaran orogeny at ca. 2.0 Ga, subducted and transformed to eclogites. The submarine hydrothermal activity supplied reduced fluids enriched in Mn^{2+} and Fe^{2+} to the deep ocean, which during upwelling were deposited in an oxic, shallow-marine environment. Economic-grade, Mn-rich marine deposits, without associated economic-grade iron deposits, are common during the early Paleoproterozoic, starting from the early stage of the GOE and continuing to the aftermath of the LCIE (Fig. 6; Bekker et al., 2003a; Maynard, 2003; Maynard, 2010; Ossa Ossa et al., 2018). Decoupling of marine Mn deposition from that of iron might reflect an intermediate deep-ocean redox state between those of iron and manganese.

Isotopic compositions of the granulite-facies marbles in the Neoproterozoic Eastern Granulites of the Mozambique Belt are distinct from those of the Paleoproterozoic Konse and Mpwapwa Group marbles as they lack elevated $\delta^{13}C_{carb}$ values (>+5‰ V-PDB) characteristic of the LCIE. This difference cannot be explained by granulite-facies metamorphism as the LCIE has been recorded in the granulite-facies marbles (Baker and Fallick, 1989a; Baker and Fallick, 1989b). According to the geodynamic model of Appel et al. (1998) and Möller et al. (2000), the Eastern Granulites experienced an counter-clockwise metamorphic P-T path (at ca. 650–600 Ma) in an active continental margin setting that was affected by magmatic activity between ca. 900 and 600 Ma ago (Möller et al., 2000). They were subsequently exhumed from the deep crust during the Kuunga event (ca. 550 Ma) when the granulites were thrust towards the Tanzania Craton and the Usagaran Orogen to the west. In this model the marbles of the Eastern Granulites represent a part of the Neoproterozoic sedimentary cover that was caught in Neoproterozoic crustal thickening processes at this active continental margin.

8. Conclusion

Dating of metamorphic monazite from lower amphibolite-facies Mn^{3+}-rich micaschists of the KG at the SE margin of the Neoarchean Tanzania Craton has established a ca. 2.03 Ga metamorphic age, which is related to the Usagaran orogeny. This age challenges the former interpretation that the KG was deposited in a post-orogenic basin near the craton margin on the top of folded Usagaran gneisses.

The isotope analysis of the KG marbles from all stratigraphic levels revealed the dominance of highly positive $\delta^{13}C_{carb}$ values (>+5‰ V-PDB and up to +12.6 ‰), which indicate sedimentation during the Paleoproterozoic Lomagundi Carbon Isotope Excursion, a worldwide chemostratigraphic marker. This points to deposition of the KG during the time interval between ca. 2.22 and 2.06 Ga.

The KG is interpreted as a passive continental margin succession and as such it represents an important lithological component of the Paleoproterozoic plate-tectonic Wilson cycle related to the Usagaran orogeny. The beginning of the Usagaran Wilson cycle is unconstrained, as a corresponding rift succession is not known. If the highest carbon isotope values of marbles from the Konse and Mpwapwa groups correspond to the peak of the LCIE at ca. 2.15 Ga ago (Bekker et al., 2003a), the lifetime of the Usagaran passive continental margin would be comparable to or slightly shorter than the mean lifespan of extinct Phanerozoic passive margins of ca. 134 million years (Bradley, 2008).

The metasediments of the Mpwapwa Group (in the Kiboriani Mountains and at the Mautia Hill) are interpreted as the northern and eastern equivalents of the KG. They generally experienced their main metamorphism in the Paleoproterozoic and were also affected by a weaker Neoproterozoic overprint during the Kuunga event at ca. 550 Ma. However, at the Mautia Hill, evidence for a Paleoproterozoic metamorphism of this group is missing (at ~20 km distance to the east from the craton margin), but the exposed lithologies of the Mpwapwa Group (highly oxidized Mn-rich schists, marbles and quartzites) resemble those of the KG (e.g., at the Mhumbirisa Hill). The Mautia Hill marbles also yielded highly positive $\delta^{13}C_{carb}$ values, clustering at +6.7 ‰ V-PDB, suggesting deposition during the LCIE.

In contrast, the isotopic compositions of marbles in the adjoining Neoproterozoic Eastern Granulites of Tanzania (east of the Usagaran Orogen) are distinct from those of the Paleoproterozoic marbles of the Konse and Mpwapwa groups. Specifically, they lack the highly positive $\delta^{13}C_{carb}$ values indicating that they were not deposited during the LCIE.

The monazite grains from the Mn^{3+}-rich micaschists of the KG consistently display extremely low U contents, which points to highly oxidizing conditions in the precursor sediments. This is in agreement with their deposition during the LCIE after the beginning of the Great Oxidation Episode (ca. 2.45–2.06 Ga). The Mn enrichment in some members of the Konse and Mpwapwa groups might be related to enhanced submarine hydrothermal and volcanic activity linked to the formation of the basaltic crust of the Usagaran ocean, which was later subducted and transformed to eclogite during the Usagaran orogeny.

The Konse and Mpwapwa groups share a similar depositional age and tectonic setting with other shallow-marine, passive continental margin successions on the southeastern African cratons, which were deposited immediately before the Paleoproterozoic assembly of the supercontinent Columbia/Nuna started: the Lomagundi Group of the Magondi Belt on the NW side and the Gumbu Group of the Limpopo Belt on the southern side of the Zimbabwe Craton as well as the Buganda Group of the Ruwenzori Fold Belt on the northern border of the Tanzania Craton.

The Konse Group thus represents a cratonic passive margin succession, belonging to the Usagaran Orogen that contains several essential lithological members of a plate-tectonic Wilson cycle, which include eclogites that formed from ocean-floor basalts. This suggests that modern-style plate tectonics already operated during the

Paleoproterozoic.

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.precamres.2025.107874.

Data availability

All data are included in the published tables

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