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Archaean crustal evolution in West Africa: A new synthesis of the Archaean geology in Sierra Leone, Liberia, Guinea and Ivory Coast

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ABSTRACT

A new synthesis of the geology and geochronology of the little-known Archaean rocks in Sierra Leone, Liberia, Guinea and Ivory Coast is presented in order to better understand the processes of Archaean crustal evolution in this region, and to attempt to interpret these data in the light of our current understanding of Archaean crustal evolution. In addition, this study seeks to identify those aspects of Archaean crustal evolution which are currently not known in this area and which need to become the subject of future studies, given the economic importance of this region in terms of the mineral deposits hosted in the Archaean rocks. These include greenstone-belt hosted iron ore, lode gold, chromite and columbite–tantalite and younger diamondiferous kimberlites intrusive into Archaean felsic gneisses.

The new results show that this cratonic nucleus comprises of four main geological units:

(1) The oldest crust is made up of 3.5–3.6 Ga TTG (tonalite–trondhjemite–granodiorite) gneisses. These only outcrop in the east of the craton in Guinea but their presence is indicated elsewhere in the central part of the craton though xenocrystic zircon cores in younger rocks.
(2) The major rock type found throughout the craton is 3.26–2.85 Ga TTG gneiss. In detail these magmas are thought to have formed in two episodes one between 3.05–3.26 Ga and the other between 2.85–2.96 Ga. The presence of inherited zircons in the younger suite indicate that this event represents the partial reworking of the older gneisses. 3.4 Ga eclogite xenoliths in kimberlite derived from the sub-continental lithospheric mantle are thought to be the restite after the partial melting of a basaltic protolith in the production of the TTG magmas.
(3) Supracrustal rocks form linear belts infolded into the TTG gneisses and metamorphosed to amphibolite and granulite grade. They are of different sizes, contain a variety of lithological sequences and may be of several different ages. The larger supracrustal belts in Sierra Leone contain a thick basalt-komatiite sequence derived by the partial melting of two different mantle sources, unconformably overlain by a sedimentary formation. They are seen as an important resource for gold, iron-ore, chromite and columbite–tantalite.
(4) A suite of late Archaean granitoids formed by the partial melting of the TTG gneisses in a craton wide deformation-metamorphic-partial melting event at 2800 ± 20 Ma. This thermal event is thought to be responsible for the stabilisation of the craton.

This new synthesis highlights major geological and geochronological similarities between the Archaean rocks of Sierra Leone, Liberia, Guinea and Ivory Coast and those in the Reguibat Shield in the northern part of the West African Craton suggesting that the two regions were once more closely related.

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1. Introduction

Archaean rocks in West Africa crop out in the southern part of the West African Craton in Sierra Leone, Liberia, Guinea and Ivory Coast and more than 1000 km to the north in the Reguibat Shield in Mauritania and Morocco (Fig. 1). In the intervening area in Guinea, Senegal, Mali and southern Mauritania Archaean and associated Palaeoproterozoic rocks are covered by the Neoproterozoic to Mesozoic sediments of the Taoudeni, and Bové Basins (Villeneuve, 2008; Ennih and Liégeois, 2008).

The Archaean rocks of West Africa are some of the least known Archaean rocks in the world for there have been few recent detailed geological or petrological studies in this region. In particular there have been very few studies published on Sierra Leone and Liberia since the 1980's and there is very little modern geochronology. In part this is a result of the political instability of the area over recent decades. Equally the Archaean geology of the Reguibat Shield in Mauritania is also very poorly known. Many previous studies of the West African Craton have also included rocks of Palaeoproterozoic age in their discussion of the evolution the Craton (see for example Pitra et al., 2010; Parra-Avilla et al., 2016). Here however, the focus is more narrow and is restricted to Archaean rocks from the southern part of the West African Craton as exposed in Sierra Leone, Liberia, Guinea and the western part of Ivory Coast (Fig. 1). There are two reasons for this. First, there is a significant time interval between the youngest Archaean rocks (ca 2.8 Ga) and the oldest Palaeoproterozoic sediments and lavas (ca 2.3 Ga) indicating that Archaean events in this region are distinct from those occurring in the Palaeoproterozoic. Second, given the huge increase in understanding of Archaean crustal processes over recent decades (see for example Kamber, 2015) it is important that we better understand the processes of *Archaean* crustal evolution of this poorly known region and interpret it in the light of current models. The results presented in this study are used to make a comparison with Archaean rocks in the northern part of the Craton in the Reguibat Shield and show that the two regions have similar geological histories.

Hence, the purpose of this review is to synthesise what is currently known about the petrology and geochronology of the Archaean rocks in Sierra Leone, Liberia, Guinea and Ivory Coast and to attempt to interpret these data in the light of our current understanding of Archaean crustal evolution. In addition, it seeks to identify those aspects of Archaean crustal evolution which are currently not known in this area and which need to become the subject of future studies. Given the economic importance of this region in terms of the mineral deposits hosted in the Archaean rocks these two goals are necessary to ensure that there is an appropriate geological basis for future mineral exploration. The Archaean rocks of the southern part of the West African Craton are host to important deposits of iron ore, lode gold, chromite, Ni–Co deposits and columbite–tantalite (see reviews by Markwitz et al., 2016a,b), and to younger diamondiferous kimberlites intrusive into the Archaean rocks of the Craton (Skinner et al., 2004).

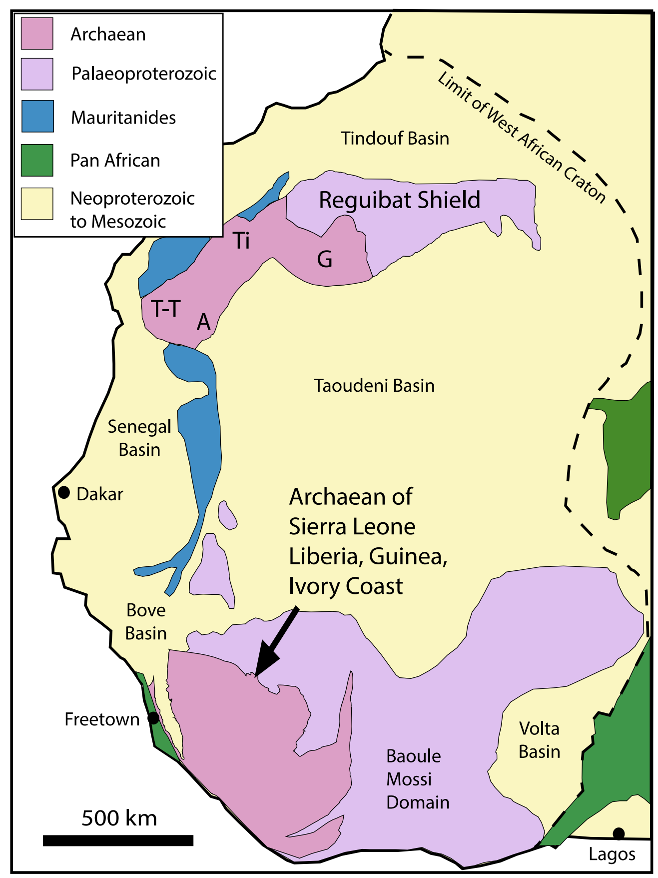

Fig. 1. The geology of the West African Craton showing the two Archaean nuclei in the north and the south. The four Archaean terranes in the Reguibat Shield are denoted T–T (Tasiast–Tijirit terrane), Ti (the Tiris Complex), A (the Amsaga Complex) and G (the Ghallaman Complex), after Schofield et al. (2012).

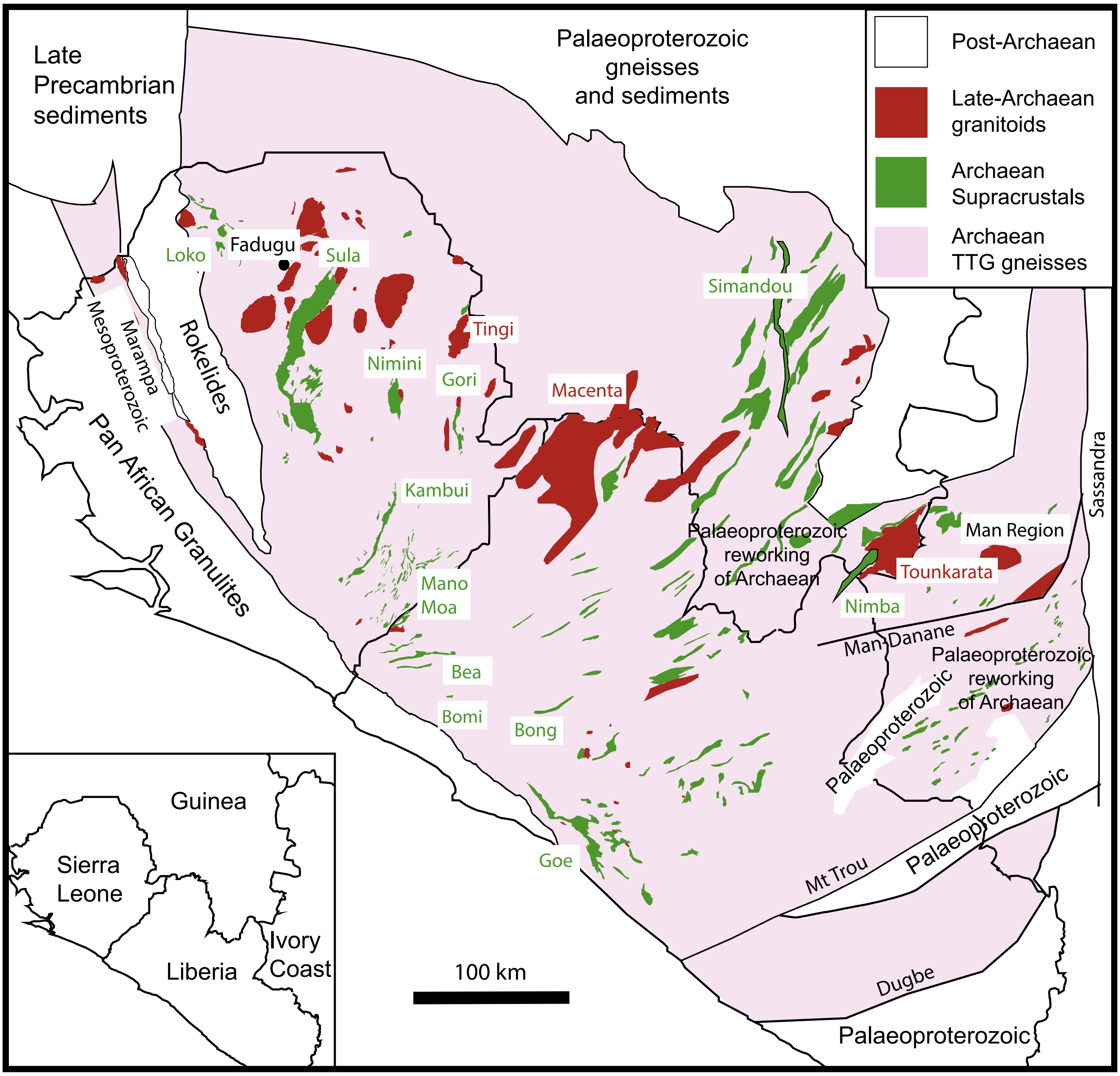

Fig. 2. Geological map showing the extent of Archaean rocks in Sierra Leone, Liberia, Guinea and Ivory Coast (see inset), showing the TTG gneisses, the principal supracrustal belts and late Archaean granitoids (data from Keyser and Mansaray (2004), Kouamelan et al. (1997), Thiéblemont et al. (2001), Macfarlane et al. (1981) and White and Leo (1969). The Neoarchaean/Palaeoproterozic supracrustal belts are show in green with a black outline. It is important to note that the quality of the geological mapping varies across the region such the larger granitoids and supracrustal belts in the east may be a simplification of similar geology seen in the west, where they have been mapped in more detail. The names of the principal supracrustal belts are shown in green and the granitoids in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Craton boundaries

The southern expression of the West African Archaean Craton outcrops over an area of about 300,000 sq km and is variably known as the 'Sierra Leone Ivory Coast nucleus' (Clifford, 1970), the 'Liberian age province' (Hurley et al., 1971), the 'Leo Rise', the 'Kenema–Man Domain' (Thiéblemont et al., 2001), the 'Man Craton' (Skinner et al., 2004), the 'Man Shield' (Barth et al., 2002) and the 'Leo-Man shield' (De Waele et al., 2015). A new synthesis of the regional geology is presented in Fig. 2.

The southwestern boundary of the craton is defined by a major shear zone separating the craton from younger granulites, known in Sierra Leone as the Kasila Series (Culver et al., 1991). These rocks may have a Palaeoproterozoic heritage (De Waele et al., 2015), but were metamorphosed to granulite grade and thrust onto the Craton during the Pan-African at ca 550 Ma (Latiff et al. (1997). It is likely that the Mesoproterozoic rocks of the Marampa Group were also thrust onto the Craton at this time (De Waele et al., 2015). The presence of deformed granitoids in Sierra Leone and the deformed supracrustal rocks of the Goe Mountains in Liberia adjacent to this shear zone indicate that the Craton margin was reworked during this event (White and Leo, 1969), see Fig. 2.

In the northwest the Craton is covered by Phanerozoic and late Precambrian sediments, in part forming the Rokelide belt (Villeneuve, 2008; Villeneuve et al., 2010). To the north and north-east the craton margin is more complex. In part it is overlain by the Palaeoproterozoic sediments of the Siguri basin and part is intruded by plutonic rocks of Eburnian age (ca 2.1 Ga; Egal et al., 2002). In the east and southeast, the craton boundary is defined by a series of shear zones, which include the Man-Danané shear zone, the Mount Trou shear zone, the Dugbe shear zone and the transcurrent Sassandra fault (Kouamelan et al., 1997; and see Fig. 2), separating Archaean rocks in the west from the Palaeoproterozoic rocks of the Baoulé-Mossi domain in eastern Ivory Coast and Ghana (Bessoles, 1977), see Fig. 1. The rocks of the Baoulé-Mossi domain were deformed during the Eburnian orogeny at ca 2.1 Ga (Parra-Avilla et al., 2016) but recent zircon geochronology shows that this region also contains older Archaean crust which was reworked during the Palaeoproterozoic (Pitra et al., 2010; Parra-Avilla et al., 2016)).

Geophysical studies using S-wave velocity anomalies show that the West African Craton is underlain by thick subcontinental lithosphere which may be as thick as 250 km (McKenzie and Priestly, 2008; Jessell et al., 2016). In detail there is a double root with depth maxima beneath the Archaean regions – the Reguibat Shield in the north and the Archaean rocks of Sierra Leone, Liberia, Guinea and Ivory Coast in the south (Begg et al., 2009; Jessell et al., 2016). Seismic anisotropy measurements change direction with depth indicating that the subcontinental lithospheric mantle beneath the West African Craton is horizontally stratified and that these layers relate to tectonic structures produced during the formation and growth of the Craton (Jessell et al., 2016). Measurements of crustal thickness are very variable with an average of about 35 km in the Sierra Leone, Liberia, Guinea and Ivory Coast area (Jessell et al., 2016). Intermediate wavelength gravity and magnetic anomalies in Sierra Leone, Liberia, Guinea and Ivory Coast indicate set of curved structures in the Archaean domain in the south of the Craton which trend from NE–SW, to N–S, to NW–SE (Jessell et al., 2016) and which for the most part follow the structural trends defined by the greenstone belts (Fig. 2).

3. A chronological framework for Archaean rocks in Sierra Leone, Liberia, Guinea and Ivory Coast

A major study by Macfarlane et al. (1981) has strongly influenced recent thinking about the geological evolution of Archaean rocks in the region. The study was based upon the geological mapping of the northern part of Sierra Leone where an attempt was made to subdivide the TTG gneisses into domains of different ages. Structural criteria were used to identify two domains – an older 'Leonian domain' with predominantly E–W striking structures and a 'Liberian domain' with N–S striking structures. These two domains were regarded as having formed in separate events such that there were older gneisses, supracrustal rocks and granitoids which were deformed during the Leonian event. Supracrustal rocks were deposited on this basement and then deformed in the later Liberian event (Macfarlane et al., 1981). Rocks in the Leonian domains were thought to represent those that escaped the later Liberian deformation. Subsequent authors such as Thiéblemont et al. (2004) have sought to assign time periods to the Leonian and Liberian events, although this geochronology is not linked to the original structural definition of the two domains.

It will be argued here that such a subdivision of an Archaean gneiss terrain is no longer tenable. With the advent of precise U–Pb zircon geochronology Archaean gneiss terrains have been shown to be much more complex than previously supposed and need to be interpreted in terms of multiple magmatic events (see for example Rollinson and Whitehouse, 2011). Thus a structural subdivision of the type proposed by Macfarlane et al. (1981) for northern Sierra Leone is too simplistic. In fact even the geochronology of the early 1980's (Macfarlane et al., 1981; Beckinsale et al., 1980; Rollinson and Cliff, 1982) did not show a clear distinction between the two age domains, suggesting that this chronological model was in doubt, a point made by Williams in 1978. Further, as will be shown later, current geochronology indicates that there are gneisses of different ages in Sierra Leone, Liberia, Guinea and Ivory Coast, but this cannot be rationalised into simply two age provinces with differing structural orientations.

Here the Archaean rocks of Sierra Leone, Liberia, Guinea and Ivory Coast have been subdivided into three units (see Fig. 2), which from oldest to youngest are:

- TTG (basement) gneisses;
- supracrustal belts (the schist belts of the older literature, or greenstone belts);
- 'younger' granitoids which intrude the supracrustal rocks and the TTG gneisses; these are relatively undeformed and so are thought to be the youngest rocks.

This subdivision forms the basis for the following sections of this paper, in which the geology of each of the three main units is briefly described and their ages evaluated on the basis of the relatively few recent geochronological studies (Kouamelan et al., 1997; Thiéblemont et al., 2001, 2004; Barth et al., 2002; De Waele et al., 2015). In contrast to the geochronology of the 1980's which was based upon whole-rock isochron ages these more recent studies use the more robust and more precise methods of U–Pb zircon geochronology. The geochronological data used in this paper are given in Appendix 1 and Supplementary Fig. 1, both available as electronic appendices to the paper.

4. Basement TTG gneisses

The basement TTG gneisses are predominantly medium grained, banded biotite gneisses. Often they contain inclusions of amphibolite, which in places can be seen to be disrupted mafic dykes. Some gneisses contain hornblende and others may have microcline porphyroblasts (Rollinson, 1973). Less-deformed gneisses (the nebulitic gneisses of Macfarlane et al., 1981) probably represent weakly deformed granitoid intrusions. Elsewhere migmatitic gneisses (the venite gneisses of Macfarlane et al., 1981) are found where there is a clear distinction between an older gneiss phase and a younger partial melt. (Rollinson, 1973).

4.1. 3.5 Ga-old TTG gneisses

A small number of TTG gneisses show ages of ca 3.5 Ga, implying a crust-forming event at about this time. This older Archaean crust, in part now reworked during the late-Archaean, is found in the central part of the Sierra Leone, Liberia, Guinea and Ivory Coast region and on the basis of the few ages currently available appears to form a WNW-trending zone in the exposed outcrop area (Fig. 3). In the southeastern part of Guinea a trondhjemitic gneiss from the Guélémata orthogneiss has a U–Pb zircon crystallisation age of 3542 ± 13 Ma and a gabbro metamorphosed at granulite grade has a U–Pb zircon crystallisation age of 3535 ± 9 Ma (Thiéblemont et al., 2001), see Fig. 3. In addition depleted mantle model Nd ages from the gneisses of the Man region of Ivory Coast, to the southeast, are 3.3–3.4 Ga (Kouamelan et al., 1997) supporting the view that there was an ancient protolith to the late Archaean gneisses of this region. Further, inherited zircons ca 3.5 Ga old, are found in some late Archaean granitoids, notably the 2.8 Ga porphyritic monzogranite from the Tounkarata batholith in Guinea contains zircons with inherited cores with U–Pb ages of 3478, 3532 and 3639 Ma (Thiéblemont et al., 2004) and a zircon from the Macenta batholith (Fig. 3) contains an inherited core with an age of 3462 ± 24 Ma (Bering et al., 1998, quoted in Thiéblemont et al., 2001). In Sierra Leone a 2.9 Ga migmatitic gneiss from Motema quarry near Yengema contains zircons with inherited

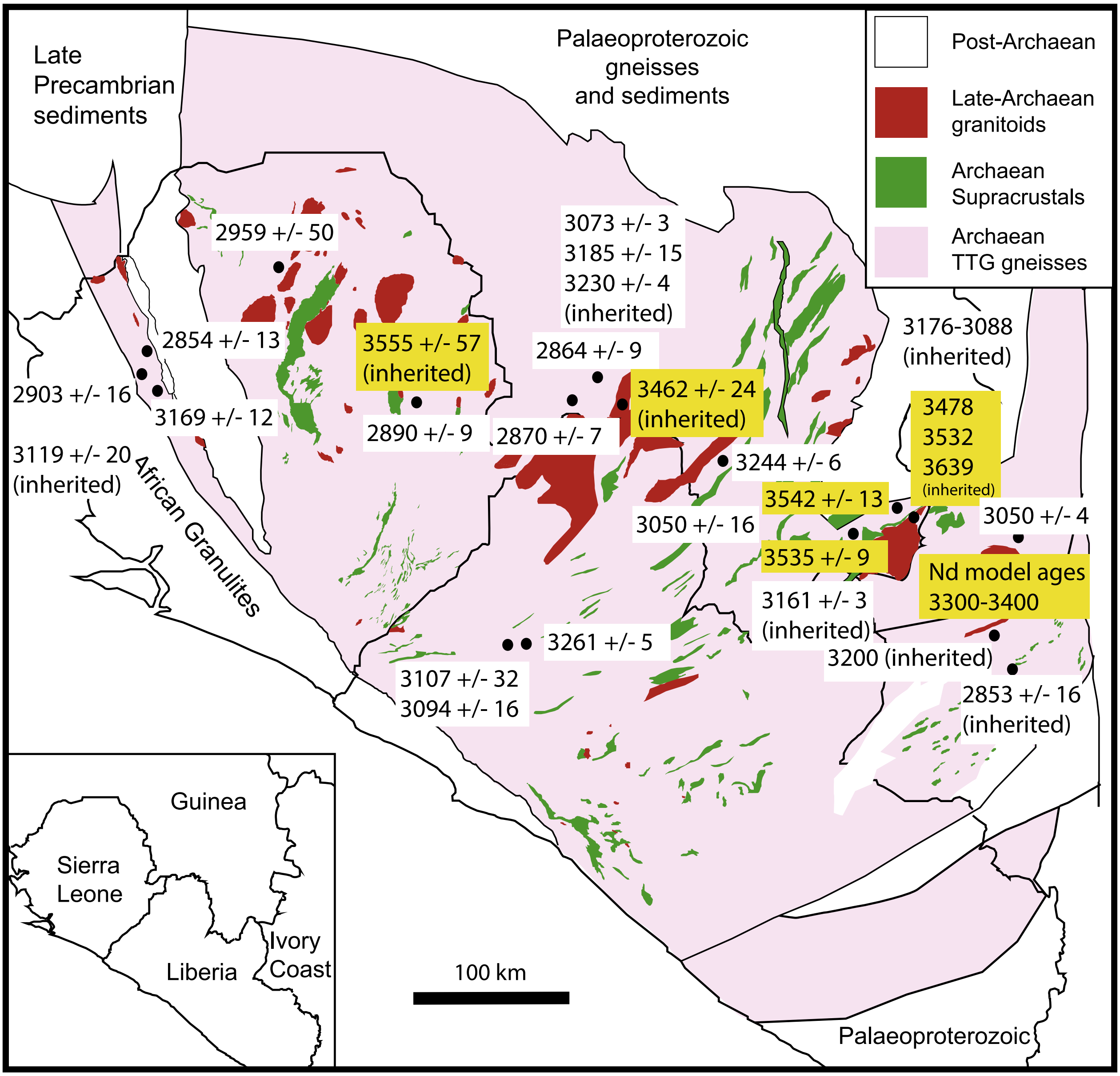

Fig. 3. U–Pb zircon ages for the older TTG gneisses (ca 3.5 Ga) shown in yellow and younger TTG gneisses (3.26–2.85 Ga) shown in white. Where the age determinations have been made on xenocrystic grains this is indicated with the caption 'inherited'. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

xenocrystic cores which yield concordant U–Pb ages of 3555 ± 57 Ma (Barth et al., 2002).

The only geochemical data on the 3.5 Ga gneisses are two analyses by Thiéblemont et al. (2001) which show that the TTG gneiss in southeastern Guinea has a similar composition to that of younger Archaean TTGs with a trace element composition which is enriched in light REE and depleted in heavy REE, Ti, Nb and Ta. This could indicate that these melts evolved in equilibrium with an eclogitic residue (Halla et al., 2009), although the data are too few for a firm conclusion.

4.2. 2.8–3.2 Ga TTG gneisses

Most U–Pb zircon ages for the basement gneisses in Sierra Leone, Liberia, Guinea and western Ivory Coast are between 2850 and 3260 Ma. In detail crystallisation ages may be subdivided into two time intervals – 2854–2959 and 3050–3261 Ma (Kouamelan et al., 1997; Barth et al., 2002; Thiéblemont et al., 2004; De Waele et al., 2015), with a gap of about 90 Ma between the two suggesting at least two crust-forming events. U–Pb monazite ages in gneisses in western Ivory Coast are 2853 ± 16 Ma consistent with this pattern of zircon ages (Kouamelan et al., 1997). Some of the gneisses in the younger group contain zircons with xenocrystic cores with ages between 3.1 and 3.2 Ga, indicating their derivation from the older group and that the 2.85–2.9 Ga event was, in part, the reworking of the earlier 3.05–3.26 Ga event (De Waele et al., 2015).

A single Pb–Pb isochron age for TTG gneisses from Fadugu in northern Sierra Leone indicates that they crystallised in the younger cycle (2959 ± 50 Ma) but with a $^{238}U/^{204}Pb$ ratio indicative of a high-μ source of about 10.5 (Beckinsale et al., 1980). Kamber (2015) has argued that TTGs of this type are derived from a source region which had a higher $^{238}U/^{204}Pb$ ratio than the coeval mantle which indicates that the separation of that source region from the depleted mantle was early in the Archaean. Kamber (2015) has proposed that there is a strong association between regions of Archaean crust showing the high-μ signature and the occurrence of early-Archaean zircons, further strengthening the evidence noted above for an older crustal precursor in this region perhaps even more ancient than 3.5 Ga.

With the current data set there is no clear lithological or geographic distinction between the older and younger TTG gneisses. There have been no detailed geochemical studies and so very little is known of their petrogenesis.

5. Supracrustal rocks

Supracrustal rocks form linear belts throughout the region (Fig. 2). Many are small but some are in excess of 100 km long. They comprise volcanic and sedimentary sequences infolded into the TTG gneises and are typical of greenstone belts found in other Archaean cratons, although metamorphosed to amphibolite and granulite grade. Many of the smaller belts such as the Mano Moa granulites in Sierra Leone and the Bomi Hills, Bong Range and Goe Range belts in western and southern Liberia are dominated by banded ironstone. Rollinson (1978) suggested that they could be subdivided into two major groups – the larger greenstone belts with thick volcanic sequences and stratigraphic thicknesses up to 6.5 km in the central part of the region and smaller supracrustal belts in the south, with thinner sequences of up to 1 km, dominated by banded iron formation, some of which are metamorphosed to granulite grade. It was proposed that the supracrustal sequences were coeval and the differences in the types of belt reflected real stratigraphic differences coupled with differences in tectonic setting in the different parts of the craton (Rollinson, 1978).

More recent studies in this craton and elsewhere must now call this interpretation into question for it can no longer be assumed that all the Archaean supracrustal rocks in the Sierra Leone/Liberia/Guinea/Ivory Coast region are all of the same age. For example, in the Zimbabwe Craton greenstone belts of three different ages are known (Blenkinsop et al., 1997). In support of this view is the work of Rollinson (1999) who showed that there is a major unconformity in some of the stratigraphic sequences of the Sierra Leone supracrustal belts and Billa et al. (1999) who showed that the Nimba and Simandou belts in Guinea, in the east of the area, are unconformable upon older amphibolites indicating at least two episodes of basaltic magmatism.

The lower volcanic successions in the larger supracrustal belts in Sierra Leone comprise komatiites, komatiitic basalts and basalts (Rollinson, 1983, 1999). A study of the immobile element geochemistry of the basaltic rocks showed that there are some similarities between supracrustal belts – suggesting that they were part of the same succession, but there are also some differences – indicating a variety of mantle sources (Rollinson, 1983). A more detailed study of volcanic rocks in the well-preserved Sula Mountains belt (Rollinson, 1999) showed that the range of magma compositions was produced by varying degrees of partial melting of two different mantle sources.

Macfarlane et al. (1981) showed that in addition to a thick volcanic succession, the rocks of the Sula Mountains supracrustal belt, contained an upper sedimentary formation comprising greywackes and banded ironstones. Rollinson (1999) showed that this upper succession lies unconformably above the volcanic succession and this unconformity may be traced across the craton to the southeast into the Nimini Hills and Gori Hills supracrustal belts in Sierra Leone (Keyser and Mansaray, 2004). The time interval between the two successions has not yet been constrained, although the two formations are deformed together.

5.1. Age constraints on the supracrustal belts

Currently there are very few constraints on the age(s) of the Archaean supracrustal belts in Sierra Leone, Liberia, Guinea and western Ivory Coast. For example:

- we do not know how many different supracrustal belt sequences of different ages there are;
- we have limited information about the age of the supracrustal belts relative to the felsic gneisses;
- there is very limited geochronology on this aspect of the Archaean geology.

Macfarlane et al. (1981) proposed, on structural grounds, that the supracrustal rocks in the Loko Hills in NE Sierra Leone were older than the main supracrustal belt sequences in the central and eastern parts of the country. Similarly Wilson (1965) proposed that the Mano Moa granulites in southeastern Sierra Leone were older than the rocks of the nearby Kambui Hill supracrustal belt, and although this proposal was not upheld by Rollinson (1974, 1978) it is now recognised that these granulites have a different stratigraphy from the larger supracrustal belts and could be of a different age.

The presence of rare TTG clasts in conglomerates and the occurrence of quartzites in some of the Sierra Leone supracrustal belts suggests that the upper sedimentary formation of these belts was derived from a pre-existing TTG-gneiss felsic crust (Rollinson, 1978). Migmatitic TTG gneisses adjacent to the Nimini Hills supracrustal belt have been dated at 2890 ± 9 Ma (Barth et al., 2002). Further, the Sula Mountains and the Nimini Hills supracrustal belts are cut by the late Archaean granitoids (discussed below) further constraining their age to a minimum of 2800 ± 20 Ma. This may constrain the time of formation of this group of greenstone belts to between 2890 and 2800 Ma. Further east in the Man granulites of Ivory Coast metasediments pre-date the 2800 Ma granulite facies metamorphism (Kouamelan et al., 1997).

Two of the supracrustal belts reported here are probably not Archaean in age. The Nimba belt (Liberia and Ivory Coast) and the Simandou belt (Guinea) form large supracrustal belts containing thick banded iron formation sequences (Fig. 2). The Simandou and Nimba supracrustal belts are known to lie unconformably on older amphibolites and TTG gneisses, of presumed Archaean age (Billa et al., 1999). On the basis of detrital zircon ages the Nimba supracrustal belt is thought to have formed between 2615 and 2250 Ma (Billa et al., 1999), whereas a quartzite from the Simandou succession contains detrital zircons with ages of between 2711 and 2871 Ma, thus constraining its age to younger than 2711 Ma (Thiéblemont et al., 2004).

5.2. Mineralisation

Most of the mineralisation in the Archaean rocks of Sierra Leone, Liberia, Guinea and western Ivory Coast is hosted in the supracrustal belts. Shear zone hosted gold is found in the Bea supracrustal belt in western Liberia (Markwitz et al., 2016a) and lode gold is found in the Sula mountains supracrustal belt in Sierra Leone at Baomahun, west of Makong and at Yirisen near Kalmoro (Marmo, 1962; Wilson and Marmo, 1958). In the Nimini Hills lode gold occurs at Komahun at the contact between pelite and ultramafic schist (Rollinson, 1975). Barrie and Touret (1999) showed that in the lode gold deposit at Yirisen in the Sula Mountains the gold occurs in aplitic sericite–quartz veins in sheared and altered komatiites. Associated wall-rock alteration includes the formation of sericite, chlorite, sulphides and carbonates. Fluid inclusions hosted in the quartz indicated two coeval fluids – an aqueous fluid with variable salinity and a pure CO_2 fluid. The high salinity aqueous fluids have geochemical similarities with basinal brines found in younger rocks. The CO_2-rich inclusions and the low to moderate salinity brines are thought to have been derived by metamorphic devolatilisation reactions in the supracrustal sequence at ca 4.4 kbar and 400 °C (Barrie and Touret, 1999). Currently this is the only detailed study of the gold mineralisation in this area. The timing of the gold mineralisation is also not known with certainty, although if, as is possible, gold mineralisation is associated with the intrusion of the late granitoid suite described below, then it formed at ca 2800 Ma.

Iron ore occurs as banded iron formation (BIF) in several of the supracrustal belts. In the Sula Mountains belt laterite-enriched BIF has been mined at Tonkolili and is known from the Pujehun and Malumpo areas (Wilson and Marmo, 1958; Marmo, 1962). In Liberia BIF has been mined in the Bomi Hills, Mano River, Bong and Goe Range supracrustal belts (White and Leo, 1969; Berge, 1973). Iron ore is also extensively mined from BIF in the younger Nimba and Simandou supracrustal belts (Berge, 1972).

Komatiite-hosted chromite has been described from Hanga in the Kambui Hills supracrustal belt in Sierra Leone (Dunham et al., 1958) and Ni–Co from supracrustal belts in western Ivory Coast and Guinea close to the margin with the Baulée-Mossi domain (Markwitz et al., 2016a). Columbite–tantalite is hosted in pegmatites emplaced at the margin of the Sula Mountains belt at the contact between the supracrustal rocks and the surrounding younger granites and is known from near Dalkuru, the Bumbuna–Kegbema area, Dandavu and Matunkara (Wilson and Marmo, 1958; Marmo, 1962). Placer deposits of columbite–tantalite are also known from the Valunia chiefdom in the Bo district (Morel, 1979). There is small scale mining but the volumes produced are not large (Melcher et al., 2015).

Diamonds, sourced from kimberlites intrusive into the Archaean felsic gneisses are found extensively as placer deposits. There are kimberite clusters near Koidu and Tongo in eastern Sierra Leone, near Kumgbo, Weasua and Mano Godua in western Liberia and in the Banankoro, Bouro, Droujba areas of eastern Guinea close to the Liberia-Sierra Leone border (Skinner et al., 2004). The kimberlites are mostly dykes although there are some pipes (Grantham and Allen, 1960; Haggerty, 1982). Most are Jurassic in age but the Weasua occurrence in Liberia is thought to be Neoproterozoic (Skinner et al., 2004). Geomorphological controls on the erosion of the kimberlites and formation of the placer diamond deposits in the Koidu and Tongo areas of Sierra Leone were described in detail by Hall (1968) and Thomas et al. (1985).

5.3. Metamorphism

The pressure and temperature conditions of metamorphism were calculated for some of the supracrustal belts in Sierra Leone by Rollinson (1982). Metasediments from the Nimini Hills record metamorphic temperatures of 595 ± 50 °C and pressures of 5.5 ± 0.5 kb, whereas metasediments from the Gori Hills record metamorphic temperatures of 565 ± 50 °C and pressures of 4.9 ± 2.5 kb. Further to the southeast metasediments in the small supracrustal belts of the Mano Moa granulites record temperatures of 770 ± 50 °C and pressures of 7.5 ± 1.5 kb. Amphibolites in the Sula Mountains supracrustal belt record hornblende-plagioclase temperatures in the range 645–734 °C (but calculated at an assumed 5 kb, Rollinson, 1999). Both Wilson and Marmo (1958) and Marmo (1962) showed that both sillimanite and andalusite occur in this supracrustal belt, with sillimanite as the primary phase. The pressure range of these rocks is taken as ca 4 kb, from the intersection of isochors in the study of Barrie and Touret (1999). At this pressure the mean hornblende-plagioclase temperature is 680 °C. Thus the estimated P–T conditions for the Sula Mountains supracrustal belt are 680 °C, 4 kb. The differences in temperature recorded in the amphibolites and the metasediments may be a function of the different geothermometers used and that the Fe–Mg exchange thermometers used in the metasediments may be under-reading as a result of down-temperature reequilibration from the metamorphic peak.

The timing of this metamorphic event or events is not well known, in fact the only evidence from Sierra Leone is a 2800 Ma U–Pb zircon age from a mafic granulite xenolith in the Koidu kimberlite (Barth et al., 2002). A similar age is recorded for the granulites of the Man region in Ivory Coast Kouamelan et al. (1997). Kouamelan et al. (1997) also reported very high pressures for a mafic granulite in this area (11–12 kb and 830 ± 50 °C), although recent work by Pitra et al. (2010) could indicate that these conditions relate to the later Palaeoproterozoic reworking of these rocks.

If these results record a single metamorphic event, then it is clear that the Archaean craton is exposed at different crustal levels with more deeply eroded areas in the south and east. This may correlate with the smaller dimensions of the supracrustal belts in the deeper crust, signifying that only the infolded 'roots' of these belts are preserved.

6. Granitoids

A suite of late-Archaean granitoids which cut the TTG gneisses and the supracrustal belts define a WNW-trending zone in the central area of the Craton (Fig. 2). In Sierra Leone they are emplaced in two different ways. First, they form large circular to oval intrusions up to several 10's of km long which form bare, exposed outcrops making up some of the highest mountains in Sierra Leone. On the Liberia–Sierra Leone–Guinea border there is an even larger intrusion, the Macenta Batholith (White and Leo, 1969; Thiéblemont et al., 2001). Second, smaller granitoids are intruded at and into the margins of the supracrustal belts. These may be deformed as discussed below.

Petrologically the late-Archaean granitoids may be porphyritic with large microcline phenocrysts, often showing a preferred orientation, alternatively they form a medium grained biotite granite with a well developed mineral fabric and sometimes a rare mineral banding (Rollinson, 1973). Many of the larger granitoids have a migmatitic margin such that there is a gradation between the TTG gneisses and the granitoids; this is particularly clear in the Gbengbe Hills and the Tingi Hills of Sierra Leone (Rollinson, 1973; Macfarlane et al., 1981). Their preservation only at the higher structural levels of the craton led Rollinson (1973) to suggest that they are sheet-like in form.

U–Pb zircon geochronology suggests that these granitoids formed at ca 2.8 Ga and over a very narrow time interval of between 2797 ± 9 Ma and 2803 ± 11 Ma as recorded in the Tounkarata and Macenta batholiths (Thiéblemont et al., 2001). In the granulite facies gneisses of the Man region of the Ivory Coast zircon U–Pb evaporation ages have been determined for the Mangouin charnockite of 2801±7 Ma and this age interpreted as its crystallisation age, the Yorogue granodiorite 2780 Ma, interpreted as a minimum emplacement age and a deformed granodiorite from the Man-Danané shear zone with a magmatic age of 2797 ± 5 Ma (Kouamelan et al., 1997), all consistent with the granitoid event recorded in Guinea (Fig. 4).

Rb–Sr isochron ages for three younger granitoids at Bumbuna, Futingaya and the Tingi Hills were dated by Rollinson and Cliff (1982) between 2770 and 2786 Ma, with relatively large errors. The Bumbuna and Futingaya intrusions cut both the volcanic and sedimentary sequences of the supracrustal sequences in the Sula Mountains and Nimini Hills belts, respectively. Recalculating these ages using the new decay constant for ^{87}Rb (Villa et al., 2015) gives slightly older ages of 2800 Ma (Bumbuna), 2793 Ma (Tingi Hills)

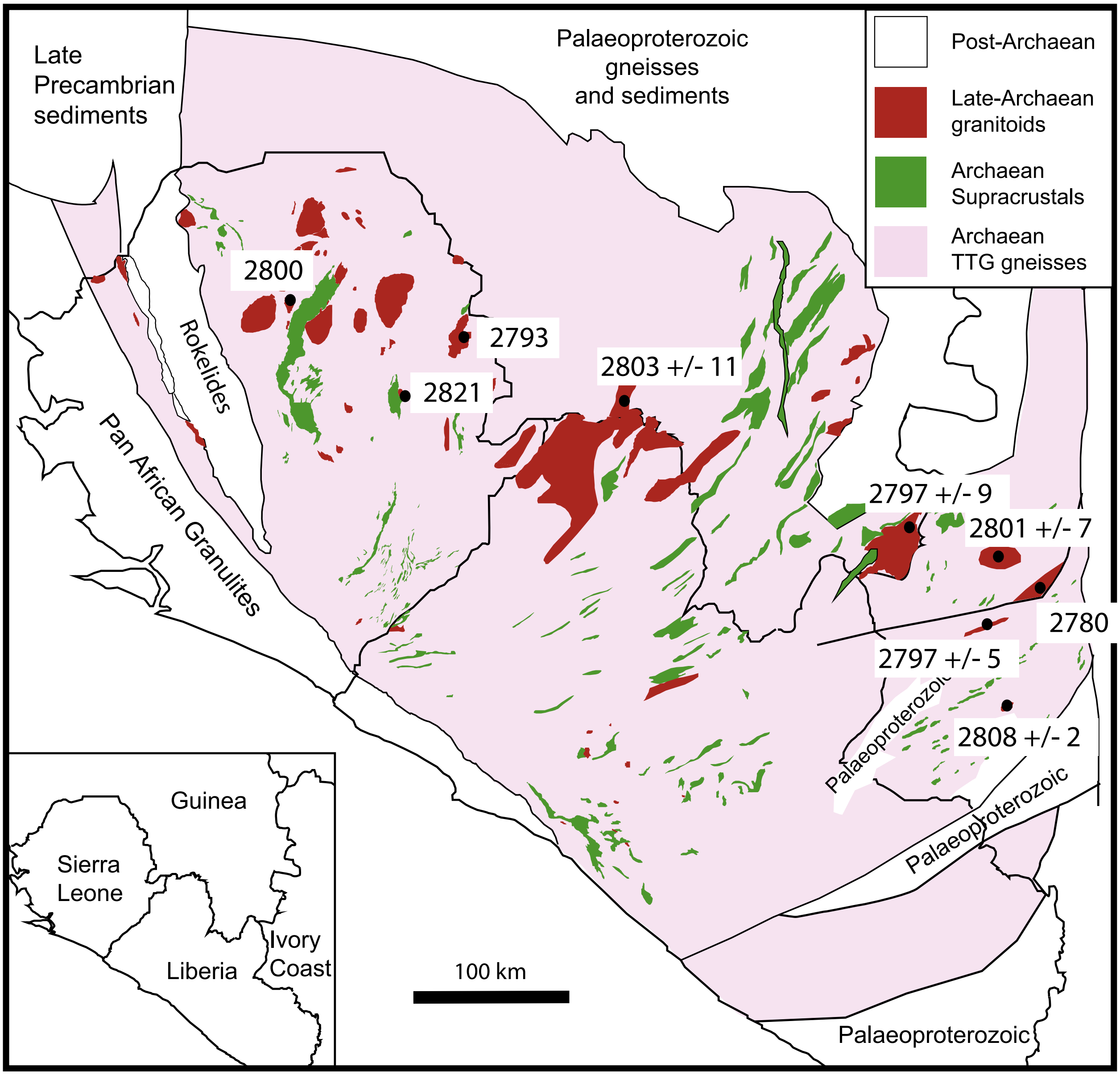

Fig. 4. U–Pb zircon and Rb–Sr isochron ages for the late Archaean granitoids.

and 2821 Ma (Futingaya). These ages are in close agreement with U–Pb zircon ages from further east in the craton and given that these rocks represent the youngest thermal event in this part of the craton these Rb–Sr isochron ages are thought to be a realistic representation of their crystallisation ages. Thus the time of emplacement of the late Archaean granitoids appears to be well defined as 2800 ± 20 Ma. However, it should be noted that Rollinson (1975) and Macfarlane et al. (1981) mapped several different types of granitoid in the east and north of Sierra Leone and many years previously Marmo (1955) had mapped four different phases of 'younger granite' in the Bumbuna area of Sierra Leone indicating that the late Archaean granitoid event may be more complex than the present geochronological data allow.

The age of 2800 ± 20 currently assigned to the emplacement of the late Archaean granitoids is close to the timing of the granulite facies metamorphism in the gneisses of the Man region of Ivory Coast – 2800 Ma (Kouamelan et al., 1997), and in Sierra Leone (Barth et al., 2002) suggesting that the two events may be linked. It is possible therefore that the late Archaean granitoids in this region are the product of deep crustal melting of the older TTG gneisses. This would be consistent with the presence of inherited old zircons in the Tounkarata and Macenta batholiths in Guinea (Thiéblemont et al., 2001 and the variable initial $^{87}Sr/^{86}Sr$ ratios found in the Sierra Leone granitoids (Rollinson and Cliff, 1982).

7. Discussion

7.1. The origin of the TTG gneisses

Rollinson (1997) proposed that there was a geochemical link between the Archaean TTG gneisses found in the West African Archaean Craton in Sierra Leone, Liberia, Guinea and Ivory Coast and the low-MgO eclogite xenoliths recovered from the kimberlites at Koidu in Sierra Leone. These eclogites have equilibration pressures in the range 3.3–3.6 GPa (Barth et al., 2001) and so are from within the sub-continental lithospheric mantle (SCLM) in this region (McKenzie and Priestly, 2008; Jessell et al., 2016). It was suggested that the TTG gneisses were the product of the partial melting in the garnet stability field of Archaean tholeiites, such as are found in the Sula Mountains supracrustal belt, leaving an eclogitic restite. Major element and trace element plots showed that such an association was plausible thus validating one of the main models for Archaean TTG genesis (Rollinson, 1997). A further outcome of this model is that melt-depleted eclogites may contain rutile thus explaining the sub-chondritic nature of many refractory element ratios in the continental crust (Rollinson, 1997; Rudnick et al., 2000).

This model was examined further by Barth et al. (2001) who showed that oxygen isotope ratios in garnets from the eclogites have values which are not typical of the mantle implying that the eclogite protolith had a supracrustal origin, perhaps as altered oceanic crust. In addition trace element concentrations in reconstructed eclogite compositions were found to be consistent with those expected of residues from TTG generation. In a later study Barth et al. (2002) showed that there may be a chronological link between eclogites and TTGs in West Africa. Low-MgO eclogite xenoliths from Koidu show a scatter on Re–Os isochron diagram about a line with a slope of 3440 ± 760 Ma. This 'errorchron' is interpreted as the age of the basaltic protolith of these samples and indicates the great antiquity of the SCLM in this region. (It is interesting to note, with the caveat of the large error, that this age is older than the 3.0 Ga maximum age for eclogites found as inclusions in diamonds by Shirey and Richardson (2011) and proposed as a marker for the advent of plate tectonics.) Granitoid gneisses in the same area have a U–Pb zircon crystallisation age of 2890 ± 9 Ma although some zircons contain cores as old as 3555 ± 57 Ma. With an age of ca 3.4 Ga, the basaltic protolith is too young to be parental to the 3.5 Ga gneisses in this region, but given a crustal residence time of 200 Ma, could be parental to the older TTGs described above which formed at ca 3.2 Ga.

The happy coincidence of well preserved and well-studied eclogite xenoliths in kimberlite and TTG gneisses of several different ages and the likelihood that at least some of these TTGs are juvenile in origin means that the West African Archaean Craton in Sierra Leone, Liberia, Guinea and Ivory Coast is an important 'test-bed' for models of Archaean crust generation. However, in the absence of any detailed geochemistry on the TTG gneisses there has been no petrological modelling.

7.2. The origin of the supracrustal belts

There are a large number of unanswered questions about the supracrustal belts in the West African Craton in Sierra Leone, Liberia, Guinea and Ivory Coast, not least the precise age(s) of their formation, deformation and metamorphism and the timing of the associated mineralisation. There has been no detailed study of the sedimentary rocks in the supracrustal belts into either their sedimentology or into possible facies variations across the craton. The only detailed petrological study in the whole of the craton is of the Sula Mountains supracrustal belt (Rollinson, 1999). This was on the lower volcanic succession of the supracrustal belt which contains a 5.5 km thick sequence of komatiites, basaltic komatiites and tholeiitic basalts. De Wit and Ashwal (1997) showed that this supracrustal belt appears to have the highest komatiite to basalt ratio in all the greenstone belts examined in their study, indicating an extensive episode of komatiite production.

Geochemical data from the Sula Mountains supracrustal belt show that there are two main mafic/ultramafic magma types. There are komatiites and tholeiites with low-Ti and depleted light REE which were derived from a depleted mantle source and there are high-Ti komatiitic basalts and tholeiites with flat REE patterns which are more typical of Archaean tholeiites world-wide (Rollinson, 1999). The field evidence suggests that both the depleted and undepleted mantle sources experienced partial melting at the same time. Given that komatiite volcanism is thought to represent deep mantle melting in a plume (Arndt et al., 2008), these data record an intense period of plume activity which incorporated undepleted mantle and in which previously depleted mantle is remelted at depth.

For the other supracrustal belts in Sierra Leone, including the Mano Moa granulites, immobile element ratios in basaltic rocks (Ti/Zr, Zr/Y) show some similarities and some differences, as noted above, indicating that mafic rocks in some supracrustal belts are from a common mantle source, but that there are differences in mantle source during the lifetime of the supracrustal sequences (Rollinson, 1983).

The variable metamorphic state of the supracrustal sequences is only partially known and the variation of metamorphic conditions within supracrustal belts and their pressure-temperature evolution over time are unknown.

7.3. The genesis of the late-Archaean granitoids

Late Archaean granitoids are found in other Archaean cratons and appear to record the process of craton stabilisation. For example, the Zimbabwe Craton which has similar dimensions to the Archaean Craton in Sierra Leone, Liberia, Guinea and Ivory Coast, is dominated by late Archaean granitoids. The smaller volume of granitoids in the West African Archaean Craton is thought to reflect a deeper level of crustal erosion.

A number of lines of evidence suggest that the late Archaean granitoids represent melted older TTG crust. These include:

- the field evidence of migmatite zones at the margins of some of the granitoids;
- the presence of inherited zircon xenocrysts;
- the variable initial $^{87}Sr/^{86}Sr$ ratios in the granitoids in Sierra Leone;
- the similarity in age of emplacement of the granitoids and the granulite facies metamorphism (ca 2800 ± 20 Ma).

These data indicate that the late Archaean granitoids were produced in a widespread event which encompassed crustal deformation, metamorphism and partial melting. The present data suggest there may be some correspondence between the zone of late Archaean granitoids and the region of old (3.5 Ga) TTG crust (Figs. 3 and 4). The cause of this thermal event is unknown, but its craton-wide nature would suggest that it was a significant thermal event in the underlying mantle.

7.4. A comparison between Archaean rocks in Sierra Leone, Liberia, Guinea and Ivory Coast with those in the Reguibat Shield

Archaean rocks are also found in the northern part of the West African Craton in the western part of the Reguibat Shield in Mauritania and Morocco (Fig. 1) although there have been few detailed studies in this region and the geology is poorly known. The Archaean rocks of the Reguibat Shield have been subdivided into four terranes (Schofield et al., 2012). In the southwest is the Tasiast–Tijirit granite greenstone belt terrane, east of which is the Amsaga granitic gneiss complex. To the northwest of the Tasiast–Tijirit terrane is the Tiris Complex a granite gneiss complex with intercalated sediments, and further to the northeast is the Ghallaman granite gneiss and granulite complex (Schofield et al., 2012; Montero et al., 2014), see Fig. 1.

The oldest rocks in the Reguibat Shield are granitic gneisses from the Amsaga Complex with U–Pb zircon ages in the range 3.42–3.52 Ga and Nd-model ages as old as 3.6 Ga (Potrel et al., 1996).

U–Pb zircon studies also indicate the formation of granitic crust at 3.1 Ga in the Tasiast–Tijirit terrane (Montero et al., 2014) and between 3.0 and 2.9 Ga in all other parts of the Reguibat Shield (Potrel et al., 1998; Schofield et al., 2012; Montero et al., 2014; Heron et al., in press). This would appear to be the main crust forming event in this region. The age of the greenstone belts in the Tasiast–Tijirit terrane is not well known but U–Pb zircon geochronology on the Tichla greenstone belt suggests that it formed between 3.01 and 3.03 Ga (Montero et al., 2014). Gold mineralisation in the Aouéouat greenstone belt has recently been dated at 2.84 Ga using U–Pb in hydrothermal overgrowths in zircon (Heron et al., in press). There are high grade, BIF-hosted iron-ore deposits in the Tiris Complex and disseminated chromite in banded serpentinites in the Amsaga complex (Markwitz et al., 2016a).

Unfoliated granites, post-dating the formation of the TTG gneisses formed at 2.83 and 2.92 in the Ghallaman Complex (Lahondere et al., 2003) and between 2.71 and 2.73 Ga in the Amsaga Complex (Potrel et al., 1998). There is also late Archaean granitic magmatism at 2.65–2.69 Ga in the Tiris Complex but Nd model ages indicate involvement of older granitic crust (Schofield et al., 2012).

Whilst the geological histories of the Archaean part of the Reguibat Shield and the Archaean rocks in Sierra Leone, Liberia, Guinea and Ivory Coast are not well known, on the basis of our current knowledge of the geology and geochronology there appear to be some significant similarities between the two regions (Schofield et al., 2012). Both have remnants of 3.5 Ga crust and both cratons appear to have grown significantly between 3.25 and 2.85 Ga with the main crust-forming event probably between about 3.0–2.9 Ga. Differences between the two cratonic blocks include the age of post tectonic granitoids which are a major feature of the southern Archaean region where they appear to have formed over a narrow time interval at ca 2.8 Ga. In addition the Reguibat Shield preserves a longer history of granitic magmatism ending at ca 2.65 Ga. Geophysical studies show that both regions represent areas of unusually thickened subcontinental lithospheric mantle (Begg et al., 2009) and it is possible that both formed as a single Archaean Craton which was subsequently fractured during Neoproterozoic basin formation.

8. Conclusions and directions for future research

The relatively few data on the West African Archaean craton in Sierra Leone, Liberia, Guinea and Ivory Coast mean that story of crustal evolution in this area appears to be relatively simple. This will of course change as we learn more about the geology of this region. Thus crustal evolution in the West African Archaean craton in Sierra Leone, Liberia, Guinea and Ivory Coast took place in four stages:

(1) The formation of TTG gneisses at 3.5–3.6 Ga. At present the only outcrop evidence comes from east in the craton in Guinea. However, a single Pb–Pb isochron age with a high-μ signature indicates a mantle source for the TTG protoliths which separated from the convecting mantle very early in the Archaean and might indicate even older crust in this area. Thus a challenge for the future is to better characterise the extent and antiquity of the earliest stages of crustal evolution in this region.

(2) There were at least two episodes of TTG formation between 3.26 and 2.85 Ga. Eclogitic rocks found in the SCLM may be melting residues from this process and might indicate the formation of the SCLM during the TTG formation. The precise episodicity of the TTG magmatism is yet to be determined as is the precise temporal and geochemical link between melts, restite and basaltic protolith. Some TTGs contain inherited zircons indicating that they are reworked older crust. It will be important therefore to determine which TTG suites are juvenile. Given the coincidence of TTGs and ancient eclogites from the SCLM there is a need for detailed geochemistry on the TTGs in order to better test models of Archaean crustal evolution in this craton.

(3) One or more sequences of supracrustal rocks formed on and adjacent to the TTGs, representing an episode of mantle plume activity, followed by uplift, erosion and the formation of sedimentary basins. However, the precise number of supracrustal sequences and their relative ages is still to be determined. These supracrustal rocks host important mineral deposits, notably iron-ore, gold, chromite and columbite–tantalite. Virtually nothing is known about the origin of these deposits. Further, the metamorphic conditions and hence the thermal evolution of the greenstone belts is not well known in detail.

(4) The terminal event in Craton formation and perhaps the craton stabilisation event is a widespread metamorphic event in which the crust was strongly deformed and melting took place in the mid- to lower-crust leading to the production of extensive, sill-like granitic intrusions in the middle and upper crust. Currently there is no mechanism to explain this craton-wide event. In the absence of detailed geochemical data on the granitoids there are no petrological models which might explain this process.

The preliminary data presented here for the Archaean rocks from Sierra Leone, Liberia, Guinea and Ivory Coast show some similarity with Archaean rocks in the Reguibat Sheild more than 1000 km to the north. Both have a thick lithospheric mantle root and they preserve a very similar temporal sequence of crust-forming events. It is possible that they may once have been a single craton.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.precamres.2016.05.005.

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