**Jurassic – Cretaceous stratigraphic
development of the Mandawa Basin, Tanzania:
An integrated sedimentological and heavy mineral
study of the early post-rift succession**

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Preface

In agreement with the dissertation requirements for the degree of Philosophiae Doctor, this thesis was submitted to the Faculty of Mathematics and Natural Sciences at the University of Oslo. The candidate was enrolled as a PhD research fellow at the Department of Geosciences from November 2013 to June 2019 under the supervision of Professor Henning Dypvik. The position was funded by Equinor through the Mandawa Basin Project.

The presented thesis discusses sedimentation in the coastal Mandawa Basin of SE Tanzania, from the Early Jurassic to present, with emphasis on sedimentary provenance and on Late Jurassic and Early Cretaceous sedimentation. Research is based on material and observations collected during fieldwork and analyses of rock and sediment samples.

The thesis includes an introduction to the project, a geological background of the study area, and three research papers (one published, two submitted), a discussion and future work.

In **Paper I**, heavy minerals were analysed to study the sedimentary provenance of Jurassic, Cretaceous and Cenozoic sandstones. **Paper II** concerns the Late Jurassic and Early Cretaceous sedimentation in the Mandawa Basin. In this paper the Upper Jurassic and Lower Cretaceous formations are discussed with regards to sedimentology, composition, petrology, and depositional environment. As a continuation of the findings presented in Paper 1, the provenance of recent fluvial sediments in SE Tanzania was the focus of **Paper III**. The provenance of the recent river sediments were compared with the provenance signatures of the Jurassic to Paleogene sandstones in the Mandawa Basin to shed light on the source-to-sink history through time.

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List of papers

Paper I – Published in Journal of African Earth Sciences

Fossum, K., Morton, A. C., Dypvik, H., and Hudson, W. E. 2019. Integrated heavy mineral study of Jurassic to Paleogene sandstones in the Mandawa Basin, Tanzania: Sediment provenance and source-to-sink relations. *Journal of African Earth Sciences* 150: 546–565.

Paper II – Submitted to the Journal of African Earth Sciences

Fossum, K., Dypvik, H., Haid, M. H. M, Hudson, W. E. Late Jurassic and Early Cretaceous sedimentation in the Mandawa Basin, coastal Tanzania.

Paper III – Submitted to the Journal of African Earth Sciences

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Conference proceedings

Oral presentations

Fossum, K., Dypvik, H., and Morton, A. C. Provenance analysis of Mesozoic and Paleogene successions in costal Tanzania (Mandawa Basin). NFW Winter meeting, 9th – 11th January 2017, Oslo, Norway.

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Additional contributions

Papers

Smelror, M., Fossum, K., Dypvik, H., Hudson, W. E., and Mweneinda, A. 2018. Late Jurassic – Early Cretaceous palynostatigraphy of the onshore Mandawa Basin, southeastern Tanzania. *Review of Palaeobotany and Palynology*, 258: 248–255.

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Poster presentations

Dypvik, H., Fossum, K., Hudson, W. E., Boniface, N., and Andresen, A. The Mandawa Basin Project - an interdisciplinary, educational-based research project in costal Tanzania. Abstract, East African Petroleum Conference and Exhibition, 4th – 6th March, 2015, Kigali, Rwanda.

Dypvik, H., Einvik-Heitmann, V., Hudson, W. E., Fossum, K., Karega, A., Gundersveen, E., Nerbråten, K., Mahmic, O., Hou, G., Van den Brink, Andreassen, A., Rwechungura, R., Boniface, N., Kaaya, C., and Schomaker, E. 2015. The Mandawa Basin of Coastal Tanzania and its Reservoir Potential. First EAGE Eastern Africa Petroleum Geoscience Forum. 16th – 19th November 2015, Dar es Salaam, Tanzania.

Einvik-Heitmann, V., Dypvik, H., Hou, G., Fossum, K., Nerbråten, K., Karega, A., Hudson, W. E. and Gundersveen, E. The Early Cretaceous Kihuluhulu Formation of the Mandawa Basin. First EAGE Eastern Africa Petroleum Geoscience Forum. 16th – 19th November 2015, Dar es Salaam, Tanzania.

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1. Introduction

Recent exploration success has turned the continental East African and Western Madagascan margins into frontiers for oil and gas discoveries. The exploration targets are located in a series of basins that developed along the margins as consequences of the Early Jurassic breakup of Gondwana and the subsequent Jurassic – Early Cretaceous separation of Madagascar from East Africa. However, many aspects of the tectono-stratigraphic history and petroleum systems of the conjugate East African and Western Madagascan margins are not well known and call for further research; this thesis focuses on some of the local tectono-stratigraphical aspects of the Mandawa Basin of SE Tanzania.

The Mandawa Basin is the onshore part of one of the marginal basins, and is located approximately 100 km west of major gas discoveries in Block 2 (Fig. 1). The near-continuous stratigraphic sequence within the basin, from Late Triassic to present, is an untapped source of knowledge of the sedimentary response to the basin's structural development, and hence the evolution of the Tanzanian Margin. However, the tectono-stratigraphic framework of the Mandawa Basin is not well defined which poses difficulties in onshore-offshore correlation, and more research is therefore necessary to understand the links between the sedimentary responses to both the local and regional tectonic developments.

By expanding our understanding of the tectono-stratigraphic history of the Mandawa Basin we are not only gaining knowledge of the evolution and petroleum systems elements of the Tanzanian Margin, but also providing data for use in regional margin-wide tectono-stratigraphic correlations along the conjugate East African and Western Madagascan margins.

Figure 1: Simplified geological map of Eastern Tanzania with the major tectonic lineaments marked (black lines) and gas the discoveries. The outlined Mandawa Basin is located between the Rufiji and Ruvuma Rivers, and separated from the Selous Basin in the west by the Masasi Spur. The map is compiled from Pinna et al. (2004), Bingen et al. (2009) and Sommer et al. (2017), while the gas discoveries (in red) was after Davidson and Steel (2018).

1.1. Mandawa Basin Project

The Mandawa Basin Project (2013–2019) is a geological research project with the University of Oslo (UiO), the University of Dar es Salaam (UDSM) and the Tanzania Petroleum Development Corporation (TDPC) as participating institutions (Dypvik et al., 2015). The Mandawa Basin Project was established and funded by Equinor.

The purpose of the Mandawa Basin Project (MBP) was to study the depositional and tectonic history of the basin and evaluate the petroleum geological characteristics. The MBP also served as an educational arena where M.Sc. and Ph.D. students were given the opportunity to work together in close co-operation with professionals from universities and the industry, combining academic and industrial experience.

1.2. Aims of study and approach

This thesis aims to present new details of the tectono-stratigraphic history of the Mandawa Basin by studying the sedimentation from the Early Jurassic breakup of Gondwana to the present.

The first objective was to study the sedimentary provenance of Mandawa Basin sandstones and recent river sediments in SE Tanzania to evaluate source-to-sink since the breakup of Gondwana, and to determine whether shifts in provenance can be related to local and/or regional tectonic effects.

The aim of the second part of the thesis was to provide more specific details on the Late Jurassic and Early Cretaceous sedimentation. The Upper Jurassic and Lower Cretaceous formations have so far not been adequately documented with regards to sedimentology and

their compositional characteristics. This part of the thesis focuses on presenting a selection of outcrops from this period and describing these in terms of the sedimentology, mineralogical and petrographic characteristics of the formations.

To evaluate the sedimentary provenance of the basin infill we undertook an extensive heavy mineral study of Lower Jurassic to Paleogene sandstones. Sandstones with comparable grain-size distributions were sampled on the least weathered sections to reduce the eventual effects of sorting and post-depositional modification of the heavy mineral assemblage.

The heavy mineral assemblages of the sandstones were determined by identifying and quantifying the non-opaque heavy mineral fraction extracted from disaggregated rock samples. Single-grain analyses of garnets, amphiboles and zircons were performed on selected samples to provide more specific provenance details.

We also analysed the heavy mineral assemblages and U-Pb zircon ages of recent river sediments in SE Tanzania (the Rufiji, Matandu, Mbemkuru and Ruvuma rivers, Figure 1). The bedrock geology of the river catchments is well known, and consequently these results were used to discriminate and identify possible sediment sources of the past and study changes in the hinterland. We therefore compared the provenance signatures of the river sediments with the sandstones in the Mandawa Basin to evaluate the origin and development of provenance and sediments through time.

The Upper Jurassic and Lower Cretaceous post-rift successions in the Mandawa Basin are inadequately represented in the published literature. In the Mandawa Basin Project one aim was to publish sedimentological reviews of these successions and to present detailed sedimentary logs, and determine the mineralogical and petrographical characteristics of the studied formations.

As no formal stratigraphic nomenclature exists for the Mandawa Basin we adopted the stratigraphic terminology of Hudson, which is a revised version of the unpublished stratigraphic scheme of Shell (Hudson, 2011).

1.3. Study area

The Mandawa Basin (Fig. 1) is located in the coastal lowland between the Rufiji and Ruvuma rivers and covers an area of about 15,000 km². This Mesozoic rift basin is demarcated from the Rufiji Trough in the north by the E-W Utete-Tagalala Lineament, while the Ruvuma Saddle forms the southern border to the adjacent Ruvuma Basin. To the west, a major NW-SE trending border fault separates the Mandawa Basin from the Masasi Spur metamorphic basement. In the east, the Mandawa Basin passes laterally into the offshore basins (Hudson, 2011).

The Mandawa Basin transected by three major rivers: the Matandu, Mavuji and Mbemkuru, all flowing eastward along old E-W to ENE-WSW oriented lineaments (Fig. 1). The headwater of the Matandu Rivers lies in the Selous Basin, whereas the Mavuji and Mbemkuru rivers flow from the Masasi Spur.

The coastal lowland of SE Tanzania is characterised by tropical savanna climate (Kottek et al., 2006). The hot and humid climate in combination with dense vegetation causes high rates of weathering which may severely alter the bedrock to depths of as much as 20 metres below the ground surface (Nicholas et al., 2006).

1.4. Fieldwork

Data utilised in this thesis were collected by the Mandawa Basin Project during fieldwork, and from studies of shallow cores drilled by the Tanzania Drilling Project (TDP). Students and staff from the UiO, UDSM, TPDC and Equinor participated in the fieldwork. Equinor kindly provided transportation.

The localities were selected based on outcrop quality, accessibility and formation age. The maps and locality descriptions of Hudson (2011) were used as guide. The Upper Cretaceous and Paleogene formations were mainly studied in the TDP cores, whereas the Lower Jurassic to Lower Cretaceous formations were only studied in outcrops.

Figure 2: Geological map of the Mandawa Basin Lineaments and faults discussed in the text modified from Hudson (2011). The central basin area is outlined in grey and is the most studied part of the basin.

The first field visit in September 2013 consisted of two parts. First, eight days were spent at the TDPC core storage facility in Dar es Salaam, logging and sampling nine TDP cores spanning Aptian to Oligocene formations. Thereafter four days of fieldwork were conducted in the Kipatimu – Matumbi area (Northern Mandawa Basin), Kandawale sub-basin, and in the Mbate – Ninjo area just south of the Matandu River (Fig. 2).

The second round of fieldwork took place in October/November the following year (2014), when two weeks were spent studying the stratigraphy south of the Matandu River.

Out of roughly 40 studied localities, 28 localities and nine TDP cores were selected for detailed sampling and logging. Together, the collected field data, including about 700 samples, formed the basis for ten Master's theses (Gundersveen, 2014; Mahmic, 2014; Nerbråten, 2014; Hou, 2015; van den Brink, 2015; Didas, 2016; Einvik-Heitmann, 2016; Mtabazi, 2016; Haid, 2018; Masawani, not yet completed).

1.5. Previous studies

At the end of the 19th century, German explorers discovered a few dinosaur bones in southeastern German East Africa (Maier, 2003; Bussert et al., 2009). A subsequent reconnaissance survey in the area revealed abundant dinosaur remains in a small area around the Tendaguru Hill (SW Mandawa Basin, Figure 2) which in turn triggered the German Tendaguru Expedition (1909–1913).

Numerous fossil bearing beds were observed in the Tendaguru area, commonly occurring just a few metres below the surface, or weathered out at the surface. One of the geologists, Edwin Hennig, wrote to the Berlin's Natural History Museum (Maier, 2003):

“By all means start to build a new museum. It appears that we must level the entire [Tendaguru] hill, since there is hardly a spot without bone remains”

The fossil richness made the Tendaguru area world famous, and more than 225 tons of bones were excavated and shipped to Germany during the four-year long expedition (Tamborini and Vennen, 2017). Great efforts were made to resolve the stratigraphy of the dinosaur-bearing beds, resulting in detailed geological coverage in the area around Tendaguru Hill.

The German Tendaguru Expedition ended with the outbreak of the First World War in 1914. As a consequence of the war, German East Africa was awarded to Britain, and a British Tendaguru Expedition (1923–1931) was initiated. The British expedition was on the same massive scale as the German, but little was ever published (Maier, 2003).

Figure 3: Timeline for geological expeditions and phases of petroleum exploration in the Mandawa Basin. The different exploration wells are marked and named separately. The first geological surveys in the Mandawa Basin were the German and British dinosaur excavations in the Tendaguru area. With the exception of Aitken’s Mandawa Basin studies in the early 1950s, most research conducted from 1950 to 2000 was by petroleum companies. Many geological research projects were conducted in the period from 2000 to 2010: the German-Tanzanian Tendaguru Expedition, the Tanzania Drilling Project (TDP) and the field studies by Hudson. In 2011 the first offshore gas discovery was made in Block 1. In 2012, gas was discovered in Block 2, and the Mandawa Basin Project (MBP) was established in the following year.

In the 1950s, geologists of the Tanganyika Territory Geological Survey surveyed the coastal Tanzanian basins (Maier, 2003). During this regional survey, geologist William G. Aitken mapped parts of the central area of the Mandawa Basin, NE of Tendaguru (Fig. 3) from 1951 to 1954, resulting in a valuable and detailed summary of the Jurassic and Cretaceous geology and palaeontology in the Mandawa Basin (Aitken, 1961).

Reports of several oil seeps along the coastal belt sparked the interest of petroleum companies, and British Petroleum was given concession rights to coastal Tanzania in 1952. Shell international Oil and British Petroleum launched a joint petroleum exploration project. From that time on several companies have been involved in exploration of the Mandawa Basin (Fig. 3), resulting in several drilled wells and seismic surveys (Hudson, 2011). Kent et al. (1971) produced a comprehensive and much referred to review of coastal Tanzania geology. This compilation was based on the geological investigations in the 1950s (mapping, drilling and geophysical investigations), and is one of the few studies in which exploration results are presented. Only a handful of other papers have been published from data obtained during petroleum explorations (e.g. Balduzzi et al., 1992; Kagya, 1996; Veeken and Titov, 1996),

In 2000, a new geological survey to the Tendaguru area took place: the German-Tanzanian Tendaguru Expedition 2000. The aim of the expedition was to investigate the conditions in which the dinosaurs had lived, and to resolve the stratigraphy of the dinosaur bearing beds (Heinrich, 2001). Following the expedition several important studies have been published from the Tendaguru area (e.g. Aberhan et al., 2002; Bussert and Aberhan, 2004; Bussert et al., 2009). The most important of these contributions is perhaps the work by Bussert et al. (2009) where the Tendaguru Formation was formally described for the first time.

Detailed investigations of subsurface Upper Cretaceous and Paleogene successions were disclosed by the Tanzania Drilling Project (2002–2009). The Tanzania Drilling Project (TDP) was an international research collaboration aiming to study the stratigraphy, micropalaeontology and palaeoclimate of Upper Cretaceous to Neogene successions in SE Tanzania. Over 40 shallow wells (<150 m) were drilled during the TDP in the Mandawa Basin and also the area near Lindi (Fig. 1). The biostratigraphic resolution of these Upper Cretaceous to Paleogene successions are very well constrained, thanks to exceptionally well-preserved microfossils, and considered a Konservat-Lagerstätte.

One of the more recent geological contributions from the Mandawa Basin is the PhD thesis of Hudson (2011) in which field research (2006–2009) and available geophysical and geological subsurface data were integrated to synthesise the geological evolution of the Mandawa Basin.

2. Regional geological background

2.1. Karoo rifting

The Karoo Rift System (Fig. 4) formed in response to the assembly and later disintegration of Pangea in the Late Carboniferous/Early Permian to Triassic/Early Jurassic. Thus, the term Karoo is used to describe mainly continental successions deposited during this widespread Gondwanian sedimentation cycle (Catuneanu et al., 2005).

Figure 4: The Karoo basins of Africa (modified from Catuneanu et al. 2005).

Gondwana, which comprised today's South America, Africa, Madagascar, India, Australia and Antarctica, formed the southern part of Pangea from 300 to 180 Ma. In this

configuration, Somalia, Kenya and Tanzania were juxtaposed against the western side of Madagascar (Fig. 5a), and the structural profile of the Morondava Basin (Fig. 5b) mirrors the profile of Tanzania, both displaying intensive faulting during the Permo-Triassic (Wopner, 2013).

The Permian Karoo basins of Tanzania follow the NNE-SSW *Tanga Fault Trend* (Kent et al., 1971; Mpanda, 1997; Nicholas et al., 2007) Figure 1, where the Karoo sequences comprise upwards-fining megacycles (alluvial, fluvial, deltaic and lacustrine) initiated by periodic faulting (Mbede and Dualeh, 1997; Wopfner, 2002), peaking in the Middle Permian (Macgregor, 2017).

Another major rifting period occurred later in the Triassic, strongly affecting the coastal strip stretching from Somalia to Tanzania, and western Madagascar (Macgregor, 2017). The Triassic rifting event is by some believed to be responsible for the formation of the Mandawa Basin (e.g. Balduzzi et al., 1992; Kagya, 1996; Veeken and Titov, 1996), which follows the *Lindi Fault Trend* (Fig.1).

The Karoo rifting failed before attaining the final stage of continental breakup. A period of thermal subsidence followed the demise of Karoo-related activities (Wopfner, 2002) and the Mandawa area experienced exceptionally high rates of subsidence (Kent et al., 1971; Hudson, 2011; Hudson and Nicholas, 2014).

2.2. Separation of East and West Gondwana

Syn-rift (Early Jurassic, c. 183 – 170 Ma)

A new phase of rifting commenced around 183–177 Ma (Geiger et al., 2004; Gaina et al., 2013; Reeves, 2018; Tuck-Martin et al., 2018). This Early Jurassic fault system partly reactivated the Triassic Karoo trends within the thinned margin, between what was to become East and West Gondwana (Reeves, 2018; Sansom, 2018). Extension occurred in a NW-SE direction in the newly formed West Somali and Mozambique basins (Figs. 5a and b), and by dextral transtension on the margin segment between the two basins (Tuck-Martin et al., 2018). While the margin segment between the two spreading centres was characterised by dextral

transtension on what later became the Davie Fracture Zone, Figure 5c (Tuck-Martin et al., 2018).

The rifting created a seaway which propagated southwards from the Tethys Ocean. Early marine incursions flooded depressions along the coastal margins of Somalia, Kenya, Tanzania (Mandawa Basin) and western Madagascar, where evaporites accumulated in restricted basins (Rabinowitz et al., 1982). The first marine transgression occurred in E Somalia, NE Kenya and NW Madagascar (Luger et al., 1994; Mbede and Dualeh, 1997).

The syn-rift sequences in Somalia, Kenya, Tanzania and Madagascar are mainly composed of reworked Karoo sediments. These successions display complex sequences separated by disconformities, developed in response to tectonic movements controlled by the bounding faults (Kruser, 1995; Mbede and Dualeh, 1997; Geiger et al., 2004; Emmel et al., 2008). The syn-rift sequences were terminated by a diachronous breakup unconformity (Kent et al., 1971, Mbede and Dualeh, 1997; Geiger and Schweiger, 2006; Hudson, 2011).

Early post-rift (Middle Jurassic – Early Cretaceous, c. 170 – 120 Ma)

At around 170 Ma, Gondwana split roughly parallel to the modern East African Margin to form West Gondwana (Africa and South America) and East Gondwana (Madagascar, India, Antarctica, Australia and Seychelles) (Geiger et al., 2004; Gaina et al., 2013; Reeves, 2018). Seafloor spreading commenced shortly after in the West Somali and Mozambique basins between the conjugate East African and Western Madagascan (EA-MAD) and East African and Antarctica (EA-ANT) margins respectively, Figure 5 (Eagles and König, 2008; Gaina et al., 2013; Tuck-Martin et al., 2018). The Seagap fault (Fig. 1) probably originated as an early dextral transform during the early stages of the seafloor spreading (Sansom, 2018). From about 140 Ma, pure dextral strike-slip motion was initiated along the 1800 km long Davie Fracture Zone, Figure 5c (Gaina et al., 2013; Reeves, 2018).

After breakup, fault activities diminished and the margin segments started to subside, marking the onset of the first major transgression. This created an epeiric sea between the conjugate East African - Western Madagascan margins (EA-MAD, Figure 5b). By the Bajocian, fully marine conditions were established in SE Kenya (Rais-Assa, 1988) and E Tanzania (Kent et al., 1971), and in the Middle Jurassic in NE Mozambique as well (Salaman and Abdula, 1995). The Bajocian – Bathonian is recognised as a period of deposition of

Figure 5: Plate reconstructions of the evolution of the East African Margin constructed using GPlates (Gaina et al., 2015). The subdivisions of the conjugate margins segments after Tuck-Martin (2018). EA-IND: conjugate East African - Indian margins, EA-MAD: conjugate East African - Western Madagascan margins, EA-ANT: conjugate East African - Antarctica margins, NSM: Northern Somali Basin, WSB: Western Somali Basin, MB: Mozambique Basin, MaB: Mascarene Basin. (a) Plate assembly fit at 180 Ma during the onset of rifting. The Mandawa Basin (pink star) was juxtaposed against the Morondava Basin in Madagascar (grey star). (b) The breakup of Gondwana occurred roughly around 170 Ma. Seafloor spreading commenced shortly after the breakup in the WSB and MB. (c) At c. 140 Ma, pure dextral strike-slip movement occurred along the entire Davie Fracture Zone (DFZ) and East Gondwana began to disintegrate. (d) Around 120 Ma, seafloor spreading and movement along the DFZ had ended, and Madagascar was incorporated in the African Plate. (e) India has separated from Madagascar, and the East African Margin experienced a prolonged period of tectonic quiescence

marine carbonates in East Africa and Madagascar (Coffin and Rabinowitz, 1988; Mbede and Dualeh, 1997).

The early phase of the separation was that of a two-plate system between East and West Gondwana. In the Early Cretaceous (c. 140 Ma), East Gondwana began to disintegrate, starting with separation of India from Western Australia in the Berriasian or Valanginian (Gaina et al., 2013; Reeves, 2018).

The cessation of seafloor spreading in the West Somali Basin in the Early Cretaceous led to a chain of plate boundary relocations and the initiation of new spreading centres. This changed plate motion vectors and kinematics within the African-Madagascan-Indian plate assembly (Tuck-Martin et al., 2018). The plate boundary relocated south of Madagascar, initiating rifting and subsequent seafloor spreading between Madagascar/India and Antarctica (Fig. 5d) (Gaina et al., 2013; Reeves, 2018; Tuck-Martin et al., 2018).

The timing of when oceanic spreading stopped in the West Somali Basin is poorly constrained, but has been tentatively placed in the Valanginian/Hauterivian (c.133 Ma, Tuck-Martin et al., 2018), or possibly later in the Aptian c.120 Ma (Gaina et al., 2013; Reeves, 2018). With the demise of oceanic spreading in the West Somali Basin, transform movement along the Davie Fracture Zone also ended (Gaina et al., 2013; Davis et al., 2016; Reeves, 2018; Tuck-Martin et al., 2018) and the East African Margin became passive. About 1000 km of dextral displacement was accomplished along the transform between EA-MAD (Fig. 5).

A short-lived period of tectonic uplift following the final movement on the Davie Fracture Zone (Mahanjane, 2014) created a major unconformity along the margin segments

bordering the Somali Basin that had formed in the end Hauterivian – Early Barremian (Tuck-Martin et al., 2018). An Early Cretaceous compressional event (Hauterivian – Aptian, c.132 – 120 Ma) is recognised west of the Davie Fracture Zone in the West Somali Basin (Sauter et al., 2018) and in the northern Mozambique Basin (Mahanjane, 2014).

After the separation of Antarctica from India, dextral strike-slip motion commenced between Madagascar and India in the Barremian c. 127 Ma. Oceanic spreading in the Mascarene Basin c. 89 – 61 Ma resulted in the separation of India from Madagascar (Fig. 5f) (Gaina et al., 2013; Reeves, 2018; Tuck-Martin et al., 2018).

Late post-rift (Early Cretaceous – Oligocene c. 120 – 28 Ma)

Madagascar was incorporated in the African Plate and there followed a prolonged period of tectonic quiescence that characterised the established East African Margin. This lasted until the East African Rift System reached the East African Margin in the Miocene (Reeves, 2018).

At the end of the Aptian a major transgression commenced. It became widespread in the Albian and led to a rapid deepening of the depositional systems on the southern Tanzanian Margin. The ramp established in Late Jurassic developed into a narrow shelf with eastward-deepening channelled slopes during the Albian (Sansom, 2018). In the Albian a northwards flowing contourite system was initiated between mainland East Africa and the East Gondwana plates, presumably a consequence of free oceanic circulation after the separation of India from Antarctica/Australia, Figure 5 (Reeves, 2017).

The offshore Tanzanian basin was characterised by turbidite-contourite deposition with migrating channel-levee complexes; a result of downslope flowing turbidite currents and northwards flowing contour currents resulting in excellent offshore reservoir sandstones (Siversen et al., 2017; Sansom, 2018).

3. Tectono-stratigraphic history of the Mandawa Basin

The Mandawa Basin is located in the southern segment of the conjugate East African-Western Madagascan margins (EA-MAD, Figure 5) where it formed predominantly under a transtensional stress regime during the separation of East and West Gondwana.

Two major transtensional deformation events are inferred from surface structures and geophysical subsurface data (Mtabazi et al., 2016). The first event created NNW-SSE trending normal faults during the regional ENE-WSW extension. The second deformation event produced NNE-SSW, NNW-SSE and ENE-WSW trending normal, transtensional and strike-slip faults during the NW-SE extension between East Africa and Madagascar, which possibly also reactivated older NNW-SSE structures (Didas, 2016; Mtabazi, 2016).

The oldest basin structures, the NNW-SSE faults, link up to a series of faults collectively referred to as the *Lindi Fault Trend*, Figure 1 (Kent et al., 1971), demarcate the basin from the Masasi Spur in the west (Hudson, 2011; Didas 2016).

As a response to the initial ENE-WSW extension, N-S oriented intrabasinal faults developed within the central basin area and formed a deep linear N-S trending graben-like structure. Subsurface data reveals that the N-S oriented intrabasinal faults were demarcated by WNW-ESE and W-E trending strike-slip transfer faults, Figure 2 (Didas, 2016).

Pre-rift

The *Mubo Formation* (Fig. 6), the oldest formation in the Mandawa Basin, lay directly upon the basement in the central graben-like structure during Late Triassic and/or Early Jurassic times. The graben evolved into a lake and the basal conglomerates and sandstones were succeeded by lacustrine claystones (Balduzzi et al., 1992; Veeken and Titov, 1996; Hudson, 2011; Hudson and Nicholas, 2014).

Figure 6: Lithostratigraphic scheme for the Mandawa Basin, modified from Hudson (2011). The main tectonic phases of the East African Margin are summarised in the left column (see chapter 2 for references).

High rates of subsidence are inferred from the central basin area during the end of Triassic/Early Jurassic, as it experienced frequent marine incursions from the Tethys that flooded the basement highs and thus the enclosed lacustrine Mandawa depression (Kent et al., 1971; Balduzzi et al., 1992; Hudson and Nicholas, 2014). Periodic ingress of seawater in combination with a semi-arid climate, created hypersaline and suboxic/anoxic conditions, favouring evaporite sedimentation and improved preservation of organic material. The resulting *Nondwa Formation* (Figs. 2 and 6) comprises evaporites and organic-rich shales with good source rock potential (Kagya, 1996; Hudson and Nicholas, 2014).

Evaporite sedimentation continued in the central graben well into the Pliensbachian, ending just prior to the final rifting event and the successful separation of East and West Gondwana. The thickness of the *Nondwa Formation* is difficult to resolve due to later halokinetic movements. Maximum thickness is probably attained in the Mandawa-7 well where a 2800 m thick sequence was proved (Kagya, 1996; Hudson and Nicholas, 2014).

Syn-rift

Renewed rifting in the Toarcian ended evaporite sedimentation in the Mandawa Basin. The *Nondwa Formation* was subsequently overlain by syn-rift sandstones of the *Mihambia Formation*, Figure 6 (Hudson and Nicholas, 2014). Similar syn-rift successions are known from Ngerengere, Kidugallo, Matumbi, Figure 1 (Quennel et al., 1956; Kent et al., 1971; Balduzzi et al., 1992; Kreuser, 1995; Kapilima, 2003). The syn-rift succession at Ngerengere comprises 500 metres of continental conglomeratic and arkosic transitional sandstones and is regarded as type section for the syn-rift deposits in Tanzania, hence Early Jurassic transitional sequences in Tanzania are commonly referred to as the Ngerengere Beds (Quennel et al., 1956; Kent et al., 1971; Balduzzi et al., 1992; Kreuser, 1995; Kapilima, 2003).

Evidence of early marine incursions is inferred from the upper part of the Ngerengere Beds and the *Mihambia Formation*, where limestones and shales are found as intercalations in the arkosic sandstones (Quennel et al., 1956; Kent et al., 1971; Mbede and Dualeh, 1997; Hudson and Nicholas, 2014).

Early post-rift

The Late Aalenian/Early Bajocian breakup of Gondwana initiated a widespread transgression, with deposition of marine limestones along the EA-MAD. In the Mandawa Basin, the early post-rift sequence commences with Bajocian limestones of the *Mtumbei Formation* (Figs. 2 and 6), deposited unconformably on basement or syn-rift sandstones (Hudson, 2011). Little is known about these Mtumbei Formation limestones as no detailed studies have yet been published.

With the exception of Bajocian strata brought to the surface by salt diapirism in the Mandawa and Pindirola anticlines (Aitken, 1955; Aitken, 1956; Aitken, 1961; Hudson, 2011), exposures of the Mtumbei Formation are restricted to the westernmost basin margin in the Northern Mandawa Basin and a minor area just south of the Matandu Lineament (Fig. 2). In the Matumbi area (Fig. 2) the Mtumbei Formation comprises oolitic limestones and calcareous sandstones that pass upwards into soft sandstones and marls (Stockley, 1943).

In the Northern Mandawa Basin, the *Kipatimu Formation* (Figs. 2 and 6) succeeds the Mtumbei Formation. The Kipatimu Formation was estimated by Kent et al. (1971) to be about 600 m thick, comprising fluvial and fluvio-deltaic deposits consisting of cross-stratified sandstones and some occasional conglomerates, intercalated with purple and green claystones (Stockley, 1943; Aitken, 1961; Kent et al., 1971; Gundersveen, 2014; Hudson, 2011).

The Kipatimu Formation is exposed in the Northern Mandawa Basin and the Rufiji Trough with the northernmost exposure in the Wingayongo area (Mpanju and Philp, 1994) on the northern flank of the Rufiji Trough (Figs. 1 and 2). Eastwards the formation is known in the subsurface at Songo Songo and Mafia islands (Fig. 1), occurring as deltaic and estuarine facies (Mkuu, 2018).

Kent et al. (1971) suggested that deposition of the Kipatimu Formation in the Mandawa Basin occurred immediately after the Bathonian. Others advocate that deposition occurred from the Oxfordian to Tithonian (Stockley, 1943; Msaky, 2007; Hudson, 2011). Smelror et al., (2018) argued that sedimentation of the Kipatimu Formation continued into the Early Cretaceous in the Mandawa Basin.

The fluvial Kipatimu Formation succession cannot stratigraphically be correlated to any particular unit south of the Matandu Lineament, where mainly littoral to shallow marine neritic facies dominate (Aitken, 1961).

The sea between East Africa and Madagascar grew wider during the creation of new oceanic crust in the West Somali Basin, and the transgression continued into the Late Jurassic. During this period a ramp margin was established in southern Tanzania (Sansom, 2018). The ramp was characterised by gently NE sloping depositional surfaces characterised by mixed siliciclastic and carbonate sedimentation (Aberhan et al., 2002).

The Late Jurassic landscape consisted of low-relief coastal plains with brackish lakes and extensive intertidal flats in a subtropical to tropical climate with seasonal rainfall and pronounced dry seasons (Aberhan et al., 2002; Bussert et al., 2009). The coast was probably barred, with quiet marine embayments and lagoons landward of the barrier bars, and ebb deltas developing around the tidal-channel inlets (Aberhan et al., 2002; Bussert et al., 2009; Hudson, 2011). The tidal range was significant during the Late Jurassic and most successions display signs of tidal influence (Aberhan et al., 2002; Bussert et al., 2009).

Dinosaurs, including herds of large sauropods, roamed the coastal lowland, possibly in search of water during drought periods. Their fossil remains have been found in great abundance within the terrestrial Tendaguru beds (Fig. 2). These animals, together with pterosaurs, reptiles and small mammals, had become mired in the muddy sediments in the shallow lagoons and on the tidal flats, and eventually drowned. Their slow burial during successive tides allowed currents, waves and scavengers to rip off exposed limbs, leaving disarticulated carcasses and incomplete fossils (Aberhan et al., 2002; Maier, 2003; Bussert et al., 2009).

The early post-rift sequence in the Mandawa Basin is characterised by cyclic deposition of transgressive-regressive sequences where transgressive limestones and high-energy calcareous sandstones are overlain by regressive terrestrial and marginal marine sandstones and claystones (Aitken 1961; Kent et al., 1971; Bussert et al., 2009; Hudson, 2011). During sea-level rise, the coastal plain was inundated and the low-energy lagoons and tidal flats were replaced by shallow marine and subtidal high-energy sandstones. Three transgressive events have been recorded in the Upper Jurassic and Neocomian formations of the Mandawa Basin (Fig. 6), occurring in the Oxfordian, Late Kimmeridgian – Early Tithonian, and during the Valanginian – Hauterivian (Aitken, 1961; Bussert et al., 2009; Hudson, 2011).

These transgressions are best documented from the *Tendaguru Formation* (Fig. 6) which comprises three low-energy, terrestrial-dominated horizons, that alternate with three high-energy marine horizons. The transgressive members of the Tendaguru Formation are comprised of high-energy, coarse-grained sandy limestones and calcite-cemented bioclastic

sandstones. They often display variable transport directions, and thus are interpreted as tidal channel sands, sand bars and beach deposits (Aberhan et al., 2002; Bussert et al., 2009). Similar transgressive-regressive sequences E and NE of Tendaguru are inferred from cores and outcrops, i.e. the *Mitole* and *Nalwehe Formations*, which both consist of a lower limestone member and an upper sandstone member (Fig. 6).

The Late Kimmeridgian – Early Tithonian *Mitole Limestone Member* (Fig. 6) comprises oolittic limestones, and is found exposed in the areas encircling the Mandawa and Pindiro anticlines (Fig. 2). The ooids are interpreted to be derived from nearby ooid shoals (Aitken, 1961; Kent et al., 1971; Bussert et al., 2009; Hudson, 2011). In older literature the Late Kimmeridgian – Early Tithonian oolittic sequence was recognised as the “*smeei Oolite*” of Hennig (Quennel et al., 1956). The “*smeei Oolite*” occurs as discrete bands of coarse grained, well-bedded oolittic limestones intercalated with siliciclastic sandstones and non-oolittic limestones (e.g. Quennel et al., 1956; Aitken 1961),

The *Mitole Limestone Member* is overlain by the friable or weakly clay-cemented sandstones of the *Mitole Sandstone Member* (Fig. 6), deposited during a regressive development from Tithonian into the Berriasian (Hudson, 2011).

Most of the Berriasian was eroded prior to the Hauterivian, creating a significant unconformity between the Tithonian and Lower Cretaceous in the Mandawa Basin (Arkell 1956; Aitken 1961; Kent et al., 1971; Bussert et al., 2009). This unconformity is still unexplained but can be traced regionally along the East African Margin segment (Tuck-Martin et al., 2018). The final phase of spreading in the Somali Basin and/or the onset of separation between Madagascar and India may have been responsible (Coffin & Rabinowitz, 1988).

The Neocomian stage (Berriasian – Barremian) was mainly regressive in Tanzania, except in the Mandawa Basin, where localised transgression occurred in the Valanginian – Hauterivian (Kent et al., 1971; Mpanda, 1997; Bussert et al., 2009). The Early Cretaceous transgression in the Mandawa Basin was likely tectonically driven. Aitken (1961) argued that Early Cretaceous dextral transtension on the NNW trending Kikundi-Mchinjiri Fault (Fig. 2) caused sag development west of the fault. Similarly, accommodation zones formed in the intersection zones between the older NNW-SSE faults and the E-W strike-slip transfer faults (Aitken, 1961; Didas, 2016).

The Valanginian – Hauterivian transgression established shallow marine depositional conditions, yet again initiating carbonate production during deposition of the *Nalwehe Limestone Member* (Fig. 6). Outcrops of the Nalwehe Limestone Member are restricted to the central area of the basin (Fig. 2) where it unconformably overlies Tithonian sandstones of the Mitole Formation (Aitken, 1961, Hudson, 2011). These Neocomian limestones are commonly reported as fossiliferous and reefal (Aitken, 1961), but we know little about their composition and depositional character.

The *Nalwehe Sandstone Member* overlies the Nalwehe Limestone Member (Hudson, 2011). The sedimentological characteristics of the Nalwehe Sandstone Member are not well constrained. It has been interpreted to represent a regressive development after the Hauterivian transgression, and carries some lithological similarities to the Tithonian Mitole Sandstone Member (Hudson, 2011).

The Nalwehe Formation is overlain, and separated from Aptian – Albian formations, by a Mid-Cretaceous unconformity (Mpanda, 1997). This unconformity is of regional extent and likely formed in response to far-field stresses associated with plate boundary reorganisation during the incorporation of Madagascar into the Somali Plate (Tuck-Martin et al., 2018).

The Aptian was locally transgressive in the Mandawa Basin, which again promoted carbonate deposition. The resulting Kiturika Formation (Figs. 5 and 6) has been described as coralliferous and crops out along the Kiturika Hinge (Fig. 2), with a maximum thickness of about 150 m (Aitken, 1961; Kent et al., 1971; Hudson, 2011). The Kiturika Formation remains more or less unstudied, thus its depositional history and stratigraphic position are poorly constrained. Presumably, the limestones pass into two time-equivalent formations: westwards into the continental *Makonde Formation* and eastwards into the distal marls and claystones of the *Kihuluhulu Formation*, Figures 2 and 6 (Quennel et al., 1956; Kent et al., 1971; Hudson, 2011).

Hennig proposed already in 1914 that the siliciclastic Makonde Formation was the continental counterpart of the Kiturika Formation (Quennel et al. 1956). Aitken however, was not convinced of Hennig's interpretation as he did not find compelling evidence of the Makonde Formation being deposited contemporaneously with the limestones of the Kiturika Formation during his field studies in the Mandawa Basin in the 1950s, and advised further

studies (Aitken, 1961). So far, no such studies have been conducted and Hennig's interpretation still stands.

Remnants of the once extensive Makonde Formation are presently found mainly on elevated coastal plateaux between the Matandu and Ruvuma rivers, e.g. the Makonde and Rondo plateaux, Figure 1 (Kent et al., 1971; Quennel et al., 1956; Hudson, 2011). The formation has proved challenging to date and its stratigraphic relations to both the Kiturika and Kihuluhulu formations are poorly constrained. A late Aptian age for the Kiturika Formation and Late Aptian – Early Albian age for the Makonde Formation have been suggested (Hudson, 2011).

The Makonde, Kiturika and Kihuluhulu formations are overlain by marls of the *Kingongo Formation* (Kent et al., 1971; Nicolas et al., 2006), in turn succeeded by eastward dipping Upper Cretaceous olive-grey clays with thin sandstone beds (Nicolas et al., 2006; Hudson, 2011).

Movement of subsurface salt occurred during the early post-rift stage of the basin's history (e.g. Aitken, 1961; Kent et al., 1971; Balduzzi et al., 1992; Hudson, 2011; Hudson and Nicolas, 2014; Didas, 2016). Interpretations of seismic sections show that faulting associated with salt movements occurred from the Late Jurassic into Aptian times (Didas, 2016). In the Kizimbani-1 well, drilled on a basement high 43 km north of the Mandawa Dome (Fig. 2), 750 m of evaporites had been emplaced between Bathonian and Late Aptian strata (Balduzzi et al. 1992).

It is likely that topographical variations, formed as a response to salt movement, affected the sea level locally, which also might explain rapid shifts in lateral facies observed within the central basin area (Aitken, 1961). However, the implications of salt tectonics on sedimentation have not been studied in detail and this calls for further research.

Late post-rift

A new transgression occurred at the end of the Aptian, which became widespread in the Albian, likely a consequence of the ongoing separation of Antarctica from Africa (Sansom, 2018). With the resulting rise in sea level, the Mandawa ramp developed into a narrow shelf passing into a deep and wide channel-slope system east. Sediments were transported offshore through structurally controlled entry points, a configuration which also characterises the modern Tanzanian Margin (Sansom, 2018).

A prolonged period of exceptional tectonic stability and increased subsidence along the Tanzanian Margin following the demise of seafloor spreading and strike-slip movement along the Davie Fracture Zone in the Aptian (Nicholas et al., 2006). The Upper Cretaceous – Oligocene Kilwa Group (the Nangurukuru, Kivinje, Masoko and Pande formations, Figure 6) is a fairly homogeneous unit of mainly deep marine clays and marly claystones with a minimum thickness of about 1000 m. The lower bounding surface marks the start of increased subsidence across the palaeo-shelf and the onset of laterally persistent transgressive deposition of clay (Nicholas et al., 2006).

Sedimentation appears to have occurred more or less continuously with little or no disturbance until the Middle Eocene (Nicholas et al., 2006). The Middle Eocene was a regressive period characterised by abnormally high sedimentation rates, especially at Mafia Island, possibly caused by short period of tectonic uplift and related erosion (Kent et al., 1971; Nicholas et al., 2006).

4. Summary of papers

Paper 1: Integrated heavy mineral study of Jurassic to Paleogene sandstones in the Mandawa Basin, Tanzania: Sediment provenance and source-to-sink relations.

Authors: Katrine Fossum, Andrew C. Morton, Henning Dypvik and Wellington E. Hudson

Published: Journal of African Earth Sciences

Keywords: sediment provenance, heavy mineral analysis, garnet and amphibole geochemistry, U-Pb zircon analysis, source-to-sink.

This paper presents a sediment provenance study of sandstones in the Mandawa Basin, southern Tanzania. The objective of the study was to shed light on the sediment source and sediment dispersal history of the basin from Early Jurassic to Paleogene.

The non-opaque heavy mineral assemblages of 38 sandstone samples were determined by conventional heavy mineral analysis. Based on these results, single grain studies of selected minerals were performed to obtain more precise evaluation of the sediment source terranes: garnet and amphibole geochemistry (determined by electron microprobe analysis) and isotopic U-Pb zircon ages (LA-ICP-MS).

The samples were grouped into four different heavy mineral assemblages: garnet-dominated, zircon-dominated, amphibole-dominated and epidote-dominated. The garnet-dominated assemblage was observed throughout the entire Lower Jurassic to Oligocene sequence and was the main heavy mineral assemblage in 23 of the samples. The three other assemblages are scattered within the stratigraphic sequence. The amphibole-dominated assemblage was detected in a few Lower Cretaceous sandstones (the Nalwehe Formation) cropping out within the Mbemkuru River Valley. The zircon-dominated assemblage appears in a few Upper Jurassic and Lower Cretaceous formations where only the ultra-stable heavy minerals remain (zircon, tourmaline and rutile). The epidote-dominated assemblages were restricted to Middle Eocene sandstones. The amphibole- and epidote-dominated assemblages

likely represent temporal variations in provenance. The zircon-dominated heavy mineral assemblage most possibly reflects different provenance and/or post-depositional modification of the other heavy mineral assemblages.

Garnet provenance was assessed by plotting their geochemical compositions in discrimination charts. The garnet populations in the Upper Jurassic sandstones showed a mixed parentage, mainly derived from various amphibolite and granulite facies rocks. The garnets in garnet-dominated assemblages did not display major variations in their garnet populations, suggesting only minor changes in source terrane during early post-rift sedimentation.

The amphibole and garnet compositions in the Lower Cretaceous amphibole-dominated sandstones indicate the same source origin, preferably a source representing amphibolite metamorphic facies conditions.

The U-Pb zircon age analyses yielded remarkably similar zircon populations throughout the sequence, indistinguishable from each other within the margins of analytical error. The only exception is the Aptian – Albian Makonde Formation, which contains a large contribution of Palaeoproterozoic zircon. This formation is characterised by a very stable heavy mineral assemblage strongly dominated by zircons. The Palaeoproterozoic zircons were interpreted to be derived mainly from recycled Karoo successions based on the restricted occurrence of sandstones carrying this provenance signal.

Main findings:

- The heavy mineral assemblages, the zircon populations and the geochemistry of garnets of garnet-dominated sandstones showed a multi-source provenance signature.
- Sediments deposited in the Mandawa Basin during the opening of the Indian Ocean were sourced from similar terranes through most of Middle Jurassic to Paleogene time, as indicated by the general consistency of garnet types and zircon age distribution.
- The palaeo-Rufiji river north of the Mandawa Basin most probably supplied the greater volume of the sediments, carrying and homogenising eroded material from several source terranes, including sedimentary rocks of the Karoo system.
- As a result of different provenance, some Lower Cretaceous sandstones were characterised by different heavy mineral assemblages, garnet compositions and zircon populations.

Paper II: Late Jurassic and Early Cretaceous sedimentation in the Mandawa Basin, coastal Tanzania.

Authors: Katrine Fossum, Henning Dypvik, Muna H. M. Haid, Wellington E. Hudson and Majkel van den Brink

Submitted manuscript: Journal of African Earth Sciences

Keywords: Mandawa Basin, sedimentology, Upper Jurassic and Lower Cretaceous formations, XRD, petrography, depositional environment, palaeographic reconstructions.

This paper describes and discusses Upper Jurassic and Lower Cretaceous stratigraphy in the Mandawa Basin, with emphasis on their mineralogical and petrographical compositions and depositional environments. The main objective was to provide new insight into the sedimentary evolution of the Mandawa Basin and translate this into palaeogeographic reconstructions.

Upper Jurassic and Lower Cretaceous sections were studied, logged and sampled during fieldwork. The mineralogical composition of the samples was determined by XRD, and petrographical analysis was accomplished by optical microscopy and SEM analysis on thin sections.

Two sections of the Kipatimu Formation in North Mandawa Basin were studied. The oldest section comprised large, sandy, braided river deposits with good reservoir properties. The younger section spans the Jurassic – Cretaceous boundary and comprises different lithologies (clay- and siltstones, sandstones and conglomerates) and possibly also several disconformities. We interpreted this section of the Kipatimu Formation to have been deposited under mainly marginal marine conditions.

The early post-rift successions south of the Matandu Lineament are characterised by series of transgressive-regressive sequences where limestones are overlain by sandstones. We presented a new interpretation of the Mitole Limestone Member, which prior to this study was regarded as oolitic. However, decisive evidence from thin section analysis strongly argues that these limestones are composed of micro-oncoids. Contrary to ooids, their origin is not restricted to a specific water depth and energy setting, but instead forms during times of high carbonate production and low sedimentation rates during transgressive and high stand conditions. The micro-oncoids in the Mitole Limestone Member are interpreted to have

formed in open, subtidal lagoons during the Late Kimmeridgian – Early Tithonian transgression. During storms the micro-oncoids were re-deposited as well-sorted grainstones.

The overlying Mitole Sandstone Member was likely deposited in shallow marine tidal-channel and foreshore conditions during a Tithonian regressive period. The sediments are rich in infiltrated and grain-coating smectitic clays.

We interpret the Lower Cretaceous Nalwehe Limestone Member to represent transgressive conditions, presumably during the Hauterivian. A restricted to open subtidal lagoonal setting was inferred as the depositional environment for these limestones. We propose that the presence of larger oncoids and stromatolites reflects high microbial activity and low sedimentation rates during deposition of the Nalwehe Limestone Member. Karstified surfaces represent significant periods of subaerial exposure which must relate to falls in relative sea-level.

The overlying Nalwehe Sandstone Member was deposited during a regressive phase, and appears lithologically similar to the Mitole Sandstone Member, with the exception of a few amphibole-rich sandstones outcropping in the Mbemkuru river valley. The immature sediment composition dominated by amphibole suggests short transportation. The depositional environment has been interpreted as a barred, river-dominated estuary.

Main findings:

- Tidally dominated, mixed carbonate-siliciclastic ramp with cyclical transgressive-regressive sequences (limestones overlain by sandstones).
- Mid- to inner-ramp settings during high stands, back-ramp settings during low sea-level stands.
- High microbial activity and low sedimentation rates characterised transgressive phases.
- High storm frequency in Late Kimmeridgian – Tithonian times.
- Early Cretaceous transtension and strike-slip faulting created localised accommodation space for sediments where amphibolitic sandstones were deposited.
- Karstified surfaces within the Nalwehe Limestone Member testify to base- or sea-level fluctuations during the Early Cretaceous.

Paper III: Provenance evaluation of river sediments in southern Tanzania: a study based on heavy mineral signatures and U/Pb zircon ages.

Authors: Katrine Fossum, Henning Dypvik and Andrew C. Morton

Submitted manuscript: Journal of African Earth Sciences

Keywords: river sediments, sediment provenance, heavy mineral analysis, U/Pb zircon analysis, source-to-sink.

As a continuation of Paper I, the provenance signatures of river sediments sampled from the Rufiji, Matandu, Mbwenkuru and Ruvuma rivers were studied. The purpose of the study was to identify the sediment sources and compare the results with the provenance signatures of the Jurassic to Paleogene sandstones in the Mandawa Basin presented in Paper I. Because the bedrock geology of the river catchment area is known, this study of river sediments may help to improve provenance interpretations of older successions in SE Tanzania and the Mandawa Basin, and shed light on the source-to-sink history through time.

The heavy mineral assemblages of the river sediments were determined by identifying and counting the non-opaque heavy minerals. In addition, U-Pb zircon analyses were performed on all samples to identify the potential sources of the detrital zircons

The samples contained different heavy mineral assemblages and U/Pb zircon populations. The smaller Matandu and Mbwenkuru rivers were both characterised by unstable heavy mineral assemblages. The Rufiji and Ruvuma rivers, by contrast, contained more stable and diverse heavy mineral assemblages, reflecting a wider catchment area and longer transport distances.

The zircons show age peaks at c. 2900–2500, 2000–1800, 1000, 800 and 700–500 Ma. Sediment samples from the Matandu and Mbwenkuru rivers displayed similar heavy mineral assemblages, but exhibited different zircon age distributions: the Matandu River contained abundant Palaeoproterozoic zircons (2000–1800 Ma), whereas only 1000 Ma and 700–500 Ma zircon ages were detected in samples from the Mbwenkuru River.

Sediments from the Rufiji and Matandu rivers had comparable zircon age groups, both containing abundant Palaeoproterozoic grains. Sediments from the Mbwenkuru and Ruvuma rivers, however, displayed a less diverse zircon population comprised of 1000 Ma and 700–500 Ma zircon ages, likely reflecting drainage of the metamorphic Mozambique Belt and the Unango-Marrupa Complex.

Because large parts of the Rufiji River catchment area comprised of Karoo bedrock, the high zircon diversity observed in the Rufiji River sample was interpreted to reflect recycling of older sedimentary successions. Both the Rufiji and Matandu Rivers carried abundant Palaeoproterozoic (2000–1800 Ma) grains which we argued as mainly derived from sediments from the Karoo successions in the NE Selous Basin. The same recycled “Palaeoproterozoic signature” has been reported from the Aptian – Albian Makonde Formation in the Mandawa Basin (Paper I) and possibly indicates the initiation of the Matandu River in the Mandawa Basin.

Diverse zircon age populations, similar to those in the Rufiji and Matandu river samples, characterise the zircon populations in the analysed Mandawa Basin sandstones in Paper I. However, the sandstones contained a much larger c. 800 Ma age fraction, whereas only a few 800 Ma grains were detected in the river samples, indicating that the c. 800 Ma zircon source was no longer present or the drainage systems had been re-organised.

Main findings:

- The heavy mineral assemblages in samples from the Matandu and Mbemkuru rivers were less diverse and contained more unstable minerals dominated by calcic amphibole, than samples from the larger Rufiji and Ruvuma rivers.
- The sediments from the Ruvuma and Mbemkuru Rivers contained the two zircon age fractions derived from the Cabo Delgado Nappe Complex of the Mozambique Belt and the Unango-Marrupa Complex.
- The high zircon diversity in the Rufiji River reflects a wide catchment area in which zircons were supplied from Karoo formations in addition to basement rocks.
- The zircon population of the Rufiji River sample displayed similar age diversity compared to the zircon population in the Mesozoic sandstones. This suggests that a large fluvial system was responsible for transporting the bulk of the sediments into the Mandawa Basin.

5. Discussion

The studies undertaken for this thesis have generated new sediment-petrographical information on the early post-rift successions and increased our overall understanding of the Mandawa Basin's depositional history. By undertaking an integrated sedimentological approach, previously unknown details on the source-to-sink relations has been presented. This study has also demonstrated that tectonic episodes can be recognised from the compositional nature of the basin fill.

Early post-rift sedimentation in the Mandawa Basin

The near complete Upper Jurassic depositional sequence suggests minimal fault activity during the Late Jurassic drift of Madagascar. Likewise, the apparent absence of changes in the sedimentary provenance of Upper Jurassic sandstones further supports the concept that the Late Jurassic was a tranquil tectonic period with sediment deposition largely controlled by sea level changes.

The stable Late Jurassic sedimentation period ended in the Early Cretaceous by renewed tectonic activity in the basin. Short-term shifts in provenance were observed in some Lower Cretaceous sandstones that are situated near to the Matandu and Mbwemkuru lineaments. These sandstones display conspicuously different heavy mineral assemblages, and interpreted be a result of this renewed tectonic phase.

The source-to-sink relations of the early post-rift successions

Provenance analysis of early post-rift formations found that most of the analysed sandstones are characterised by having garnet-dominated heavy mineral assemblages. Subsequently, this signature was interpreted to represent the stable background sedimentation during times of low tectonic activity.

Single-grain analysis of the zircon and garnet populations from garnet-dominated heavy mineral assemblages concluded that the sediments were derived from multiple source

terrane. This multi-source provenance signature was likely a result of extensive sediment mixing during transport by a fluvial system which drained an extensive and heterogeneous catchment. The sediments were delivered into the sea north of the basin, where they were further reworked and mixed with marine sediments by coastal currents and waves before their final deposition in the Mandawa Basin. Arguably this may indicate that a fairly large fluvial system, possibly the precursor to the Rufiji River, was already established by the Late Jurassic.

If the sediments were simply generated and transported from the neighbouring Masasi Spur, a more confined provenance signature would be expected from the U-Pb zircon data, similar to what was observed in the Ruvuma and Mbemkuru river samples (**Paper III**). We would also expect to see a less diverse garnet population, similar to what was observed in some Lower Cretaceous (Nalwehe Formation) from the Mbemkuru River valley (**Paper I**).

No sedimentological evidence (e.g. fluvial deposits) was found south of the Matandu Lineament that would suggest that sediments were shed from the Masasi Spur into the Mandawa Basin during the Jurassic, as discussed in **Paper II**.

Both the provenance and the sedimentological data argued that the sediment contribution from the Masasi Spur was minimal during the Late Jurassic. However, this changed during the Early Cretaceous. Restricted occurrences of Masasi Spur derived sediments have been recognised in some Neocomian Nalwehe Formation sandstones exposed within the Mbemkuru River valley.

Due to rapid burial and early calcite cementation, which is reflected by the high content of well-preserved calcic amphibole and high intergranular volume, the sediments were sheltered from any major post-depositional modification and represent first-cycle sedimentation of Masasi Spur derived sediments, as discussed in **Paper II**. Interestingly, the amphibole-dominated heavy mineral assemblage in these sandstones is remarkably similar to what was obtained from the sediment samples from the modern Mbemkuru and Matandu rivers (**Paper III**). This strong resemblance further supports the idea that the Lower Cretaceous sandstones are lithified first-cycle sediments derived from the Masasi Spur.

Changes in the sandstone composition, as a result of different provenance, are inferred to have taken place in the Early Cretaceous times; first in the Neocomian with the deposition of amphibolitic sediments of the Nalwehe Formation, and later in the Aptian with the deposition of the Makonde Formation.

Another Lower Cretaceous formation is also characterised by a having a different provenance: the Aptian – Albian Makonde Formation. This interpretation is founded on the basis of an abnormally large number of Palaeoproterozoic grains in the zircon age population. The analysed sandstones were also situated nearby the Matandu Lineament, and thus suggest that the shift in provenance was caused by tectonism.

Recognising recycled signatures in the U-Pb data

The catchment area of the fluvial system that carried the main bulk of the sediments delivered to the Mandawa Basin also drained Permo-Triassic Karoo formations. This raises an important issue that needs to be addressed: does the mixed provenance signal reflect sediments sourced from several different source terranes, or does it mainly reflect the ancient source-to-sink systems of the Karoo basins?

The zircon population characteristics for the Rufiji River sediment sample (**Paper III**) reflect a wide catchment of zircon-bearing rocks. However, since the Rufiji drains extensive Permo-Triassic basins, the diverse zircon population may partly be ascribed to recycled Karoo grains. Similar multi-source signatures have been observed in the Mesozoic sandstones (**Paper I**) which may imply that a part of the zircon population was derived from Karoo formations.

A few words on the oncoïd-discovery

This PhD study highlights the importance of detailed studies of both outcrop and rock samples, but also the value of re-examining “established facts” or interpretations. This is exemplified by the new interpretation of the Late Kimmeridgian – Early Tithonian transgressive sequence, the Mitole Limestone Member, which for more than one hundred years has been referred to as oolitic limestone. Because the micro-oncoïds are the same size as ooids (<2 mm) they are impossible to distinguish from each other in the field and consequently were mistakenly interpreted as ooids. Very detailed studies of thin sections have now provided conclusive evidence that the grains were formed biogenically by bacterial and algal activity. By careful examination of the oncoïd grains, e.g. nuclei composition, the nature and stacking of lamina, types of encrusting and oncoïd-forming organisms, and grain shape, it

has been possible to infer sedimentation rates, fluctuations in water depth and energy, and salinities (**Paper II**).

Micro-oncoids were also detected in great abundances in thin sections of the Middle Jurassic Mtumbei Formation in the Northern Mandawa Basin. Here, oncoid-bearing grainstones alternate with oolitic limestones in tidal deposits. A micro-facies analysis of these limestones may give new insights into the first marine transgression after the break-up of Gondwana. We now have strong indications that microbial sedimentation oncoid formation recurring during the early post-rift transgressions during times of active seafloor spreading.

6. Future work

So far, most of the geological surveys in the Mandawa Basin have been carried out by commercial companies that rarely publish their research. This overall state of affairs is clearly unfortunate from a scientific perspective as valuable and unknown subsurface information remains unpublished. It is therefore very welcome when petroleum companies initiate and fund geological research projects with academia, as has been the case with Equinor Tanzania and the Mandawa Basin Project.

From personal experience I can testify that it was both a time consuming and challenging task to comprehend the geology of the Mandawa Basin. Overall, the basin is inadequately understood with regards to most geological disciplines. Furthermore, our actual knowledge of the Mandawa Basin's geology is founded on relatively few studies, confined to a small area of the basin. Many aspects of the basin's geology are yet to be resolved, e.g. basin formation and deformation and sequence stratigraphy. Other topics, e.g. the burial and diagenetic histories, have yet to be presented. Overall, there are few published studies on the sedimentology and compositional character (mineralogy and petrography) of the early post-rift sequence, and none of them are very detailed.

Future tectono-stratigraphic studies should, in addition to further provenance analyses, include in-depth analysis of the early-post rift formations, and the application of various radiometric dating methods to investigate the timing and duration of tectonic episodes.

Stratigraphy and sedimentology

Most of the Mandawa Basin has not been surveyed in detail and future studies should also include more field research. New field investigations of the less-studied areas of the basin are crucial for fully understanding the history of the basin as a whole.

The early post-rift formations in the Mandawa Basin are inadequately understood. Detailed analysis of facies and facies associations, rock composition, petrography and sequence stratigraphy should be a priority.

Stratigraphic control is generally poor on the Middle Jurassic to Lower Cretaceous formations, especially outside the well-studied but relatively small Tendaguru area. These post-rift successions are often found to be barren of age-diagnostic fossils and consequently have been difficult to date.

Renewed study of already available cores ought to establish the thickness, stratigraphic range and lateral distribution of early post-rift successions. Furthermore, the core study should focus on presenting detailed sedimentological logs and analysis of facies and facies associations of each formation, enabling the results to be correlated with geophysical subsurface information already gathered from the basin.

An advantage in studying and analysing cores is that the material has not been exposed to weathering. This makes it more suitable for providing more accurately depositional ages, and better quality for petrographic, mineralogical and provenance studies.

Stratigraphic nomenclature

A formally recognised stratigraphic nomenclature does not exist for the Mandawa Basin, nor indeed for any of the coastal Tanzanian basins. In the literature we see different terms and stratigraphic ranges for the same stratum, which can cause considerable confusion when trying to understand the depositional evolution and history of the basin. A stratigraphic framework has been constructed for the offshore area, but is not available in the public domain (Verreussel et al., 2017). This situation clearly prevents any serious attempt to tie together the offshore and onshore geology of the Mandawa Basin, and causes difficulties in correlation with genetic basins elsewhere along the conjugate East African – Western Madagascan margins (EA-MAD). It is therefore important to disclose the basin stratigraphy, not just for the scientific community studying the evolution East African Margin, but also for assessing the economic and energy aspects, e.g. the discovery of future hydrocarbon reserves.

A formal stratigraphic nomenclature needs to be erected, following the guidelines for stratigraphic nomenclature set by the International Commission on Stratigraphy.

Radiometric studies

One of the main challenges in correlating local events with the EA-MAD evolution is poor age control on strata, which in turn makes it difficult to determine the duration of

stratigraphic breaks and the timing of fault movements. Alternative dating methods can be applied when biostratigraphy does not deliver, such as radiometric dating of fault gauges and authigenic feldspar overgrowths, fission track analysis, and isotopic analysis of Sr in marine limestones.

Radiometric dating of fault gauges by e.g. the $^{40}\text{Ar}/^{39}\text{Ar}$ method provides information about the basin evolution and plate interactions by confining the timing of fault movement and reactivation (van der Pluijm et al., 2001).

Dating authigenic K-feldspar overgrowths in sedimentary rocks, e.g. using Rb–Sr or K–Ar dating methods, should help clarify the burial and uplift history of the basin (Hagen et al., 2001; Faure and Mensing, 2005).

Fission track dating of uranium-bearing minerals (e.g. sphene, zircon and apatite) can disclose the low-temperature thermal history of sedimentary basins and crustal sections. The method can also be applied in provenance studies in areas where thermochronological fission track data exist from neighbouring basement complexes (Faure and Mensing, 2005; Emmel et al., 2014).

The Sr in seawater is a result of mixing of the element's four stable isotopes (^{88}Sr , ^{87}Sr , ^{86}Sr , ^{84}Sr) (Faure and Mensing, 2005). Because ^{87}Sr is mainly derived from land (weathering of felsic rocks) and ^{86}Sr from midocean ridges we can use time-dependent variations in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of marine limestones to infer seafloor spreading rates, uplift and rifting of continents, and global climate change (Faure and Mensing, 2005; McArthur, 2010).

Another advantage of isotopic Sr analysis of marine limestones is that it can be applied in stratigraphic studies (McArthur, 2010). If such a study were performed in the Mandawa Basin the resulting $^{87}\text{Sr}/^{86}\text{Sr}$ ratios could be used in margin-wide correlations to determine or constrain more precise depositional ages for various limestone units along the conjugate East African – Western Madagascan margins.

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Integrated heavy mineral study of Jurassic to Paleogene sandstones in the Mandawa Basin, Tanzania: Sediment provenance and source-to-sink relations.

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Integrated heavy mineral study of Jurassic to Paleogene sandstones in the Mandawa Basin, Tanzania: Sediment provenance and source-to-sink relations

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ABSTRACT

This paper concerns the heavy mineral composition of Jurassic, Cretaceous and Paleogene sedimentary successions in the Mandawa Basin. The nature of the heavy mineral assemblages in 38 samples was investigated to assess changes in sediment provenance through time. Further, the geochemistry of detrital amphiboles and garnets and the detrital zircon populations were used to determine possible sediment source terranes. Based on the heavy mineral compositions the sandstones were grouped into four heavy mineral assemblages: garnet-dominated, amphibole-dominated, epidote-dominated and zircon-dominated. Garnet-dominated sandstones are abundant in most Middle Jurassic to Middle Eocene samples and represent the main sediment input into the Mandawa Basin. Amphibole-dominated sandstones occur in a few Lower Cretaceous samples deposited in close proximity to their sediment source in the Masasi Spur area. A change in provenance is observed in the epidote-dominated sandstones of Middle Eocene and Early Oligocene age. This change coincides with a climatic shift towards a wetter and cooler climate associated with an uplift phase in East Africa. The detrital zircon population in the investigated samples share the same age fractions and are indistinguishable within analytical error. Mineral chemistries and zircon ages imply that the sediments deposited in the Mandawa Basin were mainly derived from several high-grade sources within the Neoproterozoic Mozambique Belt to the west of the basin.

1. Introduction

The prospective East African offshore basins host several giant gas discoveries (Fig. 1). A minimum of 200 Tcf of recoverable gas reserves have been proven in the deep-water area of the Rovuma Delta, Mozambique (Wentworth Resources Ltd., 2015). In Tanzania, gas reserves in Block 2 have a combined in-place volume of c. 23 Tcf (Equinor, 2018). The reservoir sandstones in Tanzania's Block 2 span Albian to Miocene ages, and mainly represent deep water turbidite systems (Siversen et al., 2017). A northwards directed contourite current system has improved the reservoir quality by stripping the turbidite flows (Palermo et al., 2014). The gas in Block 2 and the offshore Rovuma Basin (Fig. 1) is believed to have been sourced from over-mature Jurassic, and/or Permian Karoo shales (Davison and Steel, 2018). The Mandawa Basin (Figs. 1 and 2) has been explored for hydrocarbons on and off since the 1950s (Hudson, 2011). Oil seeps and potential source rocks have been identified but petroleum of commercial interest has yet

to be discovered. However, gas of commercial magnitude was discovered on Songo Songo Island, to the east of North Mandawa (Fig. 2), in 1974. The Mandawa Basin is located between the Rufiji River in the north and the Ruvuma Saddle in the south (Fig. 1). The Ruvuma Saddle is a structural high that separates the Mandawa Basin from the Ruvuma Basin which extends south across the Ruvuma River into Mozambique (Rovuma Basin). Because of its geographical location the Mandawa Basin may reveal clues about the sedimentological development of the coastal basins of both Tanzania and Northern Mozambique.

In this study the mineralogical composition of sandstones in the Mandawa Basin has been used to evaluate sediment source and dispersal from Jurassic to Paleogene times. The objective is to develop our understanding of the sediment source and dispersal system in southern coastal Tanzania. By adopting an integrated approach (using conventional heavy mineral analysis together with mineral chemistry and zircon age data), new information of the source to sink system from the Middle Jurassic–Paleogene is presented. This high resolution sediment

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Fig. 1. The sedimentary basins of southern Tanzania and the location of the Mandawa Basin. The major offshore gas discoveries in Tanzania and Northern Mozambique are also marked. Modified from Pinna et al. (2004) and Davidson and Steel (2018).

provenance study is, to our knowledge, the first of its kind in any of the coastal basins in Tanzania. These results can be used in correlation studies with offshore sandstones in order to map the sand distribution in the coastal and offshore basins.

1.1. Mandawa Basin

The Mandawa Basin, southern coastal Tanzania, is situated between the Rufiji River in the north and the Ruvuma Saddle to the south (Fig. 1) (Hudson, 2011). The Ruvuma Saddle is an east-west trending basement high that separates the Mandawa Basin from the Ruvuma Basin to the south. A major NNW striking border fault separates the Mandawa Basin from the Neoproterozoic Masasi Basement Spur to the west (Fig. 2). The Kandawale sub-basin lies to the west of North Mandawa and is separated from North and Central Mandawa Basin by the E-W Matandu lineament, and the NNW North Mandawa lineament (Fig. 2). The Kandawale sub-basin is characterised by Precambrian basement and Karoo rocks (Hudson, 2011). Three rivers flow from the Masasi Spur across the Mandawa Basin. These follow E-W to ENE-WSW oriented lineaments named after the rivers: Matandu, Mavuji, and Mbemwemkuru.

The geological map of the Mandawa Basin by Hudson (2011) has been adapted in this study (Fig. 2). This map was based upon an unpublished geological map of the Mandawa Basin compiled by Shell in

1990, and revised during mapping the Mandawa Basin from 2006 to 2009. Lineaments were interpreted from digital elevation models and the existences of these structures were later confirmed during structural field mapping and integrated geophysical studies of the Mandawa Basin (Didas, 2016; Matabazi, 2016). The ENE-WSW oriented lineaments appear to some of the oldest structures in the Mandawa Basin created during the initial rifting between East Africa and Madagascar. Both the Matandu and Mbemwemkuru lineaments are interpreted to be transfer zones with strike-slip faults (Didas, 2016).

1.2. Geological background and stratigraphy

The main tectonic events that controlled the evolution of the Mandawa Basin are: 1) Karoo rifting (Permian – Triassic), 2) rifting resulting in the breakup of Gondwana (Upper Triassic – Lower Jurassic), 3) opening of the Somali Basin, and 4) the East African Rift System (Fig. 3) (Mpanda, 1997; Kapilima, 2003; Hudson, 2011; Davidson and Steel, 2018; Macgregor, 2018; Reeves, 2018). Karoo rifting terminated during Upper Triassic times and was responsible for the creation of NNE-SSW trending intracratonic basins in Tanzania (e.g. Selous Basin) (Fig. 1). The fragmentation and separation of Gondwana was initiated during the Upper Jurassic, c. 180 Ma (Geiger et al., 2004; Gaina et al., 2013; Reeves, 2018). Prior to the separation of East and West Gondwana the southern margin of the Selous Basin (Fig. 1) was aligned with the southernmost margin of the Morondava Basin in Madagascar (Reeves, 2018). Sea-floor spreading and the opening of the Somali Basin commenced around 170 Ma, marking the transition from rift to drift (Eagles and König, 2008; Gaina et al., 2013). Contemporaneously with sea-floor spreading in the Western Somali and Mozambique basins, Madagascar drifted south with respect to Africa along the N-S oriented Davie ridge transform zone. Sea-floor spreading between Madagascar and Africa ceased around 120 Ma (Fig. 3) and strike-slip motion between Madagascar and India was initiated (Eagles and König, 2008; Reeves, 2018). Madagascar was from this point on a part of the African plate.

Here we apply the stratigraphic nomenclature of Hudson (2011) summarised in Fig. 3. A formal stratigraphic nomenclature for the Mandawa Basin, or for any of the other coastal basins in Tanzania, does not exist but is now being compiled (Verreussel et al., 2017). The oldest sedimentary formations in the Mandawa Basin are Upper Triassic to Lower Jurassic, syn-rift deposits (Hudson, 2011; Hudson and Nicholas, 2014). These pre-breakup successions belong to the Pindiro group (Fig. 3) and have mainly been encountered in the subsurface. The age of the Karoo formations in the Kandawale sub-basin (Fig. 2) is uncertain. Based on similarities with the Ngerengere Beds further to the north, a Lower Jurassic age has been proposed (Kent et al., 1971).

Fully marine conditions were established in Bajocian times, manifested by marine carbonates in the Middle Jurassic Mtumbei Formation (Figs. 2 and 3) (Kent, 1971; Balduzzi et al., 1992; Hudson, 2011). Shallow marine, mixed siliciclastic and carbonaceous depositional environments persisted in the Mandawa Basin from the Middle Jurassic to Lower Cretaceous. During the Upper Jurassic, sandier facies developed in North Mandawa compared to Central and South Mandawa, where more carbonate sedimentation took place (Hudson, 2011). In North Mandawa fluvio-deltaic deposition of the Kipatimu Formation occurred during the Upper Jurassic (Figs. 2 and 3). The Kipatimu Formation can be traced further east into the Indian Ocean where forms the main reservoir in the Songo Songo gas discovery; there it is of Lower Cretaceous age (Mpanda, 1997). South of the Matandu River (Fig. 2), more carbonaceous and finer grained facies developed compared to North Mandawa (Aitken, 1961; Hudson, 2011). During the time of deposition of the Kipatimu Formation to the north, a lagoonal environment has been suggested to have persisted in the south, with the deposition of the Mbaro Formation (Figs. 2 and 3) (Hudson, 2011). The depositional setting of the Tendaguru Formation (Figs. 2 and 3) was marginal marine comprising lagoon-like, shallow marine environments with widespread

Fig. 2. Stratigraphic map of the Mandawa Basin. Sampled locations are shown by black squares. The prefix TDP indicates core samples. The basin's southern border is not displayed. Modified from Hudson (2011).

tidal flats and low-relief coastal plains (Aberhan et al., 2002). The Upper Jurassic Mitole Formation crops out in the central part of the basin (Figs. 2 and 3) (Hudson, 2011). The Mitole Formation is composed of a lower oolitic limestone member and an upper sandstone member (Figs. 2 and 3) (Hudson, 2011; van Den Brink, 2015). However, neither of these are strictly pure limestone or siliciclastic units as both members have some intercalations of clastic and calcareous material (Aitken, 1961). Lower Cretaceous successions are widespread in

the Mandawa Basin (Fig. 2) and are mainly littoral facies and carbonate reefs. The Nalwehe Formation (Figs. 2 and 3) was deposited unconformably on the Mitole Formation. Like the Mitole Formation, the Nalwehe Formation is composed of a lower limestone member (consisting mainly of carbonate reef deposits) and an upper sandstone member (Figs. 2 and 3) (Aitken, 1961; Hudson, 2011). Both the Tendaguru and Nalwehe formations (Figs. 2 and 3) are unconformably overlain by the Aptian – Albian Kiturika, Kihuluhulu and Makonde

Fig. 3. Lithostratigraphic scheme of the Mandawa Basin adapted from Hudson (2011), with the major East African tectonic events important for the evolution of the Mandawa Basin. Plate reconstructions were made using GPlates. The star marks the approximate position of the Mandawa Basin.

formations (Figs. 2 and 3) (Aberhan et al., 2002; Hudson, 2011). It has been proposed that the Makonde Formation passes laterally into the Kiturika and Kihuluhulu formations (Kent, 1971; Hudson, 2011). The Makonde Formation (Figs. 2 and 3) can be traced over large parts of southern coastal Tanzania and further to the south in the Rovuma Basin, Mozambique, where it is known as the Macomia Formation (Hancox et al., 2002; Smelror et al., 2008). In the Mandawa Basin, the Makonde Formation consists of fluvio-deltatic deposits (Hudson, 2011; Gundersveen, 2014). The Kiturika Formation (Figs. 2 and 3) is a pure limestone succession of mainly reefal facies (Hudson, 2011) and is best exposed in the central part of the basin (Fig. 2). The Kihuluhulu Formation (Figs. 2 and 3) is mainly composed of fine grained sediments (clays and siltstones) with subordinate sandstones beds. An outer-shelf environment has been proposed for the Kihuluhulu formation, and the intercalated sandstones are interpreted to be turbiditic in origin (Hudson, 2011).

The Kilwa Group is made up of the Nangurukuru, Kivinje, Pande and Masoko formations (Fig. 3) (Nicholas et al., 2006). Clay and marl dominated sequences were deposited during this period of increased subsidence along the passive margin in southern coastal Tanzania (Late Cretaceous to Paleogene) (Nicholas et al., 2006). The base of the Kilwa Group was defined as the bounding surface marking the onset of increased subsidence across the shelf and the onset of laterally persistent transgressive clay deposition along the margin (Fig. 3). The newly defined Lindi Formation (upper Albian – Coniacian) has been suggested to belong to the Kilwa Group (Berrocoso et al., 2015) (Fig. 3).

A marked regression occurred during the Masoko Formation (Middle Eocene) (Kent, 1971), which ended in Late Oligocene (Fig. 3). High sedimentation rates were most likely caused by crustal uplift and a climatic shift towards a wetter and cooler climate during the Middle Eocene (Kent et al., 1971; Mpanda, 1997; Said et al., 2015).

1.3. Heavy minerals in sandstones

Heavy minerals are accessory components in most sandstones, the total quantity rarely exceeding more than one percent of the rock (Mange and Maurer, 1992). Despite this, heavy minerals may give important clues on possible sediment sources since some of these minerals have restricted parageneses and are diagnostic for specific source lithologies. Stratigraphic changes in heavy mineral distribution can be used to illustrate variations in sediment provenance. The mineralogical composition of sandstones is governed by parent rock composition, and by processes that are operating during the sedimentary cycle. These processes include: weathering of parent rock; mechanical breakdown during transport; weathering during alluvial storage; hydraulic sorting during transport and deposition; dissolution during diagenesis and weathering at outcrop (Morton and Hallsworth, 1999). Different mechanical and chemical stabilities among the heavy minerals may cause significant bias in stable minerals relative to unstable phases in most sedimentary formations. Zircon, rutile and tourmaline are regarded as stable in most environments, while apatite and garnet are stable during deep burial but unstable in the presence of percolating acidic groundwater. Epidote, titanite, kyanite and staurolite have intermediate stabilities; amphibole and pyroxene generally have low stabilities (Morton and Hallsworth, 1999).

As a way to recognise true changes in provenance signatures (that are not due to selective removal of heavy minerals during the sedimentary cycle), provenance sensitive index ratios can be used (Morton and Hallsworth, 1994). By comparing the relative abundance of mineral pairs that have similar behaviour during transport and burial, a more accurate prediction of source terrain can be achieved, because these ratio values remain relatively unaffected by hydraulic sorting and intrastratal dissolution. The most suitable ratios for this purpose are apatite to tourmaline (ATi), rutile to zircon (RuZi), garnet to zircon (GZi), monazite to zircon (MZi), and chrome spinel to zircon (CZi), since each pair has similar density (the main control on hydrodynamic

fractionation) and all are relatively stable during deep burial. However, apatite and tourmaline have markedly different behaviour in acidic weathering, since apatite is highly unstable and tourmaline is stable. Consequently, a decrease in ATi might imply apatite loss during temporal fluvial storage (Morton and Hallsworth, 1994).

Additional information on sediment source is provided by the geochemical and isotopic compositions within individual minerals or mineral groups. Such single-grain analysis integrated with information provided by the whole heavy mineral assemblage provides more accurate prediction of the source terrane (Mange and Morton, 2007). Mineral groups with a wide range of chemical compositions (e.g. garnet, tourmaline and amphibole) are prime candidates for geochemical analysis in provenance studies. The compositional range in these minerals often reflects the paragenesis of the host rock and the temperature and pressure regimes under which the mineral was formed (Mange and Morton, 2007).

Garnets possess a wide range of chemical compositions dependent upon the temperature and pressure regimes under which the mineral formed, and the initial composition of the protolith (Nandi, 1967; Deer et al., 1982; Mange and Morton, 2007; von Eynatten and Dunkl, 2012). Due to their relatively high stabilities and the abundance of garnet-bearing rocks, garnets are common in most heavy mineral assemblages and frequently used in provenance studies (Mange and Morton, 2007). Several provenance evaluation diagrams have been developed (see Krippner et al., 2014 and references therein). Provenance discrimination based on geochemical compositions alone imposes some difficulties as garnets derived from different sources may have overlapping compositional fields (Krippner et al., 2014; Mange and Morton, 2007; Wright, 1938). The study by Krippner et al. (2014) evaluated some of these discrimination diagrams by comparing chemical compositions of garnets from different host rocks. Their main conclusion was that such discrimination diagrams were only successful for certain types of garnets. In order to get more improved provenance evaluation, Krippner et al. (2014) recommended the application of at least two discrimination diagrams. In this study, the discrimination diagrams of Mange and Morton (2007) and Aubrecht et al. (2009) are used (Fig. 4). These discrimination diagrams utilised here apply straight lines to separate compositional fields. Nature, on the other hand, does not operate along straight lines. The Mange and Morton (2007) diagram (Fig. 4a) is a modification of the diagram proposed by Morton (2004) on the basis of garnet compositions in Scottish and Norwegian river sediments. The Mange and Morton diagram uses pyrope, almandine plus spessartine, and grossular as poles, and the chart is divided into four main compositional fields (A, B, C, and D) representing specific garnet compositions typical for various host rocks (Fig. 4a). Further, Type B garnets are subdivided into Bi (XCa < 10%) and Bii garnets (XCa < 10%). Type C garnets with a high proportion of the pyrope molecule (XMg > 40%) plots in a separate field, Cii. Garnets with high pyrope content (Type Cii) likely originate from mantle-derived rocks. Whereas Type C garnets most likely originate from meta-igneous rocks such as eclogites, granulites and amphibolites, and not from metasedimentary rocks. Further discrimination of these garnets is difficult. Garnets plotting as Type A are likely from high-grade granulite facies metasediments. Garnets in Bi and Bii are probably derived from metasedimentary rocks up to amphibolite facies rather than meta-igneous rocks, but some compositional overlap between meta-igneous amphibolites may occur. Metasedimentary garnets also plot in Bi and cannot clearly be discriminated from felsic to intermediate garnets. Garnets with almandine + spessartine > 97% are likely derived from granites or pegmatites.

The Aubrecht discrimination diagrams (Fig. 4c and d) consist of two ternary diagrams: one with pyrope, almandine and grossular as poles (Fig. 4c) and one with pyrope, almandine and spessartine as poles (Fig. 4d). Garnet compositions can plot in three different classes also denoted as A, B and C. Class A garnets are pyrope-rich types formed under high to ultrahigh pressure conditions. Class B garnets have formed during eclogite to granulite facies metamorphism, and Class C

Fig. 4. Ternary discrimination diagrams for provenance evaluation based on the chemical compositions of detrital garnets. (a) The Mange and Morton diagram (2007), b) Tolosana-Delgado et al. (2018) discrimination diagram for metamorphic garnets, c and d) Discrimination diagrams after Aubrecht et al. (2009) use two ternary diagrams for provenance evaluation. Letters A, B and C denote metamorphic grade, and numbers 1 to 7 give lithology of parent rock.

garnets are mainly from amphibolite facies metamorphism. Class C can further be subdivided into subgroups: C2 garnets have compositions suggesting formation during a transitional regime from amphibolite to granulite facies metamorphism, and C2₂ are amphibolite facies derived garnets. Blueschists, skarns, serpentinites and igneous derived garnets might also plot in C2. Garnets with high content of spessartine are generally indicative of a magmatic source. Igneous garnets are commonly rich in the spessartine molecule and are often found to possess an intermediate composition in the almandine–spessartine series (Wright, 1938; Deer et al., 1982). Generally, detrital igneous garnets are not as common as metamorphic garnets because most garnets have a metamorphic origin.

A new multivariate discrimination scheme for garnet geochemistry has recently been made available (Tolosana-Delgado et al., 2018). This discrimination scheme uses multivariate statistics in which the compositional nature of garnets is used to give probabilities of a garnet belonging to a specific host rock group: eclogite (A), amphibolite- (B) and granulite (C) facies metamorphic rocks ultramafic (D) and igneous (E). The discrimination scheme by Tolosana-Delgado (2018) has been applied to give some quantitative estimate of the source-rock assemblage (Fig. 4 b).

The amphiboles also display great variation in composition. Amphiboles are unstable and often lost from the heavy mineral assemblage, and consequently are less widely applicable than garnets in provenance studies. Amphiboles occur in a wide range of P-T environments and are common constituents of both igneous and metamorphic rocks, with a chemical composition reflecting both the P-T environment and the chemical composition of the protolith (Deer et al., 1997; Andò et al., 2014). Chemical substitutions in the amphibole crystal lattice during increased metamorphism are well known (Raase,

1974; Deer et al., 1997). The average composition of amphiboles displays a marked enrichment of TiO₂ and a decrease in SiO₂ with increasing metamorphic grade. During increased metamorphism from amphibolite to granulite facies, magnesio-hornblende and tschermakite change into amphiboles with pargasite and hastingsite composition (Deer et al., 1997).

The use of detrital zircons in provenance studies has increased in the recent years as a response to the development of ion probe techniques and laser ablation ICPMS facilities. Zircons incorporate uranium during crystallisation, and minimal amounts of uranium-daughter lead. The uranium to lead ratio in the zircon is consequently governed by the age of the grain, assuming the mineral has remained a closed system after crystallisation. Zircon is a highly resistant mineral to both physical and chemical alteration, and can remain a closed system even during high-grade metamorphic events (Hawkesworth and Kemp, 2006). The robustness of zircon allows it to be well preserved in the sedimentary record even through periods of erosion, and zircon is therefore a common heavy mineral in sedimentary formations. In provenance studies the detrital zircon age distribution is compared to potential source areas. However, since zircon mainly forms in granitic melts, some sources (e.g. basalts) will not be well recorded. The mineral's high durability allows for zircons to survive multiple episodes of sedimentary recycling. This is also a disadvantage for the use of zircon in provenance studies, since in such cases detrital zircon can only be traced back to its proto-source rather than the true sediment source that supplied sediments to the formation analysed. Several erosion-transport-deposition cycles may homogenise the material from different protoliths over long periods of time and considerable transport distances. In these cases, the data generally reflect information regarding sedimentary processes and not source-to-sink relations.

2. Sampling and methods

Samples were collected during fieldwork in the Mandawa Basin in 2013, 2014 and 2015. The heavy minerals from 38 sandstone samples, both from outcrops and TDP wells (Tanzania Drilling Project) have been studied (Fig. 2).

2.1. Conventional heavy mineral analysis

The non-opaque heavy minerals from the 63–125 μm fraction from 38 sandstone samples have been analysed. Samples were disaggregated and the heavy minerals separated from the light minerals using bromoform heavy liquid (2.8 gm/cc). The heavy minerals were identified by optical microscopy, and heavy mineral proportions were determined by counting 200 non-opaque detrital grains using the ribbon method (Galehouse, 1971). Heavy mineral ratios (ATi, GZi, RuZi, MZi, CZi) were determined on the basis of separate counts for each mineral pair following the procedure of Morton and Hallsworth (1994). Minerals that were not present in the basic 200 grain count but were observed in the subsequent counting process to determine the provenance sensitive index ratios (ATi, GZi, etc) are present in abundances less than 0.5%.

2.2. Geochemical composition of amphibole and garnet

Samples for further analysis were chosen based on the results from conventional heavy mineral analysis. Garnet and amphibole grains were handpicked from the heavy mineral separates, mounted in epoxy, and analysed by electron microprobe at the Department of Geosciences, University of Oslo (UiO), on a Cameca SX100 instrument fitted with 5 wavelength-dispersive (WDS) spectrometers and a Bruker SDD EDS. An accelerating voltage of 15 kV, beam current of 15 nA and a focused electron beam were used. Counting time was 10 s on peak (and 5 s on each of the 2 background positions). Calibration standards and X-ray lines used were wollastonite (Si K α , Ca K α), Al₂O₃ (Al K α), pyrophanite (Ti K α , Mn K α), Fe metal (Fe K α), MgO (Mg K α), orthoclase (K K α), albite (Na K α) and Cr₂O₃ (Cr K α). Matrix corrections were done according to the PAP procedure (Pouchou and Pichoir, 1984) implemented in the CAMECA software.

The garnet composition is expressed in terms of the relative abundance of the Mg, Fe, Ca and Mn end-members, and the molar proportions of the garnet end-members were calculated using Locock (2008) Excel spreadsheet for garnet analysis. Garnet compositions were then plotted in the Mange and Morton (2007) and Aubrecht et al. (2009) discrimination diagrams (Fig. 4 a,c,d).

Further, the Cr₂O₃, MgO, FeO, MnO, Al₂O₃ and SiO₂ content (in wt. %) of the garnets were plotted in the Tolosana-Delgado (2018) multivariate discrimination scheme using the program's default prior probabilities. A ternary discrimination diagram was constructed for each sample (Fig. 4 b).

Amphiboles were classified using the Locock (2014) spreadsheet for amphibole classification.

2.3. Detrital zircon U-Pb analysis

Zircons were randomly picked from the heavy mineral separates, mounted in epoxy, and polished. Cathodoluminescence (CL) imaging of the zircons was performed prior to analysis to ensure correct placement of the laser beam during analysis. The CL imaging was done using a SPARK system (Delmic) integrated with Hitachi SU5000 Scanning electron microscope at the Department of Geosciences, UiO. U-Pb analysis was done by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the Department of Geosciences, UiO. A Nu Plasma HR-multi collector mass spectrometer equipped with a Cetac LSX-213 G2+ laser microprobe was used on six samples. The analytical protocols G2+ of Andersen et al. (2009) were followed. One sample was analysed using a Bruker Aurora [Elite] quadrupole mass

spectrometer [equipped with a Cetac LSX-213 G2+ laser microprobe] at the Department of Geosciences, UiO. U-Pb G2+ analyses on the quadrupole instrument follow the analytical G2+ protocols of Andersen et al. (2016). The laser ablation settings were for the Nu Plasma: beam diameter 40 μm (aperture imaging mode), pulse frequency 10 Hz and beam fluence 0.78 J/cm²; and for the Bruker Aurora Elite: beam diameter 40 μm (aperture imaging mode), pulse frequency 10 Hz, beam fluence ~34 J/cm². Data reduction was done using an interactive, in-house Microsoft Excel 2003 spreadsheet. U-Pb standards used during analysis were: GJ-1 (Belousova et al., 2006), 91500 (Wiedenbeck et al., 1995), and A382 (Huhma et al., 2012). Grains with more than $\pm 10\%$ central discordance were discarded. For an analysis with $^{207}\text{Pb}/^{235}\text{U} = x$, $^{206}\text{Pb}/^{238}\text{U} = y$ and $^{207}\text{Pb}/^{206}\text{Pb} = t$, the central discordance (%) was calculated using the equation

$$\text{disc} = 100 \left(\sqrt{\frac{x^2 + y^2}{(e^{\lambda_{235}t} - 1)^2 + (e^{\lambda_{238}t} - 1)^2}} - 1 \right)$$

where λ_{235} and λ_{238} are the decay constants of ^{235}U and ^{238}U , respectively (Kristoffersen et al., 2014). The $^{206}\text{Pb}/^{238}\text{U}$ ages were used if younger than or equal to 1000 Ma, and $^{207}\text{Pb}/^{206}\text{Pb}$ ages if older than 1000 Ma.

2.3.1. Statistical and graphical treatment of detrital zircon data

Kernel density estimate curves (KDEs) and the empirical cumulative distribution function (ECDE) for the detrital zircon age distribution were constructed using detzrcr software package (version 0.2.0) written in R (Andersen et al., 2018). The open access detzrcr is available at <https://CRAN.R-project.org/package=detzrcr>.

KDE provides a simple way to visualise the age frequency distributions in a sample. The drawback of methods based on kernel density estimates is that they do not explicitly consider the uncertainty in distribution patterns caused by the sampling process. A way to correct this is to plot the age distribution patterns in cumulative distribution curves with 95% confidence bands (Andersen et al., 2018). The similarities between detrital zircon age distribution patterns taking the analytical uncertainty into consideration, is visualised by the degree of overlap between confidence bands of sample pairs in the cumulative distribution curve. The degree of overlap (O) is defined as the combined lengths of intervals along the cumulative fraction axis within which the 95% simultaneous confidence bands around a pair of cumulative distribution curves overlap ($0 < O < 1$). $(1 - O)$ is a measure of the relative difference between the pair of samples (Andersen, 2018). When the $(1 - O)$ value is zero the samples are indistinguishable (Andersen et al., 2016).

3. Results

3.1. Heavy mineral assemblages in the Mandawa Basin sandstones

Based on the heavy mineral content the samples can be subdivided into four heavy mineral assemblages on the basis of the most abundant mineral group in each sample: garnet-dominated, zircon-dominated, amphibole-dominated, and epidote-dominated.

3.1.1. Garnet dominated heavy mineral assemblage (Grt-dominated)

Garnet is the dominant translucent heavy mineral in 22 (58%) of the analysed samples (Table 1), occurring regularly throughout the stratigraphy in Middle Jurassic to Eocene sandstones. ZTR (zircon + tourmaline + rutile) values are low. Provenance sensitive parameters vary throughout the stratigraphy (Table 1). The greatest variations are observed in the ATi (apatite-tourmaline index) parameter, which varies between 0 and 95.5 (Fig. 5 and Table 1). The variations in ATi may reflect differences in the extent of apatite dissolution during meteoric water flushing. GZi is generally high with an average value of 83. Average RuZi (rutile-zircon index) in the Grt-dominated sandstones is

Table 1

Relative abundance of non-opaque detrital heavy minerals in the 63–125 µm fraction (expressed as frequency %), and provenance index values in Mandawa Basin sandstones. The provenance index ratio value for ATi (apatite:tourmaline index) is calculated using 100 x apatite count/(total apatite + tourmaline). The same procedure was followed for the rest of the provenance sensitive index values (Morton and Hallsworth, 1994).

Sample	Formation	Age	An	At	Ap	Ca	Ct	Cr	Cp	Ep	Gh	Gt	Ky	Mo	Op	Ru	Sa
TDP 1/18-1	Pande	Lower Oligocene		R	7.0					56.5		8.5			0.5	R	1.5
TDP 1/20-1	Pande	Lower Oligocene	0.5	R	9.0					44.0	R	27.0	0.5	R		R	R
TDP 2/14-2	Masoko	Middle Eocene		R	7.0					45.0		13.0	1.0	R		1.5	
TDP7B/12-2	Kivinje	Lower Eocene		R	7.0				R	1.0		37.5	4.5	0.5		4.0	
TDP 9/13-1	Nangurukuru	Upper Cretaceous		1.0	15.0					R		50.0	0.5	R		3.0	
N-C 6-14	Nangurukuru	Upper Cretaceous		R	11.5							71.0		R		6.0	
MDW58	Kihuhulu	L. – U. Cretaceous		R	8.5							69.0		R		2.0	
MDW183	Kihuhulu	L. – U. Cretaceous		R	9.0	5.0			1.0	36.5		24.0	4.0	R		R	
N5-27/1-14	Kihuhulu	L. – U. Cretaceous		R	2.0	R						67.5		R		3.5	
TDP40A-17	Kihuhulu	Lower Cretaceous		0.5	5.5							66.5		R		0.5	
WP92-19-14	Kihuhulu	Lower Cretaceous		2.0	8.0							76.0		R		0.5	
MB1-4-13	Makonde	Lower Cretaceous									0.5	3.5		3.0		5.5	
MB1-7-13	Makonde	Lower Cretaceous		1.0							0.5	1.5		5.0		4.0	
WP62-2-14	Makonde	Lower Cretaceous										8.5		R		7.5	
TDP40A-29	Nalwehe	Lower Cretaceous		R	21.0		R			23.0	R	44.5		R		0.5	
WP135-1-14	Nalwehe	Lower Cretaceous		0.5	14.5	31.5		R		30.0		19.5	0.5	R		1.0	R
WP135-4-14	Nalwehe	Lower Cretaceous		R	4.5	8.0			R	14.0		27.0	R	R	R	1.5	R
MKW1-14	Nalwehe	Lower Cretaceous		0.5	12.0	65.5			0.5	2.0		16.5	1.0	0.5	1.0	1.0	
MKW4-14	Nalwehe	Lower Cretaceous			3.0							0.5		R		15.5	
WP126-3-14	Nalwehe	Lower Cretaceous		0.5	16.5					8.0		35.0		R		1.5	
NO9-14	Nalwehe	Lower Cretaceous		0.5	22.0	R				11.5		31.0	R			3.5	R
TGU9-14	Tendaguru	Lower Cretaceous		0.5	20.0							45.5		R		1.5	
TDP40A-32	Mitole	Upper Jurassic		R							0.5	R		R		8.5	
NG1-2-13	Mitole	Upper Jurassic		2.5								2.0		7.0		3.0	
NG1-5-13	Mitole	Upper Jurassic		R						9.0		55.0	R	1.5		3.5	
M13-7	Mitole	Upper Jurassic		R	3.0	80.5			R	1.5		8.0	R	R	R	3.0	
WP252-1-14	Mitole	Upper Jurassic		R	12.5					R		40.0	R	R		4.5	
WP286-1-14	Mitole	Upper Jurassic		R	6.0		R			8.0	R	35.0	1.0	5.0		3.0	
TGU3-14	Tendaguru	Upper Jurassic		R	1.5	R				1.0	R	64.5		R		3.0	
WP92-5-14	Kipatimu	Upper Jurassic		R		R				R				0.5		11.0	
K25-6-2-14	Kipatimu	Upper Jurassic		0.5		R								R		7.5	
MN1-3-13	Kipatimu	Upper Jurassic		0.5										R		1.5	
MN1-6-13	Kipatimu	Upper Jurassic		2.5										58.5		3.5	
MN2-2-13	Kipatimu	Upper Jurassic		1.0	17.0				R	1.5		61.5		1.0		3.0	
NAB4-14	Mtumbi	Middle Jurassic		1.0	10.5	R					R	67.0		0.5		3.0	
NAB1-14	Mtumbi	Middle Jurassic		1.0	8.5					2.0		27.0		R		1.5	
MP2-1-13	Kandawale	? Lower Jurassic		R													
MP2-0-13	Kandawale	Lower Jurassic		R	29.0												

Sample	Sp	St	To	Xe	Zr	ZTR	Count	ATi	total	GZi	total	RuZi	total	MZi	total	CZi	total	HMA
TDP 1/18-1	15.0	R	4.0		7.0	11.0	200	64.0	200	75.5	200	32.9	149	8.3	109	0.0	100	Ep
TDP 1/20-1	17.0	0.5	1.0		0.5	1.5	200	68.5	200	93.5	214	42.9	175	5.7	106	0.0	100	Ep
TDP 2/14-2	23.5	1.0	5.0		3.0	9.5	200	55.5	200	83.7	239	37.5	160	0.0	100	0.0	100	Ep
TDP7B/12-2	29.5	2.0	0.5		13.5	18.0	200	88.0	100	70.9	282	23.7	262	2.0	204	0.0	200	Grt
TDP 9/13-1	22.5	3.0	1.0		4.0	8.0	200	83.0	200	93.5	214	35.6	73	2.1	48	0.0	47	Grt
N-C 6-14		R	1.0		10.5	17.5	200	84.0	100	87.7	228	38.7	163	2.0	102	0.0	100	Grt
MDW58	5.0	0.5	8.5		6.5	17.0	200	59.5	200	91.3	219	21.9	128	1.0	101	0.0	100	Grt
MDW183	16.0	0.5	0.5		3.5	4.0	200	96.2	53	87.8	181	4.3	23	4.3	23	0.0	22	Grt

(continued on next page)

Table 1 (continued)

Sample	Sp	St	To	Xe	Zr	ZTR	Count	ATI	total	GZi	total	RuZi	total	MZi	total	CZi	total	HMA
N5-27/1-14	7.5	R	4.0		15.5	23.0	200	44.0	100	82.6	242	20.3	251	5.2	211	0.0	200	Grt
TDP40A-17	13.5	0.5	2.0		11.0	13.5	200	69.0	100	87.7	228	14.5	117	2.0	102	0.0	100	Grt
WP92-19-14		1.0	0.5		14.0	15.0	200	83.0	100	85.1	235	6.1	213	5.7	212	0.0	200	Grt
MB1-4-13		2.0	14.0	0.5	69.0	88.5	200	0.0	100	3.8	208	8.7	219	6.1	213	0.0	200	Zr
MB1-7-13		2.0	3.0		76.0	83.0	200	0.0	100	1.5	203	4.3	209	12.7	229	0.0	200	Zr
WP62-2-14		4.5	10.0		63.5	81.0	200	0.0	100	9.5	221	11.5	226	5.2	211	0.0	100	Zr
TDP40A-29	20.5	2.5	6.0	0.5	4.5	11.0	200	82.0	200	90.5	221	31.0	145	6.5	107	1.0	101	Grt
WP135-1-14	11.5	2.0	3.0		3.5	9.5	200	83.5	200	87.3	229	39.4	165	3.8	104	0.0	100	Grt
WP135-4-14	9.0		0.5		3.5	5.0	200	95.0	200	88.5	226	17.4	121	2.0	102	2.0	102	Ca
MKW1-14	33.5	R	0.5		3.0	5.0	200	95.0	200	86.6	231	23.1	130	2.0	102	0.0	100	Grt
MKW4-14	7.5				1.5	2.5	200	95.0	100	93.0	215	25.8	97	2.7	74	0.0	72	Ca
WP126-3-14		6.5	55.5		21.0	92.0	200	0.0	200	4.3	209	32.4	296	4.8	210	0.0	200	Zr
NQ9-14	30.0	1.0	3.5		4.5	9.5	200	80.0	200	88.9	225	42.2	173	2.9	103	0.0	100	Grt
TGU9-14	23.0	1.0	6.0		1.5	11.0	200	74.0	200	96.6	207	69.9	186	0.0	56	0.0	56	Grt
TDP40A-32	23.5	0.5	1.5		7.5	10.5	200	88.5	200	83.0	241	18.0	122	2.0	102	0.0	100	Grt
NG1-2-13		1.5	24.5		61.0	94.0	200	0.0	200	1.0	202	11.1	225	5.2	211	0.0	200	Zr
NG1-5-13		3.0	9.0		73.5	85.5	200	0.0	100	2.5	205	3.8	208	8.3	218	0.0	200	Zr
M13-7	12.5	0.5	0.5		17.5	21.5	200	0.0	15	80.0	250	19.0	247	9.9	222	0.0	200	Grt
WP252-1-14	6.5				0.5	0.5	200	99.0	100	86.6	231	15.8	57	4.0	50	0.0	48	Ca
WP286-1-14	22.0	3.0	15.0		4.5	22.5	200	53.5	200	90.9	220	36.7	158	3.8	104	0.0	100	Grt
TGU3-14	12.5	1.0	3.0		28.0	35.5	200	60.0	100	55.8	226	11.1	225	4.3	209	0.0	200	Grt
WP92-5-14	R	R	2.0		35.0	41.5	200	41.0	100	76.5	213	6.5	214	9.1	220	0.0	200	Grt
K25-6-2-14	R		8.0	R	24.5	35.5	200	13.0	100	72.2	277	11.9	227	7.0	215	0.0	200	Grt
MN1-3-13		0.5	33.5		56.5	96.0	200	0.0	200	0.0	200	10.3	223	5.2	211	0.0	200	Zr
MN1-6-13			14.5	0.5	73.0	98.5	200	0.0	200	0.0	200	15.3	234	5.2	211	0.0	200	Zr
MN2-2-13		2.5	52.0		35.5	95.0	200	0.0	200	0.5	201	19.4	248	1.0	202	0.0	200	Zr
NAB4-14	R	R	5.5		16.5	23.5	200	74.5	200	77.2	259	11.9	227	1.5	203	0.0	200	Grt
NAB1-14			4.0		17.0	24.5	200	78.0	200	81.3	246	12.3	228	3.4	207	0.0	200	Grt
MP2-1-13	12.0	R	0.5		8.5	12.0	200	95.5	200	90.9	220	18.7	123	10.7	112	0.0	100	Grt
MP2-0-13	33.0		R		7.5	9.0	200	98.0	200	81.3	246	28.1	139	4.8	105	0.0	100	Grt

An - andalusite, At - anatase, Ap - apatite, Ca - calcic amphibole, Ct - chloritoid, Cp - clinopyroxene, Cr - , Ep - epidote, Gh - garnet, Gt - garnet, Ky - kyanite, Mo - monazite, Op - othopyroxene, Ru - rutile, Sa - sodic amphibole, Sl - sillimanite, Sp - titanite, St - staurolite, To - tourmaline, Xe - xenotime, R - rare (0.5%), Zr - zircon, ZTR - zircon + tourmaline + rutile, ATI: apatite-tourmaline index, GZi: garnet-tourmaline index, RuZi: rutile-zircon index, MZi: monazite-zircon index, CZi: chrome spinel-zircon index, HMA: heavy mineral assemblage.

Fig. 5. Scatter plots of provenance sensitive heavy mineral ratios. Samples from Zr-dominated sandstones are markedly different having very low ATi and GZi values, but RuZi values comparable with most Grt-dominated samples.

24. The Cretaceous samples have slightly higher RuZi than the other samples. Lower Cretaceous (Hauterivian – Valanginian) sample TGU9-14 immediately stands out from the rest as it has the highest RuZi value amongst all the samples analysed (RuZi = 69.9), (Table 1). Sample TGU3-14 of Tithonian age (RuZi = 11.1) lies below TGU9-14, with the two being separated by an unconformity. This six-fold increase in RuZi is strong evidence of a change in sediment source between the Tithonian and Neocomian at the Tendaguru Hill location. This is further supported by a marked increase in GZi from 55.8 in sample TGU3-14 to 96.6 in TGU9-14. No apparent trend is observed from the MZi (monazite-zircon index), which shows great variations from 0 to 10.7 (Table 1).

3.1.2. Calcic amphibole dominated heavy mineral assemblage (Ca-dominated)

Amphibole minerals are rather rare in the Mandawa sandstones, but calcic amphibole is found in great abundance in samples WP252-1-14 (Mitole Formation, Upper Jurassic), and WP135-4 and MKW4-14 (Nalwehe Formation, Lower Cretaceous) (Table 1). These amphibole-rich sandstones are located in the South Mandawa area (Fig. 2), and are highly enriched in heavy minerals. Point counting indicates that these sandstones have a heavy mineral content of up to 8 percent of the total rock volume. Sample WP252-1 (Mitole Formation) was collected from the southern culmination of the Mandawa Dome (Fig. 1) and has the highest amphibole content (80.5% of the translucent heavy minerals) (Table 1). Calcic amphibole occurs in association with garnet, sphene, apatite and epidote, with minor kyanite and staurolite. The provenance sensitive parameters show only minor variations and are characterised by very high ATi and GZi values (Fig. 5 and Table 1). ZTR is less than 4 and is the lowest amongst all samples analysed.

3.1.3. Zircon dominated heavy mineral assemblage (Zr-dominated)

Sandstones with very low heavy mineral diversity, almost entirely composed of the ultra-stable minerals zircon, tourmaline and rutile, are grouped into the Zr-dominated heavy mineral assemblage (Table 1). These Zr-dominated samples occur sporadically in Upper Jurassic and Lower Cretaceous samples and are restricted to fluvial and fluvio-deltaic facies. The ZTR in these sandstones is high, ranging from 81 to 98.5. Zircon has the greatest influence on the ZTR parameter, except for samples WP126-3-14 (Nalwehe Formation) and MN2-2-13 (Kipatimu Formation) where tourmaline is most abundant. All samples display ATi values of 0 and a very low average GZi value of 2.6 (Fig. 5). The RuZi values are within the range of other heavy mineral assemblage groups (Fig. 5) but the Makonde Formation (samples MB1-4-13, MB1-7-13 and WP62-2-14) has slightly lower RuZi values.

3.1.4. Epidote dominated mineral assemblage (Ep-dominated)

Epidote becomes an important mineral amongst the non-opaque heavy minerals in Middle Eocene and Early Oligocene samples from TDP wells 1 and 2 (Fig. 2). Also noteworthy is Cretaceous sample MDW183 (Kihuluhulu Formation) (Fig. 2) which is similarly dominated by epidote and has a similar heavy mineral assemblage to samples from TDP1 and TDP2. Associated common non-opaque heavy mineral species are: garnet, sphene, apatite, zircon and tourmaline. ZTR values are low in all samples (< 7), indicating a low degree of reworking. ATi values range from 55.5 to 64 which are less than the average values in both the Grt- and Ca-dominated assemblages (Fig. 5 and Table 1). The exception is sample MDW183, which has an ATi value of 96.2 (Table 1), but this is based on a relatively low count (only 53 apatites plus tourmalines). Middle Eocene and Early Oligocene samples have high RuZi values (average 37.8), which makes this the highest average value amongst the four heavy mineral assemblages (Fig. 5).

3.2. Garnet geochemistry

The results of the garnet analyses can be viewed in the [supplementary material](#). A summary of the garnet compositions is presented in Table 2. The probabilities of a garnet belonging to a specific host rock group are presented in Table 3. Further, discrimination of metamorphic garnets was achieved by plotting the probabilities of a garnet to be derived from eclogite (A), amphibolite (B) or granulite (C) facies host rocks in a ternary diagram (see [Supplementary data](#)). The [Mange and Morton \(2007\)](#) discrimination diagrams are presented in Fig. 6 whilst the [Aubrecht et al. \(2009\)](#) diagrams are placed in the [supplementary material](#).

3.2.1. Garnet compositions in Grt-dominated assemblages

3.2.1.1. *NAB4-14, Mtumbei formation (middle jurassic)*. The 29 analyses from sample NAB4-14 (Mtumbei Formation, Figs. 2 and 3) give the following garnet types (Fig. 6, Table 2): Type C (38%), Type Bii (34.5%), Type A (17.2%), Type Bi (10.3%). The Type C garnets have two main populations of garnets (Table 2): one with almandine-pyropo-grossular, and one with almandine-grossular-pyropo compositions. Type Bii garnets mostly cluster together and have limited chemical variability (Fig. 6). These almandine-grossular-pyropo garnets are common for most of the other analysed samples as well (see below). Type A garnets have almandine-pyropo compositions (Table 2). An amphibolite host-rock is likely origin for most garnets this sample (Table 3).

3.2.1.2. *WP92-5, Kipatimu formation (upper jurassic)*. Based on 56 analyses from WP92-5 (Kipatimu Formation, Figs. 2 and 3) the

Table 2
Summary of garnet compositions in the Mandawia Basin sandstones arranged in order of garnet type. Molecular proportions of endmembers less than 5% has been excluded from the formula.

Sample	HMA	Type A	n	Type Bi	n	Type Bii	n	Type C	n	Type D	n
TDP1	Ep	Alm53Prp34Grs9	1	Alm70Prp12Sps10Grs6	2	Alm60-68Grs15-18Prp10-15Sps < 7	11	Alm51-62Prp18-29Grs12-22Sps < 10	25	Grs50Alm32Adr12	2
n = 45				Alm49Sps42	1			Alm45Grs39Prp11	1		
MKW4-14	Ca	Alm61-72Prp22-35Grs < 7	5			Alm55-67Grs15-26Prp10-18	9	Alm58-63Prp18-19Grs11-19Sps2-10	5		
						Alm48-62Grs12-26Sps10-20Prp4-15	6				
						Alm42-69Grs19-40Prp < 11	5				
n = 31						Alm81Grs14Sps5	1				
NQ9-14	Grt	Alm53Prp43	1	Alm55Sps32	1	Alm49Prp30Grs15Adr5	1	Alm52-60Prp17-31Grs11-18Sps2-8	7		
		Alm61Prp32	2	Alm55Grs28Prp10Sps5	1	Alm55-65Grs18-24Prp3-15Sps1-10	9	Alm51-62Grs20-27Prp12-19	6		
n = 29								Grs48Alm40Adr8	1		
TGU9-14	Grt	Alm61-69Prp24-32	6	Alm63-82Prp7-21Sps < 10Grs < 11	9	Alm56-71Grs14-25Prp5-15Sps2-12	13	Alm49-60Prp16-27Grs10-25Sps2-6	17		
						Alm60-61Grs25-31Prp < 7	3	Alm50Grs35Prp11	1		
n = 50						Alm36Grs36Sps26Prp7	1				
M13-7	Grt	Alm50-57Prp31-44	5	Alm78Prp15Sps3Grs3	2	Alm42-69Grs17-36Prp2-15Sps3-12	11	Alm49-59Prp22-26Grs11-23	7		
		Alm60-63Prp21-28	3	Alm65Sps25Grs8	1	Alm36-56Sps18-38Grs13-21Prp < 10	3	Alm45-60Grs19-24Prp11-18	10		
n = 43						Sps41Grs31Alm19Prp6	1				
TGU3-14	Grt	Alm55-68Prp20-37Grs < 10Sps < 7	11	Alm60-74Prp27Grs < 10	2	Alm42-64Grs13-46Prp3-15Sps3-8Adr1-8	14	Alm40-62Prp18-35Grs10-22	18	Grs76Adr10Alm9Sps5	1
		Prp36Alm34Sps21Grs8	1	Alm50Sps45	1	Alm39-48Sps28-31Grs12-23Prp0-6Adr2-10	7	Alm40-60Grs18-35Prp10-22Sps < 7	8	Type Cii	
n = 68						Alm41-63Grs13-34Sps11-18Prp5-11	5			Prp46Alm37Grs14	1
WP2-5	Grt	Alm58-71Prp20-32Grs1-8Sps < 10	11	Alm61Sps26Prp8Grs4	3	Alm62-64Grs17-23Prp9-13Sps < 6Adr < 5	7	Alm50-63Prp13-26Grs12-26	17		
		Alm51-58Prp33-43Grs < 8	6	Alm65Prp17Sps7Grs7	2	Alm33-57Prp17-33Grs17-22	4	Alm40-51Prp31-40Grs12-19	5		
n = 56						Alm48Grs38Prp6Sps6	1				
NAB	Grt	Alm52-68Prp22-37Grs < 9	5	Alm47Sps38Prp11Grs < 6	2	Alm62-76Grs10-20Prp4-14Sps < 10	6	Alm44-55Prp20-31Grs14-17Sps < 7	6		
n = 29				Alm71Prp15Sps9Grs5	1	Alm41-63Sps15-27Grs10-15Prp10-15	4	Alm48-62Grs19-38Prp10-17	5		
HMA - heavy mineral assemblage, Ep - epidote dominated, Ca - amphibole dominated, Grt - garnet dominated, Alm - almandine, Grs - grossular, Prp - pyrope, Sps - spessartine, Adr - andradite.											

Table 3

Integrated probabilities of a garnet being derived from a specific host rock, determined by multivariate discrimination analysis (Tolosana-Delgado et al., 2018).

Sample	Eclogite (A)	Amphibolite (B)	Granulite (C)	Ultramafic (D)	Igneous (E)
TDP1/18-1	0	0.38	0.58	0	0.04
MKW4-14	0	0.74	0.26	0	0
NQ9-14	0.03	0.67	0.30	0	0
TGU9-14	0	0.54	0.46	0	0
M13-7	0.02	0.58	0.37	0	0.02
TGU3-14	0.04	0.50	0.37	0	0.09
WP92-5	0	0.48	0.48	0	0.04
NAB4-14	0	0.60	0.37	0	0.03

garnets are classified as Type Ci (39.3%), Type A (30.4%), Type Bii (21.4%) and Type Bi (9%) (Fig. 5, Table 2). The Type C garnets have almandine-pyrope-grossular compositions. Two possible populations of Type C garnets are observed (Table 2), one with pyrope contents ranging from 31 to 40% and one with pyrope content less than 30%. Type A garnets have almandine-pyrope compositions. Two main populations are also noted in the Type A group (Table 2): one with high pyrope (Prp₃₃₋₄₃) and one with lower pyrope (Prp₂₀₋₃₂). Garnets plotting as Type Bii have either almandine-grossular or almandine-pyrope-grossular compositions (Table 2).

The results from the multivariate discrimination scheme implies that the both amphibolite and granulite facies host-rocks supplied equal amounts of the garnets in samples WP92-5, with a minor contribution of igneous sources (Table 3).

3.2.1.3. TGU3-14, Tendaguru formation (Tithonian). Most of the 69 detrital garnets from sample TGU3-14 (Tendaguru Formation, Figs. 2 and 3) plot either as Type C (37.7%), Type Bii (37.7%), Type A (17.4%) or Type Bi (4.3%). Type Bi (4.4%), and Types Cii and D are rare (1.4% each) (Fig. 6 and Table 2). Most Type C garnets have almandine-pyrope-grossular compositions, with a smaller group of garnets having almandine-grossular-pyrope compositions (Table 2). Type Bii garnets are chemically diverse with three main groups observed (Table 2).

Half of the garnet population is likely derived from amphibolite facies host-rock, whereas granulite facies and igneous sources where responsible for 37% and 9% of the population, respectively. A few garnet grains were likely derived from eclogites (Table 3).

3.2.1.4. M13-7, Mitole formation (Tithonian). 43 detrital garnets from sample M13-7 (Mitole Formation, Figs. 2 and 3) have been analysed and give the following classification (Fig. 6): Type C (39.5%), Type Bii (34.9%), Type A (18.6%) and Type Bi (7%). Type C garnets are similar to those in sample TGU3-14 and can be divided into two populations (Table 2). Type Bii garnets have similar garnet compositions to TGU3-14 with the exception of one rare spessartine-rich garnet (Sps₄₁Grs₃₁Alm₁₉Prp₆). Type A garnets are similar to those from samples WP92-5 and TGU3-14 both having a Type A population with high pyrope content (Table 2 and Fig. 6).

From Table 3, an amphibolitic host rock is likely the source for more than half of the garnet population. A granulite source is likely for about 37% of the garnets with some contribution from eclogites and igneous sources. The results are similar to sample TGU3-14.

3.2.1.5. TGU9-14, Tendaguru formation (Valanginian – Hauterivian). 50 detrital garnet grains were analysed from sample TGU9-14 (Tendaguru Formation, Figs. 2 and 3). The garnet population is characterised by a larger contribution of Type Bi garnets (18%) and fewer Type A garnets (12%) compared to sample TGU3-14 (Fig. 6). Type Bii garnets (34%) have almandine-grossular compositions similar to those in TGU3-14. Almandine-spessartine-grossular species seen in TGU3-14 are not observed in TGU9-14 (Table 2). Type C garnets (36%) are mainly of one population, similar to the main population observed in TGU3-14, but with less pyrope. Type Bi garnets are almandine-rich species (Table 2).

The multivariate discrimination analysis suggests that garnets in sample TGU9-14 are sourced exclusively from metamorphic host rocks (amphibolites and granulites) (Table 3).

3.2.1.6. NQ9-14, Nalwehe formation (Hauterivian – Barremian). The chemical compositions of 29 garnets in sample NQ9-14 (Nalwehe Formation, Figs. 2 and 3) demonstrate the following types: Type Ci (50%), Bii (33.3%), Type A (10%) and Type Bi (6.7%) (Fig. 6 and Table 2). Type C garnets can be divided into are two populations, as in other samples such as TGU3-14 and M13-7 (Table 2). Type Bii garnets have mainly almandine-grossular compositions, Type A garnets are almandine-pyrope species (Table 2).

The main host-rock amphibolite-facies rocks (67%) whereas granulite facies constitute about 30% of the garnet population (Table 3). Eclogite-facies host-rocks are responsible for 4% of the population.

3.2.2. Garnet compositions in Ca-dominated assemblages

3.2.2.1. MKW4-14 – Nalwehe formation (Lower Cretaceous). The 31 garnets analysed of sample MKW4-14 (Nalwehe Formation, Figs. 2 and 3) show less diversity compared to Grt-dominated sandstone samples (Fig. 6, Table 2). Type Bii garnets are dominant (67.8%) displaying great variations in chemical composition (Fig. 6). These garnets have mainly two compositions: almandine-grossular-spessartine and almandine-grossular-pyrope, with the latter being most abundant (Table 2). The remaining garnet population is classified as Type A and C garnets (Fig. 6). Both Type A and Type C garnets have almandine-pyrope compositions similar to Type A and Type C garnets in other analysed samples (Table 2).

Multivariate discrimination analysis indicates that 74% of the garnet population is derived from amphibolite host-rocks, the remaining portion is derived from granulite facies host-rocks (Table 3).

3.2.3. Garnet compositions in Ep-dominated assemblages

3.2.3.1. TDP1/18-1 – Pande formation (Oligocene). The geochemistry of 45 garnets has been determined for sample TDP1/18-1 (Pande Formation, Figs. 2 and 3). Type C garnets are the most abundant type (55.6%), Type Bii is second most common (31.1%), while Type A (2.2%) and Type D (4.4%) are rare (Fig. 6). 80% of the garnets in TDP1 cluster together in an area spanning the upper parts of Bii and lower part of field C (Fig. 6). Both Type Bii and Type C garnets show little chemical variation (Table 2).

The majority of the garnets in sample TDP1/18-1 were likely sourced from a granulite host-rock, and that the remaining portion from amphibolite (38%) and igneous (0.4%) host-rocks (Table 3).

3.3. Amphibole geochemistry

Pargasite and magnesio-hornblende are the two most common amphibole species in the three analysed samples (Fig. 7a). Highest amphibole diversity is found in sample WP252-1 (Fig. 7a). All grains are classified as calcic amphibole with the exception of one Na-Ca amphibole in sample WP252-1 (Fig. 7a). The lowest amphibole diversity was observed in sample MKW4-14, where 90% of the grains are

Fig. 6. Garnet compositions plotted in the [Mange and Morton \(2007\)](#) provenance discrimination diagram.

Fig. 7. Various plots from the chemical compositions of amphiboles in sample WP252-1, MKW4-14 and WP135-4. (a) Pie charts displaying the different types of amphibole in the analysed samples. (b) Calcic amphibole compositions plotted in the calcic amphibole classification diagram of Hawthorne et al. (2012) (apfu - atom per formula unit). The amphiboles in the analysed samples have comparable compositions and diversity. In addition amphiboles from the Masasi basement Spur, Fig. 2 (sample AA14-20, red dots) has been plotted for comparison (see discussion). (c) Scatter plot of the weight percentages of SiO₂ and TiO₂ from the chemical analysis by electron microprobe. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 8. Age fractions from the zircon populations in seven samples plotted as histograms with Kernel density estimate curves. n = concordant analysis, numbers in brackets are the total numbers of grains analysed.

Fig. 9. (a) Empirical cumulative distribution curve for U-Pb ages (unbroken lines) displayed together with confidence bands (broken lines). All samples except from MB1-4-13 have similar cumulative distribution curves but overlapping confidence bands suggest that all samples are indistinguishable within analytical error. (b) Similarities and differences in detrital zircon ages among the analysed samples visualised by the overlap parameter *O*. Green pairs represent samples that are fully indistinguishable, white squares have confidence intervals that overlap more than 98% of the domain. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

classified as magnesio-hornblende and pargasite (Fig. 7a). Sample WP135-4 is strongly dominated by magnesio-hornblende and magnesio-ferri-hornblende (Fig. 7a). When $\text{Na} + \text{K} + 2\text{Ca}$ (A position in chemical formula) are plotted against $\text{Al} + \text{Fe}^{3+} + 2\text{Ti}$ (C position in chemical formula) (Fig. 7b), the similarities between the amphiboles in the three samples appear more clear. All samples plot mainly within the same area. The TiO_2 content vs. SiO_2 in these samples has also been plotted (Fig. 7c). All samples have amphiboles with similar TiO_2 which lies in the range of 0.24–2.3 wt%.

3.4. Detrital zircon ages

The detrital zircon populations of seven samples (Fig. 8) consist of comparable aged zircons. The zircon populations in these samples contain similar age fractions with common peaks occurring at 2000–1800 Ma, 1000 Ma, 800 Ma, 700–500 Ma, and 300–200 Ma (Fig. 8). Only a few Archean grains have been detected. The oldest grain is dated to be 2806 ± 31 Ma. The youngest zircon has a U-Pb age of 196 ± 2 Ma. The zircon population is dominated by Neoproterozoic and Early Neoproterozoic to Late Mesoproterozoic age fractions (Fig. 8). The empirical (cumulative) distribution function of the data set has also been constructed as a function of zircon age with the 95% confidence limits (dashed lines) (Fig. 9a). All the samples have similar cumulative distribution patterns with overlapping confidence bands, and with one exception are indistinguishable from each other within sampling and analytical uncertainties. The exception is MB1-4-13 (Makonde Formation, Figs. 2, 3 and 8), which displays a greater contribution of Palaeoproterozoic zircons (2000–1850 Ma) compared with the other samples. Further, the degree of similarity between two age distributions can be quantified by the *I*–*O* test (Fig. 9b). Palaeoproterozoic zircons are absent in sample M13-7 (Mitole Formation, Figs. 2 and 3). The (1–*O*) values for the detrital zircons in the analysed

Fig. 10. Various garnet compositions from literature (Tanzania and northern Mozambique) plotted in the Mange and Morton (2007) garnet discrimination chart. References are listed in the text.

Fig. 11. Possible source-to-sink relations (Upper Jurassic). Modified from Pinna et al. (2004) and Engvik and Bingen (2016). The position of the Assawa and Utete-Tagalala lineaments are from Mpanda (1997).

sandstones from the Mandawa Basin are all O except for the MB1-4-13 and M13-7 pair. Their value is 0.02 which means that their confidence intervals still overlap more than 98% of the domain of FE(t). This implies that the samples cannot be distinguished from each other.

4. Discussion

4.1. Heavy mineral assemblages and provenance signatures

Samples with a Grt-dominated heavy mineral assemblage dominate the samples ranging in age from Middle Jurassic to Lower Eocene. Differences in abundances of other minerals such as apatite, sphene and epidote can probably be ascribed to variations in burial depths, degree of diagenesis, and weathering across the basin, rather than provenance (Morton and Hallsworth, 1999). The ATi parameter (Table 1) is low in Upper Jurassic samples, indicating possible apatite dissolution during weathering (Morton and Johnsson, 1993; Morton and Hallsworth, 1999). The other index parameters do not show any stratigraphic variations that would imply any major change in provenance of the Grt-dominated sandstones (Table 1).

Short term breaks in background deposition of garnet-rich sand are reflected in the successions with different heavy mineral assemblages (e.g. epidote- and amphibole-dominated heavy mineral assemblages). Amphibole-dominated heavy mineral assemblages (as observed in samples MKW4-14, WP135-4, WP252-1), suggests a change in provenance based on the heavy mineral content, provenance sensitive parameters and garnet geochemistry (Tables 1 and 2, Fig. 6). ATi is very high and indicates sediment deposition with little or no secondary modifications of the heavy mineral assemblage, which is consistent with the high amphibole content. High GZi values are implying a large contribution from metamorphic sources (Table 1).

The nature of the heavy mineral assemblage and garnet geochemistry in Ep-dominated samples points to a change in provenance during Early to Middle Eocene times (Table 1). The high epidote content in these samples may reflect the young age of these sandstones. With increasing age, the mineral reactions have more time available, slowly removing minerals with low and intermediate stabilities. The Ep-dominated samples were collected from cores of TDP wells 1 and 2, which make them more likely to be preserved than in outcrop samples. The Kilwa Group are known to host exceptionally well preserved microfossils (Bown et al., 2008), which may indicate shallow burial and only modest intrastratal dissolution, favouring epidote preservation. Nevertheless, the distinct difference in garnet geochemistry between the Ep-dominated and Grt-dominated samples indicates that in this case, the change from Grt-to Ep-dominated assemblages is a genuine provenance effect.

The change in provenance signature during the Middle Eocene to Oligocene epoch coincides with a known period of crustal uplift in East Africa (Kent et al., 1971; Mpanda, 1997; Said et al., 2015). The Paleogene strata in offshore Mozambique wells advocate a change towards a cooler and wetter climate during the Middle Eocene to Oligocene uplift (Knezaurek et al., 2017). The combination of uplift and increased fluvial discharge affected the continental drainage patterns and catchment area of the Palaeo-Ruvuma, likely moving the system northwards (Knezaurek et al., 2017). Similar faunal responses to climate change (Pearson et al., 2008), and movement of the Palaeo-Rufiji (Mpanda, 1997) have also been documented elsewhere in Tanzania. Prior to the Middle Eocene uplift, the Palaeo-Rufiji likely followed the Utete-Tagalala lineament (Fig. 11), but as a response to uplift the system may have moved northeast to its present day position (Mpanda, 1997).

Sandstones with heavy mineral assemblages dominated by ultra-stable heavy minerals (Zr-dominated) are observed in Upper Jurassic and Lower Cretaceous fluvial and fluvio-deltaic facies (Tables 1 and 2). Their ultrastable mineralogy indicates a high degree of weathering and possible reworking. Apatite is absent in all Zr-dominated samples, and the very low GZi value suggests that the sediments may have been stored for some time prior to deposition (Morton and Johnsson, 1993; Morton and Hallsworth, 1999). All the Zr-dominated sandstones are composed of comparable heavy minerals and have similar index parameters, and consequently little provenance information can be obtained from the heavy mineral assemblage alone. The RuZi values in Zr-dominated samples are within the range of RuZi values in Grt-dominated samples. This may indicate that Zr-dominated sandstones could be weathered equivalents of Grt-dominated sandstones. Samples from the Makonde Formation have very low RuZi values and imply a slightly different heavy mineral composition than the other Zr-dominated samples (Table 1). A different provenance signature is also observed in the zircon age distribution for the Makonde Formation (Fig. 8).

4.2. Provenance evaluation based on garnet and amphibole compositions

4.2.1. Garnet-dominated sandstones

The chemical compositions of garnets in the Grt-dominated samples suggest mixed parentage. From the garnet discrimination diagrams (Fig. 4) and the results from multivariate discrimination analysis (Table 3), amphibolite and granulite facies metamorphic rocks are the likely sources of these garnets. Several Proterozoic East African orogenic cycles have resulted in abundant terranes of medium to high grade metamorphic rocks in Tanzania (e.g. Appel et al., 1998; Fritz et al., 2005; Johnson et al., 2005; Bingen et al., 2009; Engvik and Bingen, 2016; Boniface and Appel, 2018). Similar garnet types are found throughout the studied succession, thus no evidence of any major change in garnet sources from the Middle Jurassic to Early Eocene.

Type A garnets with high-pyrope content indicate a high-grade metamorphic source, such as granulite or eclogite facies lithologies (Mange and Morton, 2007; Aubrecht et al., 2009). Type A garnets with

lower pyrope content are likely derived from a protolith metamorphosed in the upper amphibolite to granulite transitional regime (Aubrecht et al., 2009).

Type Bi garnets are generally not very common in the samples analysed, with the highest abundance seen in TGU9-14 (18%). The Type Bi garnets in sample TGU9-14 have low spessartine content which implies a metamorphic origin and is consistent with the results obtained from the multivariate discrimination analysis (Table 3). Igneous garnets are commonly spessartine rich, and only a few Type Bi garnets have such compositions (Table 2), indicating that the garnets are mainly of metamorphic origin (Table 3).

Type Bii garnets (Fig. 6) were probably derived from amphibolite facies rocks whereas Type C garnets indicate a high-grade source terrane, such as granulites (Mange and Morton, 2007; Aubrecht et al., 2009). Eclogites could also plot as Type C, depending upon their pyrope content (Kripper et al., 2014). Garnet compositions from eclogites in Tanzania plot as both Type C and Type Cii (Fig. 10). A few of the analysed garnets were likely derived from eclogites but these high-pressure rocks where not important sediment sources for the Mandawa Basin sandstones (Table 3). Type C garnets with lower pyrope contents indicate formation in the upper amphibolite to granulite facies transitional regime (Aubrecht et al., 2009).

Type C garnets are the most common garnet type in the Mandawa Basin sandstones (Fig. 6). However, results from the multivariate discrimination analysis suggest amphibolite facies rocks were the major contributor to the garnets in the Mandawa Basin (Table 3).

Garnet compositions from basement rocks in Tanzania and northern Mozambique have been plotted in the Mange and Morton (2007) discrimination diagram (Fig. 10). Most of these garnets plot as Type C or Type A (Appel et al., 1998; Johnson et al., 2003; Tenczer et al., 2006; Boniface, 2009; Boniface and Schenk, 2012; Engvik and Bingen, 2016; Sommer et al., 2017). The predominance of Type A and Type C garnets may reflect the overrepresentation of published studies on high-grade rocks compared with studies on lower-grade rocks. Garnet compositions in a metapelite (sample AA14-17) and a hornblende-garnet-biotite gneiss (sample AA20-17) from the Masasi Spur (Fig. 2), sampled approximately 10 km to the west of the southern extent of the Mandawa Basin, plot as Type Bii (Mtabazi, 2016).

4.2.2. Amphibole-dominated sandstones

The garnet population in the amphibole-dominated sandstone sample MKW4-14, Nalwehe Formation; Figs. 2 and 3) is characterised by less chemical variability compared with Grt-dominated sandstones. The majority of these garnets (Type Bii, Fig. 6) signal a metasedimentary source, metamorphosed under amphibolite-facies conditions (Morton et al., 2004; Mange and Morton, 2007; Andò et al., 2014). This is in agreement with the results obtained from the multivariate discrimination analysis where the majority of the garnets in sample MKW4-14 are interpreted to be sourced from an amphibolite host-rock. The dominance of Type Bii garnets further implies a single garnet source rather than multiple sources. The compositions of the Type Bii garnets are similar to garnets from metapelite and Hbl-Grt-Bt gneiss in the Masasi Spur area (Figs. 2 and 9) (Mtabazi, 2016).

The TiO₂ content of amphiboles in this study (Fig. 7c) indicates formation under upper amphibolite facies metamorphism (Raase, 1974; Andò et al., 2014). The garnets and amphiboles in sample MKW4-14 display comparable compositions with garnets in the Hbl-Grt-Bt gneiss from the Masasi Spur (Figs. 2 and 9), which was formed under amphibolite facies metamorphism (Mtabazi, 2016). Based on the garnet and amphibole data it is suggested that amphibole-dominated sandstones were primarily sourced from amphibolite-facies metasedimentary rocks in the Masasi Spur area. The close proximity between the amphibole-dominated sandstones and the Masasi Spur suggests sediment transport into the Mandawa Basin by the Mbemkuru River network (Fig. 2). Samples MKW4-14 and WP135-4 (Nalwehe Formation) are of Lower Cretaceous age, while sample WP252-1 (Mitole

Formation) is Lower Cretaceous or uppermost Jurassic age (Fig. 3). The restricted deposition of amphibolitic sandstones is likely to be a response to tectonic activity in the hinterland, perhaps by reactivation of the Mandawa Fault (Fig. 2).

4.2.3. Epidote-dominated sandstones

Samples TDP1/18-1 and MKW4-14 have low garnet diversity compared with Grt-dominated samples (Fig. 6), indicating that the garnets in these samples (TDP1/18-1, MKW4-14) were sourced from fewer localities than the Grt-dominated samples. Most garnets in epidote-dominated sandstones (TDP1/18-1, Pande Formation, Figs. 2 and 3) cluster together in an area spanning the Bii and C composition fields (Fig. 6). These garnets have almandine compositions with variable Mg and Ca contents and could be sourced from the same parent rock based on the gradual increase in Mg at the expense of Ca, and vice versa. This observation consequently suggests most garnets were sourced from one single terrane and that this host-rock was likely formed under granulite facies metamorphism (Table 3).

4.3. Detrital zircon ages

Detrital zircon populations in the Mandawa sandstones have recorded the major Tanzania tectonic events (Fig. 8). Neoproterozoic zircons represent the most abundant age fraction in the analysed samples (Figs. 8 and 9a). The samples share comparable age distributions, indistinguishable from each other within the margins of analytical error. However, the Makonde sandstone is slightly different due to the high contribution of Palaeoproterozoic zircon (Figs. 8 and 9).

The so-called Mozambique Belt is the likely source for Neoproterozoic zircons (Pinna et al., 1993; Muhongo and Lenoir, 1994; Kröner et al., 2003; Bingen et al., 2009; Fritz et al., 2013). In Tanzania the Mozambique Belt (Fig. 11) can be divided into the Western and Eastern Granulites (Fig. 1). The Masasi Spur belongs to the Eastern Granulite, which continues further to the south into Mozambique, where it is known as the Cabo Delgado Nappe Complex (Pinna et al., 1993; Fritz et al., 2013) (Fig. 11). The diachronous nature of high-grade metamorphism of the Masasi Spur is due to the collision of several crustal terranes during the closure of the Mozambique Ocean and final amalgamation of Gondwana (Kröner et al., 2003).

A geochronological study of basement rocks in the Mandawa Basin and the neighbouring Masasi Spur revealed three tectono-stratigraphic events at c. 1056 Ma, 790 Ma and 614–554 Ma (Matabazi, 2016). These ages are consistent with results from other studies in the region (Kröner et al., 2003; Thomas et al., 2014; Mole et al., 2018) and the detrital zircon ages from this study (Figs. 8 and 9a). The Masasi Spur and other Eastern Granulite Tanzanian sources are therefore a likely site of origin for zircons in the Mandawa Basin sandstones.

The Palaeoproterozoic age fraction (2000–1800 Ma) comes from the Ubendian- Usagaran Belt further to the west (Fig. 10). Palaeoproterozoic zircons represent only a minor fraction in most of the samples here. The exception is the Makonde Formation, in which close to one third of the population is composed of Ubendian-Usagaran zircons. If the zircons were supplied directly from the Ubendian- Usagaran Belt, the river involved in sediment transport would have been large for it to allow transportation from the Ubendian-Usagaran Belt to the Mandawa Basin. Further, the river should have drained mainly Palaeoproterozoic rocks with little contribution and mixing of Neoproterozoic sources. This seems rather unlikely as it would imply a sudden and short term shift in the drainage network, and that the exhumation only affected the Ubendian- Usagaran Belt. These zircons were probably not directly sourced from their Palaeoproterozoic source because the Ubendian-Usagaran Belt was separated from the Masasi Spur and the Mandawa Basin by extensive Permo – Triassic Karoo grabens. Recycling of Karoo successions is, perhaps, the most plausible explanation of the high Palaeoproterozoic zircon content in the Makonde Formation. However, as no detrital zircon geochronology has been performed on neighbouring

Karoo successions the hypothesis of recycling cannot be tested.

Palaeozoic and Mesozoic zircons (c.200–300 Ma) are observed in only three samples. There is no obvious Tanzanian source for these young zircons. A few detrital zircons with similar age fraction (300–240 and 190 Ma) have been detected in Upper Jurassic, Lower Cretaceous and Cenozoic beds in the Congo Basin, interpreted as ashfall out from felsic volcanism in western Argentina and Chile (Linol et al., 2016). In South Africa, late Palaeozoic detrital zircons (c. 250–300 Ma) are a major constituent in some Permian, Triassic and Cenozoic successions (Andersen et al., 2016). A South African provenance is therefore a possibility but likely requires aeolian transport.

4.4. Source-to-sink

The garnet and zircon data in Grt-dominated sandstones suggest extensive sediment mixing and homogenisation of material from several sources through long periods of time. Consistency of the zircon age distribution implies that the source terranes providing zircons remained more or less constant from Jurassic to Oligocene. This could indicate that the drainage patterns have remained more or less constant during the same period. The possible reworking of Karoo formations is an alternative explanation. There is limited information regarding the heavy mineral compositions from Karoo successions in Tanzania. Some information can be found on the heavy mineralogy of Karoo successions (e.g. Diekmann and Wopfner, 1996; Nilsen et al., 2001). As no garnet geochemistry and detrital zircon analysis of Karoo successions from the Selous Basin have been published, the role of Karoo successions as sediment source can only be speculated. If Karoo rocks were involved in the sediment supply to the Mandawa Basin, these sequences must have been uplifted to the extent that significant erosion was possible. Erosion and denudation occurred during Triassic (250–200 Ma), Middle Jurassic, Upper Jurassic (c.150 Ma), Early Cretaceous (c.140–120 Ma), Campanian – Paleocene, Late Eocene – Early Oligocene, and during the Miocene (Noble et al., 1997; Van der Beek et al., 1998; Said et al., 2015).

A major part of the modern Rufiji River follows old Karoo lineaments and drains Karoo formations. The Zambezi River (2000 km to the south) is almost 280 Ma old and formed during the final phases of Gondwana assembly (Key et al., 2015). It is proposed that the modern Zambezi follows the same rift valleys as the Karoo river systems, which originally flowed westward (opposite of today) across the interior of the Gondwana continent (Key et al., 2015). Lowering of the base level during the opening of the Indian Ocean initiated erosion by the Zambezi River, exploiting the lines of weakness in the Karoo grabens (Key et al., 2015). The history of the Rufiji drainage system is poorly understood compared to the Zambezi River. Here we suggest that the proto-Rufiji system could have extended back in time to at least Upper Jurassic. The extensive fluvio-deltaic successions of the Kipatimu Formation suggest that a well-established fluvial system was operating in North Mandawa during the Upper Jurassic (Hudson, 2011). During the same time, carbonate sedimentation took place in the South and Central Mandawa Basins, implying limited sediment input from the Masasi Spur area. The Kipatimu sandstone is the main reservoir unit in the Songo Songo gas field (Figs. 1 and 2) implying that deltaic sedimentation must have lasted at least some time into the Lower Cretaceous.

The evolution of the Ruvuma River is, as with the Rufiji River, poorly understood. The Upper Jurassic depositional basins of southern Tanzania and northern Mozambique appear to have been separated by the Ruvuma Saddle (Smelror et al., 2008; Emmel et al., 2014). This implies that a southern sediment source is less likely for the Jurassic and earliest Cretaceous sandstones in the Mandawa Basin. The elevated highland is, however, believed to be the primary source area for the Macomia Formation (equivalent to the Makonde Formation in Tanzania) (Smelror et al., 2008). As this barrier was eroded the sedimentary basin in Tanzania and Mozambique became parts of the great East African basins during the Upper Cretaceous (Smelror et al., 2008).

5. Summary and conclusion

Garnet-dominated Mesozoic sandstones represent the main clastic sediment input into the Mandawa Basin. These sediments were sourced from several uplifted basement terranes and/or Karoo formations, as suggested by heavy mineral distributions, and garnet and zircon data. The general consistency of garnet types and zircon age distribution in Grt-dominated sandstones imply that the transportation system drained more or less the same terranes through most of Middle Jurassic to Eocene. The strongly progradational and extensive fluvio-deltaic Upper Jurassic sequences in northern Mandawa Basin demonstrate that a well-established fluvial system was already operating in the Upper Jurassic. The analysed heavy mineral compositions in both time equivalent and younger successions further south in the basin imply that the fluvial system to the north could have been involved in sediment deposition in the Mandawa Basin from Middle Jurassic to the Lower Cretaceous. The fluvial system eventually moved northwards, probably under some influence of tectonic pulses. As it did so, sedimentation in the Mandawa Basin became slower and finer grained, manifested by the clay-dominated Kilwa Group.

The following source-to-sink scenario for the Mandawa Basin sandstones is proposed and summarised in Fig. 11. The main sediment input was from the north by the palaeo-Rufiji with some contribution directly from the Masasi Spur to the west of the Mandawa Basin (Fig. 10). Periods of tectonic activity resulted in increased sediment supply from the Masasi Spur, transported by smaller rivers running from west to east. The Masasi Spur also probably played an important role in sediment generation as both garnet and zircon data suggest an Eastern Granulite parentage. The W-E draining rivers (e.g. Matandu and Mbemkuru rivers) was likely transporting eroded basement material eastwards and into the Mandawa Basin, in addition to the greater volume provided by the palaeo-Rufiji. Temporal changes in heavy mineral signature are manifested by the influx of amphibole-dominated and epidote-dominated sandstones, probably primarily indicating derivation from the Masasi Spur. As the amphibole-dominated sandstones are confined to a small geographical area within the Mbemkuru river valley (Fig. 2), the sediment routing system may have followed the Mbemkuru lineament where the present-day river flows. Sandstones with a heavy mineralogy dominated by ultrastable species are likely a product of deep weathering of Grt-dominated suits.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jafrearsci.2018.09.009>.

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Supplementary material

Garnet discrimination diagrams after Aubrecht et al. (2009) use two ternary diagrams for provenance evaluation. Letters A, B and C denote metamorphic grade, and numbers 1 to 7 give lithology of parent rock. Garnets formed during HP to UHP conditions plot in discrimination field A, eclogite facies to granulite facies garnets plot in B, and amphibolite facies garnets plot in C. Field C is subdivided into C1 (upper amphibolite facies to granulite transitions regime) and C2 (garnets from mainly amphibolite facies, but also igneous rocks, blueschists, skarns and serpentinites).

TDP1/18-1
Ep-dominated

MKW4-14
Amp-dominated

NQ9-14
Grt-dominated

TGU9-14
Grt-dominated

◆ Type A
 ◆ Type Bi
 ◆ Type Bii
 ◆ Type C
 ◆ Type D

M13-7
Grt-dominated

TGU3-14
Grt-dominated

WP92-5
Grt-dominated

NAB4-14
Grt-dominated

EMP results of garnets

Sample	SiO2	Na2O	K2O	FeO	MnO	Cr2O3	Al2O3	MgO	CaO	TiO2	Total
NAB4-14	38.125	0.003	0.016	25.803	0.605	0.008	20.868	4.282	10.210	0.074	99.993
NAB4-14	37.984	-0.027	-0.001	31.399	0.993	0.024	21.607	5.503	2.989	-0.011	100.462
NAB4-14	38.577	-0.005	-0.009	27.821	1.244	0.041	21.860	8.810	1.647	0.016	100.003
NAB4-14	38.565	0.011	0.012	25.045	1.299	0.002	21.083	6.566	8.180	0.144	100.905
NAB4-14	37.190	0.022	-0.010	31.787	3.953	0.003	21.348	3.731	1.906	0.041	99.972
NAB4-14	36.858	0.013	0.010	33.750	2.267	-0.008	20.507	1.826	4.083	0.039	99.345
NAB4-14	37.451	0.026	0.004	26.854	0.769	0.020	21.496	4.213	8.370	0.189	99.392
NAB4-14	38.230	0.012	0.000	25.724	0.675	0.059	22.044	7.852	5.416	0.054	100.066
NAB4-14	38.045	0.012	0.006	22.766	0.893	0.033	21.454	2.784	13.982	0.075	100.051
NAB4-14	38.308	0.019	-0.006	29.541	0.582	0.052	21.829	8.280	1.257	0.128	99.989
NAB4-14	37.816	0.005	0.009	31.874	0.582	0.033	21.457	6.899	1.381	0.028	100.085
NAB4-14	37.734	-0.009	-0.013	19.998	11.825	0.064	21.300	3.833	6.022	0.035	100.790
NAB4-14	37.245	0.009	-0.023	21.516	16.542	0.000	21.009	2.702	1.618	0.113	100.731
NAB4-14	38.955	0.001	0.000	23.966	1.173	0.088	21.885	7.912	6.516	0.099	100.595
NAB4-14	37.245	0.028	-0.011	28.687	6.578	0.024	20.731	2.371	4.438	0.248	100.340
NAB4-14	38.230	-0.001	-0.002	26.278	3.076	-0.011	21.542	5.112	6.433	0.004	100.662
NAB4-14	38.232	-0.006	-0.003	26.305	1.393	0.003	21.659	3.195	9.930	0.048	100.755
NAB4-14	37.644	-0.011	0.006	31.234	1.736	0.000	21.291	3.578	4.847	-0.017	100.309
NAB4-14	37.048	0.023	-0.005	31.069	3.274	-0.002	20.713	1.073	6.645	0.002	99.841
NAB4-14	37.128	0.056	0.012	28.346	4.160	-0.038	20.995	3.086	5.684	0.015	99.444
NAB4-14	38.498	0.001	0.008	25.721	0.642	0.050	22.048	7.038	6.553	0.040	100.598
NAB4-14	38.931	0.012	0.002	25.790	0.299	0.033	21.976	9.644	3.672	0.029	100.387
NAB4-14	38.883	0.005	-0.004	24.431	1.148	0.108	21.727	7.945	6.371	0.096	100.710
NAB4-14	37.001	0.019	-0.005	29.081	6.680	-0.009	20.849	2.365	4.388	0.227	100.596
NAB4-14	37.605	0.032	-0.003	21.587	16.695	0.040	21.215	2.694	1.709	0.122	101.695
NAB4-14	37.672	0.013	-0.004	20.061	11.730	0.000	21.299	3.937	6.009	0.039	100.755
NAB4-14	38.118	-0.013	0.004	28.831	1.036	0.011	21.541	4.011	7.177	0.080	100.796
NAB4-14	39.857	-0.016	-0.004	0.145	0.154	0.129	22.046	0.031	37.988	0.225	100.557
NAB4-14	37.056	0.003	-0.011	31.019	1.098	0.018	20.870	1.500	7.959	0.179	99.691
NAB4-14	36.939	0.021	0.015	30.735	2.798	0.005	20.852	1.134	7.334	0.021	99.851
WP92-5	39.292	0.009	0.025	24.551	2.186	0.024	22.209	10.272	1.508	0.013	100.089

EMP results of garnets

Sample	SiO2	Na2O	K2O	FeO	MnO	Cr2O3	Al2O3	MgO	CaO	TiO2	Total
WP92-5	38.918	0.020	0.006	24.912	2.300	0.043	22.032	10.238	1.496	0.040	100.003
WP92-5	39.383	0.010	0.002	25.343	0.647	-0.019	22.224	11.310	1.745	0.027	100.671
WP92-5	38.745	0.025	0.011	28.987	0.315	0.036	22.142	8.007	2.647	0.012	100.925
WP92-5	39.044	0.002	0.007	26.570	0.472	0.038	22.044	9.211	3.168	0.024	100.580
WP92-5	38.078	0.035	0.005	31.194	0.648	0.000	21.829	7.124	1.339	0.007	100.259
WP92-5	38.912	0.010	-0.010	24.511	0.754	-0.008	21.925	8.050	6.165	0.043	100.352
WP92-5	39.262	-0.008	0.002	22.689	0.657	-0.016	21.837	8.272	7.354	0.007	100.057
WP92-5	37.939	0.003	0.003	22.341	2.692	-0.023	21.056	1.613	14.197	0.055	99.876
WP92-5	36.903	0.050	-0.021	29.357	7.815	0.000	20.661	2.242	2.091	0.005	99.102
WP92-5	37.824	-0.029	-0.001	28.337	1.178	0.066	21.334	4.772	6.429	0.046	99.955
WP92-5	37.636	0.024	-0.009	28.859	1.537	0.040	21.400	3.239	7.677	0.013	100.415
WP92-5	38.165	0.022	0.001	29.073	0.998	0.052	21.154	4.511	6.643	0.094	100.712
WP92-5	37.843	0.013	0.002	29.832	1.551	0.000	20.976	3.384	7.053	0.005	100.659
WP92-5	37.694	0.006	0.017	28.857	4.652	-0.005	20.637	3.950	4.631	0.081	100.521
WP92-5	37.274	0.014	-0.001	29.227	2.521	-0.028	20.543	2.463	7.578	0.051	99.642
WP92-5	37.556	0.015	0.006	32.876	1.526	-0.011	21.218	5.022	1.959	-0.010	100.156
WP92-5	36.435	0.039	0.007	26.635	7.397	-0.024	20.540	0.307	8.180	0.012	99.528
WP92-5	37.602	-0.007	-0.002	29.787	0.745	0.082	21.458	5.493	4.942	0.021	100.121
WP92-5	38.105	0.011	0.015	25.453	1.857	0.046	21.074	6.437	6.940	0.064	100.002
WP92-5	37.718	0.021	0.012	26.385	3.405	0.003	21.393	5.258	5.916	0.009	100.120
WP92-5	37.504	-0.006	0.001	26.539	3.376	0.029	21.264	5.136	5.966	0.035	99.844
WP92-5	38.850	-0.002	0.013	22.114	0.463	0.021	21.875	8.723	7.807	0.043	99.907
WP92-5	37.923	0.001	0.004	29.342	1.717	0.022	21.528	6.135	3.134	0.020	99.826
WP92-5	37.464	0.035	-0.004	29.107	0.693	0.019	20.949	2.337	8.739	0.054	99.392
WP92-5	38.512	-0.002	-0.006	26.551	0.922	0.056	21.359	5.644	6.676	0.080	99.792
WP92-5	37.635	0.029	-0.004	31.931	1.649	0.065	21.406	5.412	1.882	0.006	100.010
WP92-5	39.871	-0.003	0.002	20.714	0.288	-0.046	22.289	10.568	7.147	0.019	100.849
WP92-5	36.231	0.042	-0.008	25.683	16.147	0.020	19.704	1.255	0.750	0.004	99.828
WP92-5	37.786	0.013	0.016	29.655	1.215	0.002	21.520	7.756	1.783	0.034	99.781
WP92-5	37.659	-0.006	-0.004	30.496	3.197	0.034	21.218	6.045	1.605	0.018	100.260
WP92-5	37.781	0.003	0.005	25.613	1.750	0.018	21.150	3.425	9.976	0.043	99.762

EMP results of garnets

Sample	SiO2	Na2O	K2O	FeO	MnO	Cr2O3	Al2O3	MgO	CaO	TiO2	Total
WP92-5	37.385	-0.009	0.021	32.741	1.211	-0.015	21.370	6.491	1.012	0.042	100.247
WP92-5	37.771	-0.006	-0.003	28.495	1.181	-0.024	21.176	2.805	8.743	0.069	100.207
WP92-5	37.986	-0.004	0.003	29.075	1.498	0.019	21.499	8.109	1.553	0.007	99.745
WP92-5	37.940	0.042	-0.006	27.515	4.372	0.055	21.394	6.893	1.779	0.003	99.987
WP92-5	37.674	0.013	-0.002	29.282	1.173	0.032	21.196	4.364	6.281	0.001	100.013
WP92-5	38.520	0.009	0.014	24.547	1.335	-0.039	21.510	6.448	7.793	0.056	100.192
WP92-5	37.561	0.016	0.004	32.724	1.899	-0.005	20.952	4.560	2.760	0.020	100.491
WP92-5	38.064	0.003	-0.002	25.849	0.722	0.003	21.298	6.108	8.049	0.077	100.172
WP92-5	38.803	-0.015	-0.002	22.354	3.041	0.029	21.682	8.701	5.922	0.063	100.576
WP92-5	37.885	0.001	-0.004	27.821	1.167	0.025	21.496	5.214	6.326	0.058	99.990
WP92-5	37.680	-0.005	0.015	26.508	2.457	0.014	21.224	5.571	6.620	0.047	100.132
WP92-5	37.795	0.007	-0.008	30.730	2.297	-0.020	21.113	5.222	3.037	0.031	100.204
WP92-5	38.136	0.011	-0.001	27.235	0.594	0.036	21.542	8.446	3.494	0.055	99.549
WP92-5	37.245	0.002	-0.001	30.141	2.061	-0.008	20.915	2.873	6.825	0.019	100.072
WP92-5	36.387	0.024	-0.002	29.385	8.595	0.019	20.433	1.980	3.296	0.016	100.131
WP92-5	37.303	0.024	0.007	29.742	1.487	0.094	21.382	4.849	5.239	0.015	100.141
WP92-5	38.345	-0.007	-0.016	24.831	1.049	0.053	21.538	6.858	7.580	0.023	100.252
WP92-5	38.681	-0.001	0.017	28.172	0.320	0.061	21.903	9.825	1.186	-0.002	100.162
WP92-5	37.748	0.016	0.006	27.894	0.604	0.003	21.354	5.209	6.864	0.011	99.708
WP92-5	37.225	0.019	0.001	29.480	1.500	0.025	20.224	2.956	7.960	0.025	99.414
WP92-5	38.110	-0.009	0.002	25.441	1.154	0.024	21.700	5.939	7.638	0.064	100.062
WP92-5	36.712	0.001	-0.005	18.016	14.472	-0.003	19.504	0.841	10.429	0.023	99.990
WP92-5	37.003	0.029	0.003	21.053	11.187	0.041	20.805	2.815	6.867	0.038	99.841
WP92-5	37.240	0.010	-0.006	21.741	8.375	-0.008	20.198	3.333	8.719	0.064	99.665
TGU3-14	38.206	0.013	0.010	27.058	1.745	0.019	21.171	5.415	6.618	0.085	100.341
TGU3-14	37.540	0.009	0.007	20.170	2.727	0.044	20.778	0.858	17.040	0.027	99.201
TGU3-14	37.635	0.017	0.007	20.048	7.083	0.075	20.677	1.299	13.218	0.042	100.100
TGU3-14	37.466	0.001	0.007	24.336	3.404	0.071	21.099	1.802	12.133	0.041	100.360
TGU3-14	37.409	0.005	0.004	30.140	1.222	-0.016	21.100	5.895	4.277	0.024	100.060
TGU3-14	36.233	0.045	-0.014	23.353	12.256	-0.035	19.866	0.333	7.497	0.001	99.533
TGU3-14	37.212	0.028	0.002	25.841	5.135	0.027	20.994	1.805	8.986	0.091	100.120

EMP results of garnets

Sample	SiO2	Na2O	K2O	FeO	MnO	Cr2O3	Al2O3	MgO	CaO	TiO2	Total
TGU3-14	37.432	0.003	-0.002	28.120	0.813	0.013	21.074	5.186	6.911	0.083	99.632
TGU3-14	37.892	0.018	0.004	20.702	0.707	0.065	21.519	5.489	12.869	0.116	99.380
TGU3-14	38.262	0.006	-0.007	23.745	1.279	0.051	21.697	7.870	6.579	0.043	99.526
TGU3-14	37.542	0.010	0.000	29.972	1.932	0.016	21.158	3.842	6.027	0.017	100.516
TGU3-14	37.382	0.026	-0.002	31.339	1.769	0.002	21.235	4.731	3.727	0.033	100.243
TGU3-14	36.855	-0.008	0.003	24.970	4.651	0.022	21.205	1.615	10.877	0.005	100.195
TGU3-14	37.532	0.037	-0.006	26.379	2.716	0.016	20.932	4.099	8.469	0.010	100.185
TGU3-14	37.316	0.020	-0.012	20.882	13.575	-0.037	20.924	1.491	6.650	-0.002	100.807
TGU3-14	38.576	0.002	0.022	21.120	0.372	0.062	21.964	8.909	8.722	0.019	99.767
TGU3-14	37.174	0.024	0.002	27.199	3.016	0.037	21.418	2.996	8.352	0.020	100.236
TGU3-14	37.384	-0.016	0.014	26.548	0.684	0.026	21.481	5.104	8.212	0.094	99.532
TGU3-14	36.909	0.027	-0.002	19.961	13.271	0.013	20.482	1.282	8.241	-0.013	100.169
TGU3-14	37.429	-0.008	-0.002	27.678	1.400	0.018	21.087	4.540	7.722	0.041	99.905
TGU3-14	37.628	0.014	0.014	28.856	1.522	0.000	21.084	3.814	6.893	0.024	99.850
TGU3-14	37.999	-0.026	0.004	26.528	0.702	0.037	21.399	6.296	7.047	0.016	100.002
TGU3-14	37.718	0.023	-0.010	28.553	0.772	0.016	20.854	4.796	7.221	0.072	100.014
TGU3-14	38.289	0.007	0.005	25.815	0.567	0.011	21.535	6.894	6.756	0.033	99.911
TGU3-14	37.905	0.030	0.006	25.468	1.831	0.003	20.915	3.659	10.683	0.046	100.546
TGU3-14	37.111	0.020	0.017	29.173	4.766	-0.022	20.901	2.683	5.235	0.050	99.934
TGU3-14	37.677	0.002	-0.013	27.630	2.538	-0.014	21.224	2.251	9.288	0.067	100.650
TGU3-14	38.498	0.022	0.001	25.228	0.601	0.003	21.943	7.517	6.583	0.080	100.475
TGU3-14	37.444	0.023	-0.001	28.119	1.106	-0.021	20.995	5.023	7.058	0.065	99.810
TGU3-14	37.041	0.037	-0.010	30.544	1.358	-0.025	21.070	2.660	7.659	0.034	100.368
TGU3-14	39.807	0.001	0.016	19.287	0.348	0.070	22.375	12.197	6.154	0.058	100.315
TGU3-14	37.252	0.003	-0.017	28.218	0.630	0.000	21.202	3.797	8.261	0.098	99.446
TGU3-14	37.634	0.022	-0.017	22.965	1.749	-0.032	20.969	2.731	13.650	0.101	99.772
TGU3-14	37.522	0.003	0.008	28.557	0.782	-0.016	21.278	4.888	6.603	0.078	99.702
TGU3-14	37.655	0.010	0.017	29.280	0.928	0.031	21.520	7.270	3.148	0.041	99.899
TGU3-14	37.047	0.015	0.011	28.856	1.618	0.017	21.207	4.461	6.395	0.077	99.703
TGU3-14	37.208	0.001	-0.004	28.009	0.727	0.016	20.888	5.445	6.839	0.079	99.209
TGU3-14	37.054	0.021	0.006	29.689	3.586	-0.008	20.681	2.474	6.529	0.120	100.152

EMP results of garnets

Sample	SiO2	Na2O	K2O	FeO	MnO	Cr2O3	Al2O3	MgO	CaO	TiO2	Total
TGU3-14	36.837	0.015	0.000	28.199	2.558	0.014	19.563	0.948	11.711	0.096	99.942
TGU3-14	36.598	0.016	0.004	29.091	3.254	0.063	20.839	3.211	6.382	0.035	99.494
TGU3-14	37.464	0.001	0.002	27.084	0.509	0.019	21.259	5.163	7.805	0.044	99.352
TGU3-14	37.732	-0.011	0.025	30.675	0.597	0.005	21.547	8.080	1.099	0.001	99.749
TGU3-14	38.158	0.021	0.005	23.971	0.980	0.035	21.433	8.154	6.638	0.039	99.434
TGU3-14	37.524	0.028	0.006	25.601	1.416	0.053	21.134	2.424	12.179	0.096	100.459
TGU3-14	37.561	0.039	0.015	26.189	0.977	0.032	21.688	5.585	7.708	0.052	99.845
TGU3-14	36.419	0.023	0.002	23.566	13.198	0.024	20.074	1.146	5.697	0.044	100.192
TGU3-14	37.375	0.004	-0.012	30.790	2.110	0.008	21.125	3.623	4.999	0.048	100.068
TGU3-14	37.920	0.037	-0.002	22.986	0.811	0.010	21.330	4.163	12.526	0.020	99.802
TGU3-14	37.096	-0.007	0.022	29.769	3.011	-0.003	21.349	5.062	3.465	0.005	99.770
TGU3-14	37.455	0.050	0.005	30.633	2.444	-0.020	21.513	5.555	2.698	-0.019	100.314
TGU3-14	37.452	0.029	0.003	32.182	1.667	0.014	21.659	5.839	1.611	0.012	100.467
TGU3-14	37.219	-0.022	-0.015	15.237	18.692	0.022	20.186	1.108	8.444	0.004	100.875
TGU3-14	37.344	0.015	-0.005	17.828	12.673	0.009	20.236	1.050	10.633	0.031	99.814
TGU3-14	36.695	0.021	-0.020	20.047	11.912	-0.011	18.607	0.102	11.135	0.216	98.702
TGU3-14	37.049	0.000	0.007	20.064	12.404	0.023	18.950	0.109	11.192	0.034	99.832
TGU3-14	37.097	0.051	-0.006	20.678	13.093	0.025	20.039	0.141	8.821	0.028	99.966
TGU3-14	37.060	-0.019	-0.006	25.059	7.833	0.109	20.950	2.074	6.489	-0.019	99.531
TGU3-14	37.495	-0.003	-0.007	30.221	1.521	0.041	21.374	5.237	4.071	0.009	99.958
TGU3-14	38.013	-0.002	-0.014	29.089	1.781	-0.011	21.197	3.915	7.099	0.026	101.093
TGU3-14	38.651	0.010	0.000	26.818	0.355	0.057	22.160	9.475	3.008	0.059	100.593
TGU3-14	37.660	-0.009	0.000	33.849	1.602	0.014	21.583	4.780	1.260	0.013	100.752
TGU3-14	38.621	0.026	-0.002	28.715	1.208	0.022	21.723	7.495	2.721	0.030	100.557
TGU3-14	37.798	0.002	-0.007	29.816	1.144	0.023	21.662	6.541	3.454	0.039	100.472
TGU3-14	35.948	0.031	-0.015	23.879	19.061	0.009	20.241	0.141	0.713	0.043	100.051
TGU3-14	37.838	0.031	0.012	28.922	1.024	0.012	21.542	6.692	3.602	0.028	99.704
TGU3-14	38.240	0.012	0.006	27.824	1.005	0.169	21.603	5.534	6.668	0.079	101.139
TGU3-14	37.451	0.001	-0.001	24.384	2.674	-0.011	21.366	2.328	12.017	0.012	100.221
TGU3-14	39.261	-0.003	-0.002	16.929	9.530	0.005	22.138	9.385	3.732	0.001	100.976
TGU3-14	38.714	0.015	-0.004	27.560	0.788	0.046	21.998	7.803	3.777	0.082	100.779

EMP results of garnets

Sample	SiO2	Na2O	K2O	FeO	MnO	Cr2O3	Al2O3	MgO	CaO	TiO2	Total
TGU3-14	38.420	0.016	-0.009	26.895	1.625	0.023	21.700	6.134	5.759	0.044	100.607
NQ9-14	37.153	0.012	0.002	28.628	3.014	0.017	20.990	2.188	8.360	0.028	100.391
NQ9-14	38.347	0.016	-0.006	25.764	1.601	0.040	21.109	6.759	6.657	0.045	100.331
NQ9-14	38.190	-0.002	-0.009	28.905	0.894	0.069	21.979	8.486	1.780	-0.005	100.287
NQ9-14	37.605	-0.018	-0.002	27.226	3.484	0.032	20.931	4.306	6.771	0.005	100.337
NQ9-14	37.625	0.007	-0.005	25.260	1.093	0.016	21.172	7.415	6.863	0.134	99.579
NQ9-14	36.979	-0.024	-0.011	28.584	1.482	-0.011	20.959	2.681	8.863	0.030	99.531
NQ9-14	37.602	0.000	-0.006	28.215	1.316	0.006	21.118	4.619	7.331	0.042	100.244
NQ9-14	37.156	-0.002	-0.006	26.552	2.046	-0.016	21.053	2.453	10.497	0.055	99.790
NQ9-14	37.588	-0.002	0.014	29.558	2.110	0.030	21.057	3.665	6.580	0.002	100.602
NQ9-14	37.618	0.043	0.000	20.987	0.755	0.023	19.953	0.733	19.537	0.086	99.736
NQ9-14	36.805	0.051	-0.013	22.810	13.105	0.008	20.371	3.098	3.616	0.002	99.852
NQ9-14	37.829	0.000	0.009	29.248	1.204	0.003	21.736	7.818	1.881	0.022	99.750
NQ9-14	36.508	0.022	0.016	25.572	13.705	-0.031	20.724	1.505	2.300	0.004	100.324
NQ9-14	37.061	-0.008	0.007	26.275	1.692	-0.006	21.446	2.998	10.516	0.021	100.001
NQ9-14	36.703	0.009	0.003	27.746	4.398	0.016	20.142	0.766	10.009	0.020	99.812
NQ9-14	37.119	-0.014	0.009	28.579	1.828	-0.003	20.228	4.139	7.472	0.030	99.387
NQ9-14	37.584	0.013	0.004	29.157	0.259	0.054	21.039	3.716	8.100	0.106	100.032
NQ9-14	37.583	-0.007	0.000	25.594	1.376	-0.006	21.302	4.520	9.441	0.068	99.872
NQ9-14	36.552	0.011	-0.008	30.602	1.589	0.016	21.114	2.977	6.714	0.016	99.582
NQ9-14	37.871	0.019	0.002	25.759	1.555	0.003	21.351	4.740	8.730	0.067	100.098
NQ9-14	38.076	0.017	0.010	25.197	0.867	-0.026	20.927	4.868	9.863	0.067	99.867
NQ9-14	38.007	-0.020	0.000	27.430	1.396	-0.029	21.173	3.619	8.627	0.025	100.227
NQ9-14	37.561	0.004	-0.007	28.143	1.840	0.011	21.310	4.395	6.332	0.036	99.626
NQ9-14	37.314	0.021	0.007	29.522	1.125	-0.002	20.732	2.989	7.830	0.083	99.623
NQ9-14	37.013	-0.003	0.022	27.027	3.104	-0.013	20.925	2.367	9.021	0.045	99.508
NQ9-14	38.135	-0.016	-0.010	26.687	0.989	0.040	22.009	7.833	4.380	0.005	100.051
NQ9-14	38.155	-0.002	-0.002	26.930	1.723	0.025	21.566	6.382	5.625	0.005	100.407
NQ9-14	37.438	0.026	0.012	30.577	0.633	0.011	20.854	3.094	7.537	0.033	100.214
NQ9-14	36.970	0.012	0.001	27.321	1.404	0.073	20.413	3.415	9.760	0.087	99.456
NQ9-14	38.751	0.023	-0.014	26.769	0.610	0.076	21.876	11.146	1.147	0.012	100.396

EMP results of garnets

Sample	SiO2	Na2O	K2O	FeO	MnO	Cr2O3	Al2O3	MgO	CaO	TiO2	Total
MKW4-14	38.923	0.005	-0.004	27.691	2.302	0.019	21.610	6.751	3.053	0.021	100.371
MKW4-14	38.226	-0.003	0.010	28.081	0.933	-0.010	21.567	4.905	6.693	0.055	100.457
MKW4-14	37.045	0.023	0.019	34.325	1.946	-0.025	20.054	0.496	5.446	0.024	99.353
MKW4-14	37.623	0.036	0.004	31.520	1.679	0.000	20.823	1.634	7.297	0.010	100.625
MKW4-14	37.873	0.012	0.004	22.506	9.470	-0.027	21.103	0.939	9.432	0.020	101.329
MKW4-14	38.253	0.017	-0.005	26.983	4.524	-0.002	20.733	4.806	4.993	0.016	100.318
MKW4-14	38.234	0.002	-0.015	30.311	1.532	-0.022	21.705	7.508	0.992	0.012	100.259
MKW4-14	38.290	0.008	0.027	31.124	0.881	0.036	21.707	5.909	2.031	0.001	100.013
MKW4-14	38.533	0.030	0.004	25.316	1.021	0.011	21.298	1.562	13.392	0.026	101.192
MKW4-14	38.378	0.020	-0.004	27.493	1.719	0.033	21.183	3.705	8.097	0.060	100.683
MKW4-14	37.250	0.019	0.022	29.091	1.338	-0.008	20.164	0.489	11.183	0.043	99.590
MKW4-14	38.064	0.019	0.009	28.302	1.724	-0.025	20.948	3.309	7.731	0.107	100.188
MKW4-14	38.265	0.016	0.004	28.919	1.347	0.065	21.103	3.573	7.346	0.033	100.671
MKW4-14	38.029	0.035	0.015	27.165	1.974	0.030	21.164	2.489	9.719	0.025	100.645
MKW4-14	38.105	0.041	-0.011	28.693	1.862	-0.003	21.222	4.580	5.917	0.032	100.439
MKW4-14	38.069	0.004	-0.002	28.754	1.437	0.061	21.384	3.882	6.490	0.068	100.148
MKW4-14	37.354	0.071	0.003	23.683	7.570	0.014	20.748	0.716	9.367	0.013	99.538
MKW4-14	37.681	0.028	0.020	22.717	8.306	0.024	21.131	2.798	7.917	0.051	100.673
MKW4-14	38.346	-0.006	0.005	27.358	1.502	-0.002	21.227	3.716	8.245	-0.006	100.386
MKW4-14	37.847	0.043	0.011	27.617	1.205	-0.008	20.806	2.414	9.837	0.086	99.857
MKW4-14	37.445	-0.008	-0.007	26.779	8.263	0.034	20.962	2.415	4.537	-0.012	100.408
MKW4-14	38.248	0.011	0.025	28.068	0.862	0.010	21.540	4.526	7.052	0.005	100.346
MKW4-14	38.050	0.018	0.015	32.838	1.463	-0.006	21.177	5.841	0.710	0.007	100.112
MKW4-14	38.168	0.006	0.016	26.946	4.314	0.005	21.258	3.843	6.327	0.022	100.903
MKW4-14	38.001	-0.005	-0.013	20.280	4.707	0.427	20.994	1.242	15.068	0.008	100.708
MKW4-14	38.003	0.043	0.002	25.818	2.204	-0.024	20.966	2.912	10.116	0.171	100.211
MKW4-14	38.100	-0.006	-0.005	30.396	0.947	-0.016	21.280	4.862	4.841	0.038	100.436
MKW4-14	36.919	0.035	-0.002	28.778	4.961	-0.003	20.710	1.021	7.709	0.007	100.136
MKW4-14	38.153	0.010	0.001	28.990	1.199	0.002	21.606	4.961	5.405	0.008	100.335
MKW4-14	37.848	-0.014	0.018	30.151	2.164	0.016	21.382	3.310	5.389	0.008	100.270
MKW4-14	39.004	0.019	0.004	29.010	0.451	0.048	21.867	9.121	1.144	-0.006	100.662

EMP results of garnets

Sample	SiO2	Na2O	K2O	FeO	MnO	Cr2O3	Al2O3	MgO	CaO	TiO2	Total
M13-7	38.256	0.000	0.012	26.674	1.263	0.011	20.581	3.012	10.830	0.044	100.684
M13-7	38.393	0.009	0.005	27.568	1.046	0.006	21.669	4.283	7.562	0.023	100.564
M13-7	37.449	0.005	0.008	31.755	1.932	0.008	20.505	2.271	6.281	0.079	100.290
M13-7	39.025	0.021	0.010	23.559	0.631	-0.006	21.805	6.258	8.874	0.038	100.213
M13-7	39.552	0.010	-0.002	24.423	0.667	0.067	22.318	11.982	1.290	0.041	100.348
M13-7	38.086	0.032	0.002	27.797	1.651	0.013	21.193	3.802	7.730	0.023	100.329
M13-7	36.285	0.022	0.015	28.305	10.534	-0.069	20.650	0.514	2.830	0.011	99.098
M13-7	38.180	0.021	0.002	22.662	5.410	0.410	20.921	2.963	9.871	0.041	100.479
M13-7	39.395	-0.032	0.013	25.137	0.699	0.051	22.132	11.302	1.398	0.000	100.095
M13-7	37.200	0.016	0.013	35.044	2.178	0.003	20.867	3.179	1.086	0.013	99.598
M13-7	38.438	0.017	0.026	29.339	0.587	0.019	21.538	7.140	2.720	0.002	99.825
M13-7	38.953	0.003	0.003	24.027	0.552	0.008	21.729	4.475	10.757	0.039	100.546
M13-7	38.271	-0.001	0.013	27.019	0.749	-0.022	21.223	4.560	7.986	0.081	99.879
M13-7	38.674	0.005	-0.005	20.697	6.233	0.000	21.496	4.945	8.218	0.020	100.283
M13-7	37.323	0.021	0.008	26.009	8.235	-0.033	20.599	2.339	5.388	0.002	99.891
M13-7	38.479	0.013	0.003	27.163	1.910	-0.027	21.653	9.131	1.194	0.038	99.557
M13-7	37.721	0.010	0.021	27.754	1.491	0.058	21.198	3.885	7.707	-0.001	99.844
M13-7	39.439	-0.021	0.002	23.874	0.619	0.091	22.098	11.601	1.392	0.006	99.101
M13-7	38.484	0.002	0.003	23.445	0.696	0.015	21.546	6.332	8.822	0.069	99.414
M13-7	36.918	-0.008	0.004	31.380	1.770	-0.014	20.575	2.353	6.155	0.034	99.167
M13-7	38.145	-0.009	-0.002	28.221	1.074	0.011	21.631	4.473	7.519	-0.003	101.061
M13-7	37.887	0.004	-0.002	9.355	18.148	0.167	20.827	1.569	12.132	0.066	100.152
M13-7	37.250	0.066	0.002	27.342	3.152	-0.008	20.625	0.556	10.824	0.134	99.942
M13-7	37.216	0.002	-0.001	27.912	2.043	-0.008	21.137	3.457	7.674	0.031	99.464
M13-7	38.280	0.001	-0.003	27.423	1.197	0.021	21.845	6.682	4.419	0.028	99.892
M13-7	37.458	-0.017	-0.004	17.368	16.548	0.043	20.746	2.797	5.874	0.075	100.888
M13-7	38.346	0.033	-0.002	27.050	1.394	0.032	21.698	6.342	5.062	0.011	99.964
M13-7	37.817	0.011	0.013	20.180	4.386	0.037	21.158	2.433	13.898	0.112	100.045
M13-7	37.051	-0.007	-0.002	34.741	0.620	0.034	21.104	4.492	1.464	-0.008	99.489
M13-7	38.913	-0.023	0.003	25.827	0.925	-0.002	21.574	6.646	6.308	0.011	100.181
M13-7	38.148	-0.010	0.008	31.149	1.176	0.006	21.689	6.850	1.223	0.012	100.251

EMP results of garnets

Sample	SiO2	Na2O	K2O	FeO	MnO	Cr2O3	Al2O3	MgO	CaO	TiO2	Total
M13-7	38.124	0.026	0.004	27.982	1.757	0.010	21.290	4.013	7.144	0.059	100.407
M13-7	37.558	-0.019	0.019	28.937	3.825	0.024	20.357	2.024	7.515	-0.007	100.232
M13-7	38.235	0.012	-0.001	26.336	0.680	0.003	21.249	5.940	6.959	0.090	99.502
M13-7	38.374	0.010	0.000	26.670	0.858	0.040	21.496	5.847	6.855	0.038	100.186
M13-7	37.954	0.003	0.001	27.635	2.736	0.011	21.261	3.874	6.811	0.018	100.303
M13-7	37.154	0.027	-0.010	17.602	15.188	0.018	20.645	1.300	8.435	0.016	100.376
M13-7	38.526	-0.036	0.010	27.280	2.310	0.054	21.814	6.511	4.463	0.039	100.971
M13-7	37.266	0.029	0.011	25.674	4.008	-0.025	20.733	3.039	8.657	0.018	99.409
M13-7	37.921	0.009	0.001	30.606	2.254	-0.023	21.176	5.755	1.843	0.009	99.551
M13-7	37.147	0.016	0.002	30.052	1.439	0.006	20.978	2.594	7.293	0.056	99.583
M13-7	37.594	0.032	0.009	29.025	2.923	0.075	20.795	2.697	7.059	0.043	100.253
M13-7	38.887	0.009	0.005	25.498	3.150	0.011	22.106	8.185	3.060	0.008	100.919
TDP1/18-1	38.229	0.037	0.009	21.661	1.512	-0.010	21.521	2.834	14.517	0.194	100.503
TDP1/18-1	37.786	0.006	-0.005	23.632	2.135	0.018	20.456	1.650	14.043	0.088	99.810
TDP1/18-1	38.187	0.007	0.011	27.320	1.607	0.019	21.092	5.417	6.914	0.039	100.613
TDP1/18-1	38.186	0.036	0.009	25.939	0.933	-0.008	21.155	6.798	6.519	0.056	99.623
TDP1/18-1	37.936	0.029	0.009	28.054	2.008	0.011	20.532	4.506	6.661	0.005	99.751
TDP1/18-1	37.841	-0.005	-0.014	28.985	0.655	-0.006	20.764	4.587	7.072	0.034	99.912
TDP1/18-1	37.322	0.024	0.007	30.671	5.682	-0.008	20.965	3.630	1.842	0.005	100.140
TDP1/18-1	37.436	0.024	-0.004	29.652	3.214	-0.005	20.289	2.614	6.701	0.041	99.963
TDP1/18-1	38.022	0.009	-0.006	27.407	1.351	-0.002	21.343	5.561	6.561	0.039	100.287
TDP1/18-1	37.988	-0.026	0.004	29.746	0.903	-0.019	20.763	3.605	7.246	0.002	100.212
TDP1/18-1	38.290	0.024	0.010	26.101	1.825	-0.027	21.255	5.946	6.576	0.017	100.016
TDP1/18-1	38.270	0.017	-0.004	27.608	1.484	0.013	21.655	5.746	5.395	0.022	100.207
TDP1/18-1	38.470	0.005	-0.001	27.511	0.651	0.041	21.868	4.679	7.306	0.056	100.587
TDP1/18-1	38.444	-0.008	0.013	28.003	1.644	0.000	21.456	5.292	5.217	0.026	100.087
TDP1/18-1	37.834	0.028	0.000	25.822	0.567	0.003	20.535	4.864	9.936	0.087	99.676
TDP1/18-1	37.247	0.021	0.012	29.645	1.184	0.022	21.001	4.287	5.524	0.014	98.956
TDP1/18-1	37.884	0.013	-0.018	27.998	0.870	-0.022	21.091	4.859	6.592	0.072	99.338
TDP1/18-1	39.141	-0.021	0.006	24.590	1.039	0.045	21.333	7.438	6.047	0.070	99.686
TDP1/18-1	38.284	-0.008	-0.005	24.570	1.437	-0.021	21.301	7.374	6.194	0.100	99.225

EMP results of garnets

Sample	SiO2	Na2O	K2O	FeO	MnO	Cr2O3	Al2O3	MgO	CaO	TiO2	Total
TDP1/18-1	37.870	-0.006	0.002	17.527	1.758	-0.005	18.364	0.064	23.680	0.089	99.343
TDP1/18-1	38.770	0.022	0.002	25.367	0.669	-0.035	21.055	5.864	8.023	0.068	99.805
TDP1/18-1	38.421	-0.001	0.006	26.338	0.627	0.034	21.060	5.777	8.376	0.031	100.668
TDP1/18-1	38.085	0.026	-0.002	26.430	1.607	0.005	21.126	5.384	7.427	0.068	100.155
TDP1/18-1	37.538	-0.009	0.000	30.132	1.304	0.014	20.881	3.485	6.360	0.036	99.741
TDP1/18-1	38.391	0.030	0.012	18.846	1.273	0.117	19.903	1.415	20.538	0.069	100.594
TDP1/18-1	38.257	0.000	0.016	25.952	1.043	0.024	21.142	6.882	6.202	0.101	99.620
TDP1/18-1	38.555	0.009	-0.003	27.742	0.921	0.071	21.339	6.453	5.016	0.007	100.109
TDP1/18-1	37.849	0.026	0.006	28.023	2.908	0.014	21.193	4.017	6.281	0.058	100.375
TDP1/18-1	37.246	0.001	0.014	30.680	3.222	0.019	21.068	3.072	4.372	0.092	99.785
TDP1/18-1	37.608	-0.007	0.007	27.819	2.226	-0.021	20.862	4.015	6.974	0.007	99.491
TDP1/18-1	38.902	0.011	0.026	25.431	0.606	0.032	21.568	7.609	6.053	0.073	100.311
TDP1/18-1	37.523	0.022	0.010	28.923	3.020	0.025	20.673	3.117	6.441	0.096	99.851
TDP1/18-1	37.363	0.041	-0.004	19.234	12.798	-0.038	20.611	1.210	9.015	0.022	100.252
TDP1/18-1	37.665	0.019	0.010	27.763	2.279	0.010	20.959	4.367	6.970	0.047	100.087
TDP1/18-1	37.899	-0.009	-0.002	30.020	0.817	-0.042	20.943	3.306	7.270	-0.006	100.197
TDP1/18-1	38.679	0.043	0.001	26.286	1.848	0.086	21.078	6.147	6.307	0.037	100.511
TDP1/18-1	37.478	0.016	0.018	33.019	3.287	0.037	20.945	2.442	3.539	0.115	100.896
TDP1/18-1	37.685	0.001	-0.005	29.638	1.703	0.022	20.997	3.876	6.164	0.108	100.188
TDP1/18-1	37.119	0.044	-0.008	28.097	1.692	-0.033	20.396	0.528	11.776	0.064	99.674
TDP1/18-1	37.759	-0.001	-0.004	29.788	1.106	0.006	20.972	3.260	6.875	0.043	99.805
TDP1/18-1	38.275	0.013	0.007	27.577	2.143	-0.022	20.943	4.727	6.601	0.045	100.309
TDP1/18-1	38.299	0.006	0.004	25.996	3.841	-0.013	21.040	4.896	6.753	0.026	100.848
TDP1/18-1	38.595	0.020	0.016	27.186	1.028	0.033	21.233	5.725	6.270	0.060	100.166
TDP1/18-1	35.453	0.061	0.000	22.921	17.367	0.023	19.852	0.692	2.159	0.069	98.597
TDP1/18-1	38.881	-0.004	-0.003	25.954	0.671	0.097	21.500	8.868	4.428	0.063	100.455
TGU9-14	38.463	0.033	0.018	22.972	0.807	0.016	20.999	3.334	12.903	0.056	99.600
TGU9-14	37.721	-0.007	-0.006	27.516	1.038	0.003	20.867	4.411	7.596	0.034	99.173
TGU9-14	37.636	0.045	0.001	33.339	3.713	0.012	21.060	3.580	1.547	0.019	100.952
TGU9-14	38.342	0.006	0.007	30.370	1.046	-0.006	21.199	4.318	5.264	0.058	100.604
TGU9-14	37.504	0.008	0.011	29.274	2.700	-0.011	20.152	2.938	6.886	0.028	99.489

EMP results of garnets

Sample	SiO2	Na2O	K2O	FeO	MnO	Cr2O3	Al2O3	MgO	CaO	TiO2	Total
TGU9-14	37.228	0.015	0.005	26.435	3.842	0.000	19.989	0.174	11.776	0.022	99.486
TGU9-14	37.253	0.012	0.003	30.625	2.195	0.016	20.299	2.297	7.113	0.029	99.841
TGU9-14	37.799	0.022	-0.002	31.325	1.309	0.046	21.377	6.163	1.526	-0.006	99.559
TGU9-14	38.182	-0.019	0.006	28.631	1.706	0.019	21.433	6.223	4.326	0.029	100.536
TGU9-14	38.236	0.008	0.024	26.165	0.772	0.018	21.661	6.379	6.688	0.038	99.986
TGU9-14	37.173	0.034	0.023	28.854	2.344	-0.011	20.341	3.473	7.026	0.028	99.285
TGU9-14	38.382	0.018	0.007	25.446	1.508	0.014	21.510	4.219	9.610	0.245	100.959
TGU9-14	37.929	0.016	0.008	27.192	2.520	-0.025	20.733	3.962	7.550	0.016	99.899
TGU9-14	38.203	-0.002	0.002	21.988	1.713	0.021	21.388	2.330	14.641	0.035	100.319
TGU9-14	37.487	0.013	-0.007	29.677	2.137	0.006	21.001	3.307	6.109	0.013	99.742
TGU9-14	37.764	-0.018	-0.002	28.277	4.518	-0.016	20.968	4.844	3.285	-0.018	99.603
TGU9-14	38.199	-0.012	0.006	26.174	2.295	0.008	20.962	5.508	6.698	0.052	99.891
TGU9-14	38.103	-0.018	-0.004	26.791	5.411	0.041	21.323	4.915	4.101	-0.004	100.659
TGU9-14	37.319	0.048	0.014	27.236	2.641	-0.003	20.518	1.425	10.359	0.172	99.729
TGU9-14	38.570	0.012	0.019	23.333	0.990	0.021	21.377	7.121	7.674	0.021	99.138
TGU9-14	38.095	-0.016	0.008	28.758	1.769	0.011	21.388	7.747	1.180	0.017	98.957
TGU9-14	36.478	0.022	0.004	24.642	14.629	-0.009	20.571	1.215	2.545	0.011	100.107
TGU9-14	38.983	0.021	-0.005	25.525	2.059	-0.032	21.603	7.023	5.291	0.047	100.514
TGU9-14	37.307	0.044	0.009	32.815	0.735	0.026	20.959	2.505	5.407	0.087	99.895
TGU9-14	38.425	-0.006	0.024	27.795	1.042	0.047	21.247	4.818	6.650	0.051	100.094
TGU9-14	38.231	0.015	0.005	26.865	2.664	-0.036	21.272	5.442	6.203	0.032	100.692
TGU9-14	36.783	0.015	0.003	35.706	2.695	-0.002	20.782	2.519	1.359	0.026	99.887
TGU9-14	38.044	0.034	0.019	29.237	1.628	0.025	21.573	7.706	1.211	0.016	99.493
TGU9-14	37.132	0.026	0.001	31.490	6.336	0.031	20.947	3.094	1.343	0.046	100.447
TGU9-14	38.445	0.013	0.020	26.826	0.886	-0.013	21.623	5.687	6.788	-0.002	100.274
TGU9-14	38.298	0.019	0.009	26.770	0.966	0.021	21.244	5.659	7.019	0.032	100.036
TGU9-14	38.191	0.017	-0.002	28.266	1.410	-0.014	21.669	6.066	4.594	0.026	100.223
TGU9-14	37.133	0.035	0.008	31.763	6.386	0.040	20.897	2.915	1.172	0.042	100.389
TGU9-14	37.563	0.012	-0.004	25.463	5.108	-0.016	20.574	1.623	9.426	0.009	99.757
TGU9-14	36.813	0.009	0.003	36.080	2.604	0.003	20.882	2.528	1.216	-0.001	100.137
TGU9-14	37.903	0.013	0.008	26.888	2.728	-0.010	21.180	5.418	5.868	0.009	100.004

EMP results of garnets

Sample	SiO2	Na2O	K2O	FeO	MnO	Cr2O3	Al2O3	MgO	CaO	TiO2	Total
TGU9-14	38.207	-0.009	-0.006	27.755	1.139	0.010	21.336	4.737	6.584	0.046	99.798
TGU9-14	37.288	0.004	-0.002	33.220	0.695	0.033	21.155	2.616	5.524	0.047	100.580
TGU9-14	39.102	0.015	0.020	25.461	1.973	0.041	21.585	7.019	5.219	0.054	100.489
TGU9-14	38.435	0.024	0.006	28.743	1.772	0.016	21.522	8.206	1.157	0.007	99.888
TGU9-14	39.299	0.036	0.000	23.095	0.967	-0.068	21.292	7.185	7.708	0.039	99.553
TGU9-14	37.072	0.018	0.001	30.384	1.520	0.019	20.756	3.099	6.391	0.033	99.293
TGU9-14	37.155	0.015	0.002	32.304	5.363	-0.002	20.867	3.535	1.163	0.012	100.414
TGU9-14	38.911	0.007	0.011	28.720	0.861	0.000	22.082	8.300	1.840	0.018	100.749
TGU9-14	37.460	0.018	-0.006	28.670	3.319	-0.002	20.765	3.716	5.808	0.017	99.763
TGU9-14	37.969	0.014	0.003	29.011	1.968	0.108	21.095	3.728	6.429	0.014	100.339
TGU9-14	37.635	-0.012	-0.010	26.951	2.638	0.014	20.740	2.833	8.689	0.006	99.484
TGU9-14	37.120	0.029	0.029	32.504	1.637	-0.003	20.677	1.848	5.732	0.040	99.611
TGU9-14	37.147	0.038	0.007	28.111	3.712	-0.005	20.838	1.466	9.140	0.022	100.475
TGU9-14	37.904	0.002	0.011	32.183	1.611	0.031	21.225	6.283	0.756	0.014	100.019

EMP results of amphiboles

	WP135	WP135	WP135	WP135	WP135	WP135	WP135	WP135	WP135	WP135	WP135	WP135	WP135	WP135	WP135	WP135	WP135	WP135	WP135	WP135
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	
SiO ₂	42.63	45.41	49.20	42.76	47.20	47.88	46.17	42.02	44.71	43.12	50.31	40.66	42.41	47.36	41.28	43.63	43.29	43.90	46.62	
TiO ₂	0.81	0.61	0.54	1.59	2.00	0.81	0.69	1.19	0.68	0.68	0.62	1.18	0.61	1.36	1.29	1.50	0.74	0.71	0.48	
Al ₂ O ₃	12.81	11.17	7.34	9.68	8.47	8.97	10.81	10.97	12.16	13.69	6.94	11.18	14.28	9.15	10.98	11.23	13.10	11.38	9.60	
Cr ₂ O ₃	0.04	0.01	0.20	0.02	-0.05	0.15	0.01	0.14	0.12	0.03	0.02	-0.01	0.00	0.07	0.00	0.03	0.04	-0.02	0.17	
MnO	0.25	0.25	0.24	0.43	0.28	0.28	0.27	0.40	0.21	0.33	0.14	0.56	0.40	0.16	0.51	0.26	0.26	0.30	0.30	
FeO	16.02	12.26	8.75	16.06	12.60	12.09	12.17	17.23	12.87	16.92	10.18	20.15	17.20	10.46	20.60	14.71	15.71	16.05	11.50	
MgO	10.09	13.99	16.37	11.01	14.32	14.01	13.54	10.07	13.18	9.08	16.03	8.29	8.84	15.58	8.69	11.68	10.48	11.33	14.13	
CaO	10.80	10.28	12.49	11.73	11.60	11.93	11.88	11.32	10.98	11.37	11.82	11.34	11.36	11.68	11.52	11.43	11.14	11.64	12.39	
Na ₂ O	1.83	2.20	0.99	1.58	0.97	1.14	1.28	1.64	1.54	1.35	0.61	1.73	1.50	1.04	1.67	1.45	1.47	1.30	1.04	
K ₂ O	1.15	0.29	0.66	1.36	0.42	0.45	0.27	1.52	0.29	0.60	0.20	1.81	0.50	0.57	1.66	0.76	0.54	0.51	0.93	
Total	96.43	96.49	96.79	96.22	97.81	97.73	97.08	96.48	96.75	97.17	96.86	96.90	97.09	97.42	98.20	96.70	96.75	97.10	97.15	
Si	6.43	6.64	7.10	6.52	6.81	6.92	6.70	6.41	6.51	6.44	7.20	6.29	6.34	6.79	6.28	6.49	6.43	6.49	6.80	
Ti	0.09	0.07	0.06	0.18	0.22	0.09	0.08	0.14	0.07	0.08	0.07	0.14	0.07	0.15	0.15	0.17	0.08	0.08	0.05	
Al	2.28	1.92	1.25	1.74	1.44	1.53	1.85	1.97	2.09	2.41	1.17	2.04	2.52	1.55	1.97	1.97	2.29	1.98	1.65	
Cr	0.00	0.00	0.02	0.00	0.00	0.02	0.00	0.02	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.02	
Mn ²⁺	0.03	0.03	0.03	0.06	0.04	0.04	0.03	0.05	0.03	0.04	0.02	0.07	0.05	0.02	0.07	0.03	0.03	0.04	0.04	
Fe ²⁺	1.82	1.14	0.95	1.82	1.14	1.24	1.14	1.89	1.02	1.92	0.97	2.24	1.81	0.86	2.13	1.49	1.55	1.41	1.17	
Fe ³⁺	0.20	0.36	0.10	0.23	0.38	0.22	0.34	0.30	0.55	0.19	0.25	0.36	0.34	0.40	0.49	0.34	0.41	0.57	0.23	
Mg	2.27	3.05	3.52	2.50	3.08	3.02	2.93	2.29	2.86	2.02	3.42	1.91	1.97	3.33	1.97	2.59	2.32	2.50	3.07	
Ca	1.75	1.61	1.93	1.92	1.79	1.85	1.85	1.85	1.71	1.82	1.81	1.88	1.82	1.80	1.88	1.82	1.77	1.85	1.94	
Na	0.54	0.62	0.28	0.47	0.27	0.32	0.36	0.48	0.43	0.39	0.17	0.52	0.44	0.29	0.49	0.42	0.42	0.37	0.29	
K	0.22	0.06	0.12	0.27	0.08	0.08	0.05	0.30	0.06	0.11	0.04	0.36	0.10	0.10	0.32	0.14	0.10	0.10	0.17	
Total	15.62	15.50	15.36	15.69	15.24	15.31	15.33	15.70	15.34	15.43	15.12	15.81	15.44	15.28	15.75	15.47	15.40	15.39	15.43	
	pargasite	magnesio-hornblende	magnesio-hornblende	pargasite	magnesio-ferric-hornblende	magnesio-hornblende	magnesio-hornblende	pargasite	magnesio-hornblende	magnesio-hornblende	magnesio-hornblende	hastingsite	magnesio-hornblende	magnesio-ferric-hornblende	hastingsite	magnesio-hornblende	magnesio-hornblende	magnesio-ferric-hornblende	magnesio-hornblende	

EMP results of amphiboles

MKW	MKW	MKW	MKW	MKW	MKW	MKW	MKW	MKW	MKW	MKW	MKW	MKW	MKW	MKW	MKW	MKW	MKW	MKW	MKW	MKW	MKW	MKW	MKW	MKW
42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66
40.16	45.34	43.09	39.68	43.15	44.14	43.42	40.25	41.45	43.26	43.81	41.67	45.25	46.11	45.62	42.14	42.48	44.67	50.89	42.62	40.39	48.08	41.28	44.98	43.87
2.16	1.10	1.01	1.11	0.84	1.20	1.21	1.52	2.26	1.49	0.85	0.96	0.65	0.55	0.94	1.41	2.23	1.30	0.24	1.44	0.32	0.47	0.81	0.43	1.00
14.89	9.39	12.28	11.49	13.66	10.65	11.61	12.40	12.85	11.53	12.93	12.10	10.96	8.46	11.15	12.82	11.67	9.16	5.85	12.92	10.54	9.69	14.45	14.40	11.89
0.00	0.04	0.07	0.03	0.07	0.05	0.01	0.02	0.10	0.07	0.06	-0.01	0.07	0.00	0.18	0.03	0.01	0.13	0.11	0.05	-0.03	-0.08	0.00	0.01	0.02
0.09	0.37	0.32	0.66	0.30	0.35	0.31	0.38	0.18	0.33	0.31	0.45	0.30	1.84	0.26	0.30	0.08	0.37	0.33	0.11	0.60	0.33	0.33	0.21	0.39
14.48	17.86	16.58	25.74	14.90	14.57	16.06	19.26	13.48	17.75	13.91	18.00	12.61	14.45	11.44	16.51	15.83	16.41	11.24	10.64	23.85	11.14	16.83	11.68	16.87
10.58	10.44	10.11	4.54	10.76	11.69	10.47	8.60	11.72	9.33	11.39	9.15	13.01	11.89	13.73	9.37	10.50	10.82	15.59	14.03	6.10	14.24	9.41	12.55	9.53
11.77	11.19	11.30	11.08	11.32	11.56	11.29	11.39	11.46	11.54	11.65	11.61	12.34	11.66	11.91	11.46	11.33	11.89	12.11	11.87	11.17	11.86	11.56	11.39	11.78
1.92	1.70	1.69	1.55	1.54	1.34	1.91	1.91	1.83	1.68	1.22	1.27	1.24	1.43	1.14	1.35	1.85	1.18	0.74	1.62	1.60	1.14	1.64	1.43	1.21
1.56	0.15	0.78	1.68	0.48	0.67	0.28	1.46	1.51	0.62	0.55	1.52	0.98	0.98	0.74	1.59	0.95	1.06	0.38	1.86	1.96	0.41	0.71	0.24	1.15
97.61	97.57	97.23	97.57	97.03	96.22	96.56	97.20	96.86	97.59	96.68	96.73	97.41	97.38	97.10	96.97	96.92	96.98	97.48	97.17	96.50	97.26	97.02	97.33	97.73
6.01	6.76	6.45	6.25	6.37	6.59	6.52	6.17	6.21	6.50	6.46	6.34	6.63	6.87	6.64	6.37	6.39	6.72	7.31	6.26	6.38	6.93	6.18	6.48	6.56
0.24	0.12	0.11	0.13	0.09	0.14	0.14	0.18	0.26	0.17	0.09	0.11	0.07	0.06	0.10	0.16	0.25	0.15	0.03	0.16	0.04	0.05	0.09	0.05	0.11
2.63	1.65	2.17	2.13	2.38	1.87	2.06	2.24	2.27	2.04	2.25	2.17	1.89	1.48	1.91	2.29	2.07	1.62	0.99	2.24	1.96	1.65	2.55	2.45	2.10
0.00	0.00	0.01	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.00	0.01	0.00	0.02	0.00	0.00	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00
0.01	0.05	0.04	0.09	0.04	0.04	0.04	0.05	0.02	0.04	0.04	0.06	0.04	0.23	0.03	0.04	0.01	0.05	0.04	0.01	0.08	0.04	0.04	0.03	0.05
1.70	2.00	1.88	2.96	1.47	1.50	1.83	2.10	1.55	2.09	1.37	1.92	1.32	1.64	1.10	1.98	1.87	1.89	1.14	1.06	2.72	1.12	1.65	1.06	2.01
0.11	0.23	0.20	0.43	0.38	0.32	0.19	0.36	0.13	0.14	0.35	0.37	0.23	0.16	0.29	0.11	0.13	0.18	0.21	0.24	0.43	0.22	0.45	0.34	0.10
2.36	2.32	2.26	1.07	2.37	2.60	2.34	1.96	2.62	2.09	2.51	2.08	2.84	2.64	2.98	2.11	2.36	2.43	3.34	3.07	1.44	3.06	2.10	2.69	2.13
1.89	1.79	1.81	1.87	1.79	1.85	1.82	1.87	1.84	1.86	1.84	1.89	1.94	1.86	1.86	1.86	1.83	1.92	1.86	1.87	1.89	1.83	1.85	1.76	1.89
0.56	0.49	0.49	0.47	0.44	0.39	0.56	0.57	0.53	0.49	0.35	0.37	0.35	0.41	0.32	0.40	0.54	0.35	0.21	0.46	0.49	0.32	0.48	0.40	0.35
0.30	0.03	0.15	0.34	0.09	0.13	0.05	0.29	0.29	0.12	0.10	0.30	0.18	0.19	0.14	0.31	0.18	0.20	0.07	0.35	0.40	0.08	0.14	0.04	0.22
15.81	15.44	15.57	15.74	15.42	15.44	15.53	15.78	15.74	15.54	15.37	15.61	15.50	15.55	15.38	15.62	15.62	15.50	15.20	15.74	15.83	15.30	15.53	15.30	15.51

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EMP results of amphiboles

MKW	MKW	MKW	MKW	MKW	MKW	WP252	WP252	WP252	WP252	WP252	WP252	WP252	WP252	WP252	WP252	WP252	WP252	WP252	WP252	WP252	WP252	WP252
67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	
42.11	45.70	47.31	45.64	43.22	41.71	39.46	44.01	42.11	43.30	43.15	42.23	44.70	44.07	40.24	42.43	44.79	42.67	45.17	43.52	43.36	42.60	
0.93	0.70	0.76	0.57	0.66	0.61	0.77	1.29	0.93	1.06	1.70	1.16	0.66	0.54	1.00	0.91	0.58	1.81	1.12	0.66	1.42	0.67	
11.87	12.04	8.73	9.12	14.65	16.22	14.88	9.96	11.65	10.02	13.42	13.08	12.01	15.40	15.12	12.42	15.44	11.39	8.89	13.27	9.95	10.84	
-0.01	0.16	0.13	0.25	-0.03	0.02	0.04	0.07	0.01	0.02	0.10	0.12	0.11	0.01	0.00	0.01	0.04	0.07	0.01	0.02	0.05	0.00	
0.53	0.26	0.42	0.48	0.28	0.22	0.53	0.36	0.22	0.41	0.22	0.40	0.30	0.07	0.31	0.36	0.21	0.35	0.46	0.32	0.35	0.44	
19.41	13.19	13.36	16.45	14.02	15.04	19.34	16.42	18.00	19.56	12.14	14.38	14.79	11.69	17.79	17.14	12.24	16.52	17.35	15.36	16.93	18.43	
8.66	11.53	13.01	10.90	11.26	9.52	7.33	10.92	9.65	8.85	11.75	10.29	10.70	12.34	7.78	9.90	11.67	10.08	10.03	10.94	10.51	9.56	
11.42	12.11	12.27	11.74	11.01	10.92	11.01	11.94	11.74	11.46	11.70	12.26	11.74	10.58	11.41	11.60	11.08	11.86	11.80	11.14	11.88	11.69	
1.42	1.18	0.86	1.02	1.65	1.77	1.41	1.15	1.30	1.47	1.69	1.38	1.36	1.59	1.42	1.43	1.41	1.42	1.07	1.57	1.02	1.34	
0.90	0.61	0.83	0.97	0.38	0.32	1.12	1.22	0.89	1.25	0.86	1.53	0.19	0.25	1.11	0.77	0.24	1.40	0.95	0.25	1.22	1.39	
97.24	97.48	97.69	97.14	97.11	96.35	95.90	97.34	96.50	97.41	96.74	96.83	96.56	96.54	96.19	96.96	97.71	97.57	96.85	97.04	96.68	96.96	
hastingsite	6.37	6.69	6.91	6.82	6.34	6.21	6.59	6.37	6.59	6.38	6.36	6.63	6.37	6.14	6.36	6.43	6.43	6.82	6.41	6.55	6.47	
	0.11	0.08	0.08	0.06	0.07	0.07	0.15	0.11	0.12	0.19	0.13	0.07	0.06	0.12	0.10	0.06	0.21	0.13	0.07	0.16	0.08	
	2.12	2.08	1.50	1.61	2.54	2.85	2.70	1.76	2.08	2.34	2.32	2.10	2.62	2.72	2.19	2.61	2.02	1.58	2.30	1.77	1.94	
	0.00	0.02	0.02	0.03	0.00	0.01	0.01	0.00	0.00	0.01	0.02	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.00	
	0.07	0.03	0.05	0.06	0.04	0.03	0.05	0.03	0.05	0.03	0.05	0.04	0.01	0.04	0.05	0.03	0.05	0.06	0.04	0.04	0.06	
	1.96	1.53	1.46	1.80	1.43	1.62	1.77	1.77	2.25	1.43	1.80	1.63	0.94	2.01	1.69	1.12	1.99	2.06	1.39	1.79	1.93	
	0.50	0.08	0.17	0.26	0.29	0.25	0.29	0.51	0.24	0.07	0.01	0.20	0.47	0.27	0.46	0.35	0.09	0.13	0.50	0.35	0.41	
	1.95	2.52	2.83	2.43	2.46	2.11	2.44	2.18	2.01	2.59	2.31	2.37	2.66	1.77	2.21	2.50	2.26	2.26	2.40	2.37	2.17	
	1.85	1.90	1.92	1.88	1.73	1.74	1.81	1.92	1.87	1.85	1.98	1.87	1.64	1.87	1.86	1.70	1.91	1.91	1.76	1.92	1.90	
	0.42	0.34	0.24	0.30	0.47	0.51	0.42	0.33	0.43	0.49	0.40	0.39	0.45	0.42	0.42	0.39	0.41	0.31	0.45	0.30	0.40	
0.17	0.12	0.16	0.18	0.07	0.06	0.22	0.23	0.24	0.16	0.30	0.04	0.05	0.22	0.15	0.05	0.27	0.18	0.05	0.23	0.27		
15.51	15.37	15.36	15.42	15.45	15.46	15.54	15.52	15.50	15.61	15.54	15.68	15.35	15.27	15.57	15.49	15.24	15.65	15.44	15.36	15.49	15.61	
magnetite	magnetite	magnetite	magnetite	magnetite	magnetite	ferro-pargasite	magnetite	magnetite	ferro-pargasite	magnetite	pargasite	magnetite	tschermakite	ferro-pargasite	magnetite	tschermakite	pargasite	magnetite	magnetite	magnetite-ferro	magnetite	

EMP results of amphiboles

[illegible]

Summary of U-Pb zircon data from Mandawa Basin sandstones

Formation	Name	U ppm	²⁰⁶ Pb ppm	Ratios										Ages									
				²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁶ Pb*	1σ	²⁰⁷ Pb/ ²³⁵ U*	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ	Rho	Discordance (%)		²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ				
Pande	TDP1-01	633	69.7	3947	0.0727	0.0008	1.1455	0.0235	0.1143	0.0020	0.839	-32.2	-28	1005	23	775	11	698	11				
Pande	TDP1-02	85	27.9	10672	0.1210	0.0008	5.6103	0.1104	0.3363	0.0063	0.945	-6	-3.8	1971	11	1918	17	1869	30				
Pande	TDP1-03	482	56.6	311	0.1120	0.0025	1.8816	0.0547	0.1219	0.0022	0.625	-62.9	-60.5	1832	40	1075	19	741	13				
Pande	TDP1-04	67	11.1	2729	0.0734	0.0005	1.7192	0.0277	0.1699	0.0025	0.905	-1.4	.	1025	13	1016	10	1012	14				
Pande	TDP1-05	294	48.1	17579	0.0739	0.0004	1.7251	0.0279	0.1694	0.0026	0.949	-3	-0.1	1037	10	1018	10	1009	14				
Pande	TDP1-06	426	37.7	21688	0.0596	0.0003	0.7570	0.0110	0.0922	0.0012	0.933	-3.3	.	587	10	572	6	568	7				
Pande	TDP1-07	102	13.6	3626	0.0686	0.0005	1.3103	0.0213	0.1386	0.0020	0.884	-5.9	-1.4	886	14	850	9	837	11				
Pande	TDP1-08	88	12.5	4270	0.0714	0.0005	1.4616	0.0240	0.1485	0.0022	0.91	-8.5	-4.7	969	14	915	10	892	12				
Pande	TDP1-09	271	110.5	15193	0.1743	0.0015	10.0476	0.2396	0.4182	0.0093	0.936	-15.8	-13.6	2599	14	2439	22	2252	42				
Pande	TDP1-10	73	8.3	3638	0.0632	0.0005	1.0301	0.0177	0.1183	0.0018	0.905	0.9	.	714	16	719	9	721	11				
Pande	TDP1-11	83	13.7	3860	0.0726	0.0005	1.7196	0.0287	0.1718	0.0026	0.912	2.1	.	1003	14	1016	11	1022	14				
Pande	TDP1-12	143	11.5	2309	0.0558	0.0005	0.6462	0.0109	0.0840	0.0012	0.857	18	7.9	443	19	506	7	520	7				
Pande	TDP1-13	175	13.9	6309	0.0557	0.0003	0.6400	0.0100	0.0834	0.0012	0.923	18.2	10.4	439	13	502	6	516	7				
Pande	TDP1-14	258	23.5	8783	0.0578	0.0003	0.7618	0.0117	0.0955	0.0014	0.927	12.9	6.6	524	12	575	7	588	8				
Pande	TDP1-15	246	36.1	11599	0.0686	0.0004	1.4523	0.0244	0.1536	0.0024	0.935	4.3	.	885	12	911	10	921	13				
Pande	TDP1-16	183	17.4	8212	0.0576	0.0004	0.7961	0.0131	0.1002	0.0015	0.913	20.4	12.7	515	14	595	7	616	9				
Pande	TDP1-17	123	26.4	3842	0.0964	0.0008	2.9859	0.0547	0.2247	0.0037	0.892	-17.7	-14.8	1555	15	1404	14	1306	19				
Pande	TDP1-18	139	11.3	7241	0.0573	0.0004	0.6765	0.0108	0.0857	0.0012	0.892	5.9	.	502	16	525	7	530	7				
Pande	TDP1-19	114	34.1	1100	0.1321	0.0013	5.6651	0.1187	0.3111	0.0058	0.892	-20.4	-17.8	2126	16	1926	18	1746	29				
Pande	TDP1-20	24	2.3	918	0.0636	0.0009	0.8725	0.0206	0.0994	0.0019	0.794	-17	-8.4	730	29	637	11	611	11				
Pande	TDP1-21	79	24.3	9409	0.1140	0.0008	5.0413	0.1018	0.3208	0.0061	0.94	-4.3	-1.8	1864	12	1826	17	1794	30				
Pande	TDP1-22	18	3.4	1295	0.0800	0.0008	2.2244	0.0422	0.2016	0.0033	0.866	-1.2	.	1197	18	1189	13	1184	18				
Pande	TDP1-23	186	21.8	12126	0.0637	0.0004	1.0876	0.0174	0.1238	0.0018	0.922	2.8	.	733	13	747	8	752	11				
Pande	TDP1-24	337	22.8	311	0.1019	0.0010	1.0133	0.0222	0.0721	0.0014	0.891	-75.4	-74.5	1659	18	711	11	449	8				
Pande	TDP1-25	97	13.2	5970	0.0711	0.0006	1.4030	0.0261	0.1431	0.0024	0.907	-11	-6.8	961	15	890	11	862	14				
Pande	TDP1-26	37	3.7	1924	0.0602	0.0006	0.8803	0.0165	0.1061	0.0017	0.834	6.9	.	610	22	641	9	650	10				
Pande	TDP1-27	83	25.3	9838	0.1120	0.0008	4.9380	0.1005	0.3198	0.0061	0.936	-2.7	.	1832	12	1809	17	1789	30				
Pande	TDP1-28	637	108.1	495	0.1020	0.0019	2.5219	0.0619	0.1793	0.0029	0.648	-39	-35.4	1661	32	1278	18	1063	16				
Pande	TDP1-29	243	41.3	697	0.0945	0.0015	2.3503	0.0542	0.1804	0.0030	0.714	-32.1	-28.2	1518	29	1228	16	1069	16				

Summary of U-Pb zircon data from Mandawa Basin sandstones

Formation	Name	U ppm	^{206}Pb ppm	Ratios										Ages					
				$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$					$\frac{^{207}\text{Pb}}{^{235}\text{U}}$					Discordance (%)			$\frac{^{207}\text{Pb}}{^{235}\text{U}}$		
				$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	Central	Min.	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$
Pande	TDP1-30	259	44.4	4799	0.0778	0.0007	1.9447	0.0354	0.1814	0.0029	0.869	-6.3	-2	1141	17	1097	12	1075	16
Pande	TDP1-31	304	12.6	3039	0.0514	0.0004	0.3076	0.0057	0.0434	0.0007	0.887	6.7	.	257	19	272	4	274	4
Pande	TDP1-32	560	150.7	63433	0.1092	0.0007	4.2739	0.0830	0.2839	0.0052	0.941	-11	-8.8	1786	12	1688	16	1611	26
Pande	TDP1-33	181	21.3	5423	0.0643	0.0004	1.1115	0.0187	0.1255	0.0019	0.912	1.7	.	750	14	759	9	762	11
Pande	TDP1-34	166	26.7	10944	0.0715	0.0005	1.6848	0.0291	0.1708	0.0027	0.929	4.8	0.4	973	13	1003	11	1016	15
Pande	TDP1-35	96	14.9	374	0.1448	0.0082	3.2903	0.1977	0.1648	0.0033	0.335	-61.3	-55.8	2286	96	1479	47	983	18
Pande	TDP1-36	94	7.7	5379	0.0580	0.0005	0.7069	0.0122	0.0884	0.0013	0.863	3.2	.	530	18	543	7	546	8
Pande	TDP1-37	199	54.6	12099	0.1064	0.0008	4.2615	0.0854	0.2904	0.0054	0.937	-6.3	-3.6	1739	12	1686	16	1643	27
Pande	TDP1-38	65	10.1	5672	0.0721	0.0006	1.6372	0.0296	0.1647	0.0027	0.897	-0.5	.	988	16	985	11	983	15
Pande	TDP1-39	88	15.7	2626	0.0763	0.0009	1.7778	0.0316	0.1691	0.0022	0.732	-9.3	-4.2	1102	24	1037	12	1007	12
Pande	TDP1-40	21	2.3	543	0.0633	0.0009	0.9517	0.0175	0.1090	0.0013	0.626	-7.6	.	719	29	679	9	667	7
Pande	TDP1-41	639	98.3	4748	0.0721	0.0008	1.4951	0.0299	0.1505	0.0025	0.828	-9.1	-3.5	988	22	928	12	904	14
Pande	TDP1-42	122	40.2	11831	0.1151	0.0012	4.9760	0.0892	0.3135	0.0047	0.831	-7.5	-4.3	1882	17	1815	15	1758	23
Pande	TDP1-43	181	17.2	3243	0.0596	0.0005	0.7825	0.0105	0.0953	0.0010	0.750	-0.3	.	588	18	587	6	587	6
Pande	TDP1-44	2	0.1	49	0.0533	0.0039	0.6024	0.0492	0.0820	0.0031	0.465	50.5	.	342	164	479	31	508	19
Pande	TDP1-45	696	124.9	8613	0.0754	0.0007	1.8422	0.0293	0.1772	0.0022	0.787	-2.7	.	1079	20	1061	10	1052	12
Pande	TDP1-46	289	27.6	291	0.1128	0.0062	1.4824	0.0834	0.0953	0.0012	0.216	-71.2	-66.1	1845	97	923	34	587	7
Pande	TDP1-47	49	7.8	2100	0.0717	0.0007	1.5506	0.0236	0.1568	0.0019	0.786	-4.3	.	978	19	951	9	939	10
Pande	TDP1-48	441	45.3	9018	0.0616	0.0005	0.8795	0.0119	0.1035	0.0011	0.790	-4.1	.	661	17	641	6	635	6
Pande	TDP1-49	278	84.2	3839	0.1288	0.0017	5.1599	0.1360	0.2905	0.0066	0.867	-23.8	-20.4	2082	22	1846	22	1644	33
Pande	TDP1-50	20	1.6	435	0.0580	0.0009	0.6632	0.0122	0.0829	0.0009	0.601	-3.6	.	531	31	517	7	513	5
Pande	TDP1-51	220	59.7	13751	0.0972	0.0009	3.5131	0.0557	0.2621	0.0034	0.806	-5.1	-1.7	1571	17	1530	13	1500	17
Pande	TDP1-52	83	7.9	2171	0.0602	0.0008	0.7597	0.0134	0.0916	0.0011	0.705	-7.8	.	610	26	574	8	565	7
Pande	TDP1-53	389	64.1	17533	0.0763	0.0007	1.7261	0.0283	0.1640	0.0023	0.856	-12.2	-8.3	1104	17	1018	11	979	13
Pande	TDP1-54	26	7.8	1635	0.1135	0.0014	4.5573	0.0857	0.2912	0.0041	0.755	-12.7	-9.2	1856	22	1741	16	1648	21
Pande	TDP1-55	399	75.2	301	0.1614	0.0085	4.1273	0.2269	0.1855	0.0031	0.3	-60.3	-55.6	2470	84	1660	45	1097	17
Pande	TDP1-56	129	10.7	2511	0.0576	0.0006	0.6675	0.0096	0.0841	0.0009	0.725	1.4	.	513	21	519	6	521	5
Pande	TDP1-57	730	76.2	17357	0.0616	0.0005	0.8981	0.0118	0.1058	0.0011	0.789	-1.6	.	659	17	651	6	648	6
Pande	TDP1-58	643	48.2	339	0.1015	0.0020	1.0692	0.0246	0.0764	0.0009	0.499	-73.8	-72.3	1651	35	738	12	475	5

Summary of U-Pb zircon data from Mandawa Basin sandstones

Formation	Name	U ppm	^{206}Pb ppm	Ratios										Ages					
				$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$					$\frac{^{207}\text{Pb}}{^{235}\text{U}}$					Discordance (%)			$\frac{^{207}\text{Pb}}{^{235}\text{U}}$		
				$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	Central	Min.	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$
Pande	TDP1-59	123	41.1	7718	0.1176	0.0012	5.1848	0.0924	0.3197	0.0046	0.806	-7.9	-4.6	1921	18	1850	15	1788	22
Pande	TDP1-60	35	12.1	690234152	0.1240	0.0015	5.6583	0.1072	0.3311	0.0048	0.758	-9.7	-6.3	2014	22	1925	16	1844	23
Pande	TDP1-61	419	108.9	20293	0.1118	0.0011	3.9415	0.0736	0.2556	0.0040	0.840	-22.1	-19.3	1829	17	1622	15	1468	21
Pande	TDP1-62	158	59.9	817	0.1999	0.0030	9.9178	0.2291	0.3599	0.0064	0.766	-34.6	-32	2825	23	2427	21	1981	30
Pande	TDP1-63	618	60.8	11668	0.0610	0.0005	0.8387	0.0118	0.0997	0.0011	0.801	-4.6	.	641	17	618	6	612	7
Pande	TDP1-64	198	24.7	7931	0.0665	0.0006	1.1571	0.0168	0.1263	0.0014	0.783	-7	-1.7	820	19	781	8	767	8
Pande	TDP1-65	516	38.9	53540	0.0609	0.0005	0.6487	0.0088	0.0772	0.0008	0.761	-25.7	-20.5	637	18	508	5	479	5
Pande	TDP1-66	80	31.2	9004	0.1816	0.0025	9.2851	0.2012	0.3709	0.0062	0.769	-27.6	-24.9	2667	22	2367	20	2034	29
Pande	TDP1-67	357	49.7	185	0.1425	0.0036	2.7729	0.0776	0.1411	0.0016	0.408	-66.3	-64.5	2258	42	1348	21	851	9
Pande	TDP1-68	695	124.8	16619	0.0772	0.0007	1.9246	0.0289	0.1808	0.0022	0.804	-5.3	-1.2	1126	17	1090	10	1071	12
Pande	TDP1-69	565	99.9	15879	0.0760	0.0007	1.8642	0.0267	0.1779	0.0020	0.788	-3.9	.	1095	17	1068	9	1056	11
Pande	TDP1-70	364	97.5	23338	0.1094	0.0011	3.9742	0.0674	0.2636	0.0036	0.798	-17.6	-14.6	1789	18	1629	14	1508	18
Pande	TDP1-71	1040	50.1	254	0.1457	0.0028	0.9926	0.0638	0.0494	0.0030	0.955	-88.5	-87.7	2296	33	700	33	311	19
Pande	TDP1-72	47	8.2	1951	0.0758	0.0008	1.8484	0.0282	0.1768	0.0021	0.764	-4.1	.	1091	19	1063	10	1049	11
Pande	TDP1-73	352	31.7	7997	0.0608	0.0006	0.7848	0.0111	0.0936	0.0010	0.771	-9	-2.4	632	19	588	6	577	6
Pande	TDP1-74	564	53.1	13166	0.0598	0.0005	0.7987	0.0109	0.0969	0.0010	0.772	.	.	596	18	596	6	596	6
Pande	TDP1-75	70	11.8	3464	0.0746	0.0008	1.7586	0.0273	0.1711	0.0020	0.755	-3.9	.	1057	20	1030	10	1018	11
Pande	TDP1-76	249	40.8	5819	0.0729	0.0007	1.6589	0.0246	0.1649	0.0019	0.770	-3	.	1012	18	993	9	984	10
Pande	TDP1-77	192	32.4	19941	0.0744	0.0007	1.7574	0.0255	0.1712	0.0020	0.785	-3.5	.	1053	17	1030	9	1019	11
Pande	TDP1-78	352	60.3	15368	0.0739	0.0007	1.7677	0.0259	0.1735	0.0020	0.786	-0.8	.	1039	18	1034	9	1031	11
Pande	TDP1-79	181	28.7	10237	0.0733	0.0007	1.6279	0.0242	0.1611	0.0018	0.767	-6.3	-1.8	1022	19	981	9	963	10
Pande	TDP1-80	332	57.8	29699	0.0740	0.0007	1.8012	0.0268	0.1767	0.0021	0.791	0.9	.	1040	17	1046	10	1049	11
Pande	TDP1-81	668	128.5	2304	0.1522	0.0019	4.0757	0.0837	0.1942	0.0031	0.789	-56.3	-54.7	2371	20	1649	17	1144	17
Pande	TDP1-82	154	51.2	21233	0.1161	0.0013	5.1684	0.0936	0.3228	0.0047	0.803	-5.7	-2.2	1897	18	1847	15	1804	23
Pande	TDP1-83	573	52	6989	0.0657	0.0024	0.8543	0.0324	0.0943	0.0011	0.318	-28.5	-5.8	798	74	627	18	581	7
Pande	TDP1-84	222	28	7613	0.0661	0.0006	1.1783	0.0176	0.1294	0.0015	0.788	-3.2	.	809	19	791	8	784	9
Pande	TDP1-85	348	108.1	15659	0.1121	0.0012	4.6914	0.0848	0.3036	0.0044	0.808	-7.7	-4.3	1833	18	1766	15	1709	22
Pande	TDP1-86	379	67.9	16331	0.0747	0.0007	1.8740	0.0284	0.1819	0.0022	0.796	1.6	.	1061	18	1072	10	1077	12
Pande	TDP1-87	407	43.3	10470	0.0615	0.0005	0.9323	0.0133	0.1100	0.0012	0.784	2.8	.	656	18	669	7	673	7

Summary of U-Pb zircon data from Mandawa Basin sandstones

Formation	Name	U ppm	^{206}Pb ppm	Ratios										Ages					
				$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$					$\frac{^{207}\text{Pb}}{^{235}\text{U}}$					Discordance (%)			$\frac{^{207}\text{Pb}}{^{235}\text{U}}$		
				$^{206}\text{Pb}^*$	1 σ	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	1 σ	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	1 σ	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	1 σ	Rho	Central	Min.	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	1 σ	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	1 σ	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$
Pande	TDP1-88	188	22.3	4996	0.0663	0.0006	1.1235	0.0174	0.1229	0.0015	0.804	-9	-3.6	816	18	765	8	747	9
Pande	TDP1-89	983	100.7	6530	0.0621	0.0006	0.9078	0.0129	0.1061	0.0012	0.775	-4.1	.	677	18	656	7	650	7
Pande	TDP1-90	122	21.5	2454	0.0848	0.0021	2.1027	0.0576	0.1798	0.0023	0.465	-20.3	-12.5	1312	45	1150	19	1066	13
Pande	TDP1-91	66	5.9	2277	0.0592	0.0007	0.7549	0.0125	0.0925	0.0011	0.703	-0.6	.	574	24	571	7	570	6
Pande	TDP1-92	161	45.2	16410	0.1158	0.0013	4.4515	0.0863	0.2788	0.0044	0.811	-18.3	-15.1	1893	20	1722	16	1585	22
Pande	TDP1-93	120	3.4	1016	0.0502	0.0006	0.2093	0.0034	0.0302	0.0003	0.667	-6.7	.	205	27	193	3	192	2
Pande	TDP1-94	23	0.7	174	0.0500	0.0014	0.2134	0.0067	0.0309	0.0004	0.393	-0.4	.	197	65	196	6	196	2
Makonde	MB-01	27	3.4	1846	0.0636	0.0006	1.0494	0.0157	0.1197	0.0015	0.816	0.2	.	728	17	729	8	729	8
Makonde	MB-02	205	36.5	4483	0.0769	0.0007	1.9508	0.0503	0.1840	0.0044	0.933	-2.8	.	1118	18	1099	17	1089	24
Makonde	MB-03	174	29.5	4644	0.0701	0.0003	1.5364	0.0207	0.1590	0.0020	0.936	2.5	.	930	9	945	8	951	11
Makonde	MB-04	166	21.9	1629	0.0744	0.0010	1.4073	0.0372	0.1372	0.0031	0.857	-22.6	-16.9	1052	27	892	16	829	18
Makonde	MB-05	160	17.4	6315	0.0604	0.0003	0.8751	0.0110	0.1050	0.0012	0.903	4.2	.	619	11	638	6	644	7
Makonde	MB-06	471	76	7287	0.0739	0.0007	1.7035	0.0432	0.1673	0.0040	0.935	-4.2	.	1038	18	1010	16	997	22
Makonde	MB-07	737	115.1	1137	0.1088	0.0011	2.5655	0.0839	0.1710	0.0053	0.947	-46.2	-44	1779	19	1291	24	1018	29
Makonde	MB-08	433	42.3	489	0.0936	0.0007	1.1518	0.0220	0.0892	0.0016	0.919	-66	-64.8	1501	14	778	10	551	9
Makonde	MB-09	594	32.7	409	0.0590	0.0008	0.4568	0.0130	0.0562	0.0014	0.864	-38.7	-30.1	565	31	382	9	352	8
Makonde	MB-10	123	18.4	3354	0.0739	0.0007	1.6196	0.0445	0.1590	0.0041	0.937	-8.9	-3.8	1038	19	978	17	951	23
Makonde	MB-11	118	12.5	2780	0.0601	0.0004	0.8273	0.0115	0.0998	0.0012	0.886	1	.	607	13	612	6	613	7
Makonde	MB-12	132	24.9	6357	0.0739	0.0004	1.7798	0.0267	0.1746	0.0025	0.939	-0.2	.	1039	10	1038	10	1038	14
Makonde	MB-13	268	81.9	8708	0.1162	0.0013	5.0125	0.1590	0.3130	0.0093	0.935	-8.6	-4.7	1898	19	1821	27	1755	46
Makonde	MB-14	296	111.4	14922	0.1151	0.0009	5.3019	0.1142	0.3340	0.0068	0.939	-1.5	.	1882	13	1869	18	1858	33
Makonde	MB-15	207	18.6	1258	0.0756	0.0007	0.9747	0.0235	0.0935	0.0021	0.92	-49	-46.3	1085	18	691	12	576	12
Makonde	MB-16	402	98.9	4723	0.1124	0.0012	3.8396	0.1145	0.2477	0.0069	0.929	-25	-21.8	1839	19	1601	24	1427	35
Makonde	MB-17	679	101.8	28845	0.0665	0.0003	1.2532	0.0202	0.1367	0.0021	0.948	0.6	.	821	10	825	9	826	12
Makonde	MB-18	84	13.9	3708	0.0728	0.0007	1.6854	0.0422	0.1680	0.0039	0.921	-0.7	.	1007	19	1003	16	1001	21
Makonde	MB-19	147	26.3	4567	0.0726	0.0004	1.6692	0.0240	0.1667	0.0022	0.938	-1.1	.	1004	10	997	9	994	12
Makonde	MB-20	222	55.9	1293	0.1239	0.0015	4.4021	0.1335	0.2577	0.0072	0.922	-29.7	-26.7	2013	20	1713	25	1478	37
Makonde	MB-21	96	35	8541	0.1175	0.0009	5.2243	0.1119	0.3224	0.0065	0.937	-7	-4.4	1919	13	1857	18	1801	32
Makonde	MB-22	75	23.7	12470	0.1132	0.0013	5.0226	0.1577	0.3218	0.0094	0.934	-3.3	.	1851	20	1823	27	1798	46

Summary of U-Pb zircon data from Mandawa Basin sandstones

Formation	Name	U ppm	²⁰⁶ Pb ppm	Ratios										Ages									
				²⁰⁶ Pb/ ²⁰⁴ Pb		²⁰⁷ Pb/ ²⁰⁶ Pb*		²⁰⁷ Pb/ ²³⁵ U*		²⁰⁶ Pb/ ²³⁸ U		Discordance (%)		²⁰⁷ Pb/ ²⁰⁶ Pb		²⁰⁷ Pb/ ²³⁵ U		²⁰⁶ Pb/ ²³⁸ U					
												Central	Min.										
Makonde	MB-23	720	50.6	597	0.0553	0.0004	0.4661	0.0090	0.0612	0.0011	0.921	-9.9	-1.2	423	17	389	6	383	7				
Makonde	MB-24	169	57.8	17311	0.1123	0.0008	4.7237	0.0995	0.3052	0.0060	0.934	-7.4	-4.7	1836	13	1771	18	1717	30				
Makonde	MB-25	634	83.3	1046	0.0839	0.0009	1.4884	0.0386	0.1286	0.0031	0.916	-42	-39	1291	19	926	16	780	17				
Makonde	MB-26	358	167.4	26672	0.1452	0.0011	8.2687	0.1989	0.4131	0.0094	0.949	-3.1	-0.7	2290	13	2261	22	2229	43				
Makonde	MB-27	65	12.8	2712	0.0753	0.0006	1.8609	0.0319	0.1793	0.0028	0.902	-1.3	.	1076	14	1067	11	1063	15				
Makonde	MB-28	252	88.3	22986	0.1228	0.0015	5.8528	0.1945	0.3456	0.0107	0.928	-4.9	-0.6	1998	21	1954	29	1913	51				
Makonde	MB-29	1540	42.7	194	0.0483	0.0004	0.1524	0.0028	0.0229	0.0004	0.868	31.3	.	112	21	144	2	146	2				
Makonde	MB-30	133	21.3	2721	0.0736	0.0007	1.6600	0.0421	0.1635	0.0038	0.921	-5.8	-0.4	1032	20	993	16	976	21				
Makonde	MB-31	136	40.1	2660	0.1097	0.0009	4.0402	0.0790	0.2671	0.0048	0.91	-16.8	-14.2	1794	14	1642	16	1526	24				
Makonde	MB-32	731	72	625	0.0933	0.0011	1.3518	0.0382	0.1051	0.0027	0.901	-59.7	-57.5	1494	22	868	16	644	16				
Makonde	MB-33	447	82.4	4816	0.0732	0.0004	1.7253	0.0257	0.1709	0.0024	0.93	-0.4	.	1021	11	1018	10	1017	13				
Makonde	MB-34	123	38.8	11640	0.1130	0.0013	4.9171	0.1500	0.3156	0.0090	0.931	-5	-0.9	1848	20	1805	26	1768	44				
Makonde	MB-35	623	57.7	2551	0.0560	0.0003	0.6518	0.0093	0.0845	0.0011	0.911	16.7	9.4	450	13	510	6	523	7				
Makonde	MB-36	36	11.7	1776	0.1152	0.0013	5.1424	0.1603	0.3238	0.0094	0.93	-4.5	-0.4	1883	20	1843	27	1808	46				
Makonde	MB-37	410	151.1	38475	0.1144	0.0007	5.2519	0.1034	0.3330	0.0063	0.954	-1.1	.	1870	10	1861	17	1853	30				
Makonde	MB-38	38	8.6	1321	0.1000	0.0012	3.1808	0.0935	0.2308	0.0062	0.919	-19.4	-15.6	1623	21	1453	23	1339	33				
Makonde	MB-39	1241	21.1	75	0.2188	0.0032	0.4742	0.0104	0.0157	0.0003	0.748	-97.3	-97.2	2972	22	394	7	101	2				
Makonde	MB-40	135	23.4	5744	0.0747	0.0007	1.8374	0.0477	0.1783	0.0043	0.925	-0.4	.	1061	20	1059	17	1058	23				
Makonde	MB-41	182	23	8778	0.0639	0.0003	1.0662	0.0141	0.1210	0.0015	0.917	-0.2	.	738	11	737	7	737	8				
Makonde	MB-42	247	22	14868	0.0589	0.0006	0.7521	0.0182	0.0926	0.0021	0.922	1.4	.	563	20	569	11	571	12				
Makonde	MB-43	2009	24.7	86	0.2017	0.0026	0.3172	0.0063	0.0114	0.0002	0.769	-97.9	-97.9	2840	19	280	5	73	1				
Makonde	MB-44	166	13.2	3847	0.0574	0.0006	0.6566	0.0155	0.0830	0.0018	0.914	1.9	.	505	21	513	10	514	11				
Makonde	MB-45	88	15.2	4809	0.0693	0.0005	1.4831	0.0256	0.1553	0.0024	0.894	2.8	.	907	16	923	10	931	13				
Makonde	MB-46	312	45	1756	0.0742	0.0008	1.5077	0.0224	0.1474	0.0016	0.710	-16.4	-12.2	1047	21	934	9	886	9				
Makonde	MB-47	827	51.1	499	0.0529	0.0008	0.3952	0.0094	0.0542	0.0010	0.741	5.3	.	324	35	338	7	340	6				
Makonde	MB-48	65	10.8	3171	0.0738	0.0008	1.7315	0.0446	0.1702	0.0040	0.919	-2.4	.	1036	20	1020	17	1013	22				
Makonde	MB-49	156	57.8	18531	0.1144	0.0008	5.2702	0.1136	0.3342	0.0068	0.943	-0.7	.	1870	13	1864	18	1859	33				
Makonde	MB-50	192	31.1	3217	0.0728	0.0008	1.5999	0.0283	0.1595	0.0023	0.803	-5.7	-0.4	1007	21	970	11	954	13				
Makonde	MB-51	139	17.6	2890	0.0630	0.0004	1.0070	0.0156	0.1159	0.0016	0.905	-0.3	.	709	13	707	8	707	9				

Summary of U-Pb zircon data from Mandawa Basin sandstones

Formation	Name	U ppm	^{206}Pb ppm	Ratios										Ages					
				$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$					$\frac{^{207}\text{Pb}}{^{235}\text{U}}$					Discordance (%)			$\frac{^{206}\text{Pb}}{^{238}\text{U}}$		
				^{206}Pb ppm	^{207}Pb ppm	^{206}Pb ppm	^{207}Pb ppm	^{206}Pb ppm	^{207}Pb ppm	^{206}Pb ppm	^{207}Pb ppm	^{206}Pb ppm	^{207}Pb ppm	Central	Min.	^{206}Pb ppm	^{207}Pb ppm	^{206}Pb ppm	^{207}Pb ppm
Makonde	MB-52	310	24.8	5161	0.0573	0.0005	0.6604	0.0157	0.0837	0.0018	0.918	3.5	.	501	20	515	10	518	11
Makonde	MB-53	646	131.9	22559	0.0747	0.0005	1.8796	0.0353	0.1824	0.0032	0.941	1.9	.	1062	12	1074	12	1080	18
Makonde	MB-54	294	75.4	3366	0.1160	0.0014	4.1834	0.1310	0.2617	0.0076	0.926	-23.4	-20	1895	20	1671	26	1498	39
Makonde	MB-55	124	5.5	39399	0.0517	0.0004	0.3013	0.0046	0.0423	0.0005	0.834	-1	.	270	18	267	4	267	3
Makonde	MB-56	71	37.5	5841	0.1976	0.0039	13.7121	0.4891	0.5033	0.0150	0.838	-7.7	-2.6	2806	31	2730	34	2628	64
Makonde	MB-57	73	13.6	2530	0.0726	0.0006	1.6830	0.0314	0.1681	0.0028	0.908	-0.2	.	1003	15	1002	12	1002	16
Makonde	MB-58	135	22.6	5233	0.0735	0.0007	1.7640	0.0459	0.1741	0.0042	0.925	0.8	.	1027	19	1032	17	1035	23
Makonde	MB-59	121	22.9	8043	0.0735	0.0006	1.7388	0.0325	0.1716	0.0029	0.912	-0.7	.	1028	15	1023	12	1021	16
Makonde	MB-60	115	11.4	8588	0.0607	0.0006	0.8723	0.0120	0.1042	0.0009	0.658	1.4	.	630	23	637	7	639	6
Makonde	MB-61	510	47	470	0.0577	0.0005	0.6705	0.0107	0.0843	0.0012	0.857	0.9	.	517	17	521	6	522	7
Makonde	MB-62	232	66.4	3990	0.1167	0.0014	4.6934	0.1495	0.2917	0.0086	0.921	-15.2	-11.3	1906	22	1766	27	1650	43
Makonde	MB-63	697	70.2	389	0.0688	0.0011	0.8337	0.0225	0.0879	0.0019	0.819	-40.9	-35.3	893	30	616	12	543	12
Makonde	MB-64	319	32.2	4222	0.0611	0.0006	0.8836	0.0217	0.1049	0.0024	0.915	.	.	643	21	643	12	643	14
Makonde	MB-65	103	37.6	13841	0.1201	0.0007	5.6587	0.1023	0.3417	0.0058	0.940	-3.7	-1.5	1958	11	1925	16	1895	28
Makonde	MB-66	152	12.9	2340	0.0588	0.0006	0.7216	0.0180	0.0890	0.0020	0.904	-1.7	.	559	22	552	11	550	12
Makonde	MB-67	492	68.7	1429	0.0711	0.0004	1.2665	0.0213	0.1291	0.0020	0.940	-19.7	-16.9	961	12	831	10	783	12
Makonde	MB-68	141	16.8	5942	0.0669	0.0008	1.1437	0.0326	0.1240	0.0032	0.918	-10.3	-3.2	834	22	774	15	754	19
Makonde	MB-69	185	15.6	9147	0.0582	0.0004	0.6625	0.0088	0.0826	0.0010	0.891	-4.9	.	537	13	516	5	512	6
Makonde	MB-70	411	53.4	1871	0.0788	0.0009	1.4718	0.0387	0.1356	0.0032	0.900	-31.6	-27.5	1166	21	919	16	819	18
Makonde	MB-71	183	62.2	26373	0.1141	0.0009	4.8007	0.1056	0.3051	0.0063	0.932	-9.1	-6.4	1866	13	1785	18	1717	31
Makonde	MB-72	430	32.5	2811	0.0565	0.0005	0.5924	0.0090	0.0760	0.0010	0.853	-0.1	.	473	17	472	6	472	6
Makonde	MB-73	176	26.8	5835	0.0715	0.0008	1.5735	0.0415	0.1596	0.0039	0.918	-1.9	.	972	20	960	16	954	21
Makonde	MB-74	458	54.6	912	0.0695	0.0010	1.0823	0.0297	0.1129	0.0026	0.847	-25.9	-19.3	914	30	745	14	690	15
Makonde	MB-75	260	26.3	15640	0.0661	0.0007	0.9674	0.0245	0.1062	0.0025	0.913	-20.6	-14.8	809	21	687	13	651	14
Makonde	MB-76	572	65.3	1256	0.0803	0.0005	1.2039	0.0188	0.1087	0.0016	0.920	-47.1	-45.4	1204	12	802	9	665	9
Makonde	MB-77	90	3	863	0.0509	0.0007	0.2516	0.0066	0.0359	0.0008	0.867	-3.8	.	236	29	228	5	227	5
Makonde	MB-78	373	28.4	7654	0.0571	0.0003	0.5735	0.0083	0.0728	0.0010	0.930	-9	-3.8	496	11	460	5	453	6
Makonde	MB-79	271	86.4	15098	0.1137	0.0014	5.1330	0.1663	0.3274	0.0098	0.924	-2.1	.	1860	21	1842	28	1826	48
Makonde	MB-80	268	47.9	23373	0.0735	0.0004	1.6876	0.0273	0.1664	0.0025	0.934	-3.8	-0.6	1029	11	1004	10	992	14

Summary of U-Pb zircon data from Mandawa Basin sandstones

Formation	Name	U ppm	^{206}Pb ppm	Ratios										Ages					
				$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$					$\frac{^{207}\text{Pb}}{^{235}\text{U}}$					Discordance (%)			$\frac{^{207}\text{Pb}}{^{235}\text{U}}$		
				$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	Central	Min.	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$
Makonde	MB-81	576	50.8	10794	0.0586	0.0006	0.7521	0.0190	0.0931	0.0022	0.919	4.2	.	552	21	569	11	574	13
Makonde	MB-82	327	120	17768	0.1150	0.0010	5.1377	0.1260	0.3240	0.0075	0.939	-4.3	-1.3	1880	15	1842	21	1809	36
Makonde	MB-83	445	38.4	11104	0.0579	0.0003	0.6670	0.0090	0.0836	0.0011	0.935	-1.3	.	524	10	519	5	518	6
Makonde	MB-84	147	22.6	13893	0.0718	0.0008	1.6040	0.0434	0.1619	0.0040	0.919	-1.5	.	982	22	972	17	967	22
Makonde	MB-85	76	26.5	19137	0.1145	0.0007	5.0458	0.0985	0.3197	0.0059	0.949	-5.1	-2.9	1872	11	1827	17	1788	29
Makonde	MB-86	369	40.5	21527	0.0631	0.0006	1.0091	0.0269	0.1160	0.0029	0.925	-0.6	.	712	22	708	14	707	17
Makonde	MB-87	44	3.5	1348	0.0575	0.0005	0.6307	0.0098	0.0795	0.0010	0.817	-3.7	.	511	18	497	6	493	6
Makonde	MB-88	601	210	38928	0.1145	0.0008	4.9233	0.1076	0.3119	0.0064	0.943	-7.4	-4.9	1872	13	1806	18	1750	32
Makonde	MB-89	713	71.3	1067	0.0798	0.0006	1.0276	0.0181	0.0935	0.0015	0.916	-53.9	-52.3	1191	14	718	9	576	9
Makonde	MB-90	280	48.9	16894	0.0736	0.0004	1.7013	0.0251	0.1677	0.0023	0.932	-3.1	-0.1	1029	11	1009	9	1000	13
Makonde	MB-91	29	4.9	1447	0.0686	0.0007	1.5200	0.0314	0.1608	0.0029	0.861	9.2	2.5	886	21	938	13	961	16
Makonde	MB-92	252	78.4	31653	0.1135	0.0007	4.6210	0.0795	0.2952	0.0048	0.936	-11.6	-9.5	1857	11	1753	14	1667	24
Makonde	MB-93	855	83.6	43814	0.0595	0.0003	0.7815	0.0109	0.0952	0.0012	0.942	.	.	586	10	586	6	586	7
Makonde	MB-94	247	95.6	44580	0.1202	0.0011	5.6042	0.1510	0.3381	0.0086	0.941	-4.8	-1.6	1959	16	1917	23	1877	41
Makonde	MB-95	640	143.2	3812	0.1162	0.0007	3.3707	0.0632	0.2103	0.0037	0.944	-38.6	-37.2	1899	11	1498	15	1230	20
Makonde	MB-96	247	81.8	114381	0.1143	0.0007	4.9785	0.0863	0.3160	0.0052	0.944	-6	-4	1868	10	1816	15	1770	25
Makonde	MB-97	571	101.7	5749	0.0728	0.0005	1.6185	0.0318	0.1614	0.0030	0.935	-4.6	-0.6	1007	14	977	12	964	16
Tendaguru	TGU-01	603	87.4	3032	0.0655	0.0011	1.1850	0.0275	0.1313	0.0021	0.694	0.8	.	789	34	794	13	795	12
Tendaguru	TGU-02	181	21.2	5236	0.0670	0.0009	0.8857	0.0400	0.0958	0.0041	0.950	-31	-24.1	839	29	644	22	590	24
Tendaguru	TGU-03	156	27	6539	0.0729	0.0009	1.4215	0.0684	0.1413	0.0066	0.965	-16.9	-10.4	1012	26	898	29	852	37
Tendaguru	TGU-04	191	28.6	7053	0.0680	0.0012	1.2687	0.0303	0.1353	0.0022	0.681	-6.1	.	868	33	832	14	818	13
Tendaguru	TGU-05	122	22.6	6723	0.0751	0.0008	1.8527	0.0662	0.1788	0.0061	0.957	-1.2	.	1072	20	1064	24	1061	33
Tendaguru	TGU-06	108	12.6	2565	0.0629	0.0007	0.9848	0.0341	0.1135	0.0037	0.951	-2	.	706	22	696	17	693	22
Tendaguru	TGU-07	145	19.2	7083	0.0664	0.0007	1.1915	0.0449	0.1301	0.0047	0.956	-4.1	.	820	22	797	21	788	27
Tendaguru	TGU-08	99	18.9	4878	0.0761	0.0009	1.9428	0.0741	0.1853	0.0067	0.954	-0.1	.	1096	21	1096	26	1096	37
Tendaguru	TGU-09	63	8.1	1825	0.0614	0.0011	0.9736	0.0236	0.1150	0.0018	0.661	7.8	.	653	38	690	12	702	11
Tendaguru	TGU-10	795	34.6	654	0.0699	0.0009	0.4105	0.0148	0.0426	0.0014	0.941	-72.4	-70.2	924	24	349	11	269	9
Tendaguru	TGU-11	51	8	6422	0.0714	0.0010	1.4796	0.0586	0.1503	0.0056	0.932	-7.3	.	969	29	922	24	903	31
Tendaguru	TGU-12	319	45.3	32103	0.0663	0.0009	1.2496	0.0499	0.1367	0.0051	0.942	1.3	.	816	28	823	23	826	29

Summary of U-Pb zircon data from Mandawa Basin sandstones

Formation	Name	U ppm	^{206}Pb ppm	Ratios										Ages				
				$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	Discordance (%)	Central	Min.	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$
				1 σ	1 σ	1 σ	1 σ	1 σ	1 σ	1 σ	1 σ	1 σ	1 σ				1 σ	1 σ
Tendaguru	TGU-13	81	11.7	3721	0.0673	0.0010	1.2916	0.0532	0.1391	0.0053	0.933	-1.1	.	848	29	842	24	840
Tendaguru	TGU-14	160	29.4	7466	0.0751	0.0011	1.8302	0.0778	0.1767	0.0071	0.942	-2.3	.	1071	28	1056	28	1049
Tendaguru	TGU-15	109	9.9	2167	0.0607	0.0009	0.7379	0.0305	0.0882	0.0034	0.929	-13.9	-1.6	628	32	561	18	545
Tendaguru	TGU-16	154	22.6	23128	0.0674	0.0010	1.3159	0.0563	0.1416	0.0057	0.939	0.4	.	850	31	853	25	854
Tendaguru	TGU-17	30	5.1	3129	0.0744	0.0012	1.7229	0.0779	0.1679	0.0071	0.934	-5.3	.	1052	31	1017	29	1001
Tendaguru	TGU-18	204	72.9	10935	0.1169	0.0015	5.3457	0.2159	0.3317	0.0127	0.95	-3.8	.	1909	22	1876	35	1846
Tendaguru	TGU-19	79	6.8	1236	0.0645	0.0011	0.7314	0.0266	0.0823	0.0026	0.885	-34.1	-25.6	758	35	557	16	510
Tendaguru	TGU-20	50	4.5	3002	0.0579	0.0011	0.6405	0.0161	0.0802	0.0013	0.629	-5.8	.	527	41	503	10	497
Tendaguru	TGU-21	184	32.3	6790	0.0775	0.0009	1.7701	0.0649	0.1657	0.0058	0.948	-13.8	-8.2	1133	22	1035	24	989
Tendaguru	TGU-22	111	13.6	2534	0.0685	0.0008	1.0974	0.0399	0.1163	0.0040	0.944	-20.8	-14.3	882	23	752	19	709
Tendaguru	TGU-23	29	5.7	1320	0.0773	0.0016	1.8365	0.0489	0.1724	0.0030	0.642	-9.8	-1.4	1128	41	1059	18	1025
Tendaguru	TGU-24	345	58	14045	0.0723	0.0013	1.5106	0.0373	0.1515	0.0025	0.662	-9.2	-0.6	995	37	935	15	909
Tendaguru	TGU-25	173	60.2	56952	0.1185	0.0016	5.2806	0.2296	0.3231	0.0134	0.951	-7.7	-3	1934	23	1866	37	1805
Tendaguru	TGU-26	358	90	23037	0.1102	0.0019	3.7672	0.1975	0.2480	0.0123	0.947	-23.1	-18	1802	29	1586	42	1428
Tendaguru	TGU-27	735	67.2	29319	0.0564	0.0006	0.6499	0.0142	0.0836	0.0016	0.895	11	0.4	468	20	508	9	517
Tendaguru	TGU-28	239	45.7	6053	0.0727	0.0008	1.7359	0.0404	0.1732	0.0036	0.895	2.5	.	1006	20	1022	15	1029
Tendaguru	TGU-29	110	39.9	9505	0.1131	0.0013	5.0434	0.1418	0.3235	0.0082	0.906	-2.6	.	1849	20	1827	24	1807
Tendaguru	TGU-30	227	42.8	17964	0.0729	0.0008	1.7185	0.0408	0.1711	0.0036	0.895	0.8	.	1010	21	1015	15	1018
Tendaguru	TGU-31	1504	181.6	44138	0.0599	0.0006	0.9104	0.0207	0.1102	0.0023	0.9	12.9	3.8	601	21	657	11	674
Tendaguru	TGU-32	572	56.2	25083	0.0616	0.0008	0.7764	0.0212	0.0915	0.0022	0.889	-15	-6.1	659	24	583	12	564
Tendaguru	TGU-33	268	40.1	16581	0.0683	0.0007	1.2876	0.0308	0.1368	0.0029	0.896	-6	.	876	21	840	14	827
Tendaguru	TGU-34	148	23.1	4968	0.0735	0.0009	1.4398	0.0350	0.1421	0.0030	0.872	-17.8	-12.3	1028	23	906	15	856
Tendaguru	TGU-35	552	55.3	194	0.1263	0.0022	1.5994	0.0433	0.0918	0.0019	0.775	-75.4	-74.1	2047	30	970	17	566
Tendaguru	TGU-36	172	29.2	17234	0.0692	0.0008	1.4681	0.0359	0.1539	0.0034	0.893	2.2	.	904	22	917	15	923
Tendaguru	TGU-37	237	28.9	8823	0.0605	0.0006	0.9262	0.0216	0.1111	0.0023	0.890	9.9	0.8	621	22	666	11	679
Tendaguru	TGU-38	235	43.4	30841	0.0705	0.0008	1.6317	0.0404	0.1680	0.0037	0.901	6.8	.	942	21	983	16	1001
Tendaguru	TGU-39	935	91.5	795	0.0745	0.0010	0.9161	0.0226	0.0892	0.0019	0.858	-49.9	-46.4	1055	24	660	12	551
Tendaguru	TGU-40	164	23.7	6718	0.0650	0.0007	1.1784	0.0287	0.1314	0.0028	0.887	2.9	.	775	22	791	13	796
Tendaguru	TGU-41	279	46.2	14438	0.0693	0.0008	1.4395	0.0352	0.1506	0.0033	0.896	-0.5	.	909	22	906	15	904

Summary of U-Pb zircon data from Mandawa Basin sandstones

Formation	Name	U ppm	²⁰⁶ Pb ppm	Ratios						Ages									
				²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁶ Pb*	1σ	²⁰⁷ Pb/ ²³⁵ U*	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ	Rho	Discordance (%), Central Min.	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ	
Tendaguru	TGU-42	123	15.6	8817	0.0639	0.0007	1.0223	0.0257	0.1160	0.0026	0.890	-4.4	.	738	22	715	13	708	15
Tendaguru	TGU-43	142	18.8	5780	0.0648	0.0013	1.0579	0.0284	0.1184	0.0022	0.689	-6.5	.	768	39	733	14	721	13
Tendaguru	TGU-44	209	29.9	7767	0.0649	0.0007	1.1653	0.0288	0.1303	0.0029	0.895	2.7	.	770	23	784	14	790	16
Tendaguru	TGU-45	430	29.8	345	0.0979	0.0012	0.8665	0.0201	0.0642	0.0013	0.844	-77	-75.9	1585	23	634	11	401	8
Tendaguru	TGU-46	235	41.2	8180	0.0719	0.0015	1.5527	0.0418	0.1566	0.0028	0.658	-5	.	984	41	952	17	938	15
Tendaguru	TGU-47	981	144.2	4995	0.0793	0.0010	1.5174	0.0598	0.1388	0.0052	0.948	-30.9	-26.2	1179	23	937	24	838	29
Tendaguru	TGU-48	264	45.4	11693	0.0703	0.0014	1.4454	0.0415	0.1492	0.0030	0.703	-4.5	.	936	41	908	17	897	17
Tendaguru	TGU-49	178	31.4	10236	0.0736	0.0008	1.6414	0.0388	0.1618	0.0034	0.881	-6.7	-0.8	1030	21	986	15	967	19
Tendaguru	TGU-50	216	23.8	6885	0.0600	0.0007	0.8402	0.0192	0.1016	0.0020	0.878	3.5	.	604	23	619	11	624	12
Tendaguru	TGU-51	204	37.5	25558	0.0726	0.0008	1.6835	0.0405	0.1683	0.0036	0.881	0.1	.	1002	23	1002	15	1003	20
Tendaguru	TGU-52	86	14.7	5759	0.0719	0.0009	1.5569	0.0387	0.1570	0.0034	0.876	-4.7	.	983	24	953	15	940	19
Tendaguru	TGU-53	351	37.7	14012	0.0585	0.0006	0.7975	0.0184	0.0990	0.0020	0.882	11.8	1.5	547	23	595	10	608	12
Tendaguru	TGU-54	30	5.6	1640	0.0723	0.0009	1.6660	0.0438	0.1672	0.0039	0.877	0.4	.	993	25	996	17	997	21
Tendaguru	TGU-55	88	7.9	2906	0.0586	0.0007	0.6689	0.0160	0.0828	0.0017	0.854	-7.4	.	552	25	520	10	513	10
Tendaguru	TGU-56	407	70.1	30009	0.0719	0.0008	1.5640	0.0384	0.1578	0.0034	0.888	-4.2	.	983	22	956	15	945	19
Tendaguru	TGU-57	588	52.9	8123	0.0581	0.0006	0.6662	0.0156	0.0832	0.0017	0.881	-3.7	.	534	23	518	10	515	10
Tendaguru	TGU-58	119	12.6	122440	0.0598	0.0007	0.8053	0.0194	0.0977	0.0021	0.875	0.8	.	596	24	600	11	601	12
Tendaguru	TGU-59	257	47.6	12209	0.0729	0.0011	1.5496	0.0682	0.1541	0.0064	0.937	-9.3	-0.8	1011	30	950	27	924	36
Tendaguru	TGU-60	130	24.1	9286	0.0749	0.0009	1.7549	0.0443	0.1700	0.0038	0.883	-5.3	.	1065	23	1029	16	1012	21
Tendaguru	TGU-62	655	63.4	2265	0.0593	0.0014	0.8029	0.0264	0.0981	0.0023	0.718	4.4	.	579	50	598	15	604	14
Tendaguru	TGU-63	119	23	6291	0.0747	0.0005	1.8252	0.0538	0.1772	0.0051	0.975	-0.9	.	1060	13	1055	19	1052	28
Tendaguru	TGU-64	28	3.4	122	0.1603	0.0019	2.4448	0.0764	0.1106	0.0032	0.929	-76.2	-75.3	2459	19	1256	23	676	19
Tendaguru	TGU-65	666	109.8	22945	0.0693	0.0004	1.4395	0.0439	0.1506	0.0045	0.980	-0.5	.	909	12	905	18	904	25
Tendaguru	TGU-66	131	17.1	3026	0.0647	0.0004	1.0653	0.0331	0.1194	0.0036	0.976	-5.1	-0.3	764	14	736	16	727	21
Tendaguru	TGU-67	36	10.6	6147	0.1046	0.0029	4.1489	0.1763	0.2878	0.0092	0.753	-5	.	1706	49	1664	35	1631	46
Tendaguru	TGU-68	296	32.5	18875	0.0598	0.0004	0.8261	0.0272	0.1001	0.0032	0.979	3.1	.	598	14	611	15	615	19
Tendaguru	TGU-69	539	59.6	17552	0.0608	0.0004	0.8372	0.0324	0.0998	0.0038	0.985	-3.4	.	634	14	618	18	613	22
Tendaguru	TGU-70	625	66.1	37004	0.0611	0.0004	0.8021	0.0322	0.0953	0.0038	0.986	-8.9	-3.5	641	14	598	18	587	22
Tendaguru	TGU-71	1240	105.3	1345	0.0821	0.0026	0.8450	0.0493	0.0747	0.0037	0.847	-65	-59.6	1247	61	622	27	464	22

Summary of U-Pb zircon data from Mandawa Basin sandstones

Formation	Name	U ppm	²⁰⁶ Pb ppm	Ratios										Ages							
				²⁰⁶ Pb/ ²⁰⁴ Pb					²⁰⁷ Pb/ ²³⁵ U					Discordance (%)				²⁰⁶ Pb/ ²³⁸ U			
				²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁶ Pb	²⁰⁷ Pb/ ²³⁵ U	1σ	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	1σ	Rho	Central	Min.	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ	
Tendaguru	TGU-72	460	65.5	19892	0.0671	0.0005	1.1730	0.0533	0.1269	0.0057	0.988	-8.8	-4.5	839	14	788	25	770	33		
Tendaguru	TGU-73	535	52.9	20211	0.0606	0.0004	0.7383	0.0343	0.0884	0.0041	0.988	-13.1	-7.5	624	15	561	20	546	24		
Tendaguru	TGU-74	1120	112.9	718	0.0836	0.0010	1.0266	0.0520	0.0891	0.0044	0.974	-59.6	-57.3	1284	22	717	26	550	26		
Tendaguru	TGU-75	211	38.4	20687	0.0743	0.0018	1.8338	0.0691	0.1790	0.0052	0.768	1.3	.	1049	46	1058	25	1062	28		
Tendaguru	TGU-76	226	78.9	23752	0.1182	0.0036	5.4331	0.2619	0.3334	0.0125	0.78	-4.4	.	1929	51	1890	41	1855	61		
Tendaguru	TGU-77	888	151.3	33473	0.0721	0.0017	1.6563	0.0626	0.1666	0.0049	0.773	0.5	.	989	48	992	24	993	27		
Mitole	M13-7-01	594	37.4	1533	0.0740	0.0039	0.7448	0.0405	0.0730	0.0010	0.249	-58.4	-43.1	1042	102	565	24	454	6		
Mitole	M13-7-02	997	61.6	2954	0.0692	0.0004	0.7470	0.0163	0.0783	0.0016	0.956	-48.1	-45.9	906	13	567	9	486	10		
Mitole	M13-7-03	960	82.9	3053	0.0685	0.0007	0.7964	0.0328	0.0843	0.0034	0.969	-42.6	-38.6	883	21	595	19	522	20		
Mitole	M13-7-04	560	70.2	17130	0.0852	0.0046	1.6973	0.0984	0.1445	0.0032	0.383	-36.4	-19.4	1319	99	1008	37	870	18		
Mitole	M13-7-05	110	2.9	898	0.0521	0.0026	0.2201	0.0111	0.0306	0.0004	0.247	-33.8	.	292	108	202	9	194	2		
Mitole	M13-7-06	461	57.8	3901	0.0714	0.0007	1.1076	0.0377	0.1125	0.0037	0.960	-30.6	-26.5	969	20	757	18	687	21		
Mitole	M13-7-07	775	89.8	6580	0.0776	0.0041	1.4357	0.0793	0.1342	0.0023	0.316	-30.4	-7.9	1137	101	904	33	812	13		
Mitole	M13-7-08	217	24.6	4173	0.0689	0.0007	0.9871	0.0316	0.1040	0.0032	0.953	-30.2	-25.7	895	19	697	16	638	19		
Mitole	M13-7-09	165	18	3813	0.0659	0.0008	0.9163	0.0317	0.1009	0.0033	0.941	-24	-17.5	803	24	660	17	619	19		
Mitole	M13-7-10	222	15.6	3870	0.0609	0.0030	0.6859	0.0350	0.0817	0.0010	0.247	-21.2	.	636	105	530	21	506	6		
Mitole	M13-7-11	234	19.9	7217	0.0643	0.0032	0.8748	0.0453	0.0987	0.0013	0.262	-20.1	.	751	98	638	25	607	8		
Mitole	M13-7-12	69	7.7	2716	0.0701	0.0016	1.2103	0.0327	0.1253	0.0017	0.507	-19.2	-7.9	930	46	805	15	761	10		
Mitole	M13-7-13	163	21.5	12402	0.0757	0.0039	1.5825	0.0849	0.1517	0.0022	0.266	-17.4	.	1087	96	963	33	910	12		
Mitole	M13-7-14	114	14.9	7069	0.0747	0.0039	1.5453	0.0835	0.1501	0.0023	0.287	-16	.	1060	101	949	33	901	13		
Mitole	M13-7-15	621	89.8	28946	0.0786	0.0041	1.7974	0.0976	0.1659	0.0025	0.275	-16	.	1161	96	1045	35	990	14		
Mitole	M13-7-16	343	27.4	13245	0.0619	0.0031	0.7931	0.0406	0.0929	0.0012	0.261	-15.4	.	672	101	593	23	573	7		
Mitole	M13-7-17	156	22.4	9218	0.0777	0.0040	1.7664	0.0953	0.1650	0.0024	0.265	-14.5	.	1138	99	1033	35	984	13		
Mitole	M13-7-18	177	37.7	7812	0.0845	0.0009	2.2574	0.0819	0.1937	0.0067	0.955	-13.6	-9	1304	21	1199	26	1142	36		
Mitole	M13-7-19	65	10	3788	0.0783	0.0041	1.8897	0.1028	0.1751	0.0024	0.257	-10.7	.	1154	101	1077	36	1040	13		
Mitole	M13-7-20	178	33.7	9683	0.0755	0.0008	1.7174	0.0598	0.1649	0.0055	0.952	-9.8	-4.3	1083	21	1015	22	984	30		
Mitole	M13-7-21	191	32.4	9598	0.0725	0.0007	1.5297	0.0522	0.1530	0.0050	0.956	-8.9	-3.3	1001	19	942	21	918	28		
Mitole	M13-7-22	74	10.9	4457	0.0757	0.0039	1.7450	0.0940	0.1673	0.0024	0.265	-8.9	.	1086	103	1025	35	997	13		
Mitole	M13-7-23	123	13.9	6979	0.0675	0.0035	1.2007	0.0639	0.1290	0.0018	0.26	-8.8	.	853	100	801	29	782	10		

Summary of U-Pb zircon data from Mandawa Basin sandstones

Formation	Name	U ppm	²⁰⁶ Pb ppm	Ratios										Ages														
				²⁰⁶ Pb/ ²⁰⁴ Pb					²⁰⁷ Pb/ ²³⁵ U*					Discordance (%)					²⁰⁷ Pb/ ²³⁵ U					²⁰⁶ Pb/ ²³⁸ U				
				²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U*	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ	Rho	Central	Min.	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ									
Mitole	M13-7-24	67	4.8	1977	0.0588	0.0029	0.6690	0.0343	0.0825	0.0011	0.253	-8.8	.	559	107	520	21	511	6									
Mitole	M13-7-25	213	15.2	9418	0.0585	0.0013	0.6559	0.0166	0.0813	0.0011	0.513	-8.4	.	548	46	512	10	504	6									
Mitole	M13-7-26	158	16.4	10320	0.0654	0.0033	1.0740	0.0561	0.1192	0.0017	0.266	-8.1	.	786	101	741	27	726	10									
Mitole	M13-7-27	501	37.5	12512	0.0593	0.0029	0.7089	0.0359	0.0866	0.0011	0.254	-7.9	.	580	103	544	21	536	7									
Mitole	M13-7-28	541	51	20040	0.0594	0.0005	0.7132	0.0223	0.0871	0.0026	0.956	-7.7	.	581	19	547	13	538	15									
Mitole	M13-7-29	71	7.2	2995	0.0644	0.0015	1.0208	0.0272	0.1149	0.0016	0.535	-7.7	.	756	44	714	14	701	9									
Mitole	M13-7-30	188	20.4	56384	0.0614	0.0007	0.8359	0.0282	0.0987	0.0032	0.949	-7.6	.	654	23	617	16	607	19									
Mitole	M13-7-31	167	26.4	10057	0.0707	0.0007	1.4311	0.0498	0.1467	0.0049	0.959	-7.6	-1.8	950	19	902	21	883	28									
Mitole	M13-7-32	437	73.9	26362	0.0716	0.0007	1.4944	0.0495	0.1513	0.0048	0.960	-7.4	-2	975	18	928	20	908	27									
Mitole	M13-7-33	87	13	6181	0.0687	0.0008	1.3043	0.0492	0.1377	0.0049	0.952	-6.9	.	889	22	848	22	832	28									
Mitole	M13-7-34	507	42	14745	0.0609	0.0030	0.8117	0.0420	0.0966	0.0014	0.282	-6.8	.	636	102	603	24	595	8									
Mitole	M13-7-35	83	32.3	5121	0.1757	0.0015	11.3459	0.3514	0.4684	0.0139	0.96	-6.3	-3.7	2613	14	2552	29	2477	61									
Mitole	M13-7-36	892	82.1	28322	0.0590	0.0006	0.7120	0.0118	0.0875	0.0012	0.797	-5.1	.	568	21	546	7	541	7									
Mitole	M13-7-37	732	95.7	32641	0.0708	0.0037	1.4824	0.0872	0.1518	0.0040	0.443	-4.7	.	952	105	923	36	911	22									
Mitole	M13-7-38	127	10	2283	0.0595	0.0030	0.7442	0.0386	0.0907	0.0011	0.243	-4.5	.	585	106	565	22	560	7									
Mitole	M13-7-39	483	53	13793	0.0617	0.0006	0.8863	0.0327	0.1042	0.0037	0.965	-4	.	664	20	644	18	639	22									
Mitole	M13-7-40	207	33.5	9554	0.0691	0.0007	1.3800	0.0453	0.1449	0.0045	0.956	-3.3	.	901	20	880	19	872	26									
Mitole	M13-7-41	415	21	57730	0.0551	0.0003	0.4879	0.0092	0.0643	0.0012	0.952	-3.2	.	415	13	403	6	402	7									
Mitole	M13-7-42	49	5.1	7096	0.0641	0.0033	1.0577	0.0555	0.1196	0.0015	0.247	-2.4	.	745	103	733	27	729	9									
Mitole	M13-7-43	125	10.3	4094	0.0598	0.0030	0.7809	0.0401	0.0948	0.0013	0.262	-2	.	595	103	586	23	584	8									
Mitole	M13-7-44	476	81.5	28178	0.0714	0.0007	1.5697	0.0557	0.1594	0.0054	0.959	-1.8	.	969	20	958	22	954	30									
Mitole	M13-7-45	96	10.9	4170	0.0616	0.0008	0.9032	0.0314	0.1063	0.0034	0.925	-1.6	.	661	28	653	17	651	20									
Mitole	M13-7-46	371	58.4	16325	0.0754	0.0040	1.8604	0.1015	0.1791	0.0024	0.246	-1.6	.	1078	103	1067	36	1062	13									
Mitole	M13-7-47	168	13.9	4128	0.0596	0.0013	0.7775	0.0202	0.0946	0.0013	0.509	-1.4	.	590	46	584	12	582	7									
Mitole	M13-7-48	208	22.1	5842	0.0602	0.0006	0.8115	0.0256	0.0978	0.0029	0.95	-1.3	.	609	21	603	14	602	17									
Mitole	M13-7-49	185	22.7	22450	0.0702	0.0004	1.4969	0.0295	0.1546	0.0029	0.950	-1	.	935	12	929	12	927	16									
Mitole	M13-7-50	87	13.4	2096	0.0670	0.0007	1.2744	0.0430	0.1380	0.0044	0.949	-0.4	.	837	21	834	19	833	25									
Mitole	M13-7-51	196	27.7	13216	0.0651	0.0006	1.1501	0.0181	0.1281	0.0016	0.795	-0.2	.	778	19	777	9	777	9									
Mitole	M13-7-52	80	12.4	4070	0.0661	0.0007	1.2213	0.0401	0.1341	0.0042	0.947	0.3	.	809	21	810	18	811	24									

Summary of U-Pb zircon data from Mandawa Basin sandstones

Formation	Name	U ppm	^{206}Pb ppm	Ratios										Ages					
				$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$					$\frac{^{207}\text{Pb}}{^{235}\text{U}}$					Discordance (%)			$\frac{^{206}\text{Pb}}{^{238}\text{U}}$		
				^{206}Pb ^{204}Pb	1σ	^{207}Pb ^{206}Pb	1σ	^{207}Pb ^{235}U	1σ	^{206}Pb ^{238}U	1σ	Rho	Central	Min.	^{207}Pb ^{206}Pb	1σ	^{207}Pb ^{235}U	1σ	^{206}Pb ^{238}U
Mitole	M13-7-53	354	40.3	14263	0.0611	0.0006	0.8955	0.0294	0.1063	0.0033	0.956	1.3	.	.	643	21	649	16	651
Mitole	M13-7-54	166	12.6	7368	0.0577	0.0013	0.6879	0.0174	0.0864	0.0011	0.522	2.9	.	.	520	46	532	10	534
Mitole	M13-7-55	67	5.2	4626	0.0596	0.0006	0.8117	0.0161	0.0988	0.0017	0.862	3.4	.	.	589	21	603	9	607
Mitole	M13-7-56	322	36	13435	0.0600	0.0006	0.8590	0.0279	0.1039	0.0032	0.957	6.2	.	.	602	19	630	15	637
Mitole	NG-01	77	7.4	2050	0.0646	0.0017	1.0114	0.0318	0.1135	0.0021	0.581	-9.4	.	.	761	53	710	16	693
Mitole	NG-02	61	5	1972	0.0596	0.0014	0.7659	0.0206	0.0932	0.0014	0.540	-2.7	.	.	590	48	577	12	574
Mitole	NG-03	257	81.6	22447	0.1242	0.0035	5.6838	0.1984	0.3320	0.0068	0.59	-9.6	-2.9	-2.9	2017	48	1929	30	1848
Mitole	NG-04	162	24.5	33040	0.0756	0.0018	1.7622	0.0493	0.1690	0.0024	0.513	-7.9	.	.	1086	45	1032	18	1006
Mitole	NG-05	86	11.7	4185	0.0744	0.0018	1.5696	0.0442	0.1530	0.0022	0.509	-13.7	-2.8	-2.8	1052	49	958	17	918
Mitole	NG-06	377	29.1	7719	0.0591	0.0013	0.7179	0.0185	0.0881	0.0011	0.502	-4.8	.	.	571	48	549	11	544
Mitole	NG-07	464	54.2	21191	0.0666	0.0015	1.2123	0.0325	0.1319	0.0018	0.519	-3.6	.	.	827	47	806	15	799
Mitole	NG-08	333	46.9	10368	0.0757	0.0018	1.6540	0.0463	0.1585	0.0023	0.524	-13.7	-3.6	-3.6	1087	45	991	18	948
Mitole	NG-09	1563	33.9	150	0.1522	0.0054	0.5301	0.0224	0.0253	0.0006	0.539	-94.3	-93.9	-93.9	2370	58	432	15	161
Mitole	NG-10	319	53.9	188885	0.0731	0.0015	1.5852	0.0750	0.1572	0.0067	0.899	-8.1	.	.	1018	40	964	29	941
Mitole	NG-11	1226	47.8	201	0.1258	0.0020	0.6345	0.0138	0.0366	0.0005	0.692	-90.2	-89.7	-89.7	2040	27	499	9	232
Mitole	NG-12	690	95.4	22366	0.0783	0.0023	1.4497	0.0811	0.1343	0.0064	0.856	-31.5	-20.9	-20.9	1154	55	910	34	813
Mitole	NG-13	814	115.1	3665	0.0793	0.0013	1.4368	0.0524	0.1314	0.0043	0.897	-34.6	-29.1	-29.1	1180	32	904	22	796
Mitole	NG-14	452	47.3	7094	0.0600	0.0012	0.7997	0.0367	0.0966	0.0040	0.908	-1.6	.	.	604	40	597	21	595
Mitole	NG-15	467	83.8	3736	0.0740	0.0015	1.6995	0.0817	0.1666	0.0072	0.905	-4.9	.	.	1041	40	1008	31	993
Mitole	NG-16	210	39.3	3765	0.0773	0.0016	1.8565	0.0907	0.1741	0.0077	0.901	-9	.	.	1129	40	1066	32	1035
Mitole	NG-17	176	16.9	30575	0.0603	0.0013	0.7581	0.0352	0.0912	0.0038	0.894	-8.9	.	.	615	44	573	20	562
Mitole	NG-18	309	48.9	25727	0.0696	0.0009	1.4284	0.0311	0.1488	0.0026	0.802	-2.6	.	.	917	25	901	13	894
Mitole	NG-19	1327	39.9	143	0.1467	0.0025	0.5693	0.0138	0.0282	0.0005	0.699	-93.5	-93.2	-93.2	2307	30	458	9	179
Mitole	NG-20	259	39.8	17737	0.0750	0.0018	1.7842	0.0498	0.1726	0.0025	0.524	-4.2	.	.	1068	46	1040	18	1026
Mitole	NG-21	125	43.5	10523	0.1134	0.0017	5.1130	0.1357	0.3270	0.0071	0.815	-1.9	.	.	1855	27	1838	23	1824
Mitole	NG-22	115	21	6928	0.0745	0.0008	1.6466	0.0928	0.1604	0.0089	0.98	-9.7	-3.8	-3.8	1054	22	988	36	959
Mitole	NG-23	125	13.3	4298	0.0663	0.0008	0.8616	0.0461	0.0943	0.0049	0.976	-30	-24	-24	815	24	631	25	581
Mitole	NG-24	71	11.9	2714	0.0733	0.0009	1.4789	0.0840	0.1462	0.0081	0.978	-15	-8.9	-8.9	1023	24	922	34	880
Mitole	NG-25	132	12.2	4216	0.0591	0.0012	0.7217	0.0328	0.0886	0.0036	0.901	-4.1	.	.	570	42	552	19	547

Summary of U-Pb zircon data from Mandawa Basin sandstones

Formation	Name	U ppm	^{206}Pb ppm	Ratios										Ages					
				$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$					$\frac{^{207}\text{Pb}}{^{235}\text{U}}$					Discordance (%)			$\frac{^{207}\text{Pb}}{^{235}\text{U}}$		
				$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	Central	Min.	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$
Mitole	NG-26	214	29.3	14359	0.0729	0.0008	1.2009	0.0680	0.1194	0.0066	0.980	-29.7	-24.9	1012	22	801	31	727	38
Mitole	NG-27	143	27.2	47607	0.0786	0.0016	1.9327	0.0970	0.1784	0.0081	0.909	-9.7	.	1162	42	1092	34	1058	45
Mitole	NG-28	205	36.6	14232	0.0761	0.0015	1.7604	0.0880	0.1677	0.0077	0.914	-9.7	.	1099	39	1031	32	999	42
Mitole	NG-29	323	50.4	20098	0.0754	0.0018	1.8242	0.0516	0.1754	0.0026	0.528	-3.8	.	1080	46	1054	19	1042	14
Mitole	NG-30	306	23.3	1878	0.0694	0.0009	0.6359	0.0378	0.0665	0.0039	0.978	-56.1	-52.5	909	25	500	23	415	23
Mitole	NG-31	126	19.7	4668	0.0704	0.0014	1.4041	0.0703	0.1446	0.0066	0.914	-8	.	941	40	891	30	871	37
Mitole	NG-32	136	23.3	5851	0.0822	0.0019	1.6603	0.1109	0.1465	0.0092	0.939	-31.5	-23.3	1250	44	993	42	882	52
Mitole	NG-33	198	15.5	4242	0.0647	0.0008	0.6058	0.0372	0.0679	0.0041	0.981	-46	-41	764	25	481	23	424	25
Mitole	NG-34	37	15.8	4130	0.1987	0.0040	9.5235	0.8203	0.3476	0.0291	0.973	-36.5	-32.7	2816	32	2390	79	1923	139
Mitole	NG-35	520	35.7	7300	0.0587	0.0007	0.4802	0.0296	0.0593	0.0036	0.982	-34.3	-26.2	557	25	398	20	371	22
Mitole	NG-36	307	27.7	9060	0.0661	0.0008	0.7063	0.0446	0.0775	0.0048	0.982	-42.1	-37	809	24	543	27	481	29
Mitole	NG-37	154	27.9	10428	0.0800	0.0010	1.6919	0.1145	0.1534	0.0102	0.983	-24.8	-19.8	1196	24	1005	43	920	57
Mitole	NG-38	32	5.7	1416	0.0813	0.0011	1.6619	0.1136	0.1483	0.0099	0.979	-29.3	-24.2	1227	27	994	43	892	56
Mitole	NG-39	259	34.1	12755	0.0709	0.0017	1.4547	0.0401	0.1487	0.0021	0.519	-6.9	.	956	47	912	17	894	12
Mitole	NG-40	183	31.9	8781	0.0781	0.0010	1.5837	0.1088	0.1471	0.0099	0.982	-24.6	-19.3	1149	24	964	43	885	56
Mitole	NG-41	65	11.6	4968	0.0786	0.0011	1.6146	0.1124	0.1490	0.0102	0.98	-24.5	-18.9	1161	26	976	44	896	57
Mitole	NG-42	220	31.8	9784	0.0714	0.0009	1.2043	0.0823	0.1224	0.0082	0.981	-24.5	-18.3	968	26	803	38	744	47
Mitole	NG-43	249	33.5	4277	0.0771	0.0010	1.2154	0.0841	0.1143	0.0078	0.983	-40	-35.9	1124	24	808	39	698	45
Mitole	NG-44	89	7.3	1453	0.0890	0.0040	0.8472	0.0687	0.0690	0.0047	0.833	-71.6	-65.8	1404	85	623	38	430	28
Mitole	NG-45	141	15.2	25998	0.0683	0.0016	1.1535	0.0319	0.1225	0.0017	0.511	-16.1	-3.1	878	47	779	15	745	10
Mitole	NG-46	133	12.2	8224	0.0610	0.0014	0.8822	0.0237	0.1049	0.0015	0.52	0.8	.	638	47	642	13	643	9
Mitole	NG-47	50	4.8	1412	0.0631	0.0015	0.9528	0.0264	0.1096	0.0015	0.509	-5.9	.	710	49	680	14	670	9
Mitole	NG-48	91	8.9	2597	0.0637	0.0016	0.9820	0.0278	0.1118	0.0016	0.516	-6.9	.	731	50	695	14	683	9
Mitole	NG-49	344	64.7	2405	0.1258	0.0038	3.6454	0.1266	0.2102	0.0036	0.491	-43.5	-39.3	2039	52	1560	28	1230	19
Mitole	NG-50	526	41.8	455	0.1304	0.0041	1.6718	0.0618	0.0930	0.0019	0.542	-75.9	-74	2103	50	998	24	573	11
Mitole	NG-51	229	32.7	14920	0.0764	0.0019	1.7034	0.0494	0.1616	0.0024	0.517	-13.7	-3.3	1107	50	1010	19	966	13
Mitole	NG-52	1112	68.5	289	0.1146	0.0040	1.1182	0.0454	0.0708	0.0015	0.525	-79	-77	1873	62	762	22	441	9
Mitole	NG-53	443	62	17892	0.0738	0.0018	1.6225	0.0472	0.1595	0.0025	0.530	-8.5	.	1036	47	979	18	954	14
Mitole	NG-54	213	17.7	8679	0.0627	0.0015	0.8299	0.0236	0.0960	0.0014	0.528	-15.9	.	697	50	614	13	591	8

Summary of U-Pb zircon data from Mandawa Basin sandstones

Formation	Name	U ppm	^{206}Pb ppm	Ratios										Ages				
				$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	Discordance (%)	Central	Min.	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$
Mitole	NG-55	188	20.4	11101	0.0688	0.0017	1.1858	0.0342	0.1250	0.0019	0.522	-16	-2.7	894	50	794	16	759
Mitole	NG-56	190	13.7	4927	0.0582	0.0014	0.6680	0.0186	0.0833	0.0012	0.514	-4	.	536	52	519	11	516
Mitole	NG-57	456	140.7	21542	0.1313	0.0041	6.0541	0.2209	0.3345	0.0065	0.532	-13.9	-7.4	2115	52	1984	32	1860
Mitole	NG-58	453	31.5	12409	0.0615	0.0015	0.6771	0.0188	0.0799	0.0011	0.516	-25.3	-8.3	655	50	525	11	496
Mitole	NG-59	205	23.1	21245	0.0679	0.0017	1.2107	0.0354	0.1294	0.0020	0.523	-9.8	.	864	51	805	16	784
Mitole	NG-60	887	79.4	3199	0.0640	0.0022	0.9436	0.0501	0.1069	0.0044	0.772	-12.3	.	742	67	675	26	655
Mitole	NG-61	218	35.8	17966	0.0756	0.0023	1.7598	0.0686	0.1688	0.0042	0.634	-7.9	.	1085	57	1031	25	1006
Mitole	NG-62	1027	176.9	704	0.1283	0.0058	3.6103	0.2369	0.2041	0.0098	0.729	-46.2	-38.9	2074	80	1552	52	1197
Mitole	NG-63	764	33	112	0.1692	0.0092	1.2794	0.0917	0.0548	0.0026	0.650	-88.7	-87.2	2550	88	837	41	344
Mitole	NG-64	902	135.5	2784	0.0801	0.0035	2.0299	0.1414	0.1839	0.0099	0.775	-10	.	1198	84	1126	47	1088
Mitole	NG-65	174	26.7	18076	0.0699	0.0031	1.8491	0.1300	0.1920	0.0105	0.777	24.5	.	924	89	1063	46	1132
Mitole	NG-66	239	47.9	13462	0.0837	0.0039	2.9080	0.2171	0.2520	0.0146	0.777	14.2	.	1285	88	1384	56	1449
Mitole	NG-67	450	50.2	1185	0.0796	0.0012	1.3306	0.0861	0.1212	0.0076	0.972	-40.1	-35.2	1187	30	859	38	738
Mitole	NG-68	368	47.1	50597	0.0683	0.0010	1.3041	0.0863	0.1385	0.0090	0.978	-5	.	877	27	848	38	836
Mitole	NG-69	175	14.4	4829	0.0591	0.0009	0.7365	0.0495	0.0904	0.0059	0.975	-2.1	.	569	32	560	29	558
Mitole	NG-70	312	46.4	541	0.0958	0.0024	2.1363	0.1574	0.1617	0.0112	0.942	-40.2	-33.6	1544	45	1161	51	966
Mitole	NG-71	173	26.3	7071	0.0717	0.0011	1.6484	0.1217	0.1668	0.0121	0.979	2	.	977	30	989	47	994
Mitole	NG-72	673	102.1	6162	0.0732	0.0023	1.6003	0.0629	0.1585	0.0039	0.621	-7.5	.	1020	60	970	25	949
Mitole	NG-73	87	42.4	18209	0.1827	0.0039	12.5188	1.2032	0.4969	0.0466	0.975	-3.5	.	2678	35	2644	90	2601
Mitole	NG-74	122	19.8	6827	0.0725	0.0011	1.7777	0.1395	0.1779	0.0137	0.98	6.1	.	999	30	1037	51	1055
Mitole	NG-75	290	47.2	27598	0.0723	0.0012	1.8096	0.1607	0.1815	0.0158	0.982	8.8	.	995	34	1049	58	1075
Mitole	NG-76	804	30.9	162	0.1407	0.0034	0.8457	0.0718	0.0436	0.0036	0.959	-89.5	-88.6	2236	40	622	39	275
Mitole	NG-77	763	76.9	2069	0.0806	0.0021	1.2666	0.1322	0.1139	0.0115	0.969	-44.9	-37.1	1212	48	831	59	696
Mitole	NG-78	355	39.5	7075	0.0661	0.0020	1.0959	0.0451	0.1203	0.0034	0.683	-9.9	.	808	57	751	22	732
Mitole	NG-79	420	92.8	2212	0.1274	0.0025	4.2796	0.4198	0.2437	0.0234	0.979	-35.3	-30.7	2062	33	1689	81	1406
Mitole	NG-80	304	46.4	3363	0.0761	0.0015	1.8080	0.1733	0.1722	0.0162	0.98	-7.3	.	1099	36	1048	63	1024
Mitole	NG-81	375	23.3	445	0.0904	0.0018	0.8986	0.0866	0.0721	0.0068	0.978	-71.1	-68.4	1435	37	651	46	449
Mitole	NG-82	288	11.7	3652	0.0518	0.0010	0.3364	0.0322	0.0471	0.0044	0.981	8.2	.	275	40	294	24	297
Mitole	NG-83	95	14.8	5236	0.0722	0.0014	1.7705	0.1788	0.1778	0.0176	0.981	6.8	.	992	38	1035	66	1055

Summary of U-Pb zircon data from Mandawa Basin sandstones

Formation	Name	U ppm	²⁰⁶ Pb ppm	Ratios										Ages														
				²⁰⁶ Pb/ ²⁰⁴ Pb					²⁰⁷ Pb/ ²³⁵ U*					²⁰⁶ Pb/ ²³⁸ U					Discordance (%)					²⁰⁷ Pb/ ²³⁵ U				
				²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U*	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ	Rho	Central	Min.	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ							
Mitole	NG-84	150	60	15397	0.1613	0.0037	9.7042	1.1109	0.4365	0.0489	0.979	-6.5	.	2469	36	2407	105	2335	220									
Mitole	NG-85	819	58.4	470	0.0827	0.0018	0.9453	0.0975	0.0829	0.0084	0.977	-61.7	-57.3	1262	40	676	51	513	50									
Mitole	NG-86	303	25.8	8399	0.0594	0.0006	0.7612	0.0235	0.0929	0.0027	0.943	-1.6	.	582	22	575	14	573	16									
Mitole	NG-87	460	41.5	1691	0.0598	0.0018	0.8191	0.0299	0.0994	0.0020	0.564	2.9	.	595	64	608	17	611	12									
Mitole	NG-88	258	33.4	13424	0.0666	0.0007	1.2888	0.0421	0.1404	0.0043	0.948	3	.	824	22	841	19	847	25									
Mitole	NG-89	293	22.4	5690	0.0575	0.0006	0.6664	0.0211	0.0841	0.0025	0.942	2	.	510	23	519	13	520	15									
Mitole	NG-90	1959	26.1	76	0.2331	0.0045	0.4801	0.0172	0.0149	0.0005	0.84	-97.6	-97.4	3073	29	398	12	96	3									
Mitole	NG-91	32	4	1134	0.0685	0.0009	1.3033	0.0449	0.1380	0.0044	0.918	-6.1	.	884	26	847	20	833	25									
Mitole	NG-92	466	72.9	18499	0.0765	0.0008	1.7959	0.0614	0.1702	0.0055	0.951	-9.3	-3.9	1109	21	1044	22	1013	30									
Mitole	NG-93	1281	49.1	275	0.1079	0.0015	0.6338	0.0220	0.0426	0.0014	0.918	-86.5	-85.7	1764	24	498	14	269	8									
Mitole	NG-94	74	7.8	3533	0.0546	0.0012	0.6730	0.0612	0.0893	0.0079	0.970	40.5	2.1	397	48	523	37	552	47									
Mitole	NG-95	970	111.2	447	0.0919	0.0023	1.2326	0.1226	0.0973	0.0094	0.969	-61.9	-57.4	1465	47	816	56	599	55									
Mitole	NG-96	458	64.7	11883	0.0597	0.0015	0.9889	0.1061	0.1202	0.0125	0.972	24.9	.	592	54	698	54	731	72									
Mitole	NG-97	627	69.6	13189	0.0566	0.0010	0.7488	0.0830	0.0960	0.0105	0.986	25.6	.	475	38	568	48	591	62									
Mitole	NG-98	100	18.9	8109	0.0658	0.0013	1.4685	0.1763	0.1618	0.0192	0.986	22.4	.	801	41	918	73	967	106									
Mitole	NG-99	325	60.2	17851	0.0734	0.0018	1.6607	0.1041	0.1641	0.0095	0.923	-4.9	.	1025	48	994	40	979	53									
Mitole	NG-100	575	116.9	38327	0.0759	0.0019	1.8934	0.1252	0.1808	0.0111	0.928	-2.2	.	1093	48	1079	44	1072	61									
Mitole	NG-101	216	40.9	29702	0.0757	0.0019	1.7450	0.1192	0.1671	0.0106	0.930	-9.1	.	1088	48	1025	44	996	59									
Mitole	NG-102	383	69.3	19634	0.0749	0.0019	1.6529	0.1163	0.1600	0.0105	0.932	-11.1	.	1067	49	991	45	957	58									
Mitole	NG-103	1644	54.8	174	0.1490	0.0048	0.6140	0.0486	0.0299	0.0022	0.915	-93.2	-92.4	2334	53	486	31	190	14									
Mitole	NG-104	1380	53.9	173	0.1657	0.0072	0.8089	0.0817	0.0354	0.0032	0.903	-92.6	-91.5	2515	72	602	46	224	20									
Mitole	NG-105	354	75.7	19125	0.0866	0.0025	2.2309	0.1941	0.1868	0.0153	0.943	-19.9	-8.3	1352	54	1191	61	1104	83									
Mitole	NG-106	166	14.3	4063	0.0580	0.0011	0.7040	0.0208	0.0881	0.0020	0.769	3.2	.	528	39	541	12	544	12									
Mitole	NG-107	599	74.4	1014	0.0872	0.0020	1.5307	0.0563	0.1272	0.0037	0.783	-46.1	-40.9	1366	40	943	23	772	21									
Mitole	NG-108	231	19.5	10864	0.0624	0.0014	0.7663	0.0282	0.0891	0.0026	0.791	-20.9	-6.3	688	47	578	16	550	15									
Mitole	NG-109	542	47.2	400	0.0999	0.0028	1.2600	0.0561	0.0915	0.0032	0.781	-68	-64.7	1623	50	828	25	564	19									
Mitole	NG-110	163	20.6	2722	0.0703	0.0018	1.3007	0.0565	0.1343	0.0047	0.799	-14	-0.5	936	53	846	25	812	26									
Mitole	NG-111	168	50.2	13823	0.1067	0.0037	4.5902	0.2719	0.3121	0.0151	0.816	0.5	.	1743	61	1747	49	1751	74									
Mitole	NG-112	563	24.3	1668	0.0718	0.0032	0.4951	0.0316	0.0500	0.0023	0.709	-69.5	-61.1	980	92	408	21	315	14									

Summary of U-Pb zircon data from Mandawa Basin sandstones

Formation	Name	U ppm	^{206}Pb ppm	Ratios										Ages					
				$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$					$\frac{^{207}\text{Pb}}{^{235}\text{U}}$					Discordance (%)			$\frac{^{206}\text{Pb}}{^{238}\text{U}}$		
				$^{206}\text{Pb}^*$	1 σ	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	1 σ	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	1 σ	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	1 σ	Rho	Central	Min.	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	1 σ	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	1 σ	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$
Mitole	NG-113	143	25.4	7257	0.0775	0.0029	2.1513	0.1378	0.2013	0.0105	0.811	4.6	.	.	1135	73	1165	44	1182
Mitole	NG-114	725	53.3	276	0.1181	0.0049	1.4275	0.0961	0.0877	0.0047	0.791	-74.8	-71.3	-71.3	1927	71	900	40	542
Mitole	NG-115	639	55.4	1053	0.0743	0.0007	0.8736	0.0248	0.0853	0.0023	0.94	-51.7	-49	-49	1049	19	637	13	528
Mitole	NG-116	291	37.7	7972	0.0657	0.0006	1.1402	0.0327	0.1258	0.0034	0.953	-4.5	.	.	798	18	773	16	764
Mitole	NG-117	543	93.5	11470	0.0737	0.0007	1.6902	0.0514	0.1664	0.0048	0.958	-4.3	.	.	1033	17	1005	19	992
Mitole	NG-118	1035	153.6	2204	0.0774	0.0007	1.5306	0.0467	0.1434	0.0042	0.955	-25.3	-21.6	-21.6	1132	17	943	19	864
Mitole	NG-119	460	44.5	11939	0.0577	0.0005	0.7570	0.0231	0.0952	0.0028	0.956	14	3.2	3.2	517	19	572	13	586
Mitole	NG-120	78	6.6	3726	0.0557	0.0007	0.6423	0.0210	0.0836	0.0025	0.931	18.3	3.3	3.3	440	25	504	13	518
Mitole	NG-121	266	49.4	11562	0.0735	0.0007	1.8098	0.0616	0.1785	0.0058	0.961	3.2	.	.	1029	18	1049	22	1059
Mitole	NG-122	192	17.4	3849	0.0559	0.0006	0.6871	0.0228	0.0891	0.0028	0.951	23.3	9.2	9.2	450	21	531	14	550
Mitole	NG-123	98	8.4	3263	0.0581	0.0008	0.6384	0.0116	0.0797	0.0010	0.704	-7.6	.	.	533	28	501	7	494
Mitole	NG-124	1497	116.4	10358	0.0745	0.0042	0.7706	0.0490	0.0750	0.0022	0.451	-57.8	-41.2	-41.2	1055	113	580	28	466
Mitole	NG-125	502	58.3	2745	0.0698	0.0009	1.0514	0.0199	0.1092	0.0016	0.759	-29	-24.1	-24.1	923	25	730	10	668
Mitole	NG-126	293	51.2	33719	0.0739	0.0016	1.6467	0.0789	0.1616	0.0070	0.899	-7.5	.	.	1039	42	988	30	966
Mitole	NG-127	128	23.9	3031	0.0767	0.0017	1.8441	0.0882	0.1743	0.0074	0.889	-7.7	.	.	1115	41	1061	31	1036
Kipatimu	MN-01	1163	51.9	131	0.1498	0.0024	0.8446	0.0181	0.0409	0.0006	0.677	-90.7	-90.3	-90.3	2344	27	622	10	258
Kipatimu	MN-02	447	80.5	1944	0.0723	0.0005	1.5027	0.0172	0.1508	0.0014	0.798	-9.4	-6.1	-6.1	993	14	931	7	906
Kipatimu	MN-03	119	10.8	1308	0.0563	0.0005	0.6125	0.0066	0.0789	0.0006	0.671	5.7	.	.	464	17	485	4	490
Kipatimu	MN-04	152	18.7	5345	0.0608	0.0003	0.8906	0.0077	0.1062	0.0007	0.817	2.9	.	.	633	11	647	4	651
Kipatimu	MN-05	45	6.5	2484	0.0634	0.0004	1.1252	0.0107	0.1288	0.0009	0.733	8.9	4.9	4.9	721	13	765	5	781
Kipatimu	MN-06	187	39.9	53638	0.0755	0.0004	1.9435	0.0184	0.1868	0.0014	0.818	2.3	.	.	1081	11	1096	6	1104
Kipatimu	MN-07	211	20.4	11753	0.0576	0.0004	0.6783	0.0065	0.0854	0.0006	0.756	2.6	.	.	515	13	526	4	528
Kipatimu	MN-08	199	89.4	20003	0.1277	0.0008	6.3422	0.0803	0.3602	0.0039	0.863	-4.7	-2.6	-2.6	2066	11	2024	11	1983
Kipatimu	MN-09	110	12	2984	0.0581	0.0010	0.7454	0.0141	0.0931	0.0007	0.403	8.1	1.2	1.2	532	37	566	8	574
Kipatimu	MN-10	87	34.5	24012	0.1133	0.0007	5.1021	0.0595	0.3267	0.0032	0.85	-1.9	.	.	1853	11	1836	10	1822
Kipatimu	MN-11	680	65.5	46572	0.0568	0.0003	0.6529	0.0061	0.0834	0.0007	0.855	7	2.2	2.2	484	11	510	4	516
Kipatimu	MN-12	224	83.2	6914	0.1293	0.0008	5.6254	0.0709	0.3155	0.0035	0.882	-17.5	-15.9	-15.9	2089	10	1920	11	1768
Kipatimu	MN-13	59	8.4	2921	0.0645	0.0004	1.1084	0.0100	0.1247	0.0009	0.776	0.1	.	.	757	12	757	5	758
Kipatimu	MN-14	76	9.4	3462	0.0628	0.0004	0.9753	0.0105	0.1127	0.0010	0.787	-1.7	.	.	700	13	691	5	689

Summary of U-Pb zircon data from Mandawa Basin sandstones

Formation	Name	U ppm	^{206}Pb ppm	Ratios										Ages				
				$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$					$\frac{^{207}\text{Pb}}{^{235}\text{U}}$					Discordance (%)				
				$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	Central	Min.	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{238}\text{U}}$
Kipatimu	MN-15	344	71.2	19473	0.0959	0.0006	2.4487	0.0297	0.1853	0.0020	0.868	-31.6	-29.9	1545	11	1257	9	1096
Kipatimu	MN-16	185	33.9	14143	0.0711	0.0004	1.5791	0.0148	0.1610	0.0013	0.847	0.1	.	961	10	962	6	962
Kipatimu	MN-17	59	8.1	3607	0.0644	0.0005	1.0918	0.0118	0.1230	0.0010	0.756	-0.8	.	753	14	749	6	748
Kipatimu	MN-18	276	29.3	7073	0.0604	0.0003	0.8237	0.0077	0.0990	0.0008	0.818	-1.5	.	617	11	610	4	608
Kipatimu	MN-19	78	15.2	11117	0.0739	0.0004	1.7596	0.0165	0.1728	0.0013	0.822	-1.1	.	1038	10	1031	6	1027
Kipatimu	MN-20	68	9.6	1879	0.0648	0.0004	1.1353	0.0103	0.1272	0.0009	0.787	0.7	.	767	11	770	5	772
Kipatimu	MN-21	107	13.5	4322	0.0615	0.0004	0.9186	0.0100	0.1084	0.0009	0.803	1.1	.	656	13	662	5	663
Kipatimu	MN-22	209	41.7	7009	0.0716	0.0004	1.6611	0.0194	0.1682	0.0017	0.874	3	.	975	11	994	7	1002
Kipatimu	MN-23	106	51.3	10437	0.1967	0.0016	11.2068	0.1524	0.4133	0.0046	0.813	-24	-22.3	2799	13	2540	13	2230
Kipatimu	MN-24	419	51	70983	0.0595	0.0004	0.8245	0.0103	0.1005	0.0010	0.803	5.9	.	585	16	611	6	618
Kipatimu	MN-25	40	19.7	6131	0.1697	0.0016	9.6810	0.1484	0.4137	0.0051	0.801	-14.9	-12.7	2555	15	2405	14	2232
Kipatimu	MN-26	64	5.9	1535	0.0573	0.0006	0.6491	0.0096	0.0822	0.0008	0.689	1.4	.	502	23	508	6	509
Kipatimu	MN-27	104	21	7361	0.0729	0.0004	1.7795	0.0171	0.1771	0.0014	0.848	4.4	1.6	1010	10	1038	6	1051
Kipatimu	MN-28	36	5	4888	0.0638	0.0004	1.0905	0.0114	0.1240	0.0010	0.769	2.8	.	734	14	749	6	754
Kipatimu	MN-29	159	18.6	31897	0.0597	0.0004	0.8324	0.0082	0.1011	0.0008	0.764	5.1	0.4	592	13	615	5	621
Kipatimu	MN-30	180	63.3	27696	0.1103	0.0006	4.6686	0.0485	0.3071	0.0027	0.843	-4.9	-3	1804	10	1762	9	1726
Kipatimu	MN-31	51	4.7	2300	0.0578	0.0005	0.6711	0.0073	0.0842	0.0006	0.677	-0.2	.	522	16	521	4	521
Kipatimu	MN-32	86	45.9	7128	0.1625	0.0013	9.7587	0.1397	0.4356	0.0053	0.844	-7.2	-5.1	2481	13	2412	13	2331
Kipatimu	MN-33	421	60.3	1005	0.0706	0.0005	1.2450	0.0151	0.1279	0.0013	0.833	-19	-15.9	946	14	821	7	776
Kipatimu	MN-34	431	75.8	4412	0.0733	0.0004	1.6907	0.0174	0.1672	0.0014	0.839	-2.8	.	1023	11	1005	7	997
Kipatimu	MN-35	142	20.7	6568	0.0659	0.0004	1.2022	0.0113	0.1322	0.0010	0.790	-0.5	.	804	12	802	5	801
Kipatimu	MN-36	149	21.7	4686	0.0653	0.0004	1.1367	0.0125	0.1262	0.0011	0.816	-2.5	.	784	13	771	6	766
Kipatimu	MN-37	233	38.2	10167	0.0677	0.0004	1.3291	0.0151	0.1424	0.0014	0.864	-0.1	.	859	12	858	7	858
Kipatimu	MN-38	63	9.4	2679	0.0689	0.0004	1.2808	0.0127	0.1349	0.0011	0.825	-9.4	-6.4	895	11	837	6	816
Kipatimu	MN-39	189	36.7	3423	0.0760	0.0004	1.8085	0.0182	0.1726	0.0014	0.826	-6.8	-4.1	1095	11	1049	7	1026
Kipatimu	MN-40	187	35.9	11583	0.0738	0.0004	1.7786	0.0162	0.1749	0.0013	0.830	0.5	.	1034	10	1038	6	1039
Kipatimu	MN-41	95	18	29213	0.0755	0.0004	1.8391	0.0178	0.1766	0.0014	0.813	-3.5	-0.8	1083	11	1060	6	1048
Kipatimu	MN-42	100	10	4869	0.0594	0.0004	0.7620	0.0073	0.0931	0.0007	0.784	-1.4	.	581	12	575	4	574
Kipatimu	MN-43	266	52.2	32752	0.0738	0.0003	1.8196	0.0161	0.1789	0.0013	0.849	2.7	0.2	1035	9	1053	6	1061

Summary of U-Pb zircon data from Mandawa Basin sandstones

Formation	Name	U ppm	^{206}Pb ppm	Ratios										Ages				
				$\frac{^{206}\text{Pb}}{^{238}\text{U}}$					$\frac{^{207}\text{Pb}}{^{235}\text{U}}$					Discordance (%)				
				$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	Central	Min.	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$
Kipatimu	MN-44	265	37	126311	0.0642	0.0003	1.1115	0.0093	0.1255	0.0009	0.837	1.8	.	749	9	759	4	762
Kipatimu	MN-45	207	39.9	37104	0.0737	0.0004	1.7515	0.0139	0.1723	0.0011	0.806	-0.9	.	1034	9	1028	5	1025
Kipatimu	MN-46	370	76.8	17924	0.0756	0.0003	1.9026	0.0164	0.1825	0.0014	0.878	-0.4	.	1085	9	1082	6	1081
Kipatimu	MN-47	504	48.6	20251	0.0584	0.0003	0.7349	0.0060	0.0912	0.0006	0.841	3.4	.	545	10	559	4	563
Kipatimu	MN-48	79	16.2	5109	0.0760	0.0004	1.9255	0.0165	0.1837	0.0013	0.796	-0.9	.	1096	10	1090	6	1087
Kipatimu	MN-49	607	65.6	404	0.0589	0.0011	0.7398	0.0168	0.0912	0.0012	0.564	0.1	.	562	40	562	10	562
Kipatimu	MN-50	151	30.8	5831	0.0750	0.0005	1.7938	0.0232	0.1735	0.0020	0.883	-3.7	-0.6	1068	12	1043	8	1031
Kipatimu	MN-51	100	18.1	4207	0.0734	0.0004	1.6905	0.0191	0.1670	0.0017	0.9	-3.2	-0.5	1026	10	1005	7	995
Kipatimu	MN-52	119	21.9	5344	0.0740	0.0004	1.7477	0.0167	0.1713	0.0014	0.87	-2.3	.	1042	9	1026	6	1019
Kipatimu	MN-53	131	11.9	3267	0.0574	0.0004	0.6302	0.0092	0.0796	0.0010	0.86	-2.7	.	507	15	496	6	494
Kipatimu	MN-54	28	3.9	542	0.0648	0.0012	1.0466	0.0294	0.1171	0.0024	0.736	-7.6	.	769	38	727	15	714
Kipatimu	MN-55	309	48.4	21552	0.0669	0.0003	1.3113	0.0106	0.1421	0.0010	0.831	2.7	.	836	9	851	5	857
Kipatimu	MN-56	138	55.9	32365	0.1159	0.0007	5.3210	0.0866	0.3330	0.0050	0.924	-2.5	-0.2	1894	10	1872	14	1853
Kipatimu	MN-57	130	18.3	6836	0.0650	0.0003	1.1392	0.0095	0.1271	0.0009	0.817	-0.3	.	774	10	772	4	772
Kipatimu	MN-58	231	89.8	27392	0.1223	0.0005	5.7196	0.0667	0.3391	0.0037	0.928	-6.3	-4.8	1990	7	1934	10	1882
Kipatimu	MN-59	264	29.3	2194	0.0613	0.0004	0.8894	0.0082	0.1053	0.0007	0.716	-0.6	.	649	13	646	4	645
Kipatimu	MN-60	648	88.4	27051	0.0634	0.0003	1.0886	0.0088	0.1245	0.0008	0.841	4.9	1.8	723	9	748	4	756
Kipatimu	MN-61	44	7.9	3183	0.0707	0.0004	1.6197	0.0173	0.1661	0.0015	0.833	4.7	1.3	950	12	978	7	991
Kipatimu	MN-62	848	142.6	33685	0.0703	0.0003	1.4710	0.0150	0.1517	0.0014	0.897	-3.1	-0.5	938	9	919	6	910
Kipatimu	MN-63	186	20.1	4685	0.0599	0.0004	0.7883	0.0106	0.0955	0.0011	0.843	-1.8	.	598	15	590	6	588
Kipatimu	MN-64	8	1.4	540	0.0761	0.0010	1.6434	0.0337	0.1566	0.0025	0.769	-15.7	-10.4	1098	24	987	13	938
Kipatimu	MN-65	221	32.8	5987	0.0668	0.0003	1.2158	0.0158	0.1321	0.0016	0.932	-3.9	-0.8	830	10	808	7	800
Kipatimu	MN-66	117	11.2	7111	0.0582	0.0004	0.6892	0.0067	0.0859	0.0006	0.747	-1.3	.	538	13	532	4	531
Kipatimu	MN-67	266	87.2	9280	0.1109	0.0006	4.5310	0.0494	0.2964	0.0028	0.880	-8.8	-7	1814	9	1737	9	1673
Kipatimu	MN-68	129	16.1	149223	0.0621	0.0003	0.9668	0.0078	0.1130	0.0007	0.792	2.1	.	676	10	687	4	690
Kipatimu	MN-69	68	9.3	3337	0.0646	0.0004	1.1106	0.0099	0.1247	0.0009	0.773	-0.4	.	760	12	758	5	758
Kipatimu	MN-70	99	11.9	3559	0.0618	0.0004	0.9147	0.0093	0.1074	0.0008	0.780	-1.4	.	666	13	660	5	658
Kipatimu	MN-71	160	29.9	9094	0.0726	0.0004	1.6125	0.0216	0.1610	0.0019	0.891	-4.4	-1.1	1003	12	975	8	963
Kipatimu	MN-72	189	73.8	13652	0.1205	0.0007	5.4990	0.0752	0.3310	0.0041	0.9	-7	-5	1963	10	1900	12	1843

Summary of U-Pb zircon data from Mandawa Basin sandstones

Formation	Name	U ppm	^{206}Pb ppm	Ratios										Ages					
				$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$					$\frac{^{207}\text{Pb}}{^{235}\text{U}}$					Discordance (%)			$\frac{^{206}\text{Pb}}{^{238}\text{U}}$		
				1σ	1σ	1σ	1σ	1σ	1σ	1σ	1σ	1σ	1σ	Central	Min.	1σ	1σ	1σ	1σ
Kipatimu	MN-73	209	41.9	14496	0.0755	0.0004	1.8715	0.0158	0.1799	0.0012	0.815	-1.4	.	1081	10	1071	6	1066	7
Kipatimu	MN-74	1039	80.7	211	0.0508	0.0043	0.4519	0.0412	0.0646	0.0023	0.389	78.2	3.3	229	174	379	29	403	14
Kipatimu	MN-75	335	33.6	23298	0.0586	0.0003	0.7373	0.0063	0.0912	0.0006	0.833	1.9	.	553	10	561	4	563	4
Kipatimu	MN-76	271	54.5	26392	0.0756	0.0004	1.8834	0.0167	0.1807	0.0013	0.825	-1.3	.	1084	10	1075	6	1071	7
Kipatimu	MN-77	812	113	699	0.0705	0.0010	1.1888	0.0285	0.1224	0.0024	0.811	-22.2	-16	942	29	795	13	744	14
Kipatimu	MN-78	98	8.7	14548	0.0574	0.0004	0.6441	0.0060	0.0814	0.0006	0.738	-0.1	.	505	14	505	4	505	3
Kipatimu	MN-79	160	28	17100	0.0716	0.0003	1.5831	0.0149	0.1603	0.0013	0.869	-1.9	.	975	9	964	6	958	7
Kipatimu	MN-80	121	23.1	10421	0.0740	0.0004	1.7538	0.0165	0.1720	0.0014	0.857	-1.8	.	1040	9	1029	6	1023	8
Kipatimu	MN-81	991	122.9	673	0.0711	0.0008	1.0705	0.0392	0.1093	0.0038	0.949	-31.9	-27	959	23	739	19	668	22
Kipatimu	MN-82	395	70.7	14683	0.0732	0.0005	1.6536	0.0195	0.1639	0.0016	0.824	-4.4	-1	1019	13	991	7	978	9
Kipatimu	MN-83	43	4.7	1859	0.0601	0.0005	0.8241	0.0095	0.0994	0.0008	0.657	0.5	.	608	18	610	5	611	4
Kipatimu	MN-84	142	15.6	7889	0.0603	0.0003	0.8322	0.0076	0.1000	0.0007	0.784	-0.1	.	616	12	615	4	615	4