Lithofacies of early Jurassic successions derived from spectral gamma ray logging in the Mandawa Basin, SE Tanzania

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Abstract
Spectral gamma ray log (SGRL) data has been widely employed to derive subsurface lithological information and to perform well correlation when the core is not available. Previous studies mainly targeted homogenous facies whereas few attempts addressed heterolithic successions. The SGRL investigation here aimed at deriving lithofacies and further constrain conditions of deposition prevailing during the early Jurassic (Mbuo, Nondwa, and Mihambia Fms.) in the Mandawa Basin, onshore Tanzania, where core and outcrop data is rare. By use of binary discrimination diagrams of U, Th, and K, composition fields were defined for various lithofacies types (black shale, red shale, siltstone, sandstone, chert, anhydrite, halite, and carbonate) compiled from literature data. Sediment composition for two wells in the Mandawa Basin was then deduced from cuttings and SGRL data and compared with literature-derived geochemical provenance data from adjacent regions and strata. Binary discrimination diagrams revealed the presence of multi-mineral components in the heterolithic facies type, which in concert with diagenetic and detrital mineral dilution effects, led to low compositional contrasts between provenance fields and to overlap of different lithofacies types, complicating interpretation and limiting the effectiveness of the SGRL-based facies differentiation. For the early Jurassic strata, an upward increase in the Th/K ratio suggests an enhanced terrigenous influx into the basin due to intensified weathering. High Th/U and Th/K in the study region indicate a relatively shallow, well mixed, and oxic depositional setting in proximity to the source area opposing the more distal, deeper, and reduced depositional settings that prevailed in the southern central part of the basin. Th/U and Th/K excursions in the Nondwa and Mihambia formations suggest a shift towards less oxic depositional conditions upon two major marine incursions, corroborated by a decline in the clastic fraction and concomitant increase in carbonate.

Keywords Th/K ratio · Th/U ratio · Pindiro group · Toarcian · Mozambique Belt · Weathering

Introduction
Over many decades, conventional natural gamma ray (GRL) geophysical logs have been widely available from exploration drilling and extensively used as primary lithology and clay-type indicators (Fertl et al. 1982; Fertl and Frost 1982; Dypvik and Bue 1984; Nielsen et al. 1987; Hurst 1990; Van Buchem et al. 1992; Rider 2000; Catuneanu 2006; Šimíček et al. 2012; Gould et al. 2014; Paredes et al. 2015; Alqubalee et al. 2019; Phujar-eanchaivon et al. 2021; Bataller et al. 2022). This geophysical technique, however, cannot differentiate distinct signals coming from either Th, U, or K that can provide more detailed lithological information. The increasing use of spectral gamma ray logging (SGRL) and the invention of portable gamma ray or XRF tools have enabled measurement of the total radiation and quantification of
individual Th, K, and U elements to be very easy and fast both in borehole and in outcrop (Myers and Wignall 1987; Wignall 1994; Parkinson 1996; Bessa and Hesselbo 1997; McRoberts et al. 1997; Ruffell et al. 2003; De Vleeschouwer et al. 2017; Dill et al. 2017; Bábek et al. 2018; Sêco et al. 2018, 2021). Relative abundances of U, Th, and K in sedimentary rocks vary in accordance with the mineral assemblage (McLennan et al. 1980; Myers and Bristow 1989; Rider 2000; Ehrenberg and Sva 2001; De Vleeschouwer et al. 2017); therefore, these elements are indicative of lithology. In addition, SGRL data can provide continuous lithological information and thus facies or provenance change for an entire succession penetrated by a borehole. Supplementary to continuous logging information, drill cuttings collected over variable intervals of a succession have been used as a complementary indicator of lithology and for calibration of geophysical logs. Drill cuttings always are taken as composites over a collection interval (usually 3 to 10 m) and hence do not represent the full range of individual lithologies or alternations thereof that may exist over a cutting composite interval. Geophysical logging allows the separation of smaller depth intervals or lithology alternations by using SGRL data. However, interpretation of SGRL data is complicated by its sensitivity to borehole conditions, drilling additives, penetration depth, vertical tool resolution (~30 cm), and lithology/minerals mixtures that may be affected by postdepositional processes (i.e., weathering and diagenetic effect that alter element composition).

To date, lithofacies and basin evolution information of the early Jurassic successions in the Mandawa Basin has been hampered by the limited number of wells drilled, a high degree of weathering, and incompleteness of exposed outcrop sections, and thus, most interpretations of lithofacies evolution rely on drill cuttings only. In this study, we attempt to elucidate the applicability of geophysical SGRL for deriving lithological information and sedimentary facies evolution over time in early Jurassic successions of the Mandawa Basin.

The methodology has been developed based on a global database compiled from the literature to define baseline Th, U, and K background concentrations from which various Th/K and Th/U lithofacies fields have been mapped. These binary discrimination diagrams were then compared with SGRL-derived Th/U, Th/K, and sediment composition data of early Jurassic strata (Mbuo, Nondwa, and Mihambia Fms.) from the Mandawa Basin including basement crystalline rock, to derive the lithofacies and paleo-redox conditions. When complementary geochemical analysis of outcrop samples was available via literature, this information was synthesized with the SGRL data to account for the regional provenance.

### Geological setting and stratigraphy of the study area

The onshore Mandawa Basin lies along the SE coast of Tanzania (Fig. 1). The basin is bounded to the S by the E-W trending basement high of the Ruvuma saddle to the N by the Rufiji trough, to the W by the border fault of the Masasi basement spur and covers an area of approximately 15,000 km² (Alconsult and TPDC 1997; TPDC 2003; Stratadata 2006).

Basin evolution and sedimentation were controlled by major rifting events associated with the breakup of Gondwana and the drifting of Madagascar (Balduzz et al. 1992; Veeken and Titov 1996; Einvik-Heitmann 2016; Fossum 2019). The Permo-Triassic Karoo rifting event, creating NNE-SSW intracratonic basins filled by continental Karoo clastic sediments, was succeeded by crustal extension during the Toarcian (~180 Ma) that further fragmented Gondwana. Crustal extension was accompanied by basin subsidence that allowed marine in-/transgression, which led to deposition of regional source and cap rocks such as the Nondwa Shale. A transition from rifting to drifting began in the ~170 Ma period (Middle Jurassic), leading to the initiation of seafloor spreading and opening of the western Somali and Mozambique Basins, and a southward drift of Madagascar along the N-S trending transform fault of the Davie Fracture Zone (Eagles and König 2008; Gaina et al. 2013). Seafloor spreading between Madagascar and Africa terminated around 120 Ma when strike-slip motion between Madagascar and India began (Eagles and König 2008; Reeves 2018; Fossum 2019; Fossum et al. 2019).

Following the Gondwana breakup, sediment accumulation was predominantly marine to partly terrestrial and continued into the Neogene resulting in a stratigraphic succession of five groups listed here in chronological order: Pindiro, Mandawa, Mavuji, Kilwa, and Songosongo (Hudson 2010; Hudson and Nicholas 2014). The Nondwa formation overlies the Pindiro group that is primarily siliciclastic with evaporites and carbonates (Fig. 2) and constituted by the Mbuo, Nondwa, and Mihambia formations.

The Mbuo formation lies unconformably upon the basement and predominantly consists of fine to coarser sandstones, intercalated with siltstones and claystones with minor dolomites (Fig. 3). Strata were deposited in alluvial, fluvial, and lacustrine environments (Stratadata 2006; Corelab and TPDC 2009; Hudson 2010; Hudson and Nicholas 2014). The Nondwa formation overlies the Mbuo formation and comprises evaporites and shales (Fig. 3) deposited in a shallow restricted marine embayment and is overlain by the Mihambia formation. The latter is constituted dominantly by clastic sediments with subordinate limestones deposited in a shallow marine setting.
Due to limited biostratigraphic information, the chronology of these formations is discussed controversially and deviating age assignments do exist for the base of Mbuo and Nondwa Formations as summarized in Fig. 2 (Kent et al. 1971; Balduzz et al. 1992; Wopfner 1994; Kagya 1996; Alconsult and TPDC 1997; Schlüter 1997; Quinton and Copestake 2007; Corelab and TPDC 2009; Hudson 2010; Robertson and CGG 2017; Davison and Steel 2018; Macgregor 2018; Godfray and Seetharamaiah 2019; Abay et al. 2019).

**Materials and methods**

Geological and geochemical methodologies were applied to achieve the objectives of this study (Fig. 4). Details of individual research methods are described below.

**Sampling of drill cuttings**

A total of 105 samples, each constituting 3 m of composite drill cuttings that cover the early Jurassic succession, was collected at the Tanzanian Oil Company core repository. Lithotypes of cuttings were documented during sampling and in combination with existing well reports (Halliburton 1996, 1997; Stratadata 2006; Quinton and Copestake 2007; Corelab and TPDC 2009; Hudson 2010; Robertson and CGG 2017; Davison and Steel 2018; Macgregor 2018; Godfray and Seetharamaiah 2019; Abay et al. 2019).

**Total carbon (TC) and total sulfur (TS) analysis**

Total carbon (TC) and total sulfur (TS) contents were determined by use of a VARIO-III elemental analyzer.
Fig. 2 Stratigraphy of the Pindiro group (?Late Triassic-Mid Jurassic), depicting two controversial age assignments according to references 1. Balduzzi et al. 1992; 2. Alconsult and TPDC, 1997; 3. Hudson 2010; 4. Hudson and Nicholas 2014; 5. Fossum 2019 versus 6. Veeken and Titov 1996; 7. Stratadata 2006; 8. Quinton and Copestake 2007; 9. Corelab and TPDC 2009; 10. Robertson and CGG 2017; 11. Macgregor 2018.

| Ma  | Period | Epoch | Age/Stage | Formation 1,2,3,4,5 | Formation 6,7,8,9,10,11 |
|-----|--------|-------|-----------|---------------------|------------------------|
| 235 | Jurassic| Late  | Norian    | Sandstone           | Limestone              |
| 220 | Jurassic| Late  | Camian    |                     |                        |
| 215 | Triassic| Late  | Norian    |                     |                        |
| 205 | Triassic| Early | Rhaetian  |                     |                        |
| 200 | Triassic| Early | Sinemurian|                     |                        |
| 195 | Triassic| Early | Pliensbachian|                    |                        |
| 190 | Triassic| Early | Toarcian  |                     |                        |
| 175 | Jurassic| Middle| Aalenian  |                     |                        |

Fig. 3 A, B Outcropping evaporite-shale intercalations in the Nondwa formation. C, D Drill core slabs showing very fine to fine grained arkosic Mbuo sandstone with abundant flasers of organic material and lithic fragments.

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(Elementar®) using 10 mg of sample weighted into a tin capsule followed by combustion at 1150 °C. The results were reproducible by ±(0.05%).

**Total organic carbon (TOC)**

Total organic carbon was obtained by decarbonatization of ~50 mg of powdered sample weighted into a ceramic
Fig. 6 Stratigraphical variability of the Th, U, and K SGRL abundances averaged for cuttings sample equivalents and their relationship to the total natural gamma ray intensity (GR API) in the sediments from the East-Lika well.

Fig. 7 Stratigraphic trends in SGRL-derived U/K, Th/U, and Th/K ratios averaged for cutting sample equivalents and their relationship to the sediment composition in the Mita-Gamma well. The lithological column on the right was established based on geochemical analysis of cuttings.
crucible via successive treatment with 10% and 25% HCl to remove calcite and dolomite if present. After washing to neutral and drying, samples were analyzed via combustion in an Eltra Helios CS Analyzer (Eltra®). The results were reproducible by ± (0.05%).

Sediment composition (carbonate, anhydrite, clastics, and crystalline rock)

Determinations of cumulative carbonate and evaporite mineral contents were achieved via dissolution and removal by 10% and 25% HCl treatment of a ~ 800–1200-mg sample aliquot followed by washing with deionized water for neutralization and drying at 40 °C for 24 h. Cumulative amounts of evaporites and carbonate in the sample were determined from the weight loss upon treatment.

Carbonate contents were calculated from proportions of total inorganic carbon (TIC) calculated by the difference of TC–TOC. TIC was converted into weight % carbonate by multiplying with a stoichiometry factor of 8.33, assuming calcite as the main carbonate phase.

Proportions of evaporite minerals (halite, gypsum, anhydrite) were determined from the difference between cumulative carbonate + salt fractions versus carbonate. The difference between the cumulative carbonate + salt fractions and the total sample weight was taken to represent the clastic fraction.

Spectral gamma ray log data acquisition

Log measurements were acquired by rising a SGRL-calibrated tool in an uncased well, with a data spacing of 0.15 ft following Halliburton® standardized procedures. All logs were processed and available in composite format in both analogue and digital form (LAS). LAS format data was imported into an Excel® spreadsheet and averaged over 10ft intervals to match with cutting sample intervals. SGRL data from the Mita-Gamma well covers the entire early Jurassic succession, whereas SGRL data from the East-Lika well was available for the Mbuo formation only.

Borehole quality check

Gamma ray log measurement is influenced by drilling-induced effects, particularly caving and additives from the drilling mud. Caving will reduce detector responses, and drilling fluid such as KCl or bentonite may increase K and/or Th concentrations measured by a spectral gamma ray tool. Gamma ray and caliper data, as well as technical drilling reports were examined to identify the potential presence of cavings and types of mud used during drilling. Caving was recognized in the Nondwa evaporitic sequences. Drilling reports showed that both of the two wells were drilled by the same contractor using a mixture of gel/polymer salt-saturated water, whereby SGRL responses were not affected by drilling additives.

Establishing U, Th, and K background concentration

Definition of U, Th, and K background concentrations representative of selected lithofacies types was achieved via a literature compilation. Element concentration ranges as well as average and median concentrations (Table 1) were

| Lithology                  | K (%) | Th (ppm) | U (ppm) | Th/U | Th/K |
|----------------------------|-------|----------|---------|------|------|
| Black shale                | 1–4   | 2.3      | 2–24    | 12   | 2.7–53 | 7.3 | 1–3 | 1.4 | 2–6 | 4.7 |
| Grey/yellow shale          | 1.6–6.8| 3.8      | 5.9–19.2| 11.8 | 1.5–5.1 | 3   | 3–4 | 3.8 | 1.6–5.4 | 3.7 |
| Red shale                  | 4.1–4.9| 4        | 14.6–19 | 17.6 | 1.8–2.8 | 2.5  | 7–8 | 7.1 | 3.6–4.8 | 4.8 |
| Siltstone                  | 1.3–3.8| 2.2      | 8–15.8  | 11.6 | 1.7–3.7 | 2.6  | 4–6 | 3.9 | 3–10.8 | 4.9 |
| Sandstone                  | 0.7–4.9| 1.6      | 2–12    | 8.4  | 0.8–3.5 | 2.4  | 2.6–5.8 | 3.5 | 2.5–11 | 5.6 |
| Carbonate                  | 0.4–1.3| 1        | 0.2–3.1 | 2.2  | 0.2–2.7 | 2.2  | 0.2–1.3 | 1   | 0.5–2.4 | 2.2 |
| Anhydrite/gypsum           | 0.2–0.25| 0.2      | 0.15–0.2 | 0.2 | 0.1–0.2 | 0.2  | 1–1.5 | 1   | 0–1.2 | 1.2 |
| Halite                     | 0.2–0.3| 0.3      | 0–0.2   | 0.2  | 0–0.1 | 0.1  | 0–2   | 2   | 0–1.2 | 1.2 |
Results

U, Th, and K concentrations according to lithofacies

Data compilation revealed a high variability in the relative abundance of the radiogenic elements in different sedimentary rocks (Table 1, Supplementary Table 1). Substantial K content is present in shale, siltstone, and sandstone, and diminished K-contents are present in carbonates and evaporites, whereas U is commonly enriched in black shales, carbonates, and other clastic rocks that do not exhibit high variability in U concentrations, as opposed to very low concentrations of U in evaporites. Likewise, sandstone, siltstone, and red shale contain high Th concentrations relative to other rock types. The results reveal that in general, sedimentary rock can be subdivided by geochemical classification into various fields based on Th/U and Th/K ratios (Table 1) that reflect minerogenic composition and depositional conditions, respectively.

Stratigraphical variability of Th, U, and K abundances

SGRL-concentration data reveal a high variability in Th, U, and K along the sediment succession of wells Mita-Gamma and East-Lika (Figs. 4 and 5; Supplementary Table 2) that follows the trend in natural gammy ray (GR API) response. The overall GR trend appears to be mainly controlled by Th and K contributions ($R^2=0.90, 0.87$, respectively) and least by U contributions ($R^2=0.35$). All anomalous GR values at depths of 2060–2070, 2140–2150, and 2230–2240 m in the Mita-Gamma and 1640–1650 and 1860–1890 m in the East-Lika wells coincide with the highest concentration in Th.

K, Th, and U abundances systematically vary with lithofacies, with enhanced Th proportions in sandstone/siltstone intervals whereas K and U contributions are elevated in shales. Minimum concentrations of all three radiogenic elements are associated with salt, carbonate, and basement intervals. A tendency of Th, U, and K concentrations to covary with carbonate abundance is noted in sediments from both wells, except for a section in the upper part of the Mihambia Fm., where carbonate influx is accompanied by an increase of U and decrease of Th and K. All major lithological boundaries including the boundary between the basement and the Mbuo Fm. or interspersed salt layers can be recognized on the basis of individual Th, U, and K concentrations (Figs. 4 and 5). Crystalline basement rock is characterized by its fairly constant concentration of the three radiogenic elements, whose abundances sharply increase at the base of the Mbuo formation and maintain at high levels in both wells. The Nondwa and Mihambia Fm. sediments in the Mita-Gamma well not only show lower concentrations of Th, K, and U than the Mbuo Fm. but also substantial variation in their respective radiogenic element concentrations (Fig. 5). Two main trends can be differentiated: a trend to comparable increase/decrease of all elements at 2280–2200 m and 2200–2150 m depth, respectively, and an opposite U covariation with Th and K at 2050 to 2010 m in the Mihambia formation. In contrast, sediments from the East-Lika well display a trend of systematic increases in Th, U, and K from the crystalline bedrock to the base of the Mbuo Fm.; from there on, a relatively invariant trend maintains throughout the entire formation (Fig. 5).

Sediment composition and stratigraphic variability of U/K, Th/U, and Th/K ratios

In addition to absolute concentrations of the three radiogenic elements used for lithofacies typing, their relative proportions can guide in deriving further information on sediment facies, in particular on the redox regime prevailing, the intensity of weathering, and the proportion of terrigenous influx into marine/limnic basins. In both wells, the U/K ratios of the rocks range between 0.3 and 2.3 and do not show much variation between the basement and the Mbuo formation. A substantial increase in average U/K ratios from about 0.7 in the Mbuo formation to average values of 1.3 in the Nondwa and Mihambia formations is noted for the Mita-Gamma site (Fig. 7). This is ascribed to a higher degree of weathering for the hanging wall strata penetrated by this well. Within basement and Mbuo strata of the East-Lika well, the U/K ratio remains rather constant at values around 0.9, recording only episodic shifts in weathering stage.

Rather invariant Th/U ratios ranging from 2 to 4 are recorded for the basement strata of the Mita-Gamma well (Fig. 7). As this ratio is mainly controlled by U uptake of sediments at low redox potential, a process not relevant in crystalline bedrock, the invariance is as expected. For the East-Lika well though, very high Th/U ratios ranging between values of 5 to 20 occur in an interval in the uppermost basement rocks (Fig. 8). Below 1950-m depth, basement rocks exhibit Th/U ratios ranging from 2 to 6 and thus quite similar to those noted for the Mita-Gamma well. The U depletion in the basement strata between 1990 and 1950 m is reflected by the basal Mbuo formation showing Th/U ratios of 5 to 20 and thus identical to the underlying basement.

The ratio of Th/K exhibits an overall upward increasing trend in the sediments from the Mita-Gamma well (Fig. 7) with values constantly below 5 in the basement rocks. Except for a single value of about 16 determined in the basement, Th/K ratios range between 1 and 8 in the East-Lika strata,
with slightly higher but rather invariant values of 4 to 8 in the Mbuo Formation (Fig. 8).

Radiogenic element ratios correlate with lithofacies in both wells. The rock record of the East-Lika well shows low variability in sediment composition in the dominantly clastic Mbuo formation. A higher variability in sediment composition occurs in the Mita-Gamma well, where evaporites are present in two intervals and various carbonate intercalations occur, both of which show elevated U/K ratios.

Discussion

Thorium-uranium as an indicator of paleo-redox conditions

Sedimentary rocks exhibit Th/U ratios ranging from $<0.02$ to $>20$, thus spanning two orders of magnitude. Th/U ratios $<2$ are typical for marine deposits and stand in contrast to Th/U ratios $>7$ common for a continental origin (Adams and Weaver 1958; Fertl et al. 1982; Isaksen and Bohacs 1995; Wignall and Twitchett 1996; Rider 2000; Lüning and Kolonic 2003; Marenco et al. 2016). Variation in Th/U ratios may reflect a series of geological processes that may ultimately enrich or deplete one of the elements either during weathering, transportation or deposition or as a function of redox conditions prevailing in pore waters (Adams and Weaver 1958; Kelepertsis 1981; McLennan and Taylor 1991). In reducing environments U tends to be precipitated as U$^{4+}$ and becomes enriched relatively to Th, whereas in oxidizing environments U$^{4+}$ is oxidized to more watersoluble U$^{6+}$, which partitions back into the water column (Osmond and Ivanovich 1992). Therefore, the Th/U ratio serves as an important paleoenvironment indicator for distinguishing lithofacies, leaching/weathering, and paleo-redox conditions. In order to assess lithofacies from SGRl-based Th/U ratios, we compiled concentration data of the two elements in various lithotypes from the literature (Table 1, Supplementary Table 1) and constructed a general lithofacies discrimination diagram (Fig. 9a). In order to account for regional provenance, we used geochemical data determined on outcrop samples in the wider study region for Jurassic (Hudson 2010) and Proterozoic strata (Kasanzu et al. 2017) as depicted in Fig. 9c and d, respectively. The data set in this study generated from SGRl is shown in the discrimination diagram of Fig. 9b.

Most of the data analyzed here cluster in a field delineated by U/Th ratios of 6 to 27 (Fig. 9b) and are ascribed to an oxic-continental source, with a few data points placed in a field delineated by U/Th ratios between 4 and 6 and ascribed to a typical siltstone-sandstone provenance. The oxic-continental field is assumed to be associated with the Mozambique Belt provenance and reveals a differentiation within that field according to Th concentration being highest.
in shales, followed by siltstones, intermediate in sandstones, and lowest in basement rocks (Fig. 9b). The lowest concentrations of both Th and U are found in evaporite samples, whereas carbonates show variable but generally low Th concentrations, exceeding those in basement rocks. This indicates that either the provenance of the crystalline basement of the Mozambique Belt has a unique signature, which is incompatible with the global Th/U systematics or that almost all sediments studied derived their Th/U signature from oxic-continental clastics subjected to intensive weathering and leaching of U. High Th/U ratios of 5 to 20 determined for crystalline basement in the East-Lika well argue for a source rock signal, but intensive leaching upon weathering and transportation cannot be excluded.

A comparison of the data generated here with those reported for the Mandawa Basin by Hudson (2010) reveals that outcrop samples from the latter study show higher U concentrations, with most shale samples clustering in the “grey/green-shale” provenance field bordered by Th/U ratios of 3 to 4 (Fig. 9c). Several shale samples are located in the marine-anoxic provenance field, which is considered to reflect the distal locations of the outcrops sampled. The study sites investigated in this work are located on the basin margin, where shallower water depth caused more intensive mixing and oxygenation of the water column, conditions not favorable for reducing pore waters and associated U-precipitation. The offset in Th/U ratios between the outcrop-derived deep basin and the well-derived basin margin samples thus reflects the redox regime prevailing.

Carbonates from the outcrop study plot in the evaporite field close to the carbonate segment potentially due to U removal by leaching. The two basement rocks from outcrop that were studied by Hudson (2010) plot in the Mozambique Belt provenance field but in comparison with the data generated in this study are highly depleted in U and Th, thus pointing to intensive weathering and leaching.

Adjacent to the Mandawa Basin and its Jurassic-Cretaceous sediment fill, the Buanji Basin of SW-Tanzania is
located. It is thought to have received its Proterozoic sediment infill from the Ubendian Belt (Kasanzu et al. 2017), which is compatible with the Mozambique Belt. Shales from the Buanji Group populate the Ubendian Belt field (Fig. 9d) and are highly compatible with the younger strata of the Mandawa Basin, which were sourced from the same basement complex. Three samples from the Buanji Group are positioned in the dysoxic marine shale field, which may indicate deposition under more restricted conditions and precipitation of U at lower Eh values.

Deviation of Mandawa and Buanji Basin samples from the standard lithological/depositional environment classification scheme can be due to a variety of factors including specific source rock chemical composition, dilution effects, hydrodynamic sorting, and diagenetic alteration or redox regimes prevailing that in turn elevate or diminish the Th/U ratio. In carbonates and evaporites, the Th/U ratios are mostly controlled by the presence of detrital minerals and organic matter (Adams and Weaver 1958; Adams et al. 1959; Graf 1962; Moore 1971). These impurities may raise Th/U ratios of carbonates to approach those of siliciclastic rocks (Adams and Weaver 1958; Adams et al. 1959). In siliciclastic rocks, the Th/U ratios are sensitive to depositional conditions (Adams and Weaver 1958; McLennan and Taylor 1980b) and will vary in accordance with the parent rock types, distance to source, and diagenetic alteration (Adams and Weaver 1958; Nielsen et al. 1987; Rider 2000). The presence of organic matter may promote uranium fixation in the water column or surface sediment (McLennan and Taylor 1980b; Myers and Wignall 1987; Rider 2000) and thereby reduce the Th/U ratio. Rapid sedimentation and hydrodynamic sorting seem to play significant roles in the distribution of Th-U in sandstones and resistate minerals (Adams and Weaver 1958). Due to fast deposition, the Th/U ratios in greywackes will be virtually identical to that of crystalline rocks and vary significantly from pure orthoquartzites (Adams and Weaver 1958; Murray and Adams 1958; Galbraith and Saunders 1983; Van Buchem et al. 1992).

Fig. 10 Binary Th/K discrimination diagrams depicting lithofacies fields and associated minerals bordered by Th/K ratios of 0.5, 1, 2, 6, and 11 based on global and regional data compilation: A (global data set), B (Mandawa Basin, Mita-Gamma well, this study), C (Mandawa Basin, Hudson 2010), and D (Proterozoic Buanji Basin, SW-Tanzania, Kasanzu et al. 2017)
We conclude that almost all samples in this study were deposited in oxic to strongly oxic environments, whereby a significant fraction of the primary U was leached and no U added via reducing conditions. In contrast, the sediments studied by Hudson (2010) and Kasanzu et al. (2017) originate from deeper basin settings and were deposited in dysoxic to dysoxic-water columns, respectively. Carbonate and evaporites may deviate from the global classification scheme due to presence of detrital minerals and diagenetic leaching while strongly oxic depositional would account for deviation in clastic rocks. The very few of the siltstones that plotted in the grey/green dysoxic shale provenance field could be associated with episodes of marine incursions into the Mandawa Basin upon sea-level highstands. These incursions were accompanied by enhanced organic matter deposition and preservation under oxygen depletion yielding higher amounts of total organic carbon (TOC) noted in Mandawa sediments (Emanuel et al. 2020; McCabe 2021). Low U content and average concentrations of TOC < 3% (Emanuel et al. 2020; McCabe 2021) could imply burn down/remobilization after brief marine incursions (Lüning and Kolonic 2003). The wide spread of data points in the oxic continental clastic field can be ascribed to hydraulic sorting for components of different grain size and presence of heavy minerals.

**Thorium-potassium as an indicator detrital mineral composition and sediment lithofacies**

Thorium is a chemically-physically stable trace element that occurs in resistate heavy minerals or, alternatively, is adsorbed to clay minerals (Langmuir and Herman 1980; Nielsen et al. 1987; Myers 1989; Davies and McLean 1996; Parkinson 1996; Rider 2000; Gould et al. 2014) as opposed to K that is commonly abundant but chemically unstable in many rock-forming minerals including feldspars, clays, and micas (Fertl et al. 1982). Fractionation of Th and K in sedimentary environments is driven by their physical and chemical properties. Th is transported as particulate solid matter and ultimately retains its original composition while K is soluble and continuously altered due to its chemical reactivity (Rider 1990; Ruffell et al. 2003). Absolute and relative abundance of Th and K may provide clues on mineralogical composition changes that may assist in clay mineral or rock typing. It has been generally observed that variation of Th/K ratios is primarily a function of detrital minerals but may also depend on neo-formed glauconite minerals. Sedimentary rocks exhibit wide variation in Th/K ratios, whereby higher ratios (Th/K > 6) may be related to heavy mineral enriched or highly matured lithology and predomiance of kaolinite clay minerals. In contrast, lower ratios (Th/K < 4) can specifically be associated with enrichment of feldspars, mica, glauconite, or illite minerals (Rider 2000; Basu et al. 2009; Inwood et al. 2013). Moreover, variation in Th/K ratios has been linked to changes in transport mechanisms, source area proximity, or topography, post-depositional processes, and other local factors involving tectonics and climate (Doveton 1991; Hesselbo et al. 1997; Schnyder et al. 2006; Basu et al. 2009; Inwood et al. 2013). The Th/K ratio despite its multifaceted influences provides an essential tool that can offer lithofacies information linked to the evolution of a sedimentary basin through time.

Globally derived data on Th and K concentrations (Table 1; Supplementary Table 1) depending on sediment type were employed to create binary discrimination diagrams defining different lithofacies types. Element ratios indicative of clay mineralogy were adapted from Quiren et al. (1982). Following the same procedure as applied in chapter 5.1 for Th/U ratios, the binary discrimination diagrams were generated for the global data compilation to define fields that are delineated by Th/K ratios of 0.5, 1, 2, 4, and 11 (Fig. 10A). These discrimination diagrams were then populated with data determined from Jurassic successions located in the marginal (Fig. 10b) and distal (Fig. 10c) parts of the Mandawa Basin (Hudson 2010) and Proterozoic successions from the Buanji Basin (Kasanzu et al. 2017).

The heterolithic nature of cuttings samples analyzed in this study prevents data to cluster exclusively in one of the end-member fields, e.g., either pure evaporites or carbonates (Fig. 10) or kaolinites. Most data points populate the clastic regime of shales, siltstones, and sandstones, whereby dispersal along the Th concentration axis is due to dilution by quartz, carbonate, or feldspars. The Mandawa Basin outcrop sediments studied by Hudson (2010) comprise mainly pelitic shales and less coarser psammitic to psephitic clastics and accordingly cluster in the shale field, indicative of mixed-layer clay minerals. Again, dilution with preferentially carbonate controls variation along the Th- and K-concentration axis (Fig. 10c). Data points from Proterozoic shales of the Buanji Basin investigated by Kasanzu et al. (2017) all cluster in the shales field as well and due to a lack of carbonate and quartz dilution display a narrow range in Th concentration (Fig. 10d).

A rather narrow range in Th/K ratio of about 2 to 6 implies the presence of similar clay mineral assemblages dominated by mixed layer clays for the Mandawa distal basin outcrop samples and the Proterozoic Buanji Basin shales (Fig. 10c and d). Higher Th/K ratios in the proximal settings of the Mandawa Basin indicate an elevated proportion of kaolinite clays (Fig. 10b). Several studies pointed out that the Th/K ratio is sensitive to grain size or mineral content of the sediment (Rider 1990, 2000; Schnyder et al. 2006; Inwood et al. 2013; Simíček and Bábek 2015), whereby a distribution of Th and K according to grain size is affected by diagenetic and hydraulic sorting during transport and deposition (van Buchem et al. 1992; Simíček et al. 2012). Such grain size and
mineralogy effects are more pronounced in heterolithic than in homogeneous facies (Rider 1990; Simiček and Bábek 2015) due to the presence of multiple mineral components. The occurrence of detrital components, organic matter, and lithic fragments/clasts in the Mbuo core samples and in shales in the Nondwa evaporitic outcrop section (Fig. 3) attest to a heterolithic nature of our samples. We further propose that a slight variation in Th/K ratios between the samples from the proximal basin section studied here and the distal basin samples studied by Hudson (2010) is controlled by source proximity. Proximal facies generally exhibit high Th/K ratios as opposed to low Th/K typical of distal facies due to differential hydraulic settings and clay flocculation (Parkinson 1996; Bessa and Hesselbo 1997; Hesselbo et al. 1997; Schnyder et al. 2006; Inwood et al. 2013). Th/K contrast in carbonates between the proximal and distal Mandawa Basin sediments may imply a reduction in terrigenous influxes due to a distant source area. The low variance in Th/K ratios determined for the Proterozoic Buanji Basin sediments shown by Kasanzu et al. (2017) may indicate chemically more mature sediments than those of the Jurassic Mandawa basin fill.

The sediments from East-Lika exhibit exceptionally high Th/K ratios and in the discrimination diagram (Fig. 11b) almost exclusively cluster in the siltstone/sandstone rather than the shale field. This can be interpreted as either a higher degree of weathering and longer transport distances of pedogenic derived kaolinite or in contrast the opposite, a rather short transport, low degree of weathering, and thus an inherence of the composition of basement source rocks. The latter option is preferred here due to a clastic dominance of the Mbuo formation in the East-Lika section (Fig. 8) and a low degree of carbonate dilution.

Th/K as provenance indicator

Th/K ratios of sedimentary rocks can provide important information on source rock composition when climate, hydraulic sorting, and postdepositional chemical changes are taken into consideration. Provenance shift may be accompanied by changes in mineral composition that can be reflected in Th-K data (Parkinson 1996; Bessa and Hesselbo 1997; Leeder et al. 1998; Ehrenberg and Sva 2001; Deconinck et al. 2003; Schnyder et al. 2006; Inwood et al. 2013; Simiček and Bábek 2015; Armstrong-Altrin et al. 2015; Chavez et al. 2016; Akinlotan et al. 2018; Bábek et al. 2018; Nkongho et al. 2022; Ramezani et al. 2022; Akono et al. 2022). Data for the proximal Mandawa Basin sediments as depicted in lithological columns (Figs. 7 and 9) and binary diagrams (Figs. 10 and 11) do not show sufficient variation to constrain shifts in provenance, possibly due a homogeneous sediment source area or sediments were well mixed prior to deposition (Fralick and Kronberg 1997; Garzanti et al. 2008; Amorosi and Sammartino 2018; Eko Bessa et al. 2021; Mounteney et al. 2021; Lučić et al. 2021).

Steady increases in Th/K ratios during deposition of the Mbuo Formation suggest that more pedogenic/detrital material was supplied from the hinterland and deposited quickly under oxic environments probably due to rejuvenated rifting associated with the breakup of Gondwana. Abrupt increases of Th/K toward the base of the Mbuo Fm. in both wells may imply either an uplift, erosion, and fast deposition that could be linked with initiation of rifting events in the region (Veeken and Titov 1996; Fossum 2019). Excursions in Th/K and Th/U trends in the Nondwa and Mihambia formations may indicate short-lived marine incursions into a restricted brackish/limnic Mandawa Basin that complementary caused minor increases in U abundance due to less oxic conditions, a process unrelated to changes in sediment source areas. In
contrary, the early Jurassic paleogeography suggests much more variable sediment sources that might include recycled older Karoo sedimentary rocks (Hudson 2010; Hudson and Nicholas 2014), a model not supported by the sediment composition of proximal Mandawa Basin sediments studied here. We propose that the Mozambique Belt basement constituted the main provenance region and sedimentation patterns were mainly controlled by rifting, periodical marine incursions, and local climatic conditions. A series of paleo-highs associated with the Pan-African basement in the study region is assumed to have generated locally variable accommodation space and restricted water circulation and communication between sub-basins that ultimately controlled sediment supply and deposition.

Conclusions

In this study, we demonstrate the application of spectral gamma-ray logging (SGRL) tools to derive lithofacies information on the lower Jurassic successions in the Mandawa Basin, Tanzania, which are not sufficiently accessible via core and outcrop.

In order to apply radiogenic U/K/Th concentrations and ratios as lithofacies and clay mineralogy indicators, we constructed discrimination diagrams compiled from a global set of literature data. Our study reveals that heterolithic facies, amalgamation of different lithologies in cutting-composite intervals, hydrodynamics sorting, and postdepositional processes, particularly diagenesis and salt diapirism, can complicate facies interpretation. Multiple mineral components in heterolithic facies and those introduced by either detrital mineral components or diagenetic effects may both lead to a lower contrast in Th, U, and K proportions thus complicating facies assignment in discrimination diagrams. Despite these limitations, the SGRL method has proven to be effective for highlighting the changes in detrital sediment input, hydrodynamics effect, weathering intensity, and diagenetic effects through time.

Although no highly reducing regime leading to deposition of organic-rich black shales was present in the Mandawa Basin, paleo-redox conditions prevailing during deposition and a source-sink relationship can be established from SGRL data. Availability of more SGRL data from the region may permit execution of well-to-well correlation that will unravel lateral variability in terms of redox conditions and sediment input between distal versus proximal parts of the basin. We propose that during the early Jurassic oxic to strongly oxic depositional condition prevailed in the western (East-Lika) and eastern flanks (Mita-Gamma) of the Mandawa Basin, whereas more oxygen deficient conditions prevailed in the southern central and deeper part of the basin. Freshly eroded sediment was supplied and deposited fast into the proximal basin part due to rifting activity during deposition of the Mbuo formation. Sedimentation was interrupted by two major episodes of marine incursions during the deposition of the Nondwa and Mihambia formations as deduced from a decline in Th/U and Th/K ratios.

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Data availability All data generated or analyzed during this study are included in this manuscript and the supplement files.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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