Atlantic will tear us apart: sand provenance correlation of Early Cretaceous aeolian strata from the conjugate margins of Africa and South America

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Non-peer reviewed preprint submitted to EarthArXiv and currently under review.

Abstract

The Twyfelfountein Formation in Namibia and the Botucatu Formation in East South America represent a single dune-field separated through rifting of Gondwana during the Cretaceous. The Early Cretaceous Botucatu desert was the last depositional system operating in the Gondwanan heartland prior to continental drift initiated by the Paraná-Etendeka large igneous province. The dry-aeolian dunes, draas and sandsheet deposits of the Botucatu Formation are also present in the Twyfelfountein Formation. We aim to test whether the two formations had a similar provenance. The provenance of the Twyfelfountein is established using a multiproxy dataset including petrography, grain-size, heavy mineral composition and geochemistry, and detrital zircon U-Pb dating (16 samples from 5 sites in the Huab Basin, Namibia). Results indicate

dominantly fine-to-medium feldspatho-quartose sands, rich in resistate minerals such as tourmaline, garnet and Fe-Ti oxides. Detrital zircon ages yielded mostly Cambrian-Neoproterozoic (450 to 650 Ma) ages. The geochemistry of garnet and tourmalines shows that these grains are originally sourced from amphibolite-facies metasedimentary rocks and acidic granitoids. The Botucatu Formation typically comprises sands that are quartzose, fine-medium sized, ZTR-rich with a predominance of Neoproterozoic detrital zircon ages. Based in this work and previously published data, the Twyfelfountein Formation sands are considered very similar to those of the Botucatu Formation, demonstrating a similar provenance for, and supporting the correlation of both units. The sands of the palaeodesert were derived from reworking of underlying strata from the Paraná and Huab basins. Furthermore, comparison of the datasets for both the Twyfelfountein and Botucatu formations shows a trend from SW to SE in sand composition due to the changes in the composition of the underlying pre-desert strata.

1. Introduction

The Paraná and Huab basins (South America and SW Africa) contain a series of sedimentary strata deposited from the Ordovician-to Cretaceous which occupy the present day territories of Brazil, Uruguay, Paraguay, Argentina, Namibia, and Angola (Milani and De Wit, 2008; Scherer et al., 2023). The Paraná and Huab basins comprise the last volcano-sedimentary geological episodes preserved on the Gondwana continent prio to continental break-up (Figure 1). In the Early Cretaceous the landscape was dominated by a vast desert- recorded by deposits of the Botucatu and Twyfelfontein Formations (Bigarella, 1979; Mountney et al., 1999a; Scherer, 2000; Scherer and Goldberg, 2007). This desert was rapidly flooded by basalts associated with the Paraná-Etendeka large igneous province during the Valanginian-Hauteverian periods (Jerram et al., 2000; Scherer, 2002; Waichel et al., 2007). The resulting volcano-sedimentary interaction produced a series of interbedded dunes within the volcanic pile. Although presently separated by the Atlantic Ocean, the Botucatu Formation (South America) and Twyfelfountein Formation (Africa) once composed a single desert that covered more than 1.5 million km^2 in the heart of Gondwana- the Botucatu palaeodesert.

The Botucatu and Twyfelfontein Formations have been well studied and comprise a series of dunes, draas, and sandsheets developed as part of a dry aeolian system within a large dune field (Mountney and Howell, 2000; Mountney et al., 1999a, 1999b; Scherer, 2002, 2000; Silva and Scherer, 2000). Correlation of the two units has been proposed (Milani and De Wit, 2008;

Scherer and Goldberg, 2007), however there is a gap in the formal stratigraphic correlation of both units. Furthermore, a series of fluvial-aeolian strata occur beneath the aeolian succession including the Krone Member and mixed fluvial-aeolian (Huab) and Pedreira Sandstone (Paraná), in which the stratigraphy and correlations are not defined. The Botucatu Formation provenance has been the focus of several studies (Bertolini et al., 2020b, 2021, 2022), while studies of the provenance of the Twyfelfountein Formation sands are restricted to detrital zircon dating (Zieger et al., 2020). The stratigraphy, sedimentology and provenance are key to correlating the sedimentary strata. This paper aims to define the stratigraphy of the units and their provenance providing new provenance and sedimentological data that, associated with bibliographic information, provide an interpretation of the latter stages of Gondwanan palaeocontinent integrity.

This study presents (1) a multiproxy provenance study of the main erg and interbedded dunes from the Twyfelfontein Formation based on petrographic, grain-size, heavy-mineral composition, varietal mineral chemistry of garnet and tourmalines and U-Pb dating of detrital zircon; and (2) correlation with South America aeolian strata from the Botucatu Formation sandstones. These studies coupled with previously published data are used to establish the provenance of the Twyfelfountein Formation sandstones and their relationship to the Botucatu Formation. Additionally, we examine the mechanism for sand input into the basin and its relationship to underlying strata with respect to recycling within the Paraná-Huab basins.

2. Geology context

The fragmentation of the South American and African continents following the break-up of Gondwana resulted in separation of a once contiguous geologic terrane. The basement rocks of the current continents comprise a series of cratons (São Luís-West African, São Francisco-Congo (Baldim and Oliveira, 2021; Santos et al., 2008)) and orogenic belts (Central African Fold Belt and Borborema Province, Ribeira- West Congo, Dom Feliciano-Kaoko (Basei et al., 2018; Caxito et al., 2021)) that can be correlated based on age, geochemistry, fossil content, and lithology. Several sedimentary basins were initiated (Keeley and Light, 1993; Loegering et al., 2013) during the fragmentation due to the extensional tectonic regime and the establishment of new passive margins (Franz et al., 2023; Lovecchio et al., 2020, 2018; Macdonald et al., 2003). Prior to break-up however, a large basin extended across SW Gondwana from what is now South America (Paraná Basin), and southern Africa (Huab Basin). Most of the basin is currently preserved in South America (ca 1,400,000 km²) (Scherer et al., 2023) while the Huab Basin comprises ca

50,000 km² (Horsthemke et al., 1990). The stratigraphy of the Huab Basin correlates with that of the southeastern margin of the Paraná Basin in the state off Rio Grande do Sul in Brazil. The Late Permian to Cretaceous stratigraphy in the Paraná Basin comprises a series of fluvial-aeolian strata that no longer have lateral continuity due to extensional tectonics and erosion (Scherer et al., 2023)(Figure 1). The last episodes of sedimentation in the basins are the fluvial-aeolian strata of the Krone Member (Namibia) and Pedreira Formation (Brazil), and lateral widespread dune field strata of the Botucatu (Brazil) and Twyfelfountein (Namibia) Formations (Mountney et al., 1999a; Scherer et al., 2023). Both these latter units share similar aspects, as both crop out at below the margins of the Paraná-Etendeka Large Igneous Province. Figure 1C displays a log correlation of the Paraná-Huab basins showing th proposed correlation of the Botucatu and Twyfelfountein Formations. Both above and below, other units also display consistent correlation as the Serra Geral Group and Etendeka Group lavas, the Permian Rio do Rasto and Gai As Formation (Scherer et al., 2023; Wanke et al., 2000), and the Pedreira Sandstones and Krone Member. Other units, such as the Guará or Santa Maria Formation are not laterally continuous, and are spatial constrained to West and Central margins of the basin (Scherer et al., 2023).

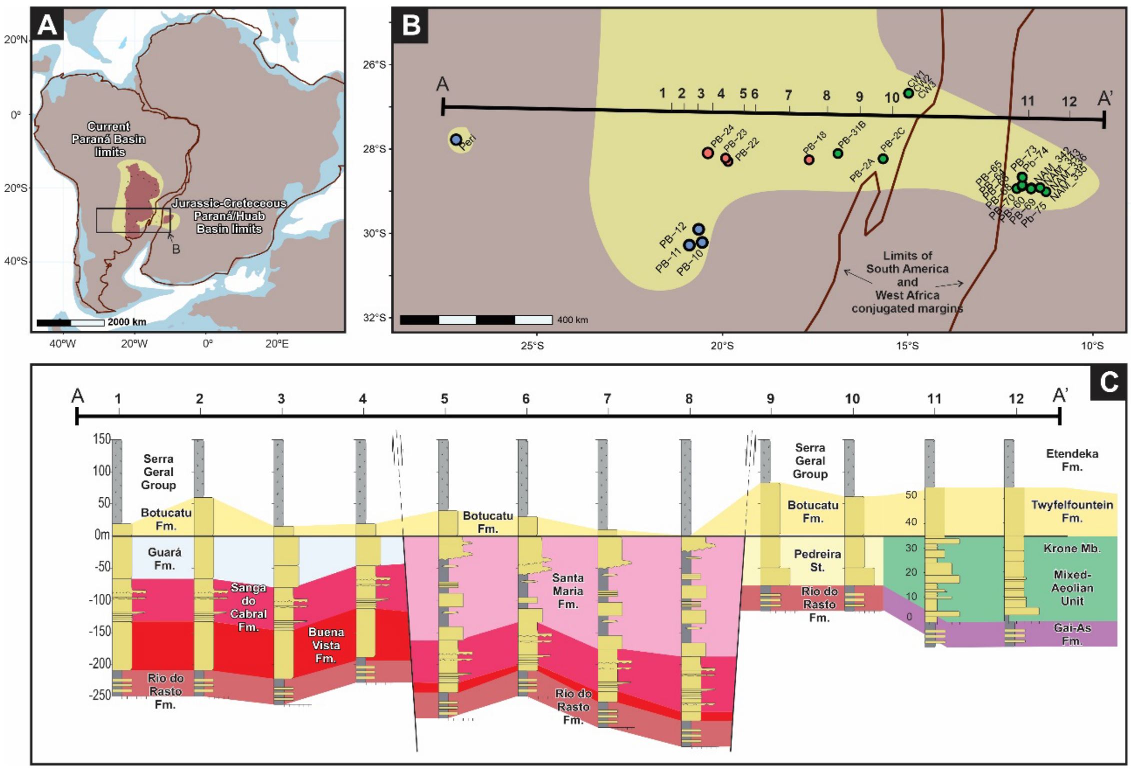

Figure 1- Geologic context of the study area; A- Early Cretaceous Gondwana with the Paraná and Huab basins limits; B- Detail of the study area with novel (Green ones starting with "PB-"in African-side) and bibliography (Bertolini et al., 2020; Peri et al., 2016; Canile et al., 2016,

Zieger et al., 2023) samples and sedimentary logs (numbers in the transect- for full details see Scherer et al., 2023); C- Log correlation of Botucatu and Twyfelfountein (and underlying strata) from South Paraná and Huab Basins (adapted from Scherer et al., 2023).

The Botucatu Formation stratigraphy is composed of sandy facies, including planar and tangential trough bedding, low-angle cross-stratification and horizontal stratification (Scherer, 2002, 2000). These facies are interpreted to have been formed as a series of crescentic- simple aeolian dunes, linear draas, and sandsheets. Water-lain deposits are locally restricted, with a single occurrence of ephemeral stream deposits at the base of the unit (Scherer, 2002), or thin interbedded mudstones within Serra Geral lavas (Cruz et al., 2021; Famelli et al., 2021; Moraes and Seer, 2018). The unit crops out along the Paraná Basin margins, including eastern, and central Brazil, Paraguay, Argentina, and Uruguay. The unit thickness averages around 100 m, but as its upper contact is with Paraná-Etendeka LIP lavas, the unit thickness can vary laterally from a few tens to 150 m.

The Botucatu Formation sands are fine-medium grained, with a feldspatho-quartzose composition (Bertolini et al., 2021, 2020b, 2020a). The heavy mineral component is rich in resistant minerals such as zircon, tourmaline, garnet, Fe-Ti oxides, with local contributions of other minerals including epidote, titanite and garnet (Bertolini et al., 2021, 2020b). Detrital zircon ages indicate contributions of Permian, Cambrian-Neoproterozoic, Tonian-Stenian, Palaeoproterozoic ages (Bertolini et al., 2021, 2020b; Canile et al., 2016; Peri et al., 2016; Pinto et al., 2015). The provenance of the Botucatu Desert is the result of intense reworking of local derived Paraná Basin strata. However, changes in the stratigraphy of subcropping strata promoted lateral variation in sand compositions (Bertolini et al., 2022, p. 202, 2020b). The southeastern margin, for instance, display an increase of Cambrian-Neoproterozoic zircons, as well as an increase in grain-size and an enrichment in garnets (Bertolini et al., 2020b).

The Twyfelfountein Formation is composed primarily of aeolian strata in the Huab Basin, in the northwest of Namibia and can reach up to 240 m in thickness. The unit has previously been referred to as the Etjo Formation – which corresponds to the Jurassic of the Karoo Basin. The Early Cretaceous age of the Etendeka lavas (Cañón-Tapia, 2018; Gomes and Vasconcelos, 2021; Jerram et al., 1999) allows correlation with the Serra Geral lavas from South America, which led to reinterpretation of the age and stratigraphic relationships of the Etjo Formation and it is now referred to as the Twyfelfountein Formation (Grove et al., 2017; Schreiber, 2006; Stanistreet and Stollhofen, 1999). The unit crops out south of the Huab River, in a strip 50 to 100 km wide. To the north, the upper boundary is represented by interbedded transition to the volcanics of the Etendeka, and to the south the lower boundary comprises an unconformity over Permo-Jurassic strata and in places the metasedimentary Damara Belt basement.

Mountney et al. (1999a) divided the Twyfelfountein Formation into three portions: the main erg- comprising aeolian sandstones that are deposited in a large-scale dune field before the volcanic activity; the minor erg - where the volcanic extrusion started laterally, but the erg was still depositing; and intertrap starved dunes- where the lava-fields predominate, but single dune deposits are developed within the lava-packages during periods of volcanic quiescence.

The detrital zircon study of Zieger et al. (2020), on the Twyfelfountein Formation found that Permian, Cambrian-Neoproterozoic, Tonian-Stenian, Palaeoproterozoic zircon ages are dominant as is also seen in the the Botucatu sands. The Ziegler et al. (2020) study also showed that underlying Triassic to Jurassic strata display similar properties, suggesting sedimentary recycling as the main mechanism of sand supply to the Twyfelfountein Formation.

3. Methods and materials

The study applied field logging and multiproxy provenance analysis in aeolian strata from the Twyfelfountein Formation of theHuab Basin. Sixteen samples were collected from the north-western region of Namibia. The sampling was undertaken in 5 main profiles, the Klein Gai-As, Dune Valley, Red & Yellow dyke, UNESCO and Krone Farm (Figure 2).

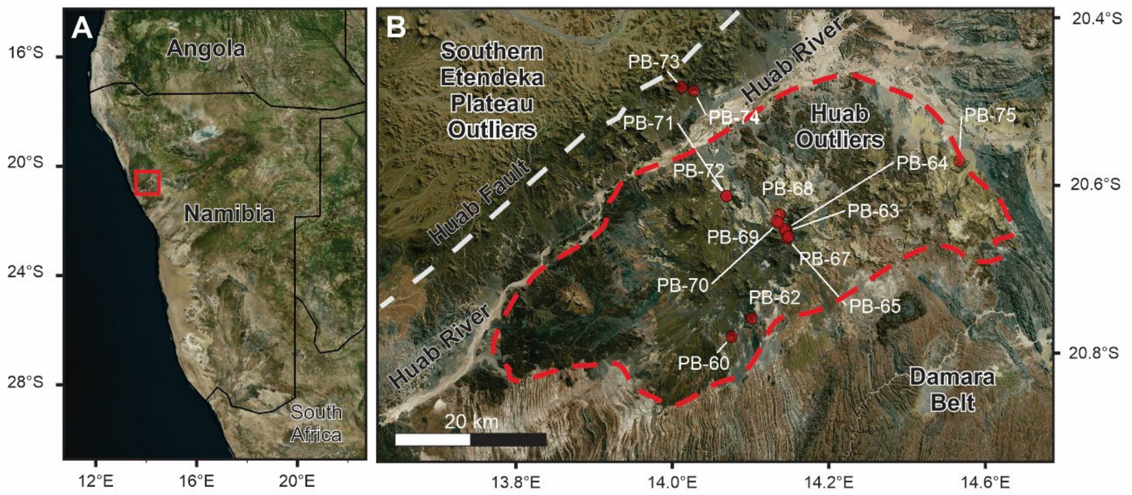

Figure 2- a) Location of study area in NW Nambia. b) Detail of sample locations in Huab River region of NW Namibia (see also Fig. 3). The main aeolian and Karoo sedimentary sequences

being restricted to the Huab Outliers, and areas along the Huab River, south of the basin bounding Huab Fault (approximate location highlighted on map), (see Jerram et al. 1999, 2000; Mountney et al., 1999a; Wanke et al., 2000).

U-Pb dating of detrital zircons was carried out in the Centro de Pesquisas Geocronológicas at the University of São Paulo. Ten samples were dated using: 193 nm ArF laser ablation system connected to a multi-collector inductively coupled (MC-ICP-MS) with the following parameters, 5 mJ pulse energy, 6 Hz pulse rate, 29 µm diameter beam (See (Sato et al., 2011) for analytical details). The data reduction uses $^{207}Pb/^{206}Pb$ ratio for >1.3 Ga zircons, and $^{206}Pb/^{238}U$ for younger grains, and filters zircon with discordances larger than 10% (Gehrels, 2012; Vermeesch, 2021).

Petrographic studies including thin section point counting coupled with sedimentological description to characterize the sandstone composition. Three hundred points were counted using the Gazzi & Dickinson method (Ingersoll et al., 1984) to obtain a proportion of framework minerals (quartz, feldspars and lithics), cements and porosity.

Heavy mineral analysis recovers the composition of the heavy fraction of minerals (>2.8 g/cm^3). A total of 6438 individual geochemical analyses were obtained of individual grains of heavy minerals using Jeol 6610-LV SEM (with coupled Brukker EDS) from 16 samples. The heavy minerals were obtained from raw samples, using dense liquids split technique (bromoform (2.80 g/mL) of the very-fine sand size (0.625-0.125 mm).

Grain-size analysis determined the proportion of the sand classes in the sandstones. The grain-size was obtained by sieving and weighing 100 g of disaggregated sand from coarse to very-fine sands (2.0 to 0.625 mm). Grain-size statistics were obtained using G2SD R package (Fournier et al., 2014), and the Gradistat spreadsheet (Blott and Pye, 2001).

The thin section petrography, heavy mineral petrography and geochemistry, and grain-size experiments were conducted in the Laboratório de Geologia Isotópica from Universidade Federal do Rio Grande do Sul. A full report of the analyses are available as a supplementary file. The document is written in R, using tidyverse style dialect, and other libraries as provenance, g2sd, sf. Auxiliary libraries were crafted to calculate mineral chemistry and plot garnets, and to plot sedimentary logs paper, are available at https://github.com/gabertol/atlantic_will_tear_use.

4. Results

The provenance study of the Twyfelfountein Formation describes the main framework components of the sandstone (petrography), the size and distribution of the grains (grain-size), the heavy mineral composition and varietal garnet mineral chemistry (heavy mineral) and detrital zircon geochronology (U-Pb zircon). The multiproxy datasets are synthesized in figure 3, with further examination within the analysis results.

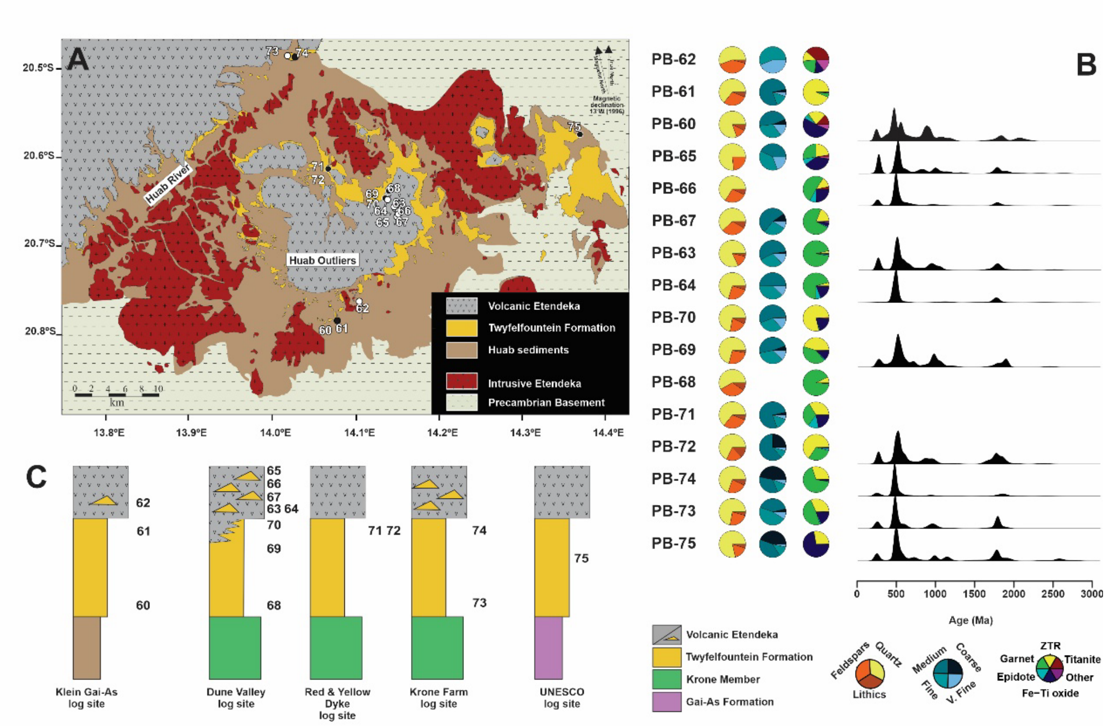

Figure 3- Compilation of the provenance dataset for Twyfelfountain Formation including (A) geologic map of the study area with the sampled positions (adapted from Jerram et al., 1999); (B) heavy minerals, bulk petrography, and grain-size pie charts and KDE plot for zircon U-Pb ages; (C) schematic sections depicting the stratigraphic levels of each sample.

4.2.1 Petrography

Sixteen thin sections were analysed, yielding a percentage of detrital quartz from 55.6 to 83.2 (mean 70.2± 1.1), feldspars from 9.5 to 40.4 (mean 21.9± 1.2), and lithics from 0 to 12.6 (mean 3.0 ± 4.0). The feldspar contribution is divided between plagioclase from 3.6 to 100 (mean 28± 6.2, microcline from 0 to 92.9 (mean 71.2± 6.2), and orthoclase from 0 to 5.1 (mean 0.8± 0.4). The lithic contribution is composed of igneous lithics from 26.3 to 100 (mean 66± 4.9), sedimentary from 0 to 50 (mean 19.2± 4.6), and metamorphic from 0 to 50 (mean 14.9± 4). The metamorphic grains are typically foliated low-grade metasedimentary (proto- sandstone and mudstone) to schists, sedimentary fragments are mostly sandstones, with associated mudstones. Igneous lithics are composed of granitoids (plutonic) grains with subordinate glassy-volcanic lithics.

The sandstones typically display pin-stripe lamination or are massive. The framework shows low mechanical packing, with local stylolites associated with chemical dissolution. Overall, diagenetic constituents consist of early Fe coats and quartz/K-Feldspar overgrowths and poikilotopic calcite.

The Twyfelfoutenin sands are composed by fedspatho-quartoze, quartoze and litho-feldspatho-quartzose sandstones according to sandstone classification scheme from Garzanti (2019)(Figure 4).

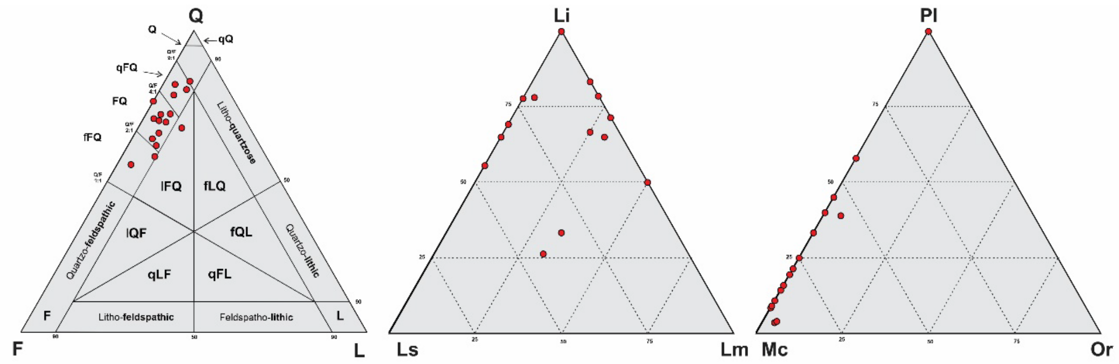

Figure 4 - Petrographic classification (A), lithics composition (B), and feldspar composition (C). Q- quartz; F- feldsapars; L- lithics; Li- lithic igneous; Ls- lithic sedimentary; Lm- lithic metamorphic ; Pl- plagioclase; Mc- microcline; Or- ortoclase.

4.2.2 Grain-size

Granulometry of the Twyfelfountein Formation is mostly fine to medium sands (Figure 5) with mean grain-size of 465 ± 92 um, sorting of 1.7 ± 0.03, skewness of -1.9 ± 0.03, and kurtosis of 0.96 ± 0.04. The grain-size modes are fine/medium sand, the sorting is mostly moderately sorted with subordinate well sorted, the distribution tends to be skewed to coarser sand (very fine to fine skew) and symmetrical, and the kurtosis is platykurtic and mesokurtic with some leptokurtic samples. Locally, coarse sand laminae occur (samples PB-70, -72, and -75) related to sandstones containing coarser granule ripples.

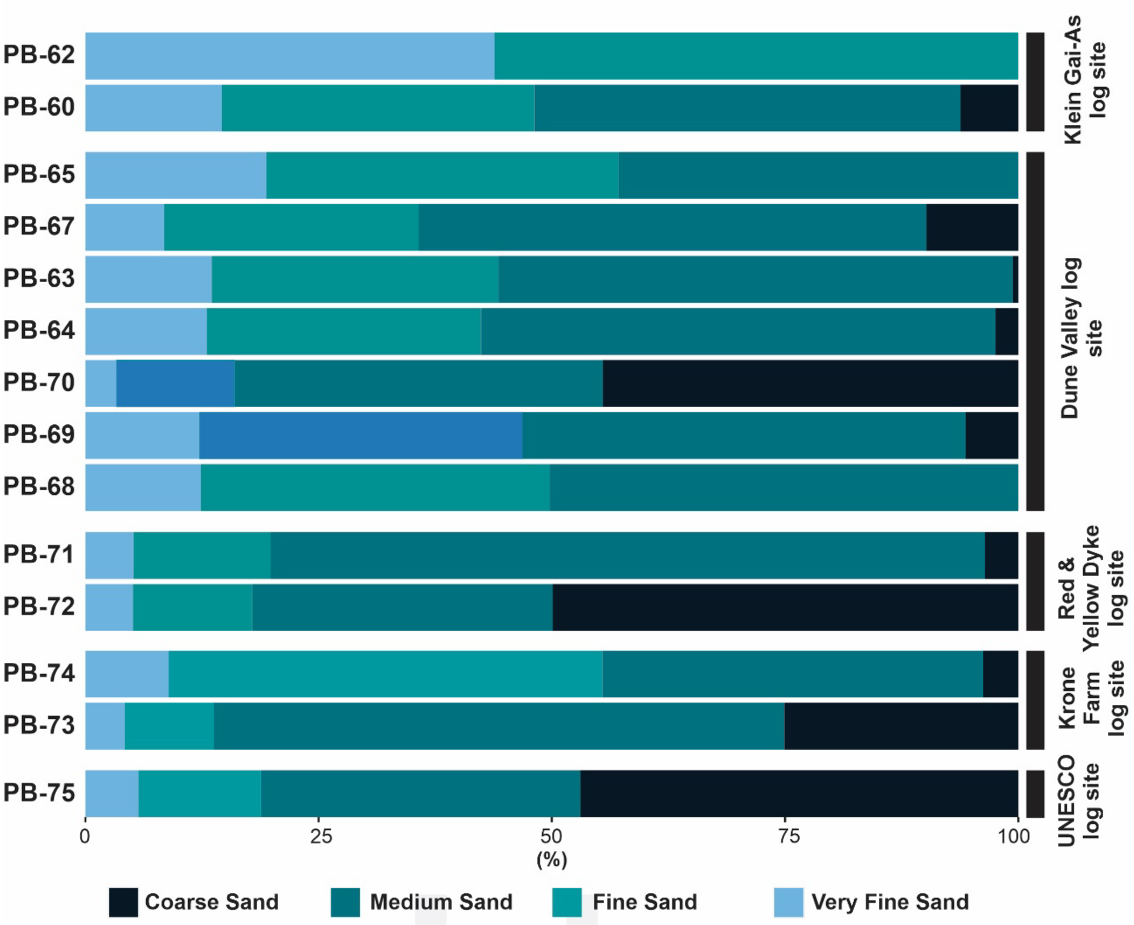

Figure 5- Grain-size characteristics of Twyfelfountein Formation

4.2.3 Heavy mineral

The Twyfelfoutein heavy mineral assemblage is composed of Fe-Ti-Mn oxides, zircon, tourmaline, garnet, titanite, epidote, amphibole with rare pyroxene, sulfides and others minerals (xenotime, rutile). Overall, the assemblage is rich in resistate minerals such as tourmaline, garnet, zircon, titanite and Fe-Ti oxides. Figure 6 compiles the heavy mineral proportions for 16 samples, organized stratigraphic-wise for Klein Gai-As, Dune Valley, Red & Yellow dyke, Krone Farm sites.

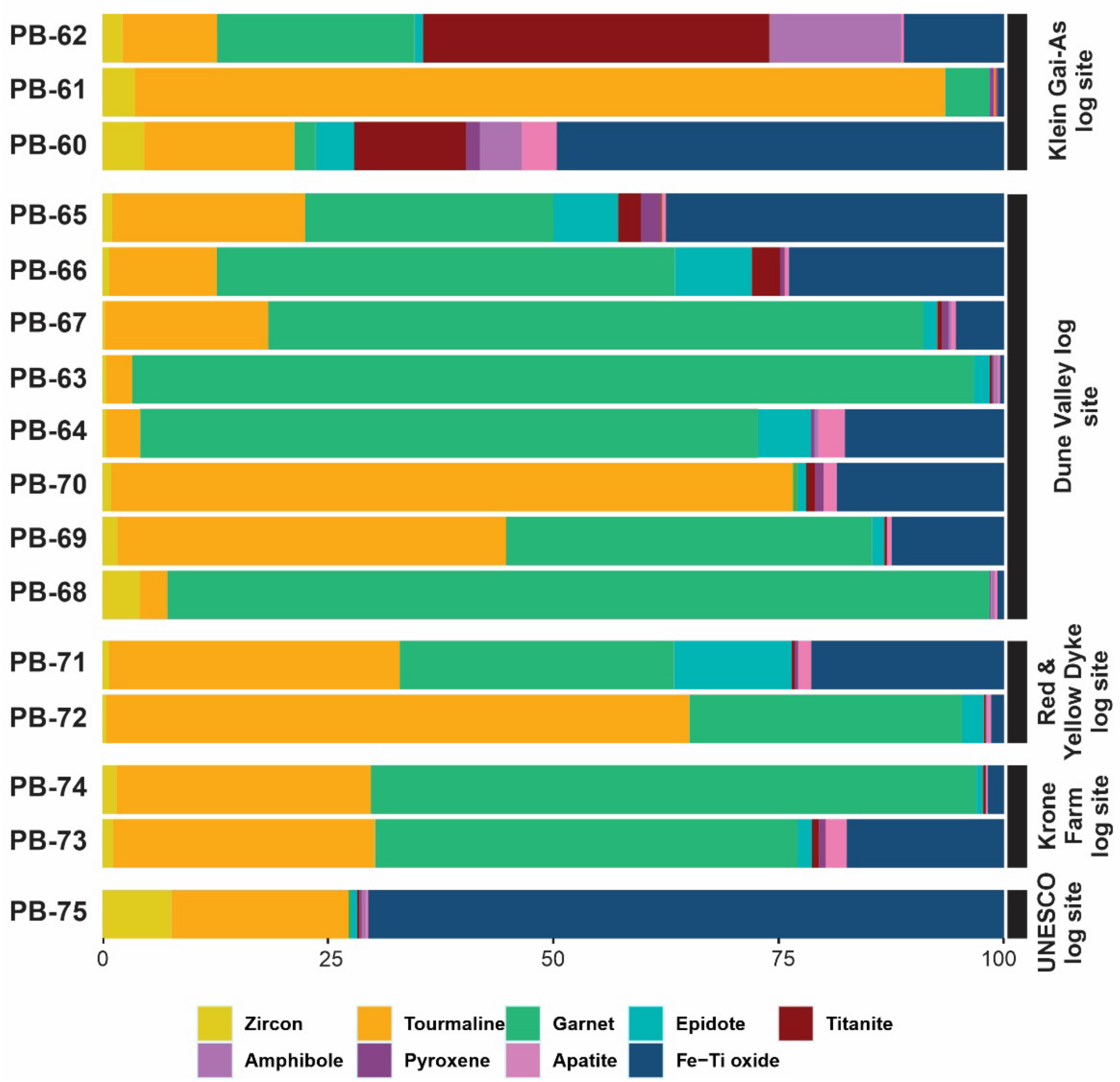

Figure 6- Heavy mineral composition of Twyfelfountein Formation

Geochemical analysis was undertaken on 875 garnets using EDS in SEM, finding a predominance of Fe- rich garnets (Type B of figure 7A), which compositionally are compatible with almandine (Fig. 7A). Secondary contributions include magnesian garnets (Type A of figure 7A). Fe-rich garnets include Bi and Bii types which forms in, respectively amphibolite-facies metasediments and acidic-intermediary igneous rocks. Type A garnets form in high-grade/granulite facies metasediments. Figure 7B explores the Mn+Ca+Mg plot finding a predominance of intermediary temperature and pressure garnets corresponding to amphibolite facies with secondary low pressure-temperature garnets and granulite garnet contributions. Analysis of 1524 tourmalines reveals a predominance of types 4 and 2 (Henry and Guidotti, 1985) grains, which correspond to dravite to schorlite compositions (Fig. 7C). Types 4 and 2 are typical for Al-rich metamorphic mudstones and sandstones, and Li-poor granitoids, respectively. Additionally, the Fe-Ca-Mg ternary plot for tourmalines (Fig. 7D) displays type 4 and 2 grains. A secondary contribution of Fe-rich tourmalines with elbaite compositions occurs (1 region in Fig. 7C), which forms in Li-rich granitoids. In general, the varietal mineral chemistry of garnet and tourmaline indicates low-to-high metamorphic and granitic source rocks.

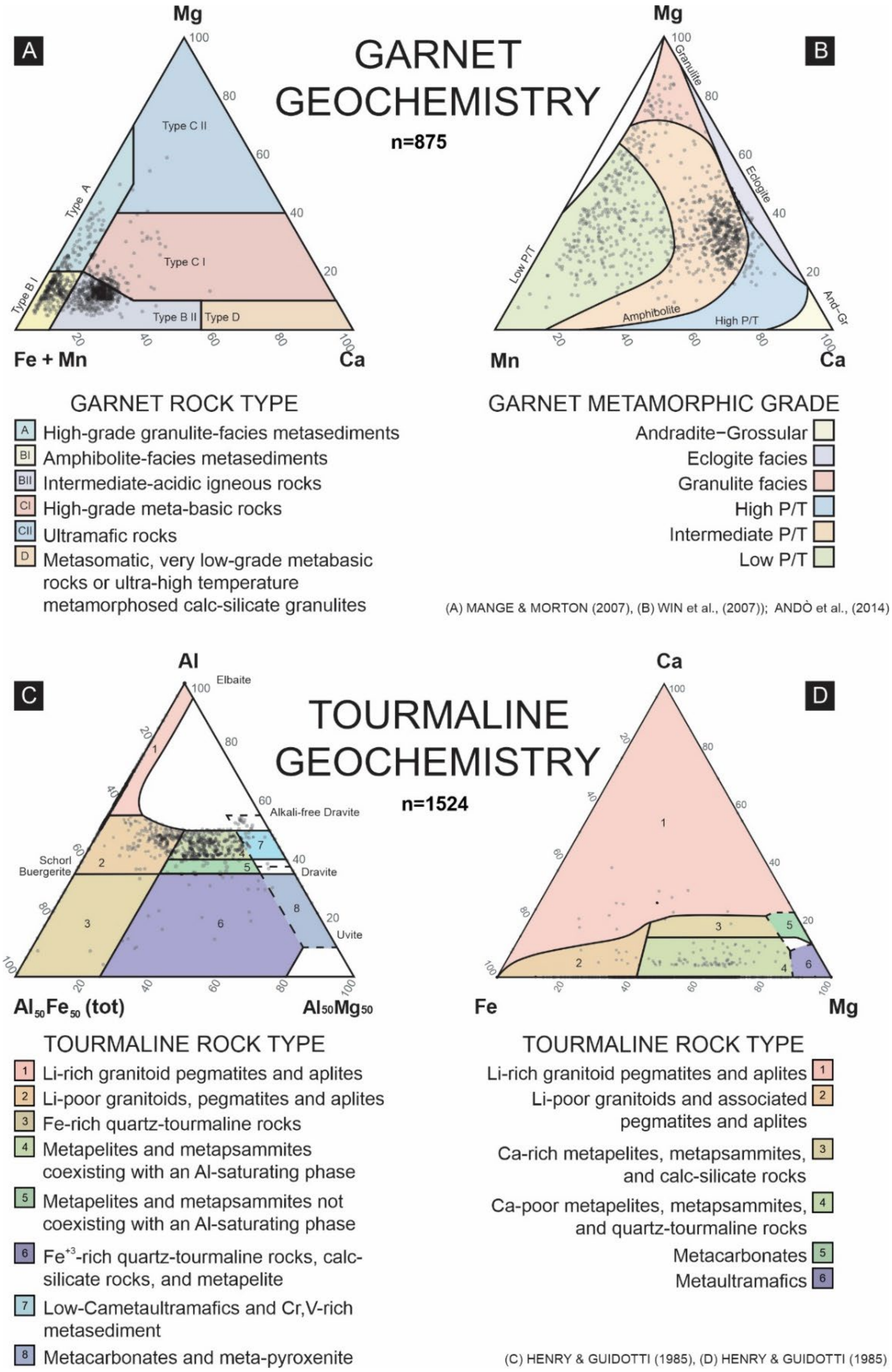

Figure 7- Garnet and Tourmaline geochemistry data of Twyfelfountein Formation. Diagrams from (Andò et al., 2014; Henry and Guidotti, 1985; Mange and Morton, 2007; Win et al., 2007).

4.2.4 Detrital zircon geochronology

The detrital zircons from the Twyfelfountein Formation are mostly composed of rounded to subrounded grains, with 80 to 400 µm in length, and a width-length of ratio of 2-3-4 to 1. The growth patterns include several styles, including oscillatory, polygonal, ghost, and rim zoning. Fractures also occur indiscriminately.

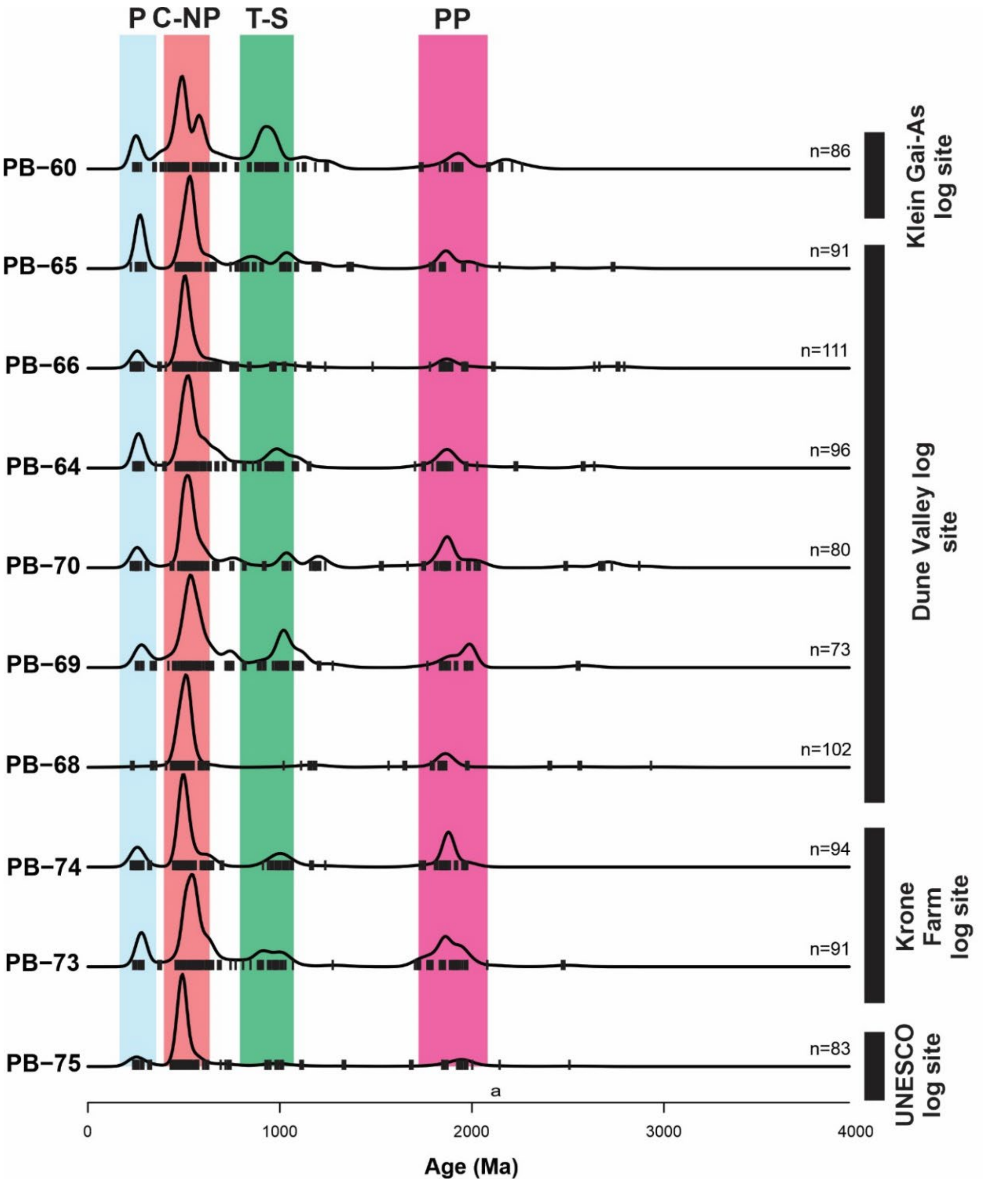

Figure 2 - Detrital zircon U-Pb ages for Twyfelfoutein Formation. C-NP – Cambrian-Neoproterozoic (450-650 Ma); P- Permian (ca 250 Ma); TS- Tonian-Stenian (900-1150 Ma); PP-Paleoproterozoic (1850-2050 Ma).

The detrital zircon geochronology yielded zircons with single ages ranging from 228 to 2964 Ma. Four main groups are identified: Permian (P)(ca 250 Ma), Cambrian to Neoproterozoic (C-NP)(450 to 650 Ma), Tonian to Stenian (T-S)(900-1150 Ma) and Palaeoproterozoic (PP)(1850-2050 Ma). The Cambrian to Neoproterozoic contribution is the most prevalent in all samples (av. 61%), while Permian (av. 11%), Palaeoproterozoic (av. 14%) and Tonian-Stenian (av. 13%) occur subordinately. Figure 8 presents the ages distributions with the principal age groups highlighted over the kernel density estimator (KDE) plot. The contributions are similar, however the P and T-S ages disappear at samples PB-75 and PB-68, while samples PB-60 or PB-69 shows important contributions of P and T-S ages (up to 23 and 27%, respectively). Zircon Th/U ratio displays a mean value of 1.01 ± 0.2 (0.007 to 72.75). In detail, the Permian grains have a mean 1.14±0.1 (0.13 to 3.99), the Cambrian-Neoproterozoic have 0.96±0.3 (72.75 to 0.007), the Tonian-Stenian have 0.85±0.1, and the Palaeoproterozoic have 2.3±0.1.

5. Twyfelfountein Formation provenance

The provenance of the Twyfelfountein Formation comprises feldspatho-quartzose sands (Fig. 4) of fine-to-medium grain size (Fig. 5). The heavy minerals display a resistate-rich composition of tourmaline, garnet, Fe-Ti oxides and zircons (Fig. 6). The geochemistry of garnets and tourmalines points to sources related to amphibolite facies meta-sandstones and -mudstones and acidic granites (Figure 7). The detrital zircon U-Pb dating indicates a predominance of Cambrian-Neoproterozoic ages, with secondary Permian, Tonian-Stenian and Palaeoproterozoic ages (Fig. 8). An important remark of Twyfelfountein Formation is the diminution of the zircons concentration in heavy minerals in compared to South America samples. Bertolini (2020b) highlighted that some samples are possibly affected by weathering - leading to secondary zircon enrichment. The dryer environments of Namibia possibly preclude strong surface weathering effects on the heavy mineral assemblage, resulting in a lower proportion of zircons.

The variations along stratigraphy- from the desert basal sections to the interbedded dunes and lava of the Twyfelfountein – display mixed results with no clear compositional trend. The detrital zircon contributions have the same peaks as the study of Zieger et al. (2020). This particular set of age contributions (Permian, Cambrian-Neoproterozoic, Tonian-Stenian and Palaeoproterozoic) are typical in Paraná Basin since Permian (Bertolini et al., 2021, 2020b; Canile et al., 2016; Peri et al., 2016; Pinto et al., 2015). The age clusters described from the Twyfelfountain Formation are virtually the same as those in the Parana Basin from at least the Permian succession. This similarity of Huab and Parana Basin detrital zircon signatures led to the same interpretation as for South America strata, where continuous reworking of older strata to supply younger sedimentary successions in the Huab Basin.

In terms of process, the reworking and recycling of detrital material from underlying strata is envisaged to be the main mechanism for sand generation and supply to the Twyfelfountein desert. Such an interpretation is compatible with provenance studies of the Botucatu Formation (Bertolini et al., 2021, 2020b). For such multicyclic basins such as the Paraná Basin, the varietal geochemistry and detrital zircon age spectra are indicative of the protosources- the rocks in which the minerals have grown but which do not directly provide the source of the sand. These protosources are important in providing the ultimate source of sand to the basin, but the timing of when these rocks were eroded and the detritus transported to the basin cannot be pinpointed in such multicycle reworking that occurs in basins such as the Huab or Parana. For instance, garnets and tourmalines indicate granitoids and intermediary metasedimens as sources. Such rocks are common adjacent to the Huab Basin, in particular, the Damara Belt rocks- composed of amphibolite facies metamorphism of heterolitic marine successions (Toé et al., 2013). To support the Damara Belt sourcing, Mountney et al. (1999a) describe gravel from the Krone Member fluvial strata as being composed of metasediments derived directly from the Damara Belt. Also, a series of granitoids with Neoproterozoic ages also occur in the Dom Feliciano/ Damara Belt (Goscombe et al., 2017; Philipp et al., 2016). The high contribution of Cambrian-Neoproterozoic detrital zircons supports the idea that these granitoids had sourced the Twyfelfountein Formation - however as these sands were already in the Huab Basin, this 1st cycle contribution is subsidiary at most. The timing of these contributions is unknown but there are indications that the Krone and Pedreira units possibly received part of their sands from these sources based on gravel composition.

In summary, the recycling of older strata is ubiquitous in the shared history of the Huab/Parana basins, however these granitoids and metasedimentary rocks revealed by garnets and tourmaline geochemistry have been contributing at some degree to the basin sandload. Based in this dataset and as well as several studies that tackles the provenance of reworked successions, the proportion and timing of the reworked sands and the 1st cycle sands cannot be properly constrained.

6. Provenance correlation of the Twyfelfountein and Botucatu formations

Overall, the provenance of the Twyfelfountein Formation is comparable with that of the Botucatu Formation. As previously discussed, the recycling is the main important sand source system for the Botucatu desert, however there are also consistent changes in provenance. The southern margin of the Botucatu outcrop displays a westerly trend indicated by a lateral change in detrital zircon, grain size and heavy mineral composition (Bertolini et al., 2020b)- which includes coarser, lithofeldspathic- and garnet-rich, and Cambrian-Neoproterozoic enriched detrital zircon. The large and multivariate dataset allows tracking of these shifts in provenance even relatively small changes recorded along the shared southern margin of the desert. Figures 9 and 10 demonstrate the lateral shifts in detrital zircons (Fig. 9) and tourmaline and garnet concentration and geochemistry (Fig. 10). In addition, figure 10 illustrates the underlying stratal changes from SW to SW- more details can be found in figure 1. The main hypothesis to explain the changes in provenance from SW to SE is the lateral change in composition of the dominant underlying strata in the basin, as depicted in figure 11.

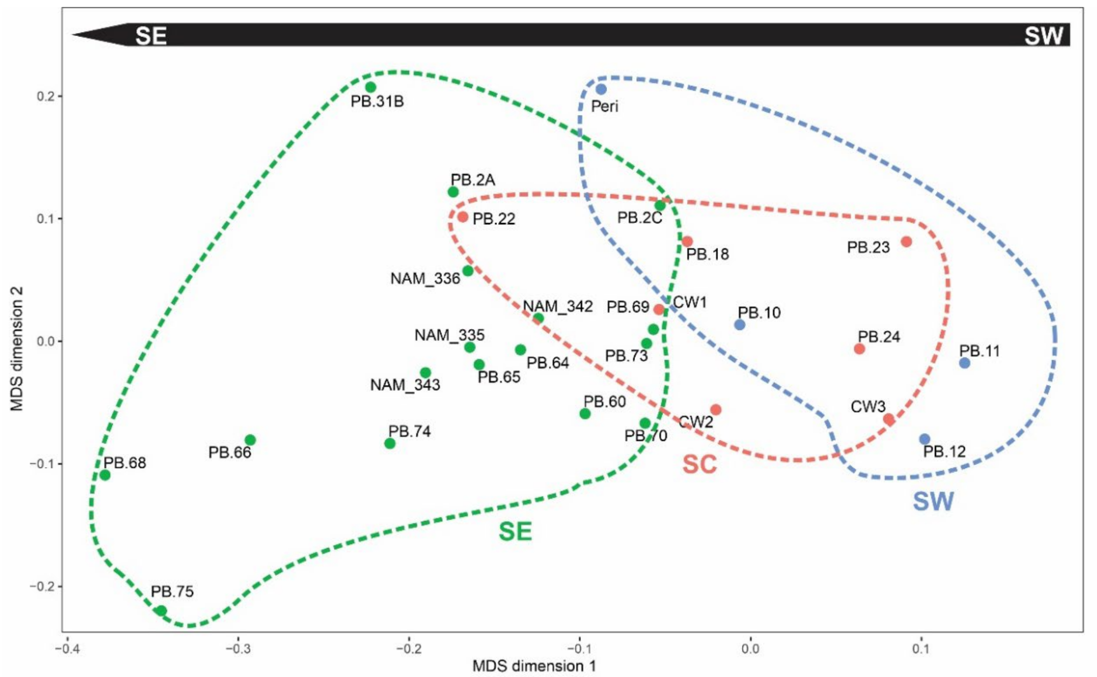

Figure 9- Multidimensional scalling plot of detrital zircon dataillustrating the lateral change from Southwast (SE) to Southewest (SW) Botucatu/Twyfelfontain Fms. Data from this work, Bertolini 2020, 2021, Peri et al 2016, Zieger, 2020, Canile 2016.

Figure 9 compiles detrital zircon U-Pb dates from this work with previously published data from the Botucatu and Twyfelfountein Formations. The MDS plot compares the sample similarities using the Kolmogorov-Sminov distances and a lateral correlation from SW to SE is present (green, red and blue areas), demonstrating such a trend in southern margin.

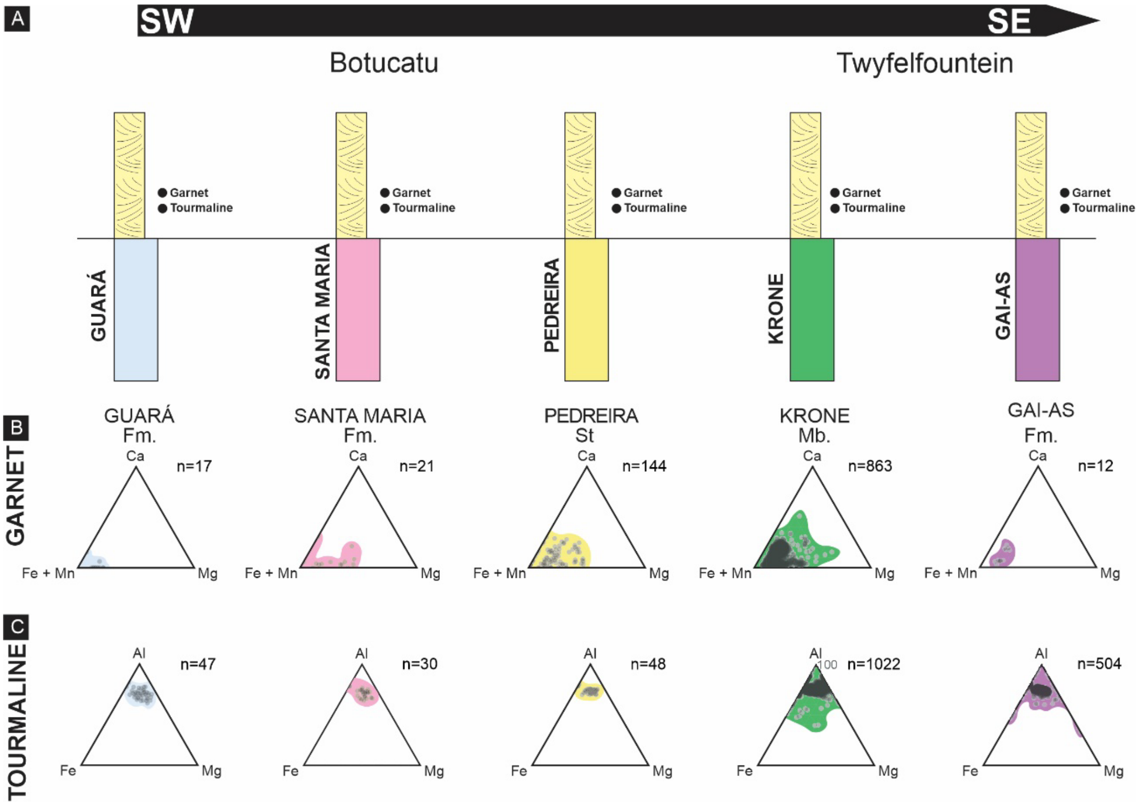

Figure 103- Ternary plots of garnet (B), and tourmaline (C) within Botucatu Desert pooling samples that overlies the Gai-As, Krone (Namibia), Guará, Santa Maria and Pedreira Formations (Brazil and Uruguay). The sample location is located in figure 2, and the model depicted in figure 11.

Figure 10 displays garnet and tourmaline compositions from the Botucatu and Twyfelfountein formations divided by the underlying strata, from west to east. The samples are always from Botucatu/Twyfelfountein pooled when the unit is overlying a particular-strata. The units are, from West to East, Guará Formation, Santa Maria Formation, Rio do Rasto Formation, Pedreira Sandstone, Krone Member, and Gai-As Formation(Scherer et al., 2023).

The Fe-rich garnets are particularly prevalent in samples from the Krone Member and Pedreira Sandstone, but are virtually absent toward the SW. In addition, the garnets from SW (over Santa Maria and Guará Formations) are mostly Bl poor in Ca, while Pedreira and Krone display BI, BII, A, and CI garnets, richer in Ca. The tourmaline geochemistry is relatively similar, composed of dravite-schorlite tourmaline, with an increase of Li-rich elbaite in Twyfelfountein samples.

Considering the consistent West-East changes in provenance mirroring the underlying strata configuration, we propose that the local recycling of older strata is the main control on the provenance of Botucatu sand composition. Figure 11 illustrates the envisaged model for sand generation and sourcing of the Botucatu and Twyfelfountein sands. The composition of the desert sands mirrors the changes in underlying rock composition, pointing to a very local sand source. Most of the sand is recycled from Paraná-Huab basin strata by axial fluvial systems to finally be reworked by aeolian activity. Such a trend is also observed in a coarsening of the sand from SW to SE as described in Bertolini et al (2023). Altogether, the detrital zircon, heavy mineral compositions and geochemistry, and the grain-size show that the Botucatu Desert only received sands rather than controlling the sources, its composition its controlled by the provenance of very localy sourced sands, that are, ultimately governed by changes in underlying basin stratigraphy.

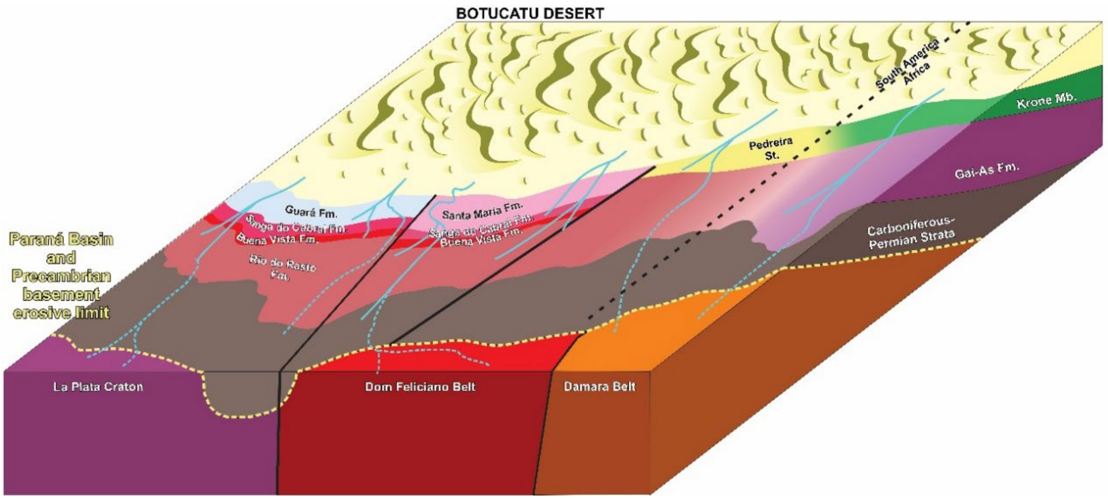

Figure 11- Model for provenance distribution in southern Botucatu Desert margin   depicting the recycling of underlying strata of Paraná basin.

Conclusion

Sixteen samples, from 5 profiles in the Huab region, of northern Namibia produceda dataset of 16 petrographic thin-sections , 14 grain-size analyses, 16 heavy mineral samples and 6,438 single-grains geochemistry analysis, 10 samples and 907 U-Pb dating in detrital zircons, show that Twyfelfountein Formation provenance is composed of:

- Fine-to-medium feldspatho-quartose sand;
- Tourmaline, garnet and Fe-Ti oxides are the predominant heavy minerals, with subsidiary garnet, titanite, epidote;
- The garnets are mostly Fe-rich (almandines) formed as (i) metasediments and amphibolite-facies and (ii) acidic igneous rocks;
- Tourmalines are composed mainly by dravite to schorlite formed as (i) metamorphic mud- and sandstones, and (ii) Li-poor granites.
- Cambrian-Neoproterozoic (450 to 650 Ma) detrital zircon U-Pb ages dominantes with subsidiary Permian (ca 250 Ma), Tonian to Stenian (900-1150 Ma) and Palaeoproterozoic (1850-2050 Ma) ages.

The composition of the Twylfefountein is similar to the Botucatu Formation, its South America counterpart. Such compositions indicate a direct rework of underlying strata as the main source of both sands. In detail, there is SW to SE trend in provenance, illustrated by detrital zircon, grain-size, heavy-mineral compositions and geochemistry. This variation mirrors a lateral change in Paraná and Huab Basin underlying strata. The rework of this different units along southern desert margins results in a similar but lateral changing provenance.

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