Cenozoic to modern-day source to sink systems of Senegal: A record of provenance, transport, recycling and climate controls

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Discerning the provenance record of fresh detritus versus recycled sediment in Tertiary to modern-day source-to-sink systems of Senegal

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1 *Cenozoic to modern-day source to sink systems of Senegal: a record of*
2 *provenance, transport, recycling and climate controls*

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18 Provenance, Heavy mineral, Senegal, Africa, West African Craton, River, Quaternary,
19 Sediment recycling

Abstract

This study presents an integrated mineralogical assessment for the provenance of sediments derived from modern-day rivers and Cenozoic deposits in Senegal and Gambia. Two distinct populations are identified from discrimination of the heavy mineral assemblages; the Senegal River sediment, sourced from the West African craton and Mauritanides and Meso-Cenozoic sediment sourced from the onshore Senegal basin, demonstrating prevalent recycling of Senegal basin sediments by the Ferlo, Saloum, Gambia and Casamance Rivers throughout the Quaternary.

The Senegal River records the occurrence of amphibole, epidote, garnet and pyroxene, which indicates denudation of Neo to Paleo-Proterozoic granites, low-medium grade meta-sediments and a skarn-type lithology. Meso-Cenozoic recycled sediments within the onshore Senegal basin exhibit a heavy mineral component which has been modified through the chemical-weathering and diagenesis of less-stable amphibole, pyroxene and garnet. U/Pb dating of zircons from the Casamance and Gambia provinces indicates that, at least in part, the Mesozoic sediments of the onshore Senegal basin may have been ultimately derived from the Leo-Man Shield.

Kaolin occurrence is associated with tropical weathering of laterites. The occurrence of terrigenous-smectite sourced from high altitude regions of the Mauritanides and West African Craton is interpreted to have formed under hyper-arid conditions prior to erosion and transportation, during the African humid periods of the Holocene.

This integrated mineralogical study of modern-day and Cenozoic sediments has established prevalent recycling of Senegal basin-sediments by the Ferlo, Saloum, Gambia and Casamance Rivers and continued erosion and recycling of hinterland-sediments via the

modern-day Senegal River. This identification of two distinct provenance groups and the strong climatic signal provides the important framework for future studies assessing the source to sink systems during the Meso-Cenozoic.

Introduction

Modern-day drainage of Senegal and Gambia is via four major river systems: The Casamance, Gambia, Saloum and Senegal rivers (Fig. 1). These have drainage catchments in Mauritania, Senegal, Gambia, Guinea Bissau, Guinea and Mali. Feeder tributaries to the Senegal River includes the Ferlo River (central Senegal), Falémé, Bakoye and Bafing rivers (Guinea), Baoule (Mali) and the Kolinbine, Karakoro and Gorgol rivers (Mauritania). During their existence, these river systems may have eroded the Mauritanide orogenic belt, the West African Craton (WAC), the Leo-Man Shield, the Kédougou-Kéniéba Inlier (KKI) sediments of the Hodh, Taoudeni, Youkounkoun, Bove and Senegal-Mauritania Basins (Villeneuve et al., 2015).

Recently there has been renewed interest in the MSGBC (Mauritania-Senegal-Guinea-Bissau-Guinea-Conakry) basin due to the discovery of significant volumes of hydrocarbons offshore, most recently the FAN-1 and SNE-1 discoveries (Hathon, 2018). Extending exploration away from these discoveries will in-part rely on an improved understanding the controls on provenance and sediment supply to the NWAAM (North-West African Atlantic Margin).

In this study, we present an integrated mineralogical assessment of modern-day river sediments from the four major river systems of Senegal and Gambia, augmented with selected samples of Cenozoic sandstones. The results allow a developing understanding of

the modern-day source-to-sink systems of Senegal, and this research presents the first published provenance study of the onshore Senegal basin.

Heavy mineral studies are frequently used to assess the stratigraphic and spatial variations of provenance over a region (Mounteney et al., 2017; Farrant et al., 2018; Fossum et al., 2019; Garzanti & Ando, 2019). The results from this project can also be used as a control to understand paleo-river drainage of NW Africa and further refine models for sand delivery into the onshore and offshore basins.

Regional Setting

River geometry

The Senegal River (Fig 1) is the longest of the four river systems, with a river-length of *ca.* 1800 km (Kattan et al., 1987), and a total catchment of *ca.* 328,825 km² (Stanzel et al., 2018). The principle section of the River Senegal, between Bakal and St Louis (*ca.* 784 km; Shahin, 2002), is known as the Middle Senegal Valley (MSV; Coutros, 2018). Headwaters of the Senegal originate from the Falémé, Bakoye and Bafing rivers (Guinea), propagating in a north-westerly direction and intersecting with the Baoule (Mali), Kolinbine, Karakoro and Gorgol rivers in Mauritania. As the Senegal River passes through Northern Senegal, it shifts to a westerly direction following the Senegal-Mauritania border. The Ferlo River feeds into the Senegal River, at the junction of Lake de Guiers, before terminating at St Louis (Isupova & Mikhailov, 2008). Prior to the construction of the Diama Dam in 1986, sediment run-off from the Senegal River averaged *ca.* 0.006 km³/yr, this was reduced to *ca.* 0.004 km³/yr after its construction (Isupova & Mikhailov, 2008). The Gambia River is the second largest river in Senegal/Gambia spanning *ca.* 1,120 km from the Fouta Djallon plateau in Northern Guinea, moving westwards through Senegal and The Gambia, exiting into the Atlantic Ocean

88 at Banjul (Simier et al., 2006) with a total catchment of 41,888 km² (Stanzel et al., 2018). The
89 Casamance River is a comparably smaller system, at 350 km in length. Its drainage
90 catchment is 13,850 km² which is restricted to the Quaternary deposits of Southern Senegal
91 (Debenay et al., 1994). The Saloum is the smallest of the four rivers, at a mere *ca.* 250 km in
92 length (Faye et al., 2004), with the smallest catchment of *ca.* 8000 km² (Pages & Citeau,
93 1990).

94 River geometry is principally governed by local factors, such as relative stream size, valley
95 slope, sediment charge and relative settling size of the sediment (Shahjahan, 1970)
96 however, in a broader context, regional physiography and changes in climate can have a far
97 greater effect on river-systems (Grimaud et al., 2018; Isupova & Mikhailov, 2008). Extreme
98 changes in climate can produce contrasting effects in fluvial systems with cessation of rivers
99 in hyper-arid conditions and flooded high-energy systems during more humid periods.

100

101 *Figure 1 Digital elevation map (DEM) of Senegal and the major rivers (Senegal, Saloum, Gambia and Casamance) including*
 102 *feeder tributaries from neighbouring countries. DEM model produced from data by the General Bathymetric Chart of the*
 103 *Oceans (GEBCO; Becker et al., 2009).*

Figure 2 Geological map of NW Africa, location of sediments collected for this study and North-African Sahel, Saharan and Sudan climate zones. KKI-Kédougou-Kéniéba Inlier, MFT-Mauritanide front thrust, WAC-West African Craton. Compiled from Bellion and Crevola, 1991; Davison, 2005 and GEM, 2020.

Physiography

Understanding the evolution of the Senegalese river systems through time is complex, with several factors governing their development. Mesozoic continental-margin tectonics resulted in the formation of a series of sub-basins along the drainage pathway, with faulting, rifting and development of topographic swells (Burke, 1976; Guiraud et al., 2005; Murlot et al., 2018; Ndiaye et al., 2016b; Uchupi, 1989). In the southern region of Senegal, a series of sub-basins are divided by the Casamance failed rift-arm, where the Gambia River now resides (Burke, 1976). The emplacement of the Dome de Guiers in Northern Senegal during the Maastrichtian (Trenous & Michel, 1971) established a dissymmetric graben-like

structure, controlling the location of Lake de Guiers. This coincided with a series of orthogonal faults, controlling the geometry of the River Ferlo.

Climate

During the Quaternary, North Africa experienced dramatic changes in climate, hydrology and vegetation. The last glacial maximum of the Pleistocene (20-12.5 ka bp; Coutros, 2019) affected global climate and sea-level; in North Africa this resulted in significant shifts to the position of the intertropical convergence zone (ITCZ; Nicholson, 2017; Adam et al., 2019). During the latter stages of this glacial period, sea-level was at least 100 m lower compared to present-day levels (Diester-Haass, 1975). Precipitation in the Sahel region (Fig 2) was reduced by 10-15% compared to modern levels, shifting the ITCZ southward by 2° (Coutros 2019). This resulted in Senegal's climate entering into a period of hyper-aridity which substantially reduced plant cover, creating an albedo-associated positive feedback loop, exacerbating local aridity (Coutros, 2019; Ehrmann et al., 2017). During this hyper-arid phase, the rivers south of 17° N (Mauritania) are believed to have ceased flowing, entering a stage of stagnation (van Zinderen-Bakker & Maley, 1977; Diester-Haass, 1975; Michel, 1973). A significant exception to the cessation of fluvial activity within the Sahel region is the River Falémé in eastern Senegal, which may have been continually flowing due to its headwaters being located further south in the Guinean Highlands (Coutros, 2019).

The ensuing Holocene interglacial period (11,700 years BP) ushered in the AHP (African Humid Period) causing a sharp drop in temperature, 5-7 °C cooler than in the Pleistocene hyper-arid period; resulting in the northward expansion of the ITCZ to at least 12° N (Coutros, 2019). Dramatic increases in precipitation of the WAM (West African Monsoon) led to the reactivation of river-systems within the Sahel region of NW Africa. This increase in renewed precipitation also resulted in the development of many lakes within the Sahel and

tropic zones. A consequence of this increased precipitation was the development of the largest pluvial lake in the world at this time; the Mega-Chad lake, covering an area of 361,000 km², with a depth of up to 160 m (Armitage et al., 2015). On the north-western edge of the Adrar region of Mauritania, the Chemchane sabkha (lat 21°N, long 12°W, elevation 256 m), is a NE-SW-orientated depression. This sabkha was transformed into a lacustrine environment 8.3 to 6.5 ka bp due to WAM precipitation during the AHP (Lézine et al., 1990). Following a comparatively short period of hyper-aridity 7.8-6.7 ka, the Sahel region of Africa returned to a second AHP peaking at 6.7 and 5 ka bp, at which time Holocene sea-level had returned to a nominal -3 m below-present (Miller et al., 2005).

Basin morphology

The MSGBC Basin is the largest continental margin basin along the NWAAM. Senegal contains approximately half of the onshore portion of the MSGBC Basin, a total area of 340,000 km² (Davison, 2005; Ndiaye et al., 2016; Murlot et al., 2018; Ritz & Bellion, 1988) extending along a 1400 km segment of the NWAAM (Ritz & Bellion, 1988; Brownfield, 2003; Brownfield, 2016). The basin is an “Atlantic-type” passive margin, with a prograding wedge of sediment that develops a broad shelf, which is in part exposed and extends offshore to form a steep shelf margin and slope, ultimately thinning onto oceanic crust. Central and western Senegal has an extremely low average elevation of <65 m above sea-level, with some floodplains <41 m below sea-level (Fig 1). There are a limited number of topographic highs, which include: the Cap Vert Peninsula (Ndiaye & Ngom, 2014; Hansen, 2008), Leona Dome (Hansen, 2008; Ritz & Bellion, 1994) and the Dome de Guiers (Trenous & Michel, 1971).

The clastic infill predominantly consists of Meso-Cenozoic strata, thickening from east to west, where it reaches a maximum thickness of >10,000 m along the western Atlantic coast

(Ndiaye et al., 2016b). These sediments overly pre-rift Palaeozoic strata of the Bove Basin (Davison, 2005) and/or Precambrian basement (Davison, 2005; Guiraud et al., 2005; Villeneuve et al., 2015).

Basin Evolution

Pre-Central Atlantic rifting and the establishment of the basin began during the Late Palaeozoic fragmentation of the Gondwana supercontinent (Binks, 1992). During the Permian/Triassic a large-scale network of rifts were established along the NWAAM, with continued extension resulting in the final separation of Gondwana during the Early Cretaceous, manifested by the complete separation of South America and Africa (Lehner, 1977; Storetvedt, 1985; Uchupi, 1989; Labails et al., 2010). The basin can be divided into three regional blocks: the Toundou Block (Northern); Cayar, Dakar, and Gambia blocks (Central); and the Casamance (Southern) (Gladimi, 1977), potentially controlling paleo-drainage.

The Senegalese segment of the basin is fringed by the Mauritanides; a *ca.* 1500 km long orogenic belt (Villeneuve et al., 2015; Villeneuve, 2008; Gueye et al., 2007), which formed as an accreted terrain along the western margin of the WAC (Fig 2) in the Carboniferous (Page, 1988; Ponsard et al., 1988).

The section of the Mauritanides fringing the MSGBC basin can be further subdivided into the Hercynian Belt to the North and the Bassaride Belt to the South, separated at 14° N latitude. The Bassaride Belt is associated with the first Pan-African II tectonic event occurring 660-650 Ma with the northern segment of the Mauritanide belt associated with the Hercynian orogeny, 370-290 Ma (Villeneuve, 2008). Palaeozoic basins surround the eastern flank of the

Mauritanides, with the Bove Basin to the south and the larger Taoudeni Basin to the East (Boudzoumou et al., 2011; Culver & Hunt, 1991; Beghina et al., 2017).

To the east of the Mauritanides is the West African Craton (WAC), this comprises two Archean Shields: the Reguibat to the North, and the Leo-Man to the South (Villeneuve et al., 2015; Villeneuve, 2008; Gueye et al., 2007).

Materials and Methods

Heavy Minerals in sandstones

Heavy minerals are defined as minerals with a density of greater than 2.9 g/cm^3 and are typically found as accessory components ($< 1\%$) in most sandstones (Morton & Hallsworth, 1994). Their occurrence is principally due to their inherent “relative” resistance to weathering, erosion and diagenesis. Identification and analysis of this heavy mineral fraction can be diagnostic of specific geological source terrains/lithologies. Variations in the heavy mineral assemblage (stratigraphically and spatially) over a region can infer shifts in sediment provenance and potential mixing of sediments from multiple sources. Care must be taken when attempting to interpret provenance indicators; as processes during the sedimentary rock-cycle can modify the preserved heavy mineral signature. These processes can include initial weathering of the source rock, mechanical abrasion during transportation, hydraulic sorting of grains based on grain size and density during both transportation and deposition, selective dissolution during burial diagenesis and preferential subaerial chemical-weathering (Morton & Hallsworth, 1999). Heavy minerals can broadly be subdivided into categories based on their inherent relative stabilities:

1. Ultra-stable (rutile, tourmaline and zircon).

2. Deep-burial stability; garnet and apatite are stable during deep burial but are more vulnerable to hydrothermal or acidic meteoric fluids.

3. Intermediate stability: epidote, kyanite, staurolite and titanite.

4. Less-stable: amphibole, olivine and pyroxene.

Heavy mineral indices are used in conjunction with the overall mineral assemblage to better refine our prediction of source. These indices are based on pairs of heavy minerals, which are chosen based on their stability during diagenesis and share similar hydraulic properties (Morton & Hallsworth, 1994). For the purpose of this study these indices include apatite:tourmaline (ATi), garnet:zircon (GZi) and rutile:zircon (RZi).

Single-mineral geochemistry can provide greater detail on source-rock lithology. In this study, the geochemistry of garnet and tourmaline are used to propose potential source lithologies and to aid in the discrimination of basin sediments. Both mineral groups possess a wide range of chemical compositions, which are dependent on their mode of formation through variations in pressure and temperature.

Garnet Speciation

Attempts to assign a source lithology based on garnet geochemistry can be fraught with problems as certain species of garnets can be associated with differing paragenesis (Wright, 1938). Mange and Morton (2007) divided garnets into different classifications based on their divalent X-site cation Mg (pyrope), Fe+Mn (almandine/spessartine series) and Ca (grossular/andradite series). They noted that the subdivision of garnets should be used to reflect natural sedimentary groupings and are not strictly indicative of a specific garnet-bearing source rock. Mange and Morton (2007) divided garnets into four classifications (Type A, B, C & D). Type A garnets are typically derived from high-grade granulite facies,

meta-sediments and charnockites. Type B garnets can be derived from amphibolite-facies meta-sediments, this type can be further divided into a type Bi group which can be indicative of intermediate-acidic igneous rocks and Bii can be derived from metasedimentary rocks up to amphibolite facies; however, some compositional overlap between the Bi and Bii groups may occur. Type C garnets are analogous of high-grade metabasic rocks; type Ci (XMg <40%) are more likely to be associated with meta-igneous rocks such as eclogites, granulites and amphibolites (Fossum et al., 2019), whereas Cii garnets (XMg >40%) are likely to be associated with mantle-derived rocks (Fossum et al., 2019). Type D garnets are associated with metasomatic rocks such as skarns, from very low-grade metabasic rocks or from ultra-high temperature metamorphosed calc-silicate granulites.

The Aubrecht classification (Aubrecht, 2009) of garnets is used to denote metamorphic grades (A, B & C): A = garnets with compositions from HP-UHP conditions, B = granulite to eclogite facies and C₁ = transitional field of garnet compositions from high amphibolite to granulite, C₂ = amphibolite facies (including garnets from blue-schists, skarns, serpentinites and igneous rocks).

Tourmaline Speciation

The tourmaline-supergroup consists of a complex suite of borosilicates sharing the common formula: $XY_3Z_6(BO_3)_3Si_6O_{18}(OH)_4$ (Henry & Guidotti, 1985; Yavuz et al., 2014). A common accessory mineral in many lithologies which is highly resistant to diagenesis and chemical weathering, tourmaline is a useful mineral for petrographic studies. Tourmaline can be subdivided based on two series; schorl-dravite and schorl-elbaite; compositional refinement is based on the four predominant substitution-elements (Al, Ca, Fe & Mg). Using the Al-Fe (tot) Mg and Ca-Fe (tot)-Mg ternary diagrams (Fig 10), some inferences on source-rock can

be made, which include: Li-rich/poor granitoids and pegmatites, Ca-rich/poor metapelites, meta-carbonates and meta-ultramafics.

Fieldwork

A total of 30 samples were collected for this study, documented in Table 1 (Appendix) and locations shown in Fig 2. Samples from three major rivers were taken, two from the Senegal River, two from the Saloum and five from the Casamance River. No samples were collected from the Gambia River due to a lack of observed sand along the riverbank.

Sediment sampling from active river channels was restricted due to access and availability of exposed sand. The Senegal River (Fig 3D), located within Northern Senegal in the Saharan environment, had a bedload dominated by sands and the riverbanks are characterised by dense grasses and scrub. The Saloum River (Fig 3A) is located within the Sahel environment, which is typically arid with abundant scrub and baobab trees. This river was more accessible, however, much of the tributary upstream had dried-up, leaving only organic-rich muds and evaporates at the surface. The Gambia (Fig 3C) is a large river system with the channel reaching 12 km at the widest point. Accessibility was extremely limited due to extensive muddy mangrove swamps flanking the riverbanks and even feeder-tributaries yielded no sand deposits for sampling. The sediment immediately surrounding the river and mangroves was typically composed of dark organic-rich clays.

The Casamance (Fig 3B) yielded better results, with several accessible sampling points along the meandering river. The environment in this region was more sub-tropical, with grasses and extensive gallery-forests flanking the river, many of these included vast areas of mango production.

The sampling regime for river sediments involved collection of sand from pits dug *ca.* 30 cm³, the size of pit was chosen to reflect an average detrital composition unaffected from seasonal variation in water-levels and flash flood events. The 30 cm depth includes the uppermost (10 cm) contemporaneous sedimentation layer (Okay & Ergun, 2005) and the lower 20 cm profile for better sample representativity (Pan et al., 2016). The sampling sites were selected in natural settings with no apparent anthropogenic influence, in order to collect 1-2 kg of sand. Where possible, multiple samples were collected from various points across the river-banks to remove any local variations in mineral assemblage due to hydraulic sorting. Due to a lack of sediments directly sourced from the rivers in some locations, extra samples were also taken from adjacent Cenozoic deposits in the form of exposures, pits and quarries (Fig 4), these were also difficult to find at times due to accessibility and the sheer scale of the distances involved in the sampling programme. Three sand pits were sampled along the Gambia's riverside, within the regions of Jenoi, Japp (Fig 4A) and Dalaba (Fig 4B). A large sand quarry located near the town of Tivaouane (77 km North-East of Dakar) was sampled containing massive units of structureless Miocene to Pliocene age sands (Fig 4E). A few exposures within this quarry exhibited transgressive lag-deposits (Nahon et al., 1977) containing sub-rounded lateritic clasts (Fig 4F). A smaller sand quarry near Thiago (Northern Senegal), east of Lake de Guiers, also yielded several samples of sand (Fig 4C, D).

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Figure 3A, Sand bank along the River Saloum, South of Kaolack. B Sand ban along the River Casamance at Diop Kounda. C Mud embankment along the River Gambia, North of Sankwin, dense mangroves border the river. D, Sand embankment along the River Senegal Northeast of Debi.

Figure 4, Photographs of Cenozoic sandstones with corresponding sample numbers and sampling locations. A, Japp sand pit, north of Sankwin, Gambia. B, Sandy exposure/pit near Dalaba, Gambia. C, Thiago quarry, Northern Senegal. Massive red/brown (upper unit), grey/brown (lower unit) sandstones in the background, studied outcrop in foreground is expanded in Figure 4D. D, fluvial sand deposits: 636, brown finely laminated sands. 637, grey/brown sand. 638, orange/brown, matrix-supported conglomeratic sand, with small (<10 mm) pieces of lignite/wood. 639, grey/brown sand. E, Tivaouane quarry, 77 km NE of Dakar, 640 marks the location of a sandstone pinicle which is expanded in Figure 4F. F, Orange/brown sandstone with a transgressive laterite lag-deposit.

Conventional heavy mineral analysis

Heavy mineral separation was conducted on the 63 μm to 125 μm sand fraction (based on the technique established by: Morton & Hallsworth, 1994, Farrant et al., 2018). Analysis of the transparent detrital heavy minerals (tdHM) was performed using a transmitted light microscope (Mange & Maurer, 1992; Farrant et al., 2018; Mounteney et al., 2017), averaging 300 tdHM per sample. Opaque heavy minerals were counted but not identified.

Petrography

Petrographic analysis was performed using the Gazzi-Dickinson method (Ingersoll et al., 1984), samples were impregnated in blue resin and polished to a thickness of 30 μm and stained for K-feldspar identification. Clast analysis of the sands and sandstones using a Qm-F-Lt plot, was conducted on 300 sand-sized counts per sample, including the identification of: monocrystalline and polycrystalline quartz, plagioclase and K-feldspar, lithic grains (metamorphic, igneous and sedimentary), clay minerals (muscovite, biotite and chlorite), carbonate, accessory minerals and fine-grained clay matrix (Ingersoll et al., 1984; Li et al., 2015; Dickinson et al., 1983).

Whole-rock mineralogy

Representative subsamples of the dried sands were ball-milled to reduce particle size to < 125 μm . Subsamples of the < 125 μm material were micronised under water for 10 min with 10% corundum (American Elements-PN:AL-OY-03-P) using a McCrone micronising mill for bulk-rock mineralogical quantification (Kemp et al., 2016b; Collier et al., 2019). Bulk-rock X-ray Diffraction (XRD) analysis was carried out using a PANalytical X'Pert Pro series diffractometer equipped with a cobalt target tube, X'Celerator detector, and operated at 45 kV and 40 mA.

< 2 μm clay mineralogy

Separation of the <2 μm clay fraction for orientated-clay XRD analysis was achieved using the methods defined in Kemp et al., 2016a. The <2 μm oriented mounts were scanned from 2-40°2 θ at 1.02°2 θ /minute after air-drying, after glycol-solvation and after heating to 550°C for 2 hours. Quantification of the <2 μm clay was calculated based on the method defined by Biscaye (1965). The < 2 μm fraction is chosen because of the reasonable assumption that 100% of the mineralogy is constituted by chlorite, illite, kaolinite and smectite (Biscaye, 1965).

Single-mineral geochemistry

Samples were analysed using an FEI Company Quanta 600 scanning electron microscope (SEM) fitted with an Oxford Instruments X-Max 50 mm² silicon-drift energy dispersive X-ray (EDX) detector running with Oxford Instruments INCA (v4) software. Analytical conditions for the SEM were: high vacuum (<10⁻⁴ Torr), an accelerating voltage of 20 keV, and a spot size of 6 (beam current ~ 2 nA).

Automated quantitative microanalysis and mineral identification was performed using the 'Feature' package within the INCA software. Multiple images were obtained over a mm-scale grid with the backscatter electron (BSE) technique. Since the brightness of a phase under BSE imaging is proportional to its mean atomic number, greyscale thresholding was used to limit microanalysis to grains with similar average greyscale values to that of a known tourmaline. Microanalytical EDX data was obtained from a centre-point site of each of the threshold-identified grains, determined as the centre of the longest chord (a straight line that can be drawn entirely within the grain boundary).

U/Pb dating by LA-MC-ICPMS

Zircon U-Pb data was acquired using a Nu Plasma HR multi-collector inductively coupled mass-spectrometer. Sample were introduced into the mass spectrometer using New Wave Research UP193SS solid state laser ablation.

All analyses were carried on a 25 μm spot, with a frequency of 10 Hz, resulting in a fluence of c. 2.0-2.5 J/cm². Samples were ablated for 30 seconds. Ablated sample material was transported to the mass spectrometer by a flow of He gas, which was continuously passed through the sample cell. Data were acquired and processed using the Nu Instruments time resolved analysis software, and the Lolite 3 data reduction package (Paton et al, 2011). Data was is exported using IsoplotR software (Vermeesch, 2018). For zircon analysis, the matrix matched zircon standard 91500 was analysed throughout each session and used as the primary standard for data reduction. The analytical uncertainties for each sample ratio are propagated relative to the reproducibility of this standard. Additional zircon standards (Plesovice and GJ1) were analysed at regular intervals during each session.

Results

Heavy mineral analysis.

Results from the heavy mineral analysis are illustrated in Figure 5, heavy mineral indices are displayed in Figure 6 and the raw data found in the Appendix. Sediments can be categorised into two provenance-groups based on their tdHM assemblages. The first provenance group is associated with sands from the Senegal River, yielding the most distinctive heavy mineral assemblage, with an average tdHM composition of: amphibole (17%), clinopyroxene (4%), epidote (19%), garnet (2%), staurolite (5%), tourmaline (10%) and zircon (40%). The second provenance-group is associated with the remaining samples that possess similar tdHM assemblages comprising of: rutile (4-11%), staurolite (1-11%), tourmaline (4-32%) and zircon (49-89%). This rutile, staurolite, tourmaline and zircon dominated assemblage is analogous of a “mature” heavy mineral component, whereby the less-stable heavy minerals are removed through mechanical abrasion, chemical weathering and diagenesis. Minor variations in the tdHM compositions include low concentrations of clinopyroxene in the Tivaouane quarry and epidote in the Thiago quarry. The differences in the bulk tdHM (Fig 5) are exemplified by the corresponding GZi, ATi and RZi (Fig 6), displaying a significant shift in the GZi associated with the River Senegal tdHM. There were no significant differences in the quantitative mineralogy for multiple samples collected across the river-bank, inferring good sample representivity.

Figure 5, Transparent detrital heavy mineral assemblages, opaque minerals have been excluded.

Figure 6, Rutile:zircon-index (RZi), garnet:zircon-index (GZi) and apatite:tourmaline-index (ATi) ternary plot.

Whole-rock mineralogy

XRD results are fully documented in the Appendix. All samples are predominantly composed of quartz (95.3-99.8%), with minor concentrations of feldspar (1.7-2.1%), mica

0.8-2.3% (including undifferentiated mica species: muscovite, biotite, illite and illite-smectite) and kaolinite 0.7-1.4%. Other trace minerals (<5%) include: bassanite, gypsum, goethite, hematite and halite.

<2 μm clay mineralogy

The results of <2 μm clay mineral XRD analysis are summarised in Figure 7. The clay mineral assemblages can be subdivided into two distinct regions: northern Senegal (Senegal River and Thiago quarry) and mid to southern Senegal (Casamance & Saloum rivers and quarry/pit samples from The Gambia and Tivaouane quarry).

The Northern Senegal <2 μm clay assemblage is predominantly composed of kaolinite (47.9-79.5%), smectite (11.5-37.5%) and illite (8.9-25.1%). The Southern Senegal clay assemblage is predominantly composed of kaolin (86.1-97.9%), with minor illite (1.7-11.4%) and trace smectite (0-5%). However, the clay mineralogy associated with sediments collected at Tivaouane are entirely devoid of smectite.

Figure 7, <2 μm clay mineral composition by orientated-clay X-ray diffraction.

410 Single-mineral geochemistry

411 Garnet speciation is restricted to the sediments collected from the Senegal River, due to an
412 absence of garnet in all of the other samples and is limited to 2% of the 63-125 μm tdHM. A
413 total of 201 garnet grains were identified by SEM, the majority classified as Type B i & ii
414 garnets, according to the scheme devised by Mange and Morton (2007) (Fig 8A). They
415 reflect one or more of the following source lithologies: amphibolite-facies, metasedimentary
416 rocks, intermediate to felsic igneous. A lesser proportion of garnets is represented by Type
417 D garnets which reflect a metasomatic source. Finally, 2.5% of the remaining garnets
418 reflect a Type Ci source, analogous of a meta-igneous source, such as eclogites, granulites
419 and amphibolites. According the Aubrecht classification scheme (Fig 8B & C) most of the
420 garnets were formed in the C field, which can include garnets from high-grade amphibolite
421 facies, granulites, blue-schists, skarns, serpentinites and igneous rocks. A small percentage
422 of garnets plot within the B field and represent granulite to eclogite facies.

Figure 8, Garnet-speciation ternary diagrams, data from SEM-based geochemical analysis of 63-125 μm tdHM from the Senegal River sands (sample 630). **A**, Garnet speciation based on the classification scheme by Mange and Morton (2007). Type-A= high-grade granulite-facies metasediments or charnockites and intermediate felsic igneous rocks, Type-B= amphibolite-facies metasedimentary rocks, Bi= intermediate to felsic igneous rocks, Ci= high-grade mafic rocks, Cii= ultramafics with high Mg (pyroxenites and peridotites), D= metasomatic rocks, very low-grademetamafic rocks and ultrahigh temperature metamorphosed calc-silicate granulites; **B & C**, Garnet speciation based on the classification scheme after Aubrecht et al., 2009: A= garnets from high-pressure to ultrahigh-pressure rocks, B= garnets from eclogite and granulite facies rocks, C= garnets from amphibolite-facies rocks. The group C is further subdivided into two subgroups. The transitional field C_1 includes garnets from higher amphibolite to granulite-facies rocks whereas the field C_2 includes garnets from amphibolite-facies rocks but also includes garnets other rocks such as blueschists, skarns, serpentinites and igneous rocks. The source lithologies for garnets are distinguished into 7 groups. (1) garnets derived from UHP eclogites or garnet peridotites, (2) garnets derived from HP eclogites and HP mafic granulites, (3) garnets derived from felsic and intermediate granulites, (4) garnets derived from gneisses metamorphosed under pressure and temperature conditions transitional to granulite and amphibolite-facies metamorphism, (5) garnets derived from amphibolites metamorphosed under pressure and temperature conditions transitional to granulite and amphibolite-facies metamorphism, (6) garnets derived from gneisses metamorphosed under amphibolite-facies conditions, (7) garnets derived from amphibolites metamorphosed under amphibolite-facies conditions.

Tourmaline speciation was performed on a total of six samples from: the Senegal, Casamance and Saloum Rivers, Thiago, Tivaouane quarries and Gambia Jenoi (Fig 9). River Senegal tourmalines are predominantly Fe-endmember schorl/buergerite, indicative of a

444 primary Li-poor granitoid, pegmatite and aplite source-lithology. Minor variations in Al_{tot} -
445 $AlFe_{50}$ - $AlMg_{50}$ (Fig 9) ratios infers a potential secondary source-lithology for the
446 schorl/buergerite including metapelites, metapsammities and Fe-rich quartz-tourmaline
447 rocks including calc-silicate rocks and metapelites. Tourmalines from the remaining sample
448 sites, including the Casamance and Saloum Rivers, Thiago and Tivaouane Quarries and
449 Gambia Jeno possess similar endmember tourmalines. The majority of the tourmalines are
450 divided between Fe-endmember schorl/buergerite and Mg-endmember dravite (Fig 9) and
451 are indicative of a primary Li-poor granitoid, pegmatite and aplite source and potential
452 secondary source-lithologies of metapelites, metapsammities and Fe-rich quartz-tourmaline
453 rocks including calc-silicate rocks and metapelites. A small percentage of tourmalines plot
454 within or very close to oxy-dravite endmember (Fig 9) which could be diagnostic of Low-Ca
455 metaultramafics and Cr,V-rich metasediments.

456

457 Figure 9, Compositional ternary diagrams of tourmalines, illustrating the host rock type (from Henry & Guidotti, 1985). **Left**
 458 **(Al-Fe_{tot}-Mg)**: 1= Li-rich granitoid pegmatites and aplites, 2= Li-poor granitoids and their associated pegmatites and
 459 aplites, 3= Fe³⁺ rich quartz-tourmaline rocks (hydrothermally altered granites), 4= Metapelites and metapsammites
 460 coexisting with an Al-saturating phase, 5= Metapelites and metapsammites not coexisting with an Al-saturating phase, 6=
 461 Fe³⁺ rich quartz-tourmaline rocks, calc-silicate rocks, and metapelites, 7= Low-Ca metaultramafics and Cr,V-rich
 462 metasediments, 8= Metacarbonates and meta-pyroxenites. **Right (Ca-Fe_{tot}-Mg)**: 1= Li-rich granitoid pegmatites and
 463 aplites, 2= Li-poor granitoids plus associated pegmatites and aplites, 3= Ca-rich metapelites metapsammites and calc-
 464 silicate rocks, 4= Ca-poor metapelites metapsammites and quartz-tourmaline rocks, 5= Metacarbonates, 6=
 465 Metaultramafics.

Petrography

Clast analysis suggests the river sands and Cenozoic sandstones are compositionally similar, exhibiting the high textural maturity of a quartz-arenite (Fig S 2). On average, 83% of the component grains identified were monocrystalline quartz with 6% polycrystalline quartz, 9% fine grained clay, 1% feldspar_{tot}, 1% lithic_{tot} and 1% accessory mineral. Based on the subdivisions devised by Dickinson et al., (1983), all the modern-day sediments may be associated with the erosion of a cratonic interior. Whilst this may reflect a cratonic source, this quartz enrichment may be exacerbated through associated weathering, transport and diagenesis within a tropical climate (Garzanti, 2017).

U/Pb zircon dating

U/Pb dating was performed on a suite of zircons from the Senegal and Casamance rivers and from Quaternary sandstone from within the Gambia paleo-river system. Kernel density estimation (KDE) plots (Fig 10) were constructed using IsoplotR (Vermeesch, 2018). All three samples have a strong Pan-African age (500-650 Ma) population of zircons and a comparable Paleo-Proterozoic age (1600-2500 Ma) zircon population. The Senegal River have far fewer Meso-Proterozoic age zircons and a small population of Neo-Archean age (2600 Ma) zircons. The Gambia River contains the oldest population of Meso-Archean zircons (3100 Ma). The River Casamance has the youngest population of zircons at 200 Ma.

Figure 10 KDE plot of U/Pb zircon ages for the Senegal, Gambia and Casamance river provinces (constructed using IsoplotR (Vermeesch, 2018))

Provenance

Heavy mineral analysis of the sediments from the River Senegal are displayed in Figure 5. The defining heavy minerals include: amphibole, clinopyroxene, epidote and garnet. The presence of these heavy minerals is indicative of a low-medium grade metamorphic source, such as green-schist facies (Villeneuve, 2008; Page, 1987; Markwitz et al., 2015). This is further supported by Michel (1973) who suggests that the Senegals' erosional catchment includes: Precambrian and Paleozoic schists, sandstones, basic volcano-sedimentary complexes and syntectonic Birimian granites emplaced within the metamorphic series appear throughout the western WAC, Fouta Djallon Plateau, and the KKI. The Falémé erosional catchment also includes Precambrian schists, a volcano-sedimentary complex and granites. This is further supported by the abundance in Type B garnets (Fig 8A), suggestive of a metasedimentary source-lithology (Mange and Morton, 2007). Tourmaline discrimination (Fig 9) indicates the Senegal River sediments are predominantly Fe-end member schorl/buergerite, indicative of a primary Li-poor granitoid, pegmatite and aplite source-lithology. Minor variations in $Al_{tot}-AlFe_{50}-AlMg_{50}$ (Fig 9) ratios suggest a potential secondary source-lithology for the schorl/buergerite including metapelites, metapsammities and Fe-rich quartz-tourmaline rocks including calc-silicate rocks and metapelites. The $< 2 \mu m$ clay mineralogy is predominantly kaolinitic with moderate smectite and illite. Sediments from Thiago quarry possess a similar clay mineralogy with the presence of significant amounts of smectite being the defining constituent. However, despite the similarities in clay mineralogy, the Thiago quarry tdHM assemblages are significantly different, comprising rutile, staurolite, tourmaline and zircon with minor amounts of apatite, epidote and kyanite. This assemblage is comparable with the tdHM assemblages of the Tivaouane, Saloum, Gambia and Casamance regions to the south (Fig 5) and is representative of a "mature"

heavy mineral assemblage. The tourmalines associated with this “mature” tdHM suite possess similar endmember tourmalines. The majority of the tourmalines are divided between Fe-end member schorl/buergerite and Mg-end member dravite (Fig 9) and are indicative of a primary Li-poor granitoid, pegmatite and aplite source and potential secondary source-lithologies of metapelites, metapsammities and Fe-rich quartz-tourmaline rocks including calc-silicate rocks and metapelites. A small percentage of tourmalines plot within or very close to oxy-dravite endmember (Fig 9) which could be diagnostic of Low-Ca metaultramafics and Cr, V-rich metasediments.

Discussion

Sediment supply to Northern Senegal

The principal source region for the sediments in the Senegal River is southwest Mali and southern Mauritania, where the Senegal Rivers’ catchment is at its largest. More specifically the source is likely associated with denudation of the Mauritanides and the western margin of the WAC, between the Reguibat Shield in the north and the Leo Man Shield in the south (Gueye et al., 2007). The Mauritanide Belt contains Pan African I basement rocks including granites, quartzites and staurolite/garnet-grade mica schists (Villeneuve, 2008), plus eclogite facies of pyroxenites and amphibole-pyroxenites (Dia, 1984). Neoproterozoic and Palaeozoic age thrust-sheets within the Hercynian Belt are limited to greenschist facies (Villeneuve, 2008; Page, 1987; Markwitz et al., 2015). The Kédougou-Kéniéba Inlier (KKI) (Fig 2) underwent transcurrent deformation along a network of ductile shear-zones (Ledru et al., 1991; Milési et al., 1992) during the Late Eburnean orogeny (Paleoproterozoic), metamorphosing almost all the lithostratigraphic units under greenschist facies (Gueye et al., 2007). These greenschist facies of the KKI are also host to various deposits of skarn-type mineralisation including iron-ore and gold (Markwitz et al., 2015; Gerson et al., 2018).

Skarn-type mineralisation within the KKI could account for the Type D garnets (Fig 8) which are associated with a metasomatic source-lithology.

U/Pb dating of the Senegal River zircons (Fig 10) further supports the sediment source of the Neo-Proterozoic Mauritanides (Gueye et al., 2007) and the Paleo-Proterozoic lithologies of the KKI (Gueye et al., 2007). A small population of Neo-Archean age zircons may represent the denudation of Archean TTG (tonalite-trondjemite-granodiorite) gneisses (Rollinson, 2016; Pawlig et al., 2006; Gueye et al., 2007) from within the northernmost limit of the western segment of Leo-Man Shield (the Kénéma-Man domain; Gunn et al., 2018).

The smectite component is associated with a terrigenous supply and suggestive of a detrital source from non-diagenetic deposits derived from poorly drained soils (Chamley et al., 1988). Smectite development is favoured within arid, high-relief terrains, where climate, weathering-duration and groundwater-conditions are optimal, inhibiting chemical weathering (McKinley et al., 2003). Given the nature of development and the time required for a significant accumulation of smectite without concurrent erosion and transportation; generation of this smectite could have occurred during the Pleistocene hyper-arid period.

The principle source for the sands at Thiago quarry are interpreted to be the Meso-Cenozoic sediments from the onshore Senegalese basin, having been eroded and transported by the Ferlo River. However, this would not account for the smectite component, whose proposed source is within the Mauritanides and Western WAC, transported via the River Senegal. This can be explained through overbank flooding of the River Senegal into the adjacent Lake de Guiers; when the maximum extent of the floodplain was reached (Pacini & Harper, 2016). Overbank flooding may have occurred during either the first or second AHP during the Holocene, supported by documented evidence of increased sea-level (Miller et al., 2005), swelling of NW African lakes (Coutros, 2019; Armitage et al., 2015; Lézine et al., 1990) and

the breaching of the Pleistocene dune-fields by the River Senegal at the entrance to the Atlantic Ocean (McIntosh et al., 2016; Hamerlynck & Duvail, 2003). This suggests the Senegal River and Lake de Guiers were interconnected and overbank flooding will have undoubtedly occurred along most of the middle Senegal valley. In this model, coarse clastic sediments of the Senegal River would continue to be transported within the high energy region of the river. However, the very fine-grained smectite would remain within the suspended load, entering the Lake de Guiers-system through overbank-flooding, mixing with uncemented sands deposited within the Lake de Guiers system via the Ferlo River.

Evidence for variations in fluvial-energy was observed at Thiago quarry (Fig 4D), where sandstone rip-up clasts demonstrate localised incision of the floodplain. The presence of lignite requires an ephemeral switch-off of the high-energy regime and overloading of the sediment column to be deposited due to their low density.

Recycling in Central and South Senegal

Whilst the provenance assemblage indicates that the Senegal River sources fresh detritus from as far away as western Mali *ca.* 800 km; the data from the Ferlo, Saloum, Gambia and Casamance rivers suggest a more confined catchment, restricted to the interior of the onshore Senegalese basin. The sediments collected all possess very similar tdHM assemblages exhibiting a “mature” heavy mineral component of rutile, staurolite tourmaline and zircon (Fig 5). The occurrence of staurolite (1-11%) and kyanite (1-4%) are indicative of a low-medium grade metamorphic source-lithology, therefore it is conceivable that garnet may also have been present in the original assemblage, despite its absence in the observed mineralogy. The lack of apatite and garnet in the heavy mineral component suggests the sediment may have undergone extensive chemical-weathering, due to the mineral’s relative instability in subaerial-conditions, indicative of a recycled sediment. Weathering of the

garnet and apatite may have occurred during temporary alluvial storage and records the subaerial exposure and recycling of the basins' sediments (Morton et al., 2013).

Alternatively, the sediments may be devoid of garnet due to the potential absence of garnet within the inherent source-lithology.

In a comparative study of the Tarfaya basin (SW Morocco), sediments were considered to be sourced from the Reguibat Shield, Mauritanides and Anti-Atlas Mountains (Ali et al., 2014; Arantegui, 2008). Heavy minerals analysed from the Tarfaya basin exhibit garnet throughout the Early Cretaceous and the Miocene-Pliocene, despite indicated variations of intense chemical weathering (Ali et al., 2014). The difference in preserved heavy mineral profiles between the Tarfaya and Senegal locations could be due to preferential chemical-weathering of recycled apatite and garnet, which is more favourable within the Sahel climate of Senegal than the Saharan climate of Morocco (Bateman & Catt, 2007; Van-Loon & Mange, 2007).

The presence of staurolite and kyanite, plus the inferred garnet ($\pm$ apatite?) subsequently lost to weathering, remains suggestive of a low to medium grade source lithology, similar to the staurolite/garnet-grade micaceous schists of the Hercynian Belt (Villeneuve, 2008). Assuming the source-terrain for the sediments of the onshore Senegalese basin is analogous to the source of the modern-day Senegal River, the absence of amphibole, epidote and pyroxene should be expected. Amphibole, pyroxene and epidote are amongst the least stable of the heavy minerals under deep-burial conditions and chemical weathering (Morton, 1984). Amphibole and pyroxene are both extremely susceptible to deep-burial diagenesis and chemical weathering, whilst epidote is moderately susceptible to both these conditions (Morton, 1984). Depending on the diagenetic bias of an individual basin, epidote

606 can remain stable at depth *ca.* 1-2 km, with partial dissolution expected at depths of *ca.* 2-
607 3.5 km and total dissolution occurring at depths of *ca.* 3.5 km (Garzanti & Andò, 2019).
608 Therefore, the lithological-source for the recycled basin sediments (transported via the
609 Ferlo, Saloum, Gambia and Casamance rivers) is potentially the same region as that of the
610 Senegal River, including unspecified granites, low-medium grade metamorphic rocks and
611 greenschist facies. Subtle variations in tourmaline speciation is suggestive of a shift from a
612 mixed metasedimentary/granitic source in the recycled Meso-Cenozoic sediments of the
613 Ferlo, Saloum, Gambia and Casamance rivers in the Senegal basin, to a principally granitic-
614 type tourmaline source for the Senegal River sediments. With a degree of overlap between
615 the tourmaline species of Meso-Cenozoic and modern-day sediments, it is plausible that this
616 is representative of an unroofing-trend of the western-margin of the WAC. The tourmalines
617 which are associated with a predominantly metasedimentary lithological source may be
618 diagnostic of a comparatively younger Hercynian belt, whilst the principally granitic-type
619 tourmalines of the Senegal River may be associated with the foremost erosion of older Pan
620 African Granites of the Mauritanides. The predominance of kaolin within the recycled basin
621 sediments is interpreted to originate from chemical-weathering and erosion of lateritic soils
622 and pedogenic kaolinitic deposits. Concentrations of up to 70% kaolin within the <2 μm clay
623 fraction are a common occurrence in Quaternary basin sediments of North Africa during
624 humid periods (Ehrmann et al., 2017). U/Pb dating of zircons from the Gambia and
625 Casamance River provinces show broadly comparable Neo-Proterozoic and Paleo-
626 Proterozoic populations, representative of a Mauritanide and KKI source. However, there is
627 a small population of Archean age zircons from the Gambia River province and whilst this
628 population of zircons is only minor, it may reflect a paleo-Gambia River which might have
629 eroded deep into the interior of the Leo-Man shield during the Mesozoic. The lack of

Archean zircons in the Casamance River sediments plus the occurrence of 200 Ma (Triassic) zircons may infer a slightly different source area for a paleo-Casamance. With the possibility that a paleo-Gambia sourced sediment from the Leo-Man Shield during the Mesozoic, it is also possible that if a paleo-Casamance existed during the Mesozoic, it may also have sourced sediment south of Senegal. This can be corroborated by the occurrence of the Central Atlantic Magmatic Province (CAMP) which was emplaced as a series of extrusive (pyroclastics and lava flows) and intrusive (sills and dykes) low-Ti continental flood basalts (Youbi et al., 2011). Whilst the full extent of the CAMP large igneous province (LIP) remains unclear in NW Africa, there is evidence to suggest that increases in mantle temperatures which led to the formation of the CAMP LIP approximately 200 Ma encompassed much of NW Africa (Whalen et al., 2015). Several studies have located CAMP dyke and sill swarms within the WAC, principally in the Leo-Man Shield, but also within the Reguibat Shield and the Taoudeni basin (Youbi et al., 2011; Gunn et al., 2018; Whalen et al., 2015).

Miocene to Pliocene sediments of Tivaouane quarry

The sands sampled at the Tivaouane quarry (Fig 2) are Miocene to Pliocene age Cuirasse sandstones located within the plateau de Thiès succession (Roger et al., 2009; Pascal & Sustrac, 2005; Flicoteaux, 1982). Below these sands are the Eocene phosphate deposits of the Lam Lam and Taiba Formations. The massive orange/brown Cuirasse sands (Fig 4 E&F) were likely deposited in a very shallow marine environment, evidence by transgressive lateritic lag deposits (Fig 4 F) and the absence of smectite from the <2 μm clay mineralogy, due to the hydraulic winnowing of sediment by wave action. During the Miocene and Pliocene, rises in global sea-levels fluctuated from *ca.* 5 to 25 m above current levels (Miller et al., 2005). Senegal's current coastal and river-plain elevation is *ca.* < 41 m above sea-level (Fig 1), this may have been lower during the Miocene and Pliocene allowing for the

development of a shallow marine environment. The heavy mineral component of the Cuirasse sandstone exhibits a “mature” heavy mineral component which includes rutile, staurolite tourmaline and zircon. This heavy mineral component is analogous to the recycled Meso-Cenozoic sediments from the Thiago quarry, Saloum, Gambia and Casamance regions. The absence of the heavy minerals which could be indicative of fresh detritus sourced from the hinterland can be suggestive of three possibilities: 1. The Cuirasse sands are sourced from pre-existing recycled Meso-Cenozoic sediments from the onshore Senegal basin, 2. The size and position of the Senegal River during the Miocene to Pliocene may have been smaller and restricted to the basin interior similar to the modern-day Saloum, Gambia and Casamance rivers, 3. If the Senegal River catchment was the same in the Miocene to Pliocene as it is today, any sediment derived from within the Mauritanides and Western-WAC may have been delivered directly offshore, beyond the continental slope through a channelised system.

6. Conclusion

Petrographic analysis of 30 samples of sediment collected from modern-day river systems and Cenozoic deposits from onshore Senegal and The Gambia record an arenitic composition, with little variation, suggestive of a cratonic source.

Discrimination of the tdHM assemblages demonstrates that sediments south of the Senegal River are representative of a recycled sediment from the Meso-Cenozoic onshore Senegal basin and whilst the tdHM is similar throughout, any subtle variations may have been lost through preferential weathering and erosion. U/Pb dating of zircons from the Casamance and Gambia provinces indicate a paleo-river system which may have sourced sediment from the Leo-Man Shield which includes Archean TTG gneisses and 200 Ma CAMP basalts.

The Senegal River contains a green-schist facies heavy mineral assemblage (amphibole, epidote, pyroxene and garnet) that indicates transport of fresh detritus from outside the Senegal Basin, sourced from up to 800 km away which includes the denudation of the western margin of the WAC and Mauritanides. U/Pb dating of zircons confirms the source region of the Senegal River, transporting detritus from both the Neo-Proterozoic Mauritanides and the Paleo-Proterozoic KKI. It is also possible that the Senegal River has at some point in its history eroded as far south as the Leo-Man Shield, due to the occurrence of Neo-Archean age zircons.

The variability of garnet and tourmaline species in samples from the Senegal River infers a mixed metasedimentary, granitic and metasomatic source-lithology, supporting the interpretation of a very large catchment region that precludes a single lithological-source. The probable lithological-source regions within the WAC include: Pan African I basement rocks, including granites, quartzites and staurolite/garnet grade schists of the Hercynian Belt. Neoproterozoic and Palaeozoic greenschists within the Hercynian Belt, and greenschists of the Paleoproterozoic KKI with associated skarn-type mineralisation. However, shifts in tourmaline species is suggestive of progressive unroofing of the Mauritanides throughout the Mesozoic to recent, exemplified by predominantly metasedimentary schorl-buergerite tourmalines of the Hercynian orogenic belt and the comparatively Mg enriched (dravitic) tourmalines from the older Pan African granites of the Mauritanides.

Whilst the provenance of these sediments share a common source region, there have been several documented changes in climate and transitional modes of deposition throughout the Quaternary. Fluvial activity in most of North Africa's Sahel region ceased during the

Pleistocene epoch due to the hyper-arid climate, coinciding with the last glacial maximum. Hyper-aridity diminished plant-cover and reduced chemical-weathering, giving rise to optimal conditions to facilitate the generation of smectite within the high-altitude regions of the Mauritanides and western WAC. During the Holocene interglacial, the northward expansion of the ITCZ marked the beginning of the first African humid periods; renewing the west African monsoon and reactivating the fluvial systems of Senegal and Gambia. This increase in precipitation resulted in increased denudation of the Mauritanides and Western-WAC and the prevalent recycling of sediments deposited in the Meso-Cenozoic Senegal basin. The occurrence of smectite within Thiago quarry is interpreted to provide evidence for overbank flooding of the Senegal River into Lake de Guiers, providing evidence for the presence of lacustrine environments during the African humid period.

The Miocene-Pliocene Age Cuirasse sandstone from the Tivaouane Quarry reveals a period of marine transgression which demonstrates coastal recycling of basin sediments. Whilst it is possible to assume the relative position of the Senegal River during the Miocene-Pliocene was similar to the modern-day river, it is difficult to predict how big the river was. There is evidence during the Quaternary to suggest that many NW-African rivers transitioned between periods of stagnation and enhanced flow. So, the lack of heavy minerals diagnostic of renewed hinterland erosion could be due to a smaller Senegal River confined to the basin interior or fresh detritus from the Western-WAC was delivered directly offshore.

This integrated mineralogical study of Cenozoic sediments has established two distinct provenance groups; 1. prevalent recycling of Senegal basin-sediments by the Ferlo, Saloum, Gambia and Casamance Rivers which may have at least in part been derived from the Leo-Man Shield and the WAC, and 2. continued erosion and recycling of hinterland-sediments via the modern-day Senegal River.

724 Supplementary Data

725

726 Figure S 1, Cross-polarised thin-section photomicrographs: P-Qtz=Polycrystalline quartz, M-Qtz=Monocrystalline quartz,
 727 Plag=Plagioclase feldspar, K-fsp=Potassium feldspar. Tur=Tourmaline and Zrn=Zircon. A, Sample 618, orange/brown sand
 728 from Dalaba pit, Gambia. B, Sample 630, brown sand from the River Senegal. C, Sample 637, grey sand from Thiago quarry.
 729 D, Sample 640, brown sand from Tivaouane quarry.

Figure S 2 Qm–F–Lt plots for classification of all modern-day sands and sandstones, displaying the potential subdivisions according to the inferred provenance type, (modified from Dickinson et al., 1983). Qm=Quartz-monocrystalline, F=feldspar, Lt=Total lithic grains. Ci=Craton interior, Tc=Transitional continental, Bu=Basement uplift, Mi=Mixed, Da=Dissected arc, Ta=Transitional arc, Ua=Undissected arc, Qr=Quartzose recycled, Tr=Transitional recycled and Lr= Lithic recycled.

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Highlights

- An integrated mineralogical provenance study of Cenozoic and modern-day sediments from Senegal.
- Modern-day Senegal River erosional catchment includes the Mauritanides, western West African Craton, Kédougou-Kéniéba Inlier.
- The Ferlo, Saloum, Gambia and Casamance rivers are currently recycling Meso-Cenozoic sediments from within the onshore Senegal basin.
- U/Pb dating of detrital zircons suggests Senegalese paleo-river systems may have eroded into the Leo-Man Shield.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: