UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL
INSTITUTO DE GEOCIÊNCIAS
PROGRAMA DE PÓS-GRADUAÇÃO EM GEOCIÊNCIAS

CONTRIBUIÇÃO A EVOLUÇÃO TECTONO-ESTRATIGRÁFICA E TERMOCRONOLÓGICA DA REGIÃO NOROESTE DE MOÇAMBIQUE - ÁFRICA

MARCOS MÜLLER BICCA

ORIENTADORA – Prof[a]. Dra. Andrea Ritter Jelinek
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RESUMO

O estudo da região noroeste de Moçambique demonstrou a importância de processos tectônicos distais (compressivos) e proximais (distensivos) na reativação de estruturas antigas do embasamento cristalino, influenciando em aspectos estruturais, sedimentares e erosivos. A caracterização tectono-estratigráfica na bacia rifte Moatize-Minjova demonstrou a forte influência de remobilização de estruturas noroeste regionais na sua configuração, sedimentação e magmatismo. A geração de espaço de acomodação na bacia foi impulsionada por esforços tectônicos na margem sul-sudoeste do Gondwana enquanto as estruturas registradas em escala de afloramento caracterizaram a influência de esforços distensivos/transtrativos pós-deposicionais atribuídos à separação Jurássico-Cretácica entre as placas da África e Antártica. A análise sedimentológica permitiu determinar na Formação Moatize (Permiano Inferior ao Superior) litofácies depositadas em sequências cíclicas marcadas por sucessões de alta e baixa energia, as quais permitiram definir associações de litofácies atribuídas a planície de inundação, depósitos de *crevasse* e canal fluvial caracterizando um sistema fluvial meandrante estando as camadas de carvão associados a lagos e pântanos em meandros abandonados. Esta sequência foi progradada por litofácies arenosas grossas a conglomeráticas com estratificações cruzadas planares e acanaladas pertencentes à Formação Matinde, composta por macroformas de leito de migração frontal e lateral associadas a um sistema fluvial entrelaçado. As medidas de paleocorrente nestas duas formações sugerem um paleofluxo para norte-noroeste. A análise de proveniência na Formação Matinde forneceu idades entre o Mesoproterozóico e Cambriano, que abrange importantes momentos de formação e deformação crustal nos domínios geotectônicos do norte de Moçambique. As populações de idades entre 950-550 Ma permitiram a definição de uma área fonte da região sul-sudoeste, juntamente com os dados de paleocorrente para norte-noroeste, correspondente aos domínios do Complexo Nampula e da Suite Guro.

As análises térmicas das amostras do embasamento forneceram idades entre o Mesozóico e o Cenozóico e uma espessura denudada de ~ 2-3,5 km

desde o Triássico Superior. Os estágios iniciais foram marcados por taxas de denudação muito baixas (1-10 m/Ma) atingindo ~ 500 m até o Cretáceo Inferior sofrendo um leve aumento até o Paleoceno (3-17 m/Ma). Altas taxas de denudação de 31-47 m/Ma trouxeram as amostras para as condições superficiais. A denudação inicial está associada a processos distensivos/transtrativos produzidos pela dissolução do Gondwana. O Jurássico Superior e o Cretáceo Superior foi um período de grande desenvolvimento do Oceano Índico e o início da deriva N-S da Antártica em relação à placa Africana. O período entre o Cretáceo Inferior e o Paleoceno, marca o desenvolvimento da margem africana e a reconfiguração dos padrões de drenagem na placa Africana. O último evento forneceu taxas de resfriamento da ordem de 1,17 a 0,88 °C/Ma, implicando na denudação de ~ 1,5 a 2 km desde o início do Neogeno até os tempos recentes. Este último evento foi relacionado ao desenvolvimento de topografia dinâmica induzida pela movimentação da pluma do manto do Rifte do Leste Africano.

ABSTRACT

The study of the northwestern region of Mozambique demonstrated the importance of distal (compressive) and proximal (extensional) tectonic processes in the reactivation of old structures of the crystalline basement, influencing structural, sedimentary and erosive aspects. The tectono-stratigraphic characterization in the Moatize-Minjova rifte basin demonstrated the strong influence of remobilization of northwest regional structures in its configuration, sedimentation and magmatism. Accommodation space generation in Permian times were driven by tectonic efforts on the south-southwestern margin of Gondwana, while the outcrop scale structures characterized the influence of post-depositional extensional/transtractive efforts attributed to the Jurassic-Cretaceous separation between the African and Antarctic plates. The sedimentary analysis allowed to determine in the Moatize Formation (Lower-Upper Permian) lithofacies deposited in cyclic sequences marked by deposits of high and low energy, which allowed to define associations of lithofacies attributed to floodplain, crevasse and fluvial channel deposits characterizing a meandering fluvial system, being the coal layers associated with lakes and swamps in abandoned meanders. This sequence was grade by coarse sandy to conglomerate lithofacies with planar and through-cross bedding belonging to the Matinde Formation, composed of frontal and lateral migration bed macroforms associated to a braided fluvial system. The paleoccurrent measurements in these two formations suggest a north-northwest paleoflux. The provenance analysis in the Matinde Formation provided ages between the Mesoproterozoic and Cambrian, which covers important crustal formation and deformation moments in the geotectonic domains of northern Mozambique. Populations between 950-550 Ma allowed the definition of a source area of the south-southwest region, together with the north-northwest paleoccurrent data, corresponding to the Nampula Complex and Guro Suite domains.

The thermal analyzes of the basement samples provided ages between the Mesozoic and the Cenozoic and a denuded thickness of ~ 2-3.5 km since Upper Triassic times. The initial stages denoted to very low denudation rates (1-10 m/Ma)

reaching ~ 500 m until the Lower Cretaceous when the region undergoes a brief increase until the Paleocene (3-17 m/Ma). High denudation rates of 31-47 m/Ma brought the samples to the present surface conditions. Initial denudation is associated with extensional/transtractive processes produced by the dissolution of Gondwana. The Upper Jurassic to Upper Cretaceous was a period of great development of the Indian Ocean and the beginning of the N-S drift of Antarctica in relation to the African plate. The period between the Lower Cretaceous and the Paleocene marks the development of the African margin and the reconfiguration of drainage patterns on the African plate. The last event provided cooling rates in the order of 1.17 to 0.88 °C/Ma implying denudation of ~ 1.5 to 2 km from the beginning of Neogene to recent times which was attributed to the development of dynamic topography Induced by the movement of the mantle plume of the East African Rift.

SUMÁRIO

TEXTO EXPLICATIVO DA ESTRUTURA DA TESE

Esta tese está estruturada em formato de artigos científicos, publicados e/ou submetidos em periódicos. Consequentemente, sua organização compreende as seguintes partes principais:

1- Introdução, na qual é feita uma abordagem sobre o estado da arte, procurando-se caracterizar os principais trabalhos desenvolvidos na região e arredores. Além disso, é apresentada a localização da área e o contexto geológico simplificado; problemática e justificativa para aplicação dos métodos empregados para o desenvolvimento da tese; e a síntese integradora a qual é composta por uma análise resumida e integradora dos dados obtidos nesta tese, salientando as suas contribuições para o aprimoramento do conhecimento geológico científico da região de estudo.

Os itens seguintes consistem no corpo principal desta tese, onde são apresentados os artigos submetidos à revistas nacionais e internacionais com corpo editorial indexado, com autoria principal do doutorando e colaboradores (incluindo orientadores). Nestes artigos encontram-se os resultados obtidos no decorrer do desenvolvimento da tese bem como a avaliação e interpretação dos dados com discussão e conclusão.

1. INTRODUÇÃO

Em termos gerais, o estudo abordou aspectos estratigráficos, tectônicos, geocronológicos e termocronológicos do Cinturão Moçambicano e bacias adjacentes, contribuindo para o aprimoramento do modelo evolutivo regional durante o Mesozóico (Permiano-Cretácico). O principal estímulo para o desenvolvimento desta tese foi a carência de trabalhos de detalhe que abrangessem análises isotópicas pertinentes a avaliação dos processos tectônicos que afetaram a região após a sua formação. Os primeiros estudos geológicos em Moçambique foram desenvolvidos ainda no século XIX com foco principal nas ocorrências de carvão que se distribuíam amplamente nas camadas do Supergrupo Karoo. Foi apenas na década de 80 que os primeiros trabalhos de mapeamento geológico de reconhecimento, e trabalhos mais detalhados, para exploração mineral foram desenvolvidos na região, em parceria com o governo de Moçambique (Hunting, 1984; Pinna *et al*., 1993).

Mais recentemente, os trabalhos realizados pelo GTK Consortium, de 2002 a 2007, que consistiu em uma parceria entre os Serviços Geológicos de Moçambique e da Finlândia (GTK), apresentaram uma caracterização mais detalhada do território de Moçambique, definidos em folhas geológicas em escala 1:250.000. Neste projeto foram integrados todos os dados geológicos disponíveis, combinados com dados geofísicos, de imagens de satélites, análises litogeoquímicas e dados isotópicos (U-Pb com TIMS e SHRIMP e análises Sm-Nd). Os dados geocronológicos obtidos durante este projeto são pouco representativos, dispersos e não atendem as dimensões e a complexidade da geologia na região de estudo, não permitindo o seu pleno entendimento. Diversas unidades tiveram seu posicionamento estratigráfico definido a partir unicamente de observações de campo e dados geofísicos.

Desde então, alguns trabalhos pertencentes a este grupo tem sido publicados em revistas internacionais de prestígio, agregando novos dados geocronológicos aplicados à evolução das entidades geotectônicas regionais e bacias Neoproterozóicas relacionadas a elas, porém abrangendo dominantemente a região nordeste de Moçambique (Viola *et al*., 2008; Bingen *et al*., 2009; Thomas *et al*., 2010; Ueda *et al*., 2012a e 2012b; Grantham *et al*., 2013; Macey *et al*., 2010; 2013). Entretanto, pouco foi desenvolvido concernente ao desenvolvimento da superfície durante o período Fanerozóico envolvendo a evolução deposicional das bacias Karoo empregando conceitos clássicos de análise estratigráfica e tectônica de bacias sedimentares (Miall, 1992; 1996).

Discussão semelhante pode ser aplicada aos estudos termocronológicos, que possuem relações intrínsecas com a história de denudação de cinturões orogênicos contribuindo diretamente para o entendimento de processos erosivos e deposicionais. A aplicação destes métodos restringe-se aos domínios nordeste de Moçambique, destinados a compreender a evolução tardi-tectônica do cinturão orogênico através de análises por termocronômetros de alta e média temperatura (Daszinnies, 2006; Daszinnies *et al*., 2009), assim como, definir os seus estágios evolutivos tardios (Fanerozóicos) no que tange processos de denudação/exumação da superfície a partir de termocronômetros de mais baixa temperatura (< 300°C; Emmel *et al*., 2011; Bauer *et al*., 2016).

Neste contexto, a proposta desta tese foi contribuir com novos dados estruturais, sedimentológicos e de proveniência para as sequências do Supergrupo Karoo e termocronológicos para região, concentrando a coleta de amostras, e consequentemente, a realização de análises em unidades estratégicas para o entendimento da evolução estrutural e termotectônica do Cinturão Moçambicano. E assim, aprimorar o conhecimento ao identificar e datar eventos tectônicos tardios, que condicionaram a evolução deste cinturão durante o Fanerozóico através de análises de traços de fissão em apatitas.

1.2. Localização da Área e Contexto Geológico Simplificado

Este estudo foi desenvolvido na região noroeste de Moçambique, nos arredores da província de Tete, região centro-leste da África. Em termos gerais, a região de estudo compreende rochas atribuídas aos ciclos orogênicos Proterozóicos apresentando uma ampla assembleia de rochas metamórficas de baixo a alto grau (orto e para derivadas) e rochas ígneas intrusivas (Fig. 1A e 1B). O continente Africano é composto por um mosaico de crátons e faixas móveis

Arqueanas, amalgamados por cinturões dobrados Proterozóico-Cambrianos e cobertos por uma associação de sedimentos indeformados e rochas extrusivas de idades Neoproterozóica, Carbonífera Superior-Jurássica Inferior e Cretácica-Quaternária.

O embasamento cristalino é composto por uma assembleia heterogênea de orto e paragnaisses, granulitos, migmatitos e rochas ígneas de diferentes níveis crustais (GTK Consortium, 2006). Estas associações correspondem, em sua maior parte, a rochas de idade Mesoproterozóicas (~1300-930 Ma) que foram retrabalhadas pela orogenia Pan-Africana (Neoproterozóica-Cambriana - Pinna, 1993; Hanson, 2003; Grantham *et al*., 2003). Esta orogenia ocorreu em dois estágios principais. O primeiro estágio de amalgamação é caracterizado pela colisão das associações do terreno Gondwana Leste e Oeste, formando o Orógeno do Leste Africano com *trend* Norte - Sul (~ 550 Ma). O segundo estágio é marcado pela colisão do recém-formado Gondwana Norte com o Gondwana Sul (Orogenia Kuunga, ~ 500 Ma) com um *trend* principal Leste – Oeste (Fig. 1A) (Ueda et al., 2012; Macey *et al*., 2013).

O norte de Moçambique pode ser dividido em dois grandes domínios Mesoproterozóicos separados pelo proeminente Cinturão Lúrio Neoproterozóico-Paleozoico (Fig. 1B) (Viola *et al*., 2008), o qual compreende uma série de zonas de cisalhamento anastomosadas com orientação NE-SW e é representado principalmente pelo Complexo Granulítico Ocua, que ocorre dominantemente no nordeste de Moçambique, enquanto que o segmento sudoeste do Cinturão Lurio está parcialmente coberto (Fig. 1B). O significado do Cinturão Lurio ainda é controverso. Alguns autores acreditam que ele representa uma importante zona de sutura que se liga com os cinturões Damara-Lufilian-Zambezi (Sacchi *et al*., 2000, Grantham *et al*., 2003). Outros sugerem que ele representa uma zona de acomodação, especialmente devido às semelhanças entre os complexos metamórficos ao norte e ao sul do Cinturão Lurio, e devido a uma aparente diminuição da tensão ao longo do cinturão de nordeste para sudoeste (Viola *et al*., 2008; Bingen *et al*. 2009).

Os dois domínios, ao norte e ao sul do Cinturão Lurio, compartilham uma história similar de crescimento crustal durante o Mesoproterozóico. O Complexo Nampula, ao sul do cinturão, desenvolveu-se entre 1125 e 1035 Ma, enquanto o Cinturão Irumide Sul é uma região estrutural e metamorficamente complexa de rochas ígneas mesoproterozóicas relacionadas a rochas magmáticas volumosas de 1300-930 Ma (GTK Consortium) atribuídas a um ambiente de arco continental, acompanhadas de metamorfismo de alta temperatura/baixa pressão (Fritz *et al*., 2013).

O Complexo Nampula forma um grande bloco crustal contíguo que consiste em ortognaisses e rochas metassedimentares com metamorfismo de alto grau (Bingen *et al*., 2009; Macey *et al*., 2010). Os ortogneisses do segmento sudoeste do Complexo Nampula (Fig. 1B) são interpretados como remanescentes do arco magmático continental Mesoproterozóico (cerca de 1100 Ma, Chaúque, 2012). A porção sudoeste do Complexo Nampula (Fig. 1B), compreendida na área de estudo desta tese, é atribuído às nappes frontais dos grupos Chimoio-Macossa e Mungari (Chaúque, 2012), constituídos por paragnaisses de baixo a alto grau, as quais estão em contato tectônico direto com as rochas do craton do Kalahari. O *nappe* de Mungari inclui as associações da Suite Guro que compõem uma associação intrusiva bimodal Neoproterozóica (Fig. 1B) (Chaúque *et al.,* 2017).

Análises U-Pb em zircão de rochas graníticas indicam uma idade de cristalização magmática de 867 ± 15 Ma. A datação do núcleo de zircões metamórficos mostra idades de recristalização em ~ 850-839 Ma, relacionada com falhas distensivas, enquanto as bordas metamórficas forneceram uma idade de 512 ± 4 Ma relacionada com a Orogenia Pan-Africana (GTK Consortium 2006). Na margem nordeste da área cratônica ocorrem rochas metavulcânicas metassedimentares e félsicas de baixo a médio grau (cerca de 800 Ma) do Grupo Rushinga que podem representar uma margem passiva de idade Neoproterozóica (Barton *et al.*, 1991; Hargrove *et al*. , 2003, GTK Consortium 2006, Chaúque, 2012).

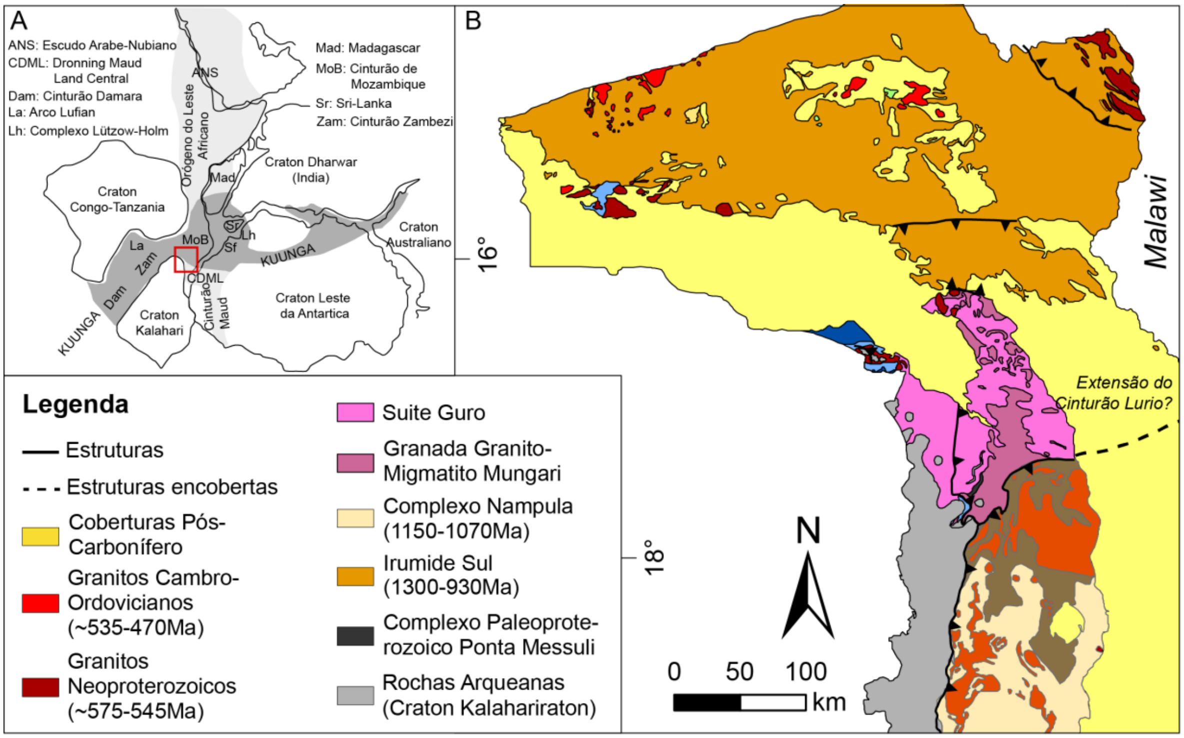

Figura 1: A) Reconstrução da margem leste da África ao final da amalgamação do Gondwana (Meert, 2003); B) Mapa geológico simplificado da região noroeste de Moçambique (Macey *et al*., 2013).

A orogênese colisional Pan-Africana foi seguida pela intrusão de granitos tardi-pós-tectônicos no Neoproterozóico (cerca de 575-545 Ma) e K-granito no Cambriano-Ordoviciano (cerca de 530-495 Ma) (Jacobs *et al*., 2008, Ueda *et al*., 2012, Macey *et al*., 2013, Grantham *et al*., 2013). Este último predomina na porção oriental do Complexo Nampula (Fig. 1B), devido ao processo de delaminação crustal que levou a uma história de resfriamento prolongada durante os períodos Cambriano e Ordoviciano (Jacob *et al*., 2008; Emmel *et al*., 2014). Estas rochas Pré-Cambrianas a Cambrianas foram parcialmente cobertas pelos depósitos vulcanossedimentares Fanerozóicos do Supergrupo Karoo e sequências mais jovens (GTK Consortium, 2006).

As sequências sedimentares e ígneas da região se depositaram em riftes intracontinentais associados às estruturas do embasamento, as quais possuem direções preferenciais noroeste-sudeste e leste-oeste. Estes depósitos são representados por dois supergrupos distintos: o supergrupo Karoo (Carbonífero

Superior – Jurássico Inferior) e depósitos contemporâneos ao rifte da margem leste Africana (Jurássico Superior ao Recente) (GTK Consortium, 2006).

O Supergrupo Karoo (SK) compreende uma sucessão de rochas sedimentares continentais, seguidas por derrames de lavas básicas e extrusões riolíticas, que atestam um processo de separação do Gondwana. A história deposicional do Supergrupo Karoo é composta por sequências glaciogênicas, fluvio-lacustres, fluviais e magmáticas. Em geral, a sedimentação do Supergrupo Karoo compreende uma mudança progressiva das condições glaciais para as condições úmidas e frias para condições quentes, semiáridas e finalmente quentes e áridas (Johnson *et al*., 1996). Sequências correlacionáveis a esses grupos, que mais ou menos podem ser observadas em todas as bacias de Karoo na África, seguem uma sequencia de ambientes glaciais, deltaicos, fluviais, lacustres e eólicos, principalmente devido à mudanças climáticas (aridificação) durante a deriva norte de Gondwana (Catuneanu *et al*., 2005).

A Formação Vúzi corresponde a base da sequência, depositada em um ambiente flúvio-glacial (Consórcio GTK, 2006, Fernandes *et al*., 2015). As litologias mais expressivas compreendem conglomerados fluviais, diamictitos, arenitos e ritmitos intercalados, folhelhos carbonosos e finas camadas de carvão no topo da sequência, repousando discordantemente sobre o embasamento cristalino Pré-Cambriano (GTK Consortium, 2006; Vasconcelos *et al*., 2014; Fernandes *et al*., 2015; Lakshminarayana, 2015). Os depósitos de Vúzi mostram uma importante assembleia palinológica que indica uma idade Sakmariana (Wopfner e Kreuser, 1986, Weiss e Wopfner, 1997). Não obstante, estudos desenvolvidos por Pereira *et al*. (2014) e Lopes *et al*. (2014) que, datando os diamictitos do topo desta formação, atribuíram uma idade Kunguriana-Roadiana (Permiano Médio-Superior), sendo mais jovem que a última idade regional proposta. Poucas idades radiométricas U-Pb estão disponíveis para as sequências cronocorrelatas à Formação Vúzi, sendo descritas no grupo Dwyka da Namíbia e da África do Sul, obtidas a partir de camadas de tufos indicando idades de 302 ± 3,0 Ma e 299 ± 3,2 Ma para as rochas da Namíbia e 288 ± 3,0 Ma e 289 ± 3,8 Ma para a África do Sul (Bangert *et al*., 1999). A formação Vúzi transiciona gradualmente para a Formação Moatize que consiste em sua maior parte, de arenitos carbonosos, arenitos arcoseanos e arenitos conglomeráticos ocasionais. Ainda ocorrem arenitos de finos com argila ou micáceo e folhelhos carbonosos com camadas cíclicas de carvão (Cairncross, 2001). A idade absoluta destas formações de carvão não está bem definida e a maior parte provém do registro palinológico, permitindo posicionar o seu ciclo deposicional durante todo o Permiano (Daber, 1984; Pereira *et al.,* 2014).

A Formação de Moatize é sobreposta pelos depósitos da Formação Matinde de idade Permo-Triássica (GTK Consortium, 2006; Pereira *et al*., 2016), compreendendo uma espessa sucessão intercalada de arenitos muito grosseiros e conglomerados polimíticos, com ocorrências subordinadas de siltitos (GTK Consortium, 2006). A sequência sedimentar atribuída ao topo do Supergrupo Karoo é dominada por depósitos aluviais grosseiros com estratificação cruzada da Formação Cádzi (GTK Consortium, 2006) a qual é classicamente posicionada entre o Permiano Superior e o Triássico Inferior (GTK Consortium, 2006). Entretanto, devido à idade atribuída à formação inferior a esta, fica evidente a necessidade de um aprimoramento dos estudos geocronológicos referentes a estas formações, ou até mesmo, quanto à sua correlação em termos estratigráficos. O ciclo basinal do Supergrupo Karoo é encerrado pelo magmatismo bimodal (195-180 Ma, Sm-Nd; 181 Ma, U-Pb TIMS) atribuído a um estágio inicial da dissolução de supercontinente Gondwana (GTK Consortium, 2006).

As sequências do SK foram parcialmente erodidas e sobrepostas por depósitos sedimentares associados aos estágios sin- e pós- abertura do Oceano Índico acompanhados por rochas vulcânicas e associações carbonatíticas e alcalinas (dados ^{40}K-^{40}Ar forneceram idades entre ~ 106-166 Ma) marcando um novo pulso de rifteamento na margem leste Africana (GTK Consortium, 2006).

1.3. Problema Científico e Justificativa Metodológica

Cinturões orogênicos consistem em zonas alongadas, comumente arqueadas, de rochas altamente deformadas que se desenvolveram durante processos da orogênese em ambiente de margens convergentes, envolvendo encurtamento intraplaca, espessamento crustal e soerguimento topográfico. Orógenos antigos, os quais já tiveram a sua topografia reduzida por processos erosivos, marcam a localização de antigos e inativos limites de placas, fornecendo informações importantes referentes aos movimentos das placas tectônicas no passado (Kearey *et al*., 2009). Os orógenos Pré-Cambrianos compreendem províncias crustais exumadas, sendo que a maioria destas províncias contém rochas com um amplo intervalo de idades e registram mais de um período de deformação, metamorfismo e plutonismo. Algumas seções das províncias crustais correspondem a rochas “novas”, derivadas do manto, denominada de juvenis, enquanto que outras partes são formadas por rochas originadas a partir do retrabalhamento da crosta antiga (Conde, 2005).

A maioria das províncias crustais e orógenos são compostos por terrenos, os quais são considerados os blocos básicos para a construção dos continentes e a colisão entre os terrenos é o processo principal para o crescimento continental. Estes terrenos apresentam um registro semelhante de idades isotópicas e exibem uma história pós-amalgamação semelhante. A maioria dos terrenos colide com a crosta continental ao longo de falhas transcorrentes ou zonas de subducção, sendo suturadas aos continentes. A crosta continental pode ser fragmentada e separada por processos de rifteamento ou por falhas transcorrentes (Conde, 2005). Os terrenos, que compõem as províncias crustais, são limitados por zonas de sutura, que são lineamentos entre as províncias crustais. Estas zonas correspondem a indícios da presença de zonas de subducção ou limites de placa. Megassuturas são aglomerados de cinturões orogênicos unidos por um limite de placas comum (Kearey *et al*., 2009).

O norte de Moçambique compreende rochas geradas em ciclos orogênicos desde o Arqueano até o Cambriano. Estes processos deixaram diversas estruturas crustais que demonstraram vital importância na reconfiguração crustal concernentes aos processos tectônicos tardios, taxas de sedimentação e estilos deposicionais em bacias sedimentares e taxas de denudação. As bacias sedimentares possuem em seu registro importantes pistas dos eventos que ocorreram nas rochas do embasamento adjacente, que atuaram como área fonte para o seu preenchimento (Fedo *et al*., 2003; Hawkesworth *et al*., 2010).

O Supergrupo Karoo compreende sequências vulcanossedimentares depositadas em um intervalo de tempo entre o Carbonífero Superior e o Jurássico Médio. Estas sequências estão amplamente depositadas em bacias de antepaís, sag e em riftes intracontinentais em toda a região centro-sul da África (Catuneanu *et al*., 2005). Estas bacias são cronocorrelatas a outras bacias sedimentares na América do Sul, Antártica e Austrália, sendo que algumas compartilham eventos deposicionais relacionados a eventos tectônicos compressivos ocorridos na margem sul-sudoeste do Supercontinente Gondwana (Milani e Ramos, 1998; Zerfass *et al*., 2003; 2004; 2005; Milani e De Wit, 2008). Em todas as bacias Africanas é possível observar uma correlação em seus registros sedimentares referente a uma mudança progressiva das condições glaciais para as condições úmidas e frias para condições quentes, semiáridas e finalmente quentes e áridas, a qual ocorre aproximadamente no limite entre o Permiano e o Triássico (Johnson *et al*., 1996; Catuneanu *et al*., 2005).

Em Moçambique, pouco tem sido feito em termos de aprimoramento tectono-estratigráfico para aperfeiçoamento dos modelos deposicionais e prospectivos. Os modelos vigentes apenas restringem-se a uma determinação superficial, caracterizando-os como ambientes glaciogênicos (Formação Vúzi), fluvial e lacustre (Formação Moatize) e fluvial (Formações Matinde e Cádzi) (Cairncross, 2001; GTK Consortium, 2006). O último estágio deposicional desta bacia é marcado por um evento magmático atribuído às primeiras fases da separação entre as placas da África e Antártica (Castaing, 1991; Salman e Abdul, 1995). Com este viés, o objetivo deste trabalho residiu em aplicar conceitos clássicos de estratigrafia, interpretação de fácies sedimentares e ambientes deposicionais (Miall, 1996; 2016), a partir do qual é possível correlacionar padrões de sedimentação e estruturas sedimentares a processos deposicionais e, por conseguinte a ambientes deposicionais. Aliado ao estudo estratigráfico foi realizada uma análise estrutural da bacia para identificar possíveis correlações com episódios tectônicos distais da margem do Gondwana, posicionando-os nos ciclos evolutivos da bacia.

Para caracterizar o comportamento do embasamento adjacente a bacia, propusemos a aplicação de um estudo de proveniência através do método U-Pb em zircões detríticos, tendo em vistas a ausência de trabalhos de proveniência nas bacias sedimentares da região. Este método é uma técnica amplamente utilizada para a determinação de idades de formação e/ou metamorfismo em minerais ricos em urânio (principalmente o zircão) permitindo a correlação destas idades com a base de dados regionais de datações disponíveis para as rochas adjacentes à bacia (Cawood, 2012; Guadagnin *et al*., 2012; Bicca *et al*., 2013; Oliveira *et al*., 2014).

Uma das questões importantes referente aos estudos tectônicos associados à evolução tardia de orógenos é a determinação das taxa dos processos térmicos e erosivos que definem a sua evolução. Estes taxas podem ser determinadas através da modelagem de dados termocronológicos, para caracterizar a história térmica destas rochas (Hodges, 2003). No tocante a região de estudo, o único trabalho trazendo informações termocronológicas foi desenvolvido nas sequências sedimentares do Supergrupo Karoo (Fernandes *et al*., 2015), onde foi possível identificar que as idades térmicas por traços de fissão de apatita encontram-se entre 146 e 84 Ma, e, são portanto mais jovens do que a idade estratigráfica das amostras, além do que, o modelo térmico indica um episódio de resfriamento rápido entre 240 e 230 Ma implicando em 2500-3000 m de denudação. A partir deste modelo foi possível identificar ainda um segundo período, também de resfriamento rápido, a partir de 6 Ma implicando em 1000 - 1500m de denudação. Os autores correlacionaram o primeiro episódio ao principal evento de deformação compressiva no *Cape Fold Belt* na África do Sul, que transferiu o estresse para o norte em sistemas de falhas transtensionais pré-existentes nas bacias do Karoo, causando inversão tectônica e elevação, enquanto que o segundo período de resfriamento rápido e denudação foi relacionado com a propagação do Sistema Rifte do Leste Africano em Moçambique.

No intuito de estudar estes processos tectônicos tardios, que afetaram as rochas da área de estudo adjacentes às bacias Karoo, utilizamos o método de traços de fissão em apatitas (60 – 120°C) para reconstruir a história de exumação e soerguimento destas rochas desde o último evento registrado e correspondente aos 5 km superiores da crosta continental (Stockli, 2005; Reiners e Brandon, 2006; Lisker *et al*., 2009).

1.4. Síntese Integradora

O desenvolvimento do trabalho envolvendo a análise estratigráfica e tectônica do Supergrupo Karoo na região noroeste de Moçambique integrado com dados da literatura (Castaing, 1991; Cairncross, 2001; Catuneanu *et al*., 2005) revelou importantes aspectos concernentes aos processos tectônicos tardios do cinturões orogênicos a noroeste de Moçambique. A atividade tectônica reconhecida demonstrou um importante controle na sedimentação e transporte das Formações Moatize e Matinde do Supergrupo Karoo depositadas na bacia rifte Moatize-Minjova. Esta bacia situa-se sobre um importante sitio estrutural da região e demonstrou a forte influência de remobilização de estruturas noroeste regionais na sua configuração, sedimentação e magmatismo. Os estágios de subsidência/acomodação da bacia foram impulsionados por esforços tectônicos na margem sul-sudoeste do Gondwana gerados pela Orogenia Gondwanides. Anteriormente, a subsidência das bacias rifte do leste da África (Carbonífero Superior-Jurássico Superior) era atribuída aos processos de rifteamento do Supercontinente Gondwana envolvendo esforços distensivos. Enquanto que neste trabalho, foi possível determinar que as influências dos esforços compressivos de sul-sudoeste também se fizeram presentes no noroeste de Moçambique movimentando estruturas regionais noroeste em regime transtrativo, deformando as camadas de carvão (Permiano) durante a sua evolução.

As estruturas registradas em escala de afloramento caracterizaram apenas a influência de esforços distensivos/transtrativos pós-deposicionais atribuídos aos processos de separação Jurássico-Cretácica entre as placas da África e Antártica. Em termos de sedimentação foi possível reconstruir os paleoambientes deposicionais para duas formações depositadas entre o Permiano e o Triássico Inferior. A Formação Moatize (Permiano Inferior ao Superior) abrange jazidas significativas de carvão na região e foi analisada detalhadamente a partir de afloramentos e de um perfil de sondagem (~500 m) permitindo a identificação de litofácies carbonosas, finas (folhelhos), arenosas com laminações tipo *ripples*, *hammoky* e *wavy*, como também estratificações cruzadas planares e acanaladas. A deposição desta sequência demonstra características deposicionais cíclicas marcadas por sucessões de alta e baixa energia. Estas características levaram a definição de cinco associações de litofácies atribuídas à planície de inundação, depósitos de *crevasse splay* e canal de *crevasse*, e canal fluvial caracterizando um sistema fluvial mandrante, estando as camadas de carvão associados a lagos e pântanos em meandros abandonados.

A análise estratigráfica de afloramentos e de uma seção de ~300m de profundidade permitiu definir que as sequências da Formação Moatize foram progradadas por litofácies arenosas grossas a conglomeráticas com estratificações cruzadas planares e acanaladas pertencentes à Formação Matinde. As relações internas e estruturais desta litofácies permitiram a definição de macroformas de leito de migração frontal e lateral associadas a um sistema fluvial entrelaçado. As medidas de paleocorrente sugerem um paleofluxo para norte-noroeste.

Neste modelo as camadas de carvão estão associadas com os depósitos de lagos e pântanos de planície de inundação e meandros abandonados da Formação Moatize. Nestes termos, as camadas de carvão devem apresentar distribuições laterais e verticais variadas e descontínuas, sendo necessário um mapeamento mais detalhado de toda a região da determinar a sua ocorrência.

A identificação de paleocorrente para o norte-noroeste a partir das análises estratigráficas realizadas neste trabalho e por Key *et al*. (2015) foram interpretadas como representativas de uma provável inversão do Rio Zambezi (que drena atualmente a região) durante a deposição das sequências Permo-Triássico do norte de Moçambique. Este comportamento foi também estudado através de dados de proveniência com U-Pb em zircões detríticos da Formação Matinde. Em litofácies de arenitos grossos a conglomeráticos, provavelmente relacionados a um rejuvenescimento topográfico na área fonte durante o Permiano por processos tectônicos.

Os espectros de idades U-Pb observados mostraram apenas idades mais antigas em relação à idade de deposição da sequência, que reflete a história do cinturão orogênico subjacente como esperado em ambientes intracratônicos (Cawood *et al*., 2012). A morfologia do zircão, as texturas internas e as idades fornecem informações sobre a história geotectônica do cinturão subjacente em termos de idades ígneas e metamórficas, permitindo a definição de quatro grupos de idades principais: i) 1.130-1.005 Ma; Ii) 992-859 Ma; Iii) 637-563 Ma; E iv) 549-493 Ma. As primeiras e as últimas são as mais proeminentes proveniências dos sedimentos de Karoo, destacando-se dois importantes eventos de geração, consumo e deformação crustais dos Supercontinentes Rodinia e Gondwana. As medições de paleocorrentes e a imaturidade do arenito amostrado sugerem áreas fontes localizadas em algum lugar no sul da Bacia de Moatize-Minjova, devido à preservação das bordas metamórficas.

A população de idades mais antigas reflete a maior componente crustal no norte de Moçambique, refletindo principalmente idades de cristalização magmática, como evidenciado pelo crescimento oscilatório nos grãos de zircão, característica comum nesta população. O final do Mesoproterozóico foi um momento importante de geração crustal para todos os domínios geotectônicos do norte de Moçambique. Esta população encontra-se na faixa de idades do segmento sudoeste do Complexo Nampula (Chaúque, 2012), ao sul da área de amostragem. Após os eventos de espessamento crustal e cavalgamentos resultantes da Orogenia Pan-Africana (~550-480 Ma), a região sul da Bacia Moatize-Minjova provavelmente formou um alto topográfico juntamente com toda a porção nordeste de Moçambique. Nestes locais se originaram as cabeceiras dos rios e afluentes que banharam a bacia do Proto-Zambeze, como sugerido por Key et al. (2015) e por esta tese.

As idades contidas entre ~550 Ma e 480 Ma são atribuídas a eventos magmáticos e metamórficos comuns na região devido ao metamorfismo de alto grau produzido pela Orogenia Pan-Africana e, portanto, não são bons marcadores para determinar a proveniência sedimentar. Por outro lado, as idades entre ~ 950Ma e 550Ma não ocorrem com ampla distribuição e correspondem a importantes períodos de evolução geotectônica da crosta na região. Estas idades foram relacionadas aos dados de U-Pb de Manjate (2015) para a Suite Guro e rochas associadas posicionadas a leste-sudeste da área amostrada, como também as idades em torno de ~ 850 Ma. As idades em torno de ~ 630 Ma e 560Ma referem-se a eventos distintos de deformação e magmatismo ao longo do norte do cinturão de Moçambique, que são registrados no nordeste de Moçambique em rochas metamórficas e magmáticas (~635 Ma, Macey *et al.*, 2013; 635 Ma e 570-590 Ma, Grantham *et al*., 2013). Esta população não está fortemente impressa na porção sudoeste do Complexo de Nampula e na Suite Guro /Granada granito-migmatito Mungari/Granito Chacocoma, embora estejam presentes nas idades de zircão individuais apresentadas por Chaúque (2012) e Manjate (2015). Dados de concentrações e taxas de Th/U também são compatíveis com as áreas fonte sugeridas, predominando razões Th/U >0,1. Outras fontes a nordeste da área apresentaram razões Th/U <0,1, atribuídas a uma origem metamórfica (Hartmann e Santos, 2004), além de concentrações muito altas de U (> 1000 ppm), as quais não foram observadas nos zircões da Formação Matinde.

As histórias térmicas determinadas para as rochas do embasamento cristalino do noroeste de Moçambique a partir das análises de termonocronologia por traços de fissão em apatitas (TFA) indicam que processos intensos de exumação afetaram amplamente a região durante a Era Mesozóica. As idades centrais TFA e as máximas paleotemperaturas modeladas puderam ser atribuídas à períodos de importantes atividade tectônica regional e local e à dinâmica mantélica associados com a abertura do Oceano Índico e do Sistema Rifte do Leste Africano. As idades mais antigas são compatíveis com os últimos estádios da atividade tectônica da *Cape Fold Belt*, podendo representar episódios de resfriamento causados por erosão e denudação associados à reativações estruturais distais. Esta proposta é pertinente e bem qualificada já através da análise estratigráfica da Bacia Karoo , onde foram observadas evidências de uma sedimentação possante nas bacias Karoo do Vale do Zambezi ainda no Permiano. Estas idades estão de acordo com o trabalho de Fernandes *et al*. (2015) em amostras sedimentares do Supergrupo Karoo na Bacia Moatize-Minjova e com os dados de Van Der Beek *et al.* (1998) para o norte do Malawi, demonstrando que se trata de eventos de denudação regionais. As demais idades são todas mais jovens que o magmatismo do Supergrupo Karoo, responsável por alterar o comportamento térmico crustal durante a sua atividade. No Jurássico Médio (170-166 Ma) ocorre o início da abertura da bacia da Somália através da Zona de Falha Davie (Mahanjane, 2014), compreendendo estágios iniciais de separação do Gondwana. Durante estes processos as maiores espessuras denudadas são da ordem de 300 m, em um período entre o Triássico superior ao Jurássico médio, implicando em taxas de resfriamento inferiores a 0.3 ^{o}C/Ma.

Um padrão semelhante é observado entre o Jurássico Médio e Cretáceo Inferior, com espessuras denudadas da ordem de 300 m, que podem estar associados à reativações dos padrões estruturais NW-SE e N-S que predominam na região. As paleotemperaturas máximas em torno de 150 Ma são frequentes nos modelos térmicos, também documentadas na Malawi e associados a uma nova fase de rifte na margem leste da África (Van der Beek *et al*., 1998). Este momento está documentado na região sul do Malawi com o desenvolvimento de magmatismo alcalino (~130-100 Ma) associado com tectônica distensiva (Eby *et al*., 1995). Dados K-Ar de rochas vulcânicas, associações carbonatíticas e alcalinas no norte de Moçambique (GTK Consortium, 2006) forneceram idades entre ~106-166 Ma, configurando um importante estágio de fluxo térmico na placa continental Africana. Este período compreende os primeiros estágios de *drift* da Antártida para o sul em relação à África (Mahanjane, 2012; Castelino *et al*., 2015) e a deriva de Madagáscar para o sul da margem da Tanzânia pela zona de cisalhamento Davie (140 Ma a 90 Ma, Emmel *et al*., 2011; Mahanjane, 2014). Esses argumentos estão de acordo com a intensificação da denudação observada em toda a área de estudo, desde o Cretáceo Superior até o Paleoceno Médio, com espessuras erodidas variando entre 254 e 1659 m, devido ao desenvolvimento da margem de Moçambique. Processos semelhantes durante o Cretáceo Inferior e Superior são também descritos por Belton e Raab (2010) para a área cratônica do Kalahari e por Emmel *et al*. (2011) para a porção nordeste de Moçambique, corroborando o modelo elevação regional da margem leste da placa africana.

Taxas de denudação de 31-47 m/Ma e espessuras de 1,5-2 km de superfície denudada trouxeram as amostras até as condições térmicas atuais a partir de ~40 Ma, atingindo desde o Triássico espessuras da ordem de 2,5-3,5 km. Condições semelhantes foram detectadas nas sequências de Karoo na bacia Moatize-Minjova implicando em 1-1,5 km de denudação a partir de 6 Ma (Fernandes *et al*., 2015). Estas taxas elevadas foram atribuídas a mudanças na topografia do norte de Moçambique devido à movimentação para norte da placa Africana, resultando na movimentação mantélica produzida pela pluma do Sistema Rifte do Leste Africano atuante na região nordeste da África (Moucha e Forte, 2011). As elevadas taxas de sedimentação na bacia *offshore* de Moçambique (Castelino *et al*., 2015) corroboram as taxas de denudação continentais, entretanto, demandam uma carga maior provavelmente suprida por área ainda mais interiores da placa Africana, implicando em alterações topográficas e nos padrões fluviais da bacia do Rio Zambezi.

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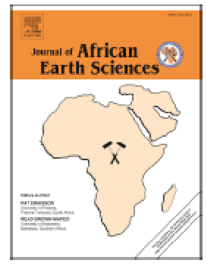

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PERMIAN-EARLY TRIASSIC TECTONICS AND STRATIGRAPHY OF THE KAROO SUPERGROUP IN NORTHWESTERN MOZAMBIQUE

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Highlights

- Permian Gondwanic tectonics led to intra-plate subsidence and sedimentation;
- Early Permian post-glaciation isostatic rebound led to high subsidence rates;
- NW-SE faults controlled Moatize-Minjova graben subsidence in Permian times;
- Fluvial plane environment dominated during Permian in the Moatize-Minjova graben;
- Paleozambezi river provided sediment for central and western southern Africa basins

Abstract

The Gondwana continent was the base of great basin inception, sedimentation and magmatism throughout the Cambrian to Middle Jurassic periods. The Northwestern Mozambique igneous and metamorphic basement assemblages host the NW-trending Moatize Minjova Basin, which has great economic potential for coal and gas mining. This rift basin was activated by an S-SW stress field during the Early Permian period, as constrained by regional and field scale structural data. Tectonically induced subsidence in the basin, from the reactivation of NW-SE and NNE-SSW regional structures is well recorded by faults, folds and synsedimentary fractures within the Early Late Permian Moatize Formation. NW-SE, N-S and NE-SW field structures consist of post-Karoo reactivation patterns related to a NNE-SSW extension produced by the Pangea breakup and early inception stages of the Great East African Rift System. The Early Late Permian sequences of the Moatize-Minjova Basin are composed of fluvial meandering, coal-bearing beds of the Moatize Formation, which comprises mostly floodplain, crevasse splay and fluvial channel lithofacies associations, deposited in a cyclic pattern. This sequence was overlapped by a multiple-story, braided fluvial plain sequence of the Matinde Formation (Late Permian – Early Triassic). Lithofacies associations in the Matinde Formation and its internal relationships suggest deposition of poorly channelized braided alluvial plain in which downstream and probably lateral accretion macroforms alternate with gravity flow deposits. NW paleoflow measurements suggest that Permian fluvial headwaters were located somewhere southeast of the study area, possibly between the African and Antarctic Precambrian highlands.

Keywords: Mozambique, Karoo Supergroup, Moatize-Minjova Basin, Tectonic and Sedimentation, Early Late Permian

1. Introduction

The Gondwana volcano-sedimentary successions of the Karoo Supergroup are widely distributed throughout South and Central Africa, hosted in retroarc-foreland (continental margin), sag and rift (intracontinental) type basins and its record preserves one of the largest testimonies of Gondwana evolution (Fig. 1A and Fig. 1B). This Supergroup was named after the Main Karoo Basin, located in South Africa, which is one of the most economically important basins, showing the most complete stratigraphic record (Smith et al,, 1993), ranging in age from Late Carboniferous to Middle Jurassic.

The Karoo basins' evolution is related to the tectonic events of the southern Gondwana margin (Gondwanides Orogeny), analogous to the Paraná and other smaller basins in the South America, Beacon (Antarctica) and Bowen (Australia) basins (Fig. 1A) (Smith et al., 1993; Trouw & de Wit, 1999; Catuneanu et al., 2005; Holz et al., 2006; Milani & de Wit, 2008; Alessandretti et al., 2013; Linol et al., 2015; Alessandretti et al., 2015). The Karoo and Paraná basin studies were the most detailed, showing great economic potential for natural gas, oil and coal. Coal bearing layers are the most common economic resource exploited in African and Brazilian basins, all Permian in age. These two basins share similarities within its stratigraphy framework and hierarchy among depositional cycles (Smith, 1993; Milani & de Wit, 2008; Linol et al., 2015).

The study of the stratigraphic record in these basins is particularly important to understand the Phanerozoic evolution of Gondwana. In this context, our study brings previous and new stratigraphic data from the successions of Karoo Supergroup from the Tete region in northwestern Mozambique, combined with a regional overview with stratigraphically and chronologically correlated basins in Africa, providing an insight into the Gondwanic/Pangea tectonics and deposition during Early Permian - Early Triassic boundaries.

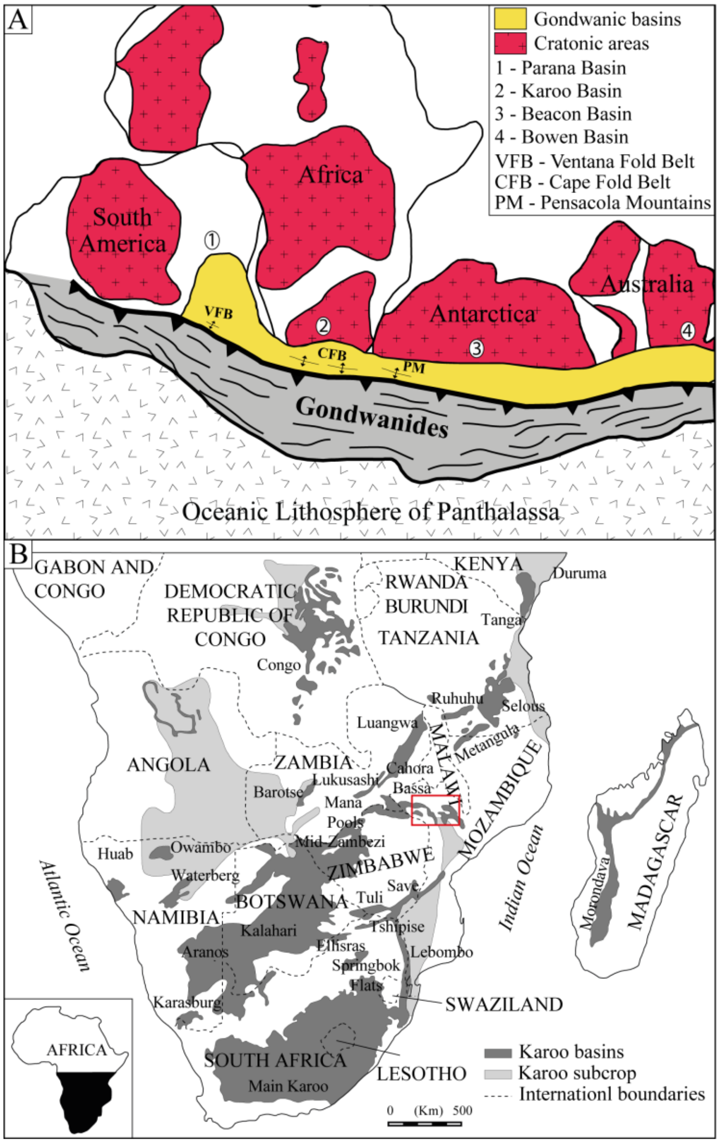

Figure 1: A) Regional tectonic setting of the southern margin of Gondwana during the Phanerozoic, illustrating the convergence and collisional tectonics developed (Gondwanides Orogeny) due to the interaction between the paleocontinent plate and the oceanic lithosphere of Panthalassa (after Milani & de Wit, 2008; and Holz et al. 2006). B) Distribution of Karoo basins in south-central Africa (modified from Catuneanu et al., 2005). The red polygon indicates the study area.

We aimed to point out the Gondwanides Orogeny influence during the Karoo basin sedimentary infilling in northwestern Mozambique, despite its great distance from the orogeny center and corroborating with the model of crustal tectonic transference leading to intraplate subsidence and basin formation (Milani, 1997; Zerfass et al., 2003; Zerfass et al., 2004; Zerfass et al., 2005; Linol et al., 2015).

For this purpose, we provide a structural characterization of the basement and adjacent Karoo sedimentary rocks, which we have integrated with those previously described in the literature, to improve the understanding of the graben architectural control during basin evolution. We also describe the Moatize and Matinde fluvial formations based on a borelog, and from outcrops identifying distinct lithofacies and lithofacies associations.

2. Geologic and Tectonic Settings

Northwestern Mozambique comprises a complex assemblage of igneous and metamorphic rocks, predominantly Mesoproterozoic (north-northeastward) and Neoproterozoic (southwestward) in age (Fig. 2B and 2C), and partially covered and intruded by Phanerozoic plutonic-volcanic-sedimentary sequences comprising the Karoo Supergroup and Post-Karoo units (GTK Consortium, 2006). These Precambrian assemblages partially preserve the records of two distinct orogenic events: 1) Late Mesoproterozoic (1.35 – 1.0 Ga); and 2) Neoproterozoic-Early Paleozoic Pan-African Orogeny (Hanson, 2003). The first one corresponds to the Rodinia Supercontinent geotectonic heritage, defined by intrusive granitic suites, associated with the Tete Gabro-Anorthosite stratiform Suite, whose emplacement was controlled by deep NW-SE trending ductile shear zones. The second one occurred in two stages. The first one comprises the N–S oriented East Africa Orogeny (EAO; Stern, 1994), referring to events of about 650 – 620 Ma in age (Fritz et al., 2013), and the younger one represents an E–W oriented orogeny that produces the Damara-Zambezi-Lurio Belts (Kuunga Orogeny; Meert, 2003), comprising

600–500 Ma events (Fritz et al., 2013; Fig. 2A and 2B). The Pan-African orogenesis partially imprints its tectonic patterns on the fabric of the older basement rocks.

North-northeast basement rocks comprise a large Mesoproterozoic landmass of supracrustal and intrusive assemblages, showing inherited magmatic rheology, or partially deformed by Pan-African Orogeny events. Otherwise, southwest units are grouped, such as the Zambezi Belt (ZB) which represents the easternmost section of a transcontinental Pan-African mobile belt system between the Congo and Kalahari cratons in southern Africa (Shackleton, 1996). This system also comprises the Lufilian Arc and Damara Belt (Fig. 2). In northeast Zimbabwe the ZB has an E-W trend, converging to a NW-SE trend in northwest Mozambique. These assemblages were deformed by Pan-African south-vergent thrusting, associated in places with transcurrent or transpressional shearing, followed by north-vergent back-thrusting (e.g. Barton et al., 1991 and 1993; Hanson et al. 1994; Hargrove et al., 2003; Hanson, 2003).

The Pan-African Orogeny left important structural zones (NW-SE and E-W trending) in northwest Mozambique, which were fundamental for Phanerozoic sedimentary basins development. One of the greatest structures is the Sanangoe Shear Zone (SSZ), which is an E-W trending transpressional ductile structure, crossing the central part of study area, over a distance of about 350 km in Mozambique (Fig. 2B). Westwards, this shear zone is largely concealed below Karoo and the younger rocks of the mid-Zambezi rift.

According to GTK Consortium (2006), the SSZ represents a Pan-African connection between the West and South Gondwana (Macey et al., 2013), generally similar in structural aspects and timing to the Mwembeshi Shear Zone (MSZ) (GTK Consortium, 2006; Fig. 2B). Deformed granitoids surrounding this large structure confirm its ductile behavior during the Pan-African tectonics. Its likely relationship with the Cahora Bassa

Basin (E-W graben in the Cahora Bassa Lake area; Fig. 2) depocenter also highlights its importance during Phanerozoic tectonic evolution.

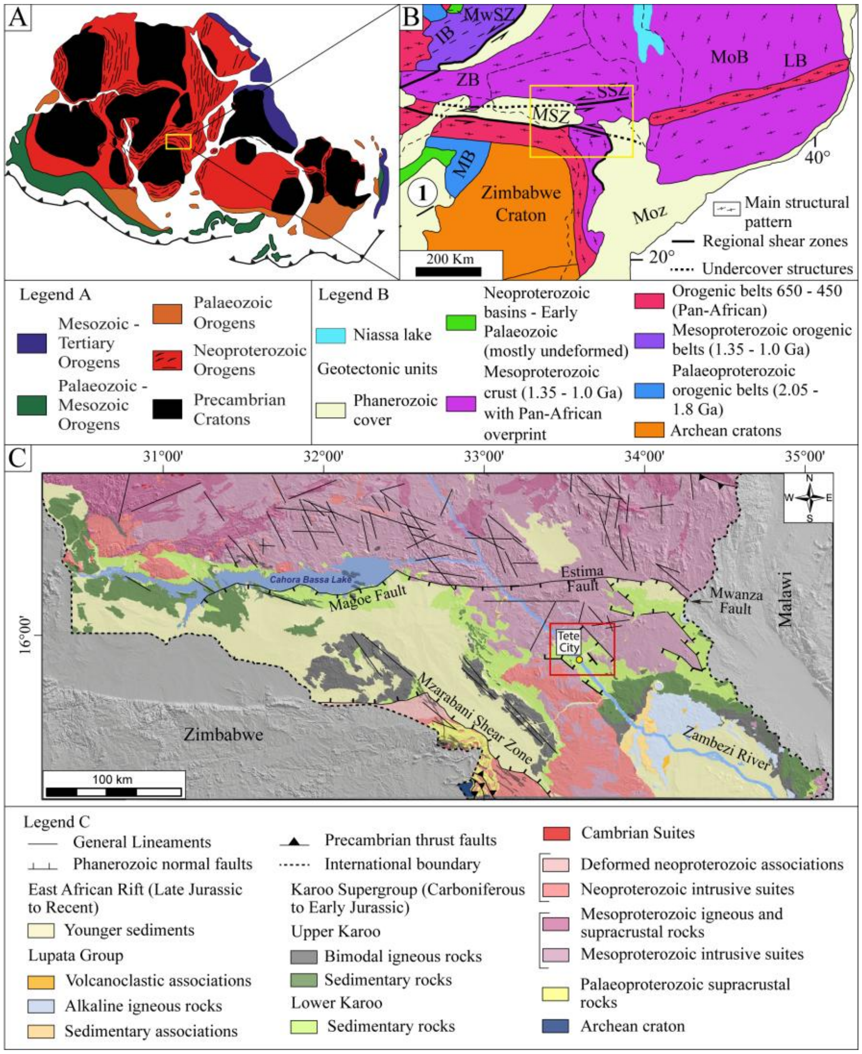

Figure 2: A) Reconstruction map of Gondwana during Phanerozoic times (after Gray et al., 2007; Cordani et al., 2013; and Rapela et al., 2015). B) Simplified Precambrian tectonic framework of the study area (after Hanson, 2003). 1 - Archean western limit (Zimbabwe); IB - Irumide Belt; LB - Lurio Belt; MB - Magondi Belt; MoB - Mozambique Belt; Moz – Mozambique Country; MSZ - Mzarabani Shear Zone; MwSZ - Mwembeshi Shear Zone; SSZ - Sanangoe Shear Zone; ZB - Zambezi Belt. C) Simplified geological map of northwestern Mozambique (after GTK Consortium map sheets: Songo (1532), Cazula/Zóbuè (1533-1534), Mecumbura/Chioco (1631-1632), Tete (1633) and Tambara (1634)).

2.1. Basin settings and stratigraphy

As a general approach, the Karoo Supergroup (KS) comprises all contemporaneous Late Carboniferous to Middle Jurassic volcano-sedimentary deposits in Central-Southern Africa (Fig. 1B). Two main tectonic fronts may have influenced subsidence processes of the Karoo basins: the southern convergent orogenic margin of Gondwana and the northern Tethyan divergent margin. In the former, extensional/transtensional tectonic movements predominated and propagated southwards into the Gondwana continent (Bumby & Guiraud, 2005). In the southern margin of Gondwana, subduction, accretion and mountain building, regionally called Gondwanides Orogeny (Du Toit, 1927), or locally the Cape Orogeny (margin of Southern Africa plate), also produced important structural rearrangements across Precambrian African and South American plates (Milani & Ramos, 1998; Zerfass et al., 2003; Zerfass et al., 2004; Zerfass et al., 2005; Linol et al., 2015).

In this study, we focused on the KS sequences from the northwestern Mozambique area, which were preferentially deposited in intracratonic half grabens, grouped as the Zambezi Valley basins. The Zambezi River is one of the great modern African rivers with an ancient history, and may have contributed for Early Permian-Early Triassic Karoo basin sedimentation, with a northwestern to western paleoflow (Key et al., 2015). The Zambezi Valley is an E-W trending graben (Cahora Bassa Basin, Fig. 1B and 2C), which inflects SE, following the Zimbabwe Cratonic northeastern margin, assuming a NW-SE trend (Moatize-Minjova Basin) in the Tete city region (Fig. 2B and 2C). The valley is bounded by Precambrian structures and the basin evolution follows distinct reactivation periods that occurred in Phanerozoic times (Castaing, 1991; GTK Consortium, 2006; Fernandes et al., 2015), under a transtensional stress regime associated with the NW-SE sinistral Zambezi pre-transform fault system (Castaing, 1991). In northwestern Mozambique, the Magoe–

Estima–Mwanza fault zone (Fig. 2C) defines a major Pre-Karoo crustal weakness zone that controlled basin inception since the Permian (Lakshminarayana, 2015). This large scale crustal discontinuity resembles the Sanangoe ductile shear zone trend.

Our study was conducted in the Moatize-Minjova Basin, which is a NW-oriented graben (Fig. 3). Northeastern and southwestern basin boundaries are against deformed Mesoproterozoic and Neoproterozoic crystalline basement rocks. The former shows marginal high strain shear zones, NW-oriented, while the latter consists of highly folded metamorphic rocks, were the axial plane trends range between NW to N-S and E-W (Hargrove et al., 2003).

In general, the Karoo Supergroup sedimentation comprises a progressive shift from glacial to cool, moist conditions to warm, semi-arid and finally hot and arid conditions (Johnson et al., 1996). Classically, the KS is divided into five major groups, according to the stratigraphic record registered in the Main Karoo Basin of South Africa, from the base to the top as: Dwyka, Ecca, Beaufort, Stormberg (sedimentary and magmatic), and Drakensberg (magmatic). Correlatable sequences of these groups, which more or less can be observed in all Karoo Basins in Africa, follow a sequence of glacial, deltaic, fluvial, lacustrine and aeolian environments, mostly due to climatic changes (aridification) during the Gondwana northward drift (Catuneanu et al., 2005).

The base of KS sequence in the Moatize-Minjova Basin is attributed to the Vúzi Formation glaciogenic deposits (GTK Consortium, 2006; Fernandes et al., 2015), which classically correlate with the Dwyka Group, which has accumulated through Late Carboniferous–Early Permian (Wopfner, 2002; Catuneanu, 2004; Catuneanu et al., 2005). These correspond mostly to interbedded tillites, diamictites, rhythmites and sandstones, resting unconformably over the Precambrian crystalline basement (GTK Consortium, 2006;

Vasconcelos et al., 2014; Fernandes et al., 2015; Lakshminarayana, 2015). Vúzi deposits show an important palynological assemblage, indicating early to middle Sakmarian age (Wopfner & Kreuser, 1986; Weiss & Wopfner, 1997). Notwithstanding, recent palynological studies developed by Pereira et al. (2014) and Lopes et al. (2014) dating diamictite beds from the top of the Vúzi Formation, assigned it a Kungurian-Roadian age (Lower-Middle Permian), younger than the previous regional proposed age. A few available U-Pb radiometric ages published for the Dwyka Group of Namibia and South Africa, obtained from tuff beds, indicate ages of 302 ± 3.0 Ma and 299 ± 3.2 Ma for the Namibian rocks, and 288 ± 3.0 Ma and 289 ± 3.8 Ma for the latter (Bangert et al., 1999).

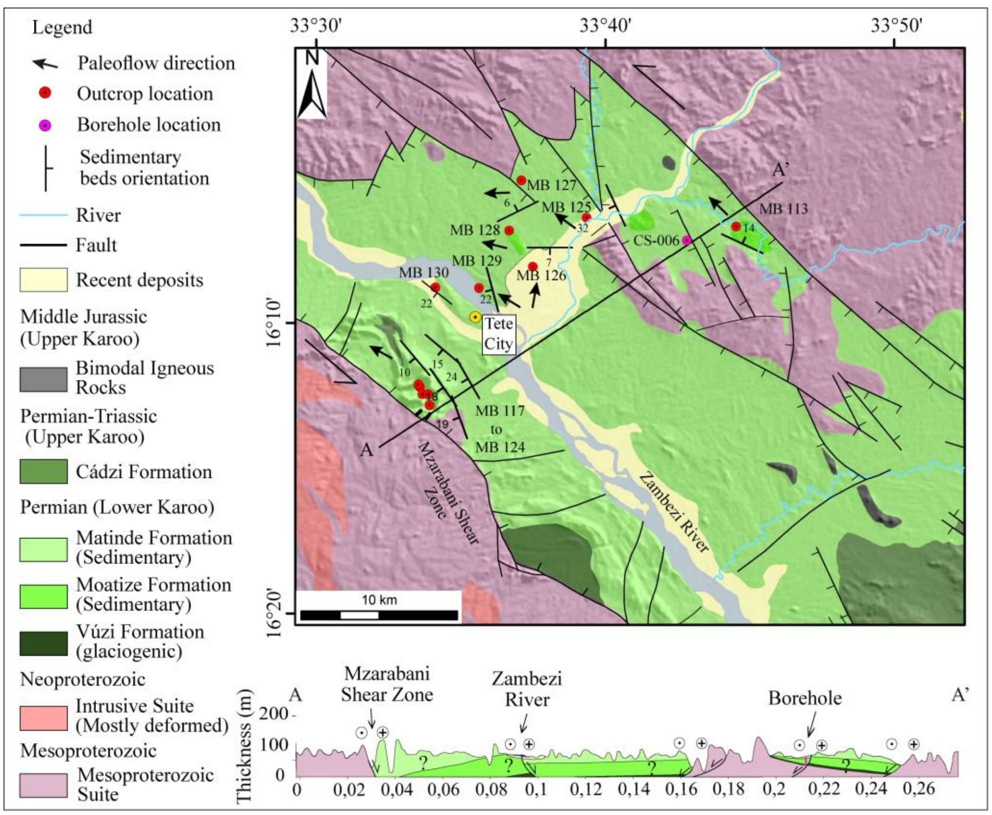

Figure 3: Detailed geological and structural map of the Moatize-Minjova Basin (compiled and modified from GTK Consortium, 2006), showing the location of the borehole and all the outcrops described in this work.

The top sequence of the Vúzi Formation comprises interbedded diamictites and thin coal beds, marking a gradational transition to the conformably overlain Moatize Formation. The latter is made of interbedded carbonaceous mudstones, rhythmites, sandstones and cyclic coal deposits (Cairncross, 2001; Lakshminarayana, 2015). The Moatize Formation in the Moatize-Minjova Basin has six main coal seams, known locally from bottom to top as Sousa Pinto, Chipanga, Bananeiras, Intermédia, Grande Falésia and André (Vasconcelos et al., 2014). Lithofacies assemblages of the Moatize Formation were interpreted by Lakshminarayana (2015) as a delta plain-mire depositional environment, representing a periglacial condition. The absolute age of these coal-bearing formations is not well constrained and most are derived from palynological records, which allow to place the Moatize Formation between the end of Early to Middle Ecca Group (Early-Late Permian; Catuneanu et al., 2005). Plant macrofossils and palynomorphs suggest a Lower to Middle Permian age for the top part of the Moatize Formation (Daber, 1984), which may be correlated with the Middle-Upper Ecca Group. However, Pereira et al. (2014) found a Kungurian/Roadian age (Lower – Middle Permian) for the basal sequences of the Moatize Formation, positioning its depositional cycle throughout the Early-Late Permian.

Overlaying the Moatize Formation there are mostly cross-bedded coarse grained alluvial deposits from the Matinde and Cádzi Formations (GTK Consortium, 2006). The Matinde Formation was assumed to be of an Early to Middle Permian age, comparable to the Middle/Upper Ecca Group (GTK Consortium, 2006). However, a recent palynological revision of the Matinde Formation has indicated that was deposited in the latest Permian, close to the Permian-Triassic boundary (Pereira et al., 2016). The latter, on the other hand, is classically correlated to the Beaufort Group, positioned between the Late Permian to Early Triassic age. Bimodal magmatism erupted between 195-180 Ma ended the basinal cycle and is attributed to an early aborted stage of the Gondwana breakup (GTK Consortium, 2006), and correlated to the Stormberg Group from the Main Karoo Basin.

3. Structural and stratigraphic analysis methods

In this study, we adopt a methodology in which we integrate stratigraphic and tectonic data acquired in the field and from remote sensing images, with those available in the literature. During fieldwork we obtained stratigraphic and structural data from outcrops and one coal exploration borehole (CS_006A), in which we gathered the main sedimentary attributes (e.g., texture, lithology), and structures related to basin inception and infilling control. The sedimentary facies framework and facies architecture of the studied interval are based on this data.

The regional distributions of the sedimentary lithofacies and architecture of the Moatize and Matinde Formations were examined in one deep borehole of about 500 m in depth and in natural exposures and road cuts (only Matinde and the top of Moatize Formations) throughout the area of Moatize-Minjova Basin (Fig. 3).

The facies analysis was based in the scheme of Miall (1992), to interpret facies associations and deduct its depositional systems. The lithofacies definition and classification used is based in Miall’s (1978; 1996) facies code, in which the first letter represents the grain size and the second letter represents the sedimentary structure (Tab. 1). In order to clarify the three-dimensional relationships of the sedimentary units, these elements were mapped and logged, and documented as field sketches, photos and maps. Paleocurrent measurements were collected from stratified beds (planar and through cross-beds), and also from imbricated clasts, observed in conglomeratic facies in order to determine sediment dispersal patterns within the Moatize and Matinde formations.

Structural and tectonic data were acquired from a compilation of geological maps of the Mozambican Geological Survey (1:250,000 scale). We also used a SRTM (Shuttle Radar Topography Mission) image to generated a shaded relief model for tracing regional lineaments (N = 1,568; Fig. 4), from which we generated rose diagrams that allow us to identify major structural lineament patterns within the basin and in the Precambrian basement in the study area. We use length and frequency rose diagrams to identify major lineaments populations. Our aim was to discriminate evidences of a possible chronology of structural reactivations within the complex geological framework in the area, using evidence of episodes of deformation, sedimentation and related magmatic activity. Subsequently, we undertook geological mapping in selected areas throughout the basin area and overlaying basement rocks, in order to complete our tectonic data acquisition by measuring fault plans orientation and kinematic indicators, which we integrated to produce a preliminary strain model for the study area. Fractures, in this work, are those structures without any evidence of movement (slickenlines, fault mirror, etc.), and for fault classification, we took into account the relationships between fault plane dipping and slickenlines dipping within this plane (Angelier, 1994).

Table 1: Lithofacies description for Moatize and Matinde Formations (based on Miall, 1992 and 1996).

Facies Code	Facies Description and Structures	Depositional process
Moatize Formation		
Gm	Conglomerate and conglomeratic coarse-sandstone, matrix (silt and mud) supported. Presents muddy intraclasts and extrabacinal clasts 0.3 a 4 cm (0.5 cm average).	Cohesive (plastic) debris flow.

St	Micaceous (muscovite) medium to coarse-sandstone, sometimes conglomeratic, poorly to moderately selected, with sets of 5 to 50 cm thick of trough cross-stratification. Foresets are commonly marked by intraclasts.	Migration of 3D dunes, under lower flow regime.
Sl	Micaceous (muscovite) medium to coarse-sandstone, sometimes conglomeratic, poorly to moderately selected, with low angle cross-stratification.	Bedforms migration under transitional conditions between lower and upper regime.
Sr	Micaceous (muscovite) very fine to fine-sandstone, moderately to well selected, with critical to subcritical ripple cross-lamination of 0.5 to 2 cm thick.	Migration of ripple cross-lamination under lower regime conditions, with variation on traction/suspension rate.
Sm	Sand, medium grained. Homogeneous. Mostly massive. Sometimes shows a very tenuous horizontal lamination. Lenticular (sigmoid) shape and irregular contact with adjacent facies are common (convex up and concave up).	Sediment-gravity flow deposits
Sh	Sand, very fine to fine. Commonly interbedded with Sr. Horizontal lamination and parting lineation.	Planar bed flow (upper flow regime).
Fl	Pelite with very fine to fine-sandstone wavy/linsen bedding of 0.3 to 5 cm thick, with ripple cross-lamination. Sometimes foresets are marked by mud layers. At the top of the sequence it presents 1 to 2 m thick and fine horizontal lamination.	Interchange of ripple cross-lamination and mud decantation. Represent overbank or abandoned channels deposits.
Fm	Massive carbonaceous pelite, with <0.5 cm thick of very fine to fine-sandstone linsen bedding and ripple cross-lamination.	Decantation of suspended mud sediments.
C	Coal	Aggradational accumulation of organic matter on peat.
Matinde Formation		
Gm	Massive or crudely bedded gravel. The matrix is composed by fine to coarse sand. Clasts are irregular and angulous of most red colored granitic composition with casts of probably intrabasinal pelitic clasts. Transition to St/Sp is probably gradual. Weak or non-grading.	Plastic debris flow (highstrength, viscous).
St	Arcosic sand, medium to very coarse and sometimes pebbly. Trough cross-beds are found interbedded with Sp. Its overlap on Fl show load casts marks.	Sinuous-crested and linguoid dunes. Migration of subaqueous ripples and dunes under low to high flow energy.
Sp	Arcosic sand, medium to coarse and sometimes pebble. Planar cross-beds of mostly 10 cm to <1 m.	Linguoid and transverse bars, sand waves (lower flow regime).
Sl	Arcosic sand, fine to medium grained with low angle planar cross-stratification.	Humpback or washed-out dunes.

4. Results

4.1. Regional tectonic and structural analysis (Lineaments)

Structural analysis created from the 1,568 lineaments identified in the shaded relief map (Fig. 4) allow visualizing a complex web of cross-cutting structures, mostly attributed to Precambrian basement rocks, with some extending to Karoo rocks and a few to Post-Karoo volcano-sedimentary rocks. Dissected valleys, crests and fluvial incision patterns are the major relief features observed.

The structural rose diagrams produced from the traced lineaments allowed the definition of six structural populations that may have a close relation with pre-, syn- and post-depositional basinal cycles, which are: a) NW-SE subgroup (N = 499; Fig. 5A); b) WNW-ESE subgroup (N = 272; Fig. 5B); c) NNE-SSW subgroup (N = 269; Fig. 5D); d) ENE-WSW subgroup (N = 233; Fig. 5C); e) E-W subgroup (N = 157; Fig. 5C); and f) N-S subgroup (N = 147; Fig. 5D).

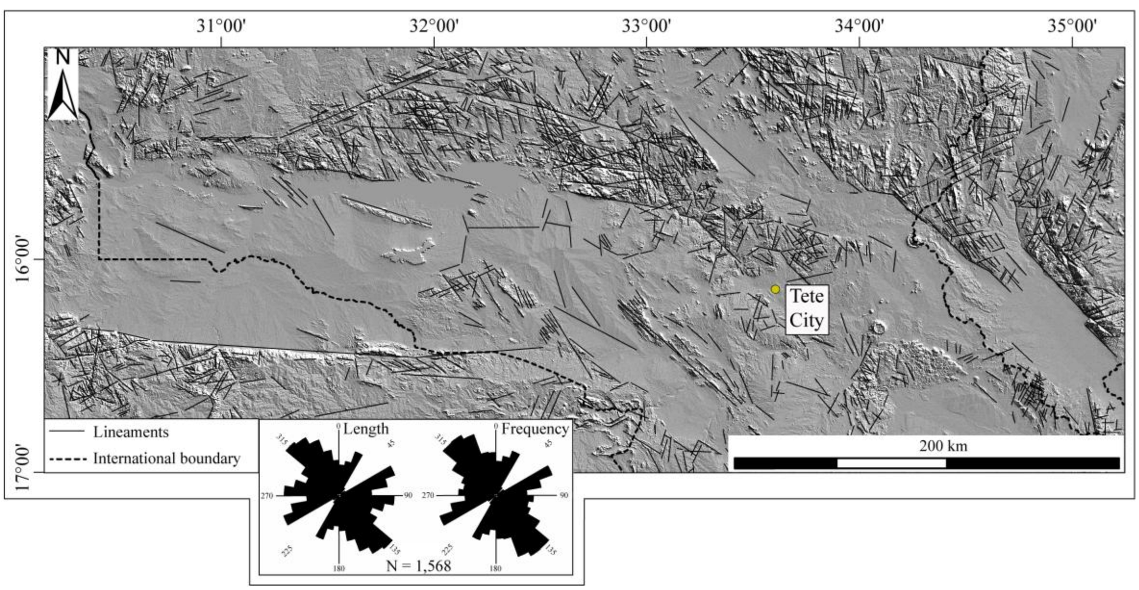

Figure 4: Terrane digital shaded relief model image and regional lineaments traced in northwestern Mozambique, with its respective length and frequency rose diagram.

The NW-SE (Fig. 5A) and WNW-ESE (Fig. 5B) subgroups are widely distributed in the North, represented by deeply dissected valleys and concordant with several fluvial courses, including the SE portion of the Zambezi River (Fig. 2C). They are also parallel to sub-parallel to Precambrian igneous intrusions in the northwestern sector of the area and to Middle Jurassic Karoo magmatic associations in the South. On the other hand, the E-W system (Fig. 5C) has the longest continuous lineament observed in the area and is pronounced in the southern and northern limits of the Cahora Bassa Basin (E-W segment of the Zambezi Valley, Fig. 1B and 2C), along with the ENE-WSW subgroup (Fig. 5C). Both patterns show greater distribution in Precambrian basement rocks in the eastern section of the area. The NNE-SSW and N-S subgroups (Fig. 5D) show great distribution throughout the area seem to be restricted to Precambrian rocks and are homogeneously shorter than the other patterns. They are lesser and more distinctive NE of the area, close to the N-S oriented Niassa Lake in Malawi. However, these structures cross the Karoo younger magmatic intrusions (Middle Jurassic) and probably comprise post-Karoo tectonic reactivations.

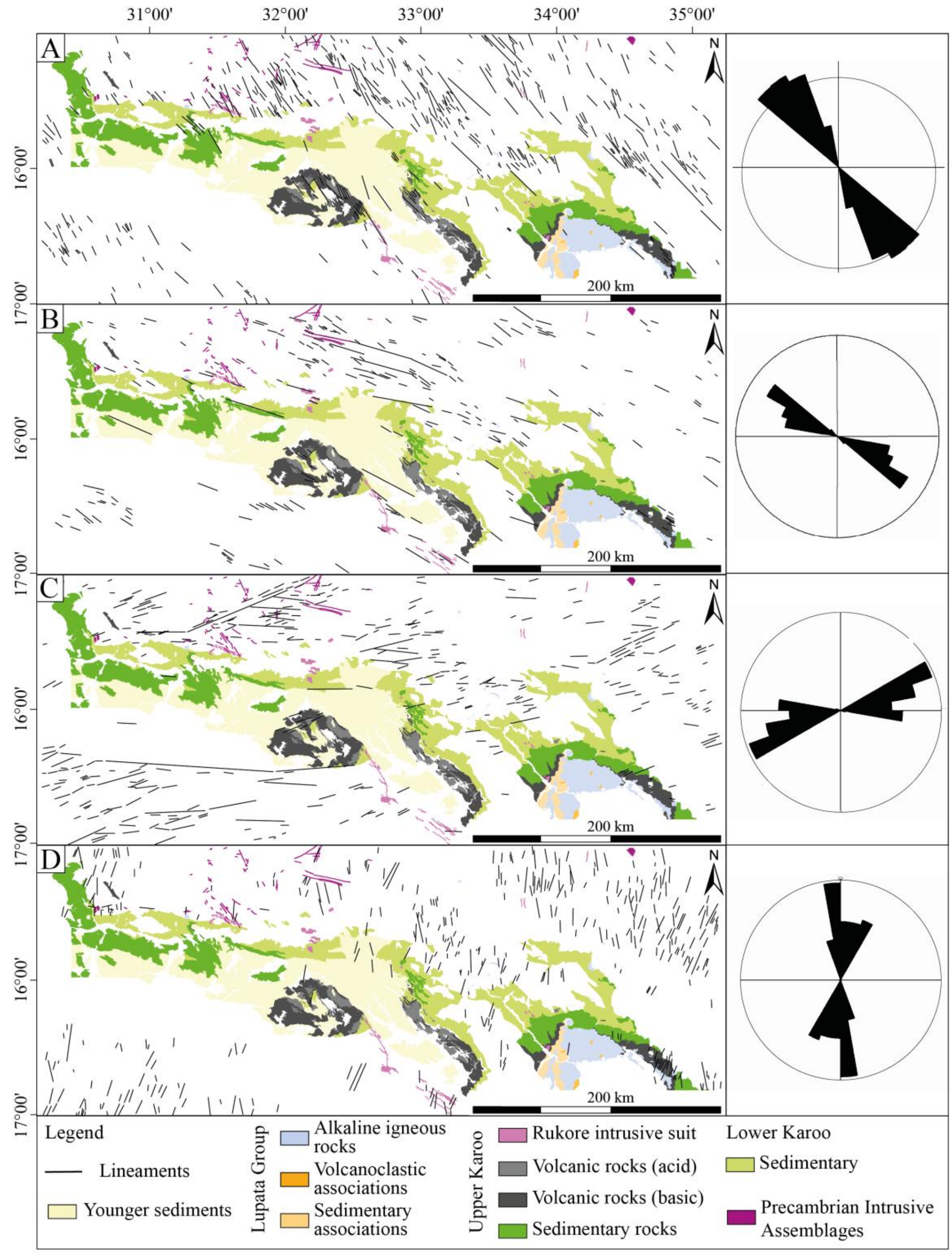

Figure 5: Structural maps of the study area with respective frequency lineaments rose diagram. Karoo Supergroup and younger lithologies occurrences were compiled from GTK Consortium (2006). A) 130-165° (NW-SE) subgroup; B) 100-130° (WNW-ESE) subgroup; C) 60-100° (E-W and ENE-WSW) subgroup; D) 165-210° (N-S and NNE-SSW) subgroup.

4.2. Field scale structural analysis

Field data provide valuable information about the structural behavior of northwestern Mozambique (see Fig. 3 for outcrop locations). Structural data were statistically analyzed from 64 measured structures with kinematic indicators and 198 fractures from the Moatize-Minjova Basin covering both, the Moatize and Matinde formations. The structural behavior of the beds was analyzed from 41 measurements. The structures were collected from sedimentary assemblages of the Moatize and Matinde formations and the Karoo volcanic rocks of the latter (Middle Jurassic). These analyses provide important and relevant structural information for post-depositional basin tectonic approaches. Stereographic projections also show different layering dip patterns in the northeastern and southwestern sections of the area (Fig. 3 and Fig. 6). Layers from the Moatize and Matinde formations mostly have a gentle dip of 14° degrees, N25°W, close to the northeastern fault edge of the basin (Fig. 3 and Fig. 6A). On the other hand, southwestern beds indicate an opposite behavior dipping preferably to SW and W, oriented southwest to the fault edge of the basin (southeastern section of the Mzarabani Shear Zone). Dips are not so gentle as the former, between 6° and 22° in central section of the graben and from 15° to 24° degrees SW of the area (Fig. 3). These patterns seem to be compatible with a fault-controlled basin, limited by listric faults (NW-SE oriented) and beds dip follow post-depositional reactivations, leading to vertical block rotation.

The analysis of fractures and faults led to definition of two important structural patterns: a) E-W and b) NNW-SSE to N-S (Figs. 6B and 6C). Those were identified as fractures and faults. Both groups are compatible with NNE-SSW, N-S (Fig. 5D) and E-W (Fig. 5C) lineament subgroups from the regional analysis. This is an interesting aspect, since these subgroups are not the most representative patterns, although the E-W subgroup has great influence over the Cahora Bassa Basin development and infilling. The kinematic indicators (silicate-filled faults and fractures) observed in the Moatize and Matinde formations rocks mainly characterize these faults as transcurrent, dextral and normal.

In general, the field structures are shallow and constantly filled by late silicate solutions. The lack of growing faults and sedimentary disturbance associated with this pattern indicates its post-depositional age. Slickenlines are present in transcurrent faults, as well as polished planes. However, steps or other kinematic indicators were absent in most cases, making it difficult to determine the sense of fault slip in several occasions. Most faults and fractures are vertical to subvertical (dipping mostly greater than 80º) indicating that kinematics must be preferably extensional or directional. Right-handed faults predominate, along with filled fractures with the same orientation, postulating a transtensional stress regime (Fig 6).

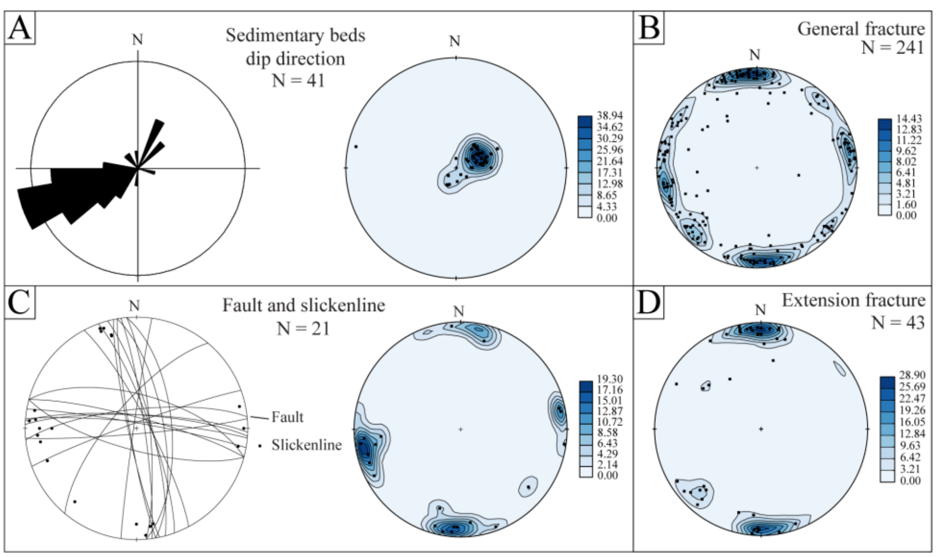

Figure 6: Structural diagrams from field work data. A) Observed sedimentary beds dip directions, showed in rose diagram and stereographic projection; B) All fractures measured in field (with tension fractures); C) Faults and slickenlines; D) Extension fracture.

Extensional fractures (2-20 mm wide) are filled by silicate solutions and show a preferable E-W and NNW-SSE trend (Fig. 6D). Both patterns are accompanied by transcurrent shear faults (principal structures), commonly showing anastomosing shape. The relative timing of these structural patterns could not be clearly deduced from our data set since very few cross-cutting relationships were found. We identify three transcurrent dextral faults, following N20°-28°W and N80W directions with high angles, whereas other transcurrent faults (N=12) present E-W, N80°-75°W and N10°-5°W major directions. Slickenlines from these faults indicate N18°-20°W directions with dips of 5° to 10° and E-W oriented with dip of 25°. Only one structure shows a NNW-SSE direction and dip of 84° with slickenlines oriented N15°W and dip of 14°. Slickenlines from transcurrent faults show dip angles between 4° e 16° degrees and directions parallel and sub parallel to the fault plane.

4.3 Facies and Facies associations

The Permian deposits of KS in northwestern Mozambique are composed of mostly interbedded coal and coarse- to fine-grained clastic deposits (Tab. 1). In this study, we have distinguished facies that comprises the Moatize and Matinde formations, composed of alluvial sequences deposited in relatively cool and humid climate (Smith et al., 1993), after Late Carboniferous glaciations, but close to transition to hotter climatic conditions (Matinde Formation), as indicated by the lack of coal and presence of commonly coarser red sequences topwards.

The Moatize and Matinde contact is very limited in outcrop in the Moatize-Minjova Basin, mostly because of the gentle dip of the beds (5° to 25°, Fig. 6D). This local structural characteristic does not allow great natural exposures, as they are commonly associated with faulting and folding areas or in road cuts, making it difficult to obtain a proper lateral correlation for this stratigraphic contact.

4.3.2 Moatize Formation

Flood plain deposits with peat

This association is composed of massive carbonaceous mudstones, <0.5 cm thick, interbedded with very fine to fine sandstones with ripple cross-lamination (Fm), defining linsen and wavy bedding. The heterolithic bedding is interbedded with coal (C) (Fig. 7 and Fig. 8). Sometimes, the black horizontal laminated coal beds (C) are interbedded with gray laminated (bituminous) siltstones/mudstones sequences (Fl) (Fig. 9A, 9B and 9C). Cairncross (2001) and Lakshminarayana (2015) indicate that the Moatize Formation consists of a coarsening upward sequence, mostly composed by interbedded coal, carbonaceous mudstones, mudstones, siltstones and feldspathic sandstones (Fig. 3 and Fig. 9D, 9E and 9F; MB-130 outcrop). These are interbedded with crevasse splay deposits.

Fluvial channel deposits

This association comprises lithofacies with fining upwards cycles (between 2 to 15 m thick). From bottom to top, the cycles comprise coarse to very coarse-sandstones with tangential cross-stratification (St) and rarely low angle cross-stratification in micaceous (muscovite) medium to coarse-sandstone, sometimes conglomeratic, poorly to moderately sorted (Sl). Sometimes they occur interbedded with massive matrix supported conglomerates (Gm). They are superimposed by fine sandstones, 0.2 to 4 m thick, composed of sets of ripple cross-lamination (Sr). The latter consist of micaceous (muscovite) very fine to fine-sandstone, moderately to well sorted, with critical to subcritical ripple cross-lamination, 0.5 to 2 cm thick (Tab. 1; Fig. 7 and Fig. 8).

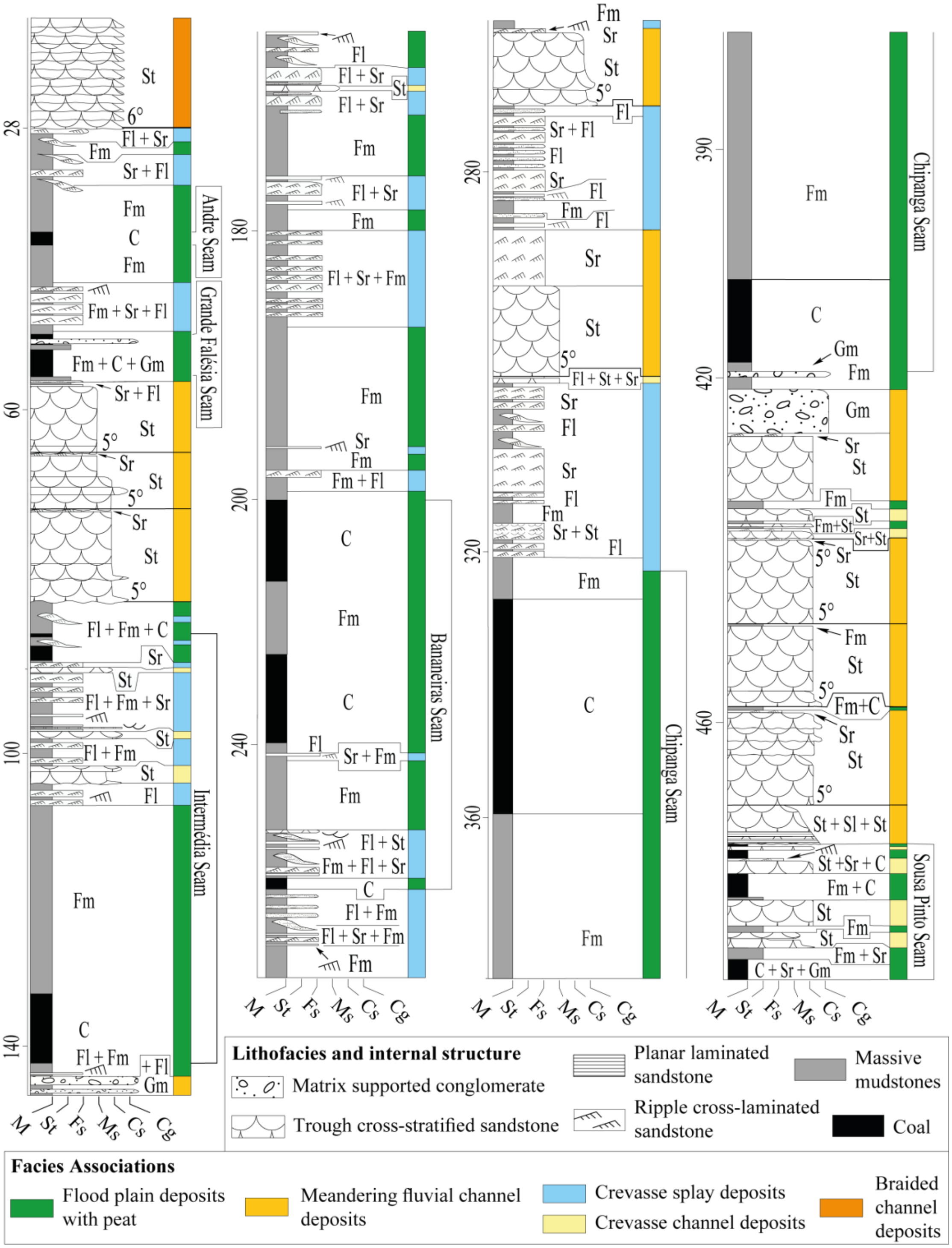

Figure 7: CS-006 borehole (ca. 500 m) schematic profile, showing lithofacies variations and lithofacies assemblages.

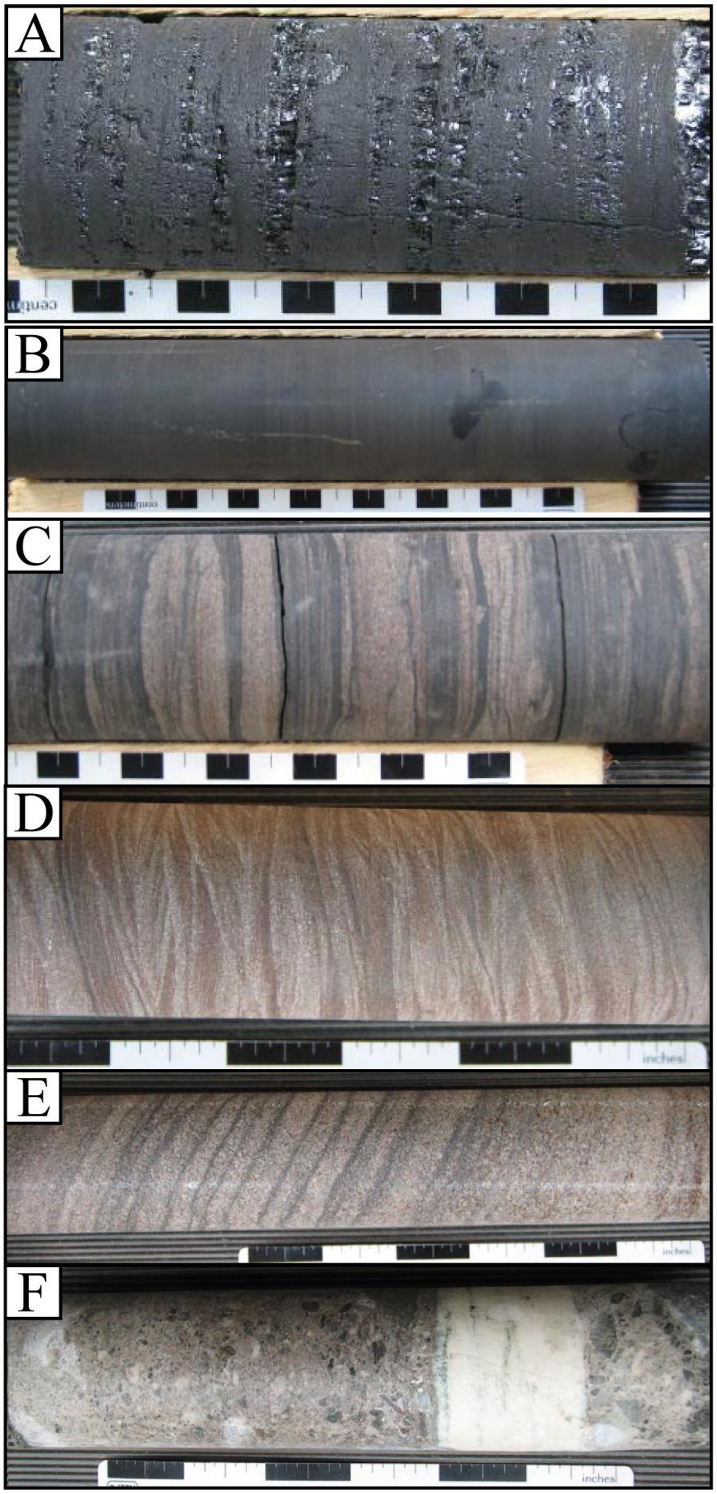

Figure 8: CS-006 borehole main lithofacies. A) C (133,2 m); B) Fm (393 m); C) Fl (147.3 m); D) Sr (282 m); E) St (294.6 m); F) Gm (424, 61 m).

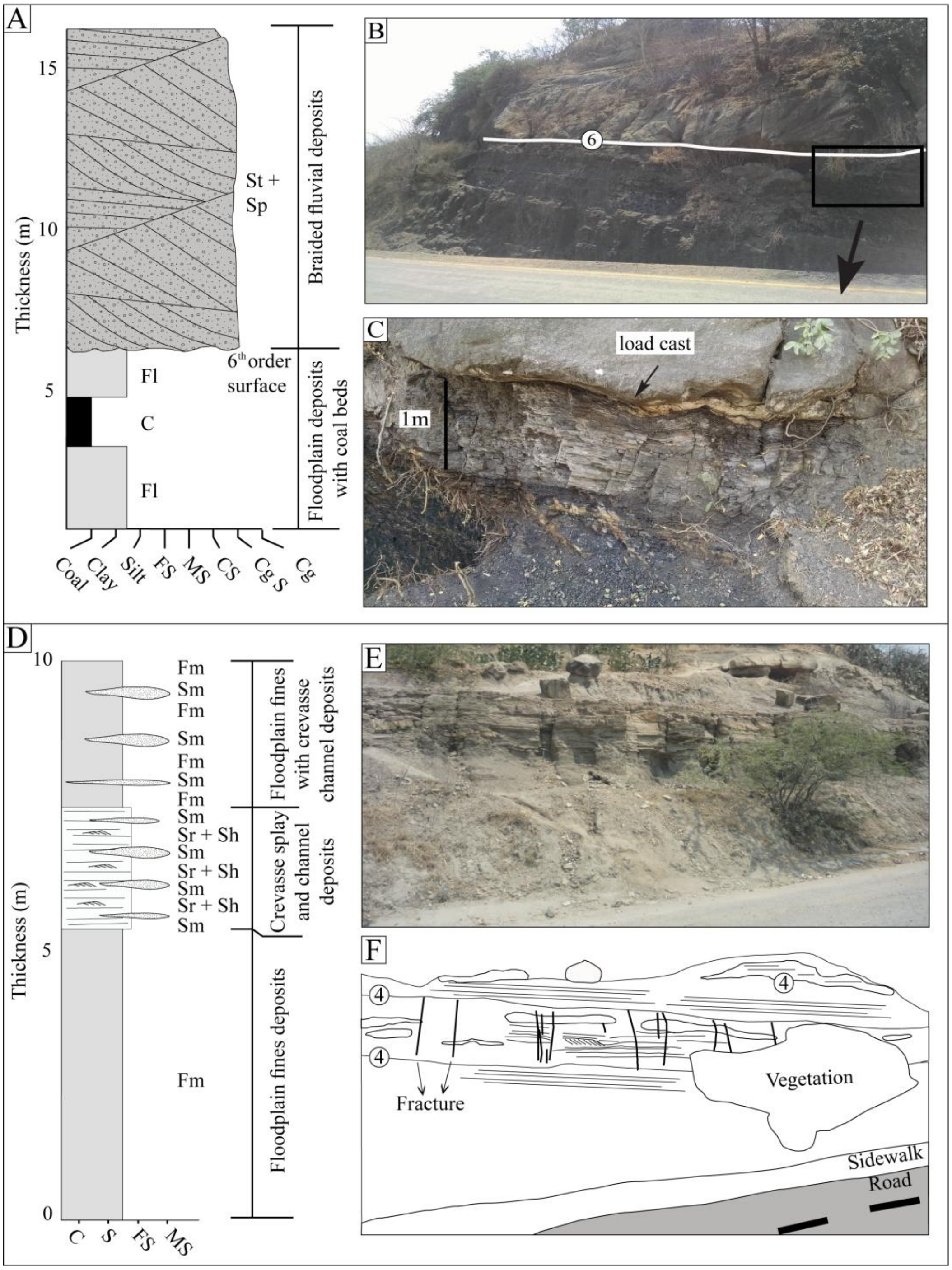

Figure 9: A) Schematic profile of the Moatize/Matinde Formations progradational transition; B) Outcrop type-section of the 6th order transition; C) Detail of load casts marks found within the unconformity. D) Schematic profile illustrating overbank lithofacies associations; E) Relationship between the floodplain fines, crevasse splay and crevasse channel associations; F) Schematic cross-section of Fig. E pointing out the distribution of lithofacies association and their relationship with each other.

Crevasse splay and crevasse channel deposits

Deposition of facies with coarsening and thickening upwards sequence (between 0.5 to 8 m thick) dominates these sedimentary deposits. From bottom to top, the succession comprise massive carbonaceous mudstones (Fm), <0.5 cm thick, of very fine to fine sandstone linsen bedding with ripple cross-lamination (Fm), superimposed on mudstones with very fine to fine-sandstone wavy/linsen bedding 0.3 to 5 cm thick, with ripple cross-lamination (Fl). These heterolithic successions are overlaid by micaceous (muscovite), very fine-grained sandstone, with 1-2 cm ripple (sometimes climbing) cross-lamination (Sr) that turning upwards to a medium to coarse-sandstone, occasionally conglomeratic, poorly to moderately sorted, with 5 to 50 cm thick sets of trough cross-stratification (St). Foresets are commonly marked by intraclasts (Fig. 3; MB-125 outcrop; Fig. 10A and 10B; MB-130 outcrop; Fig. 9D, 9E and 9F).

In this facies association we also identified medium to coarse sandstone beds, mostly 0.5 to 2 m thick, with erosive base, showing tangential cross-stratified sets that were interpreted as crevasse channel deposits. They mostly occur (Fig. 10A and 10B) associated with massive to poorly horizontally laminated tabular fine to medium sandstone (Sh). Channels are commonly <1 meter thick. This scenario implies a sporadic change between lower and upper flow regime conditions (Allen, 2014; Fielding, 2006). Massive to poorly horizontally laminated medium-grained sandstone beds (Sm) also interpreted as crevasse channel occur as lenticular bodies inside floodplain facies association deposits (Fig. 9D, Fig. 9E and Fig. 9F).

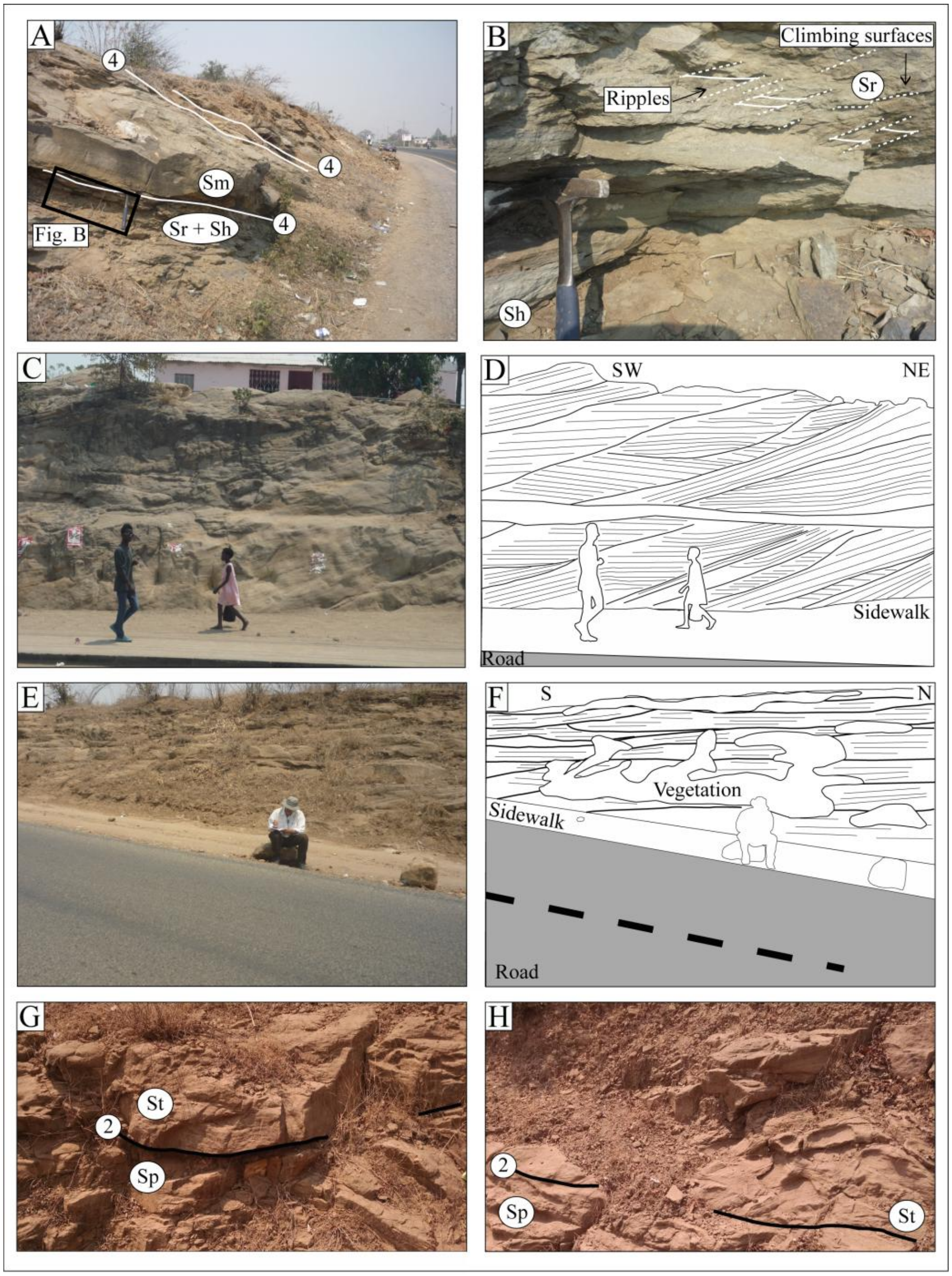

Figure 10: A) Crevasse splay and crevasse channel deposits; B) Detail of very fine sandstone with climbing ripples cross-lamination (Sr) interbedded with horizontal laminated sandstones (Sh); C) Coarse cross-bedded sandstones (Sp and St) from the Matinde Formation braided fluvial system (longitudinal bars); and D) Sketch of Fig. B illustrating the internal structural pattern of beds (W to NW paleoflow); E to H) Lithofacies (Sp and St) from a poorly confined channel, with low angle lateral accretion pattern and main westward paleoflow.

4.3.3 Matinde Formation

Fluvial channel deposits

These facies associations are 3 to 5-meter thick, bounded by high-relief basal erosion surface. Internally, the sand bodies are composed mostly by metric sets of brownish, coarse to conglomeratic sandstone with planar (Sp) and tangential cross-stratification (St) (Fig. 9A, 9B and 9C; Fig. 3; MB-126 and MB-129 outcrops) (Fig. 10C and 10D). Paleoflow measurements indicate NW to NE preferential migration trends (Fig. 3).

Poorly confined fluvial channel

This lithofacies assemblage is 3 m thick, of amalgamated sandbodies, bounded by planar to a low-relief erosive surface. The sandbodies are mainly composed of brownish, medium to coarse-grained sandstones with horizontal (Sh), low-angle cross-stratification (Sl), and rarely planar (Sp) and trough cross-stratification (St). The individual sets are 20-30 cm thick. This facies association mainly outcrops north of the study area (Fig. 3; MB-128 and MB-127 outcrops), close to the faulted basin boundary with Precambrian rocks (Fig. 10E, 10F, 10G and 10H). Western and southwestern paleoflow directions are suggested from field measurements on cross-bedded strata.

Fluvial channel and reworked alluvial fan deposits

Upwards in the profile, lithofacies assemblages attributed by us to later depositional sequences of the Matinde Formation, were observed in the southwest section of the graben (Fig. 3; MB-117 to 124 outcrops) and consists of a ~300 m thick succession of fining-upward sequences of coarse-grained to conglomeratic sandstones (Figs. 11A to 11E). These facies associations show a gradual reduction of conglomeratic lithofacies. Matrix-supported conglomerates (Gm) (Fig. 11A and Fig. 11B), with clasts of about 20 cm in size of mainly moderate rounded to subangular granitic rocks, approximately 40 meters thick, occur at the base of the sequence. Upwards there is a prominent occurrence of coarse to pebbly sandstone with planar (Sp) and trough cross-stratification (St) (Fig. 11C, 11D, 11E and F) with lenses of conglomeratic sandstones, organized in 0.5 to 1 m thick sets (Fig. 11D). Clasts are dominantly composed of rounded to subangular granitic and quartz fragments of <5 centimeters in size and commonly parallel to the cross-bed stratification. Intraclasts where not observed, but several elongated clasts shape casts, commonly oriented with the whole sequence were observed, suggesting that intrabasinal clasts may have been dissolved or loosened within post-depositional processes. In a few locations there are several occurrences of iron concretions, mostly associated with faults and fractures providing a grayish color to the sediments. Immaturity, large size and composition of the clasts and sediments reflect the proximity of this package of the border fault (Fig. 3). Paleocurrent measurements from this package indicate a NW to NE paleoflow.

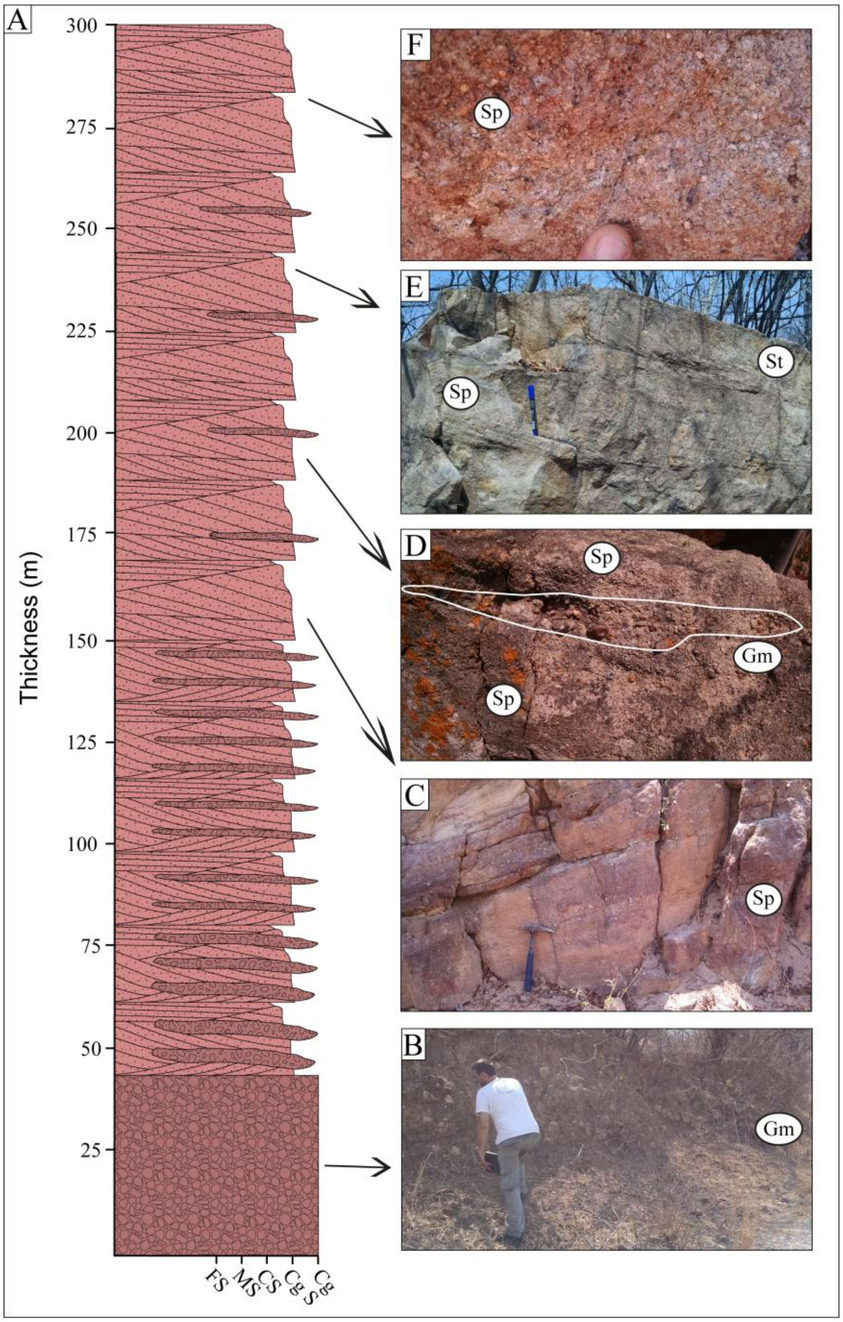

Figure 11: A) Schematic profile of coarse lithofacies (Gm, Sp and St) from a fluvial channel (coarse to conglomeratic grained bars) near southwestern basin faulted margin; B) Detail of basal Gm lithofacies; C) Coarse to conglomeratic sandstone with planar cross stratification (Sp); D) Detail of Sp irregularly interbedded with Gm; E) Interbedded Sp and St (tangential) lithofacies; F) Interbedded very coarse and coarse Sp lithofacies in the top of the sequence as a result of variability in the transport energy.

5. Discussion

Structures and sedimentation in northwestern Mozambique followed important stages of intraplate brittle reactivation of large crustal structures within Gondwana Supercontinent, as marked by the overlap of very coarse lithofacies association of Matinde Formation over the floodplains of Moatize Formation, which is cross-cut by several transtensive syn-depositional structures. NW-oriented structures such as growth faults, drag folds and folds axial planes, produced by regional tectonic activity, have exposed buried coal beds in the northeast area of Cahora Bassa Basin, which is positioned north-northwest of the Moatize-Minjova Basin (Fig. 2C), with the same sedimentation pattern of the latter. The entire sequence shows a distinct regional coarsening upwards signature, which compounds a large fluvial plane during Permian in the northwestern Mozambique basins.

Brittle faults and fractures measurements collected from the Moatize and Matinde formations point to preponderant post-Karoo depositional tectonic reactivations, probably related to the Pangea breakup event and beginning of the East African Rift System inception. Below we provide a discussion about integration of structural reactivation mechanisms and depositional environments.

5.1. Permian Tectonics and Basin Subsidence

A complex structural web was identified in northwestern Mozambique, produced by Phanerozoic brittle reactivation of inherited basement Precambrian ductile deformation zones, mostly from Pan-African orogenic cycle. NW-SE oriented structures tightly dominate the Moatize-Minjova Basin during deposition and subsidence phases of Karoo Supergroup sequences in northwestern Mozambique. The large distribution of the lineament patterns all over the region reflects the Mozambican position within the Pan-African assembly, between the interface of the Zambezi and Mozambique Orogenies.

The NW-SE pattern is concordant with the southeastern segment of the Mzarabani Shear Zone and Mwanza and Estima Faults (Fig. 2) which are the main fault systems responsible for basin subsidence. The WNW-ESE subgroup is probably a subordinate (Riedell shear) pattern generated from the NW-SE system. On the other hand, the E-W transtension system represents the southern and northern boundary of the greater Cahora Bassa Basin, while the ENE-WSW and NNE-SSW fault systems represent the Riedell shear. Shoko and Gwavava (1999) identify similar structures in the basement below Cahora Bassa Basin from geophysical data and assigned those as the main structural pattern responsible to control subsidence control within the basin, since its earliest stages. However, NE-trending fault zones show greater importance in the Moatize-Minjova Basin, near the northeastern edge of Mozambique with Malawi, where several Jurassic dikes are aligned with this trend (Casting, 1991). Our studies from granitic and metamorphic rocks in Cahora Bassa and Tete regions showed that basement ductile structures are marked by NW-SE oriented magmatic fabric and high temperature shear zones (Philipp et al., 2014). Additionally, NW-SE and NE-SW are the main Pan-African ductile shear-zones patterns, well established in northern Malawi (Ring et al., 2002), active until Ordovician times. These considerations imply that the basement fabric heritage within northern Mozambique has played an important role during basin inception and infilling.

Apparently, NW-SE, WNW-ESE, and ENE-WSW fault system subgroups appear to affect more intensively the KS sequences and the Post-Karoo sequences less (Fig. 5), comprising some of the longest continuous lineaments observed as indicative of its basin-forming character. Igneous rocks from Karoo are strongly aligned and sectioned by the

NW-SE subgroup. We interpreted these data as probable pathways for magmatic rise through the crust at the end of the Karoo basinal cycle (beginning of Gondwana Breakup), controlling regional subsidence during Karoo and Post-Karoo sedimentation. Similar descriptions could be adopted for the WNW-ESE, and ENE-WSW subgroups, which are also well recorded in the Karoo sequences; but these two subgroups host only small intrusions and are probably shallower in the crust.

The less pronounced N-S and NNE-SSW fault system scarcely affect the basins, comprising smaller lengths, and hence are probably shallower fault zones resembling subsidiary structures associated with the greater patterns. Otherwise, they intercept the Later Karoo volcanic intrusions in the southern region, constraining its post-Karoo tectonic age.

A dynamic analysis based on field scale data suggests a local NNE-SSW extensional regime to generate such structural pattern (Fig. 12). Since they post-date Karoo sedimentation, due to its large occurrence all over the basin and great fit with the N-S trending East African Rift structure (Lake Niassa), this extensional component is probably related to an N-S transtensional regime produced during the Gondwana dispersal in the eastern African margin.

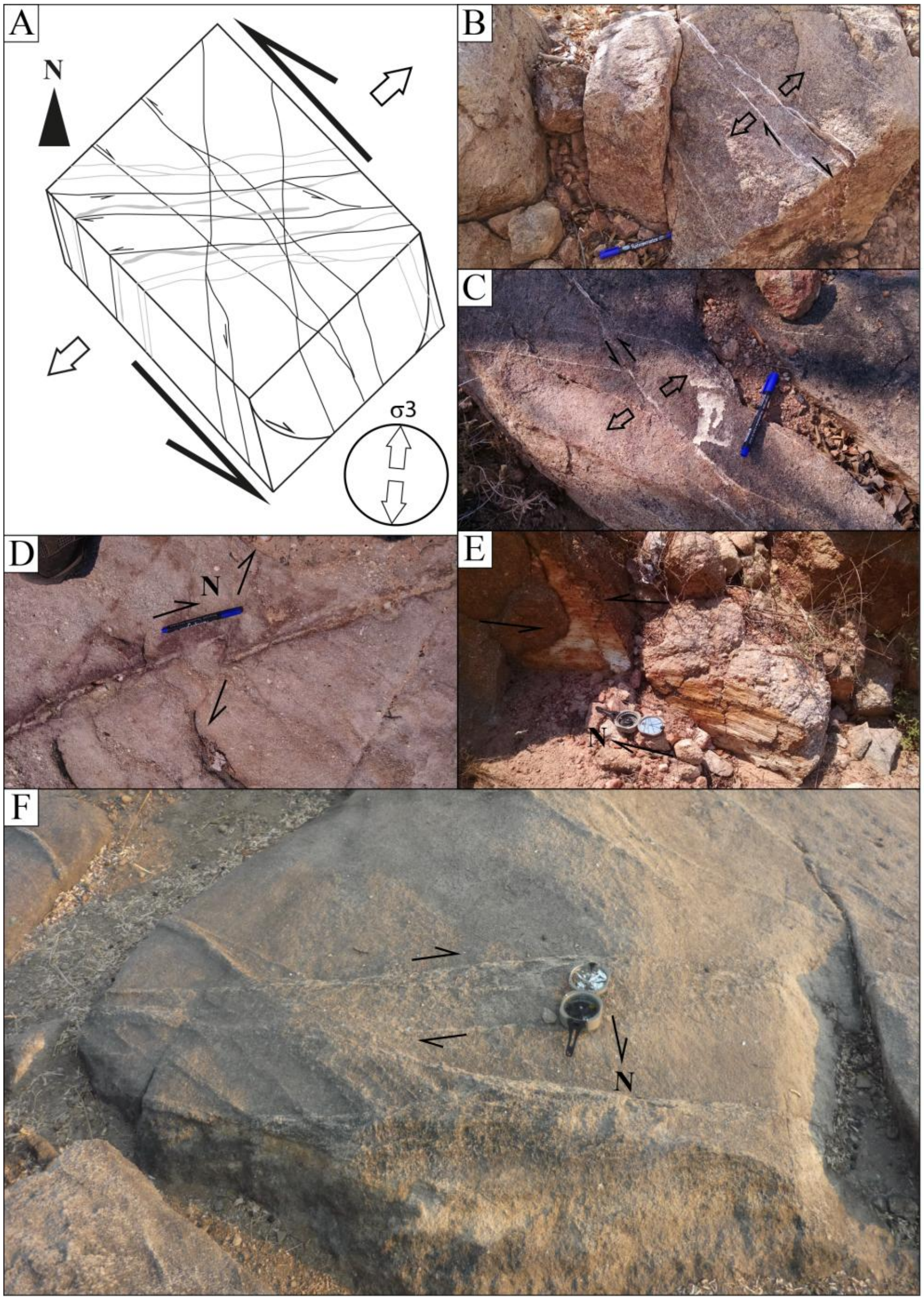

Figure 12: A) Sketch of main structural patter determined from field measurements data; B) Top-most coarse to conglomeratic lithofacies preserving structures filled by silicate solutions; C) Sinistral transtractive fault system with silicate solution, which marks the shear direction; D) NW-SE dextral strike-slip fault dislocating N-S shear fault with sediment fill (post-depositional); E) N-S trend sinistral strike-slip fault with slickenlines and shear direction indicators (steps); and F) E-W dextral fault with silicate solutions in sandstones from Moatize Formation.

In a regional context, Permian times were a period of large tectonic activity along Gondwana, such as the Pangea assembly (Variscan Orogeny) in northern Africa (Torsvik & Cocks, 2013; Linol et al., 2015) and ongoing subduction of Panthalassan oceanic crust (Gondwanides Orogeny, ca. 305–230 Ma) in the southwestern Gondwana/Pangea margin (Cawood & Buchan, 2007). Both tectonic processes may have acted as a trigger for regional inland subsidence that took place in several basins within Gondwana. This period accomplished the Cape Fold Belt Orogeny, which comprises a large deformation structural pattern with major N-S (Craddock et al., 2007) to NE-SW stress fields acting on the Gondwana margin (Tankard et al., 2009; Hansma et al., 2015), which deformed earlier glaciogenic deposits of KS in South Africa (Craddock et al., 2007; Hansma et al., 2015). Additionally, Smith et al. (1993), Cadle et al. (1993), Johnson et al. (1996). Catuneanu et al. (2005) and references therein indicate that glaciogenic deposits commonly rest non-conformably or with a slightly angular unconformity over low relief pre-Karoo landscape. These evidences suggests that it starts after the main glacial period, probably during Early Permian as constrained by Ar-Ar deformational ages of ca. 280-245 Ma within the Cape Fold Belt (Hansma et al., 2015), prior to the onset of coal-bearing layers deposition of Moatize Formation, which recorded large syn-depositional faulting and folding in its stratigraphic record (Vasconcelos et al., 2014; Lakshminarayana, 2015). Basin inversion and basement uplift during this period have also been documented by Holz et al. (2006) in the southern section of the Paraná Basin in South America, improving the influence of southern Gondwana margin tectonics inland.

In this context, we understand that the Moatize-Minjova Basin was developed by a NW-trending structural system, with sinistral transtensive regime, related to N-S/NE-SW oriented stress field from the Gondwana southern margin during the early times of the Cape

Orogeny evolution. Stress propagated along the first order, NE to NNE oriented, Precambrian Mozambique Ocean Suture and converged inland through the NW Zambezi Pre-Transform System as a synthetic Riedell shear of the main structure (Fig. 13A). Subsidence was achieved from a NE-SW extension, produced by crustal readjustment. On the other hand, episodic subsidence in Mid-Zambezi, Mana Pools, Luangwa, Metangula, Ruhuhu and Waterberg basins, that are NE-SW-trending, are related to readjustments produced by the Damara-Katanga Belt, between Kalahari and Congo/Tanzania cratonic areas (Fig. 13A).

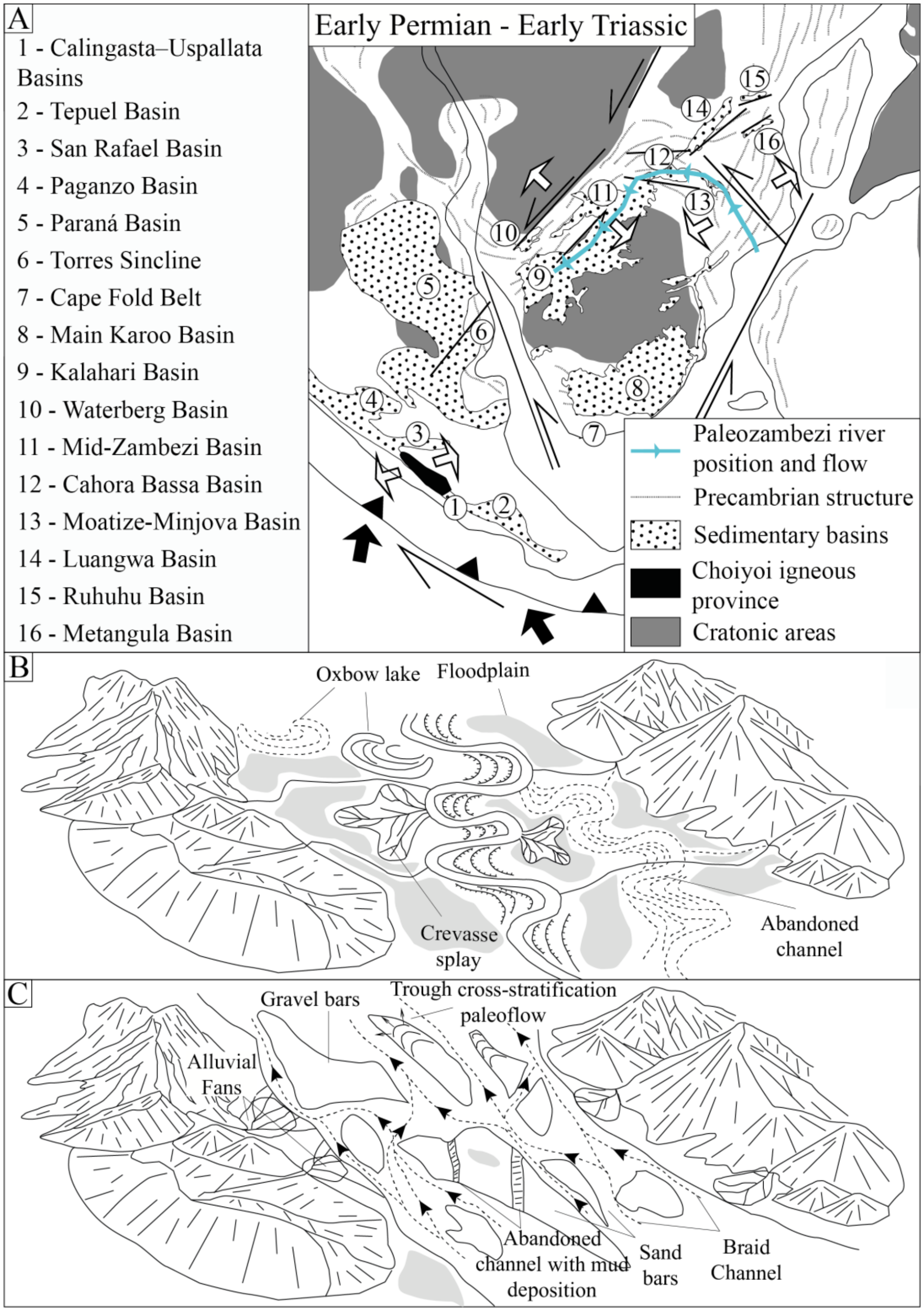

Figure 13: A) Schematic geodynamic conditions throughout Gondwana south-southwestern margin during Permian sedimentation period; B and C) Schematic depositional environment of Early-Late Permian meandering (B) and Late Permian - Early Triassic braided (C) lithofacies associations.

5.2 Stratigraphic and Depositional Implications

Fluvial channels or poorly confined channels, bars and overbanks are the main depositional elements identified in the area, composed by facies and facies associations characterizing individual bodies where the internal geometry and external form can be differentiated. These elements led us to identify meandering (Moatize Formation) and braided (Matinde Formation) fluvial systems.

The facies description and facies associations of well CS_006A have shown that the Moatize Formation was deposited in a continental environment dominated by meandering river systems. Coals may have being deposited in peat associated with floodplains and probably in oxbow lakes (abandoned meandering channel; Fig. 13B). Thus, lateral migration of fluvial channels may have played an important hole in the matter of coal seams preservation. The study of the vertical lithofacies succession showed that coal is interbedded with thin layers of siltstone and fine sandstones, marking its cyclic deposition pattern. This sedimentary change within coal-bearing layers controls the quality of coal and is directly related to the deposition of crevasse splay successions.

The stratigraphic sections demonstrated that the Chipanga seam, composed by interbedded flood fines and coal beds, occur near the base of the sequence (Fig. 7) and brings important subsidence implications with it. The great thickness of these floodplain fines deposits implies a high subsidence regime in the basin, with low fluvial channel amalgamation. This suggests an Early Permian depositional age, right after glacial retreat and consequent isostatic rebound which lead to high subsidence rates. This was followed by tectonically active periods throughout the Permian (as demonstrated earlier), due to the ongoing Panthalassa subduction along southern the Gondwana margin and the beginning of Cape Fold Belt deformation. Early Permian tectonic activity is recorded in basins on the eastern margin, such as Ruhuhu Basin, near the Tanzanian margin (Fig. 1B), an important tectonic event around Artinskian times (Middle - Early Permian), which led to braided stream deposition in the base of the Moatize correlatable sequence (Wopfner, 2002). Therefore, the entire sequence is interpreted as a great fluvial plain, with large floodplain succession with thick peat seams accumulation in cold and wet swamps in the overbank areas.

The stratigraphic analysis allowed the identification of a likely six-order sequence boundary on the uppermost portion of stratigraphic well CS_006A (depth of 28 m). It comprises an irregular surface marking the contact between the Moatize (Fig. 13B) and Matinde (Fig. 13C) formations, where load casts indicate an overlap of a coarse braided fluvial system over a meandering floodplain. However, these marks suggest that the hiatus between these two formations must not be great. This results in a very low probability of large peatland development with deposition of organic matter and coal formation in this range. Field analysis indicates a multiple-story channel fill and sandstone sheet complexes. Vasconcelos (2000) also pointed out that in some areas of northern Mozambique these two formations show some contemporarily as indicated by load casts in the contact between them. The overlap of coarse sandy to conglomeratic braided fluvial deposits implies in a change of the local geomorphology, associated with rift shoulders uplift during the Moatize Formation deposition, attributed to the earlier Gondwanides tectonic activity. The Gondwanides Orogeny was also responsible for coal seams deformation in its later stages. This tectonic activity led to distinct sedimentation patterns on different Karoo basins within Southern Africa and in South America basins. Changes in depositional style, as supported by lithofacies association through these basins, indicates plate readjustments and rejuvenation of local structural patterns.

The basin depocenter was probably located towards the southwestern limit of the basin, based on structural and coarsening upward sedimentary patterns and controlled by the Mzarabani Fault Zone, preserving a thick and more complete section of Matinde Formation. A southwestern depocenter position is also corroborated by geophysical data for the Cahora Bassa region presented by Orpen et al. (1989) and Shoko & Gwavava (1999), showing that the Mzarabani Shear Zone probably controlled basin subsidence southeastwards. These arguments are in agreement with GTK Consortium (2006) mapping, which show that these lithofacies transitioned to the Cádzi Formation (Fig. 3).

The upper conglomeratic sequences can be interpreted in two ways. Basal matrix supported (Gm) conglomerates can represent alluvial fans deposits from the faulted margin. Finning upwards pattern, clasts organization and internal structures indicate main fluvial depositional control with northwards paleoflow. These elements may represent a coarser lithofacies association from the braided fluvial system (migration of longitudinal and/or accretion macroforms) or they can mark the transition to the upper Cadzi Formation, which may have occurred near Middle Triassic times, since the Matinde Formation is probably younger than Late Permian as determined by Pereira et al. (2016) (Fig. 14).

This latter model counterpoints the GTK Consortium (2006) which interpreted these lithofacies as part of the Matinde Formation, which is the one we follow in this paper, due to the large distribution of geological mapping of these authors and to lateral stratigraphic relationships and depositional environments determined by us. Another strong aspect is the important tectonic period that commonly marks the Permian-Triassic transition in the Paraná Basin and other basins in South America and Africa (Zerfass et al., 2003; Zerfass et al., 2004; Zerfass et al., 2005; Catuneanu et al., 2005) and left an hiatus that can be observed throughout the Tanzanian Karoo basins and in Mozambique (Catuneanu et al., 2005).

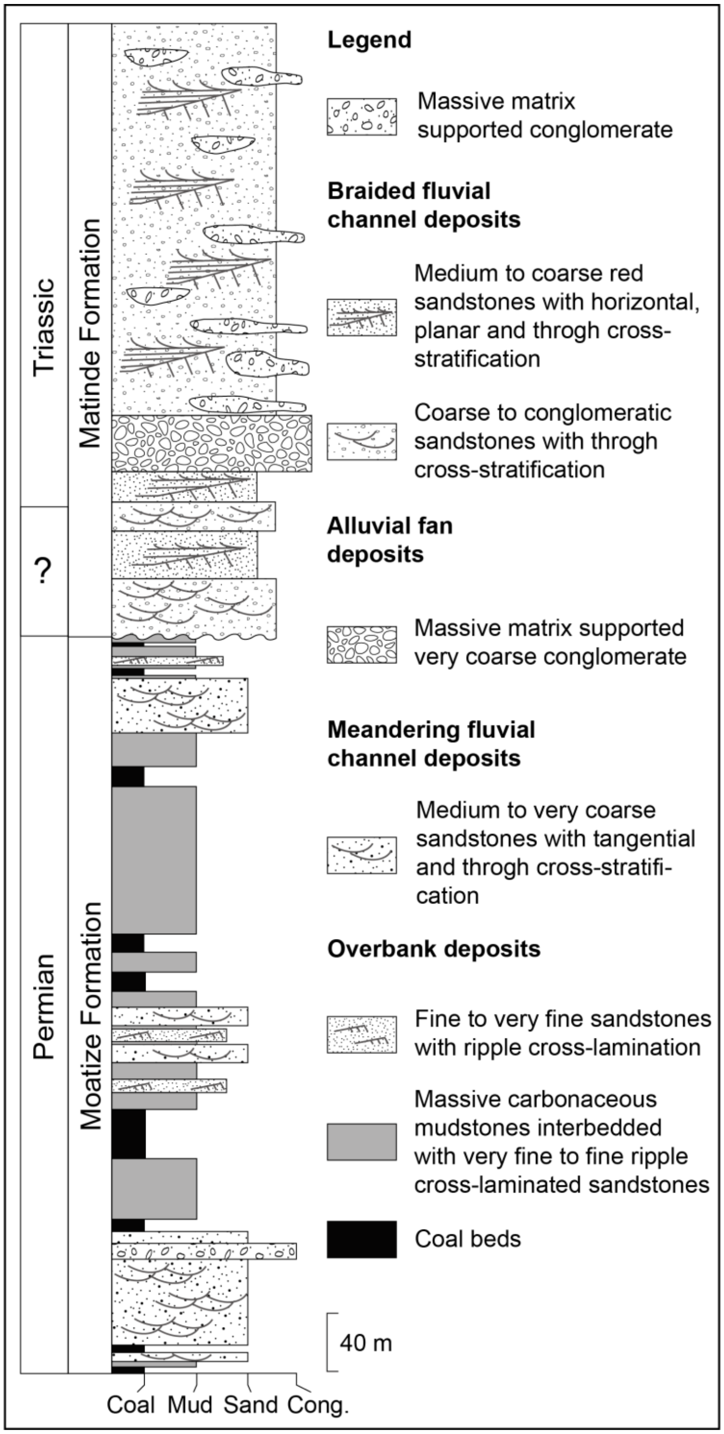

Figure 14: Schematic stratigraphic profile of the Moatize and Matinde formations.

The transition between the Moatize and Matinde formations probably approximates the Late Permian - Early Triassic period, based on palynological date presented earlier (Daber, 1984; Pereira et al., 2016) and other coal bearing seams deposits elsewhere in the Karoo basins (Catuneanu et al., 2005), although not all show clear tectonic implications. The Mid-Zambezi basin coal-bearing beds, correlatable to facies of the Moatize Formation, change to mostly mudstones with subordinate siltstones and sandstones of a lacustrine deposit (Nyambe & Utting, 1997). This suggests that high subsidence rates took place westwards from northern Mozambique, controlled by NE-SW crustal faults (Fig 13A), but produced for the same regional tectonic regime. This also improves the model proposed by Key et al. (2015) were a proto-Zambezi river with a western paleoflow since Early Permian times has influenced deposition in Central-Eastern Africa with thick proximal coarser lithofacies near the Precambrian orogenic belt and finer distal lithofacies inland towards the Mid-Zambezi and Kalahari Basins.

6. Conclusions

In summary, northwestern Mozambique basins were affected by NE-SW and NW-SE transtensive trends, along the African eastern cratonic margin, which led to crustal readjustments of Precambrian structures and inland subsidence. Tectonic reactivation was produced by far-field stress transferred from the Gondwanides Orogeny and recorded in the sedimentary records of the Karoo basins in Mozambique and Southern Africa and also in South America basins. Identification of the same structural pattern of the basement units in the Karoo Supergroup and the latest coverage underscores the importance of tectonic reactivation of the same weakness zones in the depositional control of Paleozoic and Cenozoic units.

Permian sequences in the Moatize-Minjova Basin comprise mainly meandering and braided fluvial plane deposits. The former comprise floodplain, crevasse splay and fluvial channel main lithofacies associations. This sequence was prograded by a multiple-story braided fluvial plane in the Matinde Formation. Lithofacies associations and their relationship with each other suggest deposition within a fluvial confined to poorly confined channel system with longitudinal and low-angle lateral accretion macroforms. The top of the stratigraphic sequence comprises sediment gravity flow, channel and downstream macroform accretion facies associations. Conglomerates with boulders dominate near the southwestern fault bounded graben boundary, indicating an increase in the fluvial transport energy towards the top of the sequence, due to high relief geomorphologic depositional environment, which may have started during the end of the Moatize Formation depositional cycle. Northwestward paleoflow from Matinde lithofacies suggest that the Zambezi River flow was inverted during Permian sedimentation in northern Mozambique, with its headwaters located in the southeastern highland areas, inherited from the Pan-African orogeny.

For further studies, we recommend conducting a stratigraphic detail study in the area to better understand the factors that controlled the deposition of the studied sediments. A more detailed stratigraphic model to describe the Triassic deposits in the region and Vúzi, Moatize and Matinde Formations elsewhere in northwestern Mozambique would improve tectonic and stratigraphic understanding in the area.

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Precambrian-Cambrian Provenance of Matinde Formation, Karoo Supergroup, Constrained from Detrital Zircon U-Pb Age Data, Northwestern Mozambique - Africa

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Highlights

- Detrital zircon dating provided Mesoproterozoic to Cambrian provenance;
- Neoproterozoic ages indicate an south-southwestern provenance;
- Guro Suite and SW Nampula Complex are the main source regions;
- Headwaters of Permian-Triassic fluvial systems were positioned southwards;

Abstract

Permian-Triassic times were a period of high sedimentation rates into the intracontinental Karoo rift basin of northwestern Mozambique reflecting high exhumation rates in the underlying high grounded Precambrian-Cambrian basement assemblages. The U-Pb dating of detrital zircons from Permian-Triassic Matinde Formation of Karoo Supergroup proved to be a reliable proxy to map denudation patterns of source regions.

The analytical data allow discriminate two main age populations of Late Mesoproterozoic - Early Neoproterozoic (*ca*. 1100-950 Ma) and a Late Neoproterozoic - Early Cambrian (*ca*. 550-490 Ma). The former resembles to the late stages of Rodinia Supercontinent geotectonic activity mostly represented by magmatic and less metamorphic rocks, which are present everywhere in the northern Mozambique basement. The latter register large metamorphic overprint from Pan-African Orogeny on the older Mesoproterozoic basement, although with magmatic activity related to crustal reworking.

The less pronounced populations between *ca*. 850-560 Ma together with paleoflow measurements allowed restricting the source areas when compared to a gathering of individual zircon age populations of the underlying basement. The older component refer to the bimodal magmatism related to the breakup phase of Rodinia Supercontinent registered in the Guro Suite which marks the western limit of the Moatize-Minjova rift basin. The ages between 630-560 compound the individual zircon ages of Guro Suite and SW Nampula although they are not attributed to a specific magmatic or metamorphic event.

The SW and NE Nampula Complexes must have being a unique geotectonic entity since Late Mesoproterozoic, reworked during Pan-African Orogeny. This allied to the N-NW paleoflow of Proto-Zambezi river and provenance data suggests that Nampula Complex was a probable high ground source area for fluvial sediments. Permian-Triassic rifting induced by far stress fields transferred from Gondwana margin have disrupted the Nampula Complex reactivating Precambrian structures and fabrics and the Jurassic-Cretaceous Gondwana breakup led to its actual morphology and configuration.

Keywords: Precambrian-Cambrian basement, Pan-African Orogeny, Karoo Supergroup, Provenance

1. Introduction

U-Pb geochronology applied in detrital zircon grains is a powerful tool to understand provenance patterns in sedimentary basins (Fedo et al., 2003; Hartmann et al., 2008; Hawkesworth et al., 2010; Cawood, 2012; Bicca et al., 2013; Oliveira et al., 2014; Bahlburg and Berndt, 2016). The age spectra constrained by this analysis reflect the tectonic setting of the basin in which the zircons are deposited (Cawood, 2012), assuming that the measured age distribution observed comprise an unbiased representation of the true age distribution in the sample and sedimentary unit it represents (Gehrels, 2014).

Because zircon is resistant to abrasion and chemical alteration during sedimentary processes, the determination of the ages of detrital zircons indicates the timing of events in the source regions (Hartmann et al., 2008). An additional bias in provenance studies is the variable abundance of zircons in source terrains (Moecher and Samson, 2006).

The use of U-Pb dating by LA-ICP-MS technique to determine the ages of geological processes that formed the host rocks is a modern and common procedure in provenance investigation of sedimentary rocks (Hartmann et al., 2008; Guadagnin et al., 2010; Thomas et al., 2010; Cawood, 2012; Bicca et al., 2013; Oliveira et al., 2014).

In this paper we present a provenance analysis based on LA-ICPMS U-Pb ages of detrital zircon grains from a key immature coarse-sandstone of Matinde Formation from Karoo Supergroup, with specific focus on determine the denudation patterns of the Precambrian-Cambrian basement of northern Mozambique. The Late Carboniferous to Middle Jurassic volcano-sedimentary successions of the Karoo Supergroup (Smith, 1993; Catuneanu et al., 2005) are widely distributed throughout south and central Africa hosted in marginal and intracontinental basins preserving one of the largest registers of Gondwana evolution. In northwestern Mozambique they are represented by rift basin relying over the Precambrian basement rocks that were formed over a very long time span covering the Archean, Paleoproterozoic, Mesoproterozoic and Neoproterozoic, as the result of juvenile generation of crust, terrain accretion and crustal reworking during several orogenic cycles (Stern, 1994; Hanson, 2003; Meert, 2003; GTK Consortium, 2006; Fritz et al., 2013; Macey et al., 2013; Grantham et al., 2013). A complex range of igneous and metamorphic ages, Th/U rates and zircon morphology suggest that main suturing, klippening and magmatism, related to the different stages of the protracted Pan-African orogenic cycle, controlled river catchment and provenance during Permian-Triassic sedimentation.

2. Geological Settings

The sedimentary basins of northwestern Mozambique comprise intracontinental rift basins filled by continental sediments and volcanic rocks from Karoo Supergroup and younger sequences. This basin relies over an important crustal structure, which correspond to an eastern extension of the Damara-Lufilian-Zambezi structure (Fig. 1).

Crystalline basement of northwestern Mozambique is made of a very complex assemblage of igneous and low to high-grade metamorphic rocks, from distinct crustal levels, spanning from Mesoproterozoic to Neoproterozoic-Early Paleozoic in age (Hanson, 2003; Macey et al., 2013). Most Late Mesoproterozoic rocks have being reworked by the protracted Pan-African Orogeny in the later Neoproterozoic during Gondwana-assembly (Pinna et al., 1993; Sacchi et al., 2000), which occur in two main episodes at ca. 550 Ma and ca. 500 Ma (Ueda et al., 2012). Several studies developed in the north of Mozambique allow the definition of distinct crustal entities (Fig. 1), although, the geotectonic model still a matter of discussion (Pinna et al., 1993; Jacobs et al., 2008; Viola et al., 2008; Bingen et al., 2009; Ueda et al., 2012; Fritz et al., 2013; Macey et al., 2013).

The north of Mozambique can by divided into two major Mesoproterozoic domains separated by the prominent Neoproterozoic–early Paleozoic Lurio Belt (Fig. 1) (Viola et al., 2008). This belt comprises a series of NE-anastomosing shear zones and is mostly represented by the granulite Ocua Complex, which occur mostly in the NE of Mozambique, while the SW segment of the Lurio Belt is partially undercovered (Fig. 1). U–Pb SIMS ages from selected latest-tectonic units in the Nampula Complex and the Lurio Belt give ages between 518 $\pm$ 2 and 514 $\pm$ 5 Ma, coeval with migmatisation and granitoid plutonism in the Nampula Complex (Ueda et al., 2012). The significance of the Lurio Belt is controversial. Some authors believe it represents a major suture zone connecting with the Damara-Lufilian-Zambezi Belt (Sacchi et al., 2000; Grantham et al., 2003). Others suggest it is an accommodation zone, especially because of the similarities between metamorphic complexes north of the Lurio Belt with those of the Nampula Complex to the south (Viola et al., 2008; Bingen et al., 2009), an because of an apparent decrease in strain along the belt from NE to SW.

The two domains north and south of the Lurio Belt share a similar Mesoproterozoic crustal growth history, although their evolution was diachronous. The Nampula Complex south of the belt developed between 1125 and 1035 Ma while the Unango and Marrupa Complexes to the north were between 1062 and 946 Ma. The maximum crustal thickening produced by Pan-African Orogeny in northeastern Mozambique occurred between *ca*. 570 and 530 Ma and later in the Nampula Complex (550–500 Ma) (Bingen et al., 2009; Macey et al., 2010; Thomas et al., 2010).

The Unango and Marrupa Complexes are crustal domains made of large volumes of orthogneisses related to a continental arc setting (Bingen et al., 2009) and a minor magmatic phase at ca. 799 Ma registered in the Unango Complex. These complexes were overthrust at *ca*. 550 Ma by an assemblage of Neoproterozoic granulites of the Cabo Delgado nappes (including the Xixano, M'Sawize, Muaquia and Lalamo complexes), forming a stack of west vergent nappes (Viola et al., 2008; Bingen et al., 2009; Boyd et al., 2010; Macey et al., 2013).

In northwestern Mozambique the Unango Complex overlies the small fault-bounded Ponta Messuli Complex (Viola et al., 2008; Bingen et al., 2009), which contains Paleoproterozoic metasediments affected by migmatitization at around 1950 Ma and intruded by granitic rocks at 1056 Ma. This complex is also overlain by the Neoproterozoic Txitonga Group which comprises a volcano-sedimentary complex with bimodal magmatism (Jacob et al., 2008). Westwards the Southern Irumide Belt is a structurally and metamorphically complex region of mainly Mesoproterozoic igneous rocks related to a voluminous 1090–1040 Ma continental arc-related magmatic rocks, accompanied by high-temperature/low-pressure metamorphism (Fritz et al., 2013).

Southern of the Lurio belt the Nampula Complex forms a large contiguous crustal block which consists of 1150–1030 Ma orthogneisses and metasedimentary rocks with high grade metamorphism around 1090–1030 Ma (Bingen et al., 2009; Macey et al., 2010). The ortogneisses from SW segment of the Nampula Complex (Fig. 1) are interpreted as remnants of Mesoproterozoic continental magmatic arch (*ca*. 1100 Ma; Chaúque, 2012). Over the Nampula Complex there are the tectonic emplaced Monapo and Mugeba granulite facies klippen that are assumed as equivalents of the Cabo Delgado nappes (Macey et al., 2007), considered to be erosional remnants of a larger and widespread nappe structure (Viola et al., 2008; Macey et al., 2013), which is improved by the absence of granulite-facies rocks in the underlying Nampula Complex. The Monapo Klippe consists dominantly of a mélange of granulite gneiss, deformed at 634 ±8 Ma and intruded by ultramafic and mafic gneisses and alkaline granitic rocks (637 ± 5 Ma; Macey et al., 2013).

These rocks are overlain by isolated Neoproterozoic metamorphosed molasse sediments (Fig. 1; Thomas et al., 2010; Chaúque, 2012). In the northeast section of NC the Mecubúri and Alto Benfica Groups are considered to be an autochthonous Cambrian meta-sedimentary cover of the Nampula Complex (Thomas et al., 2010). U–Pb analyses of detrital zircons from samples of the Mecubúri Group constrain a maximum deposition age of 530 ± 18 Ma, with zircon rims and metamorphic monazite grains dated at *ca*. 500 ± 10 and 499 ± 15 Ma respectively. Dating of detrital zircons from the Mecuburi Group indicate source rocks with ages peaking between *ca*. 1100–950 Ma, 750–800 Ma and 700–530 Ma, similar to the crystallisation ages in the Unango and Marrupa Complexes (Thomas et al., 2010).

The southwest Nampula Complex (Fig. 2) is attributed to the frontal nappes of Chimoio-Macossa and Mungari Groups (Chaúque, 2012), consisting of low- to high-grade paragneisses. The first is associated with the Barue magmatic arc represented by orthomagmatic rocks (*ca*. 1100 Ma; Fig. 2). These are in direct tectonic contact with the Kalahari cratonic rocks. The Mungari nappe includes the Guro Suite associations, which comprise abundant Neoproterozoic bimodal intrusive association (Fig. 2), characterize the east-dipping outer rim of the craton margin in the north (Chaúque et al., 2017). The felsic component dominantly consists of foliated aplitic granites, while the mafic one corresponds to metagabbro, locally deformed into mafic gneiss or schist with intruding pegmatite. Zircon grains from Granitic rocks indicate a magmatic crystallization age of 867 ± 15 Ma. Dating of the nucleus of metamorphic zircons show recrystallization ages at *ca*. 850 – 839 Ma, related to extensional faulting, while the metamorphic rims provided an age of 512 ± 4 Ma related to the Pan-African Orogeny (GTK Consortium 2006). At the northeastern margin of the cratonic area occur the low to medium grade metasedimentary and felsic metavolcanic (*ca*. 800 Ma) rocks of the Rushinga Group which may represent a passive margin of Neoproterozoic age (Barton et al., 1991; Hargrove et al., 2003; GTK Consortium 2006; Chaúque, 2012).

Protracted collisional orogenesis was followed by the intrusion of late- to post tectonic Late Neoproterozoic granites (ca. 575-545Ma) and Cambrian-Ordovician K-granites (ca. 530–495 Ma) (Macey et al., 2007; Jacobs et al., 2008; Ueda et al., 2012; Macey et al., 2013; Grantham et al., 2013). The latter is pronounced in the eastern Nampula Complex (Fig. 1) due to crustal delamination process that led to protract cooling history during Cambrian-Ordovician Times (Jacob et al., 2008; Emmel et al., 2014). These Precambrian-Cambrian basement rocks were partially covered by the Phanerozoic volcano-sedimentary deposits of the Karoo Supergroup and younger sequences (GTK Consortium, 2006).

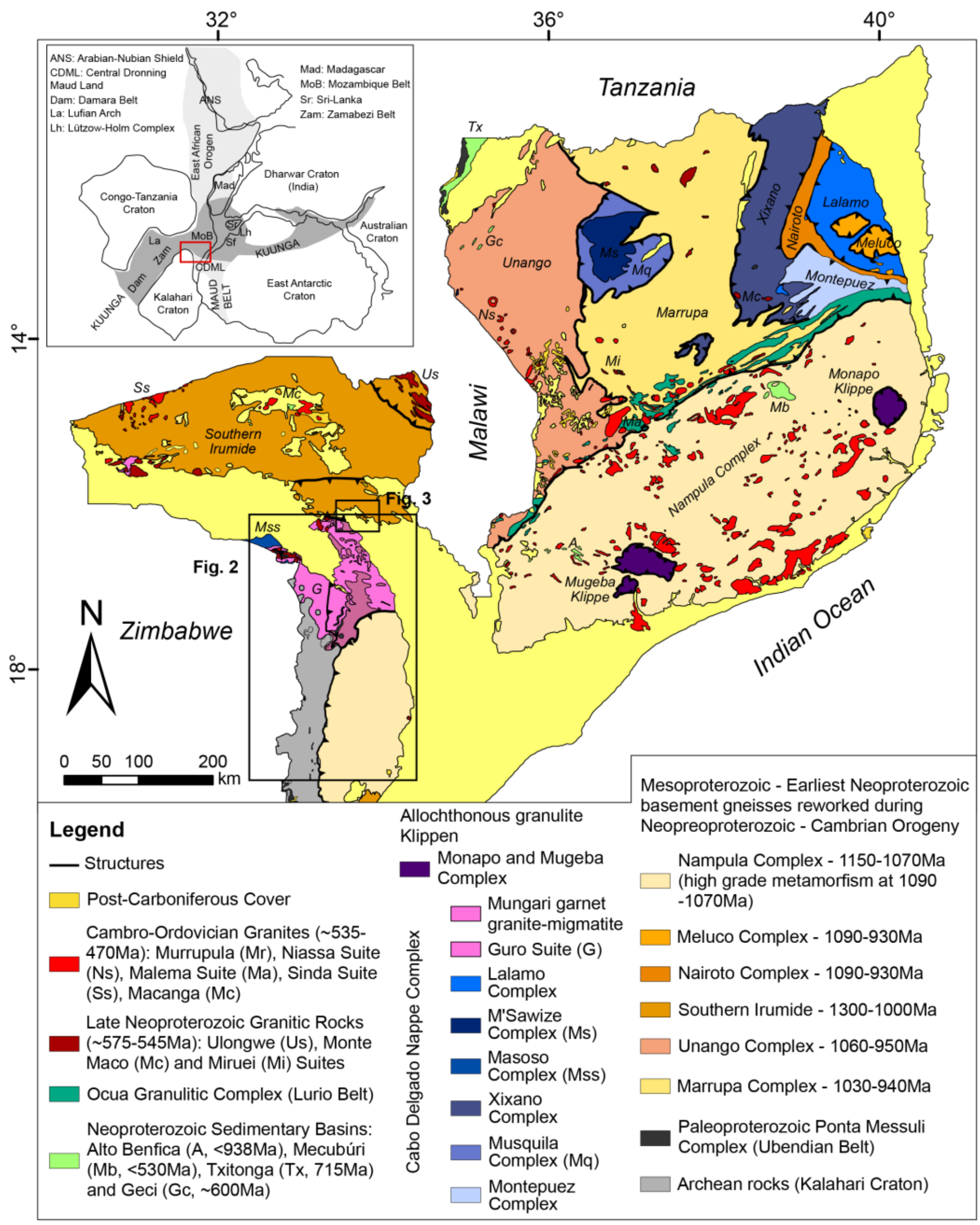

Figure 1: Simplified geological map of north Mozambique modified from Macey et al. (2013) showing the main lithostratigraphic units. In top is shown the reconstruction of Gondwana during the Cambrian after Meert (2003), with the locations of the East African Orogen and Kuunga Orogen and in the bottom the location of the geological map presented in the southern of Africa.

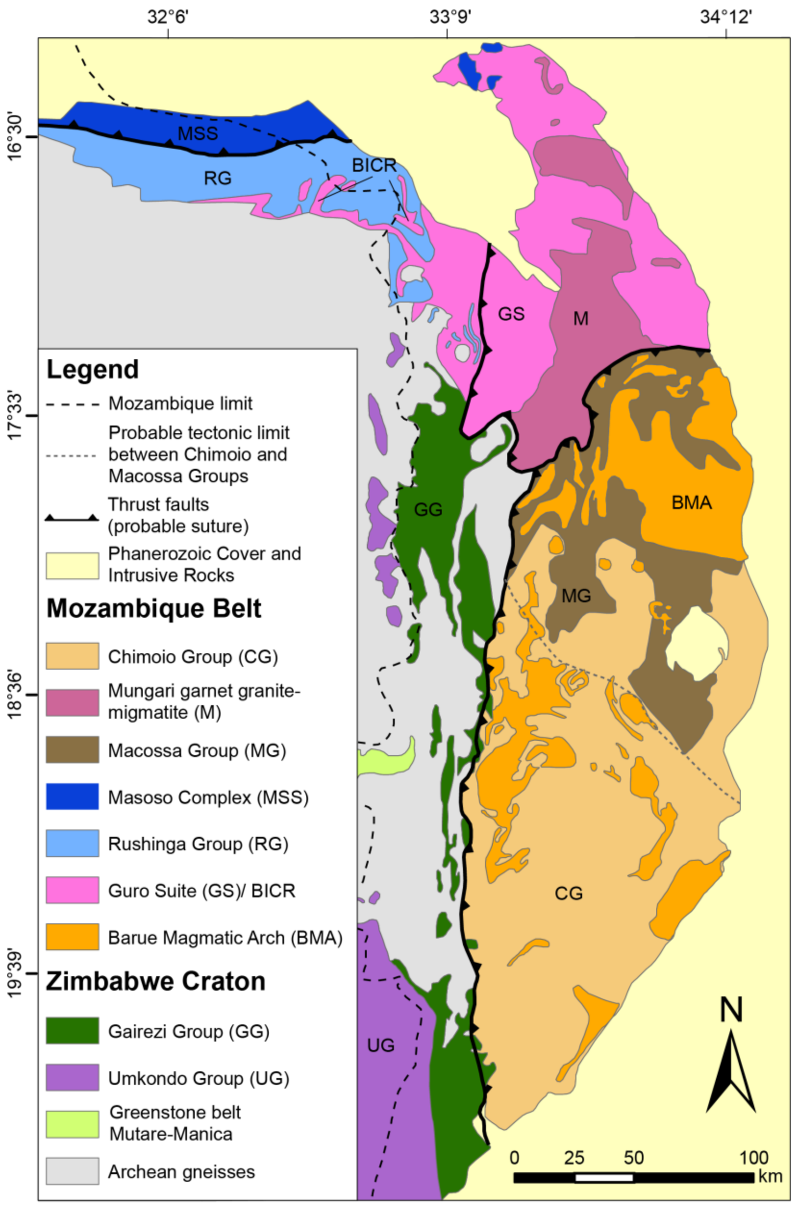

Figure 2: Geological and tectonic map of the SW section of the Nampula Complex in the contact with the cratonic margin (after GTK Consortium 2006 and Chaúque et al., 2017). BICR = Basal Intrusive Complex of de Rushinga.

2.1 Geology of the Matinde Formation

The Matinde Formation generally comprises continental sedimentation during Permian-Triassic (mostly Triassic; Pereira et al., 2016) and represents one of the Karoo Supergroup deposits of northern Mozambique. This sequence is host in an NW-striking intracontinental rift basin, locally called as Moatize-Minjova Basin (Fig. 3). The rift islimited by Precambrian structures and basin evolution follows distinct reactivation periods occurred in Phanerozoic times (Castaing, 1991; GTK Consortium, 2006; Fernandes et al., 2015; Bicca et al., 2017), under a transtensional stress regime associated with the NW-SE sinistral Zambezi pre-transform fault system (Castaing, 1991; Bicca et al., 2017). The structural control over sedimentation is evidenced by depositional cycles of the Moatize and Matinde Formations.

The Moatize Formation is made of interbedded carbonaceous mudstones, mudstones, rhythmites, sandstones and cyclic coal deposits (Cairncross, 2001; Lakshminarayana, 2015; Bicca et al., 2017) and its lithofacies assemblages are interpreted as a meandering fluvial system (Bicca et al., 2017). The coal beds represents thick peat deposits (ca. < 40m) interbedded with very thick flood plain fines sequences (ca. < 100m) (Fig. 4; Bicca et al., 2017). The absolute age of these coal-bearing formation is not well constrained and most comes from palynological record which suggests a Lower to Middle Permian age for the top part of the Moatize Formation (Daber, 1984). Although, Pereira et al. (2014) founded a Kungurian/Roadian age (Lower – Middle Permian) for the basal sequences of the Moatize Formation, positioning its depositional cycle throughout the Early-Late Permian.

Overlaying the Moatize Formation there are mostly cross-bedded coarse-grained alluvial deposits from the Matinde, its being assumed a depositional age close to the Permian-Triassic boundary but most of the depositional cycle relies in the Triassic period (Pereira et al., 2016). This formation is attributed to a braided fluvial plain system mostly represented by coarse to conglomeratic red sandstones (Fig. 4). Planar and through-cross bedding are the most common structures, separated in sets of ca. 0.5 to 2 meters by planar surfaces (GTK Consortium, 2006; Bicca et al., 2017). Lithofacies associations and its internal relationship suggest deposition of poorly channelized braided alluvial plain in which downstream and probably lateral accretion macroforms alternates with gravity flow deposits (Bicca et al., 2017). Northwestwards paleoflow from Moatize and Matinde lithofacies suggest that the Zambezi River flow was inverted during Permian sedimentation in northern Mozambique, with its headwaters located in the southeastern highland areas, inherited from the Pan-African Orogeny (Key et al., 2015; Bicca et al., 2017).

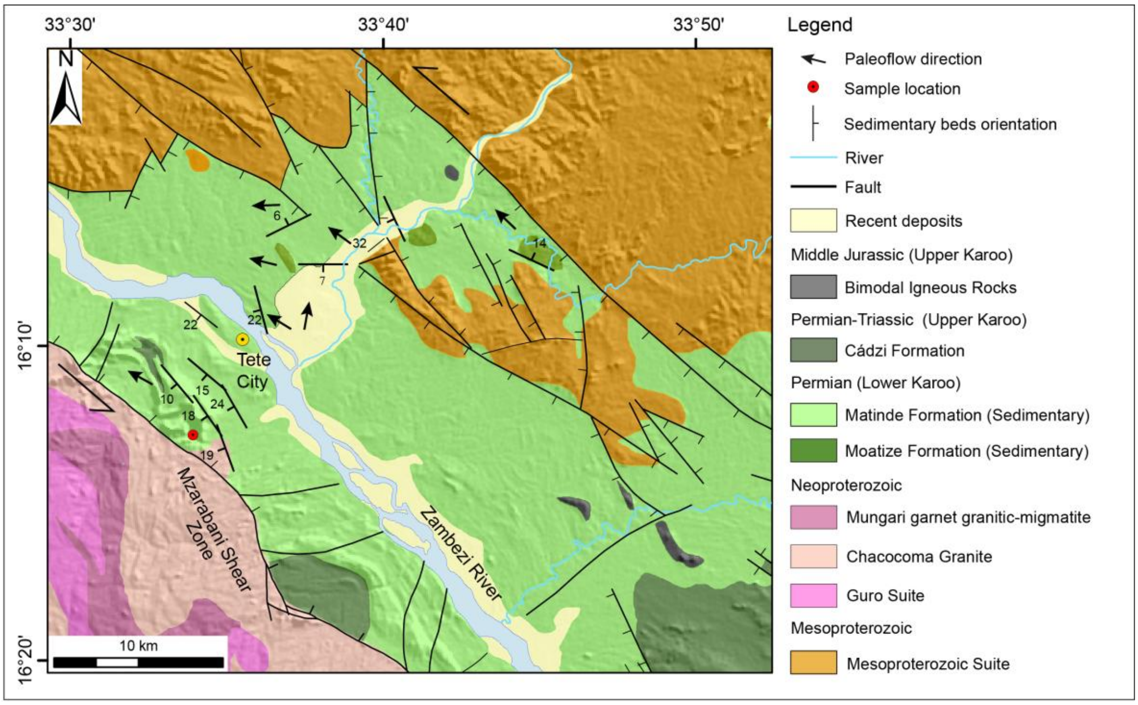

Figure 3: Simplified geological and structural map of the Moatize-Minjova Basin and sample location (modified from Bicca et al., 2017).

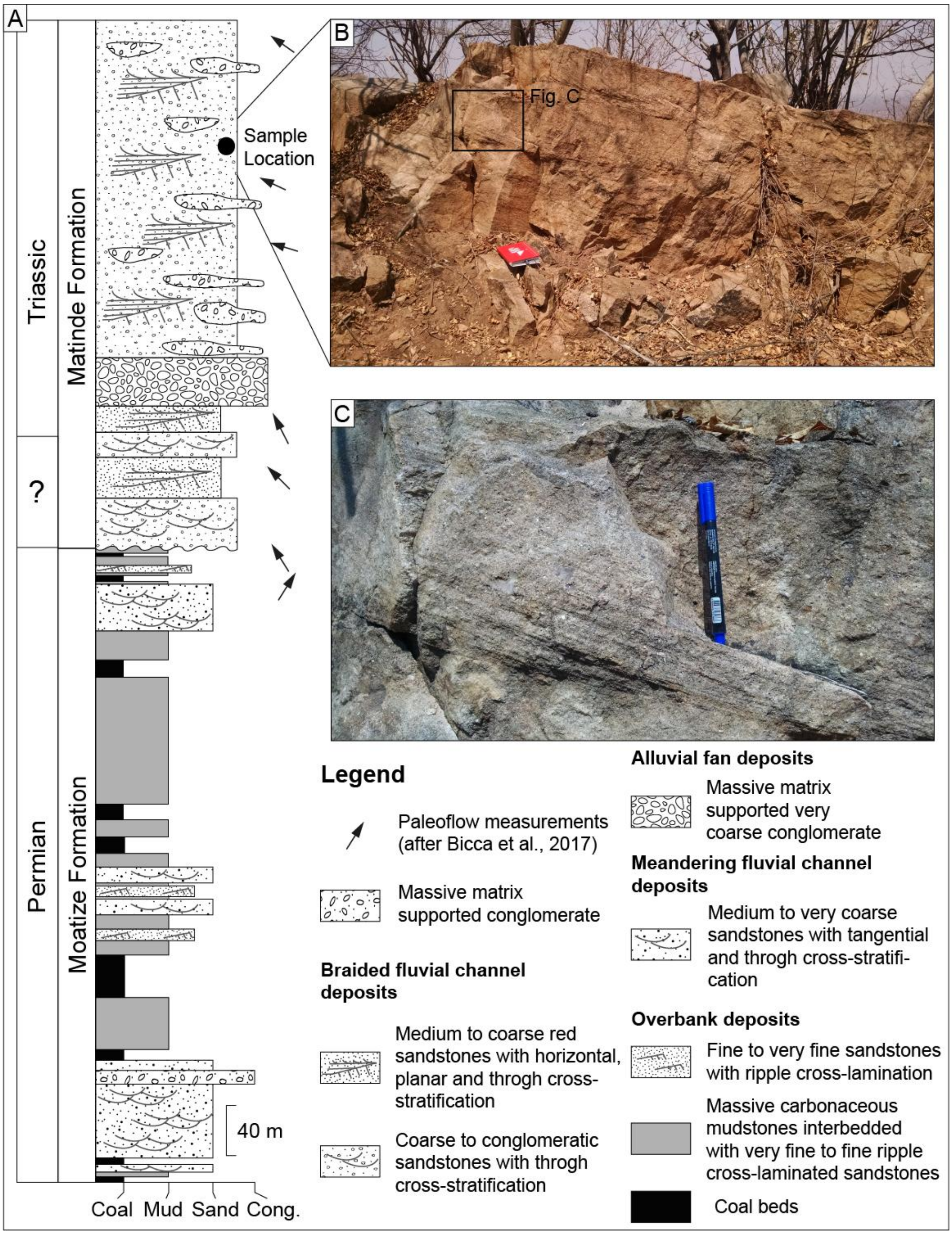

Figure 4: A) Schematic profile of the Moatize and Matinde Formations; B) Through and planar cross-bedded coarse sandstones from where we took the sample; C) detail of the coarse sandstone with quartz clasts (modified from Bicca et al., 2017).

3. Methods

We collected one sample from a coarse-sandstone of Matinde Formation exposed in the study area at coordinates 16°12'22.57"S and 33°34'5.09"E (Fig. 3 and Fig. 4). The outcrop is the top of a 300 m high profile that has thick (1–2 m) sets of coarse-sandstones and conglomerates with a fining upward pattern. This sequence marks an important process of rejuvenation in the source area, as indicated by the Permian-Triassic depositional pattern (Fig. 4) and show excellent levels of outcrop preservation in terms of weathering, tectonic and any hydrothermal processes, difficult to find in the region. In addition, more mature sandstones tend to does not preserve metamorphic overgrowths due to abrasion during transport (Hartmann and Santos, 2004).

Mineral separation was carried out at Rio Grande do Sul Federal University, using standard procedures of crushing the rock, milling and sieving. Zircons were separated using conventional heavy liquids and magnetic procedures, hand-picked and mounted on an epoxy disc, together with CZ3 (564 Ma) zircon standards and polished to expose their internal surfaces.

U-Pb analysis was performed with laser-ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) at São Paulo University. All grains used for zircon dating were imaged with cathodoluminescence to determine their internal structures and crystallization phases (to support spot location and age interpretation). Only zircon grains free of imperfections such as fractures and mineral inclusions were selected for analysis (Fig. 5). The analytical conditions and data reduction for the LA-MC-ICPMS method were identical to those described by Chemale Jr. et al. (2011). Isoplot 3 software (Ludwig, 2003) was used to generate the concordia diagrams and histograms. For the concordia age calculations and frequency histograms, only the analysis with 100 ± 10% of concordance was included. The U-Pb detrital zircon analytical data are show in Table 1. Corrections for common Pb were made using measured ^{204}Pb and the Pb isotopic composition. Results with more than 1% common Pb correction were not use to calculate the ages. Confidence limits (90%) were compiled for pooled ages and one sigma limits for individual zircons. Ages older than 1.5 Ga are express as weighed mean $^{207}Pb/^{206}Pb$ age values, and younger ages are weighed mean $^{204}Pb/^{235}U$ values. The analytical results were compared with the geological, isotopic, and geochronological data available in the literature (Macey et al., 2010; Thomas et al., 2010; Manjate, 2011; Chaúque, 2012; Manjate, 2015; Chaúque et al., 2017).

Table 1: U/Pb data of Matinde Formation

Spot	RATIOS														AGES							
	207/235	1sigma	206/238	1 sigma	coef. corr	238/206	1 sigma	207/206	1 sigma	208/206	1 sigma	Pb total comum %	U ppm	Th/U	$T_{206/238}$	1 sigma	$T_{207/235}$	1 sigma	$T_{207/206}$	1 sigma	Conc. 206/238 207/235	Conc. 206/238 207/206
10.1	0.6295	0.0185	0.0794	0.0008	0.60	12.5913	0.1275	0.0575	0.0017	0.2035	0.0038	0.16	582	0.57	0.493	0.005	0.496	0.011	0.510	0.065	99	96
26.1	0.6363	0.0201	0.0795	0.0014	0.26	12.5722	0.2254	0.0580	0.0020	0.1055	0.0038	0.86	431	0.27	0.493	0.009	0.500	0.013	0.530	0.078	98	93
2.1	0.6239	0.0360	0.0797	0.0012	0.68	12.5430	0.1863	0.0568	0.0035	0.1386	0.0127	0.29	160	0.43	0.494	0.007	0.492	0.023	0.482	0.139	100	102
38.1	0.6404	0.0223	0.0810	0.0014	0.35	12.3513	0.2140	0.0574	0.0022	0.1803	0.0067	0.58	279	0.54	0.502	0.008	0.503	0.014	0.506	0.081	99	99
18.1	0.6429	0.0177	0.0811	0.0014	0.85	12.3291	0.2130	0.0575	0.0017	0.0692	0.0026	0.78	541	0.37	0.503	0.008	0.504	0.011	0.510	0.065	99	98
43.1	0.6592	0.0229	0.0820	0.0009	0.64	12.2003	0.1330	0.0583	0.0021	0.0467	0.0041	0.79	468	0.11	0.508	0.005	0.514	0.014	0.542	0.080	98	93
3.1	0.6695	0.0246	0.0833	0.0010	0.01	12.0082	0.1373	0.0583	0.0022	0.1090	0.0060	0.24	363	0.37	0.516	0.006	0.520	0.015	0.541	0.084	99	95
48.1	0.7159	0.0813	0.0869	0.0021	0.56	11.5019	0.2841	0.0597	0.0074	0.3552	0.0258	1.10	90	0.98	0.537	0.013	0.548	0.048	0.593	0.273	98	90
4.1	0.7180	0.0575	0.0889	0.0017	0.10	11.2453	0.2132	0.0586	0.0051	0.1304	0.0157	0.89	88	0.37	0.549	0.010	0.549	0.034	0.551	0.190	99	99
24.1	0.7374	0.0552	0.0913	0.0025	0.45	10.9587	0.3032	0.0586	0.0051	0.1226	0.0174	2.33	110	0.29	0.563	0.015	0.561	0.031	0.553	0.175	100	101
61.1	0.7512	0.0919	0.0912	0.0028	0.50	10.9672	0.3412	0.0598	0.0086	0.2056	0.0206	0.82	59	0.49	0.563	0.017	0.569	0.056	0.595	0.343	98	94
39.1	0.7609	0.0403	0.0919	0.0020	0.03	10.8827	0.2349	0.0601	0.0035	0.4045	0.0181	0.41	103	1.12	0.567	0.012	0.575	0.023	0.606	0.126	98	93
20.1	0.7574	0.0420	0.0922	0.0022	0.23	10.8506	0.2607	0.0596	0.0038	0.0217	0.0132	0.74	123	0.07	0.568	0.013	0.573	0.024	0.589	0.145	99	96
4.1	0.7812	0.0479	0.0965	0.0017	0.51	10.3590	0.1871	0.0587	0.0041	0.1464	0.0185	0.76	102	0.32	0.594	0.010	0.586	0.027	0.556	0.144	101	106
22.1	0.7790	0.0583	0.0966	0.0024	0.47	10.3558	0.2587	0.0585	0.0053	0.0863	0.0201	0.78	65	0.21	0.594	0.014	0.585	0.032	0.549	0.182	101	108
3.1	0.8077	0.0300	0.0977	0.0012	0.01	10.2398	0.1293	0.0600	0.0024	0.0365	0.0082	0.81	176	0.09	0.601	0.007	0.601	0.017	0.603	0.087	99	99
14.1	0.8353	0.0430	0.0992	0.0019	0.28	10.0815	0.1920	0.0611	0.0036	0.1100	0.0094	0.69	112	0.27	0.610	0.011	0.617	0.023	0.642	0.127	98	94
2.1	0.8201	0.0400	0.0994	0.0015	0.15	10.0562	0.1553	0.0598	0.0033	0.0981	0.0116	0.48	108	0.25	0.611	0.009	0.608	0.023	0.597	0.125	100	102
19.1	0.8399	0.0627	0.0994	0.0026	0.24	10.0605	0.2620	0.0613	0.0053	0.1099	0.0210	0.98	61	0.28	0.611	0.015	0.619	0.034	0.649	0.185	98	94
11.1	0.8281	0.0725	0.0999	0.0029	0.01	10.0060	0.2914	0.0601	0.0067	0.1275	0.0161	1.15	49	0.34	0.614	0.017	0.613	0.039	0.607	0.223	100	101
5.1	0.8876	0.0368	0.1039	0.0014	0.38	9.6246	0.1331	0.0620	0.0029	0.0919	0.0079	0.42	124	0.23	0.637	0.008	0.645	0.020	0.673	0.099	98	94
32.1	1.7145	0.0550	0.1687	0.0030	0.17	5.9278	0.1054	0.0737	0.0025	0.0977	0.0058	0.34	121	0.28	1.005	0.017	1.014	0.021	1.034	0.069	99	97
15.1	1.7167	0.0653	0.1694	0.0035	0.27	5.9019	0.1233	0.0735	0.0032	0.1125	0.0076	0.90	104	0.30	1.009	0.020	1.015	0.025	1.027	0.088	99	98
8.1	1.8024	0.0873	0.1721	0.0026	0.61	5.8089	0.0875	0.0759	0.0040	0.1626	0.0100	0.56	74	0.44	1.024	0.014	1.046	0.031	1.093	0.102	97	93
58.1	1.8008	0.1107	0.1729	0.0037	0.58	5.7848	0.1248	0.0756	0.0053	0.1673	0.0188	0.24	78	0.39	1.028	0.020	1.046	0.041	1.083	0.146	98	94
9.1	1.7779	0.0629	0.1736	0.0021	0.35	5.7613	0.0698	0.0743	0.0028	0.0937	0.0061	0.38	123	0.27	1.032	0.012	1.037	0.023	1.049	0.075	99	98
57.1	1.7523	0.0649	0.1739	0.0027	0.86	5.7502	0.0886	0.0731	0.0031	0.0796	0.0097	1.02	110	0.21	1.034	0.015	1.028	0.024	1.016	0.085	100	101

6.1	1.8105	0.0680	0.1763	0.0022	0.39	5.6726	0.0704	0.0745	0.0030	0.1645	0.0079	1.05	120	0.48	1.047	0.012	1.049	0.024	1.055	0.077	99	99
7.1	1.8444	0.0507	0.1773	0.0018	0.87	5.6397	0.0582	0.0754	0.0021	0.0687	0.0030	0.34	245	0.20	1.052	0.010	1.061	0.018	1.080	0.055	99	97
62.1	1.8698	0.2047	0.1776	0.0059	0.17	5.6315	0.1872	0.0764	0.0103	0.1020	0.0439	1.24	21	0.19	1.054	0.032	1.070	0.073	1.105	0.267	98	95
50.1	1.8397	0.0510	0.1780	0.0024	0.65	5.6189	0.0752	0.0750	0.0022	0.0334	0.0051	0.23	181	0.09	1.056	0.013	1.060	0.018	1.068	0.059	99	98
19.1	1.8481	0.0736	0.1796	0.0039	0.19	5.5687	0.1203	0.0746	0.0034	0.1615	0.0129	0.21	116	0.46	1.065	0.021	1.063	0.026	1.059	0.090	100	100
29.1	1.8922	0.0622	0.1796	0.0033	0.83	5.5674	0.1014	0.0764	0.0027	0.1804	0.0089	0.75	93	0.48	1.065	0.018	1.078	0.022	1.106	0.069	98	96
14.1	1.9051	0.0462	0.1822	0.0031	0.67	5.4895	0.0922	0.0759	0.0020	0.2022	0.0222	0.22	356	0.46	1.079	0.017	1.083	0.016	1.091	0.053	99	98
49.1	1.9065	0.1046	0.1821	0.0030	0.53	5.4906	0.0915	0.0759	0.0044	0.1387	0.0163	0.51	71	0.32	1.079	0.016	1.083	0.036	1.093	0.117	99	98
16.1	1.9308	0.0516	0.1836	0.0032	0.78	5.4460	0.0956	0.0763	0.0023	0.5575	0.0116	0.22	222	1.57	1.087	0.018	1.092	0.018	1.102	0.059	99	98
56.1	2.0298	0.1413	0.1860	0.0045	0.26	5.3754	0.1303	0.0791	0.0063	0.1846	0.0214	1.81	34	0.48	1.100	0.024	1.126	0.048	1.175	0.166	97	93
13.1	2.0193	0.1078	0.1867	0.0031	0.33	5.3561	0.0894	0.0784	0.0045	0.2491	0.0248	0.87	66	0.79	1.103	0.017	1.122	0.036	1.158	0.114	98	95
37.1	1.9935	0.0725	0.1916	0.0037	0.07	5.2193	0.1001	0.0755	0.0030	0.2283	0.0138	0.56	79	0.66	1.130	0.020	1.113	0.025	1.081	0.082	101	104
17.1	1.6549	0.0399	0.1642	0.0027	0.81	6.0887	0.1005	0.0731	0.0019	0.1231	0.0026	0.14	338	0.33	0.980	0.015	0.991	0.016	1.016	0.054	98	96
27.1	2.0292	0.0633	0.1906	0.0034	0.58	5.2472	0.0930	0.0772	0.0025	0.1854	0.0091	0.42	120	0.48	1.125	0.018	1.125	0.021	1.127	0.065	99	99
1.1	1.7282	0.0472	0.1688	0.0017	0.72	5.9229	0.0606	0.0742	0.0021	0.0788	0.0070	0.15	266	0.23	1.006	0.010	1.019	0.018	1.048	0.056	98	95
12.1	1.5501	0.2015	0.1584	0.0051	0.62	6.3144	0.2042	0.0710	0.0107	0.1344	0.0343	2.98	38	0.33	0.948	0.029	0.951	0.079	0.957	0.289	99	99
52.1	1.6287	0.0665	0.1614	0.0027	0.55	6.1942	0.1024	0.0732	0.0033	0.0648	0.0092	0.99	88	0.20	0.965	0.015	0.981	0.026	1.019	0.093	98	94
25.1	0.8448	0.0515	0.0994	0.0026	0.21	10.0585	0.2581	0.0616	0.0043	0.1136	0.0127	0.54	105	0.32	0.611	0.015	0.622	0.028	0.661	0.149	98	92
40.1	1.1581	0.0709	0.1279	0.0021	0.95	7.8210	0.1285	0.0657	0.0042	0.1028	0.0323	2.33	115	0.15	0.776	0.012	0.781	0.032	0.796	0.128	99	97
23.1	1.2064	0.1164	0.1321	0.0047	0.15	7.5683	0.2718	0.0662	0.0077	0.1982	0.0381	1.72	35	0.49	0.800	0.027	0.804	0.054	0.813	0.241	99	98
5.1	1.3690	0.0657	0.1425	0.0020	0.66	7.0161	0.0998	0.0697	0.0038	0.3083	0.0160	0.59	117	0.99	0.859	0.011	0.876	0.028	0.918	0.105	98	93
28.1	1.5429	0.0430	0.1556	0.0026	0.89	6.4265	0.1055	0.0719	0.0021	0.1365	0.0060	1.22	237	0.38	0.932	0.014	0.948	0.017	0.983	0.058	98	94
1.1	0.6319	0.0381	0.0787	0.0014	0.13	12.7088	0.2261	0.0582	0.0040	0.1765	0.0166	2.14	104	0.43	0.488	0.008	0.497	0.024	0.539	0.152	98	90
23.1	0.7111	0.0210	0.0886	0.0011	0.87	11.2915	0.1374	0.0582	0.0020	0.0882	0.0201	0.00	321	0.27	0.547	0.006	0.545	0.012	0.539	0.074	100	101
13.1	1.3414	0.1158	0.1403	0.0047	0.50	7.1285	0.2386	0.0693	0.0066	0.0565	0.0529	1.08	41	0.09	0.846	0.026	0.864	0.049	0.909	0.220	97	93
17.1	1.6238	0.0421	0.1599	0.0019	0.25	6.2524	0.0757	0.0736	0.0022	0.0955	0.0089	0.41	202	0.20	0.956	0.011	0.979	0.017	1.031	0.063	97	92
6.1	1.7018	0.0513	0.1688	0.0020	0.10	5.9225	0.0705	0.0731	0.0024	0.0992	0.0043	0.67	124	0.25	1.006	0.011	1.009	0.019	1.017	0.066	99	98
18.1	1.7540	0.1503	0.1748	0.0059	0.61	5.7213	0.1947	0.0728	0.0080	0.4657	0.0297	0.71	22	1.15	1.038	0.033	1.029	0.058	1.008	0.248	100	103
35.1	0.6166	0.0196	0.0784	0.0013	0.78	12.7473	0.2134	0.0570	0.0019	0.0988	0.0115	19.39	295	0.24	0.487	0.008	0.488	0.012	0.492	0.073	99	99
45.1	0.7426	0.1325	0.0889	0.0032	0.40	11.2456	0.4036	0.0606	0.0125	0.3608	0.0446	1.02	47	0.80	0.549	0.019	0.564	0.080	0.624	0.421	97	88
41.1	0.8053	0.1805	0.0951	0.0042	0.35	10.5179	0.4657	0.0614	0.0159	0.0603	0.0479	7.86	30	0.16	0.585	0.025	0.600	0.104	0.654	0.479	97	89
54.1	1.1280	0.1580	0.1222	0.0046	0.41	8.1854	0.3049	0.0670	0.0107	0.1429	0.0384	1.06	29	0.35	0.743	0.026	0.767	0.074	0.837	0.343	96	88
30.1	1.4999	0.2657	0.1515	0.0087	0.13	6.5997	0.3811	0.0718	0.0156	0.1374	0.0695	7.37	11	0.24	0.909	0.049	0.930	0.110	0.980	0.449	97	92
36.1	1.4758	0.2043	0.1588	0.0071	0.73	6.2978	0.2805	0.0674	0.0130	0.1269	0.0700	3.35	18	0.10	0.950	0.040	0.921	0.083	0.850	0.393	103	111

31.1	1.7561	0.0742	0.1664	0.0035	0.33	6.0102	0.1281	0.0765	0.0036	0.1645	0.0139	0.94	65	0.48	0.992	0.020	1.029	0.028	1.109	0.099	96	89
60.1	1.7743	0.2101	0.1798	0.0060	0.10	5.5615	0.1866	0.0716	0.0103	0.1238	0.0348	6.30	19	0.38	1.066	0.033	1.036	0.077	0.974	0.281	102	109
21.1	1.1320	0.2825	0.1239	0.0095	0.63	8.0688	0.6181	0.0662	0.0210	0.1929	0.0937	3.09	18	0.53	0.753	0.055	0.769	0.128	0.814	0.501	97	92

4. Results

Cathodoluminescence (CL) imaging of 64 zircon crystals (Fig. 6) indicate size variation from 100 to 300 μm, but most crystals are 100–200 μm. Some crystals show rounded hedges, but many have irregular shapes; this is consistent with the immature nature of the coarse-sandstone. Rounding of the crystals was attributed to two processes: i) sedimentary abrasion during transport, and ii) preserved metamorphic rims and overgrowths (Fig. 5). The internal textures of the crystals is very complex, with cores often showing oscillatory zoning, surrounded by one or more metamorphic rims or recrystallized zoned patterns. Sector-zoned, relatively homogeneous grains as well as grains with more complex textures also occur. Chaotic textures are common trends in zircons from granulite facies rocks. Concentric zoning, when present, is rather irregular and resembles only weakly the parallel or regular geometry of zoned magmatic zircon. Distinct age populations could be identifying in the core and in metamorphic rims ranging from Late Mesoproterozoic to Cambrian times (Tab. 1 and Fig. 5).

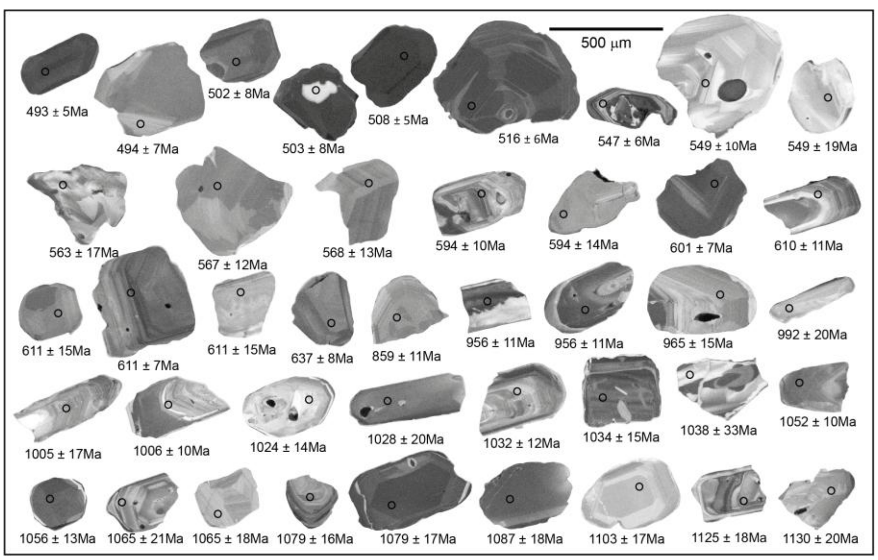

Figure 5: Cathodoluminescence image of some zircon grains that are representative of the analytical results using LA-ICP-MS. The spots and measured U-Pb ages (Ma) are indicated.

The older age component is represented by 19 zircon grains providing Late Mesoproterozoic ages (1,005 ± 17Ma to 1,130 ± 20Ma) with a concordant age of 1040 ± 4.9 Ma (N = 7) (Fig. 6). Th/U ratios of these grains are very distinct ranging from 0.09 to 1.57, which is related to the U content of each zircon grain varying from 22 to 356 ppm (Tab. 1), being the highest Th/U ratios related to an increasing in the U and Th concentrations. The zircons of this population are commonly rounded fragments of crystal, but some preserve part of its prismatic form (Fig. 5). Well-developed thin oscillatory zoning occur in several grains, sometimes surrounding earlier crystallization phases with no internal texture. Homogeneous metamorphic rims are also preserved in a few grains.

A second population of zircon ages constraining the Early-Middle Neoproterozoic times (859 ± 11Ma to 992 ± 20Ma) were identified from 5 zircon grains (Fig. 7), but did not allow to define a concordia age. These grains show distinct internal textures indicating well developed magmatic oscillatory growth in two crystals (Fig. 5). One crystal is prismatic, but with no evident internal texture and one fragment of zircon showing sector-zoning with two clear compositionally distinct areas, probably derived from a high-grade metamorphic rocks (Fig. 5). A last zircon show two homogeneous recrystallization zones around a elongated lighted nucleus evidencing a probable heritage zircon core. Th-U ratios are between 0.20 to 0.99, while the U content range from 65 to 338 ppm (Tab. 1), which we interpreted as magmatic ages, assuming the premises described above.

The younger age component from our data comprises the Late Neoproterozoic – Cambrian ages, from 637 ± 8 Ma to 493 ± 5Ma. This age population is registered in 21 zircon grains that show oscillatory growing and less metamorphic rims. Cathodoluminescence imaging reveals both sector-zoned cores with thin overgrowths and oscillatory zoned cores (Fig. 5). Local zircon resorption and reprecipitation, patchy zoning and fractures disrupting original zoning and filled by zircon with low-trace elements composition (Corfu et al., 2003; Fig. 5) are also observed. Three main peak ages could be distinguished from this age component: (1) from 8 zircon grains we determine a magmatic concordia age of 609.8 ± 3.4 Ma; (2) Six grains define a concordia age of 553.8 ± 3.9 Ma referring to zircons with oscillatory growth; (3) An younger concordant age of 501.6 ± 2.3 Ma constrained from seven zircon grains mark the late high grade metamorphism of the Pan-African Orogeny (Fig. 6). Th-U ratios are between 0.07 to 1.12 while the U content ranges from 47 to 582 ppm (Tab. 1). These concentrations suggest that the ages obtained are mostly magmatic, but a few grains that present Th/U ratios around 0.1, could be related to metamorphic processes involved into their generation (Hartmann and Santos, 2004).

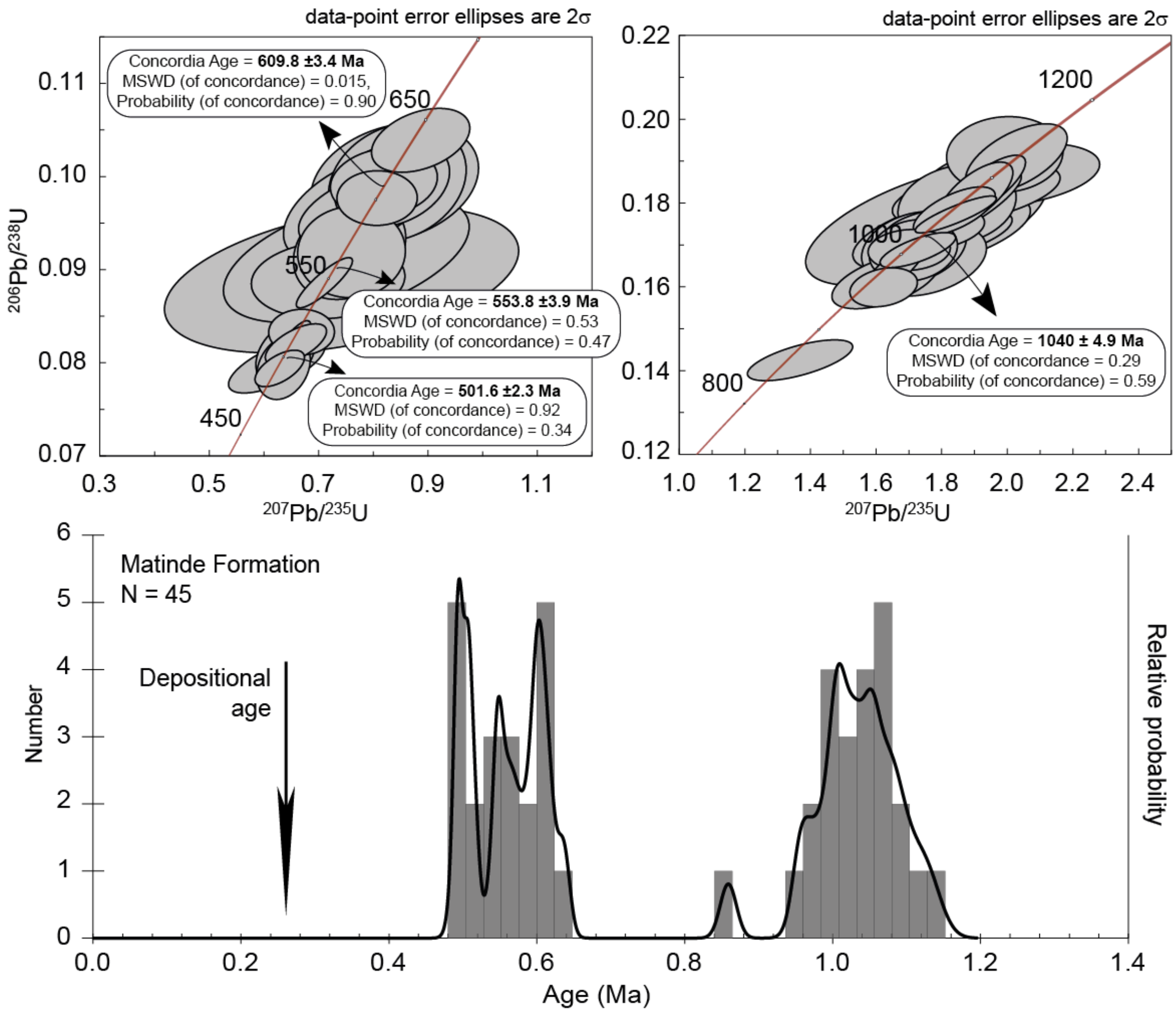

Figure 6: A) Concordia plots ($^{206}Pb/^{238}U$ - $^{207}Pb/^{235}U$) of all Late Neoproterozoic ages, with the position of three determined concordant ages: 501 ± 2.3 Ma (N = 7); 553.8 ± 3.9 Ma (N = 6); 609.8 ± 3.4 Ma (N = 8). B) Concordia plots ($^{206}Pb/^{238}U$ - $^{207}Pb/^{235}U$) of all Late Mesoproterozoic - Early Neoproterozoic ages with the position of one determined concordant ages of 1040 ± 4.9 Ma (N = 7). C) Histogram and relative density plot of all detrital ages obtained in this work.

5. Interpretation

The detrital zircon age spectra observed in the sample showed only older age's with respect to the depositional age that reflect the history of the underlying basement as expected in intracratonic settings (Cawood et al., 2012). Zircon morphology, internal textures and ages provide insights into the geotectonic history of the underlying basement, allowing the definition of four main age groups: i) 1,130-1,005 Ma; ii) 992-859 Ma; iii) 637-563 Ma; and iv) 549-493 Ma. The former and the latter are the most prominent provenances of the Karoo sediments, highlighting two important events of crustal generation, consumption and deformation of Rodinia and Gondwana (Pan-African Orogeny) Supercontinents.

Paleocurrent measurements indicate an N-NW paleoflow for the fluvial sequences of the Matinde Formation (Bicca et al., 2017). Since we collected immature sandstone, the probable source areas are located somewhere in the south of the Moatize-Minjova Basin, less then *ca*.200km (Hartmann et al., 2004) due to the preservation of the metamorphic rims.

The first and older age group reflects the greater crustal component in the north of Mozambique. They mostly reflect magmatic crystallization ages as evidenced by oscillatory grown in the zircon grains, which are a common feature in this population. Late Mesoproterozoic was an important moment of crustal generation everywhere in the distinct terrenes of northern Mozambique. These age spectrum falls in the age range of the Barue Magmatic Arch (SW Nampula; Fig. 7), as also, in the provenance record of the Chimoio-Macossa (SW Nampula) and Mungari nappes, which in turn received sediments from the Báruè Magmatic Arch (Chaúque, 2012).

The ages between *ca*. 950 and 550 Ma do not present very wide distribution and correspond to important periods of crustal geotectonic evolution in the north of Mozambique. Manjate (2011) reports an U-Pb metamorphic age at 956 ± 38 Ma (MSWD = 0.39) for the orthogneisses of SW Nampula and Grantham et al. (2011) found an age of 996.8 Ma ± 3.4 Ma (MSWD = 2.3) for a migmatitic vain of the Chimoio Group (paragneisses of SW Nampula). Similar ages are observed as metamorphic ages around *ca*. 940 Ma in the Unango and Marrupa Complexes (Bingen et al., 2009). Nevertheless, the zircon ages clusters the data of Manjate (2015) for the Guro Suite/Mungari Garnet Granite Migmatite/Chacocoma Granite zircon dating (Fig. 7). These suggests that Early Neoproterozoic population ages probably represents a late magmatic and metamorphic event associated to Rodinia amalgamation processes present in the Mesoproterozoic basement rocks (Jacobs et al., 2008; Macey et al., 2013). On the other hand, the crystallization ages around *ca*. 860 and 820 Ma (GTK Consortium, 2006; Chaúque, 2012; Manjate, 2015) are positioned near a extension tectonic period and emplacement of the protoliths of the Guro Suite, which possess a positive εnd suggesting a strong mantle contribution (Chaúque, 2012) and are related to the breakup of Rodinia Supercontinent. The Mozambique Ocean closed during a protracted period of island-arc and microcontinent accretion between *ca*. 850 and 620 Ma (Fritz et al., 2013).

The ages around *ca*. 630 and 560 Ma refers to distinct events of deformation and magmatism along the north of Mozambique basement. They are registered in the Monapo Klippe (*ca*. 635 Ma), and interpreted as a major episode of granulite-facies metamorphism and crust generation (Macey et al., 2013). SHRIMP zircon data from samples from alkaline intrusions and mafic granulites in the same complex yield crystallization and metamorphic ages of *ca*. 635 Ma and 570-590 Ma, respectively (Grantham et al., 2013).

The Cabo Delgado Nappe Complex (north of the Lurio Belt) was an extended crust that formed adjacent to the Mozambique Ocean and experienced a *ca*. 650–620Ma granulite-facies metamorphism (Fritz et al., 2013). They are also found in the Ocua Complex, which contains high-P granulite boudins dated at 557 ± 16 Ma, evidence for deformation at least until 532 ± 13 Ma and abundant on 612 ± 6 to 504 ± 11 Ma felsic plutons (Norconsult Consortium, 2007). Evidence of the closure of the Mozambique Ocean is present on data from other sections of the East Africa Orogen indicated by accretion of various volcanic arc and microcontinent fragments onto the margin of the Congo-Tanzania Craton between 655 and 610 Ma (Meert, 2003; Collins and Pisarevsky, 2005; Jöns and Schenk, 2008; Bingen et al., 2007). This age population is not strongly impressed in the SW Nampula Complex and Guro Suite/Mungari Garnet Granite Migmatite/Chacocoma Granite although they are present in the individual zircon ages presented by Chaúque (2012) and Manjate (2015), but enough to correlate with our data. Additionally, the provenance analyzes in the Alto-Benfica and Mecuburi Neoproterozoic-Cambrian basins in detrital zircons using the U-Pb method (NE Mozambique, Thomas et al., 2010) indicated a strong contribution of the northern Marrupa and Unango Complexes. The Mecuburi Group present a high contribution of zircon dated at *ca*. 600 Ma however, they are practically absent from Alto-Benfica age populations. The latter, show some ages > 1200 Ma (Thomas et al., 2010), suggesting that the Moatize-Minjova Basin has a distinct provenance, since these ages were not verified in their zircons.

After the events of crustal thickening and klippening resulting from the Pan-African Orogeny (*ca*. 550-480 Ma), the southern region of the Moatize-Minjova Basin probably formed a topographic high along with the entire NE portion of Mozambique. These sites have probably originated the headwaters of the rivers and tributaries that bathed the Proto-Zambezi basin, as suggested by Key et al. (2015) and Bicca et al. (2017). The ages contained between *ca*. 550 and 480 Ma are attributed to magmatic and metamorphic events common in the region due to high-grade metamorphism produced by Pan-African Orogeny and therefore are not good markers for determining sedimentary provenance (Fig. 7).

The concentrations and rates of Th/U of our data compared with a few available data from underlying assemblages interpreted as the main source region for the sediments allow defining some correlations. The NE Nampula Th/U rates are comparable to ours, but Th/U rates of < 0.1 were attribute to a metamorphic origin (Hartmann and Santos, 2004) as also the very high U concentrations (> 1000 ppm) which are reasonable common in that area and were not observed in the zircons from Matinde Formation (Fig. 8). This comparison strengthens the correlation of Matinde Formation sediments with SW Nampula Complex rocks, which has compositional characteristics close to those obtained in the Moatize-Minjova Basin zircons (Fig. 8).

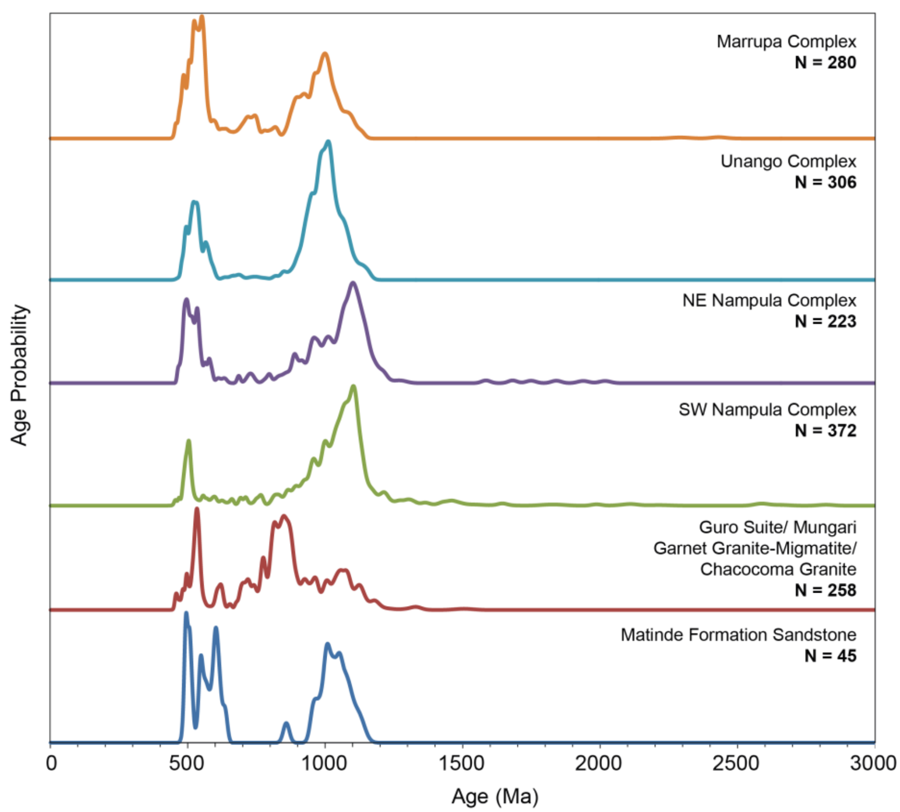

Figure 7: Comparative age graphics of our sandstone sample from the Moatize-Minjova Basin with its probable source area. The data presented in the two below graphic comprise U-Pb dating of zircon grains (LA-ICP-MS and SHRIMP) from the surrounding basement of the basin and were compiled from Chaúque (2012) and Manjate (2015).

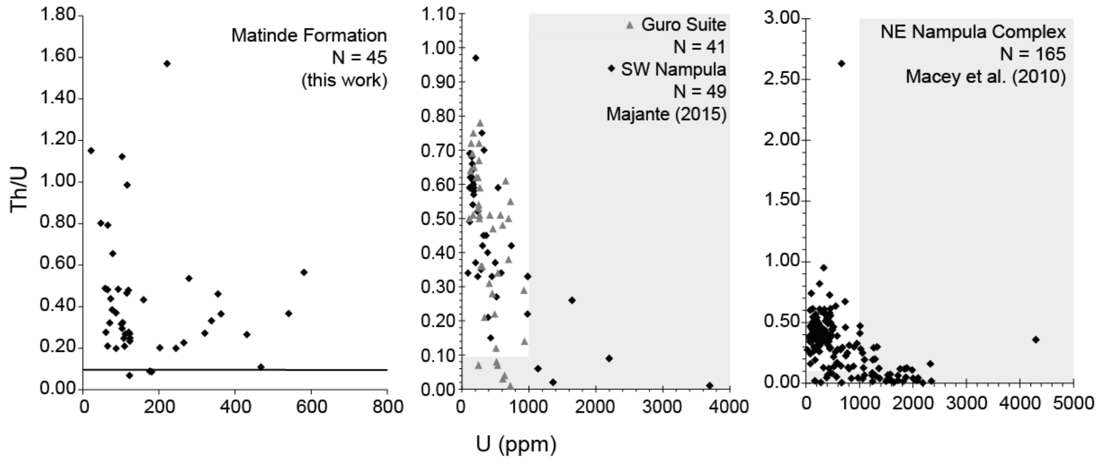

Figure 8: Relationship between U content and Th/U rates for the NE and NW Nampula complexes and of the Guro Suite. The dark line highlights the 0.1 limit of Th/U rates and light gray areas represent the less pronounced concentrations U concentrations in our data.

6. Conclusion

Provenance data from U-Pb LA-ICPMS dating of detrital zircon crystals showed to be as a reliable analytical technique to map sediment source regions from ancient fold and thrust belts underlying sedimentary basin. This information unveils to be relevant to reestablish the paleogeography allowing identifying the probable configuration of basement relief near this intracontinental rift. The choice of the sample in relation to the sand granulometry and tectono-stratigraphic relevance, allow obtaining a more comprehensive information of the magmatic and metamorphic processes in the northern Mozambique. A detailed and systematic analysis of zircon morphology and internal textures, U-Pb ages and Th/U rates allows defining the SW Nampula and the Guro Suite/Mungari Garnet Granite Migmatite/Chacocoma Granite (W-SW of the basin) as the main source areas during Permian Triassic sedimentation in our sample from the Moatize-Minjova Basin. The data revealed a strong contribution of Late Mesoproterozoic ages, which constrain the greater magmatic and metamorphic ages of the basement from northern Mozambique. A Late

Neoproterozoic-Cambrian age population, reflecting magmatic and high metamorphic ages, was provided by the large overprint of the Pan-African Orogeny. Nevertheless, it was the less pronounced zircon grain ages that allowed restricting a narrower source region.

The ages between ca. 950 Ma to 550 Ma are not prominent in northwestern Mozambique basement rocks, especially ages around ca 630-600 Ma. This moment refer to a distinct period of high-grade metamorphism and little magmatism associated with the closure of the Mozambique Ocean and mostly preserved in Cabo Delgado, Mugeba and Monapo Klippens of NE Mozambique. However, they are present as individual zircon ages in the SW Nampula Complex and Guro Suite/Mungari Garnet Granite Migmatite/Chacocoma Granite associations, which must have being the major source area for the Moatize-Minjova Basin during Permian-Triassic sedimentation. The ages between *ca*. 950 and 820 Ma are also well documented in the established provenance region.

Further investigations are needed to improve our data and map local and regional variations in provenance pattern in different stratigraphic levels and sites in all the Karoo basins from northern Mozambique. These would allow a more precise definition of paleogeomorphology evolution of the Precambrian-Cambrian basement rocks through Phanerozoic.

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Mesozoic-Cenozoic Denudation History of NW Mozambique Orogenic Belts by Apatite Fission Track Thermochronology: Implications on Rift Evolution Across Southeast African Margin

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Highligths

1 - Fanerozoic compressive/extensional tectonics affect the NW Mozambique Orogenic Belts;

2 – Differential denudation controlled landscape evolution in NW Mozambique basement;

3 – Jurassic-Cenozoic denudation patterns induced by the Africa-Antarctica rifting;

4 - Dynamic topography influenced Cenozoic denudation rates in NW Mozambique;

Abstract

The southern African plate has underwent several processes of horizontal and vertical stress since Permian times attributed to Gondwanides orogenesis and to mantle plumes upwelling from the Gondwana separation stages, respectively. Since about 30 Ma the plume related to the East Africa Rift system affects the NE Africa leading to the development of topographically high lands affecting denudation history in all region.

The NW Mozambique central apatite fission track ages range from Mesozoic to Cenozoic times and an accumulated denudation thickness of about 2 - 3.5 km since Upper Triassic times. The very early denudation stages of NW Mozambique were marked by very low and local denudation rates (1-10 m/Ma) reaching about to 500 m thick of eroded material until Lower Cretaceous. The larges amonts have being eroded from since Lower Cretaceous with rates of 3-17 m/Ma until Middle Paleocene when high denudation rates of 31-47 m/Ma bring the samples to the present conditions.

The early cooling events are associated with erosion produced by extensional / transtractive processes associated with the early break-up stages of Gondwana recorded in several rift basins with thick volcano-sedimentary sequences from Karoo Supergroup. This period also marks the drift of Madagascar through the Davie Fracture Zone from the coast of Tanzania to the coast of Mozambique and the opening of the Mozambique and Somalia basins. The Upper Jurassic and Upper Cretaceous were a period of great development of the Indian ocean and the start of the N-S drift of Antarctica in relation to the African plate marked in most of the maximum paleotemperatures observed in the region.

From Lower Cretaceous to Paleocene high amounts of denudation was attributed to the development of the African margin and the reconfiguration of inland drainage patterns. A significant increase of the cooling rates (1.17 to 0.88 °C/Ma) implying in the

denudation of about 1.5 to 2 km thick from the beginning of the Neogene to the Recent times. These cooling event was related to dynamic topography induced by the East African Rift mantle plume upwelling, which has been active since the Paleogene period.

Keywords: Apatite Fission Track, NW Mozambique, Denudation rates, East Africa Rift System, Gondwana break-up

1. Introduction

The architecture of the continental margin of northern Mozambique shows a close relationship to pre-existing Pan-African structures of the East African–Antarctic Orogen (Jacobs and Thomas, 2004; Fig. 1A) which plays an important role in margin configuration and landscape evolution (Emmel et al., 2011). Several crustal readjustments were observed during Phanerozoic period registered as brittle/ductile structures and sedimentation patterns all over south-central Africa (Catuneanu et al., 2005). Gondwana break-up was preceded by intracontinental Permian-Triassic rifting, marked by the deposition of thick sequences of Karoo Supergroup along south-central Africa (Catuneanu et al., 2005; Bicca et al., 2017), ending with a magmatic event (basalt flows) that took place during the final phase of Gondwana stability between 205 and 175 Ma (Salman and Abdula, 1995). After that, the opening of the Indian Ocean sea floor was marked by the southward drifting of the East Antarctica/Madagascar/India Seychelles block guided by the Davie transform fault (Fig. 1B) away from East Africa between *ca*. 158 and 119 Ma (Salman and Abdula, 1995; Emmel et al., 2014).

The ongoing of Gondwana break-up led to the high denudation rates on the East Africa - Antarctica Orogen (Daszinnies et al., 2009; Emmel et al., 2011; Emmel et al., 2014; Bauer et al., 2016) and provide the development of distinct onshore and offshore basins along east Africa passive margin. These basins are mostly filled with sediments discharged since Jurassic times (post-Gondwana disruption) over Karoo igneous rocks (Salman and Abdula, 1995; Reeves, 2000; Mahanjane, 2012; Castelino et al., 2015).

The study of exhumation and landscape evolution of Precambrian belts using low temperature thermochronological methods has become a robust tool for the improvement of regional tectonic models. With this in mind we used the apatite fission-track dating method to reconstruct the low-temperature cooling history (120–60 °C) of the Precambrian basement rocks of northwestern and central Mozambique (Fig. 1C). The aim of this study was to identify distinct denudation patterns on the hinterland determining the thermal ages and denudation rates of the Precambrian basement associations which contributed to sedimentation of intracratonic rift basins and with the depositional history in the north of Mozambique Basin. Therefore, we collected 27 rock samples from Mozambican shield, distributed comprehensively in the whole area in order to understand all regional structures and geotectonic domains identifying all differential denudation patterns.

2. Geological Settings

The northern and central region of Mozambique comprises a wide range of Precambrian and Cambrian igneous and metamorphic rocks formed in two distinct orogenic periods concerning the formation of the Rodinia and Gondwana Supercontinents (Norconsult Consortium, 2007). These associations can be subdivided into a northern, central and a southern provinces, by a series of E-W, N-S and NW-SE ductile crustal scale structures reactivated in a brittle regime during the Phanerozoic, caused by far compressive stress fields in the south-southwestern margin of Gondwana

(Fig. 1C; Castaing, 1991; Salman and Abdula, 1995; Norconsult Consortium, 2007; Bicca et al., 2017).

The south and central provinces are delimited by an ENE-trending structure attributed as a probable southern continuation of the Lurio Belt and the Sanangoe Shear Zone (Fig. 1C) (Norconsult Consortium, 2007; Jacobs et al., 2008; Viola et al., 2008; Bingen et al., 2009; Ueda et al., 2012). The ENE-trending structure converge southwards and mark the tectonic contact between the Southern Nampula Complex and the Kalahari Craton associations (Chaúque et al., 2017).

In the central area there are mostly Neoproterozoic ortho- and paragneisses which protoliths are related to juvenile magmatism of Rodinia break-up and marginal sedimentary basins deformed and thrust during Pan-African Orogeny (Chaúque, 2012; Manjate, 2015). These associations are surrounded by the sequences of the Karoo Supergroup (Late Carboniferous - Middle Jurassic) that comprises continental sediments and a bimodal magmatism erupted between 195-180 Ma attributed to an early aborted stage of Gondwana breakup (Salman and Abdula, 1995; Reeves, 2000) and younger igneous and sedimentary sequences related to the post-break-up period (Late Jurassic - Recent). They are hosted into E-W and NW-SE rift basins that compound the Zambezi Valley basins drained by the Zambezi River and its tributaries comprise one of the greater actual fluvial systems of Africa (Castaing, 1991; Norconsult Consortium, 2007; Fernandes et al., 2015; Bicca et al., 2017). The Zambezi delta is responsible for carry sediments into the offshore Mozambique Basin (Fig. 1B).

The Sanangoe Shear Zone (SSZ) cut off the study area over a distance of about 350 km (Fig. 1C) and represents a probable Pan-African connection between West and South Gondwana (Fig. 1A; Macey et al., 2013). In the north of this structure occur the Southern Irumide Belt (Fritz et al., 2013) comprising a large land mass of

Mesoproterozoic association intruded by Late Neoproterozoic granitoids and structurally overprinted by Pan-African Orogeny. Just south of the Sanangoe Shear Zone there is a large and merely NW-SE elongated segment of the Southern Irumide Belt that corresponds to a stratiform gabbro-anorthositic association tectonically transported with a SE-vergent during Pan-African Orogeny.

The great structures were affected by brittle reactivations under a sinistral transtensional regime induced by compressive stress fields in south-southwest Gondwana margin propagating throw NW-SE Zambezi pre-transform fault system from Late-Carboniferous to Middle Triassic. These reactivations are registered by periods of intense subsidence in the related rift basins generating great accommodation space for sedimentation and controlling depositional patterns and Mesozoic magmatic events (Castaing, 1991; Bicca et al., 2017). After that, the Gondwana break up led to large sedimentation patterns and tectonics within the extensional sedimentary basins along the east African margin basins which mostly show a continuous post-Jurassic record of sediment deposition (Salman and Abdula, 1995), reflecting high denudation histories in the onshore Mozambique basement (Salman and Abdula, 1995; Reeves, 2000; Mahanjane, 2012; Castelino et al., 2015).

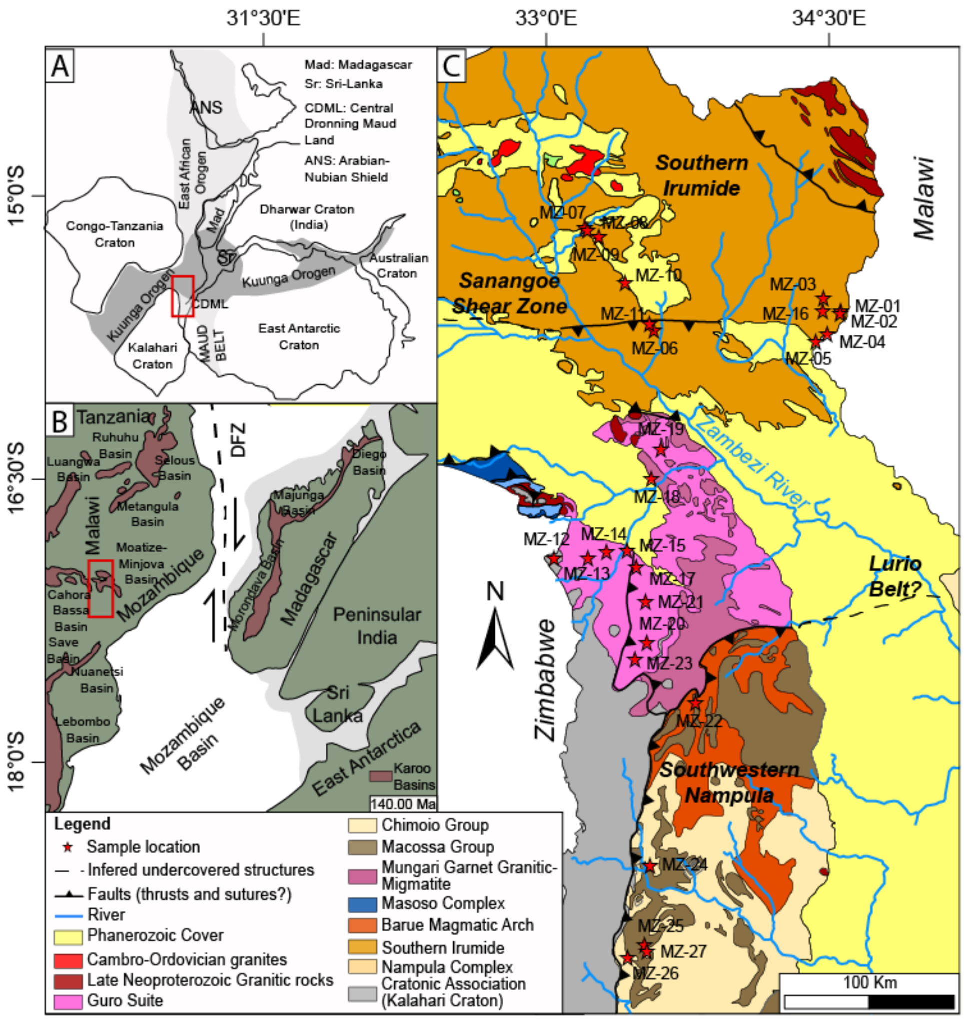

Figure 1: A) Reconstruction of Gondwana during the Cambrian after Meert (2003), with the locations of the East African Orogen and Kuunga Orogen shown. B) Gondwana at *ca*. 140 Ma after the initial break-up between Madagascar and East Africa with Karoo basins of East Africa and Madagascar (after Emmel et al., 2014). C) Simplified geotectonic map of northwestern and central Mozambique with sample location (After Norconsult Consortium, 2007 and Macey et al., 2013).

The Mozambique Basin (MB) covers the onshore and offshore parts of central and southern areas of the Mozambique margin (Fig. 1B). The MB comprises one of the oldest extensional sedimentary basins developed along the eastern African margin and the stratigraphic record of the basin is dominated by marine deposits changing gradually from deepest to shallower through time (Castelino et al., 2015). This basin registers a Mesozoic sedimentation of 5-10 cm/kyr and 1-3 cm/kyr rates during Paleogene being the former associated with high subsidence rates in the basin until Early Cretaceous times. The decrease in sedimentation rates from *ca*. 140 Ma until *ca*. 90 Ma is attributed to tectonic uplift in the onshore African basement which in consequence led to its rapid denudation increasing in the sediment influx into the basin until *ca*. 60 Ma. This uplift would be related to an epeirogenic event with Kimberlite emplacement in the African continent (Patridge and Maud, 1987). Another period of low sedimentation rates occur in the Low Paleogene attributed to a sediment-starved basin during a relative quiet tectonic phase onshore, but a tectonic uplift in the onshore basement around 30 Ma leading to another fast exhumation period onshore high sedimentation rates until Quaternary (Castelino et al., 2015).

2.1 Thermochronological Constraints

In the NW region of Mozambique apatite fission track (AFT) data are restricted to the Moatize-Minjova Basin which hosts the volcano-sedimentary sequences of Karoo Supergroup and also younger volcano-sedimentary sequences (Fig. 2). Four samples from two wells (*ca*. 500 m each) of the sedimentary rocks of Karoo Supergroup were analyzed providing a geothermal paleogradiente of 40 ° C/ km and apatite fission track ages between 146 to 84 Ma (Ferrnandes et al., 2015). According to the models, peak burial temperatures were attained shortly after deposition (3-10 Ma) and indicates two episodes of cooling and exhumation. The first between 240 and 230 Ma implying 2500 and 3000 m of denudation, while the second from 6 Ma onwards implying 1000 and 1500 m of denudation. The first denudation period was attributed to tectonic reactivation related to the Cape Fold Belt in South Africa and the latter to the southward propagation of the East African Rift System into Mozambique (Ferrnandes et al., 2015).

On the other hand, in the NE Mozambique there are a large spectrum of thermochronometric data for the basement provinces north and south of the Lurio Belt (Fig. 2; Daszinnies, 2006; Daszinnies et al., 2009; Emmel et al., 2011; Bauer et al., 2016). According to these data the region underwent differential post-orogenic thermal history (Emmel et al., 2011) as defined from titanite, zircon and apatite fission track data. The first two fission track methods provided ages north of the Lurio Belt ranging between *ca*. 578 Ma and 310 Ma, while in the south they are constrained between *ca*. 460 Ma and 219 Ma. Apatite fission track analisys from samples in the north provide ages between *ca*. 326 Ma and 91 Ma contrasting with younger ages to south (147 to 59 Ma; Fig. 2), suggesting that the southern province experience highest exhumation rates during Gondwana break-up. Thermal ages determine that the northern basement characterize rapid post orogenic cooling and exhumed to present levels during the Paleozoic, although the southern basement only underwent slow post-orogenic cooling. (Emmel et al., 2011).

Aditionally, thermal activitie during Cretaceous times was also described by Eby et al. (1995) studing the Cretaceous Chilwa Alkaline Province of southern Malawi (Fig. 2). These authors presented K-Ar in amphibole and titanite fission-track ages indicating that igneous activity occurred in distinct periods starting at *ca*. 133 Ma with thermal igneous activity ending at *ca*. 113 Ma with the emplacement of large syenite-peralkaline granite plutons. The apatite fission-track ages and track-length measurements indicated that the emplacement of the large syenite-granite pluton caused local doming, leading to a rapid exhumation rate. However, more distal plutons show a slower cooling rate, suggesting that they were on the flanks of the local uplift and more deeply buried. These authors interpreted the Chilwa magmatism produced by crustal extension which reactivate pre-existing orogenic anisotropies leading to decompressional melting.

Similar K-Ar ages are described by alcaline rocks in NW Mozambique lying between *ca*. 106-166 Ma (GTK Consortion, 2006).

Further north of the study area, Van der Beek et al. (1998) identified from AFT data, fast cooling and denudation processes on the flanks of Malawi and Rukwa rifts (Fig. 2) during the periods of 250-200 Ma, *ca*. 150 Ma and ≤ 40-50 Ma. These present correlation with different sedimentation and rifting processes in the basin associated to the rift, where erosion, tectonic and isostatic rebound would be responsible for the reconfiguration of the surface during these events. The first interval corresponds to the final processes of erosion and deposition of the Karoo Supergroup, while in ca. 150 Ma occurs a reactivation of the rift separating Gondwana. Finally, the event between ≤ 40-50 Ma was interpreted as the result of the flexural isostatic response of the lithosphere to extensional unloading during rifting.

Through the Limpopo Belt (at the south of the study area, Fig. 2; Belton and Haab, 2010) extensive regions experienced kilometer-scale exhumation at around 130 Ma and 90 Ma (Fig. 2). These period maks the strike–slip motion of the local fault patterns in this region due to the breakup of Gondwana as also igneous intrusions at *ca*. 120 Ma and *ca*. 90 Ma and demonstrated that the sedimentation and subsidence rates on the Mozambique margin are in agreement with this data.

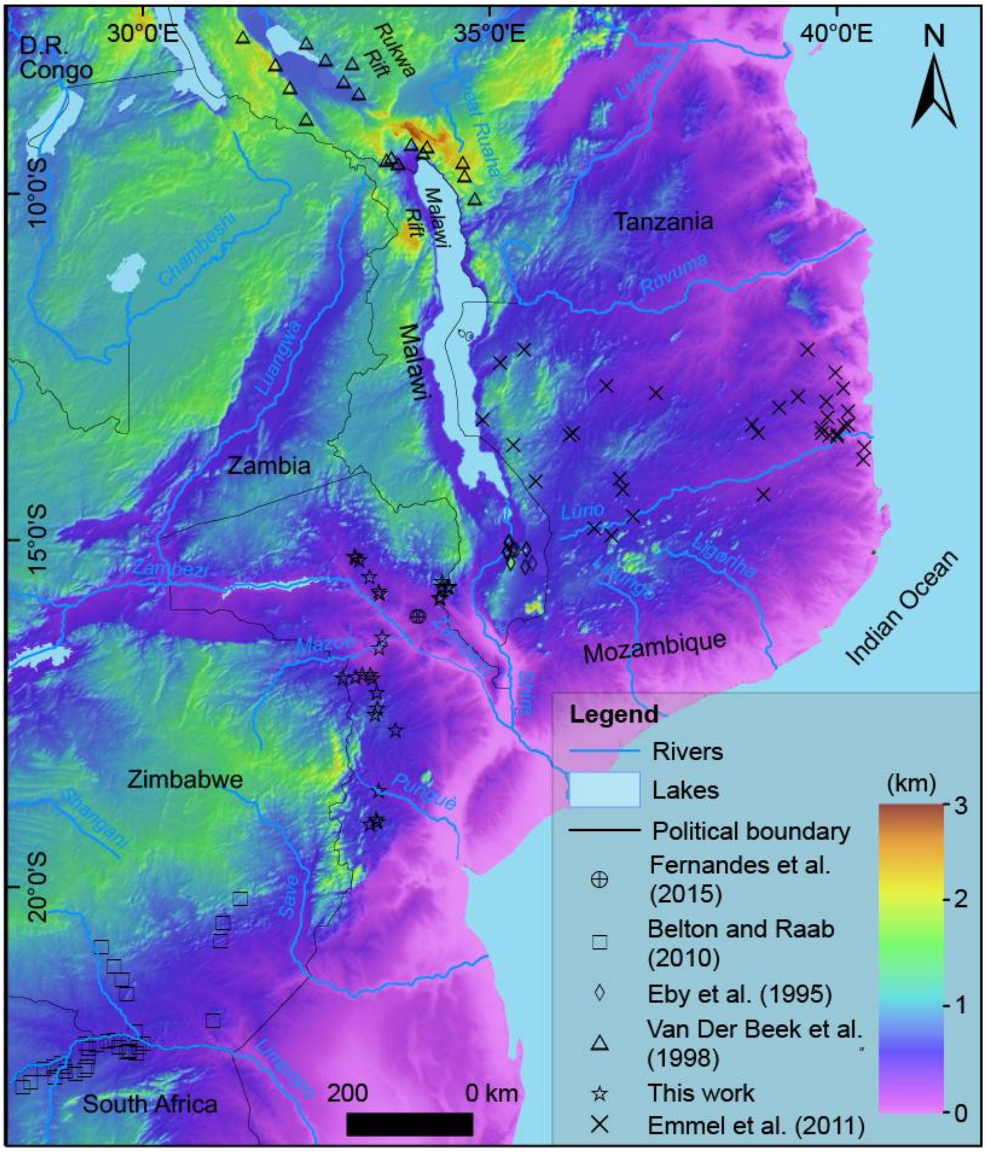

Figure 2: Geomorphological map (Jarvis et al., 2008) of central-eastern Africa with the sample locations for this study and previous works.

3. Methods

We have applied apatite fission track thermochronology technique on 27 samples from Precambrian basement rocks of NW Mozambique assemblages as indicated in Figure 1, and their lithological characteristics are listed in Table 1. The samples were collected in an area that comprehensively covers the main tectonic domains of the northwestern and central regions of Mozambique at distinct altitudes ranging from 217 to 843 m (Tab. 1 and Fig. 3A).

The analytical procedures were performed at Rio Grande do Sul Federal University. The apatite grains were concentrated by conventional magnetic, heavy liquid and hand-picking techniques and mounted in epoxy resin. Afterwards, the mounts were polished and etched, using 5.5 M HNO_3 at 21 ºC for 20s to reveal the spontaneous fission tracks (Ketcham et al., 2007). The apatite mounts were covered with mica sheets to obtain the fission track ages using the external detector method (Gleadow, 1981). Neutron irradiation was performed at the FRM-II reactor in Garching (TU München, Germany). After irradiation, the mica detectors were etched with 48% HF for 18 min to reveal the induced fission tracks.

Fission-track counting was performed with a Leica DM6000 Microscope at 1000x magnification. The fission track ages were calculated using the zeta calibration approach (Hurford, 1990) with CN5 dosimeter glass and the Durango apatite age standard. At least 20 grains were counted per sample; while 100 horizontal confined tracks were measured for the track length distribution (Gleadow et al., 1986; Gallagher et al., 1998), as its orientation relative to the c-axis. Commonly a hundred or more confined tracks were observed and measured in the samples, but some did not have the same abundance. Yet we decided to retain them nonetheless due to their agreement with the nearby samples that do have good-quality measurements. The ages are expressed as central ages with percent variation (Galbrait and Lasllet, 1993). Throughout this study, fission track age errors are quoted at the 1σ confidence level and were derived by the conventional method (Green, 1981). For each apatite grain analyzed, a mean value for the kinetic parameter Dpar (Donelick et al., 2005) was determined from five measurements. The $\chi 2$ -squared test was used to quantify age homogeneity (Galbraith and Laslett, 1993) using the software “RadialPlotter” (Vermeesch, 2009).

Thermal history modeling was carried out using the QTQt software (Gallagher, 2012) with the multi-kinetic annealing model of Ketcham et al. (2007). The priors on the general time-temperature were set by the software based on the ages observed in each sample. Each inversion model was run at 100,000 Burnin and 100,000 Post-burn-in iterations to provide more stable solutions (see discussion in Gallagher, 2012). Denudation histories were based on geothermal gradients estimated for the African plate. We assume a constant and linear geothermal gradient over geological times and suppose that the geothermal gradient is linear (25 °C/km; Martinelli et al., 1995).

4. Results

AFT ages and confined mean track length (MTL) measurements from the basement samples are presented in Table 1. The central AFT ages do not present a clear correlation with the altitude sampled and no vertical profile match was obteined, suggesting that these samples have experienced a complicated thermal history (Fig. 3A). The mean confined fission track lengths against the AFT ages houfly present a boomerang shape (Fig. 3B) indicating differential denudation patterns (Gallagher and Brown, 1997) as also medium to high standard deviation distributions (Fig. 3C) suggesting that all samples register a long residence time within the partial annealing zone.

Broadly speaking, AFT central ages (Table 1; Fig. 4A) measured from the basement rocks ranges from Middle Triassic (225 ± 15 Ma) to Upper Cretaceous (83 ± 9 Ma) and the mean confined track lengths obtained from 27 samples range from 9.67 ± 0.52 μm to 13.13 ± 0.16 μm, with track length distributions predominantly unimodal. All central AFT ages passed in the $\chi 2$ indicating one age population. The Dpar values (Table 1 and Fig. 3D) indicate a reasonably similar chemical compositions (> 1.75 μm) and relatively chlorine-rich apatite grains with a higher resistance to annealing (Donelick et al., 2005).

The oldest ages are dominantly located at the extreme northwest of the area (Fig. 4A) referring to the South Irumide Belt region (mostly NW), also presenting the smaller lengths measured (*ca*. 10 µm; Fig. 3C and 4A). Nevertheless, the largest lengths (> 10 µm) occur around the regional structures, predominantly in the southern region (Southwest Nampula Complex). This brief variation in the confined track lengths indicates that samples near the structural trends are fastly denuded.

Thermal history models for samples of the northernmost area were modeled in three major groups being one to the northeast and the other two to the northwest. The choice of the samples to be grouped was based mainly on the obtained results in their individual thermal histories and their geographical position (Fig. 4). The other samples were also pooled based on the same principles as described below.

Samples from Southern Irumide NE-SW transect (Fig. 1C; Fig. 4 and 4A) near the East African Rift System, indicate a maximum paleotemperature of 99 °C at 136 Ma and show a slow cooling pattern until 10 Ma at a temperature of 64 °C (Fig. 4 and 4A). Thereafter, the samples soffers a rapidly cooled to present surface conditions. On the other hand, the samples of the Southern Irumide north and NW-SE transect (Fig. 1C) record two distinct cooling behavior. Samples MZ-7 and MZ-8 (Fig. 4, 4B and 4C) show the oldest AFT ages of the whole area (225 ± 15 Ma and 216 ± 15 Ma, respectively) and indicate a very long time of residence into the partial annealing zone with moderate reduced mean fission trak length of 9.96 ± 0.24 µm and 10.86 ± 0.16 µm, respectively. Accelerated cooling until present day surface conditions was only acheaved in the latter *ca*. 50 Ma.

Table 1: Apatite fission track data from the northwestern Mozambique.

Sample	Elevation (m)	Rock type	N	ρs (Ns) ($x10^5$)	ρi (Ni) ($x10^5$)	ρd (Nd) ($x10^5$)	P (χ2) (%)	U Content (ppm)	Age* ± 1σ (Ma)	Dpar (μm)	n	Mean track length (μm) ± 1σ	Std. Dev. (μm)
MZ-01	843	Tonalitic Gneiss	20	27.2 (471)	39.0 (674)	9.30 (9302)	98.0	53.2	106 ± 10	2.50	113	10.75 ± 0.18	1.89
MZ-02	801	Tonalitic Gneiss	20	6.36 (238)	10.4 (390)	9.30 (9302)	100.0	14.2	94 ± 10	2.46	92	11.79 ± 0.20	1.92
MZ-03	822	Tonalitic Gneiss	20	7.25 (356)	11.6 (572)	9.30 (9302)	81.0	15.9	97 ± 10	2.76	100	11.69 ± 0.24	2.37
MZ-04	637	Tonalitic Gneiss	20	13.2 (583)	21.7 (955)	9.30 (9302)	72.0	29.6	97 ± 10	2.23	127	10.59 ± 0.18	2.08
MZ-05	451	Metagabbro	17	11.2 (126)	9.38 (106)	9.30 (9302)	100.0	12.8	188 ± 14	2.57	31	9.67 ± 0.52	2.89
MZ-06	427	Milonite	20	8.61 (124)	13.5 (195)	9.30 (9302)	87.0	18.5	109 ± 10	2.48	100	10.70 ± 0.22	2.20
MZ-07	451	Gabbro	20	21.3 (494)	13.1 (305)	8.14 (16276)	48.0	20.5	225 ± 15	2.16	102	9.96 ± 0.24	2.40
MZ-08	456	Monzogranite	20	26.6 (705)	15.9 (421)	8.14 (16276)	88.0	24.8	216 ± 15	1.79	108	10.86 ± 0.16	1.66
MZ-09	487	Monzogranite	20	21.0 (1791)	26.1 (2223)	8.14 (16276)	0.0	40.7	111 ± 11	2.36	30	11.64 ± 0.46	2.53
MZ-10	492	Garnet mafic granilite	20	10.2 (423)	8.07 (335)	8.14 (16276)	40.0	12.6	183 ± 14	2.15	13	9.86 ± 0.67	2.42
MZ-11	419	Monzogranite	20	31.3 (1100)	30.9 (1089)	8.14 (16276)	0.0	48.3	147 ± 12	2.36	39	10.43 ± 0.34	2.10
MZ-12	611	Tonalitic-throndjemitic gneiss	20	19.9 (299)	24.0 (360)	9.30 (9302)	96.0	32.8	124 ± 11	2.58	100	12.55 ± 0.16	1.56
MZ-13	482	Tonalitic-throndjemitic gneiss	20	15.5 (163)	17.0 (179)	9.30 (9302)	97.0	23.3	136 ± 12	2.30	46	11.63 ± 0.30	2.03
MZ-14	452	Tonalitic-throndjemitic gneiss	20	14.8 (124)	18.5 (155)	9.30 (9302)	100.0	25.2	119 ± 11	2.36	56	12.20 ± 0.16	1.20
MZ-15	284	Sienogranitic-Gneiss	20	7.60 (136)	9.72 (174)	9.30 (9302)	99.0	13.3	129 ± 11	2.70	57	11.33 ± 0.23	1.74
MZ-16	718	Quartz Diorite	20	11.9 (179)	14.0 (212)	9.30 (9302)	100.0	19.2	127 ± 11	2.27	103	11.95 ± 0.17	1.72
MZ-17	462	Granite-Gneiss with garnet	20	26.5 (459)	32.2 (557)	9.30 (9302)	99.0	44.0	125 ± 11	2.14	100	12.49 ± 0.18	1.79
MZ-18	217	Tonalitic Gneiss	20	10.1 (325)	10.3 (331)	9.30 (9302)	80.0	14.0	153 ± 12	2.87	109	11.50 ± 0.18	1.91
MZ-19	314	Tonalitic Gneiss	20	11.3 (263)	14.8 (346)	9.30 (9302)	69.0	20.3	123 ± 11	2.97	102	12.52 ± 0.18	1.85
MZ-20	627	Gn. Sienogr.	20	37.9 (629)	52.3 (868)	9.30 (9302)	100.0	71.4	108 ± 10	2.56	100	11.94 ± 0.15	1.48
MZ-21	591	Leucogranite	20	28.2 (463)	37.4 (613)	9.30 (9302)	90.0	50.4	120 ± 11	1.94	101	9.77 ± 0.16	1.58
MZ-22	640	Granite	20	18.2 (329)	24.5 (444)	9.30 (9302)	100.0	33.5	113 ± 11	2.64	100	13.13 ± 0.16	1.56
MZ-23	784	Granite-gnaisse	20	16.3 (294)	19.2 (346)	9.30 (9302)	79.0	26.2	130 ± 11	2.24	27	11.99 ± 0.40	2.09
MZ-24	484	Granite	20	5.36 (105)	5.61 (110)	9.30 (9302)	98.0	7.7	150 ± 12	2.15	21	12.38 ± 0.39	1.78

MZ-25	607	Ortogneiss	20	17.5 (307)	25.5 (447)	9.30 (9302)	100.0	34.9	104 ± 10	2.80	100	12.79 ± 0.17	1.71
MZ-26	644	Ortogneiss	20	8.09 (161)	12.1 (240)	9.30 (9302)	94.0	16.5	108 ± 10	2.24	62	11.67 ± 0.18	1.44
MZ-27	654	Ortogneiss	20	18,9 (347)	35.0 (644)	9.30 (9302)	96.0	47.8	83 ± 9	2.33	102	11.91 ± 0.17	1.76

N: number of grains analysed to determine track densities; ρs: measured spontaneous track density; NS: number of spontaneous tracks counted ; ρi: measured induced track density; Ni: number of induced tracks counted; ρd: track density measured in external detector adjacent to glass dosimeter during irradiation; Nd: number of tracks counted in determining ρd ; P (χ2): probability of obtaining observed χ2 value for n degrees of freedom (n = number of crystals -1); n: number of confined tracks lengths measured. * Apatite ages calculated using a zeta of 320.2 for CN5 glass on German reactor. Analyst: M.M.Bicca.

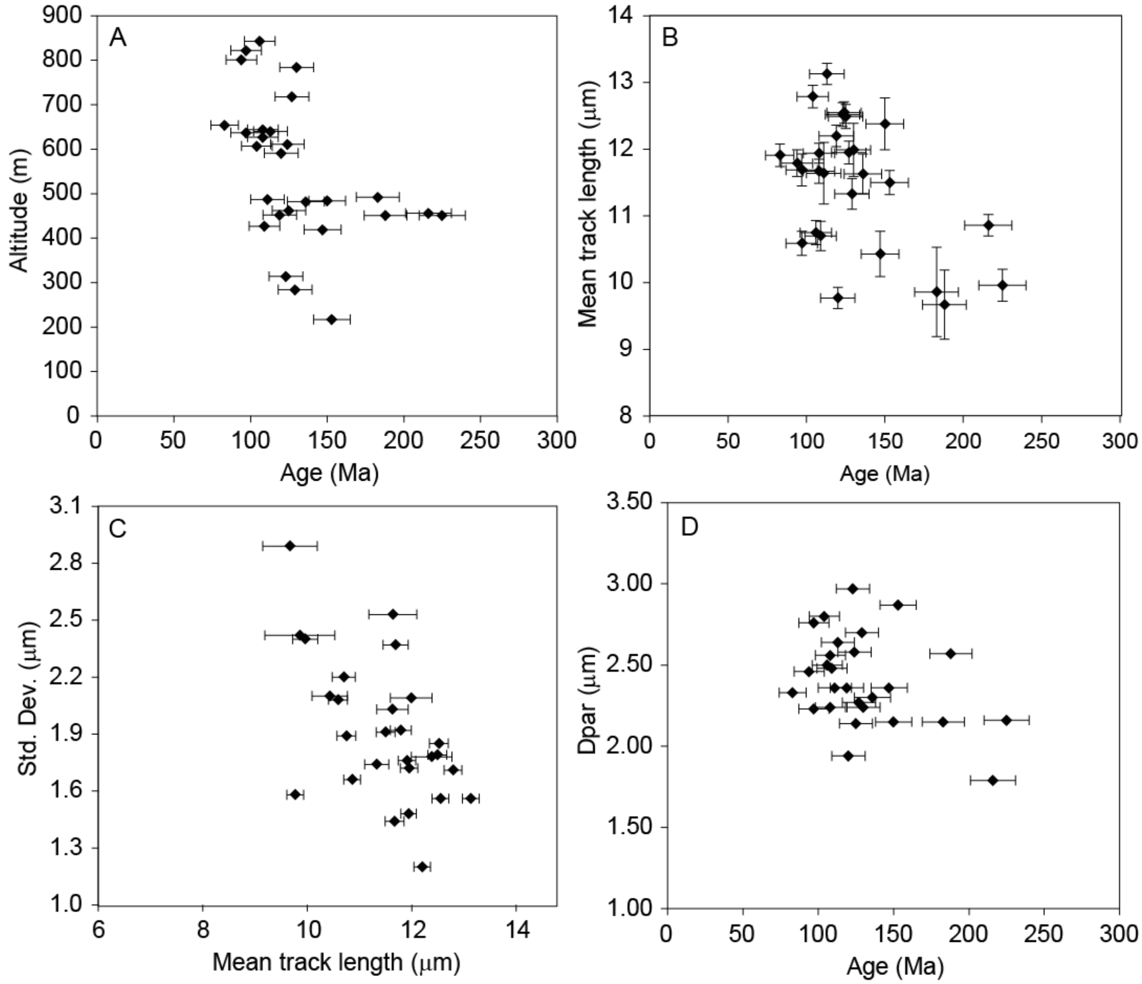

Figure 3: Relationship between AFT ages, samples elevation, MTL and Dpar values. A) AFT ages ploted against sample elevation showing no clear relationship. B) AFT ages against MTL showing a roughly boomerang shape. C) MTL plotted against Std. Dev. showing a broad standard deviation pattern of the MTL, compatible with a very slow cooling history. D) Dpar plotted against AFT ages show that the samples are of chlorine-rich apatite grains.

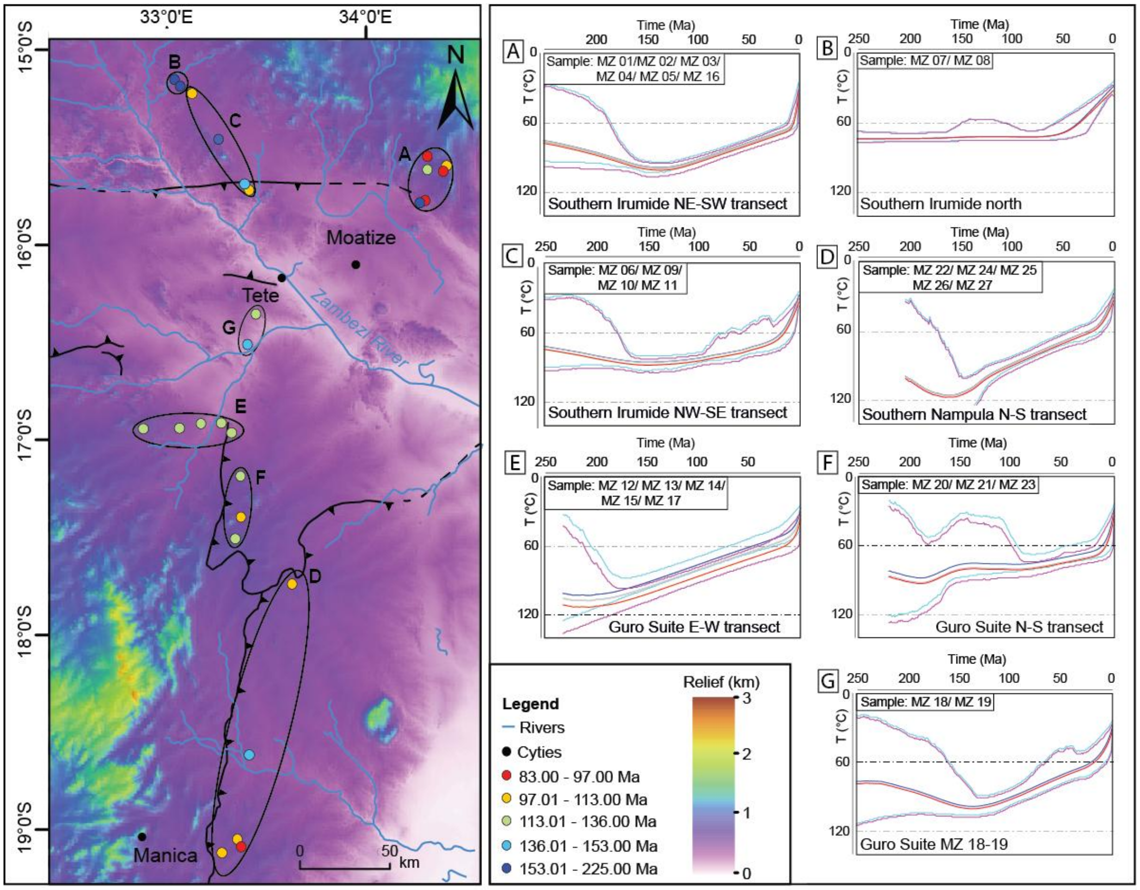

Figure 4: Geomorphologic map (Jarvis et al., 2008) of the study area with the sample locations and the thermal history models of all samples. They were grouped based on their themal history behavior and their geographic location.

The Nampula Complex N-S transect (Fig. 1C) registers a similar cooling pattern, with a relatively slow cooling from maximum paleotemperature of 116 °C at 165 Ma to 56 °C at 17 Ma continuing with a faster cooling pattern until present-day surface conditions (Fig. 4 and 4D).

Samples from the central region were separated into three groups (Fig. 1 and Fig. 4). The first comprises the Guro Suite E-W transect (Fig. 4 and 4E) with five samples. Thermal history of this groups is represented by a stady-state cooling history from 208 Ma to 15 Ma with a maximum paleotemperature of 103 ° C decreasing until 50 ° C in a time spane of *ca*. 190 Ma, followed by a fast cooling period to the present-day thermal conditions (Fig. 4E). The thermal behavior observed by the second group (formed by three samples and grouped as the Guro Suite N-S transect, Fig. 4 and 4F) differs from the former, presenting a rapid cooling between 190 Ma and 150 Ma, from tempceretures of 88 ° C to 76 ° C, followed by a period of a stationary cooling history unitl 94 Ma. From this moment samples started to cooling in the same stady-state pattern until 18 Ma when achieved present-day conditings after a fast cooling event from paleotemperature of 64 ° C. The third one comprises the samples MZ-18 and MZ-19 located in the Guro Suite of the central portion of the graben of the structural controlled Zambezi Valley (Fig. 1C) at altitudes of 217 and 314 m, respectively (Table 1), being lower than the others of this region. As the other samples, the thermal model indicates a slow cooling of paleotemperatures of the order of 99 ° C to 136 Ma to 60° C at 21 Ma. From 21 Ma these samples soffers a fast cooling until present-day conditions (Fig. 4G).

5. Discussions

The data demonstrate that the thermal histories of the analyzed samples correspond to prossess much younger than the stratigraphic age of the rocks sampled indicating that intense exhumation processes affected the region during the Mesozoic Era. The AFT central ages and the maximum modeled paleotemperatures can be attributed to important regional and local tectonic activity and mantle dynamics controlled by the tectonic evolution related to the opening of the Indian Ocean.

The time interval choosed to construct the denudation maps were based on the maximun paleotemperatures obseved in the thermal modeling (Fig. 4B to 4G). From this, four main intervals were analysed separetly as presented in Figure 5. The older ages are situated close to the latter stages of the Cape Fold Belt tectonic activity attributed to the subduction of the Panthalassa seafloor and may represent cooling episodes caused by erosion and denudation associated with tectonic reactivations induced by a far stress field propagating along the African crust. The prossess is well documented by Karoo sedimentation in the Zambezi Valley basins. Permian-Triassic times was a period of high subsidance rates in these basins filled by *ca*. 10 km of vulcano-sedimentery pile (Catuneanu et al., 2005) implaing in high denudation rates in the source areas southwards (Key et al., 2015; Bicca et al., 2017).

Cooling episodes around 200-250 Ma was also described by Van Der Beek et al. (1998) in the north of the Malawi rift, which they attributed to late Karoo erosion have affected the entire area. High denudation rates from *ca*. 190-180 Ma (Norconsul Consortium, 2007) would be expected due to thermal uplift of the rift shoulders produced by the Karoo magmatism in the north of Mozambique (Fig. 6), which extends to *ca*. 170 Ma in other parts of Africa and Antarctica (Catuneanu et al., 2005; Klausen, 2009; Mahanjane, 2012; Castelino et al., 2015). Middle Jurassic Drift onset (170-166 Ma) depict the initiation of movement on the Davie Ridge transform, which in marked by spreading in the Somali basin (Mahanjane, 2014). This period comprises the early stages of Gondwana break-up and were poorly preserved in the thermal history of our samples and the highest denudation thicknesses (about to 300 m) were observed in the central area (Fig. 5A; Guro Suite E-W and N-S transects) in a period from Upper Triassic to Middle Jurassic implying in <0.3 ^{o}C/Ma, while in the north and south these period were not registered suggesting no thermal or tectonic influence.

From Middle Jurassic to Lower Cretaceous the central and southern regions presents the highest denuded amounts (around 300 m; Fig. 5B), demonstrating that this area underwent important erosive processes that may be associated with the NW-SE and N–S structural trends that comprise important inherited structural patterns the Precambrian basement of the region (Fig. 1). Fast cooling history around 150 Ma were also documented in the Malawi Rift (Van der Beek et al., 1998) which these authors associated with a renewed rifting phase. This moment is documented in the southern region of Malawi with the development of alkaline magmatism (abouto to 130-100Ma) associated with extensional tectonics (Eby et al., 1995), near to the NE region of the study area (see Fig. 2 for location). This period (around 150 Ma) comprises the early stages of the Antarctica southwards drifting with respect to Africa (Mahanjane, 2012; Castelino et al., 2015) and the Madagascar southwards drift from Tanzania margin by the Davie shear zone with seafloor spreading in the Somali Basin during the Lower and Upper Cretaceous times (140 Ma to 90 Ma; Emmel et al., 2011; Mahanjane, 2014). After that, Madagascar occupied its present position as part of the African plate (Salman and Abdula, 1995; Castelino et al., 2015).

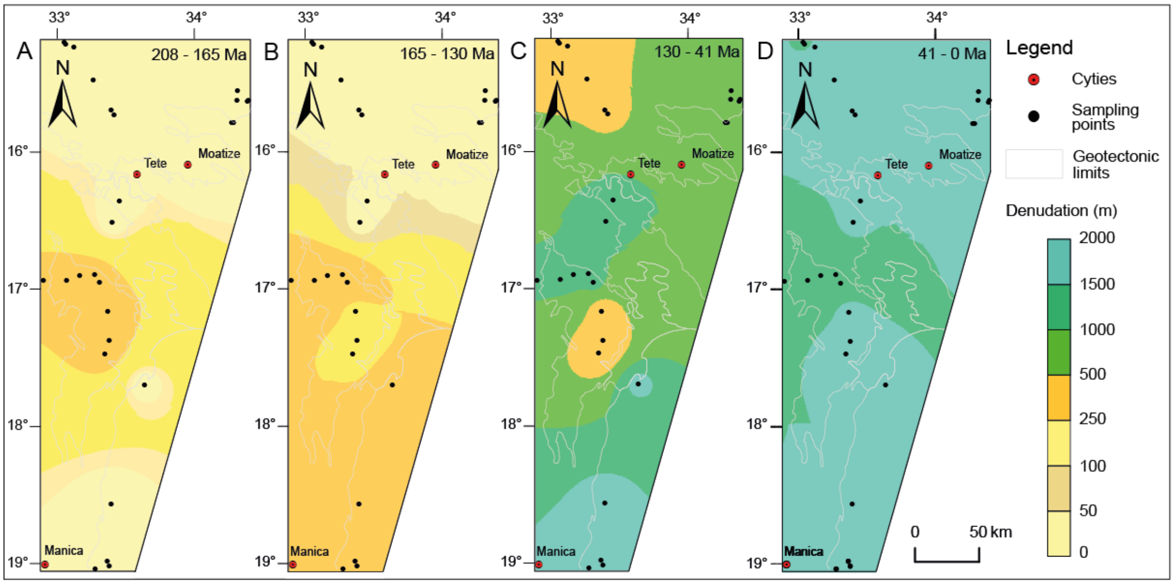

Figure 5: Reconstructed denudation history of the NW Mozambique basement. The maps show the inferred amount and the spatial variation of denudation at: A) 208 – 165 Ma, B) 165–130 Ma, C) 130 – 41 Ma, and D) 41 – 0 Ma.

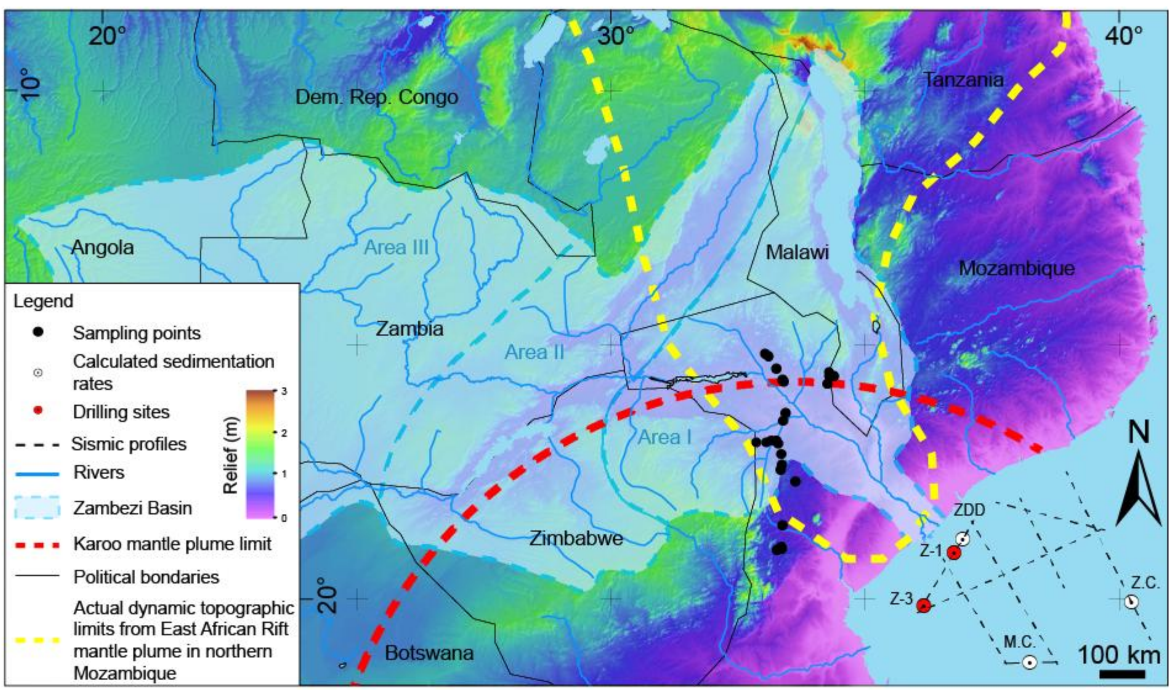

Figure 6: Geomorphological map (Jarvis et al., 2008) of central-eastern Africa highlighting important thermal limits and the extension of the Zambezi Basin. Seismic and drilling data are after Castelino et al. (2015); Karoo mantle plume limits are after Cox (1989a and 1989b); and dynamic topography limits is after Moucha and Forte (2011).

These arguments are also in agreement with the intensification of denudation observed in all the study area (Fig. 5C) from Upper Cretaceous to Middle Paleocene eroding thicknesses from 254 m to 1659 m due to the development of the Mozambique margin, being the largest thicknesses were removed from the northeast, central and south regions. Accelerated denudation processes during Lower and Upper cretaceous are also described by Belton and Raab (2010) for the Kalahari cratonic area and by Emmel et al. (2011) for NE Mozambique corroborating the regional uplift model of the hinterland in the east margin of the African plate and accelerated denudation patterns.

A well-defined pattern of rapid cooling around 40 Ma taking the samples out of the partial cooling zone with denudation rates of 31-47 m/Ma and amounts of 1.5-2 km thick of surface denuded section until the current thermal conditions. The south and north of the area have suffered the greatest influnce during this period. Until this moment the total amount of denuded sheet of NW Mozambique have reached 2.5-3.5 km. Similar conditions were detected in the Karoo sequences in the area implying 1000 and 1500 m of denudation onwards from 6 Ma (Fernandes et al., 2015). This moment is approaching crustal uplifting in the northeastern region of Africa attributed to a superswell related to the African mantle plume movements responsible for the evolution of the East African Rift System. According to the models developed by simulations of the mantle convection for the last 30 Ma (Moucha and Forte, 2011) it was possible to observe a drastic increase of topography in the NE region of Africa (since *ca*. 15 Ma) propagating south towards the north of Mozambique (Fig. 6). This southwards uplift is due to the northwards movement of the African plate due to the movement of the mantle, leading to distensive processes reactivating ancient crustal structures raising the rates of cooling and denudation throughout the northwest region of Africa (Moucha and Forte, 2011).

This dynamic topography came to contribute to the sedimentation rates in the onshore and offshore Mozambique basin sites, since the erosion amount determined from NW Mozambique does not match the higher sedimentation rates described in the basin despite of provide a good fit with the timing of major crustal uplift (Fig. 7). These additional amounts of sediment were added to the river systems from other interior regions covered by the Zambezi river basin. The African plate due to thermal uplifting firstly related to the Karoo Igneous Province and more recently by the mantle dynamics of the East African Rift System induced the capture of the Zambezi tributaries due to the structural reactivation. The Zambezi river basin possess three main regions known as basins I, II and III (Fig. 6, Castelino et al., 2015). The most distal ones have only became part of the basin from the Miocene-Paleocene times as determined by Castelino et al. (2015) from sedimentation rates in the north of the Mozambique Basin, which is in agreement with the uplift periods of the northeast region of the African plate (Moucha and Forte, 2011).

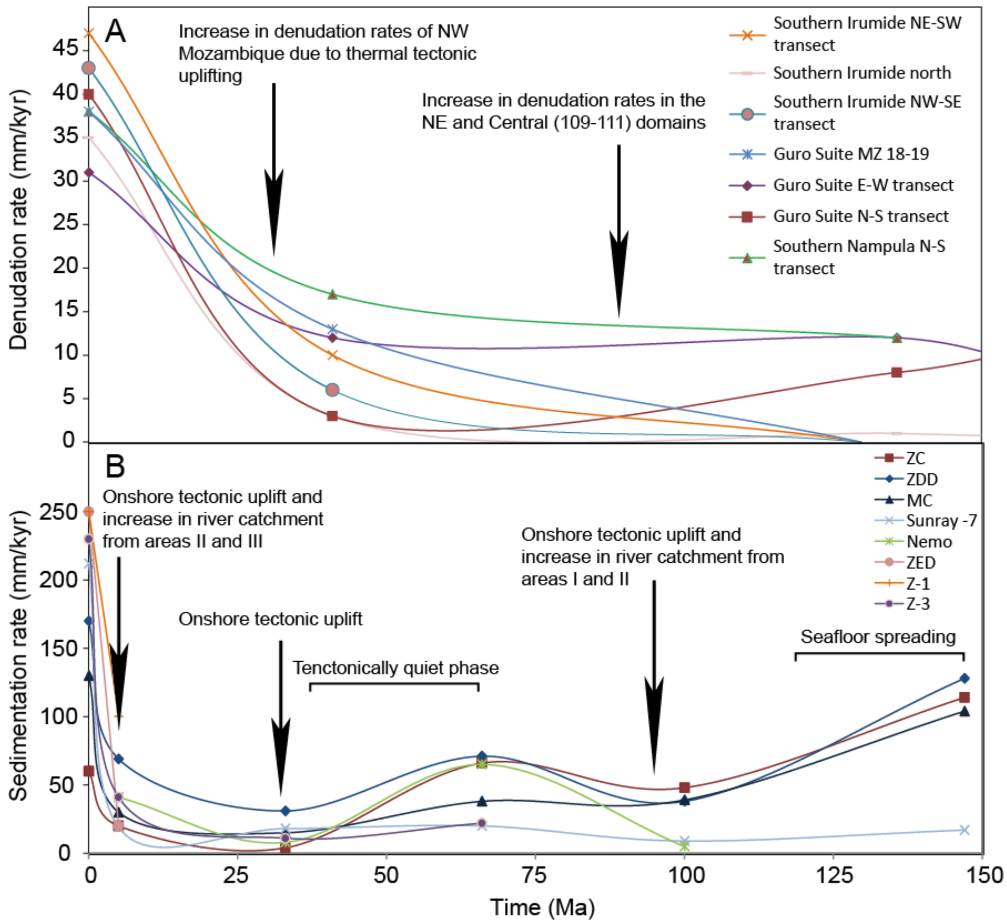

Figure 7: Plots of denudation rates from NW Mozambique (A) and thermal burial histories of the north of the Mozambique Basin nearer the Zambezi Delta determined from well and seismic data (see figure 6 for location; after Castelino et al., 2015).

With these in mind, it is possible to determine our high Pleistocene denudation rates which fit with the predicted uplift periods and river catchment as determined by Castelino et al. (2015). Although, most of the samples indicate a protracted cooling history since Late-Jurassic- Early Cretaceous with an acceleration of the cooling history only in the last *ca*. 41 Ma, probably associated with mantle upwelling of the East African Rift System and extensional tectonics related to it. The main period of uplift around 90 Ma were not clearly distinguished in our data.

6. Conclusions

The northern region of Mozambique comprises important pieces to assemble the puzzle related to the plates dynamics during the formation and separation of the Gondwana. The southern African plate has underwent several processes of horizontal and vertical stress since Permian times attributed to Gondwanides orogenesis and to mantle plumes upwelling from the Gondwana separation stages, respectively. The AFT age data provided range from Upper Triassic to Upper Cretaceous indicating that the region underwent intense denudation during earlier times, erasing these stages from thermal history. This interpretation is corroborated by intense tectonic reactivation in the Zambezi Valley region, leading to the formation of great accommodation spaces in the rift basins, filled by thick sedimentary sequences of the Karoo Supergroup. Maximum paleotemperatures in the basement samples were reached at around 200-150 Ma which led to denudation amounts of 0.3-2 km at rates varying from 3-17 m/Ma until Middle Pleistocene. The early stages of cooling is compatible with the increasing opening stage of the Indian Ocean seafloor. Since Middle Pleistocene a fast-cooling event affected the entire region taking samples to the current thermal conditions at denudation rates between 31-47 m/Ma and a final denuded section since Late Triassic of 2-3.5 km. This change were caused by important shift in the northeast portions of the African plate, mainly in terms of topography and drainage patterns induced by mantle plume activity that have uplifted the whole NE region of Africa extending to the north of Mozambique, due to a thermal induced drift of Africa northwards.

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