



Universidade de Brasília
Instituto de Geociências
Programa de Pós-graduação em Geologia

Dinâmica crustal Paleo- Mesoarqueana do Maciço São José do Campestre, nordeste do Brasil

Paleo-Mesoarchean crustal dynamics of the São
José do Campestre Massif, northeast Brazil

Carlos Vinícius Alves Ribeiro

Tese de Doutorado nº 219

Orientador: Prof. Dr. Elton Luiz Dantas

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The future sticks out its tongue in the eyes of the gentle past,
It fears its own demise but knows it cannot last
Sleepytime Gorilla Museum

RESUMO

O Maciço de São José do Campestre, no nordeste do Brasil, representa um dos fragmentos mais antigos de crosta continental da América do Sul. Rochas supracrustais, principalmente paragneisses migmatíticas, são frequentes neste embasamento, embora careçam de uma caracterização adequada. Neste trabalho, a sua idade de deposição foi investigada, bem como a idade e as condições de eventos metamórficos posteriores, com base em uma ampla gama de técnicas analíticas e de modelagem. A partir de datações U-Pb em zircão, foi possível estabelecer uma idade máxima de deposição de 3305 ± 16 Ma, com metamorfismo de alta temperatura entre 3,08 e 3,00 Ga. Modelagem termodinâmica indica um trajetória P-T no sentido horário, com uma etapa de aquecimento-exumação em condições de ultra-alta temperatura (>900 °C a 0,6 GPa). A cronometria de difusão revela um evento UHT de curta duração (< 4 Ma), seguido por resfriamento e exumação para fácies anfibolito sob rápidas taxas (>100 °C/Ma e >3 km/Ma). O metamorfismo de alta temperatura culminou na fusão parcial destas rochas por desidratação de muscovita e biotita, com datação U-Pb em zircão dos leucossomas indicando uma idade de cristalização de 3065 ± 7 Ma. Modelagem de difusão de elementos traços no magma indica que o magma interagiu por menos de 53 kyr com o resíduo antes da extração. A evolução metamórfica mesoarqueana do Maciço de São José do Campestre se correlaciona com eventos semelhantes em vários crátons arqueanos, incluindo os crátons Kaapvaal, Dharwar e São Francisco. Esses eventos estão associados com a formação do supercontinente mais antigo da Terra, denominado Ur. Reconstruções paleogeográficas sustentam a existência de um grande orógeno mesoarqueano no núcleo do supercontinente. Um anfibolito intrusivo dentro do pacote sedimentar definiu uma idade de cristalização de 2522 ± 22 Ma. Todas essas amostras investigadas registram modificação isotópica do zircão durante o Paleoproterozoico e o Neoproterozoico em condições de temperatura mais baixas. A datação de zircão por Raman indica uma exumação Cambriano-Carbonífera para essas rochas, que se alinham com idades de interceptação inferiores, demonstrando a utilidade do zircão metamítico para determinar a idade de eventos de baixa temperatura. Coletivamente, os resultados são consistentes com o funcionamento da tectônica de placas desde, pelo menos, o Mesoarqueano.

Palavras-chave: metamorfismo, sedimentar, geocronologia, supercontinentes

ABSTRACT

The São José do Campestre Massif, in northeastern Brazil, represents one of the oldest fragments of continental crust in South America. Supracrustal rocks, mostly migmatitic paragneisses, are frequent within the basement, although lacking a proper characterization. In this work, the timing of their deposition was investigated, as well as the timing and conditions of metamorphic overprint based on a wide range of analytical and modelling techniques. U-Pb in zircon dating yield a maximum depositional age of 3305 ± 16 Ma for these rocks, with metamorphic overprint between 3.08 – 3.00 Ga. Thermodynamic investigation indicates a clockwise P-T path, with a heating-exhumation step into ultra-high temperature conditions (>900 °C at 0.6 GPa). Diffusion chronometry reveals a short-lived UHT event (< 4 Ma), followed by cooling and exhumation into amphibolite facies at fast rates (>100 °C/Ma and >3 km/Ma). High temperature metamorphism led to muscovite and biotite dehydration melting, with U-Pb in zircon dating of the leucosomes indicating a crystallization age of 3065 ± 7 Ma. Diffusion of trace elements in the melt indicates that the melt interacted for less than 53 kyr with the residuum before extraction. The Mesoarchean metamorphic evolution of the São José do Campestre Massif correlates with similar events in several Archean cratons, including the Kaapvaal, Dharwar and São Francisco cratons. These events correlate with the formation of the oldest supercontinent on Earth, named Ur. Paleogeographic reconstructions support the existence of a large Mesoarchean orogen in the core of the supercontinent. An amphibolite intrusive within the sedimentary package yield a crystallization age of 2522 ± 22 Ma. All these investigated samples record metamorphic overprint during the Paleoproterozoic and Neoproterozoic at lower temperature conditions. Zircon Raman dating indicates a Cambrian to Carboniferous exhumation for these rocks, which align with lower intercept ages, demonstrating the usefulness of metamict zircon to constrain low temperature events. Collectively, the results are consistent with the operation of plate tectonics since, at least, the Mesoarchean.

Keywords: metamorphism, sedimentary, geochronology, supercontinents

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CAPÍTULO 1: INTRODUÇÃO

1.1 Apresentação do tema

Nas últimas décadas, diversas rochas arqueanas foram identificados no nordeste do Brasil (Dantas et al., 2004; Ganade et al., 2017; Santos et al., 2017a; Velásquez Ruiz et al., 2019; Santos et al., 2020; Barros et al., 2020; Ferreira et al., 2021). Estas rochas correspondem a fragmentos dos primeiros continentes formados na Terra e que foram posteriormente dispersos pela tectônica de placas. O entendimento da evolução geológica destas regiões pode fornecer informações importantes sobre o funcionamento da Terra em um período em que os mecanismos que governavam a dinâmica crustal ainda são debatidos.

Neste contexto, o Maciço São José do Campestre, localizado no extremo nordeste do Brasil, corresponde a um dos blocos arqueanos com maior diversidade litológica, com rochas plutônicas com idade U-Pb em zircão entre 3.4 a 2.7 Ga (Dantas et al., 2004; Souza et al., 2016). Rochas supracrustais são frequentes, principalmente paragneisses migmatíticos, incluindo também mármore, formações ferríferas bandadas, quartzitos e rochas calciossilicáticas. Contudo, estas rochas ainda carecem de estudos aprofundados, com apenas uma amostra de paragneisse analisada por U-Pb em zircão, que definiu uma idade de deposição em torno de 2.7 Ga, com evidências de metamorfismo em 3.0, 2.0 e 0.6 Ga (Souza et al., 2016).

Desta forma, o presente trabalho é focado em caracterizar estas rochas do ponto de vista da “*petrocronologia*”, isto é, a relação entre as texturas observadas em minerais e a sua relação com a evolução das condições de pressão (P) e temperatura (T) ao longo do tempo (t). Os resultados, divididos em quatro artigos científicos, permitem caracterizar

os mecanismos atuantes durante a evolução arqueana da região, sendo correlacionáveis com eventos ocorridos em escala global.

O primeiro artigo científico, publicado no periódico *Lithos*, discute a idade máxima de deposição das rochas supracrustais do Maciço São José do Campestre com base em isótopos de U-Pb e elementos traços em zircão. Os resultados permitiram inferir uma idade máxima de deposição em torno de 3,3 Ga e a presença de metamorfismo de fácies granulito em torno de 3,1 – 3,0 Ga, com eventos de recristalização em torno de 2,0 – 1,9 e 0,6 Ga. Também são discutidos os efeitos de múltiplos eventos metamórficos na assinatura isotópica do zircão, com ênfase em técnicas discriminar a confiabilidade das idades obtidas.

O segundo artigo científico, aceito para publicação no periódico *American Mineralogist*, descreve os efeitos de diversos processos geológicos na assinatura isotópica e de elementos traços do zircão em comparação com resultados de espectroscopia Raman. Como estudo de caso, é apresentado um afloramento da sequência supracrustal que apresenta uma intrusão máfica cristalizada no final do Arqueano (ca. 2,5 Ga). A intrusão apresenta diversos cristais com idade e textura compatível com os cristais observados na rocha encaixante, contudo, a alta temperatura do magma máfico foi responsável por homogeneizar os elementos traços e reparar a estrutura cristalina do zircão. Por outro lado, os cristais de zircão da rocha encaixante acumularam dano por radiação por um tempo maior, levando a autodestruição da sua estrutura cristalina. As diferenças entre as populações das duas rochas são comparadas, utilizando a espectroscopia Raman como acessório para quantificar o estado da estrutura cristalina destes cristais. Os resultados indicam que o zircão pode registrar eventos de baixa temperatura, marcando episódios de fluxo de fluido e exumação.

O terceiro artigo científico, a ser submetido para publicação no periódico *Precambrian Research*, descreve as condições de pressão e temperatura, bem como a duração das condições de pico e resfriamento, do metamorfismo mesoarqueano. Os resultados indicam um evento de ultra-alta temperatura ($>900\text{ }^{\circ}\text{C}$) de curta-duração ($<4\text{ Ma}$), compatível com a delaminação do manto litosférico durante um evento convergente. Este evento é compartilhado por diversos blocos arqueanos dispersos em diversos continentes, relacionando-se a formação do primeiro supercontinente da Terra, denominado Ur. Consequentemente, os resultados tem implicações para a paleogeografia da região durante o Mesoarqueano e para a teoria da tectônica de placas.

O quarto artigo científico, a ser submetido para o periódico *Journal of Metamorphic Geology*, descreve os distintos episódios de fusão parcial durante o Mesoarqueano que afetaram as rochas supracrustais do Maciço São José do Campestre. Os resultados permitem definir os mecanismos, condições e duração da fusão parcial destas rochas, tendo implicações para a geração de magmas peraluminosos e arquitetura crustal durante o Arqueano.

1.2 Localização e acesso a área de estudo

A área de estudo está localizada no extremo nordeste do Brasil, englobando os municípios de Tangará, Serra Caiada, Senador Elói de Souza, Bom Jesus e Macaíba, no estado do Rio Grande do Norte (Figura 1). O acesso ocorre principalmente através da BR-226, que cruza a área de estudo ao longo de uma direção aproximadamente NE-SW. Ao longo desta estrada, sentido Macaíba em direção a Bom Jesus, a amostra CJ-202 foi coletada em uma estrada carroçável na primeira entrada a esquerda no vilarejo conhecido como Cajazeiras, em direção ao vilarejo de Mata Verde. Seguindo na BR-226, no sentido Senador Elói de Souza em direção a Serra Caiada, a amostra CJ-128 foi coletada de um bloco na margem direita da estrada. Seguindo em direção a Tangará, as amostras CJ-211

e PJ-1 foram coletadas na margem direita da estrada. A amostra CJ-211 foi coletada de um bloco no entorno da pedreira do Teixeira (também conhecida como pedreira do DNIT), enquanto a amostra PJ-1 foi coletada dentro da pedreira.

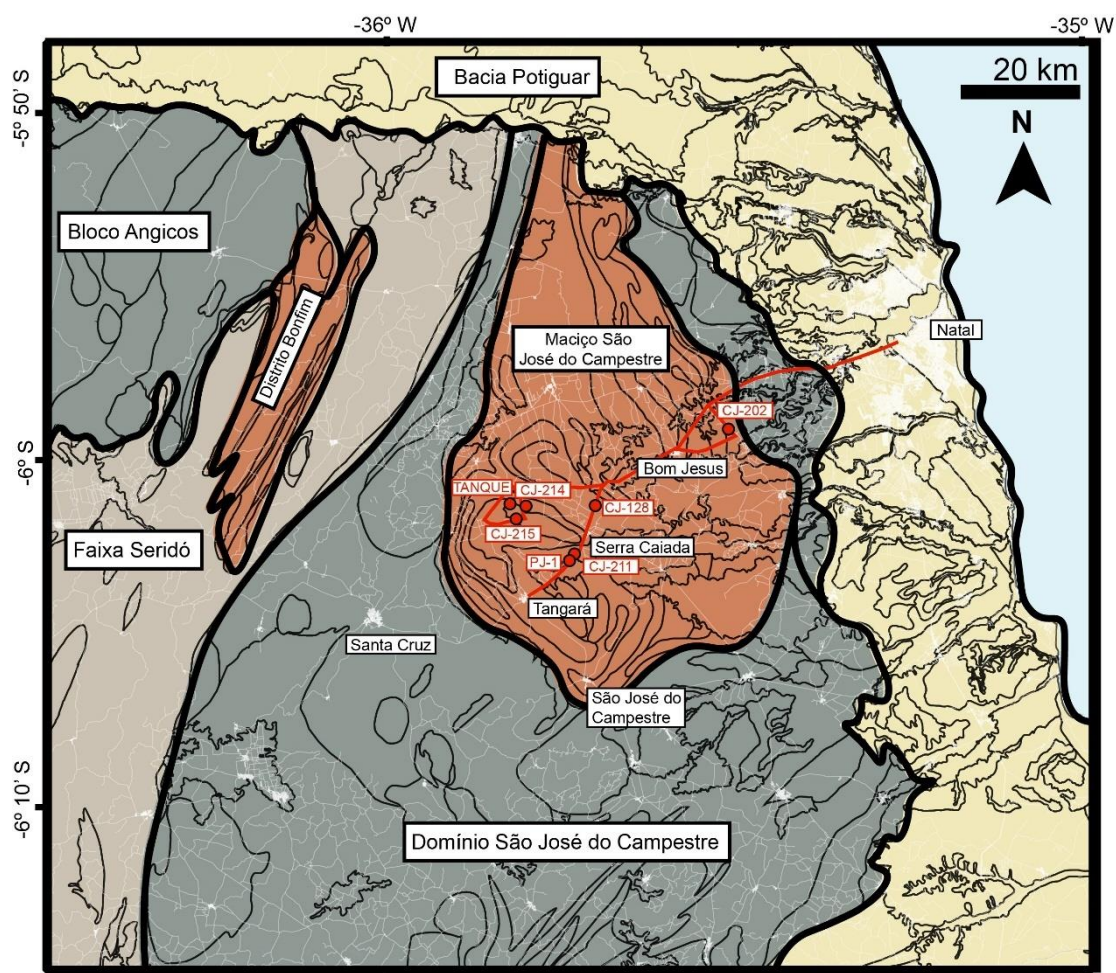


Figura 1: Mapa de localização das amostras estudadas e principais acessos. Contornos geológicos extraídos de Santos et al. (2021). Base cartográfica de acessos proveniente do OpenStreetMap.

As amostras CJ-214, CJ-215 e TANQUE (1, 2 e 3) foram coletadas próximo a Agrovila de São Tomé. O acesso se dá através de uma estrada carroçável que liga o município de Senador Elói de Souza ao vilarejo de Iguatu. As amostras CJ-214 e CJ-215 foram coletadas ao longo da estrada que conecta a agrovila e a rodovia RN-093, cortando o relevo da região conhecido como Serra do Mel. As amostras TANQUE foram coletadas no topo da serra, em uma localidade conhecida como Tanque do Guedes, frequentada pela população local para a prática de *camping*. O acesso ocorre, conforme guiado pelos

geólogos Tiago e Renato Galdino, partindo do vilarejo de Iguatu em direção a SE por aproximadamente 3 km. A entrada para a trilha que leva ao topo da serra está localizada do lado esquerdo, totalizando uma distância de aproximadamente 2800 metros, e ganho de elevação de 200 metros, até o topo da serra.

1.3 Contexto Geológico

1.3.1 A Província Borborema

A Província Borborema, nordeste do Brasil, é uma das 10 províncias estruturais que compõem o território brasileiro (Figura 2, Almeida et al., 1981). Atualmente é limitada a leste e a norte pelo oceano Atlântico, a oeste pela Bacia do Parnaíba e a sul pelo Cráton São Francisco. Uma das principais características desta província é a extensa rede de zonas de cisalhamento, que apresentam continuidade no noroeste do continente Africano, refletindo um grande sistema orogênico desenvolvido durante a formação do megacontinente Gondwana (Trompette, 1997; Van Schmus et al., 2008; Caxito et al., 2020b).

As rochas mais antigas da região estão localizadas no Distrito de Bonfim, no Rio Grande do Norte, com rochas ultramáficas formadas durante o Eo-Paleoarqueano (Velásquez Ruiz et al., 2019; Santos et al., 2020; Garcia et al., 2023) e ortognaisses formados durante o Neoarqueano (Cavalcante et al., 2018). Rochas metaplutônicas formadas durante o Paleo-Neoarqueano foram identificadas no Maciço São José do Campestre (Dantas et al., 2004, 2013; Souza et al., 2016, 2023) e no Complexo Granjeiro (Pitarello et al., 2019; Vale et al., 2023). Rochas formadas durante o Mesoarqueano são encontradas principalmente no bloco Campo Grande (Ferreira et al., 2021), Maciço de Tróia (Ganade et al., 2017) e no Domo de Itabaiana (Rosa et al., 2020). Rochas metaplutônicas formadas durante o Neoarqueano, principalmente no período entre 2.7 –

2.6 Ga são presentes em praticamente todos os blocos arqueanos da Província Borborema, incluindo também o Terreno Alto Moxotó (Santos et al., 2017) e o Complexo Entremontes (Cruz et al., 2014).

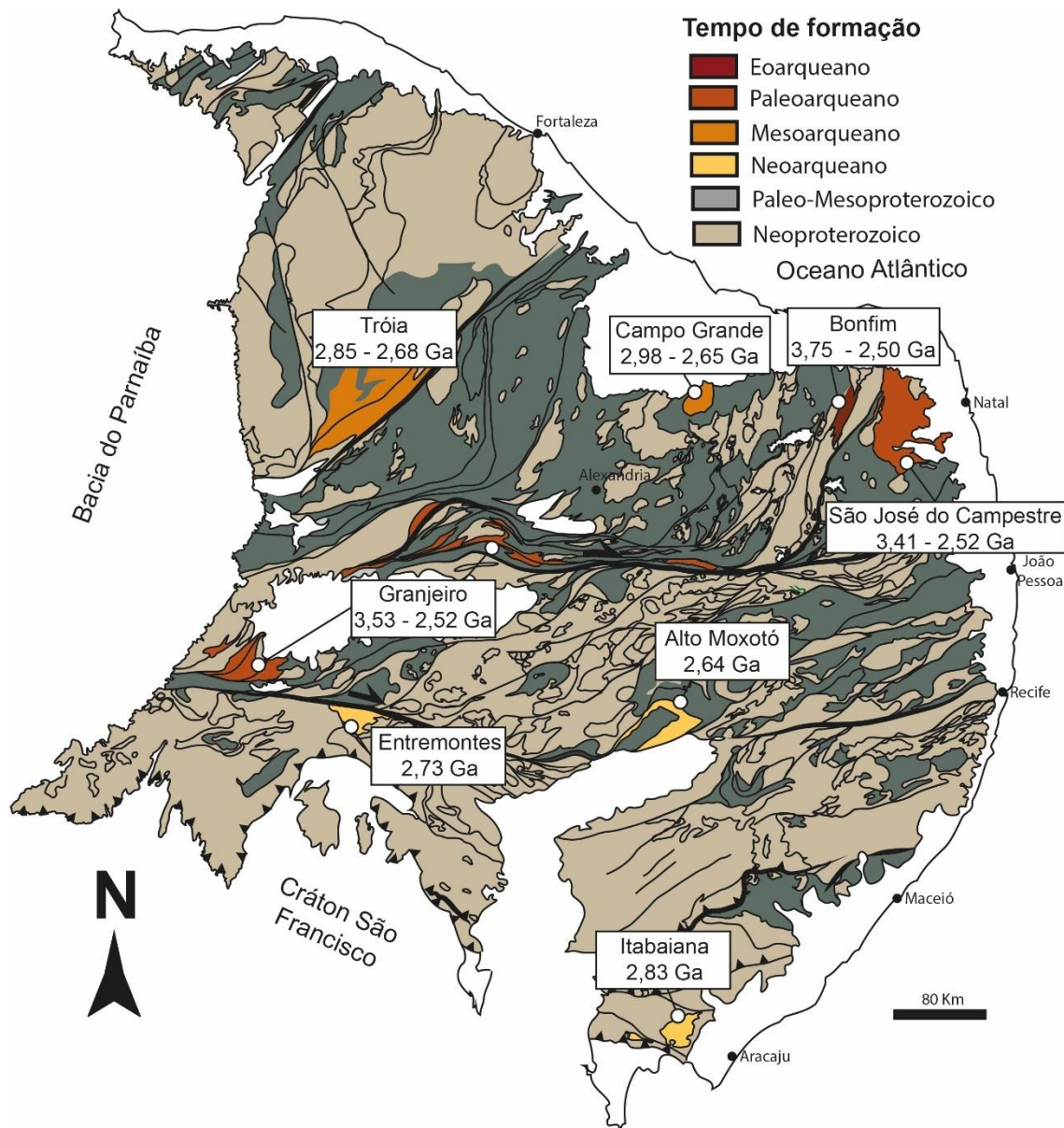


Figura 2: Mapa geológico da Província Borborema classificado por período geológico, com destaque para as ocorrências de blocos arqueanos e o seu intervalo de idades.

Rochas formadas durante o Paleoproterozoico ocorrem amplamente na Província Borborema. O pico da atividade plutônica ocorreu entre 2.3 – 2.1 Ga, com a formação de diversas rochas plutônicas em contexto de arco magmático oceânico e continental (Dantas, 1996; Souza et al., 2007, 2016; Martins et al., 2009; Costa et al., 2015; Neves,

2021). Estas rochas são cronologicamente correlatas a formação do supercontinente Atlântica, resultando na formação de extensos arcos magmáticos em diversos crátons na América do Sul (Amazônico e São Francisco) e no continente Africano (Oeste Africano e Congo) (Rogers, 1996; Neves, 2011, 2021).

O registro geológico entre 2,0 e 1,1 Ga na Província Borborema é relativamente escasso, incluindo a deposição de sequências vulcanossedimentares na Faixa Orós em torno de 1.7 Ga (Sá et al., 1995) e a intrusão de granitos anorogênicos no Terreno Alto Moxotó em 1.6 Ga (Santos et al., 2015; Lages et al., 2019).

O Neoproterozoico é marcado por intensa atividade magmática, inicialmente com a formação de sequências vulcanossedimentares entre 1.0 e 0.92 Ga durante o evento Cariris Velhos (Santos et al., 2010; Van Schmus et al., 2011). A natureza tectônica deste evento ainda é bastante debatida. Propostas incluem um ciclo orogênico completo de curta duração, com a subducção de crosta oceânica (Lages & Dantas, 2016), formação de arcos magmáticos e deposição de bacias orogênicas (Santos et al., 2010, 2019) ou eventos puramente extensionais em contexto intracontinental (Neves et al., 2021).

Tonalitos formados em torno de 830 Ma em contexto de arco oceânico foram descritos no Ceará (Ganade de Araújo et al., 2014). Estas rochas representam o início da subducção entre a Província Borborema e o Bloco do Parnaíba, culminando na colisão continental em torno de 660 – 630 Ma (Ganade de Araújo et al., 2013). Uma segunda colisão, desta vez resultante do fechamento do oceano Sergipano-Oubanguides e colisão com o Cráton São Francisco, teria ocorrido entre 590 – 570 Ma (Oliveira et al., 2010; Ganade de Araújo et al., 2013). A interação entre estas frentes colisionais teria gerado a extrusão da Província Borborema na direção NE (considerando o norte atual), com a formação da extensa rede de zonas de cisalhamento (Ganade de Araújo et al., 2013).

Outras interpretações para a formação do sistema de zonas de cisalhamento da Província Borborema incluem a acreção de terrenos exóticos (e.g., Brito Neves et al., 1999; 2014). Neste contexto, as principais zonas de cisalhamento da região representariam antigas zonas de sutura resultante da acreção de blocos alóctones durante o Neoproterozoico (e.g., Medeiros, 2004; Brito Neves et al., 2016).

Alternativamente, uma terceira corrente de pensamento atribui a formação das zonas de cisalhamento a partição heterogênea da deformação ao longo de antigas descontinuidades (e.g., Neves, 2015, 2021; Neves et al., 2021). Desta forma, a inversão de bacias de rifte intracontinental e reativação das estruturas preexistentes resultaria em diversas colisões continentais, sem a presença de crosta oceânica e, consequentemente, subducção (e.g., Neves, 2015).

Atualmente, evidências concretas da subducção de crosta oceânica são ausentes na Província Borborema. Retro-eclogitos na região do Ceará apresentam inclusões de coesita, sugerindo condições de pressão acima de 28 kbar (Santos et al., 2014). Contudo, o protólito destas rochas, com idade em torno de 1.57 Ga, é interpretado como um dique basáltico alojado na crosta continental (Amaral et al., 2015), sugerindo a subducção de parte da crosta continental. Estas rochas se alinham com correlatos no continente Africano, formando um longo cinturão orogênico com mais de 2500 km de extensão, que seria resultante do fechamento do oceano Goiás-Pharusiano (Ganade de Araújo et al., 2014).

Independentemente da evolução pré-ediocarana e dos processos que deram origem as zonas de cisalhamento da Província Borborema, estas estruturas foram responsáveis por moldar a configuração atual da região. Estima-se que o cisalhamento imposto rotacionou e deslocou diversos blocos dentro da província, por distâncias de até 550 km (e.g., Vauchez et al., 1995; Ganade et al., 2021; Neves et al., 2021; Fossen et al., 2022),

em condições de fácies xisto-verde a anfibolito superior (e.g., Neves, 2021; Cioffi et al., 2021).

1.3.2 O Maciço São José do Campestre

O Maciço São José do Campestre (Figura 3) foi inicialmente estudado por meios geocronológicos por Van Schmus et al. (1995), que obtiveram uma idade modelo Sm-Nd em torno de 2.7 Ga para uma amostra da região. Inicialmente, este bloco foi denominado Maciço Caldas Brandão, se estendendo ao sul do lineamento Patos. Contudo, em trabalhos posteriores a ocorrência de rochas arqueanas foi limitada ao estado do Rio Grande do Norte, e fora dos limites do município de Caldas Brandão, na Paraíba. Desta forma, este bloco foi renomeado para Maciço São José do Campestre (Dantas, 1996), enquanto parte do Maciço Caldas Brandão foi renomeado para Terreno Alto Moxotó (Brito Neves et al., 2001).

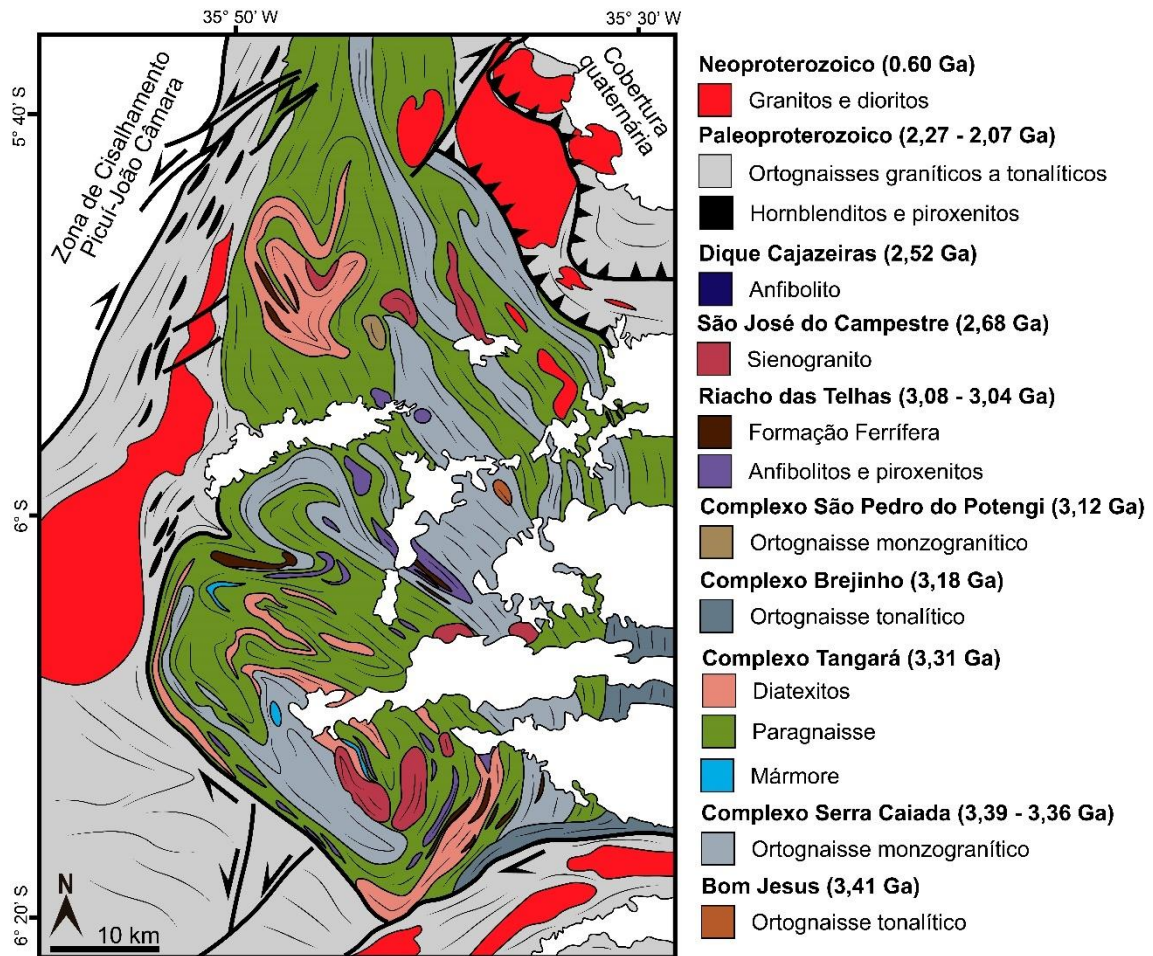


Figura 3: Mapa geológico do Maciço São José do Campestre.

Por definição, um maciço é uma entidade geomorfológica composta por um alto topográfico e estrutural que atua de forma rígida em relação as rochas ao seu redor (Neuendorf et al., 2005). Este conceito se aplica parcialmente a região de estudo, uma vez que, apesar do bloco ter sido pouco afetado pelo último evento orogênico da região (e.g., Dantas et al., 2004; Souza et al., 2016; Ribeiro et al., 2024, 2025), o seu relevo não é proeminente, sendo principalmente rebaixado em relação as rochas que o circundam. Contudo, esta definição tem origem em descrições antigas que denominavam estas porções de embasamento, que se destacam das faixas móveis neoproterozoicas, como maciços (e.g., Van Schmus et al., 1995). Portanto, de forma a diferenciar o bloco arqueano

(maciço) das demais rochas paleoproterozoicas que o circundam, é mantida a definição de Maciço São José do Campestre para as rochas arqueanas da região.

Trabalhos iniciais de mapeamento foram realizados pelo projeto Leste da Paraíba e do Rio Grande do Norte, que descreveram principalmente a presença de migmatitos homogêneos, majoritariamente de composição granítica, e migmatitos heterogêneos, com paleossoma composto principalmente por micaxistos e anfíbolitos (Bezerra et al., 1973). Posteriormente, durante o mapeamento da Folha João Câmara por Amaral (1990), esta região foi caracterizada por um embasamento arqueano (Complexo Caicó) sobreposto por rochas metavulcanossedimentares, como rochas calciossilicáticas, mármore, quartzitos, xistos e anfíbolitos, que na época foram associados ao Grupo Seridó, de idade neoproterozoica.

Posteriormente, Dantas (1996) obteve principalmente idades arqueanas para rochas metaplutônicas da região através de datações U-Pb em zircão, diferenciando estas rochas do Complexo Caicó, de idade paleoproterozoica (Souza et al., 2007; 2016). Foram caracterizados sete eventos magmáticos no período entre 3,41 Ga a 2,66 Ga (Dantas et al., 2004; 2013; Souza et al., 2016). Este longo e expressivo magmatismo foi interpretado como resultante da fusão do manto em consecutivos eventos convergentes (Dantas et al., 2004; Souza et al., 2016).

As rochas máficas presentes na região, previamente caracterizadas como anfíbolitos (e.g., Amaral, 1990), apresentam uma maior variedade litológica, incluindo sequências máficas (gabros e dioritos) e ultramáficas (piroxenitos e peridotitos), com idade U-Pb em zircão em torno de 3,08 – 3,04 Ga (Jesus, 2011; Abrahão Filho, 2016). A geoquímica destas rochas indica a formação em um ambiente de platô oceânico, cuja composição foi enriquecida em elementos traços durante um processo de subducção (Jesus, 2011). Além disso, foi observada a presença de três eventos de alto grau

metamórficos distintos em aproximadamente 3,0, 2,0 e 0,6 Ga com base em bordas recrystalizadas de zircão (Dantas et al., 2004; Souza et al., 2016).

As unidades litoestratigráficas do Maciço São José do Campestre são descritas a seguir (Figura 4).



Figura 4: A) Unidade Bom Jesus, composta por ortognaisses tonalíticos e enclaves de anfibolito com idade em torno de 3,41 Ga. B) Complexo Serra Caiada, composto principalmente por ortognaisses granodioríticos a graníticos, com idade em torno de 3,39 – 3,36 Ga. C) Complexo Tangará, composto principalmente por paragnaisses migmatíticos, incluindo lentes de mármore e quartzitos. D) Complexo Brejinho, composto principalmente por ortognaisses tonalíticos com idade em torno de 3,18 Ga. E) Complexo Riacho das Telhas, composto por sequências máficas-ultramáficas, incluindo gabros e granada-piroxenitos. F) Sienogranito São José do Campestre, com idade em torno de 2,69 Ga. G) Dique Cajazeiras, composto principalmente por anfibolitos. H) Magmatismo brasileiro, caracterizado principalmente por diques de direção N-S. I) Enxame de diques Rio Ceará Mirim, composto por diques basálticos de direção E-W e idade em torno de 0,12 Ga.

1.3.2.1 - Unidade Bom Jesus – 3,41 Ga

Corresponde à unidade mais antiga da região, composta por ortognaisses tonalíticos na porção central do maciço. Sua mineralogia inclui principalmente plagioclásio sódico e quartzo, com assembleia máfica composta por hornblenda e quartzo. Frequentemente encontram-se enclaves máficos (anfíbolitos) boudinados segundo a foliação principal. Datações U-Pb em zircão indicam uma idade de cristalização de 3412 ± 8 Ma (Dantas *et al.*, 2004). Do ponto de vista geoquímico, essas rochas são predominantemente metaluminosas com $\epsilon\text{Nd}(t)$ negativo (-2,24), indicando que sua origem está relacionada a fusão parcial de um manto enriquecido (Dantas, 1996; Dantas *et al.*, 2004; Dantas *et al.*, 2013; Souza *et al.*, 2016). Isótopos de curta meia-vida de ^{142}Nd nos anfíbolitos e tonalitos indicam que o manto que gerou estas rochas já tinha uma composição enriquecida desde o Hadeano, sendo resultante da diferenciação inicial da Terra (Garcia *et al.*, 2023).

1.3.2.2 Complexo Serra Caiada – 3,39 Ga e 3,36 Ga

É composto predominantemente por ortognaisses granodioríticos a graníticos, e localmente tonalíticos. Sua mineralogia máfica é composta por biotita $\pm$ diopsídio $\pm$ hornblenda (Dantas *et al.*, 2013). Sua tendência geoquímica é peraluminosa a metaluminosa e sub-alcalina (Dantas, 1996). Datações U-Pb em zircão dos ortognaisses indicam dois eventos magmáticos importantes, em ca. 3356 ± 21 Ma e 3393 ± 17 Ma (Dantas *et al.*, 2013; Dantas *et al.*, 2004; Souza *et al.*, 2016). Valores de $\epsilon\text{Nd}(t)$ variam de levemente positivos a negativos (+0,34 a -2,39), com idade modelo T_{DM} variando de 4,1 Ga a 3,4 Ga (Dantas *et al.*, 2013).

1.3.2.3 Complexo Tangará – 3,30 Ga

Apesar dos intensos estudos acerca dos migmatitos de origem ígnea no Maciço São José do Campestre, a sequência metassedimentar que sobrepõe este embasamento ainda carece de estudos aprofundados. Os mármores, frequentemente associados a formações ferríferas bandadas, foram estudados principalmente do ponto de vista geoquímico, sendo interpretados como depositados em ambientes de plataforma marinha e fundo oceânico (Figueiredo, 2012). Isótopos de Sm-Nd forneceram uma isócrona pouco precisa de idade 3751 ± 230 Ma, sugerindo uma deposição durante o Eo-Paleoarqueano (Silva Filho, 2012).

Por sua vez, as rochas metassedimentares, interpretadas em mapas antigos como pertencentes ao Grupo Seridó e compostas principalmente por migmatitos com paleossoma xistoso, foram pouco estudadas. Datações por U-Pb em zircão de uma única amostra forneceram uma idade máxima de deposição em aproximadamente 2700 Ma (Souza et al., 2016). Desta forma, estas rochas são distintas das rochas que compõem o Grupo Seridó, com idade máxima de deposição em aproximadamente 633 Ma (Van Schmus et al, 2003; Ribeiro et al., 2023).

Contudo, conforme os resultados do primeiro artigo desta tese, uma investigação detalhada das texturas internas do zircão, bem como a análise de um número maior de amostras e grãos, permitiu estabelecer uma idade máxima de deposição em 3305 ± 16 Ma e metamorfismo em condições de fácies granulito entre 3084 ± 4 e 3006 ± 6 Ma (Ribeiro et al., 2024). Consequentemente, de forma a diferenciar estas rochas do embasamento metaplutônico da região, é adotada a definição de Complexo Tangará para as rochas de origem sedimentar do Maciço São José do Campestre.

O Complexo Tangará é composto por paragneisses migmatíticos, com assembleia metamórfica característica marcada por granada + silimanita + espinélio $\pm$ cordierita. O protólito destas rochas provavelmente tem uma composição pelítica e uma idade máxima

de deposição em 3,30 Ga (Ribeiro et al., 2024). Frequentemente são descritas intercalações de rochas calciossilicáticas, quartzitos, formações ferríferas bandadas e mármore neste conjunto, carecendo de estudos aprofundados.

1.3.2.4 Complexo Brejinho –3,18 Ga

Engloba ortognaisses do tipo Tonalito-Trondhjemito-Granodiorito (TTG), com biotita $\pm$ diopsídio como máficos principais. Datações U-Pb em zircão indicam que este magmatismo ocorreu em aproximadamente 3178 ± 8 Ma (Dantas *et al.*, 2004). Valores de $\epsilon\text{Nd}(t)$ são predominantemente positivos (+1,20 a +1,40), indicando um magmatismo principalmente juvenil, com idade modelo T_{DM} entre 3,6 a 3,2 Ga (Dantas *et al.*, 2013).

1.3.2.5 Ortogneisse São Pedro do Potengi – 3,12 Ga

Corresponde ao *stock* Serra Branca (provavelmente na localidade denominada Pedra Branca), composto por biotita-hornblenda ortognaisses de composição granodiorítica a granítica (Souza *et al.*, 2016). Datações U-Pb em zircão indicam uma cristalização em 3118 ± 19 Ma, com idade modelo T_{DM} 3,53 Ga e valores de $\epsilon\text{Nd}(t)$ negativos (-3,21), em torno de -3,2 (Souza *et al.*, 2016).

1.3.2.6 Complexo Riacho das Telhas – 3,08 e 3,04 Ga

Associação de rochas máficas-ultramáficas intrusivas no embasamento Arqueano, com características geoquímicas que incluem magmas tholeiíticos ricos em Fe com assinatura de E-MORB (Abrahão Filho, 2016). Engloba piroxenitos, localmente enriquecidos em cromita e magnetita, lherzolitos, wherlitos, gabros e anfibolitos (Jesus, 2011; Abrahão Filho, 2016). Com base em datações U-Pb em zircão, a duração deste magmatismo foi estabelecida entre 3083 ± 17 Ma e 3041 ± 23 Ma (Jesus, 2011; Abrahão Filho, 2016). Valores de $\epsilon\text{Nd}(t)$ são levemente positivos (+0,41 a +6,41), indicando um episódio de magmatismo juvenil pela fusão de um manto empobrecido (Jesus, 2011).

Nesta unidade também estão inclusas as rochas do Complexo Senador Elói de Souza (Dantas, 1996; Dantas et al., 2004), que inclui principalmente gabros e rochas ricas em plagioclásio albitico (Costa, 2000).

1.3.2.7 Sienogranito São José do Campestre – 2,69 Ga

É composto principalmente por sienogranitos com hornblenda, ocorrendo como diversos plutons com pouca deformação (Dantas, 1996), se destacando no relevo da região. Datações U-Pb em zircão sugerem idades de cristalização de 2685 ± 9 Ma e 2664 ± 13 Ma (Dantas et al., 2004; Souza et al., 2023). Tem caráter metaluminoso sub-alcálico, possivelmente formado em contexto pós-colisional a tardi-orogênico (Dantas, 1996; Dantas et al., 2004, 2013; Souza et al., 2016, 2023). Valores negativos de $\epsilon\text{Nd}(t)$, em torno de -4,20, e idade modelo T_{DM} em torno de 3,2 Ga indicam que este magmatismo foi gerado pela fusão parcial da crosta continental arqueana ou um manto metassomatizado (Dantas, 1996; Dantas et al., 2004, 2013; Souza et al., 2016).

1.3.2.8 Diques máficos de Cajazeiras – 2,52 Ga

Um dos resultados do segundo artigo desta tese é a datação de um dique de anfíbolito, encaixado em biotita paragneisses, localizado no vilarejo de Cajazeiras, no município de Macaíba/RN (Ribeiro et al., 2025). Cristais e bordas de zircão de origem ígnea nesta amostra forneceram uma idade de cristalização de 2521 ± 22 Ma.

A amostra corresponde ao corpo mais espesso de uma série de diques de anfíbolito de direção principal NW-SE, com espessura métrica a centimétrica. Estas rochas apresentam uma foliação protomilonítica concordante com a foliação da rocha encaixante. Contudo, a rocha encaixante é fortemente migmatizada e apresenta dobras que são ausentes no anfíbolito, marcando o caráter intrusivo do anfíbolito e posterior a

deformação de alta temperatura da rocha encaixante, estimada em torno de 3.0 Ga (Ribeiro et al., 2024; 2025).

Petrograficamente, estas rochas distinguem-se das demais rochas máficas da região pela ausência de minerais de alta temperatura, como piroxênio e granada, sendo composta principalmente por plagioclásio + anfibólio + quartzo + titanita + magnetita.

1.3.2.9 Magmatismo Brasileiro – 0,60 Ga

No interior do Maciço São José do Campestre ocorrem diversos *stocks* circulares de rochas graníticas, sem deformação aparente, e diques com direção preferencial N-S (Roig & Dantas, 2013; Ribeiro, 2019). Apenas uma única amostra, um dique em São Paulo do Potengi, foi investigado por meios geoquímicos e isotópicos (Souza et al., 2016). Isótopos de U-Pb em bordas de zircão forneceram uma idade em torno 619 ± 18 Ma, interpretada como a idade de cristalização da rocha (Souza et al., 2016). Isótopos de Sm-Nd em rocha total forneceram uma idade modelo T_{DM} de 2.61 Ga e $\epsilon Nd(t)$ de -22.81, sugerindo uma origem a partir da fusão da crosta arqueana da região (Souza et al., 2016).

1.3.2.10 Magmatismo Rio Ceará-Mirim – 0,12 Ga

Diques de basalto, com direção principal E-W, foram mapeados em algumas porções do Maciço São José do Campestre (Ribeiro, 2019), sendo correlacionáveis aos Enxame de Diques Rio Ceará-Mirim, com idades $^{40}\text{Ar}/^{39}\text{Ar}$ entre 136 e 111 Ma (Araújo et al., 2001; Souza et al., 2003).

CAPÍTULO 2: OBJETIVOS

2.1 Objetivos gerais

O presente estudo tem como objetivo determinar a duração de eventos geológicos na crosta continental durante o Paleo-Mesoarqueano a partir da caracterização dos migmatitos de origem sedimentar do Maciço São José do Campestre.

O entendimento destes processos permite fazer inferências sobre a evolução da crosta continental durante o Arqueano. Os resultados obtidos tem implicações para a evolução da tectônica de placas, bem como para a paleogeografia da região na Terra primitiva.

2.2 Objetivos específicos

- Determinar uma idade máxima de deposição e de metamorfismo para as rochas supracrustais do Maciço São José do Campestre com base em isótopos de U-Pb e elementos traços em zircão.
- Quantificar a trajetória P-T-t do metamorfismo de idade Mesoarqueana que afetou estas rochas com base em dados de química mineral, modelagem termodinâmica combinada com difusão.
- Estabelecer um modelo tectônico para o Paleoarqueano-Mesoarqueano da região a partir das idades e condições de metamorfismo obtidas.
- Encontrar correlações com outros blocos arqueanos, atualmente dispersos pela tectônica de placas e localizados em outros continentes, a partir da correlação de eventos geológicos.

CAPÍTULO 3: MATERIAIS E MÉTODOS

As informações descritas neste capítulo são um resumo dos materiais e métodos analíticos utilizados durante a realização da pesquisa. sendo descritos integralmente nos respectivos artigos resultantes.

3.1 Revisão bibliográfica, atividades de campo e preparação de amostras

Foram compilados mapas previamente publicados da região (Amaral, 1990; Dantas & Roig, 2013; Ribeiro, 2019), bem como dados isotópicos e geoquímicos (Dantas et al., 2004. 2013; Souza et al., 2016, 2023). Mapas geofísicos, principalmente gamaespectrometria e magnetometria, e imagens de satélite foram utilizados para auxiliar as atividades de campo (Ribeiro, 2019). A localização e descrição de diversos afloramentos foram disponibilizadas pelo prof. Elton Dantas para a produção dos mapas geológicos.

Conforme descrito anteriormente, as amostras foram coletadas em três principais localidades (vilarejo de Cajazeiras, município Serra Caiada e agrovila São Tomé).

Inicialmente, seções delgadas das amostras coletadas foram confeccionadas pela empresa Geolab. Posteriormente, seções delgadas complementares foram confeccionadas no Laboratório de Laminação da Universidade de Brasília.

Parte do material coletado passou pelo processo de britagem e separação magnética para concentração de cristais de zircão. O material resultante foi inspecionado utilizando uma lupa binocular para a separação dos cristais de zircão, que foram então montados em resina no Laboratório de Estudos Geodinâmicos, Geocronológicos e Ambientais (LEGGA). As amostras TANQUE (1, 2 e 3) foram também pulverizadas em um almofariz de ágata para análise de elementos maiores e traços em rocha total.

As técnicas analíticas empregadas nestas amostras serão descritas nas seções a seguir. As análises foram realizadas principalmente em laboratórios da Universidade de Brasília, com análises complementares realizadas na Universidade de São Paulo e na Universidade Estadual de São Paulo.

3.2 Microscopia óptica

As seções delgadas foram descritas e fotografadas no Laboratório de Microscopia, Universidade de Brasília, utilizando um microscópio com câmera acoplada ZEISS Axio A2m. As imagens foram processadas no software ZEISS Zen (*blue edition*). As seções delgadas do afloramento TANQUE (1, 2 e 3) foram escaneadas utilizando uma lente com aproximação de 10× acoplada a um microscópio ZEISS Axioscope 5 e unidas utilizando o software ZEISS Microscopy no LEGGA.

3.3 Microscopia eletrônica

Imagens de elétrons retroespalhados (*backscattered electrons* - BSE) e catodoluminescência (CL) foram obtidas em *mounts* de zircão utilizando um Microscópio Eletrônico de Varredura (MEV) FEI Quanta 450 acoplado a um detector Gatan ChromaCL2 iBSED, utilizando uma corrente de 10 nA e 20 kV, e distância de operação de 13.8 mm no LEGGA. As imagens foram processadas no software Gatan DigitalMicrograph.

As seções delgadas também foram investigadas por meios de microscopia eletrônica utilizando o mesmo equipamento acoplado a espectroscopia de energia dispersiva (*Energy Dispersive Spectroscopy* – EDS) no LEGGA. A quantificação mineralógica da seção delgada CJ-128 foi realizada no QEMLab, Universidade de Brasília, utilizando também um FEI Quanta 450, acoplado a dois detectores EDS Bruker XFlash, operando em condições idênticas as análises do LEGGA e resolução espacial 10 µm.

3.3 Isótopos de U-Pb e elementos traços em zircão

Todas as amostras, com exceção da amostra TANQUE-1, foram analisadas para isótopos de U-Pb e elementos traços em zircão utilizando um espectrômetro de massa por plasma acoplado indutivamente Thermo Finnigan Element XR *high-resolution* coletor-

simples acoplado a um sistema de ablação a laser de 193 nm Iridia Excimer (ArF) com câmara de volume-duplo de cobalto no LEGGA. As massas ^{202}Hg , ^{204}Pb , ^{206}Pb , ^{207}Pb , ^{208}Pb , ^{232}Th e ^{238}U utilizando um sistema de detecção tripo (SEM + Faraday) através da varredura do setor eletrostático em cada massa. Foram utilizados pulsos circulares com taxa de repetição de 20 Hz, fluência do laser de 2 J/cm² e diâmetro de amostragem de 25 µm. Para controle de qualidade foram analisados os materiais de referência GJ-1 (602 ±0.7 Ma; Horstwood et al., 2016; Jackson et al., 2004), 91500 (1062.4 ±0.4 Ma; Wiedenbeck et al., 2004) e/ou Plesovice (337.13 ±0.37 Ma; Sláma et al., 2008). A estratégia de análise consistiu na aquisição de 10 segundos de branco, seguido por 20 segundos de ablação da amostra. No início de cada seção, foram realizadas duas análises de cada material de referência, seguidas por dez análises do material de composição desconhecida. Esta sequência foi mantida até o final da sessão, no qual foram realizadas mais duas análises de cada material de referência.

A análise de elementos traços foi realizada em algumas amostras utilizando o mesmo equipamento. As massas ^{29}Si , ^{43}Ca , ^{45}Sc , ^{49}Ti , ^{51}V , ^{88}Sr , ^{89}Y , ^{93}Nb , ^{139}La , ^{140}Ce , ^{141}Pr , ^{143}Nd , ^{147}Sm , ^{151}Eu , ^{157}Gd , ^{159}Tb , ^{163}Dy , ^{165}Ho , ^{166}Er , ^{169}Tm , ^{172}Yb , ^{175}Lu , ^{177}Hf , ^{206}Pb , ^{232}Th e ^{238}U foram analisadas utilizando pulsos circulares com taxa de repetição de 20 Hz, fluência do laser de 4 J/cm² e diâmetro de amostragem de 35 µm. Os materiais de referência vidro NIST-610, NIST-612 (Jochum et al., 2016), monazita Diamantina (Gonçalves et al., 2018) e a apatita Durango (Chew et al., 2016) foram analisados para controle de qualidade.

A amostra TANQUE-1 foi analisada utilizando um espectrômetro de massa Thermo Finnigan Neptune XT *high-resolution* multi-coletor de campo setorial acoplado a um sistema de ablação a laser 193 nm Teledyne Analyte Excite equipado com uma câmara de volume-duplo HeLEX II no LEGGA. As massas ^{202}Hg , ^{204}Pb , ^{206}Pb , ^{207}Pb ,

^{208}Pb , ^{232}Th e ^{238}U foram medidas simultaneamente utilizando uma combinação de detectores Faraday, SEM e CDD. Foram utilizados pulsos circulares com taxa de repetição de 8 Hz, fluência do laser de 4 J/cm² e diâmetro de amostragem de 20 µm. Para controle de qualidade foram analisados os mesmos materiais de referência utilizados no ElementXR e a mesma estratégia de análise (i.e., duas análises de cada material de referência seguidas por dez análises do material de composição desconhecida e duas análises finais de cada material de referência).

Elementos traços nas amostras TANQUE (1 e 3) foram medidos utilizando um espectrômetro de massa por plasma acoplado indutivamente Thermo Scientific iCapQ acoplado a um sistema de ablação 213 nm CETAC LSX-213 G2+ na Universidade de São Paulo. Foram analisadas as massas 7Li, 24Mg, 27Al, 29Si, 31P, 42Ca, 44Ca, 45Sc, 49Ti, 55Mn, 56Fe, 59Co, 85Rb, 88Sr, 89Y, 91Zr, 93Nb, 95Mo, 118Sn, 121Sb, 137Ba, 139La, 140Ce, 141Pr, 143Nd, 147Sm, 151Eu, 157Gd, 159Tb, 161Dy, 165Ho, 166Er, 169Tm, 173Yb, 175Lu, 179Hf, 181Ta, 206Pb, 207Pb, 208Pb, 232Th e 238U. Foram utilizados pulsos circulares com taxa de repetição de 15 Hz, fluência do laser de 15.43 J/cm² e um diâmetro de amostragem de 50 µm para o material de referência primário (vidro NIST-610 – Jochum et al., 2016) e 30 µm para o material de referência secundário (zircão GJ-1, Horstwood et al., 2016; Jackson et al., 2004; Piazzolo et al., 2017), bem como para as amostras de composição desconhecida. A estratégia de análise consistiu na aquisição do branco por 20 segundos, seguido de 40 segundos de ablação da amostra. O material de referência primário foi analisado duas vezes no início da sessão, seguido por uma análise do material de referência secundário e vinte análises do material de composição desconhecida. Em seguida, foi realizada uma análise de cada material de referência, seguido de vinte análises do material de composição desconhecida. Ao final

da sessão analítica, foram realizadas novamente duas análises do material de referência primário e uma do material de referência secundário.

Para o processamento das análises de U-Pb, foi utilizado o *software* Iolite 4.0 (Paton et al., 2011) com auxílio do *plugin* VizualAge (Petrus & Kamber, 2012). O processamento inclui a seleção das janelas (i.e., duração do sinal de ablação) a ser utilizado, subtração do branco, normalização pelo material de referência primário, GJ-1 (602 ± 0.7 Ma; Horstwood et al., 2016; Jackson et al., 2004) e correção do fracionamento elementar induzido pelo laser (*laser induced elemental fractionation* – LIEF) utilizando um modelo linear + exponencial. Os resultados foram exportados seguindo os padrões estabelecidos por Horstwood et al. (2016) para dados de LA-ICP-MS (Figura 5).

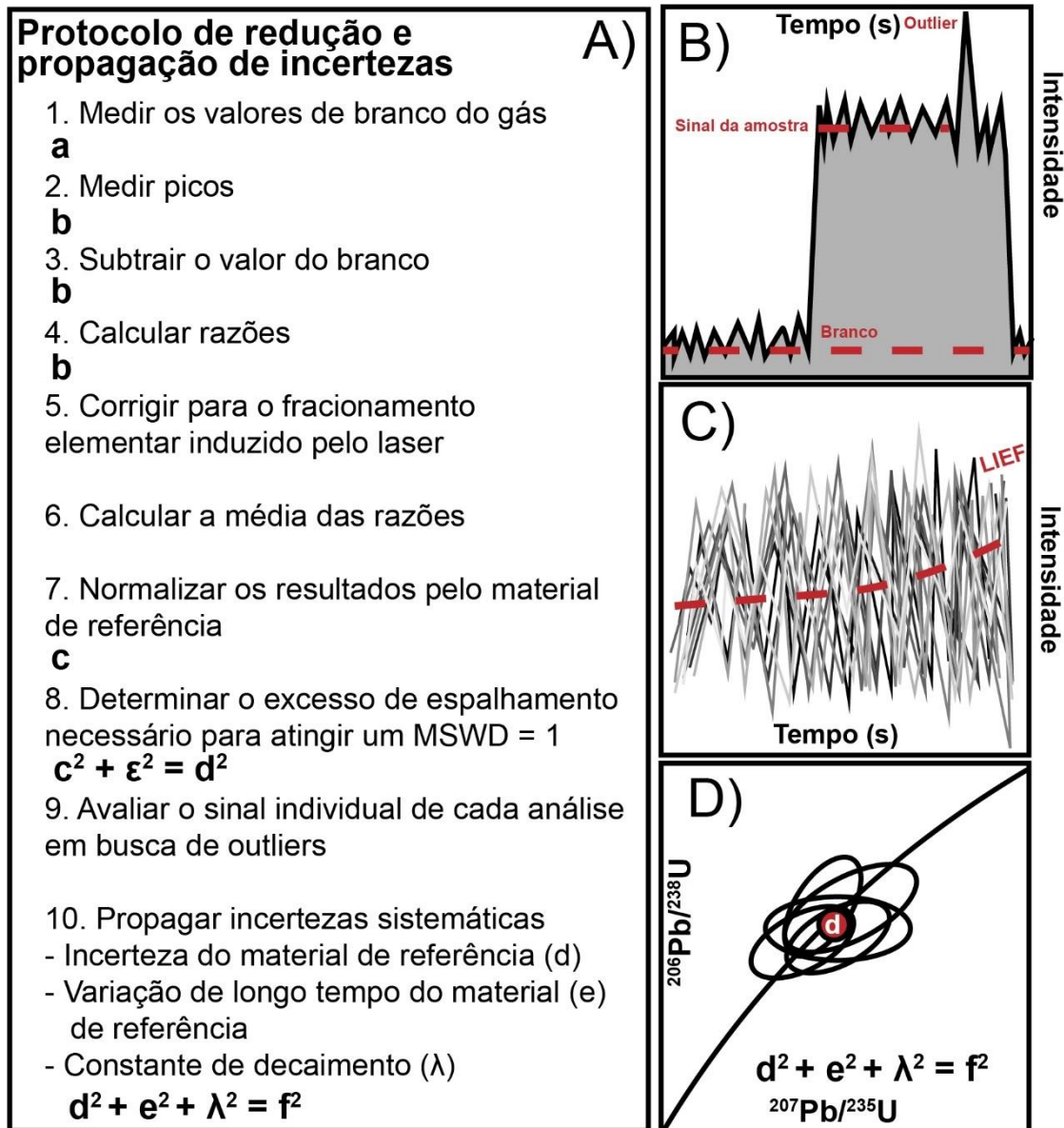


Figura 5: A) Protocolo para redução e propagação de incertezas de dados de LA-ICP-MS com base em Horstwood et al. (2016). B) Ilustração de um sinal típico de LA-ICP-MS, composto pelo branco inicial e o sinal da amostra após o início da ablação. C) Ilustração da correção de fracionamento elementar induzido por laser (LIEF). D) Ilustração da propagação final de incertezas, onde d é a incerteza associada a um conjunto de análises.

Para os elementos traços, o mesmo software, Iolite 4.0 (Paton et al., 2011) foi utilizado. O material de referência primário utilizado para normalização foi o vidro NIST-610 (Jochum et al., 2016). O valor de referência interno utilizado para os minerais correspondeu ao valor estequiométrico de Si do zircão (14,76 wt. %) e Ca para apatita (40 wt. %). Para a monazita, foi utilizado o valor obtido por EPMA por Gonçalves et al. (2018) para Ce (28 wt.%). As concentrações foram reportadas em ppm em 2 erro padrão.

3.4 Espectroscopia Raman

As análises de Espectroscopia Raman foram realizadas nas amostras de zircão do afloramento CJ-202 utilizando um Espectrômetro Raman Horiba LabRam Evolution com microscópio confocal e dispositivo de carga acoplada no Laboratório de Espectroscopia Óptica, Universidade de Brasília. Foi utilizada uma grade de difração de 600 grooves/mm e um laser semiconductor com 633 nm, 50% de potência (5 mW) e uma lente objetiva Olympus de 100× de aproximação. Os espectros foram gravados ao longo de 12 ciclos de 15 segundos, resultando em 3 minutos por análise. ao longo de duas sessões com duração de quatro horas cada. Dois cristais de zircão, caracterizados como materiais de referência, o 91500 (Wiedenbeck et al., 2004) e o BB do Sri Lanka (Santos et al., 2017b) foram analisados no começo e no final de cada sessão, com o intuito de verificar a variação instrumental ao longo da sessão.

Alguns cristais de silimanita em lâmina delgada do afloramento TANQUE também foram investigados por espectroscopia Raman, em condições de operação similares, mas com grade de difração de 1800 grooves/mm e aquisição em 5 ciclos de 10 segundos.

Os espectros gerados foram processados utilizando a biblioteca Ramanspy (Georgiev et al., 2023) para remoção de ruído, remoção da linha de base e normalização. Todos os picos foram então ajustados utilizando uma função Lorentziana e o comprimento a meia altura (*Full Width at Half Maximum* - FWHM) foi medido utilizando o *software* Fitky 1.3.1. Os valores foram então corrigidos para a variação instrumental utilizando a fórmula empírica de Váczi (2014).

3.5 Microsonda eletrônica

A composição de elementos maiores dos minerais foi obtida em seções delgadas das amostras PJ-1 e CJ-128 utilizando uma microsonda eletrônica (*Electron Probe*

Microanalyzer – EPMA) JEOL JXA-8230 com cinco espectrômetros de comprimento de onda (*wavelength-dispersive spectrometer* – WDS) no Laboratório de Microsonda Eletrônica, Universidade de Brasília. As análises foram realizadas utilizando uma voltagem de aceleração de 15 kV, corrente de feixe de 25 nA e diâmetro de amostragem de 3 µm. Análises das amostras TANQUE, bem como análises complementares da amostra PJ-1, foram obtidas utilizando uma microsonda eletrônica de mesmo modelo (JEOL JXA-8230) no Laboratório de Microsonda Eletrônica da Universidade Estadual Paulista, operando sob mesma voltagem de aceleração (15 kV) e corrente de feixe e diâmetro de amostragem maiores (100 nA e 8 µm, respectivamente). Mapas de intensidade para os elementos Al, Mg, Ca, Fe e Mn foram obtidos por WDS, enquanto os elementos F, Na, Si, P, Cl, K, Rb, Sr e Y foram obtidos por espectroscopia de energia dispersiva (*Energy Dispersive Spectroscopy* – EDS).

3.6 Elementos maiores e traços em rocha total

O material pulverizado das amostras TANQUE (1, 2 e 3) foi submetido para análise em rocha total na ALS Global Ltda, utilizando o pacote ME-ICP06 para elementos maiores (Al₂O₃, BaO, CaO, Cr₂O₃, Fe₂O₃, K₂O, MgO, MnO, Na₂O, P₂O₅, SiO₂, SrO, TiO₂ e perda ao fogo) através fusão em fluxo de borato de lítio, digestão ácida e análise por espectroscopia de emissão atômica por plasma acoplado indutivamente (ICP-AES). Os elementos traços (Ba, Ce, Cr, Cs, Dy, Er, Eu, Ga, Gd, Sn, Sr, Ta, Tb, Th, Tm, U, V, W, Y, Yb, Zr) foram analisados pelo pacote ME-MS81 por espectrometria de massa com plasma indutivamente acoplado (ICP-MS).

CAPÍTULO 4: ESTADO DA ARTE

4.1 Dinâmica crustal e tectônica

Dois principais modelos de dinâmica superficial são descritos em planetas rochosos: litosfera móvel (*mobile lid*) e litosfera fixa (*stagnant lid*). Este conceito está

relacionado a estruturação interna do planeta, onde a litosfera é caracterizada por uma camada externa com temperatura distinta das porções interiores do planeta, atuando como uma barreira termal e reológica (Figura 6; Stern et al., 2018).

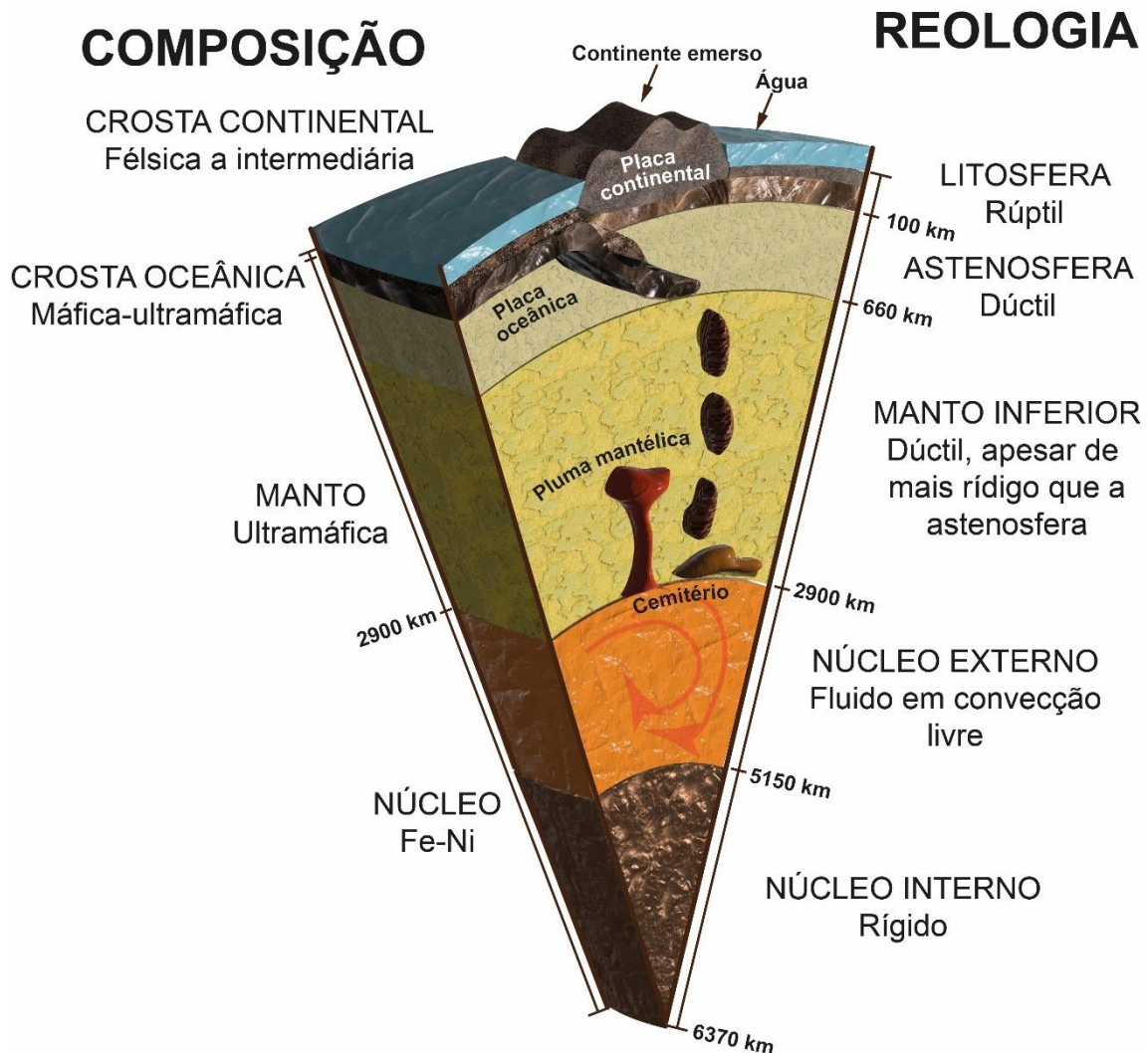


Figura 6: Estrutura interna da Terra a partir de divisões geoquímicas e reológicas. Adaptado de Palin et al. (2020).

No contexto de litosfera móvel, as movimentações da litosfera são até 2x mais rápidas que as movimentações internas (Weller & Lenardic, 2018). A rápida dinâmica superficial resulta na troca de energia e elementos com as camadas mais internas do planeta (Moresi & Solomatov, 1998; Ogawa, 2008; Rapp et al., 2008). Entre os planetas do sistema solar, a Terra é o único que apresenta este tipo dinâmica superficial, sendo uma característica típica da tectônica de placas (e.g., Stern et al., 2018).

Por outro lado, no contexto de litosfera fixa, as movimentações da litosfera são até 1000 vezes mais lentas que as velocidades internas (Weller & Lenardic, 2018). Desta forma, a troca de energia e elementos com a superfície é limitada, diminuindo o fluxo de calor e aumentando a temperatura interna do planeta (O'Neill et al., 2007). Planetas como Vênus e Marte, por exemplo, se encaixam nessas definições, tendo a sua dinâmica superficial dominada principalmente pela convecção do manto e ascensão de plumas mantélicas (e.g., Stern et al., 2018).

4.1.1 A origem da tectônica de placas

A dualidade entre os modelos de litosfera fixa e móvel dá origem ao debate em torno do surgimento da tectônica de placas. Segundo a definição atual, a tectônica de placas é caracterizada por placas litosféricas que se movem de forma independente entre si, e em velocidades maiores do que as camadas mais internas do planeta (e.g., Palin et al., 2020). Uma característica típica da tectônica de placas são as zonas convergentes, com a subducção da crosta oceânica sob a crosta continental (e.g., Stern, 2002). Este processo implica no transporte de rochas formadas no assoalho oceânico, como basaltos e sedimentos, para profundidades maiores do que 45 km (e.g., Gerya et al., 2008). A presença de fluidos, principalmente H₂O, tem papel fundamental para a lubrificação da zona de subducção, sendo também responsável pelo metassomatismo do manto litosférico adjacente (e.g., Brizzi et al., 2021). Uma das consequências da tectônica de placas é a formação de extensas cadeias de montanhas, que podem ter tido um papel importante para a distribuição de nutrientes e a evolução da vida na Terra (e.g., Zhu et al., 2022).

Conforme notado por Harrison & Lenardic (2022) no que eles denominaram informalmente como Lei de Burke com base nas palavras do geólogo Kevin Charles Anthony Burke:

“If there’s unambiguous evidence that global geodynamics is today dominated by plate tectonics, then we should assume it was operating since global silicate differentiation until we have evidence that it was not”

Ou seja, se existem evidências inequívocas de que a geodinâmica global atualmente é dominada pela tectônica de placas, então deve-se assumir que ela esteve operante desde a diferenciação da Terra, até que sejam obtidas evidências que provem o contrário.

Do ponto de vista filosófico, esta afirmação tem origem no fato de que a geologia, enquanto ciência natural e histórica, não permite provar que algo é de fato verdadeiro, apenas determinar que a hipótese nula é falsa (Harrison & Lenardic, 2022). Ou seja, dentro de um conjunto de hipóteses, só é possível determinar quais são menos prováveis dadas as observações. E, uma vez que as observações feitas correspondem a uma fração mínima do objeto natural em estudo, as explicações mais simples são sempre as mais prováveis (conceito da Navalha de Ockham). Consequentemente, não é possível determinar quando a tectônica de placas teve início (e.g., Harrison, 2024), uma vez que não existe nenhuma evidência que prove a sua não existência em determinado período do tempo, e qualquer explicação alternativa requer uma hipótese mais complexa, violando o conceito da Navalha de Ockham.

Por outro lado, uma outra corrente de pensamento sugere que após resfriamento inicial da Terra, a sua estrutura se assemelhasse a de outros planetas com uma litosfera fixa. Esta hipótese é baseada principalmente na observação da superfície de planetas como Marte e Vênus e na diferença observada no registro geológico Pré-Cambriano (e.g., Arndt, 2023). Eventualmente, a Terra teria evoluído para um sistema com litosfera móvel e tectônica de placas, com diversos autores postulando o período entre 3.2 – 3.0 Ga para esta transição (Dhuime et al., 2015; Tang et al., 2016; Kirkland et al., 2021).

Na Figura 7 são sumarizadas as principais propostas para o início da tectônica de placas, bem como as principais evidências para a sua atuação (Palin et al., 2020). Evidências diretas da subducção de crosta oceânica a profundidades extremas foram encontradas apenas até o Neoproterozoico (0.62 Ga), em eclogitos do Mali (Jahn et al., 2001). Contudo, atualmente, o Paleoproterozoico é o período mais aceito para o início da ocorrência da subducção no planeta Terra, marcado pela ocorrência retroeclogitos com idade em torno de 2.1 Ga localizados no Congo (François et al., 2018). Neste período foram formados extensos arcos magmáticos em diversos continentes durante a assembleia do supercontinente Columbia/Nuna.

Propostas para um início mais jovem da tectônica de placas são baseados em evidências indiretas, como a emergência da crosta continental félsica (e.g., Dhuime et al., 2015; Tang et al., 2016). Contudo, conforme será discutido a seguir, muitos argumentam que a geração de crosta continental félsica ocorreu em contextos em que a tectônica de placas não era atuante.

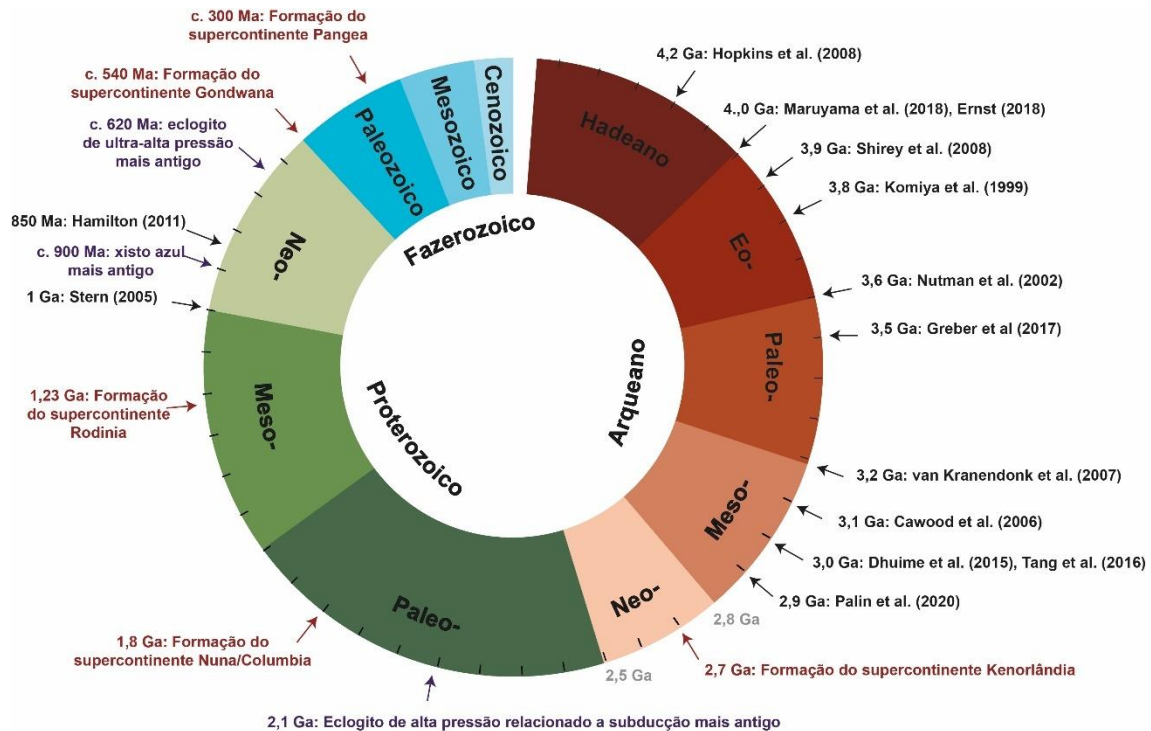


Figura 7: Escala do tempo geológico com os principais eventos e propostas para o início da tectônica de placas. Adaptado de Palin et al. (2020)

4.1.2 Formação da crosta continental

Atualmente, a composição da crosta continental é bem definida por uma composição média andesítica ($57\% \text{ SiO}_2 < 65\%$), cobrindo cerca de 40% da superfície terrestre atual (Rudnick & Gao, 2003; Hacker et al., 2011). Esta composição é distinta da composição de outros planetas no nosso sistema solar, sendo resultante da diferenciação do planeta e evolução da tectônica de placas (Hawkesworth & Kemp, 2006).

Contudo, os primeiros continentes arqueanos incluíam uma grande porção de rochas máficas e ultramáficas, formadas a partir da fusão parcial do manto, que influenciavam diretamente a dinâmica terrestre (Nebel-Jacobsen et al., 2018; Chen et al., 2020; Ptáček et al., 2020). Por exemplo, as altas temperaturas potenciais do manto durante o Arqueano induziam maiores taxas de fusão parcial, gerando espessos platôs oceânicos (e.g., Korenaga, 2006; Nebel et al., 2018). Desta forma, alguns autores argumentam que a geração de crosta continental félsica iniciou na base destes platôs oceânicos, com a

formação de magmas do tipo TTG em grandes profundidades (>30 km). O fragmento mais antigo de crosta continental, com idade em torno de 4,03 Ga e localizado no Complexo Acasta, Canadá, é interpretado como resultante deste tipo de processo (e.g., Reimink et al., 2016). Neste contexto, a tectônica de placas não tem relação com o surgimento da crosta continental félsica.

Por outro lado, o material crustal mais antigo encontrado corresponde aos cristais de zircão detrítico de Jack Hills, na Austrália, com idade em torno de 4,35 Ga (Wilde et al., 2001). Estima-se que estes cristais cristalizaram a partir de um magma de composição andesítica, similar a análogos modernos formados em contexto de subducção (Turner et al., 2020). Alternativamente, Borisova et al. (2022) interpretaram a assinatura isotópica e de elementos traços destes minerais como resultante da interação entre magmas basálticos e peridotitos hidratados. Este mecanismo seria responsável pela formação de magmas félsicos na presença de água superficial, em baixas profundidades, e na ausência de placas tectônicas.

Independentemente dos mecanismos, estima-se que cerca de 60% da crosta continental foi formada nos primeiros 1,5 bilhões de anos da Terra (Cawood et al., 2013). O período de inflexão na taxa de crescimento crustal, durante o Mesoarqueano (Figura 8), está associado a variações em diversos marcadores, como a diminuição das temperaturas potenciais do manto e surgimento de continentes emersos (e.g., Dhuime et al., 2012; Tang et al., 2016; Wang et al., 2021; Arndt, 2023). Consequentemente, muitos acreditam que estas mudanças refletem o surgimento da tectônica de placas.

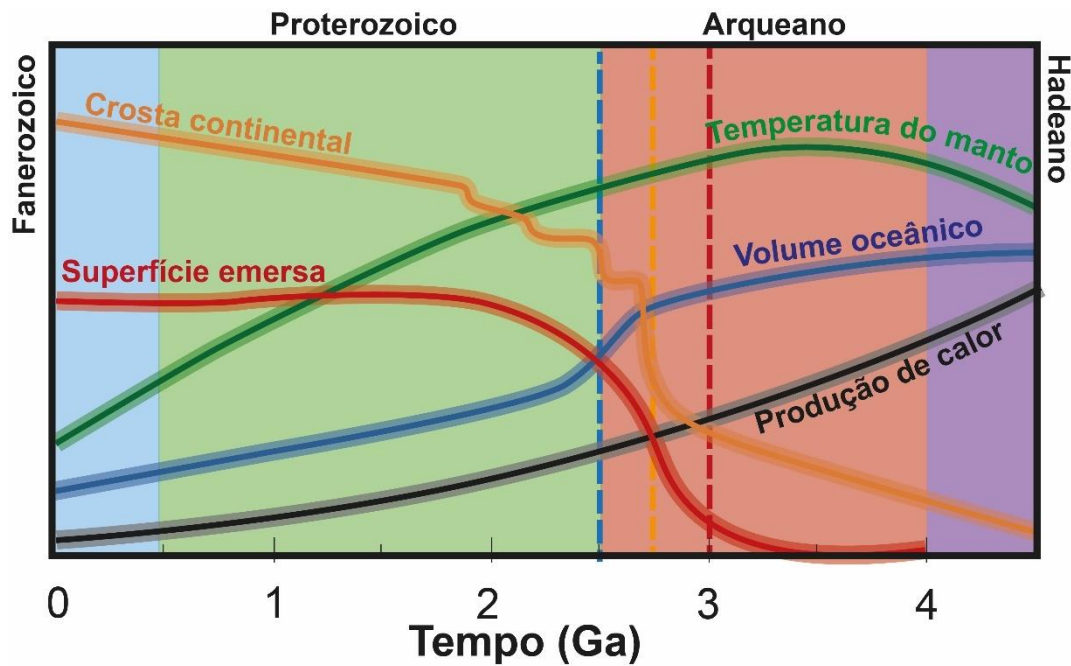


Figura 8: Variações de diversos parâmetros ao longo da evolução do planeta Terra. Linhas tracejadas marcam os principais pontos de inflexão. Adaptado de Arndt (2023).

4.1.3 Deposição de sequências sedimentares durante o Arqueano

A ocorrência de rochas sedimentares arqueanas está diretamente ligada a blocos cratônicos (Drabon et al., 2017; Khelen et al., 2020) e, localmente, pedaços de embasamento dentro de cinturões orogênicos mais jovens (Yang et al., 2016; Savko et al., 2021; Yu et al., 2021), ou como xenólitos em rochas ígneas mais jovens (Greer et al., 2020). Apesar dessas rochas ocorrerem em praticamente todos os continentes, sua distribuição não é uniforme (Figura 9). Bacias sedimentares eo- a paleoarqueanas tem ocorrência restrita, com os exemplos mais estudados na África (*greenstonebelt* de

Barberton), Groelândia (sequência supracrustal de Isua), América do Sul (*greenstone belt* Mundo Novo) e América do Norte (*greenstone belt* Nuvvuagittuq).

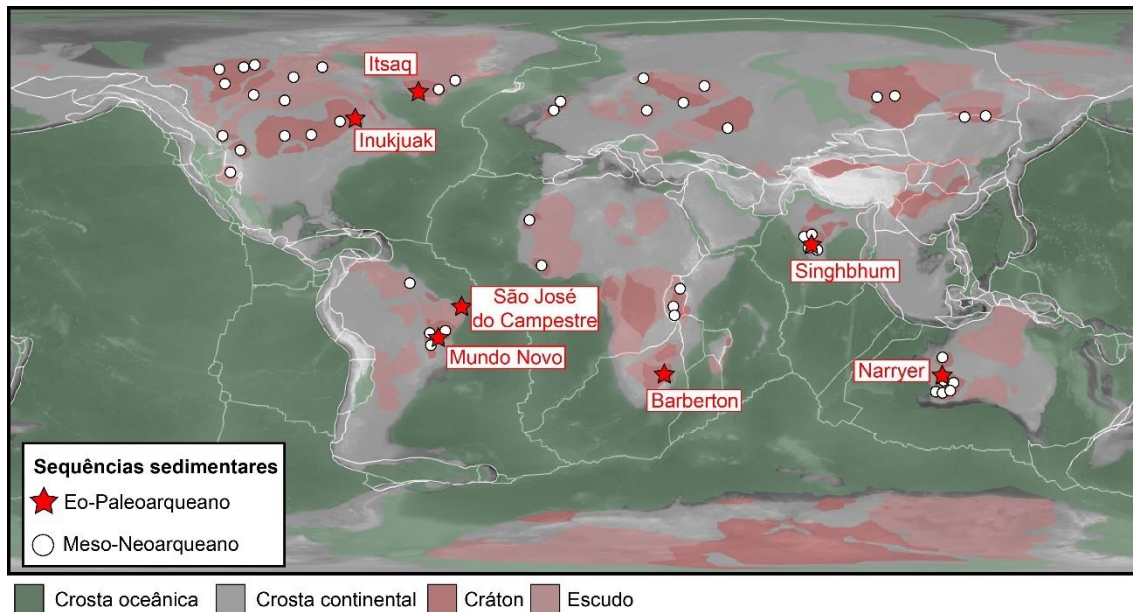


Figura 9: Localização das principais sequências sedimentares Arqueanas. Base cartográfica obtida em Puetz et al. (2021) e Hasterok et al. (2022).

Um dos exemplos mais bem preservados de sequências sedimentares arqueanas ocorre no *greenstone belt* de Barberton, na margem leste do Cráton Kaapvaal (Figura 10). A base da sequência é composta pelo Grupo Onverwacht, composto principalmente por rochas vulcânicas basálticas intercaladas com cherts, vulcanoclásticas félsicas e komatiitos com idades entre 3481 e 3258 Ma. Sobrepondo estas rochas, o Grupo Fig Tree é composto por pelitos finos, vulcanoclásticas, cherts e conglomerados com idade máxima de deposição em torno de 3223 ± 1 Ma (Drabon et al., 2019). Por fim, essas sequências são sobrepostas por rochas siliciclásticas, como arenitos e conglomerados, do Grupo Moodies com idade máxima de deposição de 3219 ± 9 Ma (Heubeck et al., 2013). Devido ao baixo grau metamórfico atingido por estas rochas, elas preservam os microfósseis e estromatólitos mais antigos do mundo (Homann, 2019).

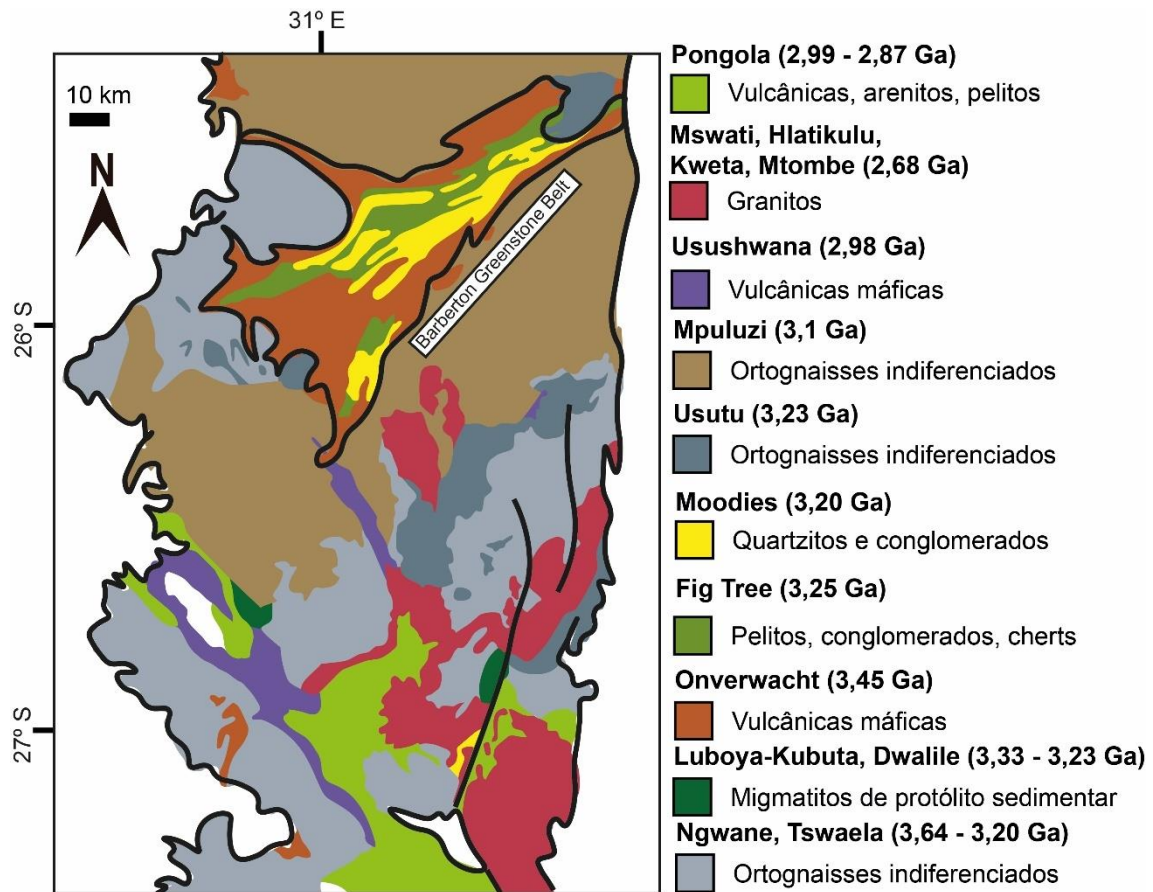


Figura 10: Mapa geológico simplificado da porção leste do cráton do Kaapvaal. Adaptado de Kröner (2007).

No Cráton São Francisco, o *greenstone belt* Mundo Novo Norte é composto por metabasaltos, formações ferríferas bandadas, rochas ultramáficas e xistos carbonáceos (Figura 11). Cristais de zircão magmáticos obtidos em um basalto almofadado indicam uma idade de cristalização em 3338 ± 34 Ma (Teles et al., 2022). Estas rochas são sobrepostas por quartzitos com idade máxima de deposição em 3353 ± 22 Ma (Teles et al., 2022). Essa sequência é sobreposta pela Bacia de Jacobina, com rochas siliciclásticas como arenitos, conglomerados e pelitos com idade máxima de deposição em 3249 ± 63 Ma (Teles et al., 2015).

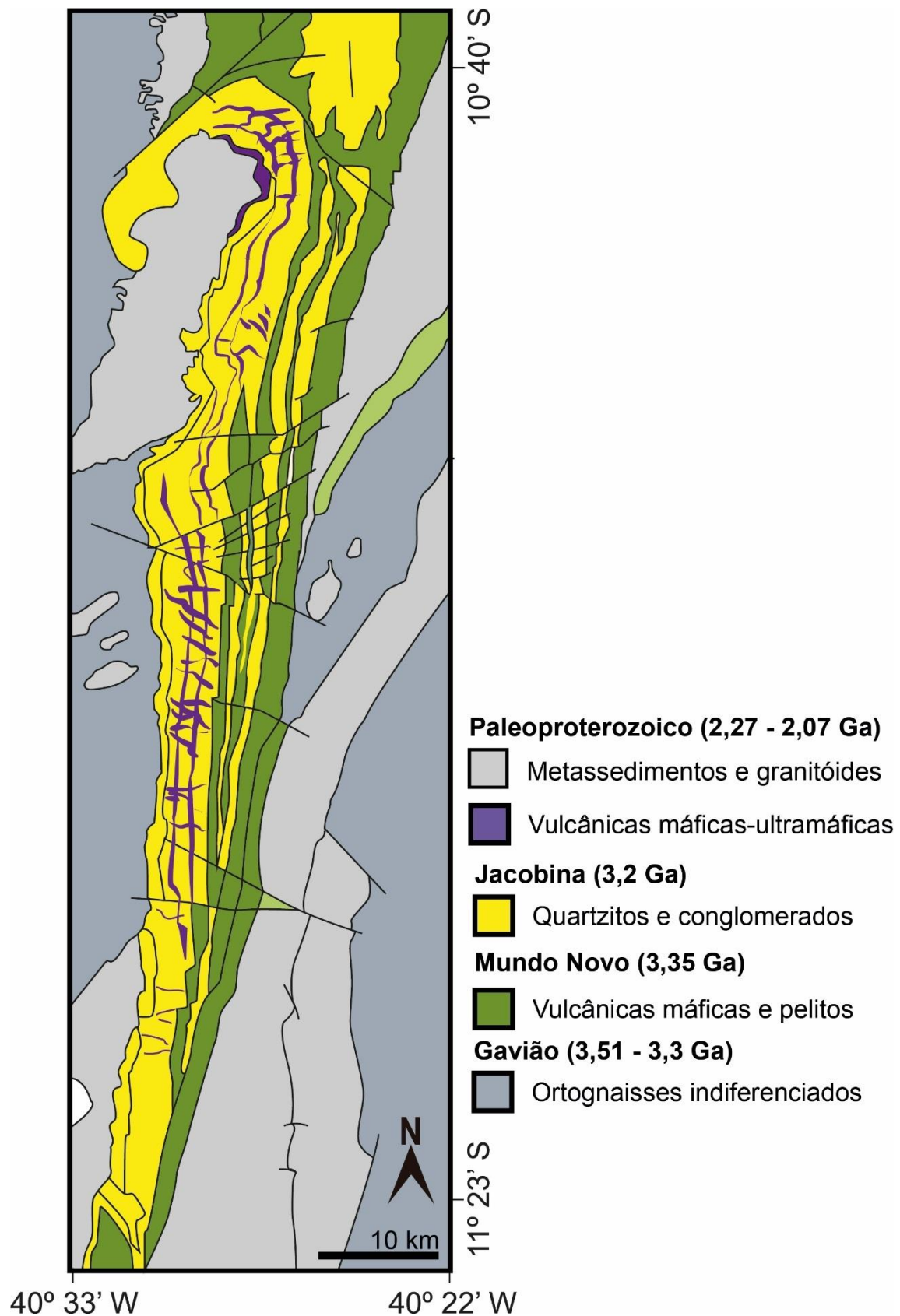


Figura 11: Mapa geológico do *greenstone belt* Mundo Novo e Bacia de Jacobina, Cráton São Francisco.

Adaptado de Teles et al. (2015).

Como visto nestes exemplos, sequências siliciclásticas arqueanas ocorrem frequentemente precedidas por magmatismo máfico-ultramáfico, provavelmente representando sistemas deposicionais associados a antigas bacias oceânicas (e.g., de Wit, 2004; Furnes et al., 2015). As espessas sequências siliciclásticas indicam a presença de grandes massas continentais acima do nível do mar a partir de, pelo menos, o Mesoarqueano (Bindeman et al., 2018; Ptáček et al., 2020), um aspecto amplamente debatido através do registro isotópico e de elementos traços destas rochas (McLennan et al., 1984; Taylor & McLennan, 1986; Nebel-Jacobsen et al., 2018; Chen et al., 2020; Garçon, 2021).

4.1.4 Regimes de deformação e metamorfismo

A crosta continental arqueana atualmente exposta no planeta Terra é caracterizada em diversas regiões por estruturas em domos e quilhas, onde domos de rochas graníticas são circundadas por quilhas compostas principalmente por *greenstone belts* (Lin, 2005; François et al., 2014). Os mecanismos responsáveis pela geração destas estruturas em larga escala ainda são bastante debatidos. Um dos principais modelos, denominado sagdução (Figura 12), afirma que a diferença de densidade entre as sequências vulcanossedimentares dos *greenstone belts* e a crosta continental félsica dos domos geraria instabilidades gravitacionais (e.g. Thebaud & Rey, 2013). As rochas supracrustais afundariam na crosta, entrando em fusão parcial para a geração de magmas félsicos em um regime com movimentações predominantemente verticais (Robin & Bailey, 2009).

Modelagens numéricas (Yu et al., 2022) indicam a presença de, pelos menos, três trajetórias possíveis para as rochas supracrustais na crosta continental durante a sagdução (Figura 12A). O primeiro deles, é caracterizado por um soterramento progressivo, até pressões em torno de 10 kbar e temperaturas de 850 °C. As rochas ficam retidas na crosta inferior, sem exumação considerável. O resfriamento ocorre em altas

pressões, resultando numa trajetória anti-horária com resfriamento isobárico (Figura 12B). Por outro lado, as rochas imersas nos domos graníticos apresentam um soterramento progressivo sucedido por rápido soerguimento e resfriamento em sentido horário (Figura 12B). Este processo como um todo é relativamente rápido, com uma duração máxima em torno de 20 Ma (Yu et al., 2022).

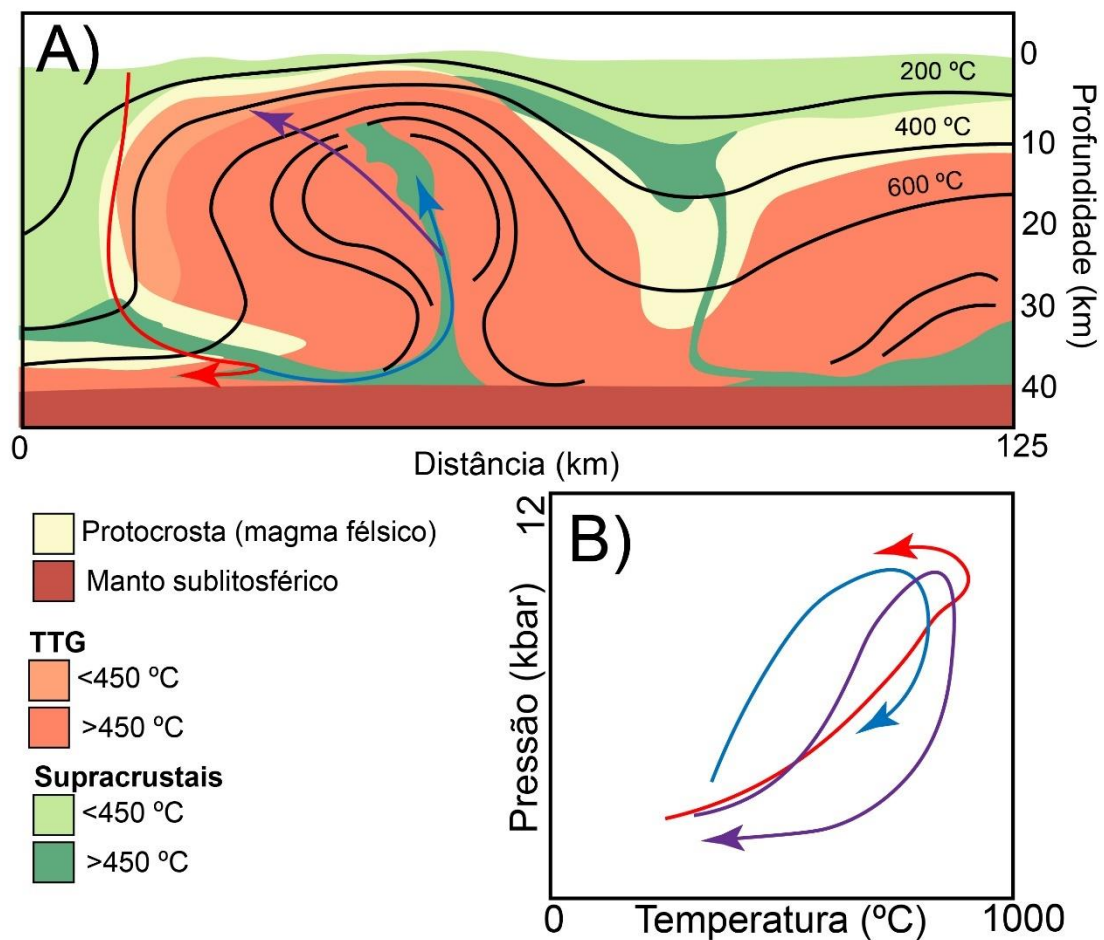


Figura 12: A) Ilustração demonstrando a estrutura 2D da crosta durante o processo de sagducção. B) Trajetórias no espaço P-T dos principais marcadores durante a sagducção. Baseado na modelagem de Yu et al. (2022).

Modelagens geodinâmicas em condições compatíveis com o manto (i.e., temperaturas potenciais maiores) e a crosta continental (i.e., maior proporção de rochas máficas) durante o arqueano sugerem a existência do processo de delaminação por convergência (Chowdhury et al., 2021). Nesse contexto, o soerguimento do manto durante a subducção reduz a resistência da crosta continental, iniciando o processo de delaminação do manto litosférico e resultando num fluxo contrário do manto em convecção (Figura 13A).

Nessas condições, as rochas podem apresentar duas trajetórias distintas (Figura 13B). Rochas próximas à frente de colisão são obductadas, atingindo condições de alta temperatura (incrementadas pelo soerguimento do manto e afinamento crustal). A trajetória dessas rochas na crosta é marcada por duas principais etapas: pico de pressão, com pressão máxima de 15 kbar a 600° C, e pico de temperatura, com temperatura máxima atingindo condições de ultra-alta temperatura (>900° C) e pressões em torno de 6 kbar (Figura 13B). As rochas mais distantes da frente da colisão seriam subductadas, atingindo condições máximas de 20 kbar a 600° C, e em seguida seriam soerguidas em direção ao domínio com afinamento crustal. Desta forma, o metamorfismo de alta pressão seria sobreposto por condições de alta a ultra-alta temperatura em pressões consideravelmente menores (Figura 13B). Estima-se uma duração em torno de 60 Ma para o ciclo completo, desde o soterramento inicial até a exumação e resfriamento para condições de temperatura abaixo de 600 °C (Chowdhury et al., 2020).

Desta forma, modelos geodinâmicos indicam a possibilidade de, pelo menos, dois processos distintos para gerar o metamorfismo de rochas sedimentares durante o Arqueano. As trajetórias destas rochas na crosta continental apresentam diversas similaridades, como uma trajetória em sentido horário e metamorfismo de alta temperatura sob baixas pressões. Contudo, eventos específicos, como a delaminação

crustal, deixam marcas distintas nesta trajetória, possibilitando a distinção entre os mecanismos responsáveis pela deformação e metamorfismo da crosta continental (e.g., Jiao et al., 2023).

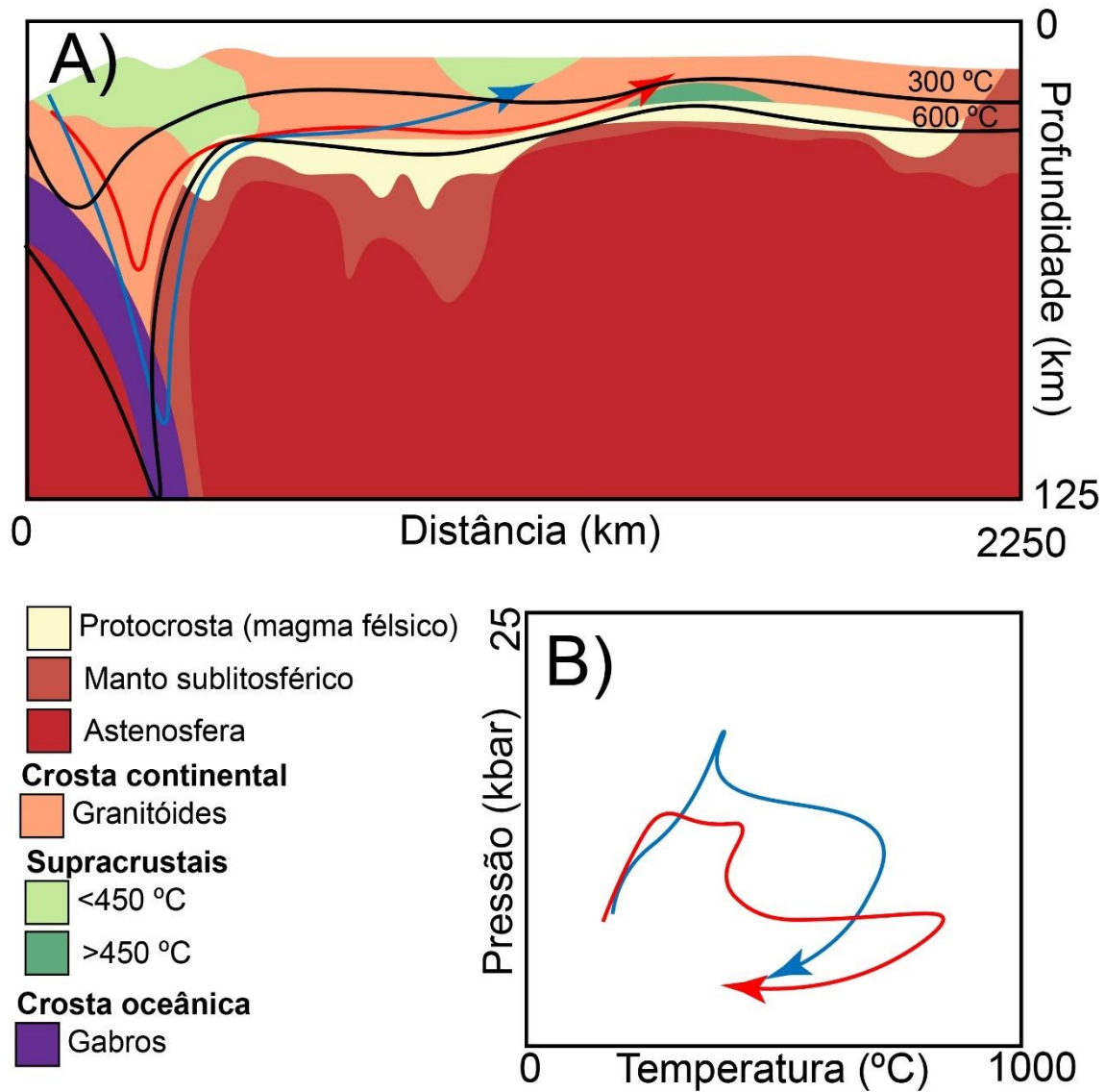


Figura 13: A) Ilustração demonstrando a estrutura 2D de um orógeno formado através de subducção e delaminação por convergência. B) Trajetórias no espaço P-T dos principais marcadores. Baseado na modelagem de Chowdhury et al. (2021).

4.2 Isótopos de U-Pb e termocronologia em zircão

4.2.1 Conceitos básicos sobre o sistema U-Pb

O decaimento radioativo é caracterizado pela perda espontânea de prótons e nêutrons do núcleo de átomos instáveis. Geralmente, este processo ocorre em cadeias de decaimento, com a formação elementos-filhos (isótopos) instáveis, até a formação de um isótopo estável.

Por exemplo, os isótopos de ^{238}U e ^{235}U sofrem decaimento através de parentes intermediários para os isótopos estáveis de ^{206}Pb e ^{207}Pb . Uma vez que as constantes de decaimento destes elementos são conhecidas, é possível calcular o tempo de formação de um mineral, considerando a temperatura em que seu sistema fechou para determinado elemento (i.e., não houve mais troca com o meio em seu redor).

Neste contexto o zircão se tornou um dos principais minerais utilizados em estudos geocronológicos. Devido ao fato de incorporar quantidades consideráveis de U e Th e muito pequenas de Pb não-radiogênico na sua estrutura cristalina, além do fato de ser presente em quase todos os tipos de rochas e ter uma alta temperatura ($>900\text{ }^{\circ}\text{C}$) de fechamento para o Pb, o zircão se tornou um dos principais minerais investigados pela técnica U-Pb.

Uma vez que as concentrações de Pb não radiogênico são baixas no zircão, a razão entre os isótopos pai e filho permitem a obtenção da idade de fechamento do mineral para o Pb. Desta forma, conhecendo-se as constantes de decaimento, a razão entre os isótopos pai e filho, é possível calcular a idade de formação do zircão através das equações:

$$t = \frac{\ln\left(\frac{^{206}\text{Pb}}{^{238}\text{U}} + 1\right)}{\lambda_{238}}$$

$$t = \frac{\ln(\frac{^{207}Pb}{^{235}U} + 1)}{\lambda_{235}}$$

Onde λ representa a constante de decaimento do isótopo pai (^{238}U ou ^{235}U). Considerando o equilíbrio secular das constantes de decaimento, as idades obtidas por ambas as cadeias de decaimento devem ser iguais. Uma terceira idade pode ser calculada a partir da razão entre $^{207}Pb/^{206}Pb$, considerando a abundância natural dos isótopos de $^{238}U/^{235}U$ (137.88) através da equação:

$$\frac{^{207}Pb}{^{206}Pb} = \frac{^{235}U}{^{238}U} \frac{e^{\lambda_{235}t} - 1}{e^{\lambda_{238}t} - 1}$$

A idade obtida através da solução numérica desta equação também deve ser igual as idades obtidas anteriormente. Contudo, na maioria dos casos naturais, esta premissa não é verdadeira, levando a denominação destas idades de “discordantes”. O conceito de discordância relaciona-se a representação gráfica das razões analisadas através do diagrama concórdia-Wetherill (Wetherill, 1956). No eixo horizontal são representadas as razões $^{207}Pb/^{235}U$ e no eixo vertical as razões $^{206}Pb/^{238}U$. Idealmente, quando as idades apresentam concordância entre si, as razões definem uma curva, denominada de “curva de concórdia”. No caso da discordância, há um desvio desta curva. Em geral, análises discordantes são excluídas de interpretações posteriores. Contudo, como será exemplificado a seguir, a discordância no sistema U-Pb tem diversas causas distintas, cada uma delas fornecendo detalhes importantes acerca da evolução rocha em que se encontram.

4.3.2 Discordância em zircão

Apesar de amplamente discutida, os mecanismos responsáveis pela discordância entre as idades U-Pb (na ausência de Pb comum) ainda são pouco entendidos (e.g., Pidgeon, 1992; Pidgeon et al., 1998; Morris et al., 2015; Andersen et al., 2019; Olierook

et al., 2021). Tradicionalmente, a interpretação mais comum é a a perda de Pb radiogênico devido ao dano causado na estrutura cristalina pelo decaimento radioativo do U (Mezger & Krogstad, 1997). Durante este processo, denominado metamictização, partículas-alfa liberadas durante o decaimento do U danificam a estrutura cristalina do zircão. Este processo é particularmente importante para cristais de zircão muito antigos (i.e., muito tempo de acumulação de dano por decaimento radioativo) ou com quantidade inicial de U muito alta. Contudo, em muitos casos, as idades obtidas são discordantes, mas o cristal não apresenta altas concentrações de U nem sinais de metamictização. Consequentemente, são necessários outros mecanismos para explicar a discordância no sistema U-Pb em zircão.

O segundo mecanismo invocado para explicar a discordância é a recrystalização durante eventos metamórficos. Ao ser submetido a altas temperaturas, a estrutura do zircão iria sofrer auto reparação, resetando o seu sistema isotópico e sua estrutura cristalina (Nasdala et al., 2002). Neste contexto, quando representadas num diagrama de concórdia, as idades irão apresentar um intercepto inferior que marca o episódio de recrystalização.

O terceiro mecanismo utilizado para explicar a discordância, sendo principalmente presente em análises por ID-TIMS e LA-ICP-MS, é causado pela mistura de domínios isotópicos distintos (e.g., Olierook et al., 2021). No caso das análises por LA-ICP-MS, apesar da alta resolução espacial, a ablação corresponde a um volume tridimensional, que em profundidade não tem como ser visualizado através de técnicas comuns de imageamento, como elétrons retroespalhados ou catodoluminescência. Desta forma, em cristais com uma evolução complexa, marcada por diversos episódios de dissolução e reprecipitação, porções com composição isotópica distinta (i.e., bordas e núcleos) podem ser analisadas, resultando em idades mistas (Figura 14).

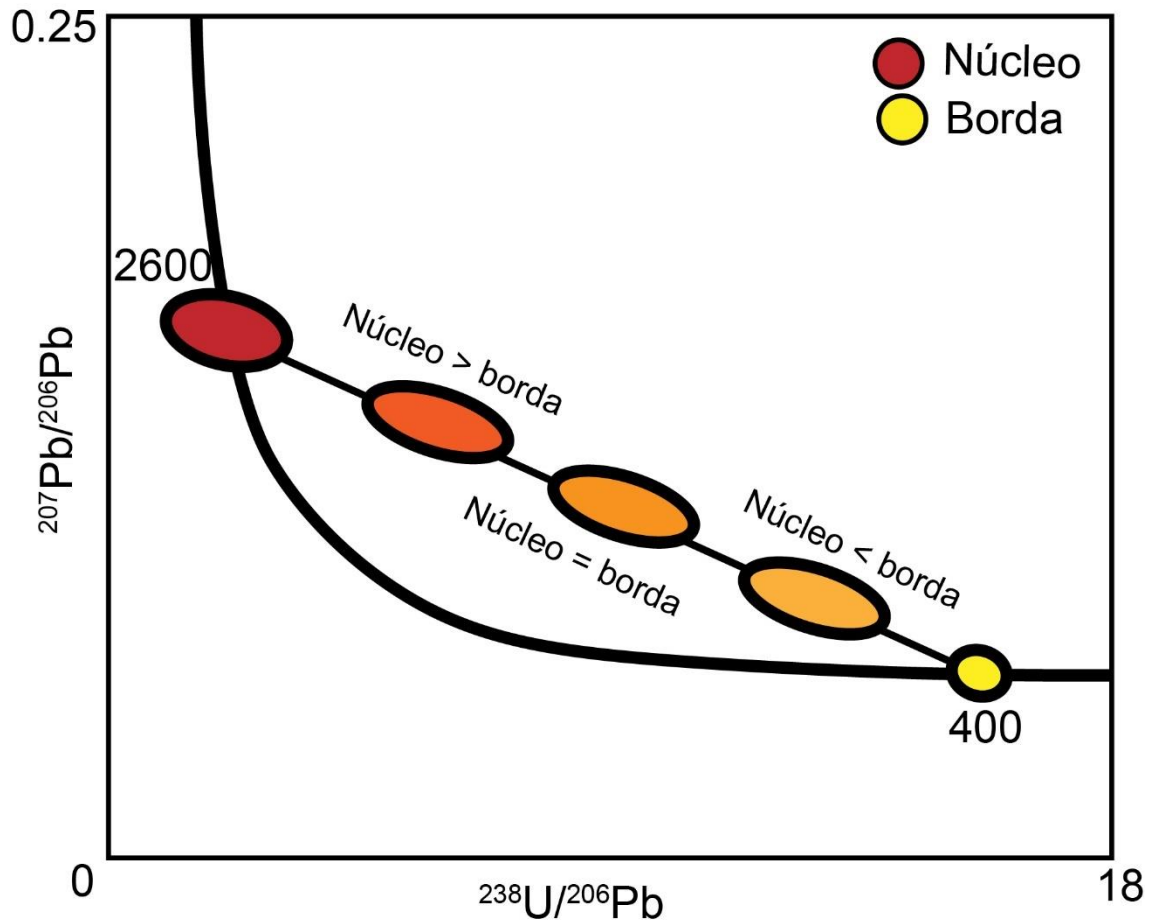


Figura 14: Modelo conceitual relacionando a mistura entre as razões isotópicas do núcleo e da borda.

Adaptado de (Olierook et al., 2021).

Matematicamente, todos estes processos podem ser descritos da mesma forma:

$$R = (R_i - R_t) - \frac{(R_i - R_t)}{p} + R_t$$

Onde R_i é a razão inicial, R_t é a razão no tempo t e p é a proporção de perda. Para o caso de perda recente (i.e., $R_t = 0$), a equação é simplificada para uma perda em função de p . Neste contexto, a discordância é diretamente proporcional ao dano por radiação sofrido pelo zircão, e consequentemente, ao teor de U inicial no sistema. No caso de mistura entre domínios isotópicos distintos (i.e., recristalização ou zoneamento

complexo), a discordância não apresenta correlação com o teor de U e, em alguns casos, apresenta correlação com a razão Th/U. Esta segunda afirmação tem como base a noção de que as razões Th/U tendem a diminuir durante eventos de recristalização, sendo importante principalmente para rochas de protólito sedimentar (Rubatto, 2017).

Ou seja, apesar dos diversos processos que alteram as idades U-Pb em zircão e causam discordância, a mistura entre razões isotópicas distintas é a causa da discordância em todas (com exceção da presença de Pb comum). Essa mistura entre razões isotópicas pode ocorrer em contextos de temperaturas muito baixas, como o fluxo de fluido orogênico em cristais de zircão metamictico (e.g., Morris et al., 2015), até o metamorfismo de alta temperatura (e.g., Andersen et al., 2019). Desta forma, entender as causas e o significado geológico da discordância requer informações complementares além das razões isotópicas de U-Pb, como elementos traços ou espectroscopia Raman.

4.2.3 Idade máxima de deposição e metamorfismo

Definir uma idade de cristalização ou deposição para uma rocha é relativamente simples. Para rochas ígneas, de modo geral, a definição é baseada no agrupamento de diversas análises concordantes. No caso da presença de múltiplas populações distintas, a população mais jovem geralmente representa a idade de cristalização da rocha. Para rochas sedimentares, em que diversas populações com morfologias e idades distintas são encontradas, o raciocínio é similar. A população (ou grão) mais jovem define a idade máxima de deposição da sequência sedimentar, ou seja, a rocha não pode ser mais antiga que o zircão mais jovem presente nela.

Tradicionalmente, as análises discordantes são ignoradas em amostras sedimentares. Entretanto, o método utilizado para definir a discordância é variado, sendo o mais comum a diferença relativa entre as idades obtidas a partir de cada razão U-Pb. Conforme demonstrado em Vermeesch (2021a), a discordância pode ser definida de

outras formas, como por exemplo a diferença absoluta entre as idades (Puetz et al., 2018) ou pela distância da curva da concórdia (Vermeesch, 2021a). Contudo, conforme notado por Vermeesch (2021b), a maioria destes filtros tem um enviesamento relacionado a idade em relação a curva da concórdia, onde idade mais jovens são sub-representadas em relação as idades mais antigas. Neste trabalho, Vermeesch (2021b) advoca pelo uso da distância da curva de concórdia como método menos enviesado.

Além dos filtros de discordância, o método usado para definir a idade máxima de deposição de rochas sedimentares é bastante variável (e.g., Coutts et al., 2019). Os métodos mais comuns consideram o zircão concordante mais jovem ou pico gráfico mais jovem (Dickinson & Gehrels, 2009). Recentemente, uma análise estatística realizada por Vermeesch (2021b) mostrou que a maioria desses métodos são falhos e, sistematicamente, sobrestimam ou subestimam as idades máximas de deposição. Neste trabalho, ele propõe o uso do Maximum Likelihood Algorithm de Galbraith & Laslett (1993) como o menos enviesado para obter idades máximas de deposição.

Contudo, a aplicação destes conceitos em rochas antigas afetadas por múltiplos eventos metamórficos não é tão simples. O intervalo entre a cristalização do zircão detrítico e o evento de recrystalização é outro fator que precisa ser considerado (e.g., Andersen et al., 2019). Quando este intervalo é curto, as idades tendem a se espalhar ao longo da curva de concórdia e permanecendo concordantes. Nestes casos, as idades aparentam representar um evento contínuo, ao invés de dois eventos distintos (Figura 15). No caso de rochas com um protólito sedimentar, por exemplo, serão geradas populações sem significado geológico, afetando também a definição de uma idade máxima de deposição.

Portanto, principalmente em contextos complexos, é necessário um bom entendimento dos processos que afetam as idades U-Pb em zircão para uma correta definição da idade de uma formação geológica.

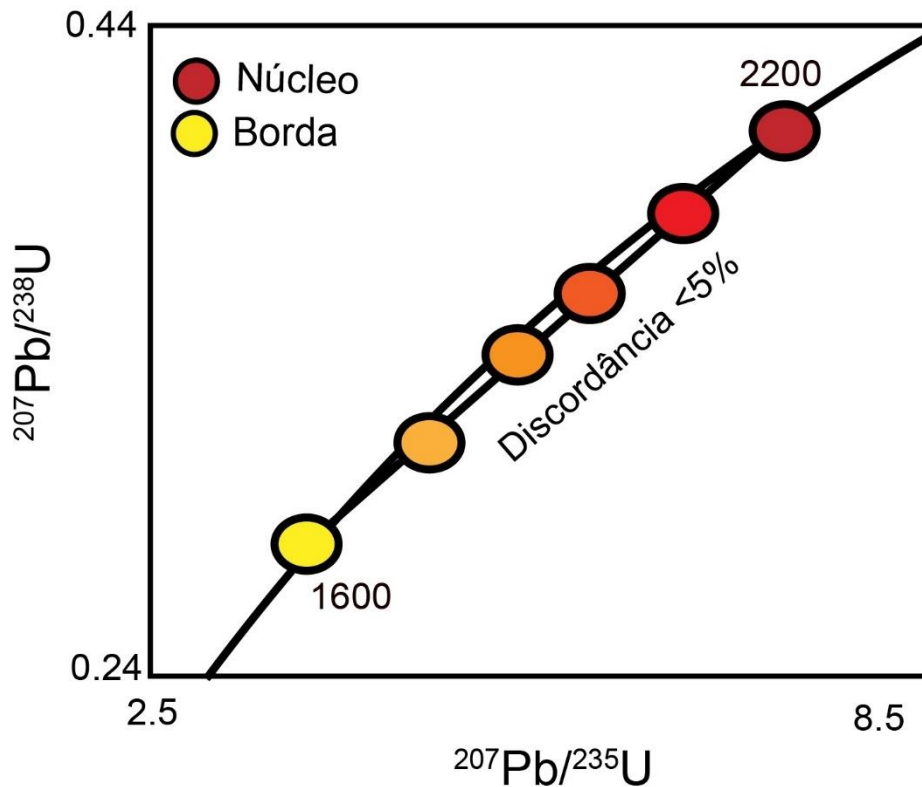


Figura 15: Perda de Pb oculta gerando espalhamento das idades ao longo da curva de concordância. Adaptado de Andersen et al. (2019).

4.2.4 Texturas e estruturas internas em zircão

Além dos efeitos observados nas razões isotópicas, o formato e as texturas internas do zircão observadas através de imagens de catodoluminescência têm uma relação direta com as condições em que ele cristalizou. Cristais de zircão cristalizados a partir de um magma geralmente apresentam uma textura interna caracterizada por padrões oscilatórios, refletindo variações na composição ou temperatura do magma (Rubatto, 2017). Por exemplo, em altas concentrações de zircônio (i.e., supersaturação), a face $\{110\}$ cresce preferencialmente em relação a face $\{100\}$, enquanto em baixas

concentrações a relação é inversa (Vavra, 1990). A concentração de U no magma também influencia a cristalografia do zircão, diminuindo o tamanho das faces {110} com o aumento do teor de U (Benisek & Finger, 1993). Estas observações foram quantificadas por Pupin (1980), que estabeleceu uma rotina para determinar a composição e temperatura do magma em que o zircão cristalizou com base na sua cristalografia.

Durante o metamorfismo, estas texturas são substituídas progressivamente. Por exemplo, Schaltegger et al. (1999), interpretaram a sobreposição de texturas como resultante de distintos estágios de metamorfismo. Cristais herdados, com núcleo preservando zonamento oscilatório, são sobrepostos por zonas com zonamento em setor, resultantes da cristalização lenta durante o início da fusão parcial (Figura 16). Com o aumento do volume de magma, as zonas externas do cristal seriam reabsorvidas, culminando em um novo episódio de cristalização, desta vez com zonamento oscilatório e em equilíbrio com o magma resultante da fusão parcial.

Outras texturas geradas durante o metamorfismo de alta temperatura incluem o zonamento em setor (Figura 16), que indica um crescimento lento a partir de um magma ou fluido (e.g., Watson & Liang, 1995), e o zonamento convoluto, cujos mecanismos de formação ainda são pouco conhecidos (e.g., Corfu et al., 2003; Rubatto, 2017).

O contexto do zircão em relação aos minerais da matriz também pode revelar informações acerca da sua origem. Por exemplo, alguns minerais, como rutilo e granada, apresentam concentrações relativamente elevadas de zircônio na sua estrutura, geralmente tendo uma correlação positiva com a temperatura (e.g., Kohn, 2020). Durante o resfriamento após o pico metamórfico, estes minerais tendem a se desestabilizar e exsolver o zircônio da sua estrutura, resultando na cristalização de cristais de zircão em suas bordas (e.g., Degeling et al., 2001; Figura 16).

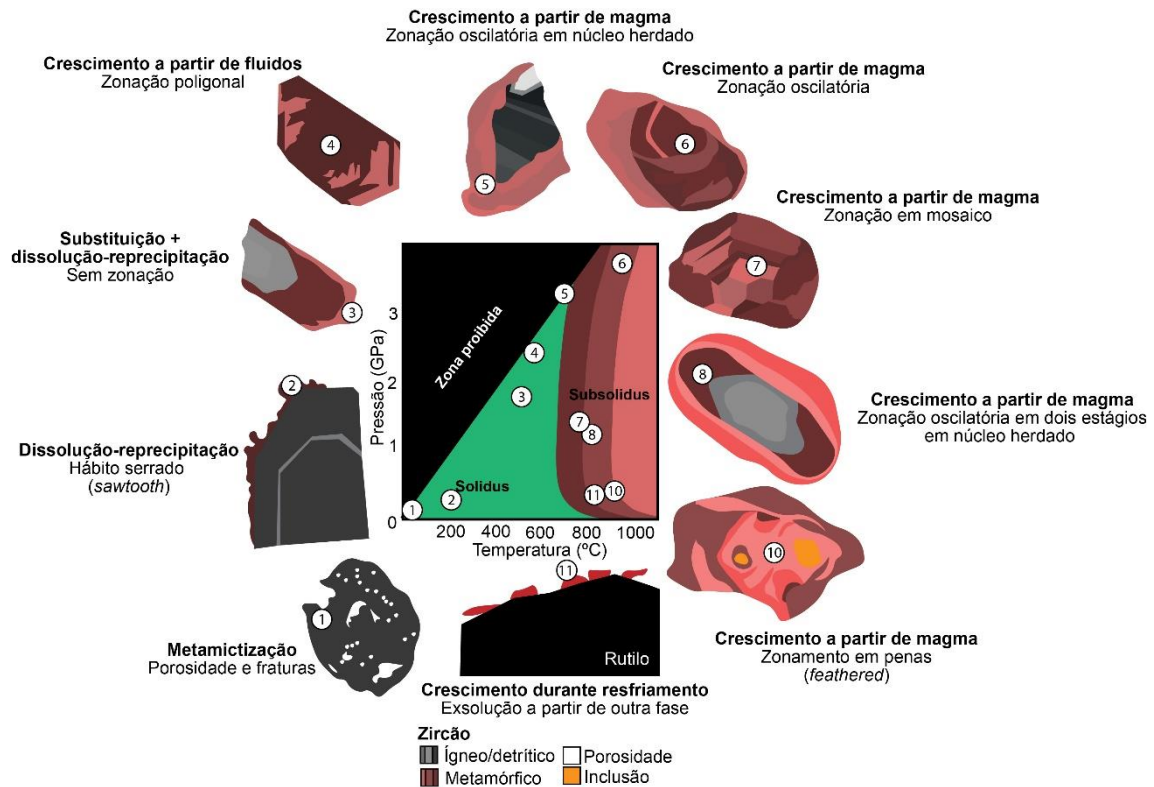


Figura 16: Texturas e estruturas geradas em cristais de zircão metamórfico em diversos contextos de pressão e temperatura. Adaptado de Rubatto (2017).

4.2.5 Aplicações da Espectroscopia Raman para estudos em zircão

Com base nos conceitos de dano por decaimento radioativo do zircão e temperatura de fechamento, Pidgeon et al. (1998) e Nasdala et al. (2001) propuseram uma relação entre dano por radiação e a idade do zircão. O acúmulo de dano por radiação causa distorções na estrutura cristalina, culminando num estado amorfo (i.e., metamictico). Conforme descrito anteriormente, o dano por radiação ocorre em função do tempo e do teor de U. Consequentemente, quantificando o dano e o teor de U inicial do zircão, é possível estimar o tempo em que cristal passou a sofrer dano por radiação.

Recentemente, Härtel et al. (2021) determinaram uma equação que relaciona o dano por radiação, determinado através do aumento da largura dos picos obtidos através

de espectroscopia Raman, com a idade de dano por radiação. Esta idade reflete o tempo em que o zircão atingiu temperaturas abaixo do anelamento termal, sendo esta temperatura entre 130 °C e 650 °C em amostras naturais (Mezger and Krogstad, 1997; Pidgeon, 2014; Jonckheere et al., 2019), com experimentos recentes indicando temperaturas entre 260 °C e 370 °C (Härtel et al., 2021b).

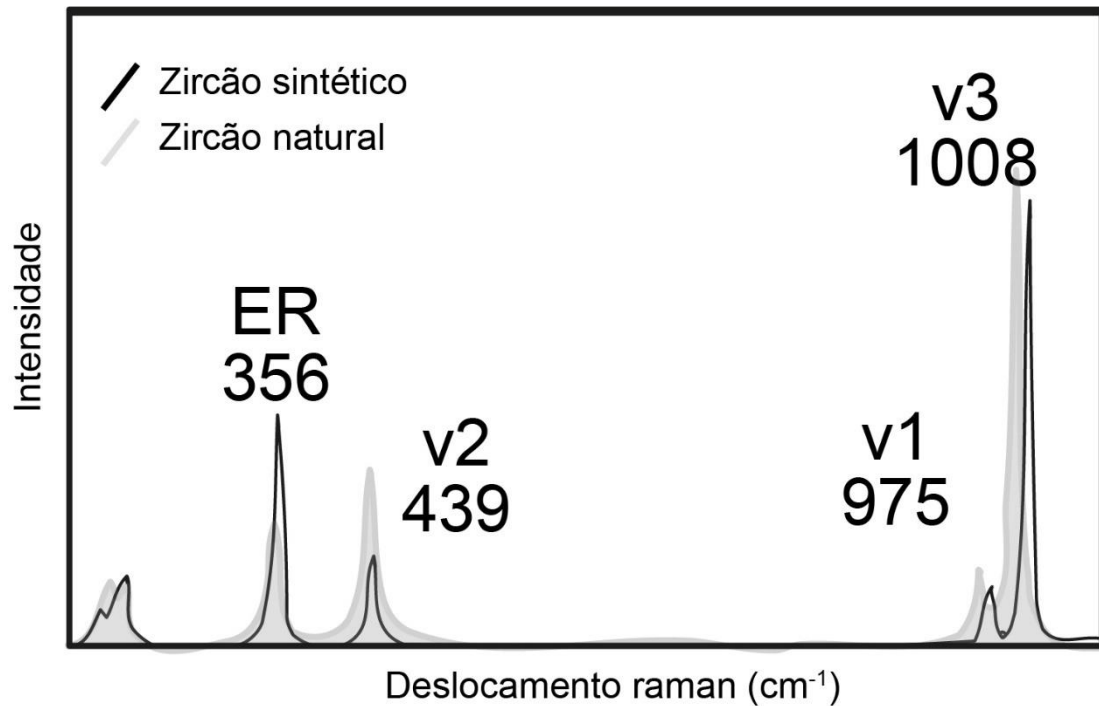


Figura 17: Comparação entre o espectro Raman de um zircão sintético (Finch et al., 2001; Lafuente et al., 2015) em comparação com um zircão natural (Ribeiro et al., 2025).

O espectro do zircão sintético (ZrSiO_4) é caracterizado por quatro picos principais (V1, V2, V3 e ER) nas posições 975, 439, 1008 e 356 cm^{-1} , respectivamente (Figura 17). O dano por radiação desloca e aumenta a largura desses picos, sendo descrito pela equação:

$$D_{\text{ER}} = \frac{\Gamma_{\text{ER}} - 4.04}{0.171 \times 10^{-16}}$$

Onde Γ_{ER} corresponde a largura a meia altura do pico da banda ER.

A idade é então calculada a partir da equação:

$$t = 19 \times 10^3 \frac{\Gamma_{ER} - 4.04}{eU}$$

Onde eU corresponde a concentração efetiva de U ($1.05U + 0.24Th$) analisada por LA-ICP-MS.

Para os demais picos, idades de dano por radiação também podem ser obtidas, refletindo temperaturas até 400 °C, porém, são mais susceptíveis a variações relacionadas a orientação do cristal (Härtel et al., 2021a). A razão entre o dano determinado por cada banda também pode fornecer informações acerca do estado termal do zircão (i.e., se ele sofreu anelamento termal ou não, Figura 18), conforme evidenciado pela razão entre D_{V2}/D_{ER} (Härtel et al., 2022).

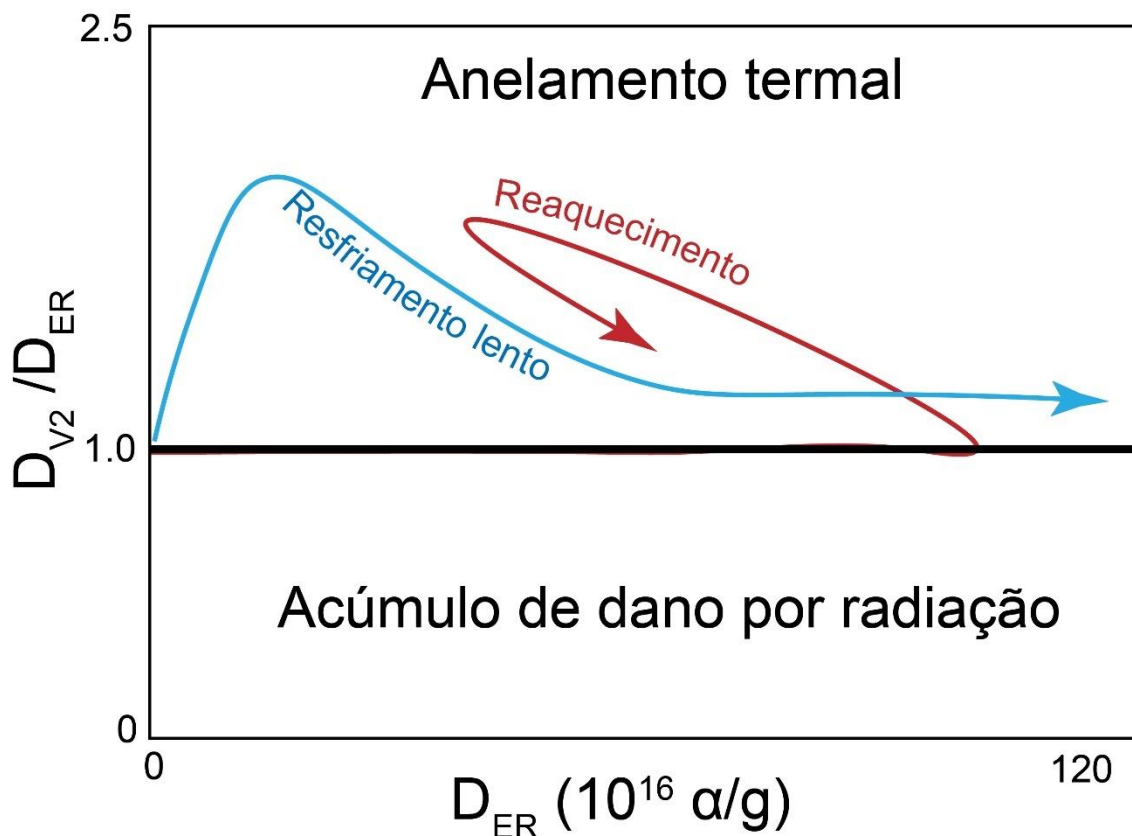


Figura 18: Relação entre o dano por radiação da banda ER e a razão entre o dano por radiação da banda V2 pela banda ER. Valores acima de 1 para a razão indicam anelamento termal. Trajetórias hipotéticas de resfriamento lento e reaquecimento também são mostradas. Adaptado de Härtel et al. (2022).

4.3 Petrocronologia

4.3.1 Modelagem termodinâmica

A modelagem por termodinâmica, conhecida também como modelagem de equilíbrio de fases (*phase equilibria*) permite estimar as condições em que diversas rochas se formam (e.g., Johnson et al., 2021). Assume-se que a rocha é um sistema fechado, cuja composição é descrita pelos principais minerais formadores de rocha. Estes minerais podem ter composição fixa, como quartzo e silimanita, ou serem descritos como soluções-sólidas. Neste caso, com base em modelos experimentais e termodinâmicos (e.g., White et al., 2014; Green et al., 2016), a composição do mineral é variável dentro de um intervalo determinado de modo a minimizar a energia de Gibbs. Esta variação composicional ocorre em função de diversos fatores, como pressão, temperatura, fugacidade de oxigênio e presença de fluido (e.g., H₂O ou CO₂).

A regra de fases de Gibbs (1878) relaciona o número de componentes (C), o número de fases (X) e o grau de liberdade (F) de um sistema em equilíbrio através da equação:

$$F = C - X + 2$$

Desta forma, para um sistema com uma fase (e.g., silimanita – Al₂SiO₅) que pode ser descrita por um único componente (Al₂O₃) variando ao longo do espaço P-T, $F = 1 - 1 + 2$. Desta forma, é possível manter o equilíbrio mesmo variando as condições de PT de forma independente (Figura 19). O mesmo sistema, agora na presença de duas fases (e.g., silimanita e cianita), é descrito por $F = 2 - 1 + 2$, o que na prática significa que o equilíbrio só é mantido quando P e T variam de forma dependente (Figura 19). O ponto tríplice de estabilidade dos três polimorfos (andaluzita, silimanita e cianita) corresponde

a $F = 3 - 1 + 2$, de forma que nenhum parâmetro pode ser alterado para se manter o equilíbrio (Figura 19)

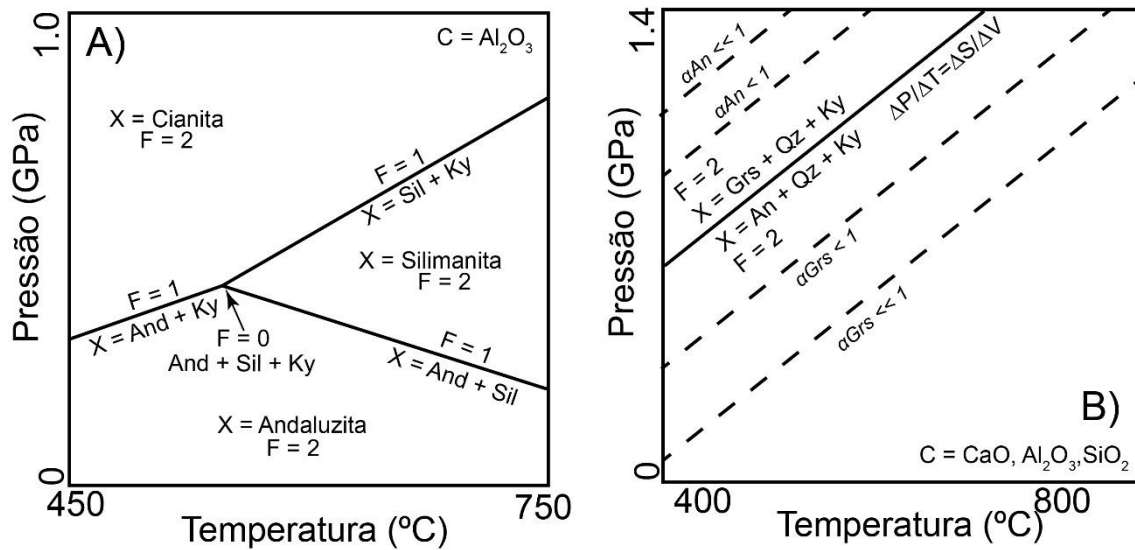


Figura 19: A) Diagrama P-T de um componente (Al_2O_3) mostrando a estabilidade dos polimorfos de Al_2SiO_5 , bem como o grau de liberdade de cada posição. B) Diagrama P-T ilustrando a reação entre grossulária e anortita na presença de cianita e quartzo. Retas tracejadas demonstram casos em que a atividade dos componentes é menor do que 1. Adaptado de Johnson et al. (2021).

Os campos de estabilidade de cada fase, onde $F = 2$, são caracterizados pela menor Energia Livre de Gibbs (G) possível, onde:

$$G = E + PV + TS$$

Sendo E a energia interna da fase, V o volume e S a entropia. Durante a reação entre duas fases, G é descrito pela variação (Δ) entre os reagentes e produtos:

$$\Delta G = \Delta E + \Delta PV + \Delta TS$$

No caso de $\Delta G > 0$ ou < 0 , o sistema encontra-se em desequilíbrio. Para um sistema em equilíbrio:

$$\Delta G = RT \ln K$$

Onde R é a constante do gás e K é a constante de equilíbrio, que define a estabilidade de fases com composição variável, como soluções-sólidas.

Por exemplo, para a reação 3 anortita (A - $\text{CaAl}_2\text{Si}_2\text{O}_8$) = grossulária (B - $\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$) + 2 silimanita (C - Al_2SiO_5) + quartzo (D - SiO_2):

$$K = \frac{\alpha_B \times \alpha_C^2 \times \alpha_D}{\alpha_A^3}$$

Onde α define a atividade do mineral em questão em função de parâmetros como temperatura, pressão e fluidos. No caso de minerais com fórmula ideal (e.g., quartzo e silimanita), $\alpha = 1$, enquanto para os que apresentam solução sólida $\alpha < 1$.

A inclinação desta reação no espaço P-T é dada por:

$$\frac{\Delta P}{\Delta T} = \frac{\Delta S}{\Delta V}$$

Onde reações entre minerais definem uma reta, enquanto a presença de fluidos tende a gerar curvas tendendo a $P = 0$. Estas relações definem as bases para a determinação da posição de retas/curvas de reação entre as diferentes fases que compõem uma rocha, assumindo o equilíbrio do sistema.

O equilíbrio do sistema pode ser assumido até determinada temperatura, quando a rocha entra em fusão parcial. Neste caso, o sistema passa a conter uma fase extra (líquido/magma) que ocorre em função da diminuição de outras fases e da presença de fluidos. As relações termodinâmicas de um magma são complexas, sendo provenientes principalmente de experimentos (e.g., Gao et al., 2016).

Estas relações podem ser modeladas através de diversos *softwares*, como Thermocalc (Powell et al., 1998), Theriak-Domino (de Capitani & Petrakakis, 2010), PerpleX (Connolly, 1990), RCrust (Mayne et al., 2016) e GeoPS (Xiang & Connolly, 2021). Desta forma, é possível estabelecer os campos de estabilidade das assembleias minerais e suas soluções-sólidas dentro do espaço P-T. Consequentemente, com base em

relações texturais, é possível reconstruir a evolução da rocha através das reações que formam os minerais que a compõem atualmente.

4.3.2 Termocronometria por difusão

O conceito da cronometria por difusão se baseia na primeira e segunda leis de Fick (1855), onde o fluxo da concentração de um elemento i (J_i , C_i) é descrito em função da distância (x), tempo (t) e difusividade (D) através das equações:

$$J_i = D_i \frac{\Delta C_i}{\Delta x}$$

$$\frac{\Delta C_i}{\Delta t} = D_i \frac{\Delta^2 C_i}{\Delta x^2}$$

Sendo a difusividade também dependente da temperatura (T) através da equação:

$$D = D_0 \times \exp\left\{\frac{-E}{RT}\right\}$$

Onde E é a energia de ativação e R é a constante do gás.

Estas relações são a base da cronometria por difusão (*geospeedometry*), sendo aplicada principalmente para determinar a duração de eventos geológicos com base em perfis de concentração em minerais.

Em rochas metamórficas, a granada é o principal mineral utilizado, uma vez que os elementos Ca, Fe, Mg e Mn tem difusividade distinta (e.g., Carlson et al., 2006) e as concentrações destes elementos refletem variações de pressão e temperatura durante a formação do cristal.

Conforme demonstrado por Caddick et al. (2010), cristais pequenos de granada tendem a perder o zoneamento desenvolvido no metamorfismo progressivo devido a

difusão. Por exemplo, para um cristal com 1000 μm de raio a 800 $^{\circ}\text{C}$, Fe, Mg e Mn são fortemente afetados por difusão para durações acima de 10 Ma, enquanto o Ca necessita de cerca de 20 Ma para desenvolver perfis similares (Figura 20). Desta forma, a preservação do zoneamento de Ca é indicativa de uma curta duração para as condições de pico de temperatura (Caddick et al., 2010).

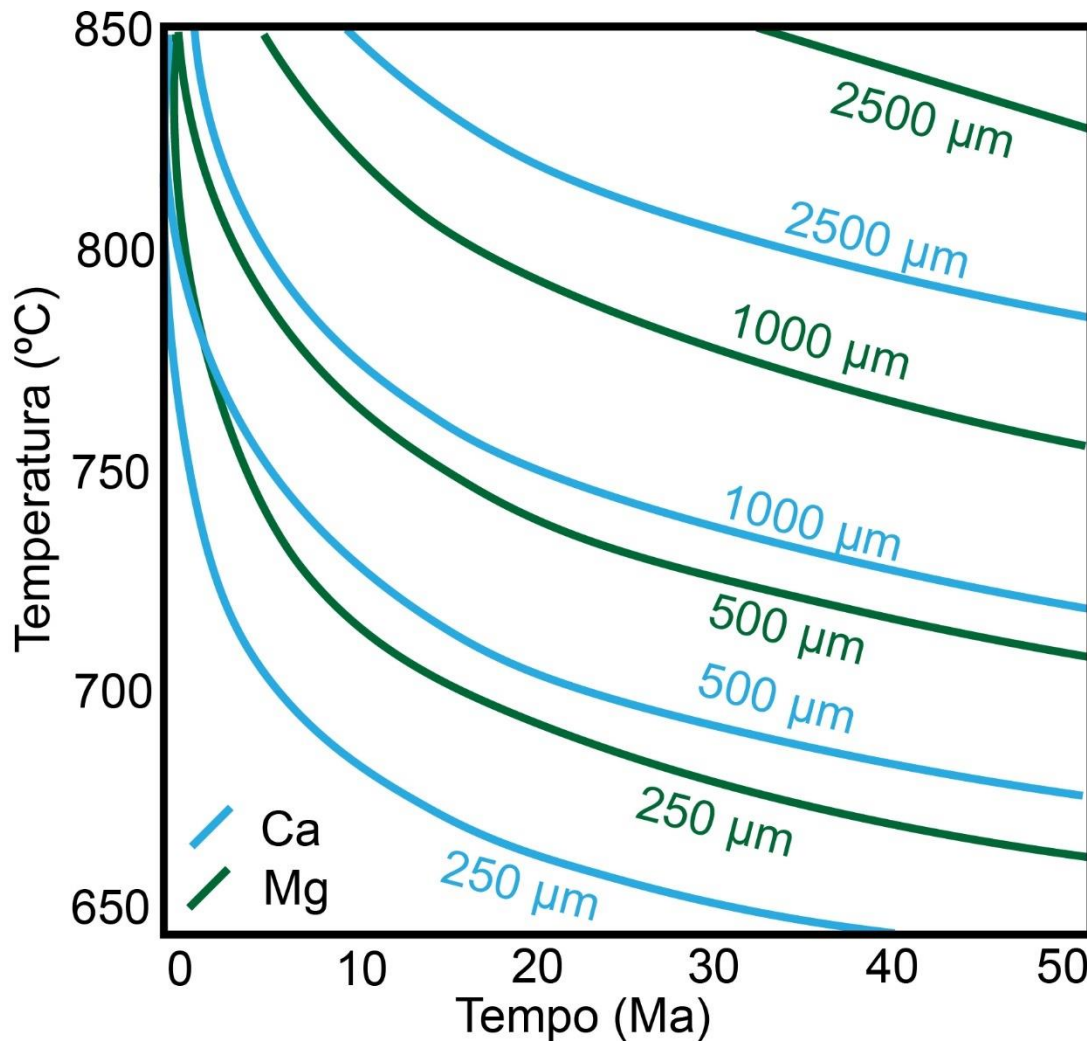


Figura 20: Solução analítica do comprimento de difusão efetivo ($\sqrt{Dt}$) para diversos comprimentos de granada em relação ao tempo de difusão (Ma) e temperatura ($^{\circ}\text{C}$). Modificado de Caddick et al. (2010).

Uma das aplicações da diferença de difusividade entre o Ca e os demais elementos é a termometria por difusão em granada de Smit et al. (2013). Com base no raio da granada e a distância de difusão dos elementos Ca e Mg, é possível determinar as condições máximas de temperatura atingidas pela rocha, bem como uma média da sua

taxa de resfriamento. Entretanto, uma das maiores limitações desta técnica é a correta identificação das condições em que a difusão ocorre (i.e., temperatura de pico e de retrometamorfismo), bem como as reações que controlam a difusão (Figura 21).

Por exemplo, se a reação ocorre sem a quebra e formação de novos minerais, o fluxo de elementos é contínuo entre a granada e a matriz. Desta forma, as condições limitantes do sistema são definidas pela composição do núcleo da granada e da matriz, e a difusão ao longo do tempo tende a homogeneizar esse perfil (Figura 21A-C). No caso da reação com a quebra e formação de novos minerais, a composição da matriz tem composição variável em função da proporção do mineral que foi decomposto e dos minerais que foram formados. Desta forma, a concentração dos elementos na matriz, bem como o tamanho do cristal de granada, variam ao longo da trajetória de resfriamento (Figura 10D-F).

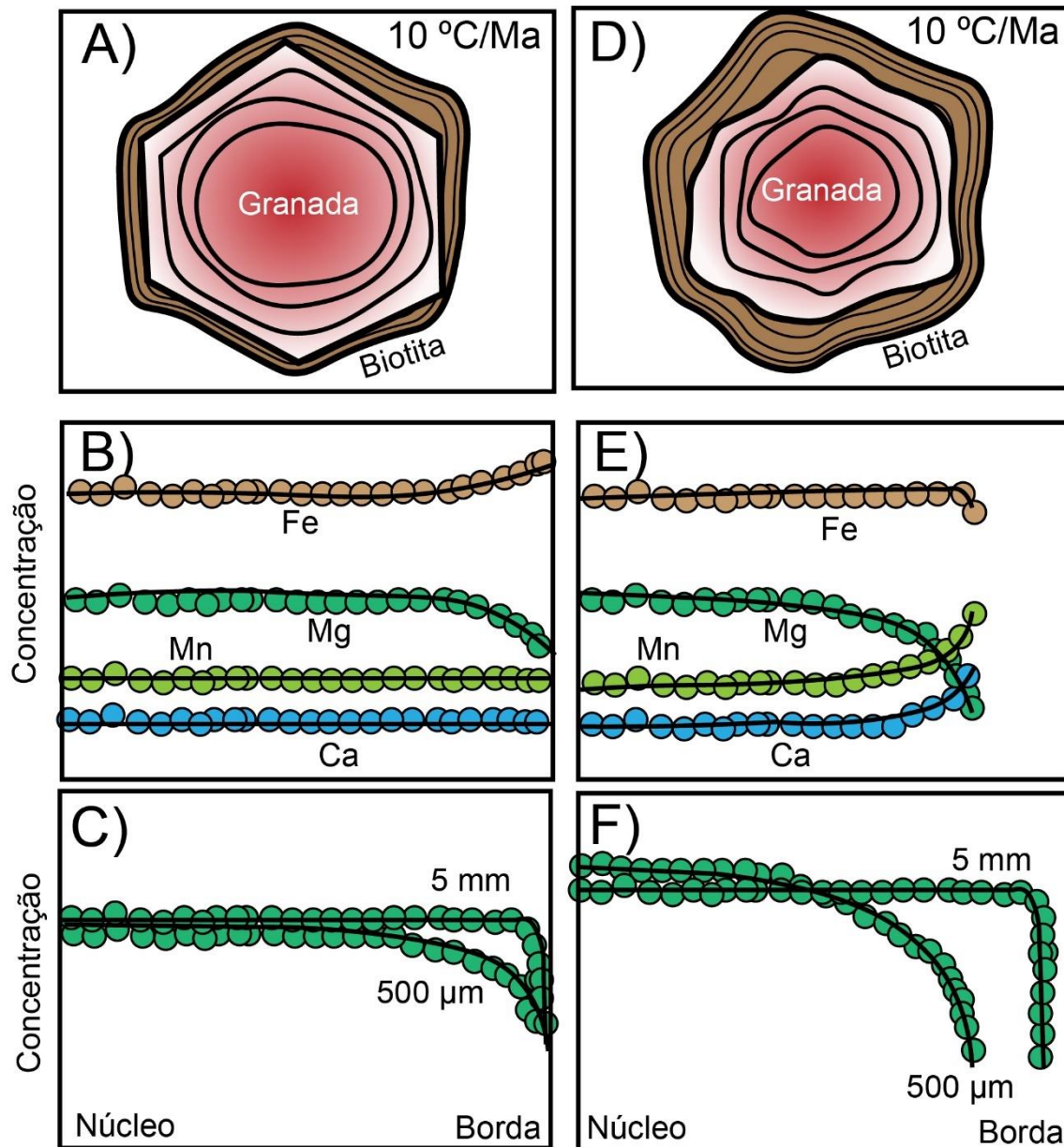


Figura 21: A) Exemplo esquemático de porfiroblasto de granada, com faces preservadas, em contato com biotita retrógrada. Neste caso, a difusão ocorre por reações retrógradadas de troca (*retrograde exchange reaction*). B) Perfil esquemático ao longo do porfiroblasto de granada, exibindo zonação por difusão apenas para os elementos Fe e Mg. C) Variação no perfil de difusão em função do raio do cristal. D) Exemplo esquemático de porfiroblasto de granada parcialmente substituído por biotita durante reações retrógradadas com dissolução e cristalização de novas fases (*retrograde net transfer reaction*). E) Perfil esquemático, exibindo zonação por difusão em todos os elementos. Neste caso, a inflexão ocorre ao longo de um intervalo mais amplo. F) Comparação entre cristais com raio distinto. Adaptado de Kohn & Penniston-Dorland (2017)

CAPÍTULO 5: ARTIGO CIENTÍFICO 1

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Paleoarchean sedimentation and Mesoarchean high-temperature metamorphism in northeastern Brazil: tracing sources and depositional ages in polymetamorphic rocks

Abstract

Supracrustal rocks offer a window into tectonic processes of the early Earth, since they are common in the Archean lithosphere. However, these rocks are usually affected by several episodes of metamorphism that can compromise their U–Pb systematics, leading to equivocal interpretations of depositional ages and sources. In northeast Brazil, supracrustal rocks are frequent within the Archean basement of the São José do Campestre Massif. These metapelitic migmatites show a high-temperature mineral assemblage, with garnet + sillimanite $\pm$ spinel and retrograde cordierite, with abundant anatectic melt migration at conditions of upper amphibolite to granulite facies. Zircon U–Pb dating coupled to trace elements analysis through LA-ICP-MS, as well as zircon internal zoning patterns suggest a maximum depositional age of 3305 ± 16 Ma followed by high-temperature metamorphism in the Mesoarchean, Paleoproterozoic and Neoproterozoic. Mesoarchean high temperature metamorphism occurred between 3084 ± 4 and 3006 ± 6 Ma and generated a wide range of textures that could be grouped in, at least, three stages of zircon growth. The first, during prograde heating, led to dissolution of detrital cores through the process of Ostwald Ripening and reprecipitation in oscillatory zoned rims. The second, probably at peak conditions, occurred above the

stability of monazite, as evidenced by high Th/U ratios within zircon grains, rounded shape and sector-zoned cores. The third, during retrograde cooling, is mostly driven by garnet breakdown, and resulted in the crystallization of convoluted rims. Ti-in-zircon temperatures indicate minimum temperatures of 712 ± 21 °C for prograde/retrograde stages and 881 ± 50 °C for peak conditions. The Paleoarchean sedimentation and Mesoarchean metamorphism are coeval with similar events in Kaapvaal and Dharwar Cratons (South Africa and South India, respectively), but show no correlation to any Archean domains in South America to date. Solid-state recrystallization during the Paleoproterozoic (ca. 2.0 Ga) and the Neoproterozoic (ca. 0.6 Ga) correlates with orogenic events in both the Borborema Province and São Francisco Craton, suggesting a common evolution since the Rhyacian.

Keywords

U–Pb dating; zircon; Archean; metamorphism; Borborema Province

1. Introduction

Archean sedimentary rocks are mostly found in the upper sections of greenstone belts, with depositional ages as early as the Eoarchean (e.g., Spencer, 2020 and references therein). These are commonly associated with mafic-ultramafic magmatism, probably representing depositional environments related to ancient oceanic basins (e.g., Furnes et al., 2015 and references therein). A common feature of the greenstone belts is thick siliciclastic sequences that suggest the presence of large landmasses above sea level since, at least, the Mesoarchean (Ptáček et al., 2020). The isotopic and trace element archive of these siliciclastic rocks reflect the primordial composition of the continental crust, once they are formed through the weathering and erosion of surface rocks (Chen et al., 2020; Garçon, 2021; McLennan et al., 1984).

The first continents included a larger proportion of mafic and ultramafic rocks that heavily influenced Earth's early dynamics (Chen et al., 2020; Ptáček et al., 2020). The late Archean compositional shift to a more felsic continental crust is credited to a change in global tectonic dynamics, from a stagnant lid to a horizontal tectonic model (Bédard, 2018; Tang et al., 2016). Although the timing of this transition is still disputed, with multi-proxy data supporting plate tectonics initiation as early as the Eoarchean (e.g., Antonelli et al., 2021; Boyd et al., 2024; Kusky et al., 2021; Polat et al., 2002; Windley et al., 2021), growing evidence points towards a period between 3.2 Ga and 3.0 Ga (Dhuime et al., 2012; Laurent et al., 2014; Tang et al., 2016). This is also the timing of peak mantle potential temperatures at 1600 – 1700 °C that are thought to have caused widespread reworking of the early continents (Kirkland et al., 2021), although evidence for Mesoarchean metamorphism is scarce in the geological record (e.g., Brown and Johnson, 2018).

Most crustal evolution studies rely on U–Pb in zircon ages for constraining the timing of crust generation and reworking (e.g., Cawood et al., 2012). However, although a powerful chronometer, preserved zircon U–Pb ages may be modified by several factors, including Pb loss and metamorphic recrystallization (Andersen et al., 2019; Kröner et al., 2014). High-grade metamorphism can generate a wide range of zircon textures, including convoluted and sector zoning (e.g., Nyström and Kriegsman, 2003; Rubatto, 2017; Schaltegger et al., 1999; Tichomirowa et al., 2005) during several stages of metamorphism (Kohn et al., 2015). These variations are likely related to an open-system behavior during anatexis, where fluid infiltration and melt extraction play a crucial role for the heterogeneous distribution of trace elements in migmatites (e.g., Johnson et al., 2021; Jung and Hellebrand, 2006; Yakymchuk, 2023; Yakymchuk and Brown, 2014). Recognizing the age of the sedimentary protolith is therefore difficult, as multiple zircon

populations with distinct morphologies are present. This can be limiting for constraining accurate maximum depositional ages and tracing global correlations to similar geodynamic provinces (e.g., Coutts et al., 2019; Kröner et al., 2014; Kuper et al., 2024; Tedeschi et al., 2023).

In this work, we investigate upper amphibolite to granulite facies Paleoproterozoic metasedimentary rocks in the São José do Campestre Massif, an Archean block within the Borborema Province, in northeast Brazil. By combining zircon U–Pb ages and trace elements together with textural observations, we demonstrate that these rocks are older than previously considered and were affected by three distinct metamorphic events in the Mesoarchean, Paleoproterozoic and Neoproterozoic. Zircon geochemistry and morphology assisted in constraining the timing and conditions of individual events and allowed for potential links to other Mesoarchean domains.

2. Geological background

The Borborema Province (BP) in northeast Brazil, extends over 400,000 km² and involves a complex deformational and metamorphic history during the Paleoproterozoic (ca. 2.2 to 1.9 Ga) and Neoproterozoic (ca. 0.8 to 0.5 Ga) (Almeida et al., 1981; Brito Neves et al., 2014; Neves, 2015, 2021).

Within the BP, several domains have been identified and separated based on large shear zones that would represent crustal discontinuities and distinct crustal blocks amalgamated during the Pan-African/Brasiliano orogeny (Brito Neves et al., 2014 and references therein). There is also a model for an intracontinental setting, which affected most of the Borborema Province during the Neoproterozoic (Neves, 2015; 2021).

Along with the abundance of Paleoproterozoic basement within the Borborema Province (Lira Santos et al., 2022; Souza et al., 2016), several Archean units and blocks

have been recognized in the last two decades, with ages that span from the Eoarchean to the Neoarchean (Neves, 2021 and references therein).

One of these Archean fragments, the São José do Campestre Massif, comprising an area of 6,000 km², is composed of Archean metaplutonic and metasedimentary lithology, with minor Paleoproterozoic and Neoproterozoic magmatism (Fig. 22A - Dantas et al., 2004, 2013; Souza et al., 2016). The São José do Campestre Massif is surrounded by 2.4 to 2.2 Ga tonalitic to granitic orthogneisses (Dantas, 1996) and voluminous Neoproterozoic mafic-felsic plutonic rocks (Souza et al., 2006, 2016). Neoproterozoic magmatism was coeval with the development of dextral NE–SW and NW–SE shear zones (Souza et al., 2006). These shear zones delineate the boundary between the Archean and the Paleoproterozoic basement. The peak of the Neoproterozoic metamorphism has been defined by Souza et al. (2006) at ca. 575 Ma based on a Sm–Nd garnet/whole-rock isochron, which is coeval with the peak of the high-temperature/low pressure (HT/LP) transpression in the Santa Luzia migmatite dome in the Rio Piranhas-Seridó Domain, ca. 100 km to the west of the São José do Campestre Massif (Cioffi et al., 2021).

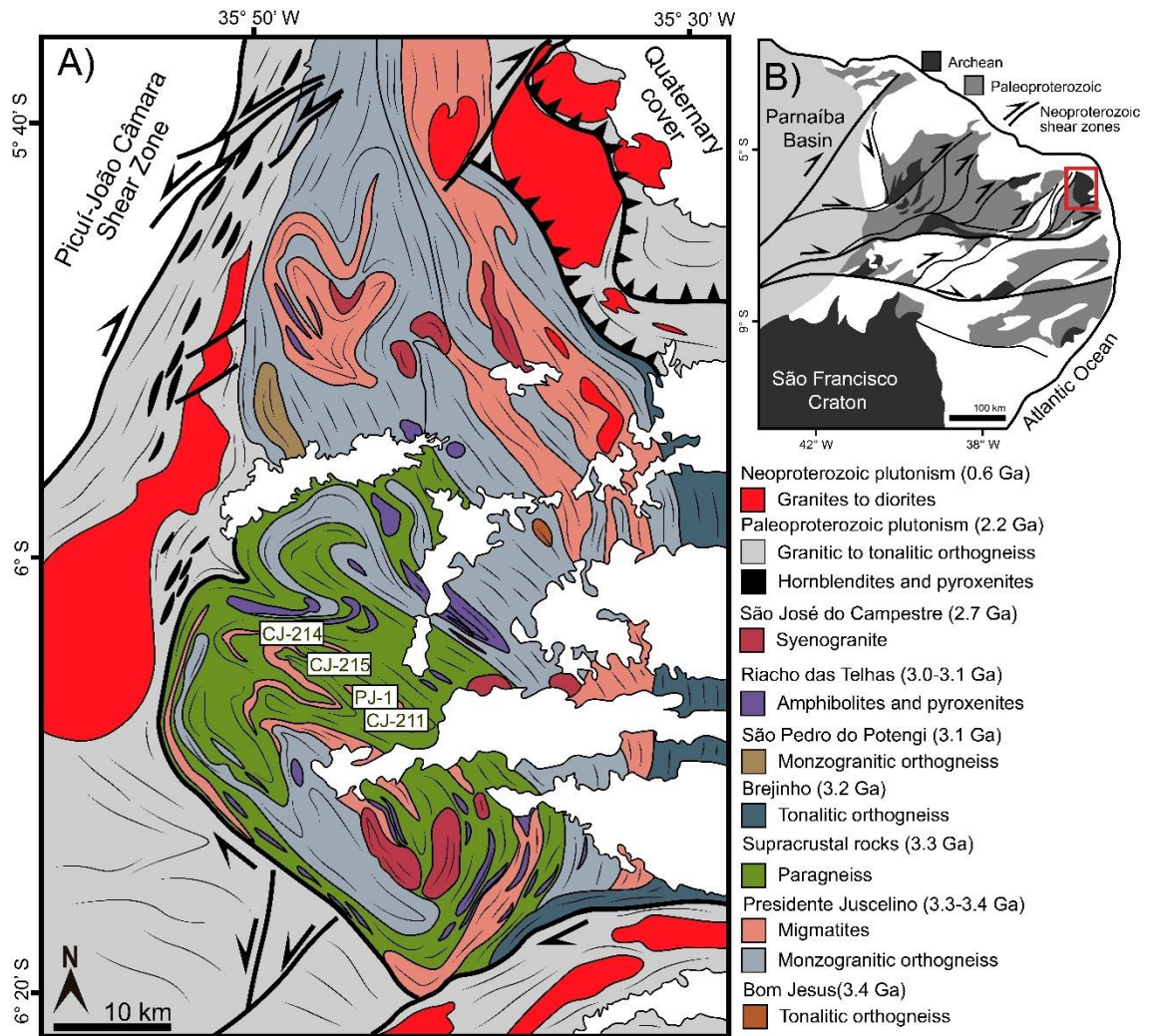


Figura 22: Geological context of the São José do Campestre Massif. A) Geological map. B) Distribution of Paleoproterozoic (light gray) and Archean (dark gray) crust in the Borborema Province.

The Archean evolution of the São José do Campestre Massif is characterized by several magmatic episodes from ca. 3.42 to 2.67 Ga (Fig. 22 - Dantas et al., 2004; Souza et al., 2016).

The oldest rocks identified so far are rare lenses of amphibolite within tonalitic orthogneisses with a zircon U–Pb age of 3412 ± 8 Ma (Dantas et al., 2004). Most of the basement in this area is composed of tonalitic to granodioritic orthogneisses of the Presidente Juscelino Complex yielding zircon U–Pb ages of 3393 ± 17 and 3356 ± 21 Ma (Dantas et al., 2004; Souza et al., 2016).

On the eastern side of the São José do Campestre Massif, granodioritic orthogneisses of the Brejinho Complex were dated at 3178 ± 8 Ma (Dantas et al., 2004). A small hill

(São Pedro do Potengi) on the western side of the São José do Campestre Massif yields a zircon U–Pb age of 3118 ± 9 Ma (Souza et al., 2016).

Several mafic-ultramafic intrusions of the Riacho das Telhas Complex are also present, with zircon U–Pb crystallization ages of 3083 ± 17 Ma and 3041 ± 23 Ma (Abrahão Filho, 2016; Jesus, 2011). The final Archean magmatic activity within the São José do Campestre Massif comprises the São José do Campestre syenogranite, with zircon U–Pb age of 2685 ± 9 Ma (Dantas et al., 2004; Souza et al., 2016).

Within the São José do Campestre Massif, several supracrustal rocks have been recognized, such as marbles, calc-silicate rocks, paragneisses and quartzites (Dantas et al., 2004, 2013; Souza et al., 2016), however, these rocks are poorly understood. Zircon U–Pb ages obtained from a garnet-bearing paragneiss suggest a maximum depositional age of the sediment strata at around 2.7 Ga (Souza et al., 2016). Metamorphic events have been previously identified at ca. 3.0, 2.0 and 0.6 Ga based on U–Pb analyses of zircon and monazite grains (Dantas et al., 2004, 2013; Souza et al., 2006, 2016).

3. Methods

3.1 U–Pb zircon geochronology and trace elements

Field work was carried out in several campaigns during 2021-2023, where Samples from four migmatitic paragneisses were chosen for petrography and U–Pb and trace elements in zircon (Supplementary Material). To aid with mineral identification, BSE imaging and EDS analysis of inclusions in garnet was undertaken at Laboratório de Estudos Geodinâmicos, Geocronológicos e Ambientais (LEGGA) of the Universidade de Brasília, Brazil using a SEM Quanta 450. The zircon grains were measured and qualitatively classified as rounded (aspect ratio <1), stubby (aspect ratio between 2 and 3) and prismatic (aspect ratio >3).

3.2 U–Pb zircon geochronology and trace elements

The samples were crushed, and magnetic minerals were separated using a Frantz magnetic barrier separator at 1.8 A and 10° slope (e.g., Sircombe and Stern, 2002). The grains were handpicked and then mounted in an epoxy resin. The internal structure of zircon grains was assessed by back-scattered imaging (BSE) using a SEM Quanta 450 at 10 nA, 20kV and 13.8 mm working distance coupled to cathodoluminescence (CL) imaging using a Gatan ChromaCL2 iBSED at LEGGA, Universidade de Brasília.

The samples were analyzed for U–Pb isotopes in zircon with a Thermo Finnigan Element XR high-resolution single-collector sector field ICP-MS coupled to a 193 nm Iridia Excimer (ArF) laser ablation system, with a Cobalt dual-volume chamber at LEGGA, Universidade de Brasília, Brazil. Measured masses were ^{202}Hg , ^{204}Pb , ^{206}Pb , ^{207}Pb , ^{208}Pb , ^{232}Th , ^{238}U using the triple detection mode (SEM+Faraday) by sweeping the electrostatic sector on each mass. Blank acquisition was set at 10 s followed by 20 s of ablation. The spot size was set as 25 μm , running at 20 Hz and 2.0 J/cm^{-2} . The primary reference material used was the GJ-1 zircon (602 ± 0.7 Ma; Horstwood et al., 2016; Jackson et al., 2004). Quality control was performed using the 91500 zircon (1062.4 ± 0.4 Ma; Wiedenbeck et al., 2004) and/or the Plešovice zircon (337.13 ± 0.37 Ma; Sláma et al., 2008). Data reduction was performed on the Iolite 4.0 software (Paton et al., 2011) with the assistance of VizualAge plugin (Petrus and Kamber, 2012). Data correction included blank subtraction, LIEF correction using an exponential plus linear model and normalization for the primary reference material. Excess variance of the primary reference material was propagated on each analytical point. No common Pb correction was applied. Detailed specifications of analytical data are available in supplementary files.

Trace element compositions for a few zircon grains from samples CJ-211, CJ-214 and CJ-215 were also obtained at the Laboratório de Estudos Geodinâmicos, Geocronológicos

e Ambientais of the Universidade de Brasília, Brazil, using a Thermo Finnigan Element XR high-resolution single-collector sector field ICP-MS coupled to a 193 nm Iridia laser ablation system. The following masses were analyzed: ^{29}Si , ^{43}Ca , ^{45}Sc , ^{49}Ti , ^{51}V , ^{88}Sr , ^{89}Y , ^{93}Nb , ^{139}La , ^{140}Ce , ^{141}Pr , ^{143}Nd , ^{147}Sm , ^{151}Eu , ^{157}Gd , ^{159}Tb , ^{163}Dy , ^{165}Ho , ^{166}Er , ^{169}Tm , ^{172}Yb , ^{175}Lu , ^{177}Hf , ^{206}Pb , ^{232}Th , ^{238}U . The laser parameters included an ablation spot size of 35 μm , a laser fluence of 4.0 J/cm² and a laser repetition rate of 20 Hz. Each spot analysis consisted of 10 s of background measurement and 30 s of sample ablation. The primary reference material was the NIST-610 glass (Jochum et al. 2016) and the reference materials used for quality control were the NIST-612 glass (Jochum et al. 2016), Diamantina monazite (Gonçalves et al. 2018) and Durango apatite (Chew et al., 2016). Raw data were processed off-line on Iolite 4.0 (Paton et al. 2011) as time-resolved signals. The internal reference value used for calibration was the stoichiometric Si value for zircon (14.76 wt%), Ca for apatite (40 wt.%) and EPMA Ce data for monazite (28 wt.%). The precision of multiple analyses of quality control reference material is better than 5% for most elements and agrees within uncertainty with published data from Gonçalves et al. (2018), Chew et al. (2011) and Jochum et al. (2016). Trace elements concentrations are reported in ppm with 2 standard error.

Concordance was calculated considering the ratio between $(^{238}\text{U}/^{206}\text{Pb})/(^{207}\text{Pb}/^{206}\text{Pb})$ ages for grains older than 1100 Ma and $(^{238}\text{U}/^{206}\text{Pb})/(^{235}\text{U}/^{207}\text{Pb})$ for grains younger than 1100 Ma. Individual grain ages are also reported following the same reasoning, with $^{207}\text{Pb}/^{206}\text{Pb}$ for grains older than 1100 Ma and $^{238}\text{U}/^{206}\text{Pb}$ ages for grains younger than 1100 Ma, unless stated otherwise. For regression of the ages and U–Pb data plotting we used the IsoplotR software (Vermeesch, 2018). All uncertainties reported in the text and figures are quoted at 2σ .

4. Results

4.1 Field features and petrography

The supracrustal rocks crop out over an area of ca. 40 x 20 km width with a slight elongation in the N–S direction. The structural framework is composed of low angle tangential folding with E–W to WNW–ESE axial plane. Late NW–SE synforms and antiforms imprint a macroscale coaxial fold interference pattern (Fig. 22A; Fig. 23A). Gentle folding with N–S subvertical axial planes represents the last stage of ductile deformation. These rocks are strongly metamorphosed at conditions from upper amphibolite to granulite facies.

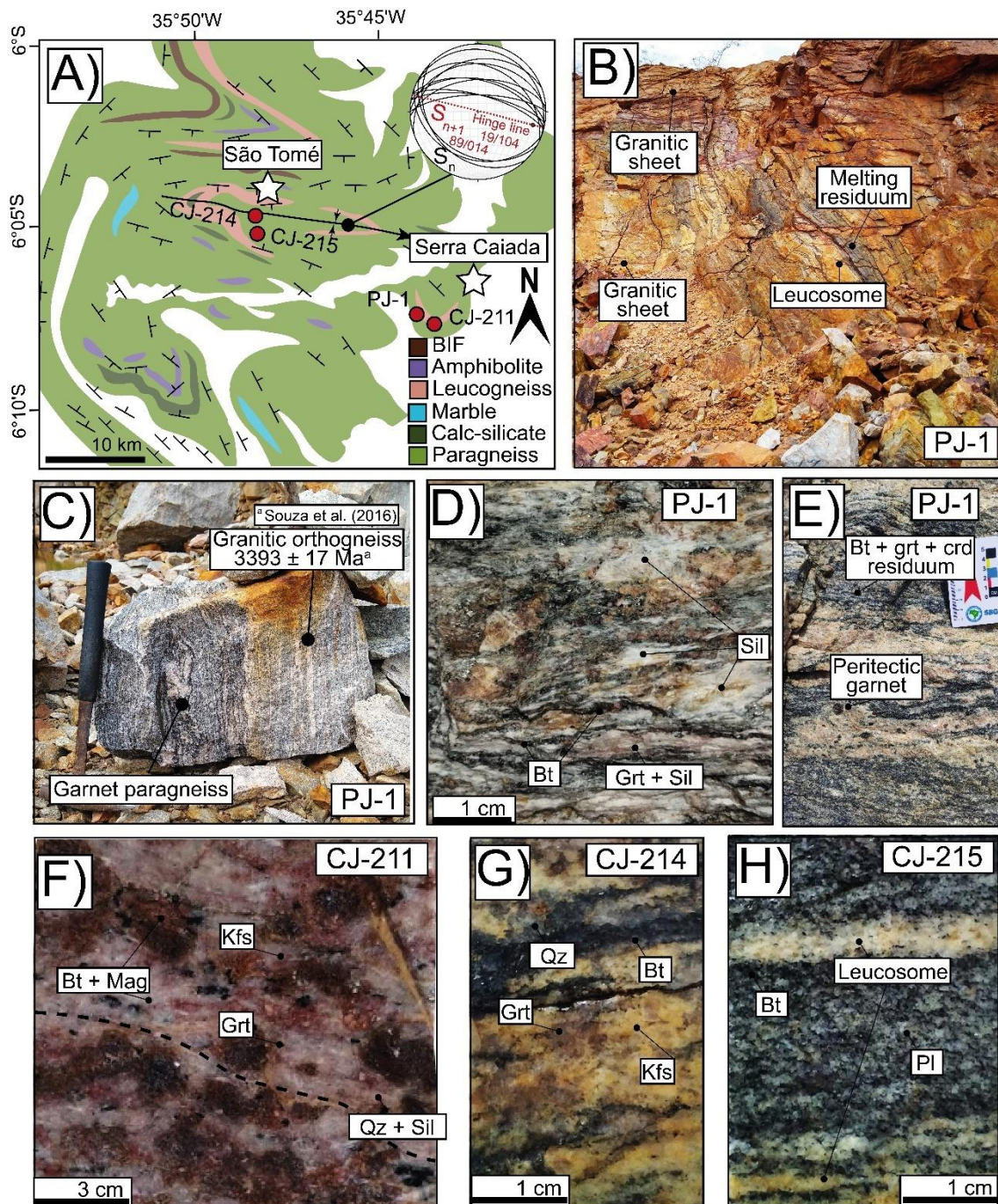


Figura 23: Field features of the supracrustal rocks. A) Detailed geological map of the supracrustal rocks in the western São José do Campestre Massif and location of investigated samples. B) NE-SW view of the Teixeira Quarry, locality of sample PJ-1. The main foliation is nearly vertical and strikes 330 Az. Late sub horizontal granitic sheets (presumably Neoproterozoic) intrude the paragneisses. C) Contact between paragneiss and slightly older basement rock from the Presidente Juscelino Complex sampled by Souza et al. (2016) at the Teixeira Quarry. D) Hand sample PJ-1. Sillimanite (Sil) and biotite (Bt) occur along the foliation and overgrow garnet (Grt) porphyroblasts. E) Outcrop PJ-1 at Teixeira Quarry showing a metamorphic banding characterized by a biotite (Bt) + garnet (Grt) + cordierite (Crd) residuum and leucosomes with peritectic garnet. F) Hand sample CJ-211 with large porphyroblasts of garnet (Grt) and a matrix of quartz (Qz) + sillimanite (Sil) + K-feldspar (Kfs) in a mylonitic fabric. Biotite (Bt) and magnetite (Mag) slightly define the foliation. G) Hand sample CJ-214, mostly composed of leucosome and minor biotite-rich residuum. Garnet (Grt) is present in both leucosome and residuum. H) Hand sample CJ-215 with a biotite (Bt) + plagioclase (Pl) matrix and injected leucosome.

All the outcrops investigated are characterized by intense partial melting, with portions ranging from banded metatexites to poorly foliated diatexites. At the Teixeira Quarry (Sample PJ-1), where a granitic orthogneiss was previously dated at 3393 ± 17 Ma (Souza et al., 2016), a garnet paragneiss (Fig. 23B) shows a mylonitic contact (presumably subvertical) in a loose block with the orthogneiss (Fig. 23C). Garnet and biotite are the main ferromagnesian minerals of the paragneisses, occurring in all of the samples (Fig. 23D, E; 24). In the melting residuum, the garnet porphyroblasts show coronae of cordierite + quartz, with minor chlorite, while in the leucosomes coronae of biotite + chlorite are featured (Fig. 23E; 24A, B). The matrix of the melting residuum is composed by quartz (45%), plagioclase (30%), K-feldspar (10%) (Fig. 23H), while in the leucosome it presents quartz (50%), K-feldspar (20%), plagioclase (10%) (Fig. 24G). In some samples, sillimanite occurs along shearing structures (e.g., S-C foliation) (Fig. 23E, 24C, D).

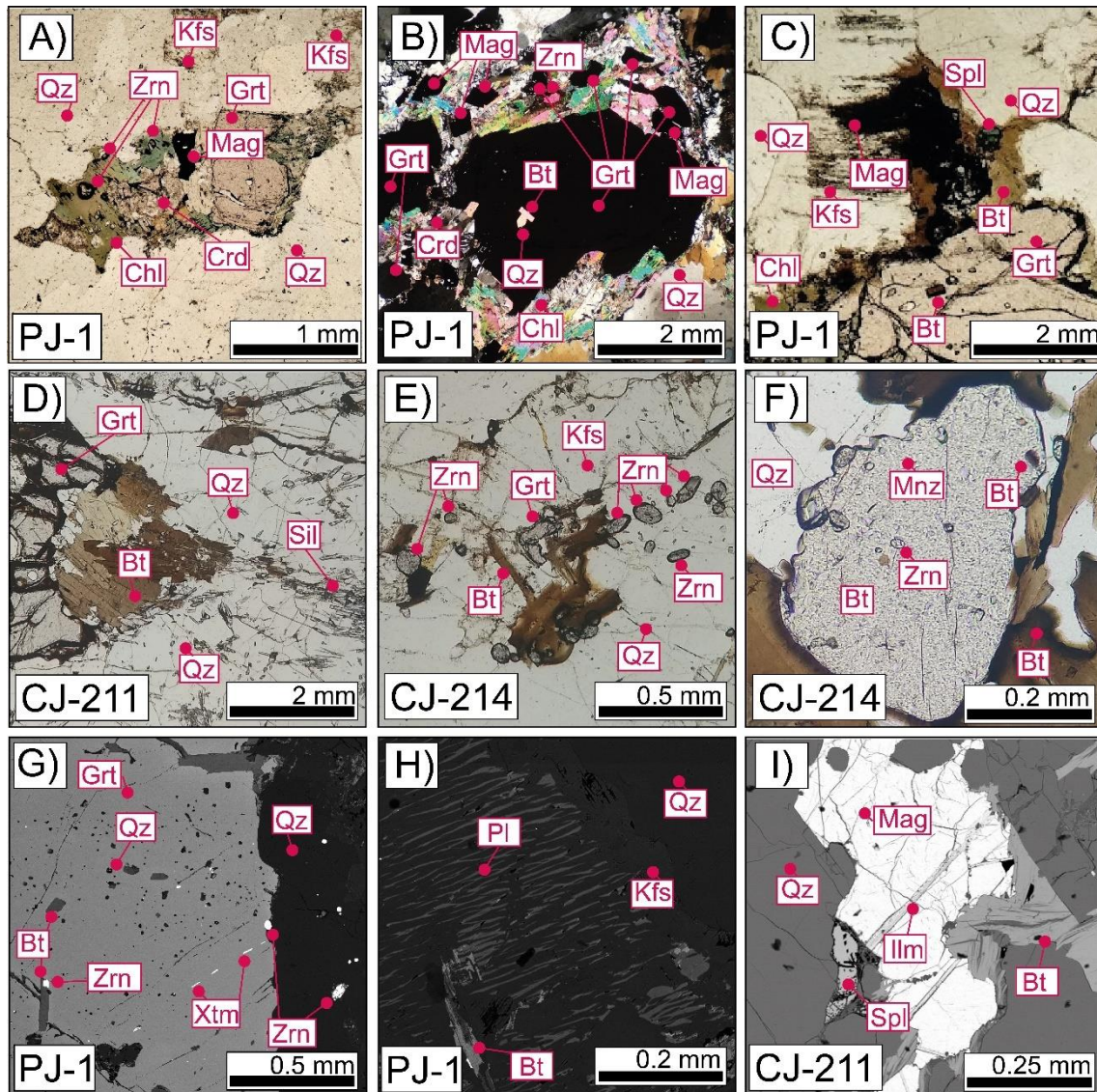


Figura 24: Petrography and mineral assemblages. A) Sample PJ-1. Garnet porphyroblast with retrograde cordierite (Crd) + magnetite (Mag) + zircon (Zrn). Late chlorite replaces cordierite. The matrix is composed of K-feldspar (Kfs) and quartz (Qz). B) Sample PJ-1. Garnet porphyroblast with quartz + biotite inclusion and a retrograde corona of cordierite (Crd) + magnetite (Mag) + chlorite (Chl) + zircon (Zrn). C) Sample PJ-1. Large garnet (Grt) surrounded by magnetite (Mag) + biotite (Bt) + spinel (Spl) + quartz (Qz) + K-feldspar (Kfs) and late chlorite (Chl). Inclusions in garnet include quartz and biotite. D) Sample CJ-211. Garnet (Grt) porphyroblast with retrograde biotite (Bt) + sillimanite (Sil). E) Sample CJ-214. Relict garnet (Grt) crystal with retrograde biotite (Bt) close to a cluster of rounded zircon grains (Zrn). F) Sample CJ-214. Monazite (Mnz) porphyroblast with inclusions of zircon (Zrn) and biotite (Bt). G) Sample PJ-1. BSE image of inclusions in garnet showing quartz (Qz), biotite (Bt), zircon (Zrn) and xenotime (Xtm). H) Sample PJ-1. BSE image of plagioclase (Pl) exsolution in K-feldspar (Kfs). I) Sample CJ-211. Magnetite (Mag) with ilmenite (Ilm) exsolution close to a spinel crystal (Spl).

Sample PJ-1 is a migmatitic paragneiss from the Teixeira Quarry, near Serra Caiada (latitude, longitude: -6.123078°, -35.722438°). Thin-sections from both residuum and leucosome were described at this outcrop. The residuum is composed of large garnet porphyroblasts (up to 4 mm) with coronae of cordierite + quartz + magnetite + zircon

(Fig. 24A, B). Garnet bears inclusions of quartz, biotite, xenotime and zircon (Fig. 24G). The matrix is composed of quartz > plagioclase > K-feldspar. Biotite occurs along the main foliation and surrounding garnet porphyroblasts. The matrix of the leucosome is composed by quartz > K-feldspar > plagioclase. Many samples feldspar display exsolution lamellae between K-feldspar and plagioclase (Fig. 24H). Garnet porphyroblasts (up to 6 cm) in the leucosome are usually replaced by retrograde biotite + chlorite, locally with small sillimanite needles. Common matrix accessory minerals are spinel, ilmenite and apatite.

Sample CJ-211 is an aluminous granulite near the Teixeira Quarry (latitude, longitude: -6.121168°, -35.719585°). Large garnet porphyroblasts are replaced by biotite + sillimanite (Fig. 24D). The slight foliation is defined by biotite + sillimanite + magnetite. Magnetite crystals show ilmenite lamellae and occur in association with spinel, biotite and quartz (Fig. 24I). The matrix is mostly composed of quartz (55%) K-feldspar (15%), and plagioclase (5%). Accessory phases are ilmenite, zircon, apatite and monazite that occur mostly in the matrix.

Sample CJ-214 is a migmatitic paragneiss near the São Tomé on the northern flank of the synform (latitude, longitude: -6.076966°, -35.803817°). Metamorphic banding is well developed in this sample, precluding a clear separation between melting residuum and leucosome. In this sample, garnet porphyroblasts (up to 2 cm) are well developed and show inclusions of quartz, monazite and zircon. Retrograde chlorite surrounds garnet porphyroblasts and frequently show inclusions of zircon. In-situ partial melting can be observed as thin melt rims surrounding quartz crystals. In these zones, clusters of rounded zircon, sometimes with visible inherited cores, can be observed around decomposed garnet + biotite crystals (Fig. 24E). Large monazite crystals (up to 0.6 mm) are also found in the matrix with inclusions of biotite and zircon (Fig. 24F). The matrix is mostly

composed by quartz (40%), plagioclase (25%) and K-feldspar (15%). Accessory ilmenite, magnetite, and apatite are also present.

Sample CJ-215 is a migmatitic paragneiss also near the São Tomé, but on the southern flank of the synform (latitude, longitude: -6.083100°, -35.802197°). Garnet porphyroblasts (up to 6 mm) are well developed and show inclusions of quartz. Biotite and minor retrograde muscovite define the main foliation. The matrix is composed of quartz (35%), plagioclase (25%) and K-feldspar (15%). Accessory minerals are ilmenite, magnetite, zircon, monazite and apatite

4.2 Zircon morphology and U–Pb geochronology

From sample PJ-1, most of the analyzed grains are rounded (aspect ratio < 2) to stubby (aspect ratio between 2 and 3), with a few grains that are elongated to prismatic (aspect ratio > 3). The grains range from 75 to 214 μm in length and from 42 to 97 μm in width (Fig. 25A). 134 analyses were obtained on zircon cores and 16 are from zircon rims. From these, a total of 67 analyses are less than 5% discordant and 101 analyses are less than 10% discordant. In the concordia diagram four zircon populations can be identified within sample PJ-1 (Fig. 25B). The first population has $^{207}\text{Pb}/^{206}\text{Pb}$ ages that spread between 3363 ± 53 Ma and 3184 ± 39 Ma. These ages are found in the core of stubby to prismatic grains. These cores rarely preserve any kind of zoning and are either homogeneously bright or dark in CL (Fig. 25C). The second population comprises several slightly discordant analyses with one concordant analysis that yield a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3018 ± 35 Ma. These ages are found mostly in the cores of rounded zircon grains with sector zoning, as well as in the rims of a few ca 3.3 Ga cores (Fig. 25D). Th/U ratios are consistently lower in the zircon rims than in their sector-zoned cores. The third and fourth populations, with $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1910 ± 33 Ma and $^{238}\text{U}/^{206}\text{Pb}$ age of 576 ± 12 Ma, respectively, appear as rims on older cores that are visually indistinguishable from

ca. 3.0 Ga rims in CL images (Fig. 25D). Th/U ratios show an exponential decrease with age, with most of the grains older than 3.1 Ga featuring higher Th/U ratios (Fig. 25D).

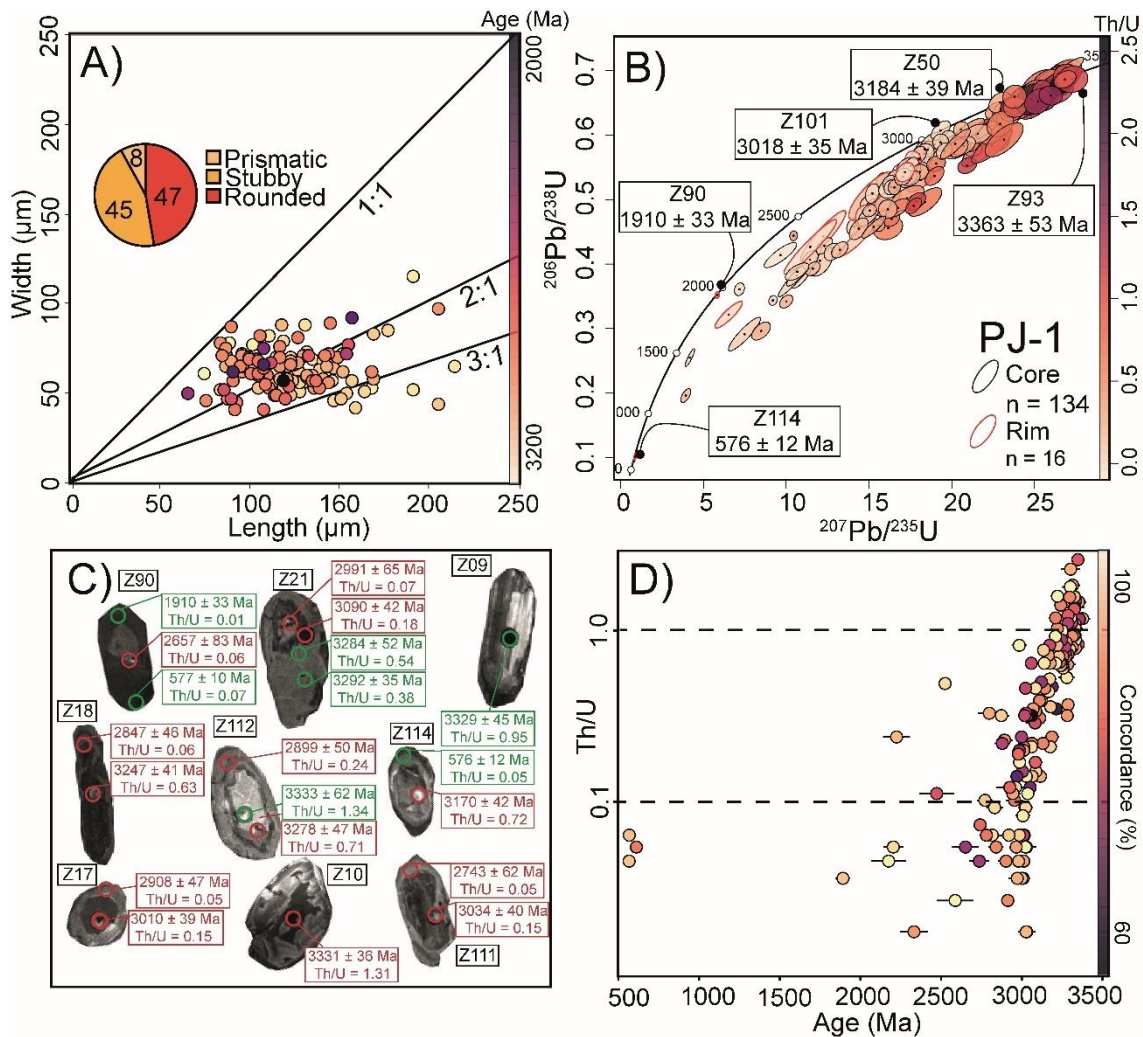


Figura 25: Geochronological results of sample PJ-1. A) Relationship between zircon grain length and width color-coded by age (Ma). Pie chart shows the percentage of rounded, stubby and prismatic types. B) Wetherill concordia diagram showing the analyzed isotopic ratios for zircon cores and rims color-coded by Th/U. Representative ages of individual analyses are also shown. C) Cathodoluminescence images of selected grains. Analyses with discordance < 5% are shown in green. D) Th/U ratios versus Age (Ma) color-coded by concordance (%).

From sample CJ-211, most of the analyzed grains are rounded, with only a few stubby grains, ranging from 43 to 171 μm in length and 26 to 82 μm in width (Fig. 26A). 64 analyses were performed on zircon cores and 6 on zircon rims. A total of 13 analyses are less than 5% discordant and 26 are less than 10% discordant. The oldest zircon grain yield a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3084 ± 31 Ma and the youngest has an $^{238}\text{U}/^{206}\text{Pb}$ age of $668 \pm$

33 Ma (Fig. 26B). The majority of zircon grains (67/70) form a regression line with an upper intercept age of 3080 ± 10 Ma and lower intercept age of 582 ± 30 Ma (Fig. 26B). In CL images, rounded grains are usually small ($< 50 \mu\text{m}$) and show sector-zoned cores (Fig. 26C). Dark cores in stubby zircon grains show variate morphology, from rounded to prismatic with faint oscillatory zoning. All of them yield ages in the range of 3.1 – 3.0 Ga that are indistinguishable from the metamorphic rims (Fig. 26C). A single nearly concordant rim with $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1970 ± 49 Ma could be found in a 2989 ± 44 Ma old grain (Fig. 26C). Th/U ratios also are mostly below 0.3, with younger and most discordant zircon grains featuring lower Th/U ratios (Fig. 26D).

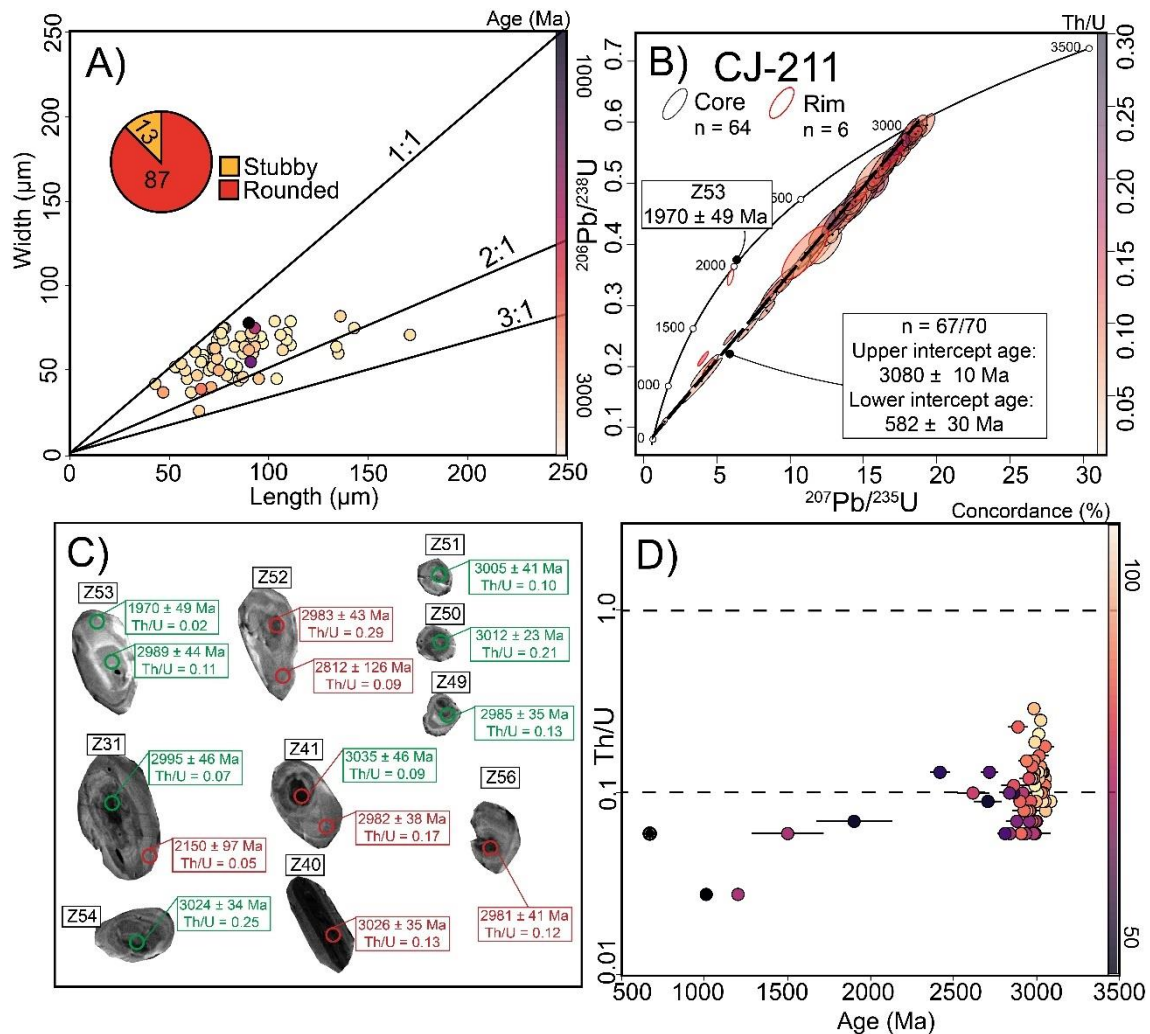


Figura 26: Geochronological results of sample CJ-211. A) Relationship between zircon grain length and width color-coded by age (Ma). Pie chart shows the percentage of rounded, stubby and prismatic types. B) Wetherill concordia diagram showing the analyzed isotopic ratios for zircon cores and rims color-coded by

Th/U and regression line with an upper intercept age of 3080 ± 10 Ma and lower intercept age of 582 ± 30 Ma. Analyses included in the calculation are shown with a black dot inside. C) Cathodoluminescence images of selected grains. Analyses with discordance $< 5\%$ are shown in green. D) Th/U ratios versus Age (Ma) color-coded by concordance (%).

From sample CJ-214, most of the zircon grains are rounded, with several stubby and only a few prismatic (Fig. 27A). The grains range in length from 41 to 281 μm and from 35 to 133 μm in width (Fig. 27A). A total of 137 analyses were performed on zircon cores and 19 on zircon rims. From these, 76 analyses are less than 5% discordant and 116 are less than 10% discordant. The oldest grains yield an $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3361 ± 36 Ma and the youngest has an $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2515 ± 50 Ma (Fig. 27B). Most of the grains (151/156) can be fitted on a discordia line with an upper intercept age of 3095 ± 5 Ma and a lower intercept age of 741 ± 54 Ma (Fig. 27B). The two results around 3.3 Ga were found in bright zircon cores with a dark rim with faint oscillatory zoning and ages around 3.1 – 3.0 Ga (Fig. 27C). A few grains with dark prismatic core could also be identified with ages of ca. 3.1 Ga (Fig. 27C). The 3.1 Ga population also comprises several rounded grains, characterized by a bright sector-zoning in the core and darker convolute-zoned rim (Fig. 27C). Zircon Th/U ratios within this sample span from 1 to 3.5, being mostly close to 1 in ca. 3.3 Ga zircon grains (Fig. 27D). Younger discordant zircon grains show consistently lower Th/U ratios (Fig. 27D).

From sample CJ-215, most of the analyzed zircon grains are with a few stubby grains with length ranging from 43 to 153 μm and width ranging from 27 to 108 μm (Fig. 28A). A total of 95 analyses were performed on zircon cores and 12 on zircon rims. From these, 15 analyses are less than 5% discordant and 24 analyses are less than 10% discordant. In the concordia diagram, four zircon populations can be identified (Fig. 28B). In this sample, a single zircon yielded an $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3370 ± 31 Ma. In CL images, this grain has a bright rounded core and is surrounded by dark and bright rims (Fig. 28C). The second zircon population comprises several concordant and discordant grains, with the concordant ones having $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 3054 ± 31 Ma to 2904 ± 100 Ma.

(Fig. 28B). These grains usually show rounded cores with sector zoning and surrounded by convoluted-zoned rims. The third and fourth populations comprise a few concordant zircon grains, as well as several discordant ones, with the concordant ones having $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1990 ± 73 Ma and $^{238}\text{U}/^{206}\text{Pb}$ age of 557 ± 16 Ma (Fig. 28B). These ages were identified in unzoned rims (Fig. 28C). Th/U ratios are higher than 1.0 in the ca. 3.3 Ga zircon grain and lower than 0.5 in younger zircon grains (Fig. 28D).

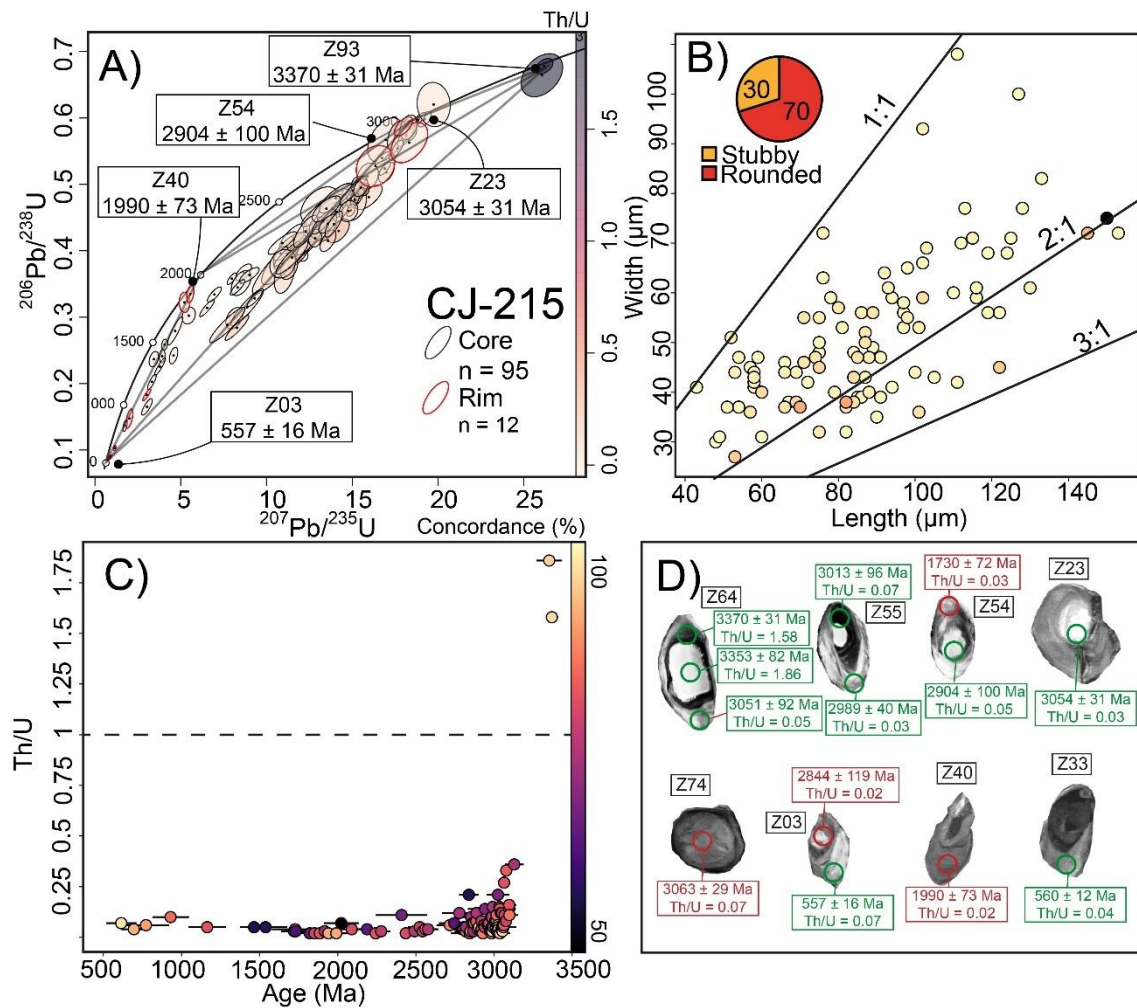


Figura 28: Geochronological results of sample CJ-215. A) Relationship between zircon grain length and width color-coded by age (Ma). Pie chart shows the percentage of rounded, stubby and prismatic types. B) Wetherill concordia diagram color-coded by Th/U showing the analyzed isotopic ratios for zircon cores and rims. Representative ages of individual analyses are also shown. C) Cathodoluminescence images of selected grains. Analyses with discordance < 5% are shown in green. D) Th/U ratios versus Age (Ma) color-coded by concordance (%).

4.3 Trace elements in zircon

Trace elements compositions in zircon were obtained for a few grains in samples CJ-211 (n = 13), CJ-214 (n = 9) and CJ-215 (n = 8). In some grains, we were able to perform analyses on both core and rim, however, in most cases the small size of the grains prevented more than two ablation spots (including the U–Pb analysis). As light rare earth elements (LREE) concentrations are usually low in zircon and strongly influenced by inclusions, we preferred to calculate La and Pr values following the Chondrite-Onuma method of Carrasco-Godoy and Campbell (2023) instead of using the measured values. This method is based on the quadratic relationship between ionic radius and partition coefficients. REE values are reported normalized to chondrite values of Anders and Grevesse (1989).

Overall, rare earth elements (REE) concentrations differ per sample, suggesting that whole-rock geochemistry mainly controls the REE budget within zircon. In sample CJ-211, REE values in zircon are generally low ($\Sigma\text{REE} = 188 - 436$ ppm) and slightly increases towards heavy rare earth elements HREE (Fig. 29A). REE patterns for Mesoarchean cores generally display more flattened HREE, with $\text{DyN}/\text{YbN} > 1$ and negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.11$ to 0.66). Three Paleoproterozoic rims yield positive Eu anomalies, and a single analysis exhibiting elevated HREE.

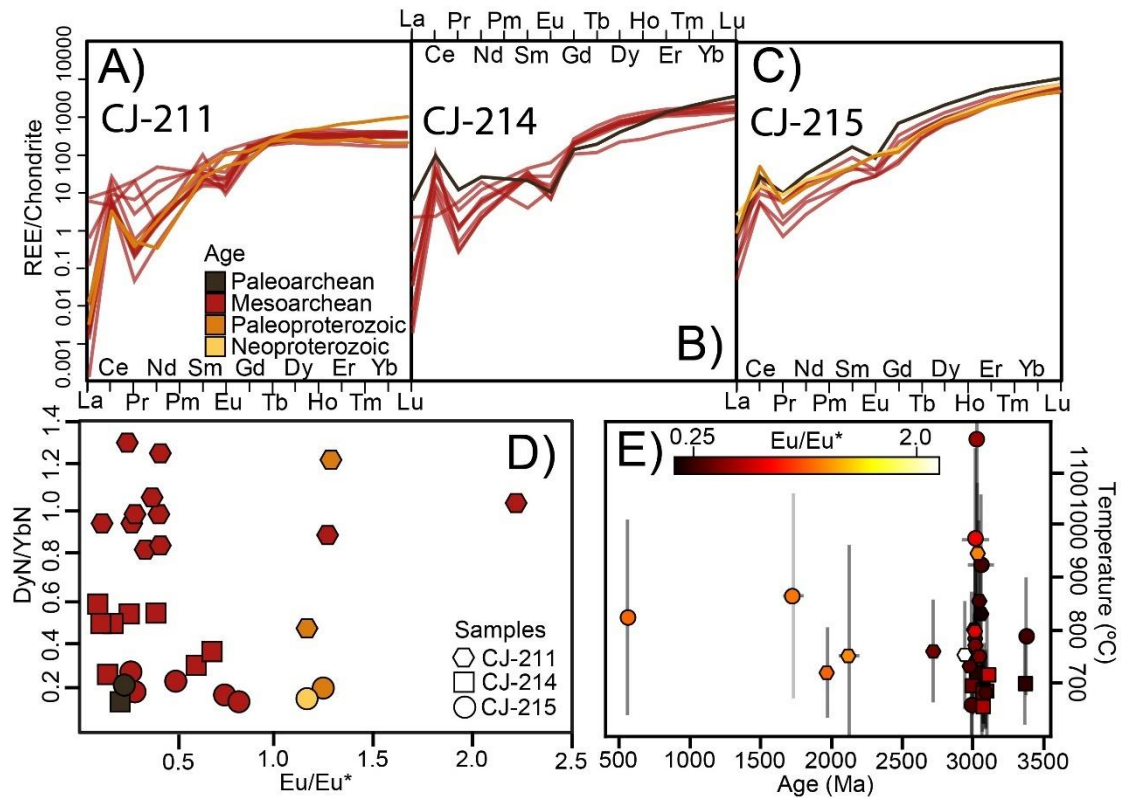


Figura 29: Trace elements in zircon. A – C) Rare-earth element patterns normalized to the chondrite values of Anders & Grevesse (1989). D) Eu/Eu^* ratios versus DyN/YbN ratios. Colors are the same as in (A). E) Age (Ma) versus Ti (ppm) and Ti-in-zircon temperature ($^{\circ}\text{C}$). Colors are based on Eu/Eu^* ratios and symbol shape are the same as (D).

In sample CJ-214, the overall REE concentrations in zircon are higher ($\Sigma\text{REE} = 320 - 1077$ ppm). A single Paleoarchean zircon core displays elevated HREE with $\text{Dy}/\text{Yb} = 0.22$. Mesoarchean analyses are depleted in HREE when compared to the Paleoarchean zircon core, but DyN/YbN values are consistently below 1. Varying degrees of negative Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.07 - 0.67$) are observed in all analyses.

Most zircon grains within sample CJ-215 show higher REE concentrations ($\Sigma\text{REE} = 1465 - 3503$ ppm), with elevated HREE ($\text{Dy}/\text{Yb} = 0.14 - 0.26$). Eu anomalies are mostly negative, from 0.25 to 0.80, with a Paleoproterozoic and a Neoproterozoic rim with nearly flat patterns ($\text{Eu}/\text{Eu}^* = 1.22$ and 1.17 , respectively)

Ti-in-zircon temperatures (e.g., Watson et al., 2006) were calculated following the recent pressure-dependent calibration of Crisp et al. (2023). Based on the absence of

kyanite, we can infer pressures below 10 kbar can be inferred and, therefore, an average pressure of 0.7 ± 0.2 GPa was applied. These would broadly correspond to thermal gradients of $800\text{ }^{\circ}\text{C/GPa}$ to $1800\text{ }^{\circ}\text{C/GPa}$ for a temperature range of 700 to $900\text{ }^{\circ}\text{C}$, which is the common range from other Archean localities (e.g., Brown and Johnson, 2018). a_{TiO_2} was set at 0.7 ± 0.1 based on the absence of rutile and is the common range for rutile-absent metapelitic rocks (Yakymchuk et al., 2017). a_{SiO_2} was set at 1 due to the ubiquitous presence of quartz (Watson et al., 2006)

In sample CJ-211, metamorphic cores and rims of ca. 3100 – 3000 Ma yielded Ti concentrations between 5 ± 1 and 47 ± 18 ppm and temperatures in the range of $699 \pm 57\text{ }^{\circ}\text{C}$ to $949 \pm 134\text{ }^{\circ}\text{C}$ (Fig. 29E). Two different Paleoproterozoic rims yielded Ti concentrations of 6 ± 2 and 9 ± 8 ppm, for temperatures of $722 \pm 86\text{ }^{\circ}\text{C}$ and $754 \pm 211\text{ }^{\circ}\text{C}$, respectively. In sample CJ-214, a single ca. 3300 Ma bright core yielded Ti concentration of 5 ± 2 ppm and a temperature of $700 \pm 77\text{ }^{\circ}\text{C}$. Metamorphic cores and rims of ca. 3100 – 3000 Ma yielded Ti concentrations between 4 ± 1 ppm to 6 ± 1 ppm and temperatures in the range of 661 ± 104 to $722 \pm 78\text{ }^{\circ}\text{C}$. In sample CJ-215, a single ca. 3300 Ma old core yielded a Ti concentration of 12 ± 5 ppm and a temperature of $791 \pm 112\text{ }^{\circ}\text{C}$. The 3100 – 3000 Ma population yield Ti concentrations in the range of 3 ± 2 ppm to 186 ± 100 ppm and temperatures ranging from $660 \pm 102\text{ }^{\circ}\text{C}$ to $1169 \pm 244\text{ }^{\circ}\text{C}$. The extremely high concentration of Ti in one grain could be related to the ablation of a Ti-bearing inclusion. A single Paleoproterozoic rim yielded a Ti concentration of 25 ± 17 ppm for a temperature of $868 \pm 195\text{ }^{\circ}\text{C}$ and a Neoproterozoic rim yielded a Ti concentration of 17 ± 12 ppm and a temperature of $827 \pm 186\text{ }^{\circ}\text{C}$.

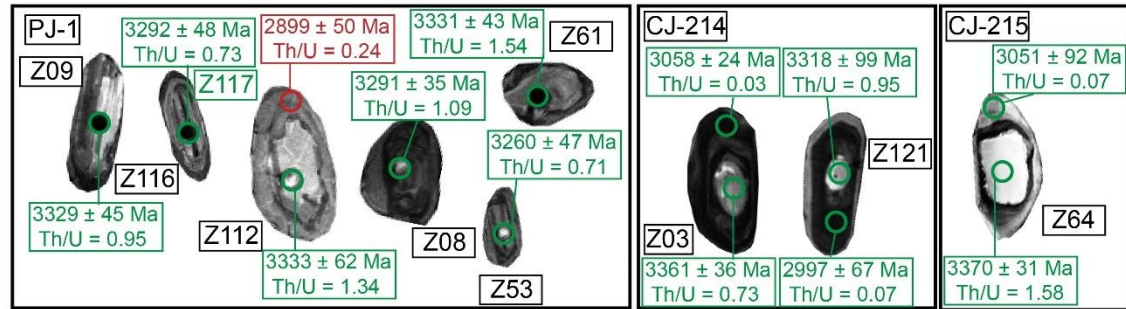
5. Discussions

5.1 Zircon textures and populations

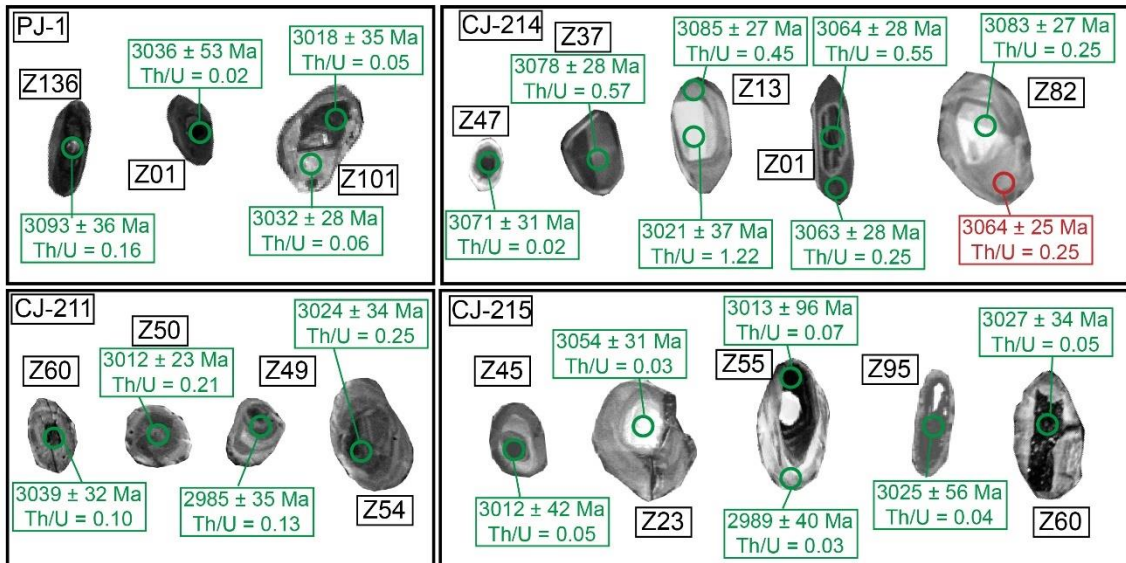
The shape and internal textures of zircon grains are useful tools to constrain crystallization processes and provenance (e.g., Markwitz and Kirkland, 2018 and references therein). However, high-temperature metamorphism and partial melting can modify the external and internal morphology of zircon, leading to equivocal interpretations of sources and depositional ages (e.g., Kuper et al., 2024; Nyström and Kriegsman, 2003; Schaltegger et al., 1999; Tedeschi et al., 2023; Tichomirowa et al., 2005)

In CL, the analyzed grains display metamorphic recrystallization with detrital core often erased. Based on U–Pb data coupled to zircon textures, four groups with distinctive zircon growth domains, representing different (re)crystallization events, could be identified: Paleoarchean (3.4 – 3.3 Ga), Mesoarchean (3.1 – 3.0 Ga), Paleoproterozoic (2.0 – 1.9 Ga) and Neoproterozoic (0.6 Ga). Sample PJ-1 features the highest number of Paleoarchean cores, in many cases with no visible overgrowth. The morphology of these grains is mostly stubby to prismatic (Fig. 30). Dark cores usually show a higher concentration of U (up to 648 ppm), whereas bright cores are low in U and enriched in Th. Faint oscillatory zoning is the most common type of internal morphology of the dark cores, whereas bright cores are mostly unzoned (Fig. 30). In samples CJ-214 and CJ-215, only a few Paleoarchean cores could be found. These cores are bright in CL, with low U and higher Th/U (Fig. 30). Overall, Th/U ratios are also higher in these cores, mostly above 0.5 and frequently above 1.0. The Paleoarchean cores are interpreted to reflect unmodified detrital zircon, as their textural and geochemical features are similar to zircon grains of magmatic origin.

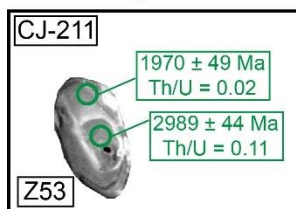
Detrital cores - Paleoarchean



Metamorphic cores and rims - Mesoarchean



Metamorphic rims - Paleoproterozoic



Metamorphic rims - Neoproterozoic

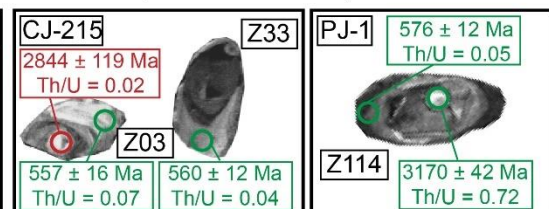


Figura 30: Summary of detrital and metamorphic zircon populations. Populations are grouped by range of U-Pb ages. Red analyses are more than 5% discordant.

Several types of overgrowths surrounding the detrital cores were identified. Most of the overgrowths are of Mesoarchean age with varied morphology, including faint oscillatory and bright convolute zoning. Th/U ratios within Mesoarchean rims are mainly below 0.1. Mesoarchean cores within rounded to stubby grains are also present. In several cases, these cores show sector and/or fir-tree zoning and range from brighter (low U) to darker (high U) CL responses and are common textures of high-temperature metamorphism (e.g., Rubatto, 2017; Schaltegger et al., 1999; Tichomirowa et al., 2005)

Overgrowths with Paleoproterozoic and Neoproterozoic ages are mostly homogeneous or display faint convolute zoning with low U and low Th/U (Fig. 30). Zircon rims with similar textural characteristics are visible but are too narrow to be analyzed.

Overall, Paleoarchean cores record detrital ages, whereas Mesoarchean, Paleoproterozoic and Neoproterozoic ages are related to high-temperature recrystallization.

5.2 Maximum depositional age and provenance

Stratigraphic relationships in high-grade terrains are often difficult to recognize in the field, especially when polyphase deformation and metamorphism are present. U–Pb geochronology in zircon is a powerful tool for constraining the evolution of sedimentary basins and several methods for constraining their maximum depositional ages have been employed in the past years (e.g., Coutts et al., 2019; Kröner et al., 2014 and references therein). The most common methods are the youngest single concordant grain and the youngest graphic peak (e.g., Coutts et al., 2019), although recent statistical analysis by Vermeesch (2021b) showed that most of the methods are flawed and either systematically underestimate or overestimate maximum depositional ages.

Beyond the method itself, the discordance filter employed might also bias maximum depositional ages. Commonly, a cut-off of 10% or 5% of discordance between $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{238}\text{U}/^{206}\text{Pb}$ ages is applied for ages older than 1100 Ma (Spencer et al., 2016). Ages younger than 1100 Ma are filtered based on the discordance between $^{238}\text{U}/^{206}\text{Pb}$ and $^{235}\text{U}/^{207}\text{Pb}$ ages. However, these methods are subjective and can either underestimate or overestimate populations (Vermeesch, 2021b).

In our particular dataset, the main problem is that even a narrow 5% discordance cut-off still leaves behind several analyses that do not intercept the concordia line (Fig. 31A). The concordia distance is the most unbiased method for defining discordance (Vermeesch, 2021a). Therefore, we only considered grains with concordia distance < 3 to assess the maximum depositional age. Single-grain concordia ages instead of $^{207}\text{Pb}/^{206}\text{Pb}$ ages were also employed (e.g., Vermeesch, 2021a).

From the filtered data, single grain concordia ages range from 3390 ± 26 Ma to 3210 ± 23 Ma. (Fig. 31A, B). However, a decrease in Th/U ratios with decreasing age may indicate that the youngest grains are partially recrystallized (Fig. 31B, C). The internal structure of these grains is also devoid of any type of zoning, suggesting that they are in fact recrystallized. The most pristine youngest core yielded a single grain concordia age of 3286 ± 33 Ma (Fig. 31B). Therefore, even using a narrow statistical approach for filtering discordant data, recrystallized grains were still present in the dataset. Therefore, individual inspection of the textures of zircon grains is fundamental for constraining accurate protolith ages in polymetamorphic rocks.

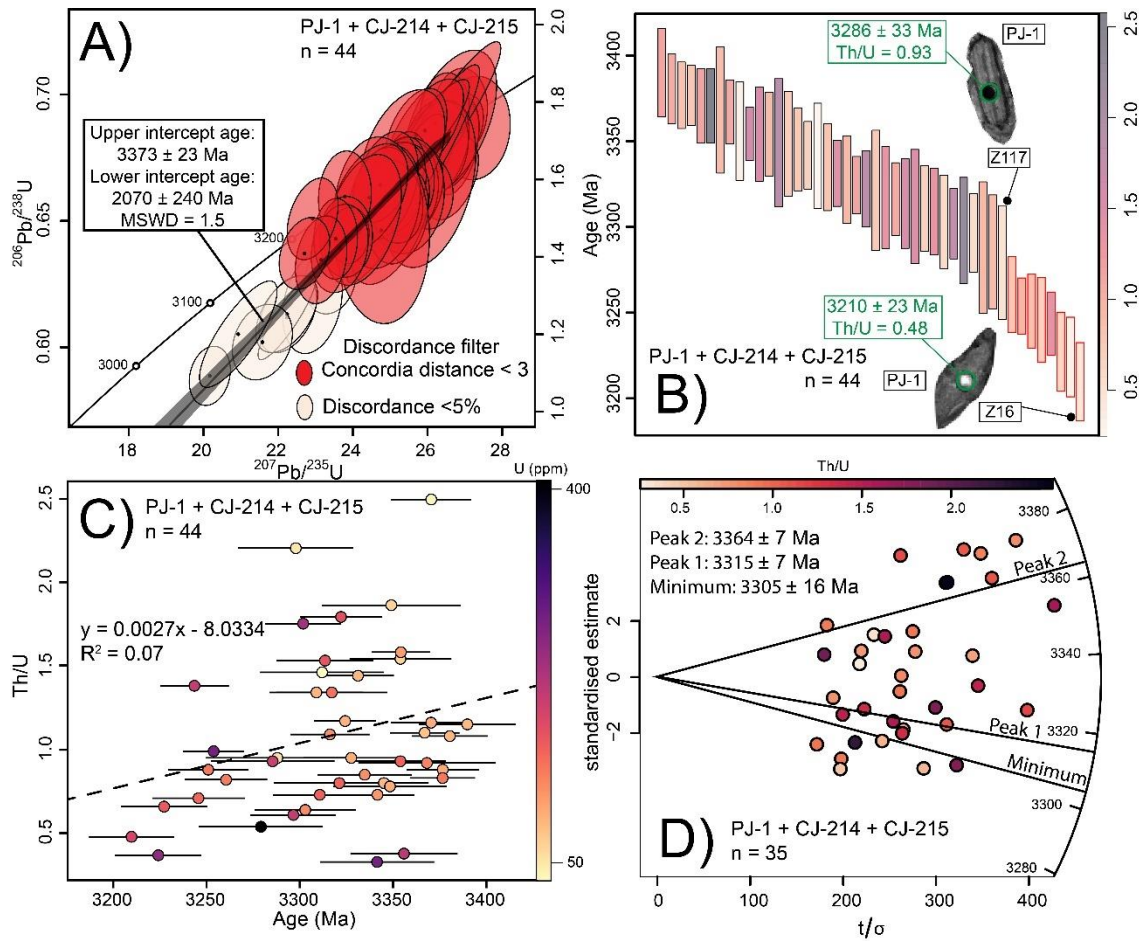


Figura 31: Maximum depositional age of the supracrustal rocks. A) Detrital cores with less than 5% discordance and with less than 3 of concordia distance. B) Weighted average of single-grain concordia ages of detrital cores color-coded by Th/U. Red outlines indicate the grains that are devoid of internal zoning and were excluded from maximum depositional age calculation in (D). C) Single-grain concordia ages (Ma) versus Th/U ratios of detrital cores color-coded by U (ppm). A negative slope indicates a decrease in Th/U ratios over time and increase in U concentrations. D) Radial plot with single-grain concordia ages clustered in two peaks and the minimum (maximum depositional) age of the Maximum Likelihood Algorithm (Galbraith & Laslett, 1993).

In Vermeesch (2021), the least flawed method for constraining the maximum depositional age is the Maximum Likelihood Algorithm of Galbraith and Laslett (1993). In our dataset, this method achieved a maximum depositional age of 3305 ± 16 Ma (Fig. 31D). This age is within the uncertainty of the most pristine youngest single grain and best represents the maximum depositional age of these rocks. The preservation of Paleoarchean zircon cores indicates a much older maximum depositional age of the sedimentary package at ca. 3305 Ma than the previously assumed sedimentation age at around 2700 Ma (Souza et al., 2016)

However, the maximum depositional age of these supracrustal rocks is ca. 90 Ma younger than proximal granitic gneisses from the same sample locality (Teixeira Quarry, 3397 ± 17 Ma; Souza et al., 2016). We therefore interpret the sedimentary package to be deposited on top of the felsic basement, with potential sources being the orthogneisses of Presidente Juscelino (3356 ± 21 Ma; Souza et al., 2016) and Bom Jesus (3412 ± 8 Ma; Dantas et al., 2004) complexes. The small time-span between the oldest and the youngest detrital zircon grains are suggestive of a collisional tectonic setting, where zircon grains are mostly sourced from magmatic arcs with low variability in zircon ages (e.g., Cawood et al., 2012).

5.3 Zircon growth and recrystallization during high-temperature metamorphism

During high-temperature metamorphism and partial melting, zircon growth is not expected to occur during prograde heating reactions (e.g., Yakymchuk, 2023). Instead, in most cases, zircon growth occurs during cooling and exhumation (e.g., Kohn et al., 2015; Yakymchuk, 2023). Zircon growth during metamorphism can either occur as dissolution-reprecipitation or as direct growth from the melt (e.g., Kohn et al., 2015; Rubatto, 2017). Dissolution-reprecipitation is mostly related to Ostwald Ripening, where smaller grains dissolve in the melt phase to form larger grains and minimize surface energy (e.g., Nemchin et al., 2001). Experimental data indicate that fluid saturation is necessary for grain coarsening (Ayers et al., 2003). On the other hand, direct growth from the melt might be achieved during Zr saturation following garnet breakdown upon cooling and/or decompression (e.g., Bea et al., 2006; Degeling et al., 2001; Fraser et al., 1997).

Typical high-temperature metamorphic zircon shows weak internal zoning, usually as sector or fir-tree zoning (Rubatto, 2017; Vavra et al., 1996, 1999). This type of zoning is common in H₂O-undersaturated subsolidus melting, whereas oscillatory zoning indicates crystallization directly from the melt (e.g., Schaltegger et al., 1999).

During metamorphism, oscillatory zoning might be progressively replaced by unzoned textures due to solid-state recrystallization (Hoskin and Black, 2000; Pidgeon, 1992).

5.3.1 Stage I: Mesoarchean prograde metamorphism

From the relationships observed in CL images, the Paleoproterozoic detrital cores are often surrounded by dark Mesoarchean rims with faint oscillatory zoning (Stage I – Fig. 32). U concentrations are higher in these rims and Th is lower. In Schaltegger et al. (1999), this kind of morphology is related to prograde dehydration melting and crystallization from the melt phase. Lower Th concentrations indicate that zircon was in competition with other Th-bearing phases, such as monazite, during crystallization. Several dark cores (now relict) with similar trace elements characteristics and Mesoarchean ages were also developed during this stage (Fig. 32). The detrital cores are also rounded and smaller than the rims, suggesting that dissolution of detrital grains and reprecipitation in larger grains (i.e., Ostwald Ripening) might explain zircon growth during fluid-saturated prograde metamorphism. Prismatic cores with oscillatory zoning are probably developed later during this stage, directly from the melt phase, and is in accordance with higher Th/U ratios typical of igneous zircon (e.g., Schaltegger et al., 1999).

5.3.2 Stage II: Mesoarchean peak metamorphism

The next stage of Mesoarchean zircon growth (Stage II – Fig. 32) comprises bright sector-zoned overgrowths, as well as several sector-zoned cores, that are bright in CL due to Th enrichment and can be ascribed to the breakdown of monazite at conditions above 800° C, which probably represents the timing of peak temperature conditions (e.g., Yakymchuk and Brown, 2014; Yakymchuk et al., 2018).

5.3.3 Stage III: Mesoarchean retrograde metamorphism

Late Mesoarchean overgrowths, frequently with convolute zoning and bright CL response, cross-cut internal structures of earlier metamorphic grains (Fig. 32). Further, Th and U concentrations are lower within this convoluted growth domains. These overgrowths are interpreted as being related to cooling following garnet breakdown and is supported by petrographic analysis, where zircon grains are commonly found as a retrograde phase along with cordierite + biotite + magnetite surrounding relict garnet fragments (Fig. 24).

5.3.4 Stage IV and V: Proterozoic recrystallization

Younger rims of Paleoproterozoic and Neoproterozoic ages are also found (Stages IV and V). They are mostly unzoned and feature consistently lower values of U, Th and Th/U ratios, probably related to solid-state recrystallization (e.g., Hoskin and Black, 2000; Pidgeon, 1992).

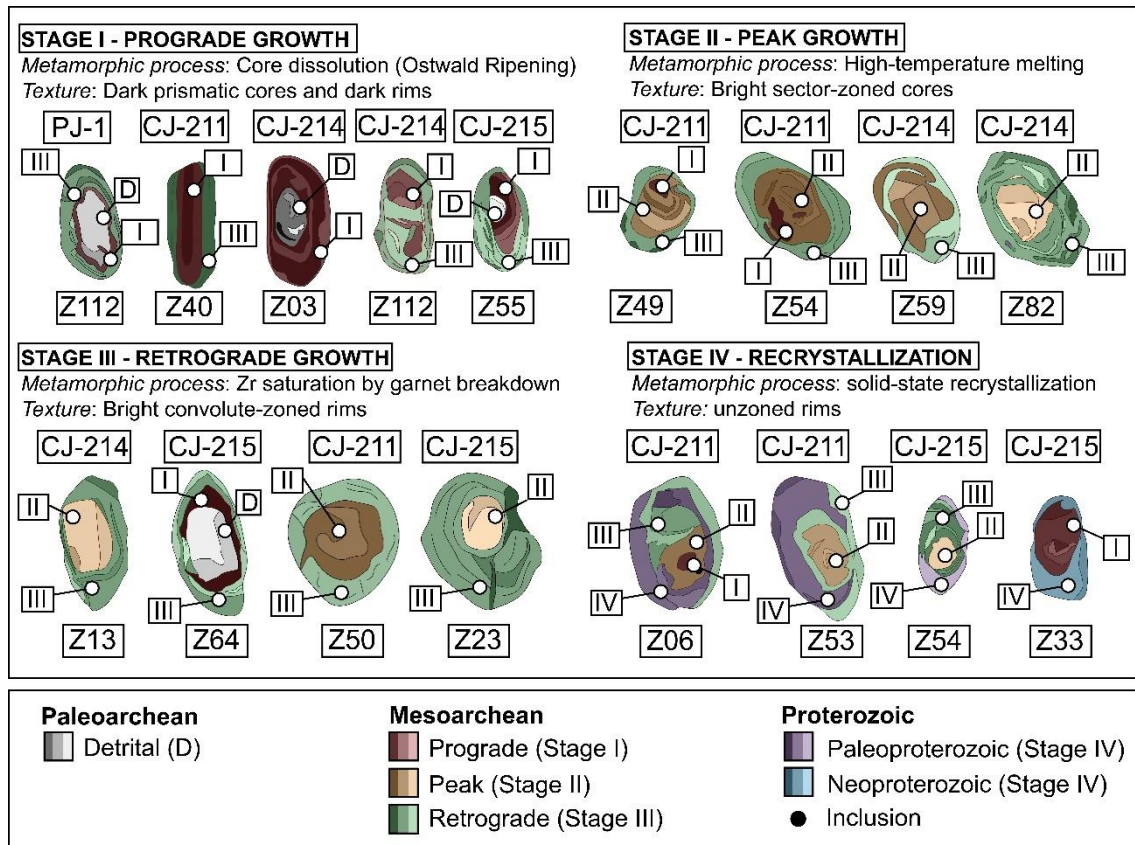


Figura 32: Zircon growth and recrystallization during anatexis. Summary of the zircon growth stages based on CL relationships, U-Pb ages, Th and U contents. Sketches are not to scale.

One interesting thing to note is that most of the grains dated in this work are discordant and yield lower intercept ages towards the Neoproterozoic and, locally, Paleoproterozoic (Figs. 23–26). However, considering only the concordant grains, they consistently yield Paleoproterozoic lower intercept ages (Fig. 31A, 33A), suggesting that even the most pristine grains with concordant ages were likely affected by some degree of solid-state recrystallization during the Paleoproterozoic. Beyond that, although we applied a relatively small spot size (25 μm) for the grains and carefully selected homogeneous zones in CL and BSE images, we can only assess the 2D morphology of the zircon grain. For example, a 193 nm excimer laser, after 20 pulses, produces an ablation pit of ca. 20 μm that in most cases would cross the entire grain and, possibly, more than one crystal zone. Therefore, late Proterozoic solid-state recrystallization might also explain why the

ages between different stages of Mesoarchean metamorphism are indistinguishable from each other.

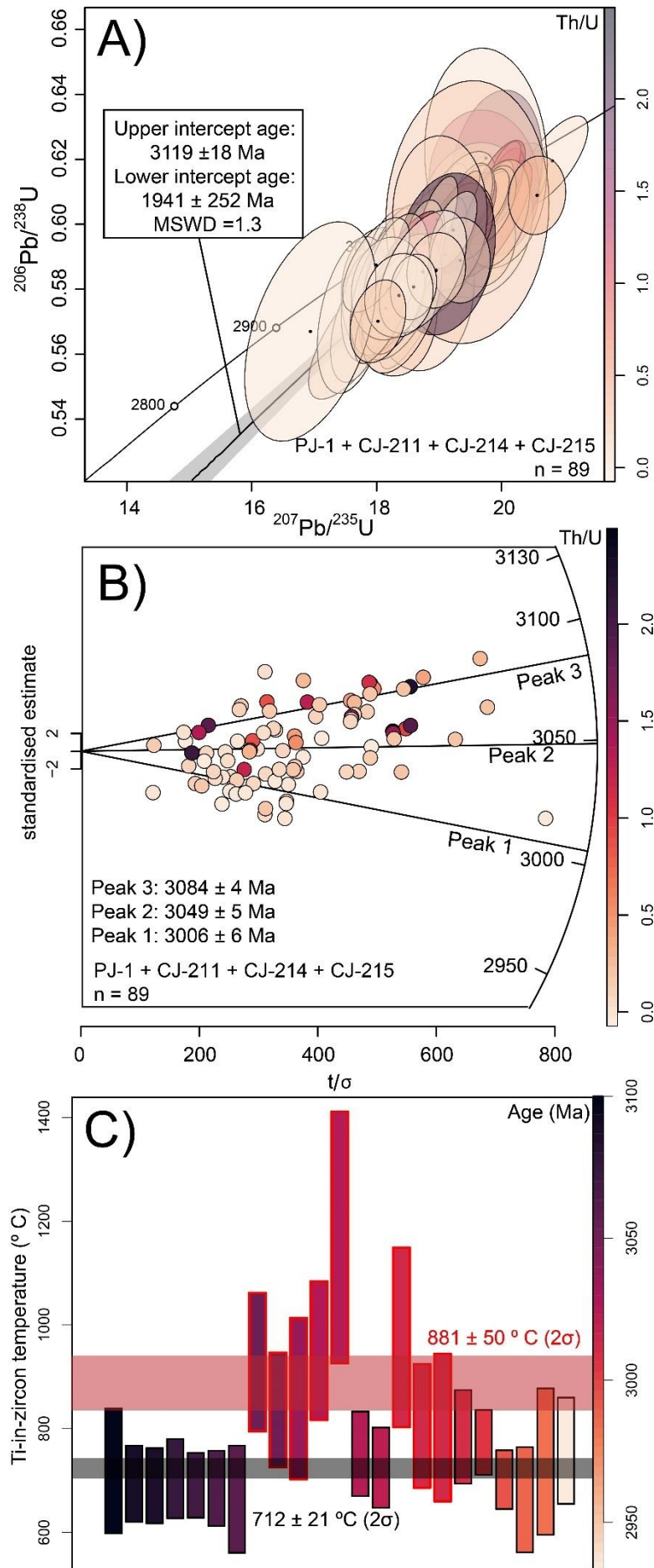


Figura 33: Timing and conditions of metamorphic zircon growth. A) Wetherill concordia diagram showing analyses with less than 3 of concordia distance and regression of all the analyses B) Radial plot of $^{207}\text{Pb}/^{206}\text{Pb}$ ages considering three finite mixtures. C) Weighted average of Ti-in-zircon temperatures color-coded by $^{207}\text{Pb}/^{206}\text{Pb}$ ages (Ma).

We attempted to estimate the age of individual events through finite mixtures of concordant ages in radial plot. Considering a model with three mixtures, peaks at 3084 ± 4 , 3049 ± 6 and 3006 ± 6 Ma were obtained (Fig. 33B). These might be related to the stages I, II and III of zircon dissolution-reprecipitation and growth. The second peak is within the uncertainty of a metamorphic zircon rim from a granitic orthogneiss dated by Souza et al. (2016) that yield an age of 3058 ± 14 Ma, the same locality of our sample PJ-1 (Fig. 23C).

Ti-in-zircon thermometry yielded variations that do not correlate with texture. although analyzed grains with $^{207}\text{Pb}/^{206}\text{Pb}$ ages between 3051 ± 92 Ma and 3013 ± 96 Ma yield higher Ti concentrations (Fig. 33C). Most of the grains (15/23) yield a weighted average of 712 ± 21 °C, while the remaining (8/23) yield a weighted average of 881 ± 50 °C. A single grain yielded an extremely high Ti concentration (186 ± 100 ppm) that could be related to the ablation of a Ti-bearing inclusion. Nonetheless, this may might indicate that peak conditions have been achieved around 3050 Ma. However, U–Pb ages are commonly decoupled from trace elements and textures in zircon during high-temperature metamorphism (e.g., Flowers et al., 2010; Kunz et al., 2018). Beyond that, uncertainties regarding aTiO₂ undermine the confidence of these estimates, since aTiO₂ is commonly variable during the evolution of melt-bearing systems (e.g., Teixeira et al., 2023). Therefore, these estimates can be considered as a minimum constraint and further assessment from other chronological systematics (e.g., U–Pb in monazite and xenotime or Lu–Hf in garnet) are needed.

5.4 Tectonic implications

The Archean geological record is highly fragmented in several cratons and small basement inliers that are thought to be part of ancient supercontinents (Bleeker, 2003). Fitting the puzzle pieces is crucial for understanding the early earth dynamics and their bearing on the evolution of the continental crust (e.g., Kock et al., 2009; Liu et al., 2021; Smirnov et al., 2013).

The Mesoarchean metamorphic record is relatively scarce (e.g., Brown and Johnson, 2018). Examples include 3.11 to 3.07 high temperature metamorphism of 3.34 Ga pelitic rocks in the Kaapvaal Craton (Taylor et al., 2012). High-temperature conditions are also recorded between 3.1 to 3.0 Ga in the Dharwar Craton (Dasgupta et al., 2019; Yu et al., 2021). During the period between 3.2 and 3.0 Ga, higher mantle potential temperatures are thought to have caused injection of hot mantle-derived mafic magmas into the crust, leading to widespread reworking of previous continents (Kirkland et al., 2021).

These Mesoarchean metamorphic events recorded in other cratons and global crustal melting could be correlated with the Mesoarchean metamorphism of the São José do Campestre Massif, since mafic-ultramafic magmatism is also recorded between 3.1 and 3.0 Ga (Abrahão Filho, 2016; Jesus, 2011). In South America, the only evidence for Mesoarchean metamorphism comes from the Uauá block, in the São Francisco Craton, where ca. 3.1 Ga mafic granulites reached high-pressure and high-temperature peak conditions at 2820 Ma (Oliveira et al., 2019). However, the large time gap between these two events suggest that they are not related. Therefore, there are no correlates in South America so far for the 3.1 – 3.0 Ga metamorphism of the São José do Campestre massif.

The Paleoproterozoic was an important era in the building of the São Francisco Craton (Barbosa and Sabaté, 2004; Neves, 2021), as well as in the Borborema Province as a whole (Souza et al., 2016; Lira Santos et al., 2022). The similarities in the ages of magmatic events in both terranes led to proposals of both comprising a single landmass

by the end of the Rhyacian (Neves, 2021 and references therein). The timing of the Paleoproterozoic high-temperature metamorphism of the São José do Campestre Massif is broadly coeval with the peak of high temperature metamorphism in the São Francisco Craton at 2.0 Ga (e.g., Barbosa and Sabaté, 2004; Neves et al., 2021) and with the crystallization ages of several plutonic rocks throughout the Borborema Province (Neves, 2021; Lira Santos et al., 2022; Souza et al., 2016). Therefore, it concurs with the idea that, at least part of the Borborema Province and São the Francisco Craton, were part of the same plate by the end of the Rhyacian (e.g., Neves, 2021 and references therein).

Neoproterozoic ages are within estimates for most of the HT-LP metamorphism in the northern Borborema Province with a peak at ca. 575 Ma (Souza et al., 2006, 2016), suggesting that the Neoproterozoic shear zone deformation also affected the inner portions of the São José do Campestre Massif.

6. Conclusions

Constraining the timing of deposition of ancient rocks is a difficult task due to commonly superposed metamorphic events. In northeastern Brazil, supracrustal rocks in the São José do Campestre Massif are strongly affected by several episodes of partial melting and deformation. Detailed investigation of zircon internal morphology, U–Pb ages and trace elements show that the supracrustal rocks are older than previously thought, with a Paleoarchean maximum depositional age of 3305 ± 16 Ma, and were strongly affected by a Mesoarchean metamorphic event. Metamorphic zircon grains exhibit a broad range of textures that were interpreted to record several high-grade metamorphic processes at temperatures approximately between 710 °C and 880 °C.

Metamorphic events during the Mesoarchean have not been identified yet in South America and might correlate with events in the Kaapvaal and Dharwar cratons, as well as

with the global event of crustal melting proposed by Kirkland et al. (2021). Paleoproterozoic and Neoproterozoic solid-state recrystallization also affected most of the grains, broadly coeval with metamorphic ages in the São Francisco Craton and the Borborema Province, respectively, suggesting a common evolution since, at least, the Rhyacian.

We demonstrate that a detailed investigation of zircon internal textures coupled with geochronology and trace element analysis may deconvolve poly-metamorphic events that affected precursor detrital zircon.

CAPÍTULO 6: ARTIGO CIENTÍFICO 2

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Effects of high temperature annealing and low temperature metamictization on Archean zircon: constraints from U–Pb isotopes, trace elements and Raman dating

ABSTRACT

Zircon is a common accessory mineral that can survive extreme temperature conditions in the crust, although U–Th series radioactive decay is responsible for its self-destruction over long time scales. Upon exhumation at lower temperatures, metamict zircon grains are then more susceptible to isotopic and trace element disturbance. In this work, we investigated the isotopic and trace element behavior of zircon through LA-ICP-MS, coupled with Raman spectroscopy, from two Archean mylonitic samples within the São José do Campestre Massif, northeastern Brazil. U–Pb in zircon dating indicates Paleoarchean (3.3 Ga) sedimentation followed by Mesoarchean (3.0 – 2.9 Ga) high temperature metamorphism in the mylonitic paragneiss sample, while the mylonitic amphibolite was emplaced during the late Neoarchean (2521 ± 22 Ma) and reached high-temperature conditions during shear zone development and deformation during the Paleoproterozoic (2.0 Ga). Inherited zircon grains in the amphibolite are consistent in morphology and ages with zircon grains from the host paragneiss. However, high temperature annealing and structure recovery upon entrainment of inherited zircon grains in the hot mafic magma led to homogenization of trace elements and preservation of internal textures. On the other hand, zircon grains from the host paragneiss accumulated radiation damage for a longer time, leading to self-destruction of the crystalline structure. Upon later low temperature fluid influx, non-formula elements were incorporated in

metamict grains, as evidenced by the positive correlation between trace elements and radiation damage. Raman zircon dating indicates Cambrian to Late Paleozoic exhumation for these rocks, which agrees with U–Pb in zircon lower intercept ages. Although often avoided in geochronological studies, metamict zircon can provide important constraints on low temperature events. Collectively, these observations show a complex trans-crustal history of zircon recycling and exhumation from the Paleoproterozoic to the Paleozoic and the rock-dependent behavior of zircon upon fluid flow and deformation. The results have implications for the interpretation of trace elements in naturally annealed zircon grains, especially those inherited in mafic rocks.

KEYWORDS

U–Pb in zircon; Raman spectroscopy; Archean, Borborema Province

INTRODUCTION

Zircon is the most popular mineral employed in geochronological studies due to its resistance to several geological processes and decades of experimental and empirical studies of its composition and structure (e.g., Cherniak et al., 1997; Cherniak and Watson, 2001; Geisler et al., 2001; Bindeman et al., 2018). Large databases of isotopes and trace elements are becoming widely used to constrain global tectonic and climatic events (e.g., Puetz et al., 2021; Tang, et al. 2021; Brudner et al., 2022; Moreira et al., 2023; Roberts et al., 2024). However, several works have demonstrated that low temperature events can disturb isotopic and trace elements systematics in zircon, hindering its reliability as a petrogenetic indicator (e.g., Horie et al., 2006; Pidgeon et al. 2017, 2019, 2023; Cameron et al., 2024).

Upon radioactive decay of the U-Th series, alpha-disintegration and atom recoil leads to lattice damage in zircon and self-destruction of its crystalline structure over

geological timescales (Murakami et al., 1991; Nasdala et al., 1996, 2001; Pidgeon et al., 1998; Pidgeon, 2014). The time since zircon annealing, and accumulation of radiation damage, has been recently calibrated based on the relationship between the broadening of Raman spectra bands and U and Th concentrations measured by LA-ICP-MS (Härtel et al., 2021a). The obtained ages reflect alpha-damage annealing in temperatures in the range of ca. 130 °C to 650 °C for natural samples (Mezger and Krogstad, 1997; Pidgeon, 2014; Jonckheere et al., 2019), while annealing experiments yield temperatures in the range of 260 °C to 370 °C (Härtel et al., 2021b). Closure temperatures for Raman zircon dating are slightly higher than fission-track (193 to 230 °C) and (U-Th)/He (160 to 230 °C) systematics, suggesting a complementary role to constrain low temperature events in the upper crust (Zaun and Wagner, 1985; Reiners et al., 2002; Fan et al., 2023). Although a relatively low cost and fast non-destructive methodology, Raman radiation damage zircon dating has been poorly explored in thermochronology (e.g., Pidgeon, 2014; Hueck et al., 2018; Shi et al., 2023; Härtel et al., 2024).

Here we assess the differential behavior of zircon through a combination of LA-ICP-MS U–Pb dating and trace elements, coupled with Raman spectroscopy, to constrain a long and complex history of crustal recycling since the Paleoproterozoic in northeastern Brazil. The results have implications for the interpretation of zircon U–Pb and trace elements systematics in ancient rocks, fluid-flow in the shallow crust and the exhumation history of northeastern Brazil.

GEOLOGICAL BACKGROUND

The study area is located in the São José do Campestre Massif, an Archean basement block within the Borborema Province. The geological evolution of the area includes Paleoproterozoic to Neoproterozoic metaplutonic rocks with U–Pb in zircon ages between 3412 ± 8 Ma and 2664 ± 13 Ma (Dantas et al., 2004, 2013; Souza et al., 2016,

2023), as well as Paleoproterozoic metasedimentary rocks (Ribeiro et al., 2024). High-temperature metamorphism and partial melting were previously constrained at 3.1 – 3.0 Ga, 2.0 and 0.6 Ga based on U–Pb in zircon ages (Dantas et al., 2004, 2013; Souza et al., 2016; Ribeiro et al., 2024). Both Mesoproterozoic and Paleoproterozoic metamorphic events are thought to represent collision between distinct crustal blocks at upper amphibolite to granulite facies (Dantas et al., 2004; Souza et al., 2016; Ribeiro et al., 2024). On the other hand, Neoproterozoic metamorphism is mostly related to intracontinental shear-zone deformation at greenschist to amphibolite facies (Souza et al., 2006; Cioffi et al., 2021). Peak conditions of ca. 650 °C and 4 kbar were reached around 575 Ma (Souza et al., 2006; Cioffi et al., 2021), with further cooling to temperatures below 400 °C until ca. 500 Ma, as constrained by $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages (Corsini et al., 1991).

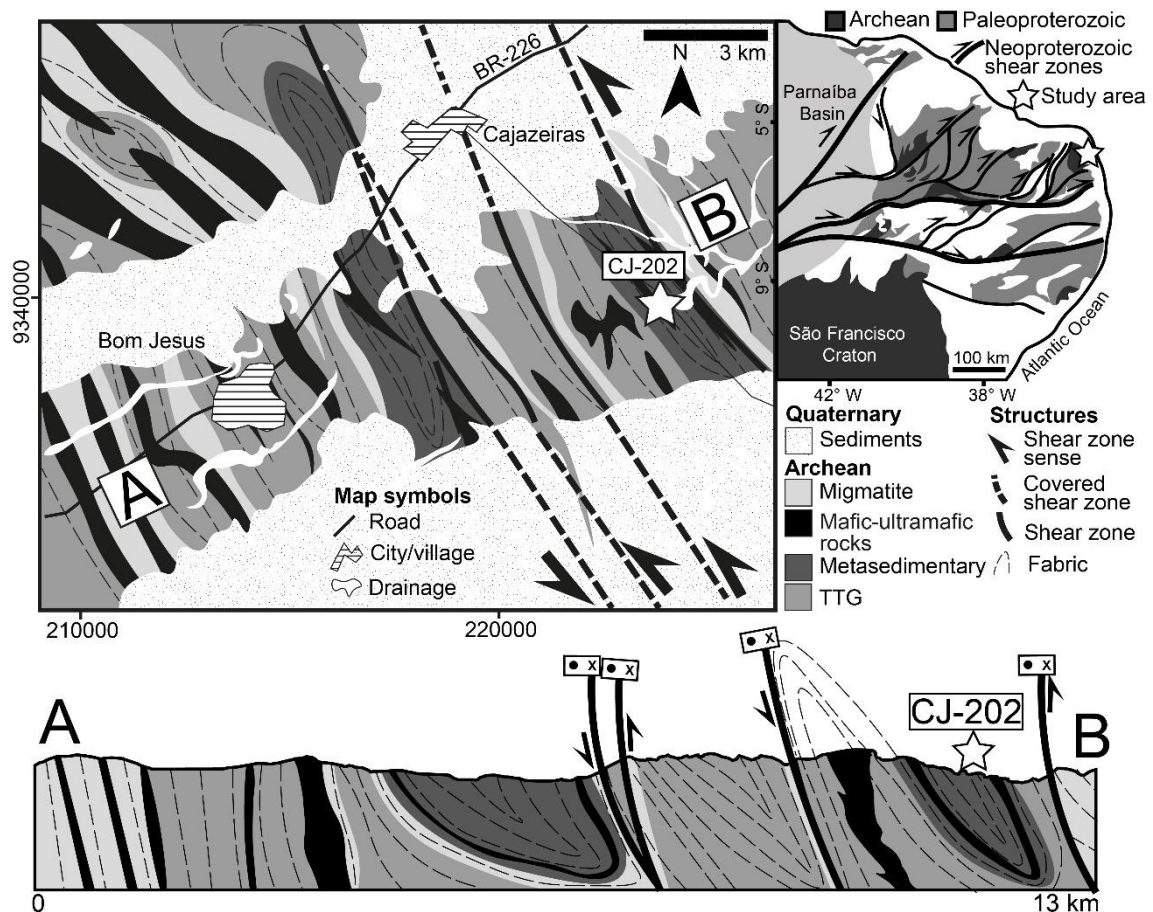


Figura 34: Geological map of the study area in the eastern São José do Campestre Massif and geological profile. Vertical axis is not to scale. Map on the right shows the simplified geological map of Borborema Province and location of outcrop CJ-202.

The investigated outcrop occurs on the eastern side of the São José do Campestre Massif, near the Cajazeiras village (Fig. 34). In this area, the overall fabric trends NNW-SSE and is strongly controlled by sinistral shear zones of the same direction. Supracrustal rocks, mostly biotite paragneisses, occur at the core of synforms, are strongly migmatitic and rarely preserved as biotite-rich melting residuals. Together with tonalitic to granodioritic orthogneisses, these rocks compose the basement of this area. Mafic-ultramafic intrusions are abundant, following the overall NNW-SSE trend. The fabric of all the lithotypes is mostly gently dipping (<30 degrees) towards NE, with tangential folds that suggest NW transport.

METHODS

Thin sections were investigated through conventional petrography techniques, as well as qualitative Backscattering (BSE) images and EDS analyzes using a SEM Quanta 450 at 10 nA, 20kV and 13.8 mm working distance at Laboratório de Estudos Geodinâmicos, Geocronológicos e Ambientais (LEGGA) at Universidade de Brasília. Rock samples of ca. 5 kg were crushed and minerals were separated using a Frantz magnetic barrier at 1.8 A and 10° slope (Sircombe and Stern, 2002) six months apart to avoid cross-contamination. Zircon grains were then hand-picked, mounted in epoxy, polished, coated in carbon and investigated using a Gatan ChromaCL2 iBSED for cathodoluminescence images. Mineral abbreviations follow Whitney and Evans (2010).

U–Pb and trace elements in zircon were analyzed through LA-ICP-MS at the LEGGA following the methods described in Ribeiro et al. (2024) and also in the supplementary material. Discordance is reported as $^{238}\text{U}/^{206}\text{Pb} / ^{207}\text{Pb}/^{206}\text{Pb}$ and as concordia distance following Vermeesch (2021a). We also calculated single grain concordia ages in IsoplotR (Vermeesch, 2018) and used them for analyzes that yield ages with less than 3 of discordia distance. These will be called as “concordant” hereafter. La and Pr values were calculated following the Onuma-Chondrite method of Carrasco-Godoy and Campbell (2023) and were used in diagrams instead of the measured values.

For Raman analysis, grains were selected based on their U-Pb ages, in order to represent each population of each sample, and also based on their U concentration and discordance. Grains with variate degrees of discordance, from concordant to strongly discordant were analyzed. Raman analyzes were performed on the same textural zone of the zircon (based on CL and BSE images), but away from the LA-ICP-MS crater to avoid any thermal effects of the laser ablation (e.g., Fan et al., 2023). Raman spectra were recorded using a Horiba LabRam Evolution Raman Spectrometer coupled to a confocal

microscope and a charge-coupled device (CCD) detector at Laboratório de Espectroscopia Ótica, Universidade de Brasília. Diffraction grating was set at 600 grooves/mm and the excitation of the sample was carried out using a semiconducting laser of 633 nm at 50% (5 mW) power and a 100× Olympus objective lens. This choice of laser wavelength was based on the achievement of higher intensities for the main peaks in zircon reference material 91500. Raman spectra were recorded along 12 cycles of 15 seconds, resulting in 3 minutes per analysis. Samples were analyzed in two different four-hour sessions and two zircon reference materials (Sri Lankan BB and 91500 – Wiedenbeck et al., 2004; Santos et al., 2017b) were measured at the beginning and end of the session to check for instrumental drift. The Raman spectra were then processed using the Ramanspy python library (Georgiev et al., 2023) for denoising, baseline removal and normalization. All peaks were then fitted in the Fityk 1.3.1 software using a Lorentzian function and then Full Width at Half Maximum (FWHM) values were measured. These values were then corrected using the empirical correction formula of Váczi (2014) and compared with published values for the ν_3 band ($\sim 1008 \text{ cm}^{-1}$) of the reference materials (91500 - Wiedenbeck et al., 2004; Sri Lankan BB - Santos et al., 2017b). Peak positions are reported as $\omega \text{ (cm}^{-1}\text{)}$ and FWHM as $\Gamma \text{ (cm}^{-1}\text{)}$ in figures and throughout the text. Uncertainties for Raman measurements were assumed as 10% (2σ standard error) (e.g., Härtel et al., 2021a).

Oxygen fugacity relative to the Fayalite-Magnetite-Quartz buffer (ΔFMQ) was determined based on the Ce, U and Ti concentrations of zircon (Loucks et al., 2020) following the equation:

$$\Delta\text{FMQ} = 3.998 (\pm 0.124) \times \log \left[\frac{\text{Ce}}{\sqrt{U_i \times Ti}} \right] + 2.284 (\pm 0.101) \quad (1)$$

where Ce and Ti are the values measured in ppm, whereas Ui denotes the initial U concentrations, in ppm, at the time of zircon crystallization.

Ti-in-zircon temperatures (Watson et al., 2006) were calculated following the pressure-dependent calibration of Crisp et al. (2023) assuming $a_{\text{TiO}_2} = 1$, $a_{\text{SiO}_2} = 1$ and a pressure of 5 kbar. Since rutile is absent in both samples, a_{TiO_2} is expected to be below 1. Therefore, these can be considered as minimum temperatures for zircon crystallization.

Expected alpha dose ($D\alpha$) values (α/g) in zircon were calculated from LA-ICP-MS data following Murakami et al. (1991) and Drollner et al. (2022):

$$D\alpha = \frac{XU \times A \times PU_{238}}{MU_{238} \times 10^3} [(\exp(\lambda_{238}t) - 1)] + \frac{XU \times A \times PU_{235}}{MU_{235} \times 10^3} [(\exp(\lambda_{235}t) - 1)] + \frac{XTh \times A}{MTh_{232} \times 10^3} [(\exp(\lambda_{232}t) - 1)] \quad (2)$$

where XU and XTh are U and Th concentrations in ppm, respectively. A is the Avogadro Constant. PU_{238} and PU_{235} are the natural abundances of ^{238}U and ^{235}U following the $^{238}\text{U}/^{235}\text{U}$ ratio of 137.88 of Steiger and Jäger (1977). λ_{238} , λ_{235} and λ_{232} are the decay constants of ^{238}U , ^{235}U and ^{232}Th , respectively, also following Steiger and Jäger (1977). MU_{238} , MU_{235} and MTh_{232} are the masses of ^{238}U , ^{235}U and ^{232}Th , respectively. t is the time of crystallization of the zircon grain (in Ma), which in our case was the $^{207}\text{Pb}/^{206}\text{Pb}$ age.

True alpha dose (D_{ER}) values (α/g) were calculated from FWHM values of the External Rotation (ER) band of zircon at ca. 356 cm^{-1} following the equation of Härtel et al. (2021a):

$$D_{\text{ER}} = \frac{\Gamma_{\text{ER}} - 4.04}{0.171 \times 10^{-16}} \quad (3)$$

Dose values for the V₂ (Härtel et al., 2021a) band were calculated to evaluate the state of annealing in each grain, considering the ratio D_{ER}/D_{V2} of 1.0 for unannealed zircon (Härtel et al., 2022):

$$D_{V2} = \frac{\Gamma_{V2}-5.16}{0.141 \times 10^{-16}} \quad (4)$$

Single grain zircon radiation damage ages were also calculated from the ER band following the equation of Härtel et al. (2021a), where eU is the effective uranium concentration (1.05U + 0.24Th, in ppm) measured through LA-ICP-MS:

$$t = 19 \times 10^3 \frac{\Gamma_{ER}-4.04}{eU} \quad (5)$$

These ages are thought to reflect the timing since closure of zircon for radiation damage at temperatures below 260 to 370 °C (Härtel et al., 2021b). The ages can then be combined in isochron (or daughter-parent plots, e.g., Härtel and Enkelmann, 2024), where the slope of the isochron represents the D_{ER}/eU and, multiplied by 3.19×10^{-13} yields an isochron age (Härtel et al., 2021b). The isochrons are expected to yield a zero intercept, with deviations being related to partial annealing or systematic bias (e.g. Härtel et al., 2021b; Härtel and Enkelmann., 2024).

The results obtained from measurements and calculations are available in the Supplementary Material.

RESULTS

Outcrop description and petrography

The outcrop CJ-202 is located near the Cajazeiras village on the extreme eastern side of the São José do Campestre Massif. Banded migmatites, with biotite-rich and leucocratic layers that are interpreted as the melting residuum and leucosomes, respectively, are interlayered with several centimetric to metric sheets of amphibolite

(Fig. 35A). The banded migmatite displays inclined folds, now nearly parallel to the main foliation, that suggest NW transport (Fig. 35B). The amphibolite sheets are not affected by these inclined folds but are nearly parallel to the main fabric of the banded migmatite, dipping towards NE (Fig. 35B). The main fabric is mylonitic, with kinematic indicators suggesting an overall sinistral shear sense. One sample from the melting residuum of the biotite paragneiss (CJ-202A) and one sample from the amphibolite (CJ-202B) were collected for petrography, U–Pb isotopes and trace elements analysis, and Raman spectroscopy on zircon.

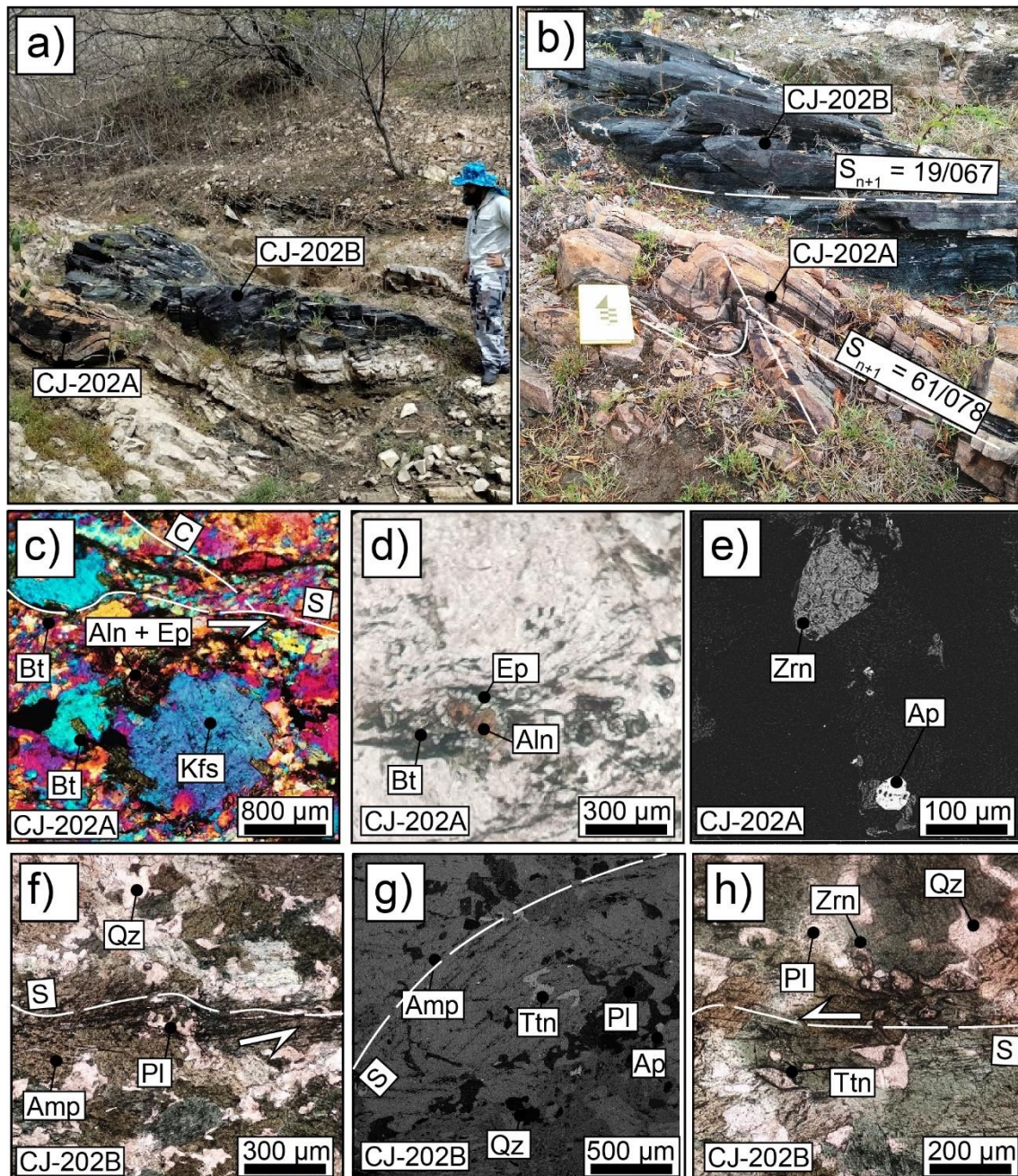


Figura 35: a) Broad view of outcrop CJ-202 with location of samples CJ-202A and CJ-202B. b) Detailed view of outcrop CJ-202. High-temperature metamorphic banding, with alternation of leucosomes and biotite-rich melting residuum can be observed. Inclined folds with NW transport are present. The amphibolite (CJ-202B) shows a gently dipping foliation, and its precursor was emplaced after folding of the CJ-202A biotite paragneiss. Thin planar leucosomes are parallel to the main foliation. c) Cross-polarized light image showing a well-developed sinistral S-C fabric surrounding rounded K-feldspar porphyroclasts. d) Plane-polarized light image showing retrograde allanite with epidote corona surrounded by biotite along a shearing surface. e) Backscattering image showing zircon and apatite within the fine-grained matrix. f) Plane-polarized light image showing a well-developed sinistral shearing fabric, with rotation of plagioclase porphyroclast. g) Plane-polarized light image showing foliation parallel quartz ribbons with late perpendicular fracture. h) Plane-polarized light image showing sheared titanite with sinistral kinematic. Rounded zircon with dark core is also visible.

Sample CJ-202A comprises the melting residuum of the biotite paragneiss. This sample is composed mostly of quartz and K-feldspar, with small biotite flakes in a well-defined sinistral S-C fabric (Fig. 35C). K-feldspar porphyroclasts frequently show inclusions of biotite in their rims, which are surrounded by small fragments of biotite + K-feldspar (Fig. 35C). Along the shearing surfaces, retrograde allanite with epidote rim is also identified (Fig. 35D). Zircon grains are hardly visible, mostly scattered within the matrix and frequently fractured (Fig. 35E). Apatite and magnetite were also identified within the matrix.

Sample CJ-202B was collected in the amphibolite sheet, being mostly composed of hornblende, quartz and plagioclase, with accessory titanite, apatite, magnetite and zircon (Fig. 35F-H). Quartz is mostly found as vein-parallel quartz ribbons (Fig. 35G), while plagioclase occurs interstitial within the amphibole matrix. Zircon grains are mostly rounded, sometimes with a visible dark core, while titanite occurs along shearing planes, frequently sigmoidal with a sinistral shear sense (Fig. 35G). Titanite grains also show inclusions of amphibole.

U–Pb and trace elements in zircon

From sample CJ-202A, 125 individual zircon grains, as well as 13 rims, were analyzed for U–Pb isotopes (Fig. 36A). $^{207}\text{Pb}/^{206}\text{Pb}$ ages range from 3404 ± 29 Ma to 2631 ± 80 Ma. U concentrations range from 1791 to 26 ppm and Th concentrations range from 847 to 2 ppm, with Th/U ratios from 2.36 to 0.02. The oldest cluster of concordant ages spreads between 3475 ± 36 Ma and 3229 ± 34 Ma and the second cluster between 2966 ± 30 Ma and 2840 ± 14 Ma (Fig. 36B). Rare-earth elements (REE) are similar in both populations, apart from the increase in Light Rare Earth elements (LREE) that is most pronounced in some grains of the 3.4 – 3.2 Ga population (Fig. 36C). In cathodoluminescence images, the 3.4 – 3.2 Ga grains are mostly stubby to prismatic, with

most of the cores partially dissolved and replaced by dark rims (Fig. 36E). In some cases, the grains are nearly completely replaced by these dark rims. While the 3.4 – 3.2 Ga grains show low concentrations of U, Th, Ti, Nb and Ta, as well as high Y, dark grains and rims show the inverse relationship, with exception of Th (Fig. 36E). Nb and Ta are particularly enriched in the dark grains, with up to 130 ppm of Nb and 95 ppm of Ta. From these relationships, the 3.4 – 3.2 Ga population reflects the detrital grains from the protolith, while the 2.9 Ga population represents the timing of high-temperature melting and metamorphic zircon (re)crystallization.

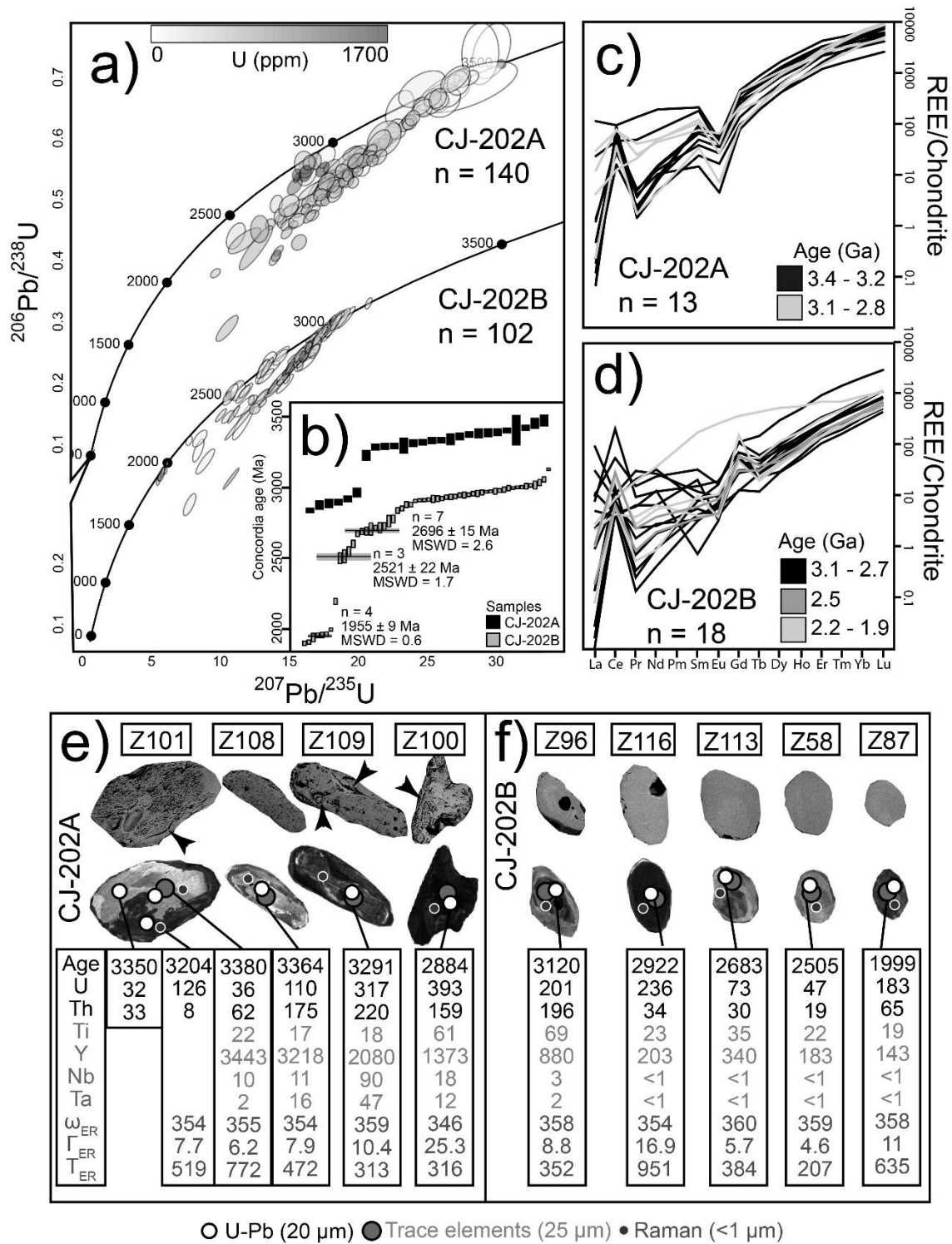


Figura 36: a) Wetherill concordia diagram of samples CJ-202A and CJ-202B. Shades of gray are proportional to U concentrations (ppm). b) Single-grain concordia ages of concordant grains (concordia distance < 3) of samples CJ-202A and CJ-202B. The weighted average of the three youngest populations in CJ-202B is shown. c, d) Rare-earth elements of zircon grains in samples CJ-202A and CJ-202B normalized to the chondrite of Anders and Grevesse (1989). Lines are color-coded by age from U–Pb data. e, f) Back-scattering and cathodoluminescence images of representative grains analyzed for U–Pb isotopes, trace elements and Raman spectra in samples CJ-202A and CJ-202B. Black arrows indicate dissolution channels. Age (207Pb/206Pb) and TER (radiation damage age from ER band) are shown in Ma and U, Th, Ti, Y, Nb and Ta are shown in ppm, ω and Γ are shown in cm⁻¹.

From sample CJ-202B, 102 individual grains were analyzed for U–Pb isotopes. $^{207}\text{Pb}/^{206}\text{Pb}$ ages range from 3120 ± 24 Ma to 1948 ± 46 Ma (Fig. 36A). U concentrations range from 1523 to 11 ppm and Th concentrations range from 1658 to 5 ppm, with Th/U ratios from 2.63 to 0.03. Four distinct clusters of concordant ages could be identified in this sample. The oldest cluster spreads from 3055 ± 18 Ma to 2862 ± 39 Ma (Fig. 36B). The second cluster ($n = 7$) has a weighted average age of 2696 ± 15 Ma. The third cluster, with only three concordant grains, yields a weighted average age of 2521 ± 22 Ma. Finally, the last cluster ($n = 4$) yields a weighted average age of 1955 ± 9 Ma. REE are strongly variable in these populations (Fig. 36D), with most of them within the same range of Heavy Rare Earth elements (HREE) concentrations. A single grain from the 2.2 – 1.9 Ga interval yields a flat HREE pattern, typical of co-crystallization with garnet, although garnet is not found in this sample. In cathodoluminescence images, most of the grains show dark cores that are overgrown by narrow bright rims (Fig. 36F). These rims yield mostly ages of 2.5 Ga and 2.0 Ga. A few grains from the 2.5 population are also bright in CL. Overall Y concentrations are low (< 1000 ppm), with Nb and Ta concentrations usually below 1 ppm. U and Th concentrations are higher in dark grains, and below 100 ppm in bright grains and rims. The interpretation of the geological meaning of each of these populations is not straightforward, since neither zircon textures or trace elements are able to distinguish the grains that crystallized from the melt (i.e., crystallization age of the protolith) from those that are inherited from the host-rock. Therefore, the significance of each population and timing of crystallization of the protolith will be discussed in the following sections.

Calculated oxygen fugacity conditions for sample CJ-202A yield $\log f_{\text{O}_2}$ between -10.78 and -16.61 and ΔFMQ between +4.88 and -1.79, while sample CJ-202B yield

$\log f_{O_2}$ between -7.69 and -17.18 and ΔFMQ between +1.86 and -4.21 (Supplementary Material).

Ti in zircon concentrations and calculated temperatures for sample CJ-202A ranged from 3.3 ± 0.9 to 113.0 ± 20.4 ppm and 610 ± 42 to 1015 ± 71 °C, respectively, while in sample CJ-202B concentrations ranged from 19.0 ± 2.8 to 120.5 ± 64.8 ppm and temperatures from 794 ± 43 to 1025 ± 192 °C (Supplementary Material).

Raman zircon spectra and radiation damage dating

Synthetic $ZrSiO_4$ shows four distinct peaks around 356 (ER), 439 (V2), 975 (V1) and 1008 (V3) cm^{-1} (Fig. 37A), while all of our natural zircon samples showed a wider number of peaks, as well as broadening and shift of ER and SiO_4 bands (Figs. 35B, C).

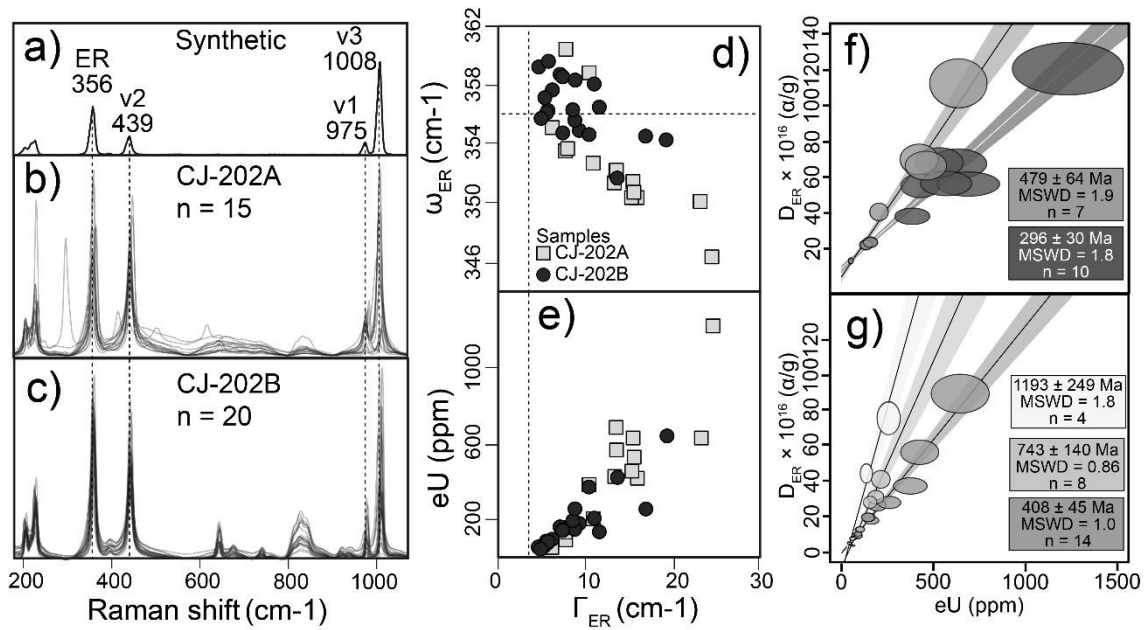


Figura 37: a) Raman spectra of synthetic zircon (Finch et al., 2001) obtained from the RRUFF database (Lafuente et al., 2015) and position of External Rotation (ER) and SiO_4 (v1, v2 and v3) bands. b, c) Raman spectra of zircon grains in samples CJ-202A and CJ-202B. d) Γ_{ER} (cm^{-1}) versus ω_{ER} (cm^{-1}). e) Γ_{ER} (cm^{-1}) versus eU (ppm). f, g) eU (ppm) versus $D_{ER} \times 10^{16}$ (α/g) and isochron ages.

From sample CJ-202A, corrected Γ_{ER} ranges from 6.2 to 24.5 cm^{-1} and ω_{ER} ranges from 346 to 360 cm^{-1} (Fig. 37D). Alpha-dose values calculated from the Γ_{ER} range from 12.5 to 120.24 (10^{16} α/g), yielding ages in the range of 260 to 772 Ma. The ratio D_{ER}/D_{V2}

ranged from 0.6 and 2.0, with an average of 0.8(0.4) (Supplementary Material). Isochron ages calculated from eU and D α yield ages of 479 ± 64 Ma and 296 ± 30 Ma. Both ages are not anchored at the zero-intercept and yield zero-damage bandwidths (4.70 ± 0.43 and 5.38 ± 0.27 cm⁻¹, respectively) above the reported value of 4.04 from Härtel et al. (2021a).

From sample CJ-202B, corrected Γ_{ER} ranges from 4.6 to 19.2 cm⁻¹ and ω_{ER} ranges from 352 to 360 cm⁻¹ (Fig. 37E). Alpha-dose values calculated from the Γ_{ER} range from 3.5 to 89.5 (10¹⁶ α /g), yielding ages in the range of 207 to 1051 Ma. The ratio D_{ER}/D_{V2} ranged from 1.4 to 3.0, with an average of 2.0(0.5). Isochron ages calculated from eU and D α yield ages of 1193 ± 249 Ma, 743 ± 140 and 408 ± 45 Ma. These yield non-zero intercept ages with zero-damage bandwidths of 1.98 ± 0.87 , 2.51 ± 0.90 and 3.96 ± 0.21 , with only the latter within the 4.04 cm⁻¹ value of Härtel et al. (2021a).

DISCUSSION

Crystallization, recrystallization and discordance

Zircon is a common accessory mineral in most crustal rocks. Due to its high resistance to several geological processes, including erosion, transport and high-temperature metamorphism (e.g., Cherniak et al., 1997; Cherniak and Watson, 2001; Geisler et al., 2001; Bindeman et al., 2018), it is one of the most used minerals in crustal evolution studies. However, due to the radioactive damage from the decay of U and Th, its crystalline structure may be weakened. When interacting with fluids during high-temperature metamorphism or even weathering, zircon may lose radiogenic Pb and yield discordant ages (Mezger and Krogstad, 1997). Although widely discussed, the reasons behind discordance are still poorly understood, but may be related to weathering, metamorphic overprint or mixed core-rim analysis (e.g., Pidgeon, 1992; Pidgeon et al., 1998; Morris et al., 2015; Andersen et al., 2019; Olierook et al., 2021). Pb loss is not

expected to occur above the temperature of annealing of zircon due to lattice self-repair at high temperature (Mezger and Krogstad, 1997). Temperatures for annealing and structure recovery in zircon vary as a function of time and radiation damage, with short-time experiments yielding temperatures in the range of 850° C to 1200 °C under dry conditions (Geisler et al., 2001). Lower intercept ages that are unrelated to physical evidence of recrystallization have been ascribed to low-temperature fluid flow during deformation (e.g., Nemchin and Cawood, 2005; Morris et al., 2015; Reimink et al., 2016; Hermann et al., 2021).

In this study, most of the analytical data falls outside the concordia curve. Due to the small time-lapse between populations, disturbance of the isotopic system, either by recrystallization or Pb loss, is unable to deviate the ratios from the concordia curve. This effect is commonly called concealed Pb loss (e.g., Andersen et al., 2019) and leads to the spread of concordant ages. To assess this problem, we explored the effects of mixing each population (Fig. 38A, B). In sample CJ-202A, reworking of the 3.4 Ga population at 3.0 Ga is unable to displace the ages from the concordia curve. However, the ages do not spread across the entire modelled path. In CL images, the 3.0 Ga population occurs mostly as dark rims, with clear features of dissolution of the detrital cores (Fig. 36E). Therefore, it is likely that these rims crystallized from a melt phase, resetting the U–Pb isotopic system. Their morphology and high U concentrations are similar to the features described in Ribeiro et al. (2024) as related to Mesoarchean prograde high-temperature melting.

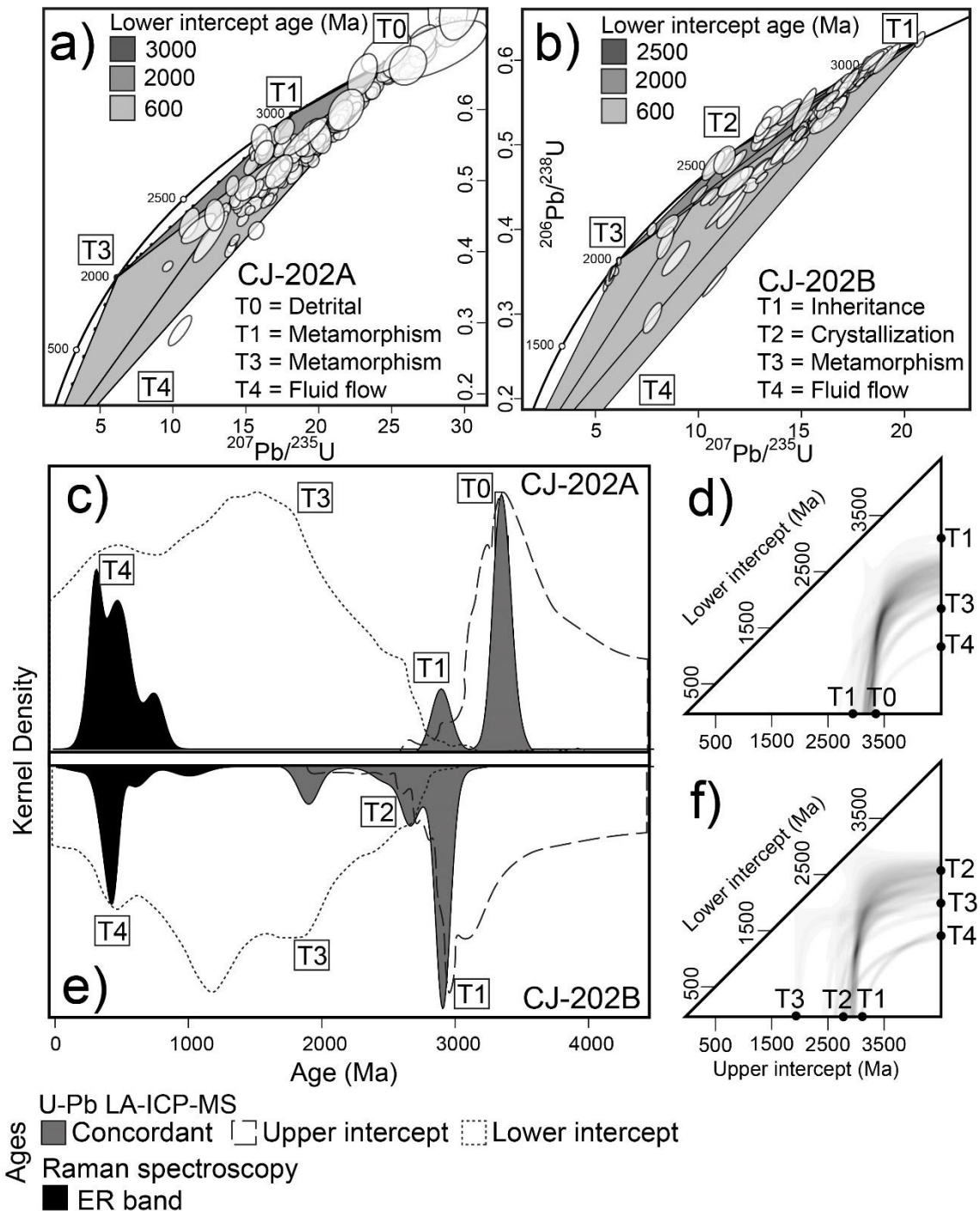


Figura 38: a, b) Wetherill concordia diagram of samples CJ-202A and CJ-202B showing the measured U–Pb data and the possible discordance paths during the mixing of each population. The interpretation of each population is also shown. c, e) Kernel density estimation (peaks normalized) of the ages of concordant analyses compared with the likelihood spectrum of single-grain lower and upper intercept ages from the code of Reimink et al. (2016) and Raman dating ages. d, f) Single-grain upper and lower intercept ages (Ma).

Disturbance of the isotopic system during the Paleoproterozoic and Neoproterozoic can only be identified through lower intercept ages (Fig. 38A, C, D). While most of the detrital grains display isotopic ratios that are consistent with

disturbance of the isotopic system at 2.0 Ga, the 3.0 Ga old grains were mostly inert to the 2.0 Ga event and strongly affected by the 0.6 Ga event. This differential behavior is likely related to the higher U concentrations of the 3.0 Ga grains, which consequently underwent more radiation damage over time and were more susceptible to disturbance in the Neoproterozoic. Some analyzes follow mixed paths, which are also visible in the likelihood spectrum (Reimink et al., 2016) of single-grain lower intercept ages as a major peak near 1500 - 1700 Ma (Fig. 38C). This peak has no geological meaning and results from the mixing between 2.0 and 0.6 Ga events.

In sample CJ-202B, there are no grains that could be related to the detrital populations of sample CJ-202A. However, several grains dated between 3.1 and 2.8 Ga are dark in CL and rich in U. These are similar to the 2.9 Ga population in CJ-202A but spread towards younger ages (Fig. 36A, 38B). The spread in ages can be explained by concealed Pb loss during the interaction of the inherited grains from the host rock with the mafic melt presently represented by the amphibolite. The timing of interaction (i.e., crystallization of the protolith) could be either 2696 ± 15 Ma, 2521 ± 22 Ma or 1955 ± 9 Ma based on the weighted average of single grain concordia ages (Fig. 36B). The age of 2696 ± 15 Ma is within the uncertainty of the granitic magmatism in this area (Souza et al., 2016, 2023). These ages were also found in the core of a few grains of the 2.5 Ga population, suggesting that the age of 2521 ± 22 Ma best represents the timing of emplacement of the mafic rock. Although mafic magmas usually do not crystallize zircon, local Zr saturation can be achieved at mineral-melt interfaces (e.g., Bea et al., 2022), which might explain fully crystallized grains such as Z58 (Fig. 36F). The preferred age is within the uncertainty of the Lavras I dyke swarm emplaced at 2551 ± 10 Ma in the southern São Francisco Craton (Caxito et al., 2020a). The younger age of 1955 ± 9 Ma is within the uncertainty of a regional metamorphic event in the Borborema Province

(Dantas et al., 2004; Souza et al., 2016; Neves, 2021; Ribeiro et al., 2024) and is also found as lower intercept ages in sample CJ-202A (Fig. 38A, E), suggesting that mylonitization under amphibolite facies conditions took place in the Paleoproterozoic. Akin to sample CJ-202A, disturbance of the isotopic system at 2.0 and 0.6 Ga can be observed in most of the discordant grains in sample CJ-202B. In the likelihood spectrum of single-grain lower intercept ages, three peaks around 1.9, 1.2 and 0.6 Ga can be clearly distinguished (Fig. 38E, F). The peak around 1.2 Ga has no geological meaning and, similarly to sample CJ-202A, represents the mixing between the 2.0 and 0.6 Ga events.

Raman radiation damage ages of zircon are thought to reflect accumulation of radiation damage in temperatures below 310 to 260 °C (Härtel et al., 2021b). The radiation damage ages obtained from our samples are closely related to the lower intercept ages, suggesting a Cambrian to Late Paleozoic exhumation for these rocks (Fig. 38C - F). The isochron ages of 479 ± 64 Ma for sample CJ-202A (Fig. 37F) and 408 ± 45 Ma (Fig. 37G) are within the uncertainty to slightly younger than $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages in the northern Borborema Province (Corsini et al., 1998). These ages are also within the uncertainty of epidote fission-track ages in the Brejuí Mine (ca. 150 km to the southwest of the study area), which yield a corrected age of 496 ± 66 Ma (Curvo et al., 2005). The Carboniferous to Permian isochron age of 296 ± 30 Ma obtained in this work is also within the uncertainty of a younger epidote fission-track age of 355 ± 57 Ma in the Brejuí Mine (Curvo et al., 2005). Zircon fission-track ages of 499 ± 6 Ma and 307 ± 5 Ma are also recorded in the southern São Francisco Craton and are linked to lithospheric rebound and ice retreat following the Late Paleozoic Ice Age, respectively (Dias et al., 2024). The older isochron ages obtained from our dataset are probably related to incomplete annealing of the grains or differences in zero-damage bandwidth (e.g., Härtel et al.,

2021a). Therefore, zircon lower intercept ages might indeed record low-temperature exhumation events (e.g., Morris et al., 2015; Reimink et al., 2016; Hermann et al., 2021).

Trace elements behavior upon annealing and metamictization

Trace elements in zircon are commonly employed to track variations in crystallization conditions, oxygen fugacity, conditions of metamorphism, crustal thickness and so on (e.g., Tang, et al. 2021; Brudner et al., 2022; Moreira et al., 2023; Roberts et al., 2024). However, the reliability of these petrogenetic information is always a matter of debate. Several works have shown that U–Pb ages are commonly decoupled from textures and trace elements during high temperature (>850 °C) metamorphism (e.g., Flowers et al., 2010; Whitehouse et al., 2014; Kunz et al., 2018; Garber et al., 2020). Beyond that, low temperature fluid-flow can lead to the influx of non-formula elements in metamict grains (e.g., Hay and Dempster, 2009; Pidgeon et al., 2019, 2023). Porosity is created during the prolonged alpha-decay of U and Th, leading to the formation of voids and fractures through which the fluid can flow (Pidgeon et al., 2023).

Alpha-dose values can be used to estimate the degree of radiation damage in individual grains based on their U and Th concentrations (e.g., Murakami et al., 1991). The zircon grains analyzed in this work yield higher values between 3100 and 2800 Ma in both samples (Fig. 39A). Discordance yields a positive linear relationship with alpha-dose values, suggesting that metamictization is directly related to discordance (Fig. 39B). This relationship is clear in the biotite paragneiss, but not in the amphibolite sample. The same can be observed for Nb and Ta concentrations, which show a positive correlation with alpha-dose values in the biotite paragneiss but are nearly the same for all the grains in the amphibolite (Fig. 39C). ΔFMQ values (calculated based on Ce, Ti and U concentrations) also shift towards negative values in Nb and Ta-rich grains of the biotite paragneiss, but are mostly negative in the amphibolite (Fig. 39D), suggesting that influx

of non-formula elements also correlates with shifts in oxygen fugacity towards more reducing conditions. Ti-in-zircon temperatures are more variable and yield higher uncertainties in the biotite paragneiss sample, with temperatures as low as 610 ± 42 °C up to 1015 ± 71 °C (Fig. 39E). Eight detrital grains yield an average temperature of 803 ± 30 °C. On the other hand, all the analyzed grains from the amphibolite yield similar Ti in zircon concentrations, with an average temperature of 838 ± 14 °C (Fig. 39F). Although the average temperature retrieved from each sample is within the uncertainty of each other, zircon grains from the amphibolite yield more homogeneous results, despite the U-Pb ages that span for more than 1.0 Ga (Fig. 38). Recent high temperature diffusion experiments indicate that diffusion of Ti and possibly other trace elements in zircon is strongly anisotropic and faster parallel to the c-axis (Bloch et al., 2022). Therefore, due to the rounded morphology and small size (<100 μm), diffusion at high temperature should be able to homogenize trace elements compositions in zircon grains from the amphibolite sample.

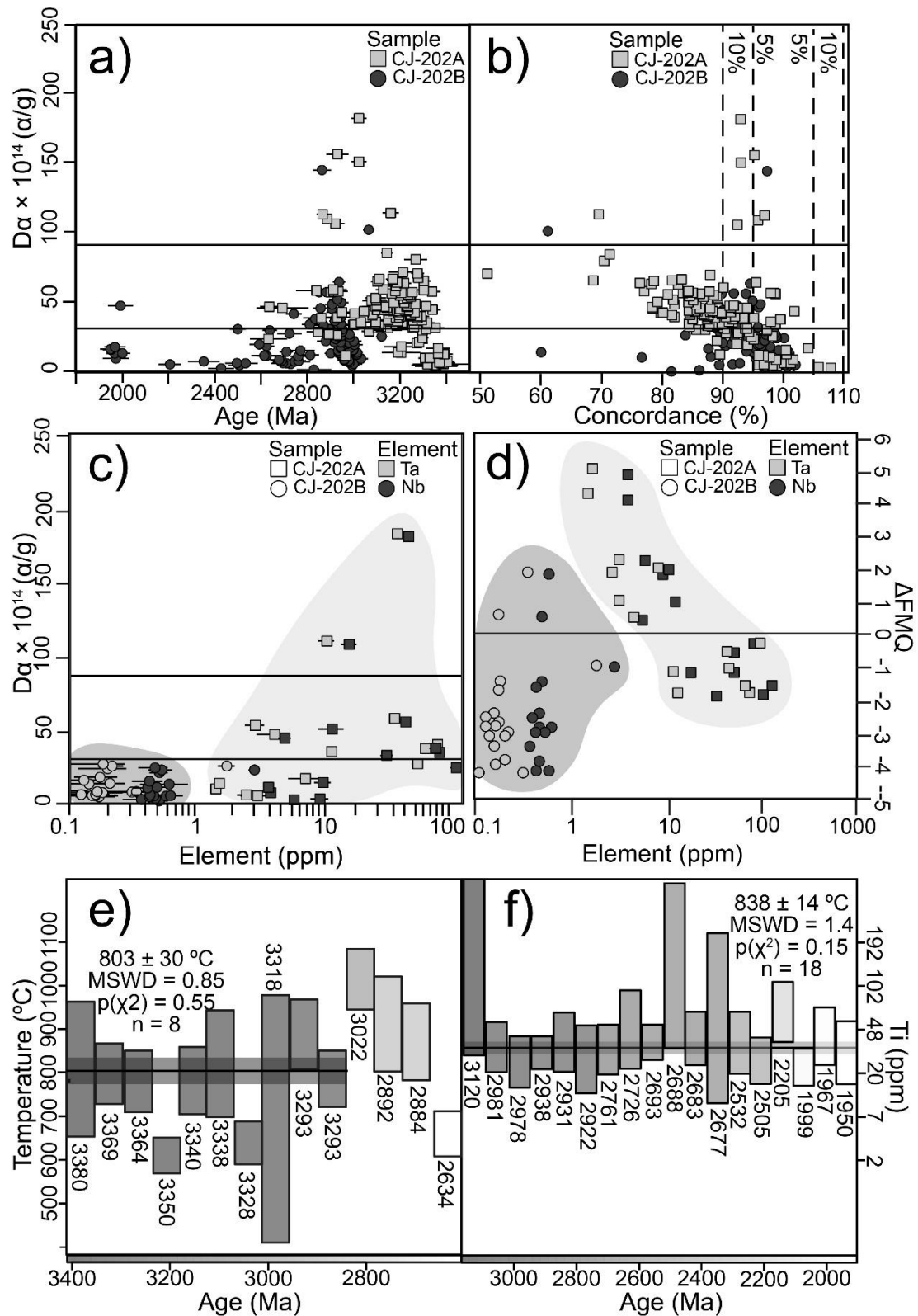


Figura 39: a) $^{207}\text{Pb}/^{206}\text{Pb}$ ages (Ma) versus $D\alpha \times 10^{14}$ (α/g). Solid horizontal lines represent stages of metamictization from Murakami et al. (1991). b) Concordance (%) versus $D\alpha \times 10^{14}$ (α/g). Dashed lines represent commonly employed discordance cut-offs. Solid horizontal lines same as a. c) Ta and Nb (ppm) versus $D\alpha \times 10^{14}$ (α/g). Each sample is surrounded by a shaded area. Solid horizontal lines same as a. d)

ΔFMQ versus Ta and Nb (ppm). Each sample is surrounded by a shaded area. e, f) Weighted average of Ti-in-zircon temperatures. Shades of gray are proportional to $^{207}\text{Pb}/^{206}\text{Pb}$ ages.

Collectively, these variations indicate a relationship between radiation damage, discordance, oxygen fugacity and influx of non-formula elements. Although zircon of both samples underwent radiogenic Pb loss upon fluid flow during shear zone reactivation in the Neoproterozoic, Nb and Ta concentrations in zircon grains from the amphibolite sample were mostly homogeneous, despite being related to populations with distinct ages and varied REE patterns (Fig. 36C, D). In Murakami et al. (1991), three stages of damage accumulation are described. The first stage, for $<30 \times 10^{14}$ alpha-decay events/mg, is characterized by isolated point defects. The second, for the range between 30 and 80×10^{14} alpha-decay events/mg, features distortion of the crystalline structure and areas of amorphization. The third, for values above 80×10^{14} alpha-decay events/mg, is characterized by aperiodic crystals. From the calculated values, most of the grains of the biotite paragneiss are within the range of distorted crystalline structure and amorphization (Fig. 39A, B). On the other hand, most of the grains from the amphibolite are within the range of isolated point defects (Fig. 39A, B). The ratio $D_{\text{ER}}/D_{\text{V2}}$ for the amphibolite is consistently above the value of 1.0 for unannealed zircon (Härtel et al., 2022), with an average of 2.0(0.5), while the biotite paragneiss yield an average of 0.8(0.4) (Supplementary Material). These features are consistent with thermal annealing and structure recovery for the amphibolite sample, but not for biotite paragneiss. These observations are not in agreement with previous works that suggested that high temperature metamorphism might cause structure recovery in zircon and reset of U-Pb ages (e.g., Schaltegger et al., 1999; Laurent et al., 2018). In our particular case, resetting of U-Pb ages is directly related to dissolution-reprecipitation processes, as observed in CL images (Fig. 36).

We hypothesize that high-temperature annealing of the inherited zircon grains in the hot mafic magma shielded their structure against later low-temperature disturbance of trace elements and preservation of crystalline structure (e.g., Geisler et al., 2001). On the other hand, high-temperature partial melting was unable to shield the grains from the biotite paragneiss, leading to longer accumulation of radiation damage (Fig. 40). Upon fluid flow, porous metamict grains were then enriched in non-formula elements (e.g., Geisler et al., 2007; Seydoux-Guillaume et al., 2015; Pidgeon et al., 2023). These observations, from outcrop to mineral scale, also suggest that metasedimentary rocks are efficient fluid pathways, while mafic rocks are less reactive (e.g. Rutter et al., 1985; Hacker and Christie, 1990; Getsinger and Hirth, 2014).

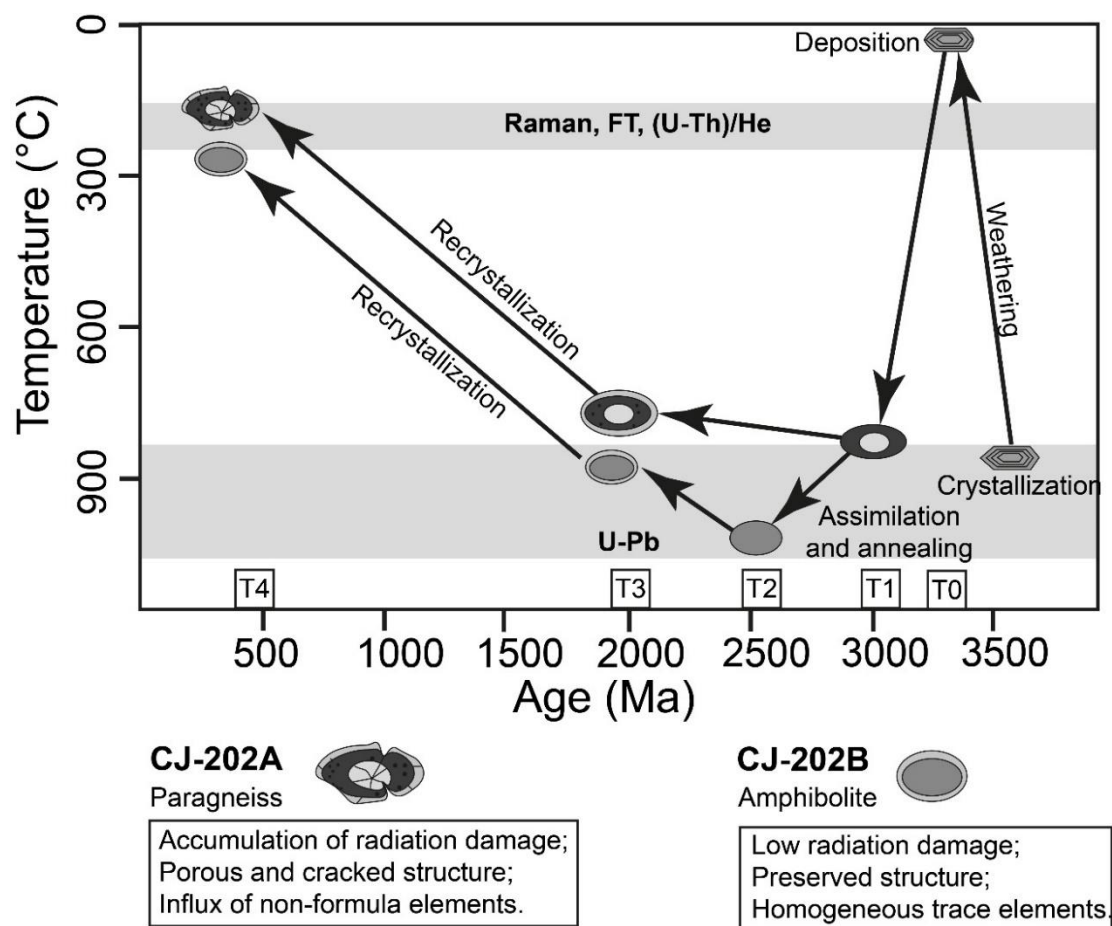


Figura 40: Representation of changes in zircon during the stages described in this work. Gray bands represent closure temperatures from Zaun and Wagner (1985), Reiners et al. (2002), Kohn et al. (2015) and Härtel et al. (2021b). T0 = Deposition. T1 = Metamorphism. T2 = Crystallization. T3 = Metamorphism. T4 = Exhumation and fluid flow.

IMPLICATIONS

In this work, we investigated the differential isotopic and trace element behavior of zircon from an outcrop perspective, where zircon grains from the host Paleoproterozoic biotite paragneiss record a different thermal history than the intrusive Neoproterozoic amphibolite. Zircon grains from the Paleoproterozoic paragneiss sample underwent strong radiation damage, leading to amorphization of its crystalline structure and disturbance of U–Pb isotopes and trace elements. On the other hand, zircon grains in the intrusive amphibolite were inherited from the paragneiss, but high temperature annealing upon entrainment in the hot mafic magma during the Neoproterozoic led to homogenization of trace elements and preservation of the crystalline structure. High-temperature mylonitic fabrics were then developed during the Paleoproterozoic, as observed in U–Pb in zircon upper and lower intercept ages. Raman dating and U–Pb lower intercept ages in zircon indicate a final Cambrian to Late Paleozoic exhumation for the São José do Campestre Massif, with zircon grains recording a long history of trans-crustal recycling.

The results indicate that zircon U–Pb ages and trace elements might be decoupled during high temperature annealing and structure recovery, especially when inherited in mafic magmas. Concealed Pb loss also promotes the spread of concordant ages, leading to concordant populations with no geological meaning. Therefore, U–Pb ages and petrogenetic information obtained from trace elements, particularly in naturally annealed zircon grains from mafic rocks, should be interpreted with great caution. On the other hand, high temperature partial melting in the host paragneiss was unable to promote zircon structure recovery, contrary to previous works that suggested annealing as a mechanism for partial reset of U–Pb ages in metamorphic rocks. Instead, dissolution and reprecipitation of U-rich rims are responsible for the reset of U–Pb ages. Accumulation of radiation damage led to metamictization, which further facilitated non-formula trace

elements influx at lower temperatures. Raman spectroscopy provided additional constraints on the annealing state and radiation damage of zircon grains and should be more commonly employed in zircon studies.

Beyond that, this is the first application of Raman dating to polymetamorphic Archean rocks and the results showed an overall consistency with previous low-temperature methodologies results, including epidote and zircon fission-track, highlighting the potential of Raman dating as a thermochronological tool. Although metamict zircon grains are often avoided in geochronological studies, they can provide important constraints on low temperature events, even after being subject to three distinct metamorphic events. Single grain lower intercept ages, particularly in the most discordant grains, yield similar peaks to single grain Raman radiation damage ages, suggesting that lower intercept ages, especially in metamict zircon grains, can successfully track low temperature thermal events in the upper crust.

CAPÍTULO 9: DISCUSSÕES FINAIS E CONCLUSÕES

A investigação de rochas metamórficas de origem sedimentar do Maciço São José do Campestre permitiu inferir os mecanismos e a duração de diversos processos na crosta continental Arqueana.

Os resultados do primeiro artigo científico indicam que estas rochas foram provavelmente depositadas durante o Arqueano, com a população mais jovem de zircão detrítico fornecendo uma idade de 3.3 Ga. Esta idade é cerca de 50 Ma mais jovem que os ortognaisses encontrados na Pedreira do Teixeira (Souza et al., 2016), sugerindo que as rochas sedimentares foram originalmente depositadas sobrepondo o embasamento do Complexo Serra Caiada. A ausência de cristais de zircão mais antigos do que 3.4 Ga sugere que estas rochas foram depositadas num contexto de fontes limitadas, possivelmente convergente. O principal evento metamórfico que afetou estas rochas, responsável pela sua intensa migmatização, teve uma duração determinada entre 3.08 – 3.0 Ga, em condições de fácies granulito. Eventos metamórficos mais jovens, em aproximadamente 2.0 e 0.6 Ga, também foram identificados nestas rochas. Estes resultados permitiram estabelecer que estas rochas são mais antigas do que trabalhos anteriores definiram (Souza et al., 2016), ressaltando a importância de uma investigação detalhada das texturas de zircão para interpretações adequadas.

O segundo artigo consistiu na primeira aplicação da datação por Raman, através da recente calibração de Härtel et al. (2021a), em rochas arqueanas. Os resultados permitiram confirmar que os interceptos inferiores de cristais de zircão muitas vezes marcam episódios de baixa temperatura. Além disso, foi obtida a primeira idade de uma sequência de diques de anfíbolito na região de Cajazeiras, com idade em torno de 2.5 Ga, até então não identificada na região. Os resultados indicam dois importantes eventos de exumação na região durante o Cambriano e durante o Carbonífero-Permiano.

O terceiro artigo descreveu as condições e a trajetória do metamorfismo em torno de 3,08 – 3,0 Ga que afetou estas rochas. As estimativas indicam que foram atingidas condições de ultra-alta temperatura, acima de 900 °C, sendo marcada principalmente pela ocorrência de espinélio com quartzo. Cronometria por difusão indica estas condições foram mantidas por um curto tempo, com duração máxima de 4 Ma, seguido por um resfriamento e soerguimento rápido para fácies anfibolito superior. A trajetória obtida se assemelha em parte com modelos geodinâmicos de convergência por delaminação, permitindo-se inferir processos similares para a área de estudo. O metamorfismo registrado por estas rochas, apesar de escasso no registro geológico, apresenta correlatos em diversos crátons antigos. A comparação entre a idade dos eventos destas regiões indica que o metamorfismo em torno de 3,08 – 3,0 no Maciço São José do Campestre corresponde ao estágio colisional de uma convergência iniciada a partir da subducção de crosta oceânica em aproximadamente 3,2 Ga, preservada principalmente no cráton Kaapvaal e no oeste da Índia. Reconstruções paleogeográficas permitem relacionar este evento a um grande orógeno colisional que resultou na formação do supercontinente Ur.

O quarto artigo focou em descrever as relações geoquímicas, geocronológicas e metamórficas envolvidas na formação de leucossomas peraluminosos resultantes da fusão parcial do Complexo Tangará durante o Mesoarqueano. A partir da combinação de diversas técnicas, foi possível inferir uma duração mínima de 19 Ma para a fusão parcial, com rápida segregação do magma da fonte em menos de 53 kyr. Os resultados, quando comparados com granitos peraluminosos dos Himalaias, formados nos últimos 50 Ma, indicam durações similares para os processos de fusão parcial, segregação e cristalização de magmas peraluminosos.

De modo geral, os resultados obtidos nesta tese corroboram a atuação da tectônica de placas durante o Arqueano. A duração dos processos ígneos e metamórficos obtidos

para as rochas do Maciço São José do Campestre são comparáveis a exemplos modernos, sugerindo que os processos que moldam a Terra atualmente ocorrem de forma similar desde, pelo menos, 3,2 bilhões de anos atrás.

Diversos autores sugerem que eventos geológicos durante o Arqueano tem uma longa duração, impulsionados pelos altos gradientes geotérmicos da época (e.g., Chowdhury et al., 2021). Contudo, a maioria dos eventos geológicos são episódicos e de curta duração (e.g., Viete & Lister, 2007). Para o registro Fanerozóico, a geocronologia isotópica apresenta uma resolução capaz de discernir eventos de curta duração. Contudo, para o registro Pré-cambriano e, principalmente Arqueano, não é possível quantificar rápidos eventos. Por exemplo, para um evento de 50 Ma, uma incerteza de 2% corresponde a 1 Ma, enquanto para um evento de 3000 Ma, a mesma incerteza corresponde a 60 Ma. Consequentemente, somente a cronometria por difusão é capaz de resolver eventos de curta duração durante o Arqueano.

A caracterização do Complexo Tangará como uma sequência sedimentar Paleoarqueana sugere a sua relação com sequências do tipo *greenstone belt* (e.g., Dantas, 2009). Consequentemente, rochas máficas mais antigas são esperadas na base desta sequência. *Greenstone belts* são conhecidos por hospedarem diversos tipos de mineralização, principalmente ouro orogênico e depósitos de Fe-Mn sedimentar (e.g., Anhaeusser, 2014). Além disso, o evento metamórfico de idade Mesoarqueana se relaciona a depósitos de Au-Cu em rochas vulcanossedimentares na Groelândia (3,07 – 3,02 Ga; Garde et al., 2012) e Cu-Co-Au na Austrália (2.96 Ga; Fox et al., 2021). Remobilização de Au durante a fusão parcial também é possível, em contextos similares ao depósito de Challenger, Austrália, onde o ouro é hospedado em leucossomas formados em condições de >800 °C e 7 kbar (Tomkins & Mavrogenes, 2002).

Um aspecto ainda pouco discutido é a relação entre o metamorfismo mesoarqueano (3,2 – 3,0 Ga em outros crátons, 3,08 – 3,0 no Maciço São José do Campestre) e rochas plutônicas de idade similar em diversos blocos e crátons arqueanos, como o bloco Campo Grande, na Província Borborema, e o Cráton São Francisco. Seriam estas rochas plutônicas parte de um extenso arco magmático continental?

Por fim, ainda permanecem lacunas em relação as condições e papel de eventos metamórficos mais jovens, principalmente o Paleoproterozoico. Este evento afetou de modo sutil as rochas estudadas, cujo efeitos foram observados principalmente pelo intercepto inferior de alguns cristais de zircão e, localmente, bordas recrystalizadas. Contudo, devido a intensa deformação do evento Mesoarqueano, é difícil distinguir seus efeitos nas amostras estudadas. Rochas mais jovens, como o Sienogranito São José do Campestre ou as rochas máficas de Cajazeiras podem fornecer informações relevantes sobre as condições deste evento metamórfico.

REFERENCIAS

- Abrahão Filho, E.A., 2016. Rochas piroxeníticas ricas em ferro do maciço São José do Campestre, Rio Grande do Norte, Brasil. Universidade de Brasília, Brasília. <https://doi.org/10.26512/2016.07.D.22068>
- Alfing, J., Johnson, T.E., Kaempf, J., Brown, M., Szilas, K., Rankenburg, K., Clark, C., 2024. Eoarchean granulite-facies metamorphism in the Itsaq Gneiss Complex, southwest Greenland. *Earth Planet Sci Lett* 646, 118977. <https://doi.org/10.1016/j.epsl.2024.118977>
- Almeida, F.F.M. de, Hasui, Y., Brito Neves, B.B. de, Fuck, R.A., 1981. Brazilian structural provinces: An introduction. *Earth Sci Rev* 17, 1–29. [https://doi.org/10.1016/0012-8252\(81\)90003-9](https://doi.org/10.1016/0012-8252(81)90003-9)
- Amaldev, T., Santosh, M.W., Tang, L., Baiju, K.R., Tsunogae, T., Satyanarayanan, M., 2016. Mesoarchean convergent margin processes and crustal evolution: Petrologic, geochemical and zircon U–Pb and Lu–Hf data from the Mercara Suture Zone, southern India. *Gondwana Research* 37, 182–204. <https://doi.org/10.1016/j.gr.2016.05.017>
- Amaral, W., Santos, T.J., Ancelmi, M.F., Fuck, R.A., Dantas, E.L., Matteini, M., Moreto, C.P., 2015. 1.57 Ga protolith age of the Neoproterozoic Forquilha eclogites, Borborema Province, NE-Brazil, constrained by U–Pb, Hf and Nd isotopes. *J South Am Earth Sci* 58, 210–222. <https://doi.org/10.1016/j.jsames.2014.10.001>
- Anders, E., Grevesse, N., 1989. Abundances of the elements: Meteoritic and solar. *Geochim Cosmochim Acta* 53, 197–214. [https://doi.org/10.1016/0016-7037\(89\)90286-X](https://doi.org/10.1016/0016-7037(89)90286-X)
- Andersen, T., Elburg, M.A., Magwaza, B.N., 2019. Sources of bias in detrital zircon geochronology: Discordance, concealed lead loss and common lead correction. *Earth Sci Rev* 197, 102899. <https://doi.org/10.1016/j.earscirev.2019.102899>
- Andrehs, G., Heinrich, W., 1998. Experimental determination of REE distributions between monazite and xenotime: potential for temperature-calibrated geochronology. *Chem Geol* 149, 83–96. [https://doi.org/10.1016/S0009-2541\(98\)00039-4](https://doi.org/10.1016/S0009-2541(98)00039-4)
- Anhaeusser, C.R., 2014. Archaean greenstone belts and associated granitic rocks – A review. *Journal of African Earth Sciences* 100, 684–732. <https://doi.org/10.1016/j.jafrearsci.2014.07.019>

- Anoop, K.S., Anilkumar, Y., Santosh, M.W., Yu, B., Delna Joy, K., Kavyanjali, K.V., Sathyan, A., Mathew, A., Sajinkumar, K.S., 2022. Magmatic and metamorphic evolution of a layered gabbro-anorthosite complex from the Coorg Block, southern India: Implications for Mesoarchean suprasubduction zone process. *Gondwana Research* 103, 105–134. <https://doi.org/10.1016/j.gr.2021.07.026>
- Antonelli, M.A., Kendrick, J., Yakymchuk, C., Guitreau, M., Mittal, T., Moynier, F., 2021. Calcium isotope evidence for early Archaean carbonates and subduction of oceanic crust. *Nat Commun* 12, 2534. <https://doi.org/10.1038/s41467-021-22748-2>
- Araujo, I.L. de, 2012. Caracterização do Arcabouço Tectônico Do Terreno São José Do Campestre, Província Borborema, com base em dados de Aerogeofísica (Doctorate Thesis). Universidade de Brasília, Instituto de Geociências, Brasília.
- Arndt, N., 2023a. How did the continental crust form: No basalt, no water, no granite. *Precambrian Res* 397, 107196. <https://doi.org/10.1016/j.precamres.2023.107196>
- Arndt, N., 2023b. How did the continental crust form: No basalt, no water, no granite. *Precambrian Res* 397, 107196. <https://doi.org/10.1016/j.precamres.2023.107196>
- Ayers, J.C., DeLaCruz, K., Miller, C., Switzer, O., 2003. Experimental study of zircon coarsening in quartzite $\pm$ H₂O at 1.0 GPa and 1000 °C, with implications for geochronological studies of high-grade metamorphism. *American Mineralogist* 88, 365–376. <https://doi.org/10.2138/am-2003-2-313>
- Ayres, M., Harris, N., Vance, D., 1997. Possible constraints on anatectic melt residence times from accessory mineral dissolution rates; an example from Himalayan leucogranites. *Mineral Mag* 61, 29–36.
- Ballouard, C., Massuyeau, M., Elburg, M.A., Tappe, S., Viljoen, F., Brandenburg, J.-T., 2020. The magmatic and magmatic-hydrothermal evolution of felsic igneous rocks as seen through Nb-Ta geochemical fractionation, with implications for the origins of rare-metal mineralizations. *Earth Sci Rev* 203, 103115. <https://doi.org/10.1016/j.earscirev.2020.103115>
- Ballouard, C., Poujol, M., Boulvais, P., Branquet, Y., Tartèse, R., Vigneresse, J.-L., 2016. Nb-Ta fractionation in peraluminous granites: A marker of the magmatic-hydrothermal transition. *Geology* 44, 231–234. <https://doi.org/10.1130/G37475.1>

- Barbey, P., 2007. Diffusion-controlled biotite breakdown reaction textures at the solid/liquid transition in the continental crust. *Contributions to Mineralogy and Petrology* 154, 707–716. <https://doi.org/10.1007/s00410-007-0220-x>
- Barbosa, J.S.F., Sabaté, P., 2004. Archean and Paleoproterozoic crust of the São Francisco Craton, Bahia, Brazil: geodynamic features. *Precambrian Res* 133, 1–27. <https://doi.org/10.1016/j.precamres.2004.03.001>
- Barros, R. de A., Caxito, F. de A., Egydio-Silva, M., Dantas, E.L., Pinheiro, M.A.P., Rodrigues, J.B., Basei, M.A.S., Virgens-Neto, J. das, Freitas, M. de S., 2020. Archean and Paleoproterozoic crustal evolution and evidence for cryptic Paleoarchean-Hadean sources of the NW São Francisco Craton, Brazil: Lithochemistry, geochronology, and isotope systematics of the Cristalândia do Piauí Block. *Gondwana Research* 88, 268–295. <https://doi.org/10.1016/j.gr.2020.07.004>
- Bartoli, O., 2021. Granite geochemistry is not diagnostic of the role of water in the source. *Earth Planet Sci Lett* 564, 116927. <https://doi.org/10.1016/j.epsl.2021.116927>
- Basak, S., Hasenstab, E., Bhowmik, S.K., Gerdes, A., Dasgupta, S., Münker, C., Kumar, Gr.R., Chakraborty, S., 2023. Thermal and Chemical Evolution of an Archean Collision Zone: Insights from P – T – t History of Mafic Granulites from the Coorg Block, S. India. *Journal of Petrology* 64. <https://doi.org/10.1093/petrology/egad026>
- Bea, F., Montero, P., Ortega, M., 2006. A LA-ICP-MS evaluation of Zr reservoirs in common crustal rocks: implications for Zr and Hf geochemistry, and zircon-forming processes. *The Canadian Mineralogist* 44, 693–714. <https://doi.org/10.2113/gscanmin.44.3.693>
- Bea, F., Pereira, M.D., Stroh, A., 1994. Mineral/leucosome trace-element partitioning in a peraluminous migmatite (a laser ablation-ICP-MS study). *Chem Geol* 117, 291–312. [https://doi.org/10.1016/0009-2541\(94\)90133-3](https://doi.org/10.1016/0009-2541(94)90133-3)
- Bédard, J.H., 2018. Stagnant lids and mantle overturns: Implications for Archaean tectonics, magmagenesis, crustal growth, mantle evolution, and the start of plate tectonics. *Geoscience Frontiers* 9, 19–49. <https://doi.org/10.1016/j.gsf.2017.01.005>
- Benisek, A., Finger, F., 1993. Factors controlling the development of prism faces in granite zircons: a microprobe study. *Contributions to Mineralogy and Petrology* 114, 441–451. <https://doi.org/10.1007/BF00321749>

- Benn, K., Mareschal, J.-C., Condie, K.C., 2006. Archean Geodynamics and Environments. American Geophysical Union, Washington, D. C. <https://doi.org/10.1029/GM164>
- Bhattacharya, A., Mazumdar, A.C., Sen, S.K., 1988. Fe-Mg mixing in cordierite; constraints from natural data and implications for cordierite-garnet geothermometry in granulites. *American Mineralogist* 73, 338–344.
- Bhowmik, S.K., Chakraborty, S., 2017. Sequential kinetic modelling: A new tool decodes pulsed tectonic patterns in early hot orogens of Earth. *Earth Planet Sci Lett* 460, 171–179. <https://doi.org/10.1016/j.epsl.2016.12.018>
- Bindeman, I.N., Schmitt, A.K., Lundstrom, C.C., Hervig, R.L., 2018. Stability of Zircon and Its Isotopic Ratios in High-Temperature Fluids: Long-Term (4 months) Isotope Exchange Experiment at 850°C and 50 MPa. *Front Earth Sci (Lausanne)* 6. <https://doi.org/10.3389/feart.2018.00059>
- Bleeker, W., 2003. The late Archean record: a puzzle in ca. 35 pieces. *Lithos* 71, 99–134. <https://doi.org/10.1016/j.lithos.2003.07.003>
- Bloch, E.M., Jollands, M.C., Tollan, P., Plane, F., Bouvier, A.-S., Hervig, R., Berry, A.J., Zaubitzer, C., Escrig, S., Müntener, O., Ibañez-Mejia, M., Alleen, J., Meibom, A., Baumgartner, L.P., Marin-Carbonne, J., Newville, M., 2022. Diffusion anisotropy of Ti in zircon and implications for Ti-in-zircon thermometry. *Earth Planet Sci Lett* 578, 117317. <https://doi.org/10.1016/j.epsl.2021.117317>
- Boehnke, P., Watson, E.B., Trail, D., Harrison, T.M., Schmitt, A.K., 2013. Zircon saturation re-revisited. *Chem Geol* 351, 324–334. <https://doi.org/10.1016/j.chemgeo.2013.05.028>
- Borisova, A.Y., Nédélec, A., Zagrtchenov, N.R., Toplis, M.J., Bohron, W.A., Safonov, O.G., Bindeman, I.N., Melnik, O.E., Pokrovski, G.S., Ceuleneer, G., Jochum, K.P., Stoll, B., Weis, U., Bychkov, A.Y., Gurenko, A.A., 2022. Hadean zircon formed due to hydrated ultramafic protocrust melting. *Geology* 50, 300–304. <https://doi.org/10.1130/G49354.1>
- Boyd, A.J., Rosing, M.T., Harding, M.A.R., Canfield, D.E., Hassenkam, T., 2024. 3.7 billion year old detrital sediments in Greenland are consistent with active plate tectonics in the Eoarchean. *Commun Earth Environ* 5, 201. <https://doi.org/10.1038/s43247-024-01376-w>

- Brito Neves, B.B. de, Fuck, R.A., Pimentel, M.M., 2014. The Brasiliano collage in South America: a review. *Brazilian Journal of Geology* 44, 493–518. <https://doi.org/10.5327/Z2317-4889201400030010>
- Brito Neves, B.B. de, Santos, E.J. dos, Fuck, R.A., Santos, L.C.M.L., 2016. A preserved early Ediacaran magmatic arc at the northernmost portion of the Transversal Zone central subprovince of the Borborema Province, Northeastern South America. *Brazilian Journal of Geology* 46, 491–508. <https://doi.org/10.1590/2317-4889201620160004>
- Brizzi, S., Becker, T.W., Faccenna, C., Behr, W., van Zelst, I., Dal Zilio, L., van Dinther, Y. van, 2021. The Role of Sediment Accretion and Buoyancy on Subduction Dynamics and Geometry. *Geophys Res Lett* 48. <https://doi.org/10.1029/2021GL096266>
- Brown, M., 2014. The contribution of metamorphic petrology to understanding lithosphere evolution and geodynamics. *Geoscience Frontiers* 5, 553–569. <https://doi.org/10.1016/j.gsf.2014.02.005>
- Brown, M., Johnson, T., 2019. Time's arrow, time's cycle: Granulite metamorphism and geodynamics. *Mineral Mag* 83, 323–338. <https://doi.org/10.1180/mgm.2019.19>
- Brown, M., Johnson, T., 2018. Secular change in metamorphism and the onset of global plate tectonics. *American Mineralogist* 103, 181–196. <https://doi.org/10.2138/am-2018-6166>
- Brown, M., Johnson, T., Gardiner, N.J., 2020. Plate Tectonics and the Archean Earth. *Annu Rev Earth Planet Sci* 48, 291–320. <https://doi.org/10.1146/annurev-earth-081619-052705>
- Brudner, A., Jiang, H., Chu, X., Tang, M., 2022. Crustal thickness of the Grenville orogen: A Mesoproterozoic Tibet? *Geology* 50, 402–406. <https://doi.org/10.1130/G49591.1>
- Bucholz, C.E., Spencer, C.J., 2019. Strongly Peraluminous Granites across the Archean–Proterozoic Transition. *Journal of Petrology* 60, 1299–1348. <https://doi.org/10.1093/petrology/egz033>
- Caddick, M.J., Konopásek, J., Thompson, A.B., 2010. Preservation of Garnet Growth Zoning and the Duration of Prograde Metamorphism. *Journal of Petrology* 51, 2327–2347. <https://doi.org/10.1093/petrology/egq059>
- Cameron, E.M., Blum, T.B., Cavosic, A.J., Kitajima, K., Nasdala, L., Orland, I.J., Bonamici, C.E., Valley, J.W., 2024. Evidence for oceans pre-4300 Ma confirmed by preserved igneous compositions in Hadean zircon. *American Mineralogist* 109, 1670–1681. <https://doi.org/10.2138/am-2023-9180>

- Cao, H.-W., Pei, Q.-M., Santosh, M., Li, G.-M., Zhang, L.-K., Zhang, X.-F., Zhang, Y.-H., Zou, H., Dai, Z.-W., Lin, B., Tang, L., Yu, X., 2022. Himalayan leucogranites: A review of geochemical and isotopic characteristics, timing of formation, genesis, and rare metal mineralization. *Earth Sci Rev* 234, 104229. <https://doi.org/10.1016/j.earscirev.2022.104229>
- Carlson, W.D., 2006. Rates of Fe, Mg, Mn, and Ca diffusion in garnet. *American Mineralogist* 91, 1–11. <https://doi.org/10.2138/am.2006.2043>
- Carrasco-Godoy, C., Campbell, I.H., 2023. Application of Onuma and lattice strain derived methods to calculate missing REE and Ce and Eu anomalies in magmatic zircons. *Contributions to Mineralogy and Petrology* 178, 42. <https://doi.org/10.1007/s00410-023-02025-9>
- Cavalcante, R., Medeiros, V.C., Costa, A.P., Sá, J.M., Santos, R.V., Rodrigues, J.B., Dantas, A.R., Nascimento, M.A.L., Cunha, A.L.C., 2018. Neoproterozoic, Rhyacian and Neoproterozoic units of the Saquinho region, eastern Rio Piranhas-Seridó domain, Borborema Province (northeastern Brazil): implications for the stratigraphic model. *Journal of the Geological Survey of Brazil* 1, 11–29. <https://doi.org/10.29396/jgsb.2018.v1.n1.2>
- Cawood, P.A., Hawkesworth, C.J., Dhuime, B., 2013a. The continental record and the generation of continental crust. *Geol Soc Am Bull* 125, 14–32. <https://doi.org/10.1130/B30722.1>
- Cawood, P.A., Hawkesworth, C.J., Dhuime, B., 2012. Detrital zircon record and tectonic setting. *Geology* 40, 875–878. <https://doi.org/10.1130/G32945.1>
- Cawood, P.A., Kröner, A., Pisarevsky, S., 2006. Precambrian plate tectonics: Criteria and evidence. *GSA Today* 16, 4. <https://doi.org/10.1130/GSAT01607.1>
- Caxito, F. de A., Hagemann, S., Dias, T.G., Barrote, V., Dantas, E.L., Chaves, A. de O., Campello, M.S., Campos, F.C., 2020a. A magmatic barcode for the São Francisco Craton: Contextual in-situ SHRIMP U Pb baddeleyite and zircon dating of the Lavras, Pará de Minas and Formiga dyke swarms and implications for Columbia and Rodinia reconstructions. *Lithos* 374–375, 105708. <https://doi.org/10.1016/j.lithos.2020.105708>
- Caxito, F. de A., Santos, L.C.M. de L., Ganade, C.E., Bendaoud, A., Fettous, E.-H., Bouyo, M.H., 2020b. Toward an integrated model of geological evolution for NE Brazil-NW Africa: The Borborema Province

and its connections to the Trans-Saharan (Benino-Nigerian and Tuareg shields) and Central African orogens. *Brazilian Journal of Geology* 50. <https://doi.org/10.1590/2317-4889202020190122>

Chelle-Michou, C., McCarthy, A., Moyen, J.-F., Cawood, P.A., Capitanio, F.A., 2022. Make subductions diverse again. *Earth Sci Rev* 226, 103966. <https://doi.org/10.1016/j.earscirev.2022.103966>

Chen, J., Zou, Y., Chu, X., 2024. DIFFUSUP: A graphical user interface (GUI) software for diffusion modeling. *Applied Computing and Geosciences* 22, 100157. <https://doi.org/10.1016/j.acags.2024.100157>

Chen, K., Rudnick, R.L., Wang, Z., Tang, M., Gaschnig, R.M., Zou, Z., He, T., Hu, Z., Liu, Y., 2020. How mafic was the Archean upper continental crust? Insights from Cu and Ag in ancient glacial diamictites. *Geochim Cosmochim Acta* 278, 16–29. <https://doi.org/10.1016/j.gca.2019.08.002>

Cherniak, D.J., Watson, E.B., 2001. Pb diffusion in zircon. *Chem Geol* 172, 5–24. [https://doi.org/10.1016/S0009-2541\(00\)00233-3](https://doi.org/10.1016/S0009-2541(00)00233-3)

Chew, D.M., Babechuk, M.G., Cogné, N., Mark, C., O’Sullivan, G.J., Henrichs, I.A., Doepke, D., McKenna, C.A., 2016. (LA,Q)-ICPMS trace-element analyses of Durango and McClure Mountain apatite and implications for making natural LA-ICPMS mineral standards. *Chem Geol* 435, 35–48. <https://doi.org/10.1016/j.chemgeo.2016.03.028>

Chowdhury, P., Chakraborty, S., Gerya, T. V., 2021. Time will tell: Secular change in metamorphic timescales and the tectonic implications. *Gondwana Research* 93, 291–310. <https://doi.org/10.1016/j.gr.2021.02.003>

Chowdhury, P., Chakraborty, S., Gerya, T. V., Cawood, P.A., Capitanio, F.A., 2020. Peel-back controlled lithospheric convergence explains the secular transitions in Archean metamorphism and magmatism. *Earth Planet Sci Lett* 538, 116224. <https://doi.org/10.1016/j.epsl.2020.116224>

Chowdhury, P., Gerya, T., Chakraborty, S., 2017. Emergence of silicic continents as the lower crust peels off on a hot plate-tectonic Earth. *Nat Geosci* 10, 698–703. <https://doi.org/10.1038/ngeo3010>

Cioffi, C.R., Meira, V.T., Trindade, R.I.F., Lanari, P., Ganade, C.E., Gerdes, A., 2021. Long-lived intracontinental deformation associated with high geothermal gradients in the Seridó Belt (Borborema Province, Brazil). *Precambrian Res* 358, 106141. <https://doi.org/10.1016/j.precamres.2021.106141>

- Clark, C., Healy, D., Johnson, T., Collins, A.S., Taylor, R.J., Santosh, M., Timms, N.E., 2015. Hot orogens and supercontinent amalgamation: A Gondwanan example from southern India. *Gondwana Research* 28, 1310–1328. <https://doi.org/10.1016/j.gr.2014.11.005>
- Clarke, D.B., 2019. The Origins of Strongly Peraluminous Granitoid Rocks. *The Canadian Mineralogist* 57, 529–550. <https://doi.org/10.3749/canmin.1800075>
- Connolly, J.A.D., 1990. Multivariable phase diagrams; an algorithm based on generalized thermodynamics. *Am J Sci* 290, 666–718. <https://doi.org/10.2475/ajs.290.6.666>
- Corfu, F., 2003. Atlas of Zircon Textures. *Rev Mineral Geochem* 53, 469–500. <https://doi.org/10.2113/0530469>
- Corsini, M., de Figueiredo, L.L., Caby, R., Féraud, G., Ruffet, G., Vauchez, A., 1998. Thermal history of the Pan-African/Brasiliano Borborema Province of northeast Brazil deduced from $^{40}\text{Ar}/^{39}\text{Ar}$ analysis. *Tectonophysics* 285, 103–117. [https://doi.org/10.1016/S0040-1951\(97\)00192-3](https://doi.org/10.1016/S0040-1951(97)00192-3)
- Costa, F.G. da, Palheta, E.S. de M., Rodrigues, J.B., Gomes, I.P., Vasconcelos, A.M., 2015. Geochemistry and U–Pb zircon ages of plutonic rocks from the Algodões granite-greenstone terrane, Troia Massif, northern Borborema Province, Brazil: Implications for Paleoproterozoic subduction-accretion processes. *J South Am Earth Sci* 59, 45–68. <https://doi.org/10.1016/j.jsames.2015.01.007>
- Coutts, D.S., Matthews, W.A., Hubbard, S.M., 2019. Assessment of widely used methods to derive depositional ages from detrital zircon populations. *Geoscience Frontiers* 10, 1421–1435. <https://doi.org/10.1016/j.gsf.2018.11.002>
- Crisp, L.J., Berry, A.J., Burnham, A.D., Miller, L.A., Newville, M., 2023. The Ti-in-zircon thermometer revised: The effect of pressure on the Ti site in zircon. *Geochim Cosmochim Acta* 360, 241–258. <https://doi.org/10.1016/j.gca.2023.04.031>
- Cruz, R.F. da, Pimentel, M.M., Accioly, A.C. de A., Rodrigues, J.B., 2014. Geological and isotopic characteristics of granites from the Western Pernambuco-Alagoas Domain: implications for the crustal evolution of the Neoproterozoic Borborema Province. *Brazilian Journal of Geology* 44, 627–652. <https://doi.org/10.5327/Z23174889201400040008>

- Curvo, E.A.C., Hadler Neto, J.C., Iunes, P.J., Guedes, S.O., Tello Sáenz, C.A., Paulo, S.R., Hackspacher, P.C., Palissari, R., Moreira, P.A.F.P., 2005. On epidote fission track dating. *Radiat Meas* 39, 641–645. <https://doi.org/10.1016/j.radmeas.2004.06.016>
- Cutts, K.A., Stevens, G., Hoffmann, J.E., Buick, I.S., Frei, D., Munker, C., 2014. Paleo- to Mesoarchean polymetamorphism in the Barberton Granite-Greenstone Belt, South Africa: Constraints from U-Pb monazite and Lu-Hf garnet geochronology on the tectonic processes that shaped the belt. *Geol Soc Am Bull* 126, 251–270. <https://doi.org/10.1130/B30807.1>
- Dantas, E.L., 1996. Geocronologia U-Pb e Sm-Nd de terrenos arqueanos e paleoproterozóicos no maciço de Caldas Brandão, NE Brasil. UNESP, Rio Claro.
- Dantas, E.L., de Souza, Z.S., Wernick, E., Hackspacher, P.C., Martin, H., Xiaodong, D., Li, J.-W., 2013. Crustal growth in the 3.4–2.7Ga São José de Campestre Massif, Borborema Province, NE Brazil. *Precambrian Res* 227, 120–156. <https://doi.org/10.1016/j.precamres.2012.08.006>
- Dantas, E.L., Van Schmus, W.R., Hackspacher, P.C., Fetter, A.H., de Brito Neves, B.B., Cordani, U., Nutman, A.P., Williams, I.S., 2004. The 3.4–3.5 Ga São José do Campestre massif, NE Brazil: remnants of the oldest crust in South America. *Precambrian Res* 130, 113–137. <https://doi.org/10.1016/j.precamres.2003.11.002>
- Dasgupta, A., Bhowmik, S.K., Das, A., Bhandari, A., Ravindra Kumar, G.R., 2023. Paired metamorphism in peel back tectonics at the Archaean-Proterozoic boundary: New insights into Early Earth Plate tectonics from the Western Dharwar Craton, South India. *Earth Planet Sci Lett* 622, 118414. <https://doi.org/10.1016/j.epsl.2023.118414>
- Dasgupta, A., Bhowmik, S.K., Dasgupta, S.S., Ávila, J.N., Ireland, T.R., 2019. Mesoarchaeon clockwise metamorphic P-T path from the Western Dharwar Craton. *Lithos* 342–343, 370–390. <https://doi.org/10.1016/j.lithos.2019.06.006>
- de Capitani, C., Petrakakis, K., 2010. The computation of equilibrium assemblage diagrams with Theriak/Domino software. *American Mineralogist* 95, 1006–1016. <https://doi.org/10.2138/am.2010.3354>
- De Souza, Z.S., Martin, H., Peucat, J.-J., Jardim De Sá, E.F., Macedo, M.H.D.F., 2007. Calc-Alkaline Magmatism at the Archean–Proterozoic Transition: the Caicó Complex Basement (NE Brazil). *Journal of Petrology* 48, 2149–2185. <https://doi.org/10.1093/petrology/egm055>

- de Wit, M.J., 2004. Archean Greenstone Belts Do Contain Fragments of Ophiolites. pp. 599–614. [https://doi.org/10.1016/S0166-2635\(04\)13018-1](https://doi.org/10.1016/S0166-2635(04)13018-1)
- Degeling, H., Eggins, S., Ellis, D.J., 2001. Zr budgets for metamorphic reactions, and the formation of zircon from garnet breakdown. *Mineral Mag* 65, 749–758. <https://doi.org/10.1180/0026461016560006>
- Dhuime, B., Hawkesworth, C.J., Cawood, P.A., Storey, C.D., 2012. A Change in the Geodynamics of Continental Growth 3 Billion Years Ago. *Science* (1979) 335, 1334–1336. <https://doi.org/10.1126/science.1216066>
- Dhuime, B., Wuestefeld, A., Hawkesworth, C.J., 2015. Emergence of modern continental crust about 3 billion years ago. *Nat Geosci* 8, 552–555. <https://doi.org/10.1038/ngeo2466>
- Dias, A.N.C., Martins-Ferreira, M.A.C., Pereira, V.Q., Sales, A.S.W., Chemale, F., 2024. Insights into the Phanerozoic evolution of the São Francisco Craton based on detrital zircon thermochronology and U-Pb-Hf geochronology. *Geol Soc Am Bull* 136, 5109–5122. <https://doi.org/10.1130/B37281.1>
- Dickinson, W.R., Gehrels, G.E., 2009. Use of U–Pb ages of detrital zircons to infer maximum depositional ages of strata: A test against a Colorado Plateau Mesozoic database. *Earth Planet Sci Lett* 288, 115–125. <https://doi.org/10.1016/j.epsl.2009.09.013>
- Santos, E.J., Schmus, W.R. Van, Kozuch, M., Neves, B.B. de B., 2010. The Cariris Velhos tectonic event in Northeast Brazil. *J South Am Earth Sci* 29, 61–76. <https://doi.org/10.1016/j.jsames.2009.07.003>
- Santos, T.J.S., Amaral, W. da S., Ancelmi, M.F., Pitarello, M.Z., Fuck, R.A., Dantas, E.L., 2014. U–Pb age of the coesite-bearing eclogite from NW Borborema Province, NE Brazil: Implications for western Gondwana assembly. *Gondwana Research* 28, 1183–1196. <https://doi.org/10.1016/j.gr.2014.09.013>
- Drabon, N., Galić, A., Mason, P.R.D., Lowe, D.R., 2019. Provenance and tectonic implications of the 3.28–3.23 Ga Fig Tree Group, central Barberton greenstone belt, South Africa. *Precambrian Res* 325, 1–19. <https://doi.org/10.1016/j.precamres.2019.02.010>
- Drabon, N., Lowe, D.R., Byerly, G.R., Harrington, J.A., 2017. Detrital zircon geochronology of sandstones of the 3.6–3.2 Ga Barberton greenstone belt: No evidence for older continental crust. *Geology* 45, 803–806. <https://doi.org/10.1130/G39255.1>

- Dröllner, M., Barham, M., Kirkland, C.L., 2022. Gaining from loss: Detrital zircon source-normalized α -dose discriminates first- versus multi-cycle grain histories. *Earth Planet Sci Lett* 579, 117346. <https://doi.org/10.1016/j.epsl.2021.117346>
- Droop, G.T.R., 1987. A general equation for estimating Fe ³⁺ concentrations in ferromagnesian silicates and oxides from microprobe analyses, using stoichiometric criteria. *Mineral Mag* 51, 431–435. <https://doi.org/10.1180/minmag.1987.051.361.10>
- Engi, M., Lanari, P., Kohn, M.J., 2017. Significant Ages—An Introduction to Petrochronology. *Rev Mineral Geochem* 83, 1–12. <https://doi.org/10.2138/rmg.2017.83.1>
- Fan, M., Liu, X., Sun, S., Dong, Y., Ayers, J.C., Santosh, M., 2023. Effect of chemical composition on zircon radiation damage dating: Implications for low-temperature thermochronology. *Geoscience Frontiers* 14, 101675. <https://doi.org/10.1016/j.gsf.2023.101675>
- Farina, F., Dini, A., Davies, J.H.F.L., Ovtcharova, M., Greber, N.D., Bouvier, A.-S., Baumgartner, L., Ulianov, A., Schaltegger, U., 2018. Zircon petrochronology reveals the timescale and mechanism of anatectic magma formation. *Earth Planet Sci Lett* 495, 213–223. <https://doi.org/10.1016/j.epsl.2018.05.021>
- Ferreira, A. da C.D., Filho, C.F.F., Dantas, E.L., Souza, V. da S., 2019. Paleoproterozoic Mafic-Ultramafic Magmatism in the Northern Borborema Province, Northeast Brazil: Tectonic Setting and Potential for Deposits. *J Geol* 127, 483–504. <https://doi.org/10.1086/704256>
- Ferreira, A.C.D., Dantas, E.L., Fuck, R.A., 2021. The previously missing c. 2.9 Ga high-K continental crust in West Gondwana revealed in Northeast Brazil. *Terra Nova* 33, 184–194. <https://doi.org/10.1111/ter.12504>
- Fick, A., 1855. V. On liquid diffusion. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 10, 30–39. <https://doi.org/10.1080/14786445508641925>
- Figueiredo, B.S., 2012. Geoquímica e gênese das formações ferríferas e metacarbonatos da porção sul do Maciço São José do Campestre, Província Borborema (Master's Thesis). Universidade de Brasília, Instituto de Geociências, Brasília.

- Finch, R.J., Hanchar, J.M., Hoskin, P.W.O., Burns, P.C., 2001. Rare-earth elements in synthetic zircon: Part 2. A single-crystal X-ray study of xenotime substitution. *American Mineralogist* 86, 681–689. <https://doi.org/10.2138/am-2001-5-608>
- Flowers, R.M., Schmitt, A.K., Grove, M., 2010. Decoupling of U–Pb dates from chemical and crystallographic domains in granulite facies zircon. *Chem Geol* 270, 20–30. <https://doi.org/10.1016/j.chemgeo.2009.11.002>
- Teixeira, L.M.F., Troch, J., Bachmann, O., 2024. The dynamic nature of a TiO₂: Implications for Ti-based thermometers in magmatic systems. *Geology* 52, 92–96. <https://doi.org/10.1130/G51587.1>
- Fossen, H., Harris, L.B., Cavalcante, C., Archanjo, C.J., Ávila, C.F., 2022. The Patos-Pernambuco shear system of NE Brazil: Partitioned intracontinental transcurrent deformation revealed by enhanced aeromagnetic data. *J Struct Geol* 158, 104573. <https://doi.org/10.1016/j.jsg.2022.104573>
- Fox, D.C.M., Spinks, S.C., Barham, M., Kirkland, C.L., Pearce, M.A., Aspandiar, M., Birchall, R., Mead, E., 2021. Working up an Apatite: Enigmatic Mesoarchean Hydrothermal Cu-Co-Au Mineralization in the Pilbara Craton. *Economic Geology* 116, 1561–1573. <https://doi.org/10.5382/econgeo.4842>
- François, C., Debaille, V., Paquette, J.-L., Baudet, D., Javaux, E.J., 2018. The earliest evidence for modern-style plate tectonics recorded by HP–LT metamorphism in the Paleoproterozoic of the Democratic Republic of the Congo. *Sci Rep* 8, 15452. <https://doi.org/10.1038/s41598-018-33823-y>
- François, C., Philippot, P., Rey, P.F., Rubatto, D., 2014. Burial and exhumation during Archean sagduction in the East Pilbara Granite-Greenstone Terrane. *Earth Planet Sci Lett* 396, 235–251. <https://doi.org/10.1016/j.epsl.2014.04.025>
- Fraser, G., Ellis, D., Eggins, S., 1997. Zirconium abundance in granulite-facies minerals, with implications for zircon geochronology in high-grade rocks. *Geology* 25, 607. [https://doi.org/10.1130/0091-7613\(1997\)025<0607:ZAIGFM>2.3.CO;2](https://doi.org/10.1130/0091-7613(1997)025<0607:ZAIGFM>2.3.CO;2)
- Frost, C.D., Da Prat, F.A., 2021. Petrogenetic and tectonic interpretation of strongly peraluminous granitic rocks and their significance in the Archean rock record. *American Mineralogist* 106, 1195–1208. <https://doi.org/10.2138/am-2022-8001>

- Furnes, H., Dilek, Y., de Wit, M.J., 2015. Precambrian greenstone sequences represent different ophiolite types. *Gondwana Research* 27, 649–685. <https://doi.org/10.1016/j.gr.2013.06.004>
- Galbraith, R.F., Laslett, G.M., 1993. Statistical models for mixed fission track ages. *Nucl Tracks Radiat Meas* 21, 459–470. [https://doi.org/10.1016/1359-0189\(93\)90185-C](https://doi.org/10.1016/1359-0189(93)90185-C)
- Ganade, C.E., Basei, M.A.S., Grandjean, F.C., Armstrong, R., Brito, R.S., 2017. Contrasting Archaean (2.85–2.68 Ga) TTGs from the Tróia Massif (NE-Brazil) and their geodynamic implications for flat to steep subduction transition. *Precambrian Res* 297, 1–18. <https://doi.org/10.1016/j.precamres.2017.05.007>
- Ganade, C.E., Weinberg, R.F., Caxito, F.A., Lopes, L.B.L., Tesser, L.R., Costa, I.S., 2021. Decratonization by rifting enables orogenic reworking and transcurrent dispersal of old terranes in NE Brazil. *Sci Rep* 11, 5719. <https://doi.org/10.1038/s41598-021-84703-x>
- Ganade de Araujo, C.E., Rubatto, D., Hermann, J., Cordani, U.G., Caby, R., Basei, M.A.S., 2014a. Ediacaran 2,500-km-long synchronous deep continental subduction in the West Gondwana Orogen. *Nat Commun* 5, 5198. <https://doi.org/10.1038/ncomms6198>
- Ganade de Araujo, C.E., Weinberg, R.F., Cordani, U.G., 2013. Extruding the Borborema Province (NE-Brazil): a two-stage Neoproterozoic collision process. *Terra Nova* 26, 157–168. <https://doi.org/10.1111/ter.12084>
- Ganguly, J., Bhattacharya, R.N., Chakraborty, S., 1988. Convolution effect in the determination of composition profiles and diffusion coefficients by microprobe step scans. *American Mineralogist* 73, 901–909.
- Gao, L.-E., Zeng, L., Asimow, P.D., 2017. Contrasting geochemical signatures of fluid-absent versus fluid-fluxed melting of muscovite in metasedimentary sources: The Himalayan leucogranites. *Geology* 45, 39–42. <https://doi.org/10.1130/G38336.1>
- Gao, P., Zheng, Y., Zhao, Z., 2016. Experimental melts from crustal rocks: A lithochemical constraint on granite petrogenesis. *Lithos* 266–267, 133–157. <https://doi.org/10.1016/j.lithos.2016.10.005>
- Garber, J.M., Smye, A.J., Feineman, M.D., Kylander-Clark, A.R.C., Matthews, S., 2020. Decoupling of zircon U–Pb and trace-element systematics driven by U diffusion in eclogite-facies zircon (Monviso meta-

- ophiolite, W. Alps). *Contributions to Mineralogy and Petrology* 175, 55. <https://doi.org/10.1007/s00410-020-01692-2>
- Garcia, V.B., O'Neil, J., Dantas, E.L., 2023. Rare evidence for the existence of a Hadean enriched mantle reservoir. *Geochem Perspect Lett* 28, 1–6. <https://doi.org/10.7185/geochemlet.2336>
- Garçon, M., 2021. Episodic growth of felsic continents in the past 3.7 Ga. *Sci Adv* 7. <https://doi.org/10.1126/sciadv.abj1807>
- Garde, A.A., Whitehouse, M., Christensen, R., 2012. Mesoarchean Epithermal Gold Mineralization Preserved at Upper Amphibolite-Facies Grade, Qussuk, Southern West Greenland. *Economic Geology* 107, 881–908. <https://doi.org/10.2113/econgeo.107.5.881>
- Geisler, T., Schaltegger, U., Tomaschek, F., 2007. Re-equilibration of Zircon in Aqueous Fluids and Melts. *Elements* 3, 43–50. <https://doi.org/10.2113/gselements.3.1.43>
- Geisler, T., Ulonska, M., Schleicher, H., Pidgeon, R.T., van Bronswijk, W., 2001. Leaching and differential recrystallization of metamict zircon under experimental hydrothermal conditions. *Contributions to Mineralogy and Petrology* 141, 53–65. <https://doi.org/10.1007/s004100000202>
- Georgiev, D., Pedersen, S.V., Xie, R., Fernández-Galiana, Á., Stevens, M.M., Barahona, M., 2024. RamanSPy: An Open-Source Python Package for Integrative Raman Spectroscopy Data Analysis. *Anal Chem* 96, 8492–8500. <https://doi.org/10.1021/acs.analchem.4c00383>
- Gerya, T. V., Connolly, J.A.D., Yuen, D.A., 2008a. Why is terrestrial subduction one-sided? *Geology* 36, 43. <https://doi.org/10.1130/G24060A.1>
- Gibbs, J.W., 1878a. On the equilibrium of heterogeneous substances. *Am J Sci* s3-16, 441–458. <https://doi.org/10.2475/ajs.s3-16.96.441>
- Glassley, W.E., Korstgard, J.A., Sorensen, K., Platou, S.W., 2014. A new UHP metamorphic complex in the 1.8 Ga Nagssugtoqidian Orogen of West Greenland. *American Mineralogist* 99, 1315–1334. <https://doi.org/10.2138/am.2014.4726>
- Gonçalves, G.O., Lana, C., Scholz, R., Buick, I.S., Gerdes, A., Kamo, S.L., Corfu, F., Rubatto, D., Wiedenbeck, M., Nalini, H.A., Oliveira, L.C.A., 2018. The Diamantina Monazite: A New Low-Th Reference Material for Microanalysis. *Geostand Geoanal Res* 42, 25–47. <https://doi.org/10.1111/ggr.12192>

- Gordilho-Barbosa, R., Ferreira, A. da C.D., Leitzke, F.P., Cortez, Í. de M., Lana, C. de C., Conceição, R.V., Barbosa, J.S.F., Ribeiro, C.V.A., 2024. Paleo-to-Mesoarchean crustal evolution in the Uauá Block, Northeastern São Francisco Craton, Brazil: New insights from petrography, U–Pb geochronology, Lu–Hf isotopes and trace elements in zircon. *J South Am Earth Sci* 144, 105022. <https://doi.org/10.1016/j.jsames.2024.105022>
- Greber, N.D., Dauphas, N., Bekker, A., Ptáček, M.P., Bindeman, I.N., Hofmann, A., 2017. Titanium isotopic evidence for felsic crust and plate tectonics 3.5 billion years ago. *Science* (1979) 357, 1271–1274. <https://doi.org/10.1126/science.aan8086>
- Green, E.C.R., White, R.W., Diener, J.F.A., Powell, R., Holland, T.J.B., Palin, R.M., 2016. Activity–composition relations for the calculation of partial melting equilibria in metabasic rocks. *Journal of Metamorphic Geology* 34, 845–869. <https://doi.org/10.1111/jmg.12211>
- Greer, J., Caro, G., Cates, N.L., Tropper, P., Bleeker, W., Kelly, N.M., Mojzsis, S.J., 2020. Widespread poly-metamorphosed Archean granitoid gneisses and supracrustal enclaves of the southern Inukjuak Domain, Québec (Canada). *Lithos* 364–365, 105520. <https://doi.org/10.1016/j.lithos.2020.105520>
- Guevara, V.E., Caddick, M.J., Dragovic, B., 2017. Rapid high-T decompression recorded by Archean granulites in the northern Wyoming Province: Insights from petrological modelling. *Journal of Metamorphic Geology* 35, 943–965. <https://doi.org/10.1111/jmg.12262>
- Hacker, B.R., Christie, J.M., 1990. Brittle/ductile and plastic/cataclastic transitions in experimentally deformed and metamorphosed amphibolite. pp. 127–147. <https://doi.org/10.1029/GM056p0127>
- Hacker, B.R., Kelemen, P.B., Behn, M.D., 2011. Differentiation of the continental crust by relamination. *Earth Planet Sci Lett* 307, 501–516. <https://doi.org/10.1016/j.epsl.2011.05.024>
- Hallett, B.W., Spear, F.S., 2011. Insight into the cooling history of the Valhalla complex, British Columbia. *Lithos* 125, 809–824. <https://doi.org/10.1016/j.lithos.2011.05.002>
- Hamilton, W.B., 2011. Plate tectonics began in Neoproterozoic time, and plumes from deep mantle have never operated. *Lithos* 123, 1–20. <https://doi.org/10.1016/j.lithos.2010.12.007>
- Harley, S.L., 2008. Refining the P–T records of UHT crustal metamorphism. *Journal of Metamorphic Geology* 26, 125–154. <https://doi.org/10.1111/j.1525-1314.2008.00765.x>

- Harris, N., Massey, J., Inger, S., 1993. The role of fluids in the formation of High Himalayan leucogranites. *Geological Society, London, Special Publications* 74, 391–400. <https://doi.org/10.1144/GSL.SP.1993.074.01.26>
- Harris, N., Vance, D., Ayres, M., 2000. From sediment to granite: timescales of anatexis in the upper crust. *Chem Geol* 162, 155–167. [https://doi.org/10.1016/S0009-2541\(99\)00121-7](https://doi.org/10.1016/S0009-2541(99)00121-7)
- Harrison, T.M., 2024. We don't know when plate tectonics began. *J Geol Soc London* 181. <https://doi.org/10.1144/jgs2023-212>
- Harrison, T.M., Lenardic, A., 2022. Burke's Law: Toward a Reasoned Discussion of Deep Time. *Elements* 18, 354–355. <https://doi.org/10.2138/gselements.18.5.354>
- Härtel, B., Enkelmann, E., 2024a. The daughter–parent plot: a tool for analyzing thermochronological data. *Geochronology* 6, 429–448. <https://doi.org/10.5194/gchron-6-429-2024>
- Härtel, B., Enkelmann, E., Jonckheere, R., Ludwig, T., Krause, J., Ratschbacher, L., 2024b. In search of lost time: Raman thermochronology of FC-1 zircon. *Contributions to Mineralogy and Petrology* 179, 2. <https://doi.org/10.1007/s00410-023-02083-z>
- Härtel, B., Jonckheere, R., Krause, J., Ratschbacher, L., 2022. Spurious age-eU associations in thermochronological data. *Earth Planet Sci Lett* 599, 117870. <https://doi.org/10.1016/j.epsl.2022.117870>
- Härtel, B., Jonckheere, R., Wauschkuhn, B., Hofmann, M., Frölich, S., Ratschbacher, L., 2021a. Zircon Raman dating: Age equation and calibration. *Chem Geol* 579, 120351. <https://doi.org/10.1016/j.chemgeo.2021.120351>
- Härtel, B., Jonckheere, R., Wauschkuhn, B., Ratschbacher, L., 2021b. The closure temperature(s) of zircon Raman dating. *Geochronology* 3, 259–272. <https://doi.org/10.5194/gchron-3-259-2021>
- Hasterok, D., Halpin, J.A., Collins, A.S., Hand, M., Kreemer, C., Gard, M.G., Glorie, S., 2022a. New Maps of Global Geological Provinces and Tectonic Plates. *Earth Sci Rev* 231, 104069. <https://doi.org/10.1016/j.earscirev.2022.104069>
- Hawkesworth, C.J., Kemp, A.I.S., 2006. Evolution of the continental crust. *Nature* 443, 811–817. <https://doi.org/10.1038/nature05191>

- Hay, D.C., Dempster, T.J., 2009. Zircon Behaviour during Low-temperature Metamorphism. *Journal of Petrology* 50, 571–589. <https://doi.org/10.1093/petrology/egp011>
- Henry, D.J., Guidotti, C. V., Thomson, J.A., 2005. The Ti-saturation surface for low-to-medium pressure metapelitic biotites: Implications for geothermometry and Ti-substitution mechanisms. *American Mineralogist* 90, 316–328. <https://doi.org/10.2138/am.2005.1498>
- Herrmann, M., Söderlund, U., Scherstén, A., Næraa, T., Holm-Alwmark, S., Alwmark, C., 2021. The effect of low-temperature annealing on discordance of U–Pb zircon ages. *Sci Rep* 11, 7079. <https://doi.org/10.1038/s41598-021-86449-y>
- Heubeck, C., Engelhardt, J., Byerly, G.R., Zeh, A., Sell, B., Lubert, T., Lowe, D.R., 2013. Timing of deposition and deformation of the Moodies Group (Barberton Greenstone Belt, South Africa): Very-high-resolution of Archaean surface processes. *Precambrian Res* 231, 236–262. <https://doi.org/10.1016/j.precamres.2013.03.021>
- Hillenbrand, I.W., Gilmer, A.K., Souders, A.K., Bindeman, I., 2024. Geochemical and geochronologic evidence for a contiguous northeastern Wyoming Province. *Precambrian Res* 407, 107419. <https://doi.org/10.1016/j.precamres.2024.107419>
- Holland, T., Powell, R., 2003. Activity?composition relations for phases in petrological calculations: an asymmetric multicomponent formulation. *Contributions to Mineralogy and Petrology* 145, 492–501. <https://doi.org/10.1007/s00410-003-0464-z>
- Holland, T.J.B., Powell, R., 2011. An improved and extended internally consistent thermodynamic dataset for phases of petrological interest, involving a new equation of state for solids. *Journal of Metamorphic Geology* 29, 333–383. <https://doi.org/10.1111/j.1525-1314.2010.00923.x>
- Holland, T.J.B., Powell, R., 1998. An internally consistent thermodynamic data set for phases of petrological interest. *Journal of Metamorphic Geology* 16, 309–343. <https://doi.org/10.1111/j.1525-1314.1998.00140.x>
- Homann, M., 2019. Earliest life on Earth: Evidence from the Barberton Greenstone Belt, South Africa. *Earth Sci Rev* 196, 102888. <https://doi.org/10.1016/j.earscirev.2019.102888>

- Hopkins, M., Harrison, T.M., Manning, C.E., 2008. Low heat flow inferred from 4 Gyr zircons suggests Hadean plate boundary interactions. *Nature* 456, 493–496. <https://doi.org/10.1038/nature07465>
- Horie, K., Hidaka, H., Gauthier-Lafaye, F., 2006. Elemental distribution in zircon: Alteration and radiation-damage effects. *Physics and Chemistry of the Earth, Parts A/B/C* 31, 587–592. <https://doi.org/10.1016/j.pce.2006.01.001>
- Horstwood, M.S.A., Košler, J., Gehrels, G., Jackson, S.E., McLean, N.M., Paton, C., Pearson, N.J., Sircombe, K., Sylvester, P., Vermeesch, P., Bowring, J.F., Condon, D.J., Schoene, B., 2016. Community-Derived Standards for LA-ICP-MS U-(Th)-Pb Geochronology – Uncertainty Propagation, Age Interpretation and Data Reporting. *Geostand Geoanal Res* 40, 311–332. <https://doi.org/10.1111/j.1751-908X.2016.00379.x>
- Hoskin, P.W.O., Black, L.P., 2000. Metamorphic zircon formation by solid-state recrystallization of protolith igneous zircon. *Journal of Metamorphic Geology* 18, 423–439. <https://doi.org/10.1046/j.1525-1314.2000.00266.x>
- Huang, G., Chen, Y., Guo, J., Palin, R., Zhao, L., 2022. Nb and Ta intracrustal differentiation during granulite-facies metamorphism: Evidence from geochemical data of natural rocks and thermodynamic modeling. *American Mineralogist* 107, 2020–2033. <https://doi.org/10.2138/am-2022-8260>
- Huang, G., Liu, H., Guo, J., Palin, R.M., Zou, L., Cui, W., 2024. Partial melting mechanisms of peraluminous felsic magmatism in a collisional orogen: An example from the Khondalite belt, North China craton. *Journal of Metamorphic Geology* 42, 817–841. <https://doi.org/10.1111/jmg.12774>
- Huang, H., Polat, A., Fryer, B.J., 2013. Origin of Archean tonalite–trondhjemite–granodiorite (TTG) suites and granites in the Fiskenæsset region, southern West Greenland: Implications for continental growth. *Gondwana Research* 23, 452–470. <https://doi.org/10.1016/j.gr.2011.12.001>
- Hueck, M., Dunkl, I., Heller, B., Stipp Basei, M.A., Siegesmund, S., 2018. (U-Th)/He Thermochronology and Zircon Radiation Damage in the South American Passive Margin: Thermal Overprint of the Paraná LIP? *Tectonics* 37, 4068–4085. <https://doi.org/10.1029/2018TC005041>
- Inger, S., Harris, N., 1993. Geochemical Constraints on Leucogranite Magmatism in the Langtang Valley, Nepal Himalaya. *Journal of Petrology* 34, 345–368. <https://doi.org/10.1093/petrology/34.2.345>

- Jackson, S.E., Pearson, N.J., Griffin, W.L., Belousova, E.A., 2004. The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon geochronology. *Chem Geol* 211, 47–69. <https://doi.org/10.1016/j.chemgeo.2004.06.017>
- Jahn, B., Caby, R., Monie, P., 2001. The oldest UHP eclogites of the World: age of UHP metamorphism, nature of protoliths and tectonic implications. *Chem Geol* 178, 143–158. [https://doi.org/10.1016/S0009-2541\(01\)00264-9](https://doi.org/10.1016/S0009-2541(01)00264-9)
- Janoušek, V., Farrow, C.M., Erban, V., 2024a. GCDkit.Mineral: A customizable, platform-independent R-language environment for recalculation, plotting, and classification of electron probe microanalyses of common rock-forming minerals. *American Mineralogist* 109, 1598–1607. <https://doi.org/10.2138/am-2023-9032>
- Jesus, B.A. de, 2011. Rochas máficas e ultramáficas do complexo riacho da telha, Maçico São José do Campestre, província Borborema – NE do Brasil. Instituto de Geociências, Brasília.
- Jiao, S., Brown, M., Mitchell, R.N., Chowdhury, P., Clark, C., Chen, L., Chen, Y., Korhonen, F., Huang, G., Guo, J., 2023. Mechanisms to generate ultrahigh-temperature metamorphism. *Nat Rev Earth Environ* 4, 298–318. <https://doi.org/10.1038/s43017-023-00403-2>
- Jochum, K.P., Weis, U., Schwager, B., Stoll, B., Wilson, S.A., Haug, G.H., Andreae, M.O., Enzweiler, J., 2016. Reference Values Following ISO Guidelines for Frequently Requested Rock Reference Materials. *Geostand Geoanal Res* 40, 333–350. <https://doi.org/10.1111/j.1751-908X.2015.00392.x>
- Johnson, T., Yakymchuk, C., Brown, M., 2021. Crustal melting and suprasolidus phase equilibria: From first principles to the state-of-the-art. *Earth Sci Rev* 221, 103778. <https://doi.org/10.1016/j.earscirev.2021.103778>
- Jonckheere, R., Heinz, D., Hacker, B.R., Rafaja, D., Ratschbacher, L., 2019. A borehole investigation of zircon radiation damage annealing. *Terra Nova* 31, 263–270. <https://doi.org/10.1111/ter.12395>
- Jung, S., Hellebrand, E.W.G., 2006. Trace element fractionation during high-grade metamorphism and crustal melting—constraints from ion microprobe data of metapelitic, migmatitic and igneous garnets and implications for Sm–Nd garnet chronology. *Lithos* 87, 193–213. <https://doi.org/10.1016/j.lithos.2005.06.013>

- Kaempf, J., Johnson, T.E., Clark, C., Alfing, J., Brown, M., Lanari, P., Rankenburg, K., 2024. Paleoproterozoic metamorphism in the Acasta Gneiss Complex: Constraints from phase equilibrium modelling and in situ garnet Lu–Hf geochronology. *Journal of Metamorphic Geology* 42, 373–394. <https://doi.org/10.1111/jmg.12759>
- Kelsey, D.E., Hand, M., 2015. On ultrahigh temperature crustal metamorphism: Phase equilibria, trace element thermometry, bulk composition, heat sources, timescales and tectonic settings. *Geoscience Frontiers* 6, 311–356. <https://doi.org/10.1016/j.gsf.2014.09.006>
- Khelen, A.C., Manikyamba, C., Tang, L., Santosh, M., Subramanyam, K.S.V., Singh, T.D., 2020. Detrital zircon U–Pb geochronology of stromatolitic carbonates from the greenstone belts of Dharwar Craton and Cuddapah basin of Peninsular India. *Geoscience Frontiers* 11, 229–242. <https://doi.org/10.1016/j.gsf.2019.04.010>
- Kirkland, C.L., Hartnady, M.I.H., Barham, M., Olierook, H.K.H., Steenfelt, A., Hollis, J.A., 2021. Widespread reworking of Hadean-to-Eoarchean continents during Earth’s thermal peak. *Nat Commun* 12, 331. <https://doi.org/10.1038/s41467-020-20514-4>
- Kock, M.O. de, Evans, D.A.D., Beukes, N.J., 2009. Validating the existence of Vaalbara in the Neoproterozoic. *Precambrian Res* 174, 145–154. <https://doi.org/10.1016/j.precamres.2009.07.002>
- Kohn, M.J., 2020. A refined zirconium-in-rutile thermometer. *American Mineralogist* 105, 963–971. <https://doi.org/10.2138/am-2020-7091>
- Kohn, M.J., Corrie, S.L., Markley, C., 2015. The fall and rise of metamorphic zircon. *American Mineralogist* 100, 897–908. <https://doi.org/10.2138/am-2015-5064>
- Kohn, M.J., Penniston-Dorland, S.C., 2017. Diffusion: Obstacles and Opportunities in Petrochronology. *Rev Mineral Geochem* 83, 103–152. <https://doi.org/10.2138/rmg.2017.83.4>
- Komiya, T., Maruyama, S., Masuda, T., Nohda, S., Hayashi, M., Okamoto, K., 1999. Plate Tectonics at 3.8–3.7 Ga: Field Evidence from the Isua Accretionary Complex, Southern West Greenland. *J Geol* 107, 515–554. <https://doi.org/10.1086/314371>

- Kröner, A., 2007. Chapter 5.2 The Ancient Gneiss Complex of Swaziland and Environs: Record of Early Archean Crustal Evolution in Southern Africa. pp. 465–480. [https://doi.org/10.1016/S0166-2635\(07\)15052-0](https://doi.org/10.1016/S0166-2635(07)15052-0)
- Kröner, A., Wan, Y., Liu, X., Liu, D., 2014. Dating of zircon from high-grade rocks: Which is the most reliable method? *Geoscience Frontiers* 5, 515–523. <https://doi.org/10.1016/j.gsf.2014.03.012>
- Kunz, B.E., Regis, D., Engi, M., 2018. Zircon ages in granulite facies rocks: decoupling from geochemistry above 850 °C? *Contributions to Mineralogy and Petrology* 173, 26. <https://doi.org/10.1007/s00410-018-1454-5>
- Kuper, K.M., Armstrong, R., Kirkland, C.L., Olierook, H.K.H., Clark, C., Evans, K., 2024. Implications of high-grade metamorphism on detrital zircon data sets: A case study from the Fraser Zone, Western Australia. *Chem Geol* 647, 121918. <https://doi.org/10.1016/j.chemgeo.2023.121918>
- Kusky, T., Windley, B.F., Polat, A., Wang, L., Ning, W., Zhong, Y., 2021. Archean dome-and-basin style structures form during growth and death of intraoceanic and continental margin arcs in accretionary orogens. *Earth Sci Rev* 220, 103725. <https://doi.org/10.1016/j.earscirev.2021.103725>
- Lafuente, B., Downs, R.T., Yang, H., Stone, N., 2015. 1. The power of databases: The RRUFF project, in: *Highlights in Mineralogical Crystallography*. DE GRUYTER, pp. 1–30. <https://doi.org/10.1515/9783110417104-003>
- Lages, G.A., Montefalco de Lira Santos, L.C., Brasilino, R.G., Rodrigues, J.B., Dantas, E.L., 2019. Statherian-Calymmian (ca. 1.6 Ga) magmatism in the Alto Moxotó Terrane, Borborema Province, northeast Brazil: Implications for within-plate and coeval collisional tectonics in West Gondwana. *J South Am Earth Sci* 91, 116–130. <https://doi.org/10.1016/j.jsames.2019.02.003>
- Lanari, P., Hermann, J., 2021. Iterative thermodynamic modelling—Part 2: Tracing equilibrium relationships between minerals in metamorphic rocks. *Journal of Metamorphic Geology* 39, 651–674. <https://doi.org/10.1111/jmg.12575>
- Lanari, P., Vho, A., Bovay, T., Airaghi, L., Centrella, S., 2019. Quantitative compositional mapping of mineral phases by electron probe micro-analyser. *Geological Society, London, Special Publications* 478, 39–63. <https://doi.org/10.1144/SP478.4>

- Lanari, P., Vidal, O., De Andrade, V., Dubacq, B., Lewin, E., Grosch, E.G., Schwartz, S., 2014. XMapTools: A MATLAB®-based program for electron microprobe X-ray image processing and geothermobarometry. *Comput Geosci* 62, 227–240. <https://doi.org/10.1016/j.cageo.2013.08.010>
- Laurent, A.T., Bingen, B., Duchene, S., Whitehouse, M.J., Seydoux-Guillaume, A., Bosse, V., 2018. Decoding a protracted zircon geochronological record in ultrahigh temperature granulite, and persistence of partial melting in the crust, Rogaland, Norway. *Contributions to Mineralogy and Petrology* 173, 29. <https://doi.org/10.1007/s00410-018-1455-4>
- Laurent, O., Martin, H., Moyen, J.F., Doucelance, R., 2014. The diversity and evolution of late-Archean granitoids: Evidence for the onset of “modern-style” plate tectonics between 3.0 and 2.5Ga. *Lithos* 205, 208–235. <https://doi.org/10.1016/j.lithos.2014.06.012>
- Li, X., Zhang, L., Wei, C., Bader, T., Guo, J., 2023. Cold subduction recorded by the 1.9 Ga Salma eclogite in Belomorian Province (Russia). *Earth Planet Sci Lett* 602, 117930. <https://doi.org/10.1016/j.epsl.2022.117930>
- Lin, S., 2005. Synchronous vertical and horizontal tectonism in the Neoarchean: Kinematic evidence from a synclinal keel in the northwestern Superior craton, Canada. *Precambrian Res* 139, 181–194. <https://doi.org/10.1016/j.precamres.2005.07.001>
- Lira Santos, L.C.M. de, Almeida Lages, G. de, Lima, H.M., Araújo Neto, J.F. de, Santos, G.L., Paixão, M.S. da, 2022a. An overview on the Rhyacian–Orosirian (ca. 2.1–2.0 Ga) granitic magmatism of the Alto Moxotó Terrane and its implications for the crustal evolution of the Borborema Province, NE Brazil. *Journal of Iberian Geology* 48, 225–239. <https://doi.org/10.1007/s41513-022-00191-6>
- Lira Santos, L.C.M. de, de Almeida Lages, G., Lima, H.M., de Araújo Neto, J.F., Santos, G.L., da Paixão, M.S., 2022b. An overview on the Rhyacian–Orosirian (ca. 2.1–2.0 Ga) granitic magmatism of the Alto Moxotó Terrane and its implications for the crustal evolution of the Borborema Province, NE Brazil. *Journal of Iberian Geology* 48, 225–239. <https://doi.org/10.1007/s41513-022-00191-6>
- Liu, Y., Mitchell, R.N., Li, Z.-X., Kirscher, U., Pisarevsky, S.A., Wang, C., 2021. Archean geodynamics: Ephemeral supercontinents or long-lived supercratons. *Geology* 49, 794–798. <https://doi.org/10.1130/G48575.1>

- Loucks, R.R., Fiorentini, M.L., Henríquez, G.J., 2020. New Magmatic Oxybarometer Using Trace Elements in Zircon. *Journal of Petrology* 61. <https://doi.org/10.1093/petrology/egaa034>
- Markwitz, V., Kirkland, C.L., 2018. Source to sink zircon grain shape: Constraints on selective preservation and significance for Western Australian Proterozoic basin provenance. *Geoscience Frontiers* 9, 415–430. <https://doi.org/10.1016/j.gsf.2017.04.004>
- Marschall, H.R., Hawkesworth, C.J., Storey, C.D., Dhuime, B., Leat, P.T., Meyer, H.-P., Tamm-Buckle, S., 2010. The Annandagstoppane Granite, East Antarctica: Evidence for Archaean Intracrustal Recycling in the Kaapvaal-Grunehogna Craton from Zircon O and Hf Isotopes. *Journal of Petrology* 51, 2277–2301. <https://doi.org/10.1093/petrology/egq057>
- Martins, G., Oliveira, E.P., Lafon, J.-M., 2009. The Algodões amphibolite–tonalite gneiss sequence, Borborema Province, NE Brazil: Geochemical and geochronological evidence for Palaeoproterozoic accretion of oceanic plateau/back-arc basalts and adakitic plutons. *Gondwana Research* 15, 71–85. <https://doi.org/10.1016/j.gr.2008.06.002>
- Maruyama, S., Santosh, M., Azuma, S., 2018. Initiation of plate tectonics in the Hadean: Eclogitization triggered by the ABEL Bombardment. *Geoscience Frontiers* 9, 1033–1048. <https://doi.org/10.1016/j.gsf.2016.11.009>
- Mayne, M.J., Moyen, J., Stevens, G., Kaislaniemi, L., 2016. Rcrust: a tool for calculating path-dependent open system processes and application to melt loss. *Journal of Metamorphic Geology* 34, 663–682. <https://doi.org/10.1111/jmg.12199>
- Mazoz, A., Gonçalves, G.O., Lana, C., Buick, I.S., McSwiggen, P.L., Corfu, F., Kamo, S.L., Fu, B., Wang, H., Moreira, H., Scholz, R., Martins, L., Peixoto, E., Dantas, E.L., Santos, R.V., 2024. Vermilion monazite: A new Archean reference material for U-Pb and Sm-Nd microanalysis. *Chem Geol* 658, 122121. <https://doi.org/10.1016/j.chemgeo.2024.122121>
- McLennan, S.M., Bock, B., Hemming, S.R., Hurowitz, J.A., Lev, S.M., McDaniel, D.K., 2003. The Roles of Provenance Sedimentary Processes in the Geochemistry of Sedimentary Rocks, in: Lentz, D.R. (Ed.), *Geochemistry of Sediments and Sedimentary Rocks: Evolutionary Considerations to Mineral Deposit-Forming Environments*. Geological Association of Canada, Toronto, pp. 7–31.

- McLennan, S.M., Taylor, S.R., McGregor, V.R., 1984. Geochemistry of Archean metasedimentary rocks from West Greenland. *Geochim Cosmochim Acta* 48, 1–13. [https://doi.org/10.1016/0016-7037\(84\)90345-4](https://doi.org/10.1016/0016-7037(84)90345-4)
- Medeiros, V.C. de, 2004. Evolução geodinâmica e condicionamento estrutural dos terrenos Piancó-Alto Brígida e Alto Pajeú, domínio da zona transversal, NE do Brasil (Doctorate Thesis). Universidade Federal do Rio Grande do Norte, Natal.
- Mezger, Klaus., Krogstad, E.J., 1997. Interpretation of discordant U-Pb zircon ages: An evaluation. *Journal of Metamorphic Geology* 15, 127–140. <https://doi.org/10.1111/j.1525-1314.1997.00008.x>
- Montel, J.-M., 1993. A model for monazite/melt equilibrium and application to the generation of granitic magmas. *Chem Geol* 110, 127–146. [https://doi.org/10.1016/0009-2541\(93\)90250-M](https://doi.org/10.1016/0009-2541(93)90250-M)
- Moreira, H., Buzenchi, A., Hawkesworth, C.J., Dhuime, B., 2023. Plumbing the depths of magma crystallization using $^{176}\text{Lu}/^{177}\text{Hf}$ in zircon as a pressure proxy. *Geology* 51, 233–237. <https://doi.org/10.1130/G50659.1>
- Moresi, L., Solomatov, V., 1998. Mantle convection with a brittle lithosphere: thoughts on the global tectonic styles of the Earth and Venus. *Geophys J Int* 133, 669–682. <https://doi.org/10.1046/j.1365-246X.1998.00521.x>
- Morris, G.A., Kirkland, C.L., Pease, V., 2015. Orogenic paleofluid flow recorded by discordant detrital zircons in the Caledonian foreland basin of northern Greenland. *Lithosphere* 7, 138–143. <https://doi.org/10.1130/L420.1>
- Moyen, J.-F., Laurent, O., 2018. Archaean tectonic systems: A view from igneous rocks. *Lithos* 302–303, 99–125. <https://doi.org/10.1016/j.lithos.2017.11.038>
- Murakami, T., Chakoumakos, B.C., Ewing, R.C., Lumpkin, G.R., Weber, W.J., 1991. Alpha-decay event damage in zircon. *American Mineralogist* 76, 1510–1532.
- Nance, R.D., Murphy, J.B., Santosh, M., 2014. The supercontinent cycle: A retrospective essay. *Gondwana Research* 25, 4–29. <https://doi.org/10.1016/j.gr.2012.12.026>
- Nandi, A., Mukherjee, S., Sorcar, N., Vadlamani, R., 2023. Relict Mesoarchean (2.99–2.94 Ga) metamorphism overprinted by late Neoarchean tectonothermal event(s) from the Sukma Group supracrustal

- rocks, Bastar craton, India: Evidence from new Lu-Hf and Sm-Nd garnet isochron and Th-U-total Pb monazite ages. *Precambrian Res* 390, 107056. <https://doi.org/10.1016/j.precamres.2023.107056>
- Nasdala, L., Lengauer, C.L., Hanchar, J.M., Kronz, A., Wirth, R., Blanc, P., Kennedy, A.K., Seydoux-Guillaume, A.-M., 2002. Annealing radiation damage and the recovery of cathodoluminescence. *Chem Geol* 191, 121–140. [https://doi.org/10.1016/S0009-2541\(02\)00152-3](https://doi.org/10.1016/S0009-2541(02)00152-3)
- Nasdala, L., Pidgeon, R.T., Wolf, D., 1996. Heterogeneous metamictization of zircon on a microscale. *Geochim Cosmochim Acta* 60, 1091–1097. [https://doi.org/10.1016/0016-7037\(95\)00454-8](https://doi.org/10.1016/0016-7037(95)00454-8)
- Nasdala, L., Wenzel, M., Vavra, G., Irmer, G., Wenzel, T., Kober, B., 2001. Metamictisation of natural zircon: accumulation versus thermal annealing of radioactivity-induced damage. *Contributions to Mineralogy and Petrology* 141, 125–144. <https://doi.org/10.1007/s004100000235>
- Nash, W.P., Crecraft, H.R., 1985. Partition coefficients for trace elements in silicic magmas. *Geochim Cosmochim Acta* 49, 2309–2322. [https://doi.org/10.1016/0016-7037\(85\)90231-5](https://doi.org/10.1016/0016-7037(85)90231-5)
- Nebel, O., Capitanio, F.A., Moyen, J.-F., Weinberg, R.F., Clos, F., Nebel-Jacobsen, Y.J., Cawood, P.A., 2018. When crust comes of age: on the chemical evolution of Archaean, felsic continental crust by crustal drip tectonics. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376, 20180103. <https://doi.org/10.1098/rsta.2018.0103>
- Nebel-Jacobsen, Y., Nebel, O., Wille, M., Cawood, P.A., 2018. A non-zircon Hf isotope record in Archean black shales from the Pilbara craton confirms changing crustal dynamics ca. 3 Ga ago. *Sci Rep* 8, 922. <https://doi.org/10.1038/s41598-018-19397-9>
- Nemchin, A.A., Cawood, P.A., 2005. Discordance of the U–Pb system in detrital zircons: Implication for provenance studies of sedimentary rocks. *Sediment Geol* 182, 143–162. <https://doi.org/10.1016/j.sedgeo.2005.07.011>
- Nemchin, A.A., Giannini, L.M., Bodorkos, S., Oliver, N.H.S., 2001. Ostwald ripening as a possible mechanism for zircon overgrowth formation during anatexis: theoretical constraints, a numerical model, and its application to pelitic migmatites of the Tickalara Metamorphics, northwestern Australia. *Geochim Cosmochim Acta* 65, 2771–2788. [https://doi.org/10.1016/S0016-7037\(01\)00622-6](https://doi.org/10.1016/S0016-7037(01)00622-6)

Neuendorf, K.K.E., Mehl Jr, J.P., Jackson, J.A., 2008. Glossary of Geology, 5th ed. American Geosciences Institute. <https://doi.org/10.1017/S0016756807004141>

Neves, S.P., 2021. Comparative geological evolution of the Borborema Province and São Francisco Craton (eastern Brazil): Decratonization and crustal reworking during West Gondwana assembly and implications for paleogeographic reconstructions. *Precambrian Res* 355, 106119. <https://doi.org/10.1016/j.precamres.2021.106119>

Neves, S.P., 2015. Constraints from zircon geochronology on the tectonic evolution of the Borborema Province (NE Brazil): Widespread intracontinental Neoproterozoic reworking of a Paleoproterozoic accretionary orogen. *J South Am Earth Sci* 58, 150–164. <https://doi.org/10.1016/j.jsames.2014.08.004>

Neves, S.P., 2011. Atlantica revisited: new data and thoughts on the formation and evolution of a long-lived continent. *Int Geol Rev* 53, 1377–1391. <https://doi.org/10.1080/00206814.2010.527676>

Neves, S.P., Bezerra, J.P.S., Bruguier, O., França, R.H.M., 2021. Evidence for Early Tonian (Ca. 1000-940 Ma) continental rifting in southern Borborema Province (NE Brazil): tectonic inheritance and shear zone nucleation during assembly of West Gondwana. *Int Geol Rev* 63, 851–865. <https://doi.org/10.1080/00206814.2020.1734877>

Neves, S.P., Lages, G.A., Brasilino, R.G., Miranda, A.W.A., 2015. Paleoproterozoic accretionary and collisional processes and the build-up of the Borborema Province (NE Brazil): Geochronological and geochemical evidence from the Central Domain. *J South Am Earth Sci* 58, 165–187. <https://doi.org/10.1016/j.jsames.2014.06.009>

Nutman, A.P., Friend, C.R.L., Bennett, V.C., 2002. Evidence for 3650–3600 Ma assembly of the northern end of the Itsaq Gneiss Complex, Greenland: Implication for early Archaean tectonics. *Tectonics* 21. <https://doi.org/10.1029/2000TC001203>

Nyström, A.I., Kriegsman, L.M., 2003. Prograde and retrograde reactions, garnet zoning patterns, and accessory phase behaviour in SW Finland migmatites, with implications for geochronology. *Geological Society, London, Special Publications* 220, 213–230. <https://doi.org/10.1144/GSL.SP.2003.220.01.13>

Ogawa, M., 2008. Mantle convection: A review. *Fluid Dyn Res* 40, 379–398. <https://doi.org/10.1016/j.fluidyn.2007.09.001>

- Ohta, T., Arai, H., 2007. Statistical empirical index of chemical weathering in igneous rocks: A new tool for evaluating the degree of weathering. *Chem Geol* 240, 280–297. <https://doi.org/10.1016/j.chemgeo.2007.02.017>
- Olierook, H.K.H., Kirkland, C.L., Barham, M., Daggitt, M.L., Hollis, J., Hartnady, M., 2021. Extracting meaningful U-Pb ages from core-rim mixtures. *Gondwana Research* 92, 102–112. <https://doi.org/10.1016/j.gr.2020.12.021>
- Oliveira, E.P., Talavera, C., Windley, B.F., Zhao, L., Semprich, J.J., McNaughton, N.J., Amaral, W.S., Sombini, G., Navarro, M., Silva, D., 2019. Mesoarchaean (2820 Ma) high-pressure mafic granulite at Uauá, São Francisco Craton, Brazil, and its potential significance for the assembly of Archaean supercratons. *Precambrian Res* 331, 105366. <https://doi.org/10.1016/j.precamres.2019.105366>
- Oliveira, E.P., Windley, B.F., Araújo, M.N.C., 2010. The Neoproterozoic Sergipano orogenic belt, NE Brazil: A complete plate tectonic cycle in western Gondwana. *Precambrian Res* 181, 64–84. <https://doi.org/10.1016/j.precamres.2010.05.014>
- O'Neill, C.J., Jellinek, M.A., Lenardic, A., 2007. Conditions for the onset of plate tectonics on terrestrial planets and moons. *Earth Planet Sci Lett* 261, 20–32. <https://doi.org/10.1016/j.epsl.2007.05.038>
- Palin, R.M., Santosh, M.W., Cao, W., Li, S.-S., Hernández-Urbe, D., Parsons, A., 2020. Secular change and the onset of plate tectonics on Earth. *Earth Sci Rev* 207, 103172. <https://doi.org/10.1016/j.earscirev.2020.103172>
- Paton, C., Hellstrom, J., Paul, B., Woodhead, J., Hergt, J., 2011. Iolite: Freeware for the visualisation and processing of mass spectrometric data. *J Anal At Spectrom* 26, 2508. <https://doi.org/10.1039/c1ja10172b>
- Perchuk, A.L., Safonov, O.G., Smit, C.A., van Reenen, D.D., Zakharov, V.S., Gerya, T. V., 2018. Precambrian ultra-hot orogenic factory: Making and reworking of continental crust. *Tectonophysics* 746, 572–586. <https://doi.org/10.1016/j.tecto.2016.11.041>
- Perchuk, L.L., 2009. Derivation of a thermodynamically consistent set of geothermometers and geobarometers for metamorphic and magmatic rocks, in: Perchuk, L.L. (Ed.), *Progress in Metamorphic and Magmatic Petrology: A Memorial Volume in Honour of D. S. Korzhinskiy*. Cambridge University Press, pp. 93–112.

- Petrus, J.A., Kamber, B.S., 2012. VizualAge: A Novel Approach to Laser Ablation ICP-MS U-Pb Geochronology Data Reduction. *Geostand Geoanal Res* 36, 247–270. <https://doi.org/10.1111/j.1751-908X.2012.00158.x>
- Piazolo, S., Belousova, E., La Fontaine, A., Corcoran, C., Cairney, J.M., 2017. Trace element homogeneity from micron- to atomic scale: Implication for the suitability of the zircon GJ-1 as a trace element reference material. *Chem Geol* 456, 10–18. <https://doi.org/10.1016/j.chemgeo.2017.03.001>
- Pichavant, M., Erdmann, S., Kontak, D.J., Michaud, J.A.-S., Villaros, A., 2024. Trace element partitioning in strongly peraluminous rare-metal silicic magmas – Implications for fractionation processes and for the origin of the Macusani Volcanics (SE Peru). *Geochim Cosmochim Acta* 365, 229–252. <https://doi.org/10.1016/j.gca.2023.11.021>
- Pidgeon, R.T., 2014. Zircon radiation damage ages. *Chem Geol* 367, 13–22. <https://doi.org/10.1016/j.chemgeo.2013.12.010>
- Pidgeon, R.T., 1992. Recrystallisation of oscillatory zoned zircon: some geochronological and petrological implications. *Contributions to Mineralogy and Petrology* 110, 463–472. <https://doi.org/10.1007/BF00344081>
- Pidgeon, R.T., Nemchin, A.A., Hitchen, G.J., 1998. Internal structures of zircons from Archaean granites from the Darling Range batholith: implications for zircon stability and the interpretation of zircon U-Pb ages. *Contributions to Mineralogy and Petrology* 132, 288–299. <https://doi.org/10.1007/s004100050422>
- Pidgeon, R.T., Nemchin, A.A., Roberts, M.P., Guagliardo, P., Fougereuse, D., 2023. Reliability of petrogenetic information obtained from the distribution of trace elements in zircon in light of the complex infusion by foreign-element-bearing low temperature solutions. *Chem Geol* 621, 121357. <https://doi.org/10.1016/j.chemgeo.2023.121357>
- Pidgeon, R.T., Nemchin, A.A., Roberts, M.P., Whitehouse, M.J., Bellucci, J.J., 2019. The accumulation of non-formula elements in zircons during weathering: Ancient zircons from the Jack Hills, Western Australia. *Chem Geol* 530, 119310. <https://doi.org/10.1016/j.chemgeo.2019.119310>
- Pidgeon, R.T., Nemchin, A.A., Whitehouse, M.J., 2017. The effect of weathering on U–Th–Pb and oxygen isotope systems of ancient zircons from the Jack Hills, Western Australia. *Geochim Cosmochim Acta* 197, 142–166. <https://doi.org/10.1016/j.gca.2016.10.005>

- Polat, A., Hofmann, A.W., Rosing, M.T., 2002. Boninite-like volcanic rocks in the 3.7–3.8 Ga Isua greenstone belt, West Greenland: geochemical evidence for intra-oceanic subduction zone processes in the early Earth. *Chem Geol* 184, 231–254. [https://doi.org/10.1016/S0009-2541\(01\)00363-1](https://doi.org/10.1016/S0009-2541(01)00363-1)
- Powell, R., Holland, T., Worley, B., 1998. Calculating phase diagrams involving solid solutions via non-linear equations, with examples using THERMOCALC. *Journal of Metamorphic Geology* 16, 577–588. <https://doi.org/10.1111/j.1525-1314.1998.00157.x>
- Ptáček, M.P., Dauphas, N., Greber, N.D., 2020. Chemical evolution of the continental crust from a data-driven inversion of terrigenous sediment compositions. *Earth Planet Sci Lett* 539, 116090. <https://doi.org/10.1016/j.epsl.2020.116090>
- Puetz, S.J., Ganade, C.E., Zimmermann, U., Borchardt, G., 2018. Statistical analyses of Global U-Pb Database 2017. *Geoscience Frontiers* 9, 121–145. <https://doi.org/10.1016/j.gsf.2017.06.001>
- Puetz, S.J., Spencer, C.J., Ganade, C.E., 2021. Analyses from a validated global U Pb detrital zircon database: Enhanced methods for filtering discordant U Pb zircon analyses and optimizing crystallization age estimates. *Earth Sci Rev* 220, 103745. <https://doi.org/10.1016/j.earscirev.2021.103745>
- Pupin, J.-P., 1980. Zircon and granite petrology. *Contributions to Mineralogy and Petrology* 73, 207–220. <https://doi.org/10.1007/BF00381441>
- Qi, Y., Jiao, S., Chen, L., Liu, J., Liu, Y., Guo, J., 2024. Heating–cooling–heating cycles within ca. 70 Myr recorded in UHT granulites in the Khondalite Belt, North China Craton. *Precambrian Res* 411, 107508. <https://doi.org/10.1016/j.precamres.2024.107508>
- Rapp, R.P., Irifune, T., Shimizu, N., Nishiyama, N., Norman, M.D., Inoue, T., 2008. Subduction recycling of continental sediments and the origin of geochemically enriched reservoirs in the deep mantle. *Earth Planet Sci Lett* 271, 14–23. <https://doi.org/10.1016/j.epsl.2008.02.028>
- Rapp, R.P., Watson, E.B., 1986. Monazite solubility and dissolution kinetics: implications for the thorium and light rare earth chemistry of felsic magmas. *Contributions to Mineralogy and Petrology* 94, 304–316. <https://doi.org/10.1007/BF00371439>
- Reimink, J.R., Chacko, T., Stern, R.A., Heaman, L.M., 2014. Earth’s earliest evolved crust generated in an Iceland-like setting. *Nat Geosci* 7, 529–533. <https://doi.org/10.1038/ngeo2170>

- Reimink, J.R., Davies, J.H.F.L., Waldron, J.W.F., Rojas, X., 2016. Dealing with discordance: a novel approach for analysing U–Pb detrital zircon datasets. *J Geol Soc London* 173, 577–585. <https://doi.org/10.1144/jgs2015-114>
- Reiners, P.W., Farley, K.A., Hickes, H.J., 2002. He diffusion and (U–Th)/He thermochronometry of zircon: initial results from Fish Canyon Tuff and Gold Butte. *Tectonophysics* 349, 297–308. [https://doi.org/10.1016/S0040-1951\(02\)00058-6](https://doi.org/10.1016/S0040-1951(02)00058-6)
- Rey, P.F., Coltice, N., Flament, N., 2024. Archean Geodynamics Underneath Weak, Flat, and Flooded Continents. *Elements* 20, 180–186. <https://doi.org/10.2138/gselements.20.3.180>
- Ribeiro, C.V.A., 2019. Evolução estrutural e metamórfica da porção sul do Domínio São José do Campestre, Província Borborema, NE do Brasil: do Arqueano ao Neoproterozoico (Undergraduate Monograph). Universidade Federal do Rio Grande do Norte, CCET.
- Ribeiro, C.V.A., Dantas, E.L., Fuck, R.A., 2024. Paleoarchean sedimentation and Mesoarchean high-temperature metamorphism in northeastern Brazil: Tracing sources and depositional ages in polymetamorphic rocks. *Lithos* 478–479, 107641. <https://doi.org/10.1016/j.lithos.2024.107641>
- Ribeiro, Carlos V. A., Dantas, E.L., Fuck, R.A., 2025a. Effects of high temperature annealing and low temperature metamictization on Archean zircon: constraints from U–Pb isotopes, trace elements and Raman dating. *American Mineralogist*. <https://doi.org/10.2138/am-2024-9502>
- Ribeiro, C.V.A., Sales, M.C.C., de Oliveira, A.L.S., Sallet, R., 2023. Linking sedimentary provenance, climate and tectonics in the Neoproterozoic Seridó Belt, Borborema Province (NE Brazil). *Geoscience Frontiers* 14, 101681. <https://doi.org/10.1016/j.gsf.2023.101681>
- Roberts, N.M.W., Spencer, C.J., Puetz, S., Keller, C.B., Tapster, S., 2024. Regional trends and petrologic factors inhibit global interpretations of zircon trace element compositions. *Geoscience Frontiers* 15, 101852. <https://doi.org/10.1016/j.gsf.2024.101852>
- Robin, C.M.I., Bailey, R.C., 2009. Simultaneous generation of Archean crust and subcratonic roots by vertical tectonics. *Geology* 37, 523–526. <https://doi.org/10.1130/G25519A.1>
- Rogers, J.J.W., 1996. A History of Continents in the past Three Billion Years. *J Geol* 104, 91–107. <https://doi.org/10.1086/629803>

- Rogers, J.J.W., Santosh, M.W., 2003. Supercontinents in Earth History. *Gondwana Research* 6, 357–368. [https://doi.org/10.1016/S1342-937X\(05\)70993-X](https://doi.org/10.1016/S1342-937X(05)70993-X)
- Roig, H.L., Dantas, E.L., 2013. Carta geológica: folha São José do Campestre. Folha SB.25-Y-A-I São José do Campestre: carta geológica - escala 1:100.000. [Brasília]. CPRM.
- Rosa, M. de L. da S., Conceição, J.A. da, Marinho, M.M., Pereira, F. dos S., Conceição, H., 2020. U-Pb SHRIMP dating of the Itabaiana Dome: a Mesoarchean basement inlier (2.83 Ga) in the Sergipano Orogenic System, Borborema Province. *Brazilian Journal of Geology* 50. <https://doi.org/10.1590/2317-4889202020190106>
- Rosenberg, C.L., Handy, M.R., 2005. Experimental deformation of partially melted granite revisited: implications for the continental crust. *Journal of Metamorphic Geology* 23, 19–28. <https://doi.org/10.1111/j.1525-1314.2005.00555.x>
- Rubatto, D., 2017. Zircon: The Metamorphic Mineral. *Rev Mineral Geochem* 83, 261–295. <https://doi.org/10.2138/rmg.2017.83.9>
- Rudnick, R.L., Gao, S., 2003. Composition of the Continental Crust, in: *Treatise on Geochemistry*. Elsevier, pp. 1–64. <https://doi.org/10.1016/B0-08-043751-6/03016-4>
- Rutter, E.H., Peach, C.J., White, S.H., Johnston, D.C., 1985. Experimental ‘syntectonic’ hydration of basalt. *J Struct Geol* 7, 251–266. [https://doi.org/10.1016/0191-8141\(85\)90136-1](https://doi.org/10.1016/0191-8141(85)90136-1)
- Sá, J.M., McReath, I., Leterrier, J., 1995. Petrology, geochemistry and geodynamic setting of Proterozoic igneous suites of the Orós fold belt (Borborema Province, Northeast Brazil). *J South Am Earth Sci* 8, 299–314. [https://doi.org/10.1016/0895-9811\(95\)00015-8](https://doi.org/10.1016/0895-9811(95)00015-8)
- Sallet, R., Price, J.D., Babinski, M., Moritz, R., Souza, Z.S., Chiaradia, M., 2015. Experimental anatexis, fluorine geochemistry and lead-isotope constraints on granite petrogenesis in the Seridó Belt, Borborema Province, northeastern Brazil. *Chem Geol* 400, 122–148. <https://doi.org/10.1016/j.chemgeo.2015.02.011>
- Sallet, R., Price, J.D., Ribeiro, C., Hollanda, M.H.B.M., Sayeg, I.J., Harlov, D., 2023. Fluorine behavior during experimental muscovite dehydration melting and natural partitioning between micas: Implications for the petrogenesis of peraluminous leucogranites and pegmatites. *American Mineralogist* 108, 1201–1212. <https://doi.org/10.2138/am-2022-8663>

- Salminen, J.M., Oliveira, E.P., Piispa, E.J., Smirnov, A. V., Trindade, R.I.F., 2019. Revisiting the paleomagnetism of the Neoproterozoic Uauá mafic dyke swarm, Brazil: Implications for Archean supercratons. *Precambrian Res* 329, 108–123. <https://doi.org/10.1016/j.precamres.2018.12.001>
- Santos, F.G., Cavalcanti Neto, M.T.O., Ferreira, V.P., Bertotti, A.L., 2020. Early to Paleoproterozoic metamafic-ultramafic rocks from the central portion of the Rio Grande do Norte Domain, Borborema Province, northeast Brazil: The oldest South American platform rocks. *J South Am Earth Sci* 97, 102410. <https://doi.org/10.1016/j.jsames.2019.102410>
- Santos, L.C.M. de L., Dantas, E.L., Cawood, P.A., José dos Santos, E., Fuck, R.A., 2017a. Neoproterozoic crustal growth and Paleoproterozoic reworking in the Borborema Province, NE Brazil: Insights from geochemical and isotopic data of TTG and metagranitic rocks of the Alto Moxotó Terrane. *J South Am Earth Sci* 79, 342–363. <https://doi.org/10.1016/j.jsames.2017.08.013>
- Santos, L.C.M. de L., Dantas, E.L., Santos, E.J. dos, Santos, R.V., Lima, H.M., 2015. Early to Late Paleoproterozoic magmatism in NE Brazil: The Alto Moxotó Terrane and its tectonic implications for the Pre-West Gondwana assembly. *J South Am Earth Sci* 58, 188–209. <https://doi.org/10.1016/j.jsames.2014.07.006>
- Santos, M.M., Lana, C., Scholz, R., Buick, I., Schmitz, M.D., Kamo, S.L., Gerdes, A., Corfu, F., Tapster, S., Lancaster, P., Storey, C.D., Basei, M.A.S., Tohver, E., Alkmim, A., Nalini, H., Krambrock, K., Fantini, C., Wiedenbeck, M., 2017b. A New Appraisal of Sri Lankan BB Zircon as a Reference Material for LA-ICP-MS U-Pb Geochronology and Lu-Hf Isotope Tracing. *Geostand Geoanal Res* 41, 335–358. <https://doi.org/10.1111/ggr.12167>
- Savko, K.A., Samsonov, A. V., Larionov, A.N., Chervyakovskaya, M. V., Korish, E.H., Larionova, Y.O., Bazikov, N.S., Tsybulyaev, S. V., 2021. A buried Paleoproterozoic core of the Eastern Sarmatia, Kursk block: U-Pb, Lu-Hf and Sm-Nd isotope mapping and paleotectonic application. *Precambrian Res* 353, 106021. <https://doi.org/10.1016/j.precamres.2020.106021>
- Scaillet, B., Pichavant, M., 2024. Himalayan Leucogranites: An Experimental Petrology Perspective. *Elements* 20, 388–394. <https://doi.org/10.2138/gselements.20.6.388>
- Schaltegger, U., Fanning, C.M., Günther, D., Maurin, J.C., Schulmann, K., Gebauer, D., 1999. Growth, annealing and recrystallization of zircon and preservation of monazite in high-grade metamorphism:

conventional and in-situ U-Pb isotope, cathodoluminescence and microchemical evidence. *Contributions to Mineralogy and Petrology* 134, 186–201. <https://doi.org/10.1007/s004100050478>

Seydoux-Guillaume, A.-M., Bingen, B., Paquette, J.-L., Bosse, V., 2015. Nanoscale evidence for uranium mobility in zircon and the discordance of U–Pb chronometers. *Earth Planet Sci Lett* 409, 43–48. <https://doi.org/10.1016/j.epsl.2014.10.044>

Shang, S., Lin, Y., van Westrenen, W., Brouwer, F.M., 2024. Evolution of magma compositions and phosphorus availability in early Earth’s crust: New constraints from zircon-melt partitioning experiments. *Geology* 52, 794–798. <https://doi.org/10.1130/G52304.1>

Shi, G., Shen, C., Wauschkuhn, B., Härtel, B., Ratschbacher, L., Xia, B., Ge, X., Zeng, X., Fu, H., 2023. A zircon classification scheme for sedimentary provenance analysis using radiation damage. *Geological Journal* 58, 3087–3095. <https://doi.org/10.1002/gj.4751>

Shirey, S.B., Kamber, B.S., Whitehouse, M.J., Mueller, P.A., Basu, A.R., 2008. A review of the isotopic and trace element evidence for mantle and crustal processes in the Hadean and Archean: Implications for the onset of plate tectonic subduction, in: *Special Paper 440: When Did Plate Tectonics Begin on Planet Earth?* Geological Society of America, pp. 1–29. [https://doi.org/10.1130/2008.2440\(01\)](https://doi.org/10.1130/2008.2440(01))

Silva Filho, C.V.R. da, 2012. *Isótopos De Nd Aplicados À Datação Direta De Formações Ferríferas Paleoarqueanas Do Maciço São José Do Campestre, Rio Grande Do Norte-RN* (Master’s Thesis). Universidade de Brasília, Instituto de Geociências, Brasília.

Sircombe, K.N., Stern, R.A., 2002. An investigation of artificial biasing in detrital zircon U-Pb geochronology due to magnetic separation in sample preparation. *Geochim Cosmochim Acta* 66, 2379–2397. [https://doi.org/10.1016/S0016-7037\(02\)00839-6](https://doi.org/10.1016/S0016-7037(02)00839-6)

Sisson, T.W., Bacon, C.R., 1992. Garnet/high-silica rhyolite trace element partition coefficients measured by ion microprobe. *Geochim Cosmochim Acta* 56, 2133–2136. [https://doi.org/10.1016/0016-7037\(92\)90336-H](https://doi.org/10.1016/0016-7037(92)90336-H)

Sizova, E., Gerya, T., Brown, M., Stüwe, K., 2018. What drives metamorphism in early Archean greenstone belts? Insights from numerical modeling. *Tectonophysics* 746, 587–601. <https://doi.org/10.1016/j.tecto.2017.07.020>

- Sláma, J., Košler, J., Condon, D.J., Crowley, J.L., Gerdes, A., Hanchar, J.M., Horstwood, M.S.A., Morris, G.A., Nasdala, L., Norberg, N., Schaltegger, U., Schoene, B., Tubrett, M.N., Whitehouse, M.J., 2008. Plešovice zircon — A new natural reference material for U–Pb and Hf isotopic microanalysis. *Chem Geol* 249, 1–35. <https://doi.org/10.1016/j.chemgeo.2007.11.005>
- Smirnov, A. V., Evans, D.A.D., Ernst, R.E., Söderlund, U., Li, Z.-X., 2013. Trading partners: Tectonic ancestry of southern Africa and western Australia, in Archean supercratons Vaalbara and Zimgarn. *Precambrian Res* 224, 11–22. <https://doi.org/10.1016/j.precamres.2012.09.020>
- Smit, M.A., Scherer, E.E., Mezger, K., 2013. Peak metamorphic temperatures from cation diffusion zoning in garnet. *Journal of Metamorphic Geology* 31, 339–358. <https://doi.org/10.1111/jmg.12024>
- Smithies, R.H., Van Kranendonk, M.J., Champion, D.C., 2007. The Mesoarchean emergence of modern-style subduction. *Gondwana Research* 11, 50–68. <https://doi.org/10.1016/j.gr.2006.02.001>
- Sotiriou, P., Polat, A., Windley, B., Kusky, T., 2023. Temporal variations in the incompatible trace element systematics of Archean TTGs: Implications for crustal growth and tectonic processes in the early Earth. *Earth Sci Rev* 236, 104274. <https://doi.org/10.1016/j.earscirev.2022.104274>
- Souza, Z.S. de, Dantas, E.L., Oliveira, E.P., Vilalva, F.C.J., Motta, R.G. da, Martin, H., Valcácio, S. do N., 2023. Zircon U-Pb dating and petrogenesis of the São José do Campestre Granite Complex, NE Brazil: an example of neoarchean mantle-derived post-collisional magmatism. *Brazilian Journal of Geology* 53. <https://doi.org/10.1590/2317-4889202320220079>
- Souza, Z.S. de, Kalsbeek, F., Deng, X.-D., Frei, R., Kokfelt, T.F., Dantas, E.L., Li, J.-W., Pimentel, M.M., Galindo, A.C., 2016. Generation of continental crust in the northern part of the Borborema Province, northeastern Brazil, from Archaean to Neoproterozoic. *J South Am Earth Sci* 68, 68–96. <https://doi.org/10.1016/j.jsames.2015.10.006>
- Souza, Z.S. de, Montel, J.-M., Gioia, S.M.L.C., Maia de Hollanda, M.H.B., Leite do Nascimento, M.A., Jardim de Sá, E.F., Amaro, V.E., Pimentel, M.M., Lardeaux, J.-M., Veschambre, M., 2006. Electron microprobe dating of monazite from high-T shear zones in the São José de Campestre Massif, NE Brazil. *Gondwana Research* 9, 441–455. <https://doi.org/10.1016/j.gr.2005.11.008>
- Souza, Z.S., Vasconcelos, P.M., Nascimento, M.A.L., Silveira, F.V., 2003. $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of Mesozoic and Cenozoic magmatism in NE Brazil. IV South American Symposium on Isotope Geology.

- Spear, F.S., 2014. The duration of near-peak metamorphism from diffusion modelling of garnet zoning. *Journal of Metamorphic Geology* 32, 903–914. <https://doi.org/10.1111/jmg.12099>
- Spear, F.S., 2004. Fast Cooling and Exhumation of the Valhalla Metamorphic Core Complex, Southeastern British Columbia. *Int Geol Rev* 46, 193–209. <https://doi.org/10.2747/0020-6814.46.3.193>
- Spencer, C.J., 2020. Continuous continental growth as constrained by the sedimentary record. *Am J Sci* 320, 373–401. <https://doi.org/10.2475/04.2020.02>
- Spencer, C.J., Kirkland, C.L., Taylor, R.J.M., 2016. Strategies towards statistically robust interpretations of in situ U–Pb zircon geochronology. *Geoscience Frontiers* 7, 581–589. <https://doi.org/10.1016/j.gsf.2015.11.006>
- Steiger, R.H., Jäger, E., 1977. Subcommittee on geochronology: Convention on the use of decay constants in geo- and cosmochemistry. *Earth Planet Sci Lett* 36, 359–362. [https://doi.org/10.1016/0012-821X\(77\)90060-7](https://doi.org/10.1016/0012-821X(77)90060-7)
- Stepanov, A.S., Allen, C.M., Jiang, S.-Y., Zhukova, I.A., Duan, D.-F., Wang, L., 2024. Geochemistry of metasedimentary restitic rocks and implications for melting conditions and metal potential of crustal felsic magmas. *Earth Sci Rev* 254, 104799. <https://doi.org/10.1016/j.earscirev.2024.104799>
- Stepanov, A.S., Hermann, J., Rubatto, D., Rapp, R.P., 2012. Experimental study of monazite/melt partitioning with implications for the REE, Th and U geochemistry of crustal rocks. *Chem Geol* 300–301, 200–220. <https://doi.org/10.1016/j.chemgeo.2012.01.007>
- Stern, R.J., 2005. Evidence from ophiolites, blueschists, and ultrahigh-pressure metamorphic terranes that the modern episode of subduction tectonics began in Neoproterozoic time. *Geology* 33, 557. <https://doi.org/10.1130/G21365.1>
- Stern, R.J., 2002. SUBDUCTION ZONES. *Reviews of Geophysics* 40. <https://doi.org/10.1029/2001RG000108>
- Stern, R.J., Gerya, T., Tackley, P.J., 2018. Stagnant lid tectonics: Perspectives from silicate planets, dwarf planets, large moons, and large asteroids. *Geoscience Frontiers* 9, 103–119. <https://doi.org/10.1016/j.gsf.2017.06.004>

- Suhr, N., Hoffmann, J.E., Kröner, A., Schröder, S., 2015. Archaean granulite-facies paragneisses from central Swaziland: inferences on Palaeoarchaean crustal reworking and a complex metamorphic history. *J Geol Soc London* 172, 139–152. <https://doi.org/10.1144/jgs2014-007>
- Tang, M., Chen, K., Rudnick, R.L., 2016. Archean upper crust transition from mafic to felsic marks the onset of plate tectonics. *Science* (1979) 351, 372–375. <https://doi.org/10.1126/science.aad5513>
- Tang, M., Chu, X., Hao, J., Shen, B., 2021. Orogenic quiescence in Earth's middle age. *Science* (1979) 371, 728–731. <https://doi.org/10.1126/science.abf1876>
- Tavazzani, L., Peres, S., Sinigoi, S., Demarchi, G., Economos, R.C., Quick, J.E., 2020. Timescales and Mechanisms of Crystal-mush Rejuvenation and Melt Extraction Recorded in Permian Plutonic and Volcanic Rocks of the Sesia Magmatic System (Southern Alps, Italy). *Journal of Petrology* 61. <https://doi.org/10.1093/petrology/egaa049>
- Taylor, J., Stevens, G., Buick, I.S., Lana, C.C., 2012. Successive midcrustal, high-grade metamorphic events provide insight into Mid-Archean mountain-building along the SE margin of the proto-Kaapvaal craton. *Geol Soc Am Bull* 124, 1191–1211. <https://doi.org/10.1130/B30543.1>
- Taylor, S.R., McLennan, S.M., 1995. The geochemical evolution of the continental crust. *Reviews of Geophysics* 33, 241–265. <https://doi.org/10.1029/95RG00262>
- Taylor, S.R., Rudnick, R.L., McLennan, S.M., Eriksson, K.A., 1986. Rare earth element patterns in Archean high-grade metasediments and their tectonic significance. *Geochim Cosmochim Acta* 50, 2267–2279. [https://doi.org/10.1016/0016-7037\(86\)90081-5](https://doi.org/10.1016/0016-7037(86)90081-5)
- Tedeschi, M., Leonardo Rossi Vieira, P., Kuchenbecker, M., Ribeiro, B. V., Barrote, V., Reis, H., Stutenbecker, L., Lana, C., Pedrosa-Soares, A., Dussin, I., 2023. Unravelling the protracted U-Pb zircon geochronological record of high to ultrahigh temperature metamorphic rocks: Implications for provenance investigations. *Geoscience Frontiers* 14, 101515. <https://doi.org/10.1016/j.gsf.2022.101515>
- Teles, G., Chemale, F., de Oliveira, C.G., 2015. Paleoarchean record of the detrital pyrite-bearing, Jacobina Au–U deposits, Bahia, Brazil. *Precambrian Res* 256, 289–313. <https://doi.org/10.1016/j.precamres.2014.11.004>

- Teles, G.S., Chemale, F., Ávila, J.N., Ireland, T.R., 2022. The Paleoproterozoic Northern Mundo Novo Greenstone Belt, São Francisco Craton: Geochemistry, U–Pb–Hf–O in zircon and pyrite $\delta^{34}\text{S}$ – $\Delta^{33}\text{S}$ – $\Delta^{36}\text{S}$ signatures. *Geoscience Frontiers* 13, 101252. <https://doi.org/10.1016/j.gsf.2021.101252>
- Teng, F.-Z., Wu, F.-Y., 2024. Himalayan Leucogranites: Petrogenesis and Significance. *Elements* 20, 367–372. <https://doi.org/10.2138/gselements.20.6.367>
- Thébaud, N.J.M., Rey, P.F., 2013. Archean gravity-driven tectonics on hot and flooded continents: Controls on long-lived mineralised hydrothermal systems away from continental margins. *Precambrian Res* 229, 93–104. <https://doi.org/10.1016/j.precamres.2012.03.001>
- Thompson, A.B., 1976. Mineral reactions in pelitic rocks; I, Prediction of P–T–X(Fe–Mg) phase relations. *Am J Sci* 276, 401–424. <https://doi.org/10.2475/ajs.276.4.401>
- Tichomirowa, M., Whitehouse, M.J., Nasdala, L., 2005. Resorption, growth, solid state recrystallisation, and annealing of granulite facies zircon—a case study from the Central Erzgebirge, Bohemian Massif. *Lithos* 82, 25–50. <https://doi.org/10.1016/j.lithos.2004.12.005>
- Tomkins, A.G., Mavrogenes, J.A., 2002. Mobilization of Gold as a Polymetallic Melt during Pelite Anatexis at the Challenger Deposit, South Australia: A Metamorphosed Archean Gold Deposit. *Economic Geology* 97, 1249–1271. <https://doi.org/10.2113/gsecongeo.97.6.1249>
- Touret, J.L.R., Santosh, M.W., Huizenga, J.M., 2022. Composition and evolution of the continental crust: Retrospect and prospect. *Geoscience Frontiers* 13, 101428. <https://doi.org/10.1016/j.gsf.2022.101428>
- Trompette, R., 1997. Neoproterozoic (~600 Ma) aggregation of Western Gondwana: a tentative scenario. *Precambrian Res* 82, 101–112. [https://doi.org/10.1016/S0301-9268\(96\)00045-9](https://doi.org/10.1016/S0301-9268(96)00045-9)
- Trumbull, R.B., 1993. A petrological and Rb–Sr isotopic study of an early Archean fertile granite-pegmatite system: The Sinceni Pluton in Swaziland. *Precambrian Res* 61, 89–116. [https://doi.org/10.1016/0301-9268\(93\)90059-B](https://doi.org/10.1016/0301-9268(93)90059-B)
- Tucker, N.M., Hammerli, J., Kemp, A.I.S., Rowe, M.L., Gray, C.M., Jeon, H., Whitehouse, M.J., Roberts, M.P., 2024. Ultrahigh thermal gradient granulites in the Narryer Terrane, Yilgarn Craton, Western Australia, provide a window into the composition and formation of Archean lower crust. *Journal of Metamorphic Geology* 42, 425–470. <https://doi.org/10.1111/jmg.12752>

- Turner, S., Wilde, S., Wörner, G., Schaefer, B., Lai, Y.-J., 2020. An andesitic source for Jack Hills zircon supports onset of plate tectonics in the Hadean. *Nat Commun* 11, 1241. <https://doi.org/10.1038/s41467-020-14857-1>
- Tuttle, L., Henry, D.J., 2023. Metamorphic P – T paths of Archean granulite facies metasedimentary lithologies from the eastern Beartooth Mountains of the northern Wyoming Province, Montana, USA: constraints from quartz-in-garnet (QuiG) Raman elastic barometry, geothermobarometry, and thermodynamic modeling. *European Journal of Mineralogy* 35, 499–522. <https://doi.org/10.5194/ejm-35-499-2023>
- Váczi, T., 2014. A New, Simple Approximation for the Deconvolution of Instrumental Broadening in Spectroscopic Band Profiles. *Appl Spectrosc* 68, 1274–1278. <https://doi.org/10.1366/13-07275>
- Van Kranendonk, M.J., Hugh Smithies, R., Hickman, A.H., Champion, D.C., 2007. Review: secular tectonic evolution of Archean continental crust: interplay between horizontal and vertical processes in the formation of the Pilbara Craton, Australia. *Terra Nova* 19, 1–38. <https://doi.org/10.1111/j.1365-3121.2006.00723.x>
- Van Schmus, W.R., de Brito Neves, B.B., Hackspacher, P., Babinski, M., 1995. and geochronologic studies of the eastern Borborema Province, Northeastern Brazil: initial conclusions. *J South Am Earth Sci* 8, 267–288. [https://doi.org/10.1016/0895-9811\(95\)00013-6](https://doi.org/10.1016/0895-9811(95)00013-6)
- Van Schmus, W.R., de Brito Neves, B.B., Williams, I.S., Hackspacher, P.C., Fetter, A.H., Dantas, E.L., Babinski, M., 2003. The Seridó Group of NE Brazil, a late Neoproterozoic pre- to syn-collisional basin in West Gondwana: insights from SHRIMP U–Pb detrital zircon ages and Sm–Nd crustal residence (TDM) ages. *Precambrian Res* 127, 287–327. [https://doi.org/10.1016/S0301-9268\(03\)00197-9](https://doi.org/10.1016/S0301-9268(03)00197-9)
- Van Schmus, W.R., Oliveira, E.P., da Silva Filho, A.F., Toteu, S.F., Penaye, J., Guimarães, I.P., 2008. Proterozoic links between the Borborema Province, NE Brazil, and the Central African Fold Belt. *Geological Society, London, Special Publications* 294, 69–99. <https://doi.org/10.1144/SP294.5>
- Vauchez, A., Neves, S.P., Caby, R., Corsini, M., Egydio-Silva, M., Arthaud, M.H., Amaro, V.E., 1995. The Borborema shear zone system, NE Brazil. *J South Am Earth Sci* 8, 247–266. [https://doi.org/10.1016/0895-9811\(95\)00012-5](https://doi.org/10.1016/0895-9811(95)00012-5)

- Vavra, G., 1990. On the kinematics of zircon growth and its petrogenetic significance: a cathodoluminescence study. *Contributions to Mineralogy and Petrology* 106, 90–99. <https://doi.org/10.1007/BF00306410>
- Vavra, G., Gebauer, D., Schmid, R., Compston, W., 1996. Multiple zircon growth and recrystallization during polyphase Late Carboniferous to Triassic metamorphism in granulites of the Ivrea Zone (Southern Alps): an ion microprobe (SHRIMP) study. *Contributions to Mineralogy and Petrology* 122, 337–358. <https://doi.org/10.1007/s004100050132>
- Vavra, G., Schmid, R., Gebauer, D., 1999. Internal morphology, habit and U-Th-Pb microanalysis of amphibolite-to-granulite facies zircons: geochronology of the Ivrea Zone (Southern Alps). *Contributions to Mineralogy and Petrology* 134, 380–404. <https://doi.org/10.1007/s004100050492>
- Velásquez Ruiz, F., Della Giustina, M.E.S., de Oliveira, C.G., Dantas, E.L., Hollanda, M.H.B., 2019. The 3.5 Ga São Tomé layered mafic-ultramafic intrusion, NE Brazil: Insights into a Paleoproterozoic Fe-Ti-V oxide mineralization and its reworking during West Gondwana assembly. *Precambrian Res* 326, 462–478. <https://doi.org/10.1016/j.precamres.2018.03.011>
- Vermeesch, P., 2021a. On the treatment of discordant detrital zircon U–Pb data. *Geochronology* 3, 247–257. <https://doi.org/10.5194/gchron-3-247-2021>
- Vermeesch, P., 2021b. Maximum depositional age estimation revisited. *Geoscience Frontiers* 12, 843–850. <https://doi.org/10.1016/j.gsf.2020.08.008>
- Vermeesch, P., 2018. IsoplotR: A free and open toolbox for geochronology. *Geoscience Frontiers* 9, 1479–1493. <https://doi.org/10.1016/j.gsf.2018.04.001>
- Vielzeuf, D., Baronnet, Alain., Perchuk, A.L., Laporte, D., Baker, M.B., 2007. Calcium diffusivity in aluminosilicate garnets: an experimental and ATEM study. *Contributions to Mineralogy and Petrology* 154, 153–170. <https://doi.org/10.1007/s00410-007-0184-x>
- Viete, D.R., Lister, G.S., 2017. On the significance of short-duration regional metamorphism. *J Geol Soc London* 174, 377–392. <https://doi.org/10.1144/jgs2016-060>
- Wang, C., Mitchell, R.N., Murphy, J.B., Peng, P., Spencer, C.J., 2021. The role of megacontinents in the supercontinent cycle. *Geology* 49, 402–406. <https://doi.org/10.1130/G47988.1>

- Wang, W., Cawood, P.A., Spencer, C.J., Pandit, M.K., Zhao, J.-H., Xia, X.-P., Zheng, J.-P., Lu, G.-M., 2022. Global-scale emergence of continental crust during the Mesoarchean–early Neoproterozoic. *Geology* 50, 184–188. <https://doi.org/10.1130/G49418.1>
- Watson, E.B., Harrison, T.M., 1983. Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. *Earth Planet Sci Lett* 64, 295–304. [https://doi.org/10.1016/0012-821X\(83\)90211-X](https://doi.org/10.1016/0012-821X(83)90211-X)
- Watson, E.B., Liang, Y., 1995. A simple model for sector zoning in slowly grown crystals; implications for growth rate and lattice diffusion, with emphasis on accessory minerals in crustal rocks. *American Mineralogist* 80, 1179–1187. <https://doi.org/10.2138/am-1995-11-1209>
- Watson, E.B., Wark, D.A., Thomas, J.B., 2006. Crystallization thermometers for zircon and rutile. *Contributions to Mineralogy and Petrology* 151, 413–433. <https://doi.org/10.1007/s00410-006-0068-5>
- Weinberg, R.F., Hasalová, P., 2015. Water-fluxed melting of the continental crust: A review. *Lithos* 212–215, 158–188. <https://doi.org/10.1016/j.lithos.2014.08.021>
- Weller, M.B., Lenardic, A., 2018. On the evolution of terrestrial planets: Bi-stability, stochastic effects, and the non-uniqueness of tectonic states. *Geoscience Frontiers* 9, 91–102. <https://doi.org/10.1016/j.gsf.2017.03.001>
- Wetherill, G.W., 1956. Discordant uranium-lead ages, I. *Eos, Transactions American Geophysical Union* 37, 320–326. <https://doi.org/10.1029/TR037i003p00320>
- White, R.W., Powell, R., Clarke, G.L., 2002. The interpretation of reaction textures in Fe-rich metapelitic granulites of the Musgrave Block, central Australia: constraints from mineral equilibria calculations in the system $K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O-TiO_2-Fe_2O_3$. *Journal of Metamorphic Geology* 20, 41–55. <https://doi.org/10.1046/j.0263-4929.2001.00349.x>
- White, R.W., Powell, R., Holland, T.J.B., Johnson, Tim.E., Green, E.C.R., 2014. New mineral activity–composition relations for thermodynamic calculations in metapelitic systems. *Journal of Metamorphic Geology* 32, 261–286. <https://doi.org/10.1111/jmg.12071>
- Whitehouse, M.J., Ravindra Kumar, G.R., Rimša, A., 2014. Behaviour of radiogenic Pb in zircon during ultrahigh-temperature metamorphism: an ion imaging and ion tomography case study from the Kerala

Khondalite Belt, southern India. *Contributions to Mineralogy and Petrology* 168, 1042. <https://doi.org/10.1007/s00410-014-1042-2>

Whitney, D.L., Evans, B.W., 2010. Abbreviations for names of rock-forming minerals. *American Mineralogist* 95, 185–187. <https://doi.org/10.2138/am.2010.3371>

Wiedenbeck, M., Hanchar, J.M., Peck, W.H., Sylvester, P., Valley, J., Whitehouse, M., Kronz, A., Morishita, Y., Nasdala, L., Fiebig, J., Franchi, I., Girard, J. -P., Greenwood, R.C., Hinton, R., Kita, N., Mason, P.R.D., Norman, M., Ogasawara, M., Piccoli, P.M., Rhede, D., Satoh, H., Schulz-Dobrick, B., Skår, O., Spicuzza, M.J., Terada, K., Tindle, A., Togashi, S., Vennemann, T., Xie, Q., Zheng, Y. -F., 2004. Further Characterisation of the 91500 Zircon Crystal. *Geostand Geoanal Res* 28, 9–39. <https://doi.org/10.1111/j.1751-908X.2004.tb01041.x>

Wilde, S.A., Valley, J.W., Peck, W.H., Graham, C.M., 2001. Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago. *Nature* 409, 175–178. <https://doi.org/10.1038/35051550>

Windley, B.F., Kusky, T., Polat, A., 2021. Onset of plate tectonics by the Eoarchean. *Precambrian Res* 352, 105980. <https://doi.org/10.1016/j.precamres.2020.105980>

Xiang, H., Connolly, J.A.D., 2022. GeoPS: An interactive visual computing tool for thermodynamic modelling of phase equilibria. *Journal of Metamorphic Geology* 40, 243–255. <https://doi.org/10.1111/jmg.12626>

Yakymchuk, C., 2023. Prograde zircon growth in migmatites. *Journal of Metamorphic Geology* 41, 719–743. <https://doi.org/10.1111/jmg.12715>

Yakymchuk, C., Brown, M., 2014. Behaviour of zircon and monazite during crustal melting. *J Geol Soc London* 171, 465–479. <https://doi.org/10.1144/jgs2013-115>

Yakymchuk, C., Clark, C., White, R.W., 2017. Phase Relations, Reaction Sequences and Petrochronology. *Rev Mineral Geochem* 83, 13–53. <https://doi.org/10.2138/rmg.2017.83.2>

Yakymchuk, C., Kirkland, C.L., Clark, C., 2018. Th/U ratios in metamorphic zircon. *Journal of Metamorphic Geology* 36, 715–737. <https://doi.org/10.1111/jmg.12307>

- Yang, C.-X., Santosh, M., Lloyd, J.C., Glorie, S., Gao, P., Yu, B., Anilkumar, Y., Anoop, K.S., Kim, S.-W., 2023. The Coorg Block, southern India: Insights from felsic and mafic magmatic suites on Mesoarchean plate tectonics and correlation with supercontinent Ur. *Gondwana Research* 118, 1–36. <https://doi.org/10.1016/j.gr.2023.02.015>
- Yang, C.-X., Santosh, M.W., Tsunogae, T., Shaji, E., Gao, P., Kwon, S., 2021. Global type area charnockites in southern India revisited: Implications for Earth's oldest supercontinent. *Gondwana Research* 94, 106–132. <https://doi.org/10.1016/j.gr.2021.03.003>
- Yu, B., Santosh, M., Amaldev, T., Jang, Y., Yang, C.-X., 2022. Paleo-Mesoarchean crustal evolution in the Coorg Block, southern India: Insights from magmatic and metamorphic records in mafic granulites. *Precambrian Res* 370, 106537. <https://doi.org/10.1016/j.precamres.2021.106537>
- Yu, B., Santosh, M.W., Amaldev, T., Palin, R.M., 2021. Mesoarchean (ultra)-high temperature and high-pressure metamorphism along a microblock suture: Evidence from Earth's oldest khondalites in southern India. *Gondwana Research* 91, 129–151. <https://doi.org/10.1016/j.gr.2020.12.015>
- Yu, C., Yang, T., Zhang, J., Zhao, G., Cawood, P.A., Yin, C., Qian, J., Gao, P., Zhao, C., 2022. Coexisting diverse P–T–t paths during Neoproterozoic subduction: Insights from numerical modeling and applications to the eastern North China Craton. *Earth Planet Sci Lett* 586, 117529. <https://doi.org/10.1016/j.epsl.2022.117529>
- Zaun, P.E., Wagner, G.A., 1985. Fission-track stability in zircons under geological conditions. *Nuclear Tracks and Radiation Measurements* (1982) 10, 303–307. [https://doi.org/10.1016/0735-245X\(85\)90119-X](https://doi.org/10.1016/0735-245X(85)90119-X)
- Zhu, Z., Campbell, I.H., Allen, C.M., Brocks, J.J., Chen, B., 2022. The temporal distribution of Earth's supermountains and their potential link to the rise of atmospheric oxygen and biological evolution. *Earth Planet Sci Lett* 580, 117391. <https://doi.org/10.1016/j.epsl.2022.117391>
- Zou, H., 2007. *Quantitative Geochemistry*. Imperial College Press, London. 287 p.
- Zou, Y., Zhai, M., Mitchell, R.N., Zhao, L., Zhou, L., Liu, B., Wang, Y., Chen, M., 2020. Discovery of kyanite in typically cordierite/sillimanite-bearing low- to medium-pressure pelitic granulites from the Jiaobei terrain, North China Craton. *Precambrian Res* 342, 105677. <https://doi.org/10.1016/j.precamres.2020.105677>

Supplementary Table S1: U-Pb in zircon data (P1-1)

LEGEA, Universidade de Brasília										Data for Tera-Wasserburg plot										Data for Wetherill plot										Ages (Ma)										Concordance	
Spot ID	Grain	Length	Width	Type	Spot location	Comments	ChRc	206Pb	Uppm	Th/U	206Pb/204Pb	1 σ	238U/206Pb	1 σ	206Pb/238U	1 σ	207Pb/235U	1 σ	Rho	208Pb/232Th	1 σ	207Pb/206Pb	2 σ (abs)	235pb (abs)	206Pb/238U	2 σ (abs)	235pb (abs)	207Pb/235U	2 σ (abs)	235pb (abs)	Concordia age	2 σ (abs)	208Pb/232Th	2 σ (abs)	235pb (abs)	% concordance	Concordia distance				
P1-01-32.Fn2	201	123	66	Rounded	Core	Session 1	0.058	216830	88	0.02	-6255	-	1.76	1.7	0.22988	1.59	0.003	15.449	18.7402	1.5	0.58535	1.3	0.493	0.17	15.20	3036	53	2963	62	62	3019	29	30	3029	29	2775	618	699	97.6	2.0	
P1-01-29.Fn2	202	152	62	Rounded	Core	Session 1	0.165	268109	135	0.05	-6530	-10	2.20	1.8	0.25997	2.62	0.080	6.266	16.1523	2.2	0.45593	1.6	0.223	0.15	15.746	3182	82	82	66	66	2885	45	45	2731	45	2804	139	693	76.0	22.0	
P1-01-30.Fn2	203	157	92	Rounded	Core	Session 1	0.052	102558	56	0.02	-3048	-5	2.53	1.7	0.15861	2.65	0.004	8.624	6.5653	4.1	0.41387	1.9	0.895	0.21	13.27	2339	86	86	2263	69	69	2303	70	71	2210	85	3297	628	744	10.8	17.0
P1-01-30.Fn2	204	115	49	Rounded	Core	Session 1	0.116	446403	174	0.11	-7962	-	2.22	1.2	0.22037	1.60	0.012	13.925	14.1106	1.3	0.45803	1.2	0.210	0.11	8.005	2965	53	53	2426	47	47	2749	24	25	2700	25	2009	343	304	81.9	14.0
P1-01-22.Fn2	205	127	81	Rounded	Core	Session 1	0.054	508649	243	0.18	-10193	-5	2.17	0.9	0.22427	1.19	0.019	5.352	14.6384	1.2	0.46692	0.9	0.280	0.11	7.42	2992	39	39	2466	36	36	2783	20	22	2711	23	2148	87	802	82.4	14.0
P1-01-23.Fn2	206	108	41	Rounded	Core	Session 1	0.127	216222	161	0.13	-5876	-11	2.52	2.3	0.21657	2.65	0.015	5.678	12.0497	2.6	0.40525	2.4	0.424	0.12	9.14	2932	85	85	8128	90	90	2598	49	49	2556	53	2224	242	386	74.6	18.0
P1-01-24.Fn2	207	109	40	Rounded	Core	Session 1	0.052	325703	112	0.09	-8361	-5	1.51	0.9	0.27077	1.14	0.094	1.567	25.2365	1.1	0.66830	0.9	0.327	0.17	7.26	3291	35	35	2191	45	45	3309	20	22	3316	21	3229	85	426	100.0	0.6
P1-01-25.Fn2	208	119	79	Rounded	Core	Session 1	0.052	325703	112	0.09	-8361	-5	1.51	0.9	0.27077	1.14	0.094	1.567	25.2365	1.1	0.66830	0.9	0.327	0.17	7.26	3291	35	35	2191	45	45	3309	20	22	3316	21	3229	85	426	100.0	0.6
P1-01-26.Fn2	209	214	45	Prismatic	Core	Session 1	0.081	250594	88	0.95	-5937	-4	1.53	1.2	0.27842	1.43	0.096	3.287	25.9398	1.3	0.61614	1.1	0.342	0.16	7.25	3329	45	45	3262	58	58	3335	21	24	3328	25	3057	81	412	98.0	1.9
P1-01-28.Fn2	210	191	115	Rounded	Core	Session 1	0.099	270689	107	1.31	-6442	-7	1.71	1.0	0.27842	1.46	0.134	2.768	21.8134	1.2	0.59608	0.9	0.15	7.21	3331	36	36	2976	45	45	3316	21	22	3197	24	2815	63	379	89.3	8.4	
P1-01-35.Fn2	211	123	49	Prismatic	Core	Session 1	0.090	523140	191	0.92	-15588	-5	1.65	1.0	0.25911	1.27	0.117	3.896	22.2289	1.5	0.66106	1.0	0.498	0.16	7.23	3214	40	40	3373	51	51	3181	28	30	3184	29	3024	77	419	95.6	3.8
P1-01-36.Fn2	212	128	51	Prismatic	Core	Session 1	0.076	282743	116	1.21	-8591	-4	1.83	1.0	0.27213	1.21	0.109	1.763	20.9360	1.1	0.55289	0.9	0.274	0.14	7.23	3292	38	38	2830	43	43	3126	20	22	3090	22	2730	66	368	86.0	11.0
P1-01-33.Fn2	213	117	76	Rounded	Core	Session 1	0.063	145521	57	0.06	-3880	-7	1.77	1.0	0.23155	1.54	0.026	7.998	18.3455	1.3	0.57130	1.1	0.188	0.17	13.11	3034	49	49	2907	50	50	2998	25	26	2993	24	2839	521	620	95.8	3.8
P1-01-34.Fn2	214	87	75	Rounded	Core	Session 1	0.058	284434	139	0.65	-8856	-4	2.10	1.0	0.23504	1.00	0.075	3.410	15.8938	1.2	0.48625	1.0	0.364	0.14	7.32	3065	39	39	2547	43	43	2858	22	23	2836	24	2579	86	360	83.1	12.0
P1-01-42.Fn2	215	111	82	Rounded	Core	Session 1	0.083	480094	170	1.79	-12776	-6	1.53	1.1	0.27546	1.46	0.168	3.570	25.5320	1.2	0.66352	1.1	0.048	0.16	7.23	3320	46	46	3274	55	55	3332	21	23	3322	22	2927	72	396	98.6	1.7
P1-01-40.Fn2	216	147	64	Prismatic	Core	Session 1	0.049	47062	181	0.48	-15599	-5	1.59	0.9	0.25582	1.30	0.080	5.745	22.7038	1.2	0.61311	0.9	0.283	0.17	7.24	3154	41	41	3170	45	45	3203	23	24	3210	22	3149	81	432	99.3	1.3
P1-01-39.Fn2	217	106	82	Rounded	Core	Session 1	0.097	352020	147	0.16	-11480	-3	1.87	0.9	0.27285	1.22	0.134	2.096	17.1218	1.0	0.54286	0.9	0.151	0.14	7.42	3030	39	39	2790	39	39	2934	18	19	2919	18	2650	105	363	92.7	1.6
P1-1	217	106	82	Rounded	Rim	Session 2	0.152	143383	97	0.05	-14978	33	1.94	1.2	0.21132	1.45	0.007	5.605	15.2029	1.1	0.50958	1.0	0.226	0.15	5.18	2908	47	47	2653	53	53	2826	22	22	2814	21	2738	268	435	91.2	6.5
P1-01-37.Fn2	218	205	44	Prismatic	Core	Session 2	0.092	584180	219	0.63	-16650	-5	1.67	1.0	0.26502	1.30	0.106	4.405	22.4241	1.4	0.60775	1.0	0.233	0.15	7.21	3247	41	41	3052	47	47	3186	26	28	3181	27	2860	65	386	94.0	5.1
P1-1	218	205	44	Prismatic	Core	Session 2	0.095	575766	237	0.06	-31373	28	2.22	0.9	0.20869	1.98	0.012	5.458	12.3031	1.6	0.42808	1.2	0.556	0.13	7.73	2847	46	46	2295	48	48	2622	32	32	2590	34	2500	126	336	80.4	14.0
P1-01-38.Fn2	219	146	57	Prismatic	Core	Session 1	0.145	425640	150	0.93	-13395	-6	1.50	1.2	0.27855	1.55	0.096	4.433	26.2476	1.3	0.67936	1.1	0.344	0.16	7.34	3328	48	48	3333	60	60	3347	25	26	3354	24	3019	101	409	100.2	0.5
P1-01-101.Fn2	220	101	62	Rounded	Rim	Session 1	0.146	141488	62	0.04	-4782	-4	1.81	1.0	0.22757	1.34	0.006	29.831	17.6706	1.1	0.56147	1.0	0.074	0.19	13.71	3004	43	43	2865	45	45	2964	19	20	2953	19	3031	437	511	95.4	3.9
P1-1	221	205	97	Prismatic	Core	Session 1	0.066	309921	220	0.38	-27786	31	1.44	2.3	0.28481	1.07	0.124	7.057	26.4535	2.3	0.68838	1.9	0.522	0.19	1.89	2929	35	35	3368	104	104	3351	51	51	3356	28	3489	109	439	102.3	0.6
P1-1	221	205	97	Prismatic	Core	Session 1	0.064	705369	408	0.54	-74768	37	1.50	1.3	0.29722	1.07	0.132	14.867	24.2767	1.7	0.65041	1.6	0.396	0.18	2.83	3284	52	52	3227	51	51	3277	34	34	3424	178	449	98.3	1.6		
P1-01-102.Fn2	221	205	97	Prismatic	Core	Session 1	0.035	517447	235	0.18	-18975	-4	1.86	1.0	0.29454	1.34	0.028	6.461	18.1138	1.1	0.54506	1.0	0.175	0.18	7.65	3000	42	42	2798	46	46	2987	21	22	2969	21	3037	168	422	90.6	7.2
P1-1	221	205	97	Prismatic	Core	Session 2	0.039	380813	308	0.07	-35197	37	2.09	1.5	0.22278	2.05	0.011	3.926	14.7826	1.6	0.47397	1.5	0.091	0.13	4.21	2991	65	65	2499	61	61	2799	31	31	2743	30	2528	201	375	83.6	12.0

PJ-1 22	Z101	95	65	Rounded	Core	Session 2	0.010	422869	268	0.05	17383	35	1.63	1.1	0.22582	1.09	0.008	6.004	19.3352	1.2	0.60736	1.0	0.539	0.16	3.44	3018	35	35	3058	51	51	3056	22	22	3059	23	3038	195	423	101.3	0.0
PJ-1 24	Z102	119	53	Rounded	Core	Session 2	0.007	477806	275	0.99	12116	51	1.53	0.8	0.26202	1.10	0.150	5.790	23.9025	0.9	0.64425	0.7	0.081	0.16	0.60	3255	35	35	3205	37	37	3264	17	17	3254	16	3020	34	373	98.5	2.1
PJ-1 25	Z102	119	53	Rounded	Rim	Session 2	0.282	113359	108	0.10	2304	44	2.62	1.9	0.20307	1.55	0.022	5.165	10.8940	2.2	0.38039	1.9	0.757	0.14	3.75	2838	52	52	2073	69	69	2511	42	42	2605	42	2638	188	382	73.1	19.0
PJ-01-1.FIN2	Z103	159	42	Prismatic	Core	Session 1	0.116	460820	150	0.80	-9909	-9	1.51	1.5	0.26853	1.76	0.078	4.208	25.3126	1.8	0.67668	1.5	0.427	0.17	7.33	3273	55	55	3321	78	78	3308	34	35	3321	34	3206	107	435	101.5	-0.3
PJ-01-83.FIN2	Z104	142	71	Rounded	Core	Session 1	0.038	365812	155	0.07	-7176	-4	1.78	0.8	0.22933	1.17	0.008	7.014	18.0486	0.9	0.56990	0.8	0.040	0.16	7.74	3021	37	37	2902	37	37	2986	16	18	2978	16	2929	164	416	96.1	3.2
PJ-01-84.FIN2	Z105	117	70	Rounded	Core	Session 1	0.004	399670	194	0.33	-7809	-5	2.03	0.8	0.22984	1.17	0.032	3.417	15.8725	1.0	0.49769	0.8	0.092	0.12	7.34	3024	38	38	2599	34	34	2862	17	18	2794	17	2319	81	325	85.9	12.0
PJ-01-82.FIN2	Z106	124	57	Rounded	Core	Session 1	0.038	917140	395	1.55	-14288	-11	1.66	1.0	0.26245	1.36	0.355	7.054	22.2583	1.4	0.61304	1.0	0.417	0.19	7.67	3227	43	43	3072	50	50	3179	27	28	3184	27	3431	174	465	95.2	3.9
PJ-01-81.FIN2	Z107	108	75	Rounded	Core	Session 1	0.008	248501	228	0.12	-6276	-7	4.00	4.0	0.17072	3.00	0.019	5.866	7.4854	5.2	0.29119	3.6	0.897	0.10	7.86	2479	106	106	1623	105	105	2019	110	110	1015	83	1829	117	275	65.5	110.0
PJ-01-80.FIN2	Z108	137	57	Prismatic	Core	Session 1	-0.014	144083	67	0.03	-3322	-5	1.92	0.9	0.21592	1.26	0.006	19.562	15.8906	1.1	0.52995	0.9	0.079	0.09	186.26	2919	41	41	2735	40	40	2865	18	20	2844	19	2578	390	391	93.7	5.2
PJ-01-79.FIN2	Z109	87	72	Rounded	Core	Session 1	0.047	441051	163	1.53	-10219	-6	1.53	1.2	0.27408	1.70	0.146	3.446	25.3026	1.4	0.66270	1.1	0.152	0.15	7.36	3302	53	53	3271	58	58	3315	27	29	3314	26	2891	101	388	99.0	1.5
PJ-01-77.FIN2	Z110	147	65	Prismatic	Rim	Session 1	0.154	329418	146	0.40	-8537	-5	1.95	1.3	0.24408	1.36	0.043	3.984	18.1093	1.8	0.53044	1.4	0.666	0.14	7.30	3116	43	43	2730	61	61	2969	34	35	3021	35	2579	80	354	87.6	8.9
PJ-01-76.FIN2	Z111	168	62	Prismatic	Core	Session 1	0.235	671511	290	0.15	-20118	-5	1.82	0.8	0.23100	1.23	0.014	2.129	17.8027	0.9	0.55510	0.8	0.096	0.14	7.31	3034	40	40	2845	39	39	2972	16	18	2951	15	2711	85	369	93.8	5.3
PJ-1 29	Z111	168	62	Prismatic	Rim	Session 2	0.011	198349	157	0.05	4353	41	2.42	4.9	0.19127	1.95	0.011	4.805	12.2371	4.5	0.44323	3.6	0.925	0.15	4.40	2743	62	62	2340	149	149	2574	97	97	2820	49	2846	237	427	85.3	17.0
PJ-01-74.FIN2	Z112	177	85	Prismatic	Core	Session 1	0.216	461462	136	1.34	-7973	-12	1.54	1.4	0.27920	1.97	0.114	2.814	25.4411	1.6	0.66001	1.4	0.087	0.18	7.36	3331	62	62	3160	70	70	3317	30	31	3317	29	3357	118	455	97.8	2.6
PJ-1 26	Z112	177	85	Prismatic	Core	Session 2	0.097	356310	234	0.71	8634	46	1.72	2.5	0.26657	1.40	0.112	3.101	22.0321	2.6	0.58555	2.4	0.821	0.16	3.01	3378	47	47	2961	116	116	3172	54	54	3262	19	3012	168	407	90.4	8.5
PJ-1 27	Z112	177	85	Prismatic	Rim	Session 2	0.004	105122	77	0.24	3002	40	2.03	3.0	0.21050	1.53	0.042	5.336	15.1820	3.7	0.50568	3.0	0.806	0.15	2.59	2899	50	50	2624	128	128	2812	76	76	2892	61	2744	133	365	90.5	8.0
PJ-01-75.FIN2	Z113	144	72	Prismatic	Core	Session 1	0.174	278991	116	0.47	-8211	-5	1.86	0.9	0.22981	1.26	0.045	2.820	17.3674	1.1	0.54531	0.9	0.019	0.14	7.34	3029	41	41	2799	41	41	2946	19	20	2921	19	2689	102	407	92.4	6.1
PJ-01-73.FIN2	Z114	130	71	Rounded	Core	Session 1	0.006	288372	145	0.72	-7164	-5	2.17	1.1	0.25283	1.32	0.079	2.639	16.3661	1.2	0.47004	1.0	0.289	0.14	7.35	3170	42	42	2477	41	41	2886	23	24	2814	25	2658	93	371	78.1	17.0
PJ-1 28	Z114	130	71	Rounded	Rim	Session 2	0.602	46800	189	0.05	1266	40	10.59	1.1	0.05839	2.46	0.016	11.566	0.7820	2.7	0.09347	1.1	0.375	0.05	9.30	523	103	103	576	12	12	583	24	24	577	12	892	161	198	98.7	1.9
PJ-01-72.FIN2	Z115	127	63	Rounded	Core	Session 1	0.071	397488	161	0.65	-9849	-4	1.75	0.8	0.26574	1.30	0.077	4.542	21.2613	1.1	0.57842	0.8	0.034	0.15	7.28	3250	41	41	2936	39	39	3141	19	21	3097	20	2736	79	370	90.4	8.4
PJ-01-69.FIN2	Z116	164	51	Prismatic	Core	Session 1	-0.013	400210	151	0.73	-8232	-6	1.53	1.2	0.27273	1.53	0.100	15.969	25.1509	1.3	0.66314	1.1	0.244	0.15	7.31	3292	48	48	3270	58	58	3303	25	27	3311	25	2854	89	385	99.3	1.2
PJ-01-68.FIN2	Z117	157	57	Prismatic	Core	Session 1	0.059	515467	155	0.93	-8408	-7	1.55	1.3	0.25602	1.65	0.139	4.673	24.4398	1.7	0.65919	1.3	0.460	0.15	7.02	3256	53	53	3252	67	67	3269	33	34	3286	33	2796	85	380	95.9	0.7
PJ-01-70.FIN2	Z118	96	62	Rounded	Core	Session 1	0.060	552499	217	0.23	-10864	-5	1.72	0.8	0.24686	1.22	0.031	3.756	20.1681	1.1	0.58870	0.8	0.197	0.16	7.29	3137	39	39	2978	40	40	3091	20	22	3077	20	3008	90	407	94.9	4.4
PJ-01-71.FIN2	Z119	108	64	Rounded	Core	Session 1	0.248	222354	112	0.07	-4583	-7	2.06	1.1	0.21790	1.44	0.041	14.985	15.0100	1.5	0.49460	1.1	0.364	0.20	10.18	2926	47	47	2582	47	47	2803	28	29	2772	29	3289	421	588	88.2	9.2
PJ-01-1.FIN2	Z120	138	56	Prismatic	Rim	Session 1	0.055	45225	92	0.06	-1018	-8	10.17	1.4	0.06230	3.33	0.060	62.762	0.8851	2.9	0.10132	2.2	0.370	0.09	36.48	675	154	154	621	26	26	638	27	28	622	22	1495	740	754	97.4	3.0
PJ-01-27.FIN2	Z121	100	69	Rounded	Core	Session 1	0.032	298627	140	0.87	-7720	-5	2.07	1.1	0.22518	1.48	0.076	2.183	15.3339	1.0	0.48862	1.1	0.206	0.12	7.29	2990	47	47	2565	47	47	2826	25	26	2775	26	2328	70	320	85.8	11.0
PJ-1 10	Z122	86	52	Rounded	Core	Session 2	0.273	96712	80	0.11	3796	51	2.72	3.7	0.19533	1.49	0.030	3.331	10.8410	4.9	0.38736	4.0	0.956	0.19	3.98	2778	48	48	2093	142	142	2466	88	88	2887	34	3523	256	497	75.3	32.0
PJ-1 9	Z123	90	47	Rounded	Core	Session 2	0.187	115601	105	0.07	5907	36	2.61	1.7	0.19614	1.26	0.011	3.908	10.6424	2.3	0.38201	1.7	0.839	0.10	4.33	2787	42	42	2083	60	60	2482	43	43	2644	44	1977	163	298	74.7	20.0
PJ-1 7	Z124	191	52	Prismatic	Core	Session 2	-0.124	152727	78	0.80	7120	42	1.45	1.6	0.27146	1.06	0.125	3.556	26.2115	1.4	0.68879	1.0	0.830	0.18	1.52	3317	30	30	3375	53	53	3350	30	30	3345	24	3374	94	421	101.8	-0.9
PJ-1 30	Z125	123	70	Rounded	Core	Session 2	0.120	165073	89	0.78	4116	40	1.50	2.2	0.27038	0.97	0.125	4.911	25.6157	2.8	0.66859	2.6	0.932	0.20	4.20	3303	31	31	3282	132	132	3326	48	48	3349	30	3596	275	512	99.4	1.4
PJ-1 32	Z127	124	86	Rounded	Rim	Session 2	0.773	40488	47	0.05	1159	36	3.17	2.6	0.14031	3.04	0.008	12.737	6.5327	5.1	0.12134	2.6	0.886	0.09	10.97	2182	109	109	1790	80	80	2001	91	91	1582	81	1641	345	403	82.1	41.0
PJ-1 31	Z128	105	68	Rounded	Core	Session 2	0.071	255064	178	0.13	13862	23	1.85	0.9	0.21906	1.07	0.018	2.760	16.4980	1.1	0.53412	0.9	0.404	0.14	1.90	2967	34	34	2757	40	40	2903	21	21	2894	21	2604	97	338	92.9	5.4
PJ-1 34	Z129	152	72	Rounded	Core	Session 2	-0.218	38896	23	1.46	707	78	1.53	1.5	0.27718	1.71	0.211	3.618	24.9975	1.7	0.64904	1.5	0.518	0.17	3.88	3339	54	54	3222	75	75	3316	40	40	3312	33	3149	224	445	96.5	2.6
PJ-1 35	Z130	124	69	Rounded	Core	Session 2	0.017	242683	131	0.83	7047	41	1.46	1.0	0.27944	1.06	0.139	6.416	26.7806	0.9	0.67883	1.1	0.402	0.18	1.89</																

Supplementary Table S3: U-Pb in zircon data (CJ-214)

LEGGA, Universidade de Brasília										Data for Tera-Wasserburg plot										Data for Wetherill plot										Ages (Ma)										Concordance									
Spot	Grain	Length	Width	Type	Session	Spot local	GeoQ	GeoP	Uppm	Tb/U	206Pb/204Pb	1σ	207Pb/206Pb	1σ	206Pb/238U	1σ	207Pb/235U	1σ	207Pb/238U	1σ	Rho	208Pb/232Th	1σ	207Pb/206Pb	2σ (abs)	2σys (abs)	206Pb/238U	2σ (abs)	2σys (abs)	207Pb/235U	2σ (abs)	2σys (abs)	Concordia age	2σ (abs)	208Pb/232Th	2σ (abs)	2σys (abs)	% concordance	Concordia distance										
AM27-1.Fm2	201	180	56	Rounded Core	Session1	0.019	386128	168	0.55	-1020	-24	1.77	0.6	0.23270	0.8	0.192	3.904	18.2657	0.6	0.56700	0.6	0.556	0.14	2.09	3064	19	28	2892	28	43	3005	11	19	3014	11	2707	111	2195	94.4	3.8									
AM27-1.Fm2	201	180	56	Rounded Rim	Session1	0.052	354948	160	0.25	-920	-27	1.72	0.6	0.23273	0.62	0.037	2.076	18.6752	0.6	0.58385	0.6	0.605	0.15	2.67	3063	20	28	2965	28	44	3023	12	20	3032	11	2742	144	2215	96.8	2.1									
AM27-1.Fm2	203	196	91	Rounded Core	Session1	0.028	256818	106	0.73	-794	-39	1.51	0.1	0.28015	0.99	0.135	4.797	25.7866	1.1	0.67385	1.1	0.689	0.16	5.16	3361	31	36	3313	58	68	3332	22	28	3342	19	2992	305	2451	98.6	0.6									
AM27-1.Fm2	203	196	91	Rounded Rim	Session1	0.020	350461	412	0.03	-2726	-10	1.74	0.4	0.23170	0.41	0.005	2.425	18.4310	0.4	0.57921	0.4	0.602	0.15	2.42	3020	18	24	2931	20	38	3010	7	18	3016	8	2727	126	2155	95.8	2.7									
AM27-1.Fm2	205	161	68	Rounded Core	Session1	-0.015	364617	173	0.34	-1226	-17	1.96	0.5	0.23273	0.49	0.136	4.053	16.7816	0.5	0.51280	0.5	0.483	0.14	1.886	3066	15	25	2666	20	36	2902	10	19	2909	10	2660	98	2148	87.0	8.1									
AM27-1.Fm2	206	159	66	Rounded Rim	Session1	0.036	1464707	170	0.02	-3802	-46	1.65	0.9	0.24103	0.78	0.040	3.985	19.9715	0.7	0.61600	0.9	0.608	0.15	8.01	3122	24	31	3063	43	55	3088	14	22	3093	12	2847	456	2390	98.1	0.8									
AM27-1.Fm2	208	116	73	Rounded Core	Session1	0.066	140387	169	0.02	-1787	-16	1.63	1.0	0.24078	0.65	0.018	3.907	19.4607	0.6	0.60837	0.6	0.608	0.16	1.40	3067	19	29	3012	18	39	3032	16	28	3038	12	2847	456	2390	98.1	0.8									
CJ-214	3	208	116	73	Rounded Core	Session2	0.200	391771	122	0.01	-7805	-46	1.86	1.4	0.23273	2.86	0.151	6.069	16.8682	0.5	0.53770	0.23	0.302	0.15	3.81	2889	91	91	2769	102	102	52	165	2921	47	7	2814	48	2817	200	400	92.6	5.6						
AM27-1.Fm2	208	116	73	Rounded Rim	Session1	-0.018	230925	132	0.19	-956	-12	2.38	0.8	0.21650	0.50	0.028	2.306	12.8851	0.10	0.42773	0.8	0.859	0.11	2.16	2948	16	26	2292	31	41	2660	18	24	2814	15	2118	88	1686	77.8	20.0									
AM27-1.Fm2	209	134	73	Rounded Core	Session1	0.176	213599	102	0.08	-927	-15	2.18	0.2	0.21519	0.71	0.012	2.940	14.4576	1.6	0.47993	1.4	0.912	0.14	3.10	2937	23	31	2513	58	65	2751	35	40	2937	18	2665	157	2094	85.6	14.0									
CJ-214	5	209	134	73	Rounded Rim	Session2	0.155	624768	463	0.10	-2550	-10	2.05	2.3	0.23239	2.33	0.009	5.15	15.5756	0.1	0.49144	0.1	0.576	0.18	4.03	2974	76	76	2569	97	97	2822	41	41	2824	40	2814	56	854	9.5	1.0								
AM27-10.Fm2	210	86	62	Rounded Core	Session1	0.045	234997	112	0.17	-972	-16	1.93	0.9	0.23148	0.98	0.027	2.162	16.8156	1.0	0.52716	0.9	0.456	0.15	2.98	3043	31	37	2723	39	49	2913	20	27	2920	19	2765	159	2200	89.5	7.0									
CJ-214	2	211	96	68	Rounded Core	Session2	0.033	215735	141	0.15	-8304	33	1.73	1.5	0.22779	2.00	0.025	2.575	18.4024	1.4	0.57556	1.5	0.472	0.16	2.45	3015	65	65	2925	69	69	3006	28	28	3014	26	2933	133	383	97.0	2.7								
AM27-11.Fm2	211	96	68	Rounded Rim	Session1	0.545	131730	87	0.18	-578	-16	2.53	1.1	0.18545	1.08	0.041	4.538	10.2321	1.3	0.40032	1.1	0.611	0.14	4.13	2681	37	42	2170	40	48	2447	24	29	2453	26	2568	202	2022	80.9	12.0									
AM27-12.Fm2	212	71	42	Rounded Core	Session1	0.025	346538	163	0.16	-1556	-18	1.81	0.9	0.22857	1.07	0.002	2.700	17.4125	1.1	0.55623	0.9	0.470	0.14	2.62	3027	34	40	2846	44	54	2931	21	27	2954	21	2543	213	2066	94.0	1.8									
AM27-13.Fm2	213	164	79	Rounded Core	Session1	0.009	403147	157	1.22	-1798	-23	1.72	1.2	0.22680	1.00	0.180	4.051	18.5091	1.2	0.58794	1.1	0.681	0.15	1.05	3021	31	37	2976	54	64	3010	24	30	3023	22	2885	57	2217	98.5	1.2									
AM27-14.Fm2	213	164	79	Rounded Rim	Session1	0.009	339364	128	0.45	-1598	-13	1.66	0.7	0.23557	0.55	0.087	3.246	19.8995	0.6	0.60895	0.7	0.654	0.17	1.15	3085	18	27	3061	33	47	3083	12	21	3090	11	3101	66	2357	99.2	0.7									
AM27-15.Fm2	215	60	59	Rounded Core	Session1	0.008	603506	277	0.08	-2709	-19	1.77	0.6	0.23065	0.63	0.021	4.269	18.3039	0.6	0.54837	0.6	0.676	0.15	2.73	3055	20	28	2897	29	38	3021	13	22	3024	11	2743	145	2189	94.8	2.7									
AM27-16.Fm2	216	96	50	Rounded Core	Session1	-0.078	594087	291	0.06	-3599	-11	1.89	0.7	0.22959	0.68	0.013	5.576	16.8049	0.9	0.63158	0.7	0.679	0.13	3.24	3045	21	29	2744	33	41	2923	16	23	2945	17	2493	157	2005	80.1	6.3									
AM27-17.Fm2	217	163	53	Rounded Core	Session1	0.071	457185	212	0.12	-2256	-13	1.81	0.7	0.23131	0.56	0.030	2.986	17.7648	0.7	0.55499	0.7	0.729	0.17	3.10	3056	18	27	2845	30	43	2973	13	21	3007	12	3050	176	2347	93.1	4.9									
AM27-18.Fm2	218	67	51	Rounded Core	Session1	0.455	559363	240	0.08	-1780	-34	1.71	1.5	0.23010	1.09	0.024	7.887	18.9446	1.4	0.59947	1.4	0.692	0.17	3.10	3042	35	41	3002	68	76	3031	28	33	3045	25	3131	179	2393	98.7	1.0									
AM27-19.Fm2	219	117	57	Prismatic Core	Session1	0.123	499716	205	1.62	-2136	-36	1.69	0.9	0.23289	1.00	0.223	1.645	19.1294	1.1	0.52048	1.0	0.393	0.16	0.97	3064	35	40	2997	45	56	3045	21	26	3047	21	2977	53	2176	97.8	1.7									
AM27-20.Fm2	220	112	59	Rounded Core	Session1	0.090	425943	197	2.01	-1717	-20	1.75	0.6	0.23457	0.75	0.291	1.268	18.5114	0.7	0.57267	0.6	0.371	0.14	3.11	3077	25	32	2920	29	43	3013	13	22	3010	13	2994	161	2132	94.9	3.4									
AM27-21.Fm2	221	117	50	Rounded Core	Session1	0.066	558763	235	0.36	-2762	-22	1.72	0.9	0.23392	0.99	0.096	5.564	19.0292	1.1	0.58432	0.9	0.534	0.18	1.76	3072	31	37	2964	42	54	3039	20	26	3045	21	3330	108	2527	96.5	2.6									
AM27-22.Fm2	222	66	50	Rounded Core	Session1	0.059	1050218	508	0.02	-5442	-15	1.79	0.7	0.23458	0.69	0.006	3.995	18.0852	0.7	0.64631	0.7	0.522	0.20	4.44	3077	22	30	2878	33	46	2992	14	22	3001	13	3535	302	2814	91.6	3.9									
AM27-23.Fm2	223	104	53	Rounded Core	Session1	0.207	180403	179	0.36	-1087	-15	1.80	1.2	0.23403	0.73	0.007	3.166	17.466	1.6	0.58257	1.6	0.611	0.18	1.76	3086	19	24	3061	19	35	3086	12	21	3081	10	3086	12	2186	98.2	1.2									
AM27-24.Fm2	224	100	53	Rounded Core	Session1	0.306	221780	116	0.18	-1157	-13	2.07	0.8	0.21419	0.73	0.031	2.342	14.4260	1.1	0.48906	0.7	0																											

AM27-103.FIN2	2103	51	49	Rounded	Core	Session1	1.390	368309	231	0.12	-2141	-18	2.51	2.7	0.22350	1.14	0.047	10.128	13.0432	2.3	0.42355	2.2	0.898	0.12	4.80	2999	36	42	2258	87	91	2647	49	52	2913	25	2222	208	1799	75.3	22.0
AM27-104.FIN2	2104	208	104	Rounded	Core	Session1	0.096	677057	315	0.03	-4171	-9	1.79	0.5	0.23215	0.35	0.009	8.029	18.1482	0.5	0.56297	0.5	0.772	0.15	3.07	3066	11	23	2876	44	40	2995	9	19	3031	8	2843	165	2223	98.8	4.5
AM27-105.FIN2	2105	164	73	Rounded	Core	Session1	0.117	214525	83	0.22	-1763	-13	1.66	1.2	0.23726	0.85	0.036	2.985	20.0406	1.3	0.60610	1.1	0.755	0.20	3.35	3097	27	34	3051	56	65	3088	25	30	3104	23	3589	220	2707	93.5	1.4
AM27-106.FIN2	2106	87	65	Rounded	Core	Session1	0.028	1126032	562	0.03	-5890	-15	1.78	0.5	0.23252	0.48	0.007	5.340	18.1761	0.5	0.56565	0.5	0.869	0.16	3.37	3065	15	26	2887	25	41	2998	9	19	2996	10	2910	189	2314	94.2	3.8
AM27-107.FIN2	2107	100	73	Rounded	Core	Session1	0.133	630112	303	0.06	-3799	-11	1.86	0.6	0.23155	0.44	0.011	4.429	17.3498	0.6	0.53932	0.5	0.610	0.16	3.00	3064	14	25	2780	25	41	2951	11	20	2967	11	2898	165	2723	90.7	6.1
AM27-108.FIN2	2108	126	55	Rounded	Core	Session1	0.101	564477	289	0.70	-3583	-11	1.84	0.6	0.23044	0.58	0.133	2.597	17.3799	0.7	0.54606	0.6	0.589	0.15	3.34	3052	18	27	2810	30	44	2952	13	22	2966	13	2762	183	2257	92.1	5.1
AM27-109.FIN2	2109	64	51	Rounded	Core	Session1	0.056	1464437	774	0.03	-5377	-36	1.80	0.8	0.23649	0.74	0.005	2.939	18.0663	0.6	0.55556	0.7	0.405	0.16	7.82	3093	23	30	2847	32	45	2992	12	21	2996	11	2870	441	2364	92.1	5.0
AM27-110.FIN2	2110	65	45	Rounded	Core	Session1	0.319	413482	192	0.90	-1334	-59	1.70	1.5	0.23057	1.20	0.145	5.051	18.9930	1.5	0.59239	1.5	0.862	0.18	2.11	3052	38	43	2996	71	79	3039	29	33	3058	21	3333	130	2534	98.2	1.8
AM27-111.FIN2	2111	108	78	Rounded	Core	Session1	-0.006	404029	189	0.97	-2782	-11	1.67	0.7	0.23299	0.53	0.157	2.719	19.3078	0.6	0.60123	0.7	0.569	0.15	2.87	3072	17	26	3031	33	47	3056	12	21	3060	11	2741	156	2240	98.7	0.8
AM27-112.FIN2	2112	157	84	Rounded	Core	Session1	0.008	444433	212	0.24	-3520	-10	1.67	0.5	0.23267	0.47	0.034	1.435	19.2520	0.6	0.60217	0.5	0.385	0.14	4.02	3067	15	25	3037	27	43	3053	11	20	3054	11	2618	208	2141	99.0	0.6
AM27-113.FIN2	2112	157	84	Rounded	Core	Session1	0.013	269363	117	0.26	-1984	-7	1.67	0.6	0.23359	0.45	0.036	1.440	19.4571	0.5	0.60382	0.6	0.641	0.15	2.16	3072	14	25	3041	28	44	3062	10	20	3068	9	2854	120	2287	99.0	0.7
AM27-114.FIN2	2114	126	87	Rounded	Core	Session1	0.057	296446	145	0.21	-2184	-8	1.84	0.6	0.23156	0.69	0.033	9.429	17.3911	0.8	0.54388	0.5	0.000	0.14	2.14	3057	14	19	2802	22	37	2956	10	14	2905	13	2684	111	2133	91.7	7.1
AM27-115.FIN2	2114	126	87	Rounded	Rim	Session1	1.437	283214	142	0.19	-1833	-9	1.92	1.5	0.23043	0.47	0.028	1.739	17.0567	0.5	0.53578	0.5	0.564	0.13	2.24	3046	14	24	2765	23	39	2934	10	19	2952	9	2505	108	1994	90.8	6.1
AM27-116.FIN2	2114	126	87	Rounded	Rim	Session1	0.059	242278	123	0.08	-1519	-9	1.86	0.8	0.22950	0.73	0.013	2.690	17.3027	1.1	0.54611	0.8	0.026	0.15	2.78	3028	17	22	2801	35	47	2935	21	27	2914	19	2723	144	2137	92.5	6.0
AM27-117.FIN2	2117	162	71	Rounded	Core	Session1	0.088	398172	182	1.48	-2439	-11	1.67	0.6	0.23098	0.48	0.227	2.611	19.3129	0.6	0.60260	0.6	0.392	0.15	2.36	3053	16	26	3037	27	43	3054	11	20	3058	11	2811	132	2302	99.5	0.6
AM27-118.FIN2	2118	100	72	Rounded	Core	Session1	0.122	250336	142	0.06	-1516	-11	2.03	0.8	0.21856	0.59	0.010	9.480	15.9572	0.9	0.49796	0.8	0.762	0.13	4.54	2967	19	27	2600	33	44	2815	17	24	2878	15	2388	209	1913	87.4	8.8
AM27-119.FIN2	2119	104	82	Rounded	Core	Session1	0.074	506738	243	0.06	-3786	-8	1.78	0.7	0.23220	0.51	0.023	40.102	17.9910	0.5	0.56412	0.6	0.838	0.16	3.24	3065	16	25	2874	26	39	2986	10	20	3022	7	2915	174	2219	93.8	4.2
AM27-120.FIN2	2119	104	82	Rounded	Core	Session1	-0.139	136033	55	0.17	-894	-16	1.70	1.1	0.23471	0.96	0.023	4.985	19.4108	1.0	0.59587	1.1	0.577	0.16	4.60	3076	30	36	3009	51	61	3058	20	26	3068	18	2960	259	2331	97.8	1.7
CI-214_24	2121	175	74	Rounded	Core	Session2	0.041	77366	47	0.95	398	119	1.56	2.3	0.27880	3.13	0.158	3.390	24.7627	2.1	0.64627	2.3	-0.059	0.19	3.60	3318	99	99	3303	115	115	3300	37	37	3288	38	2582	231	485	95.5	2.9
CI-214_33	2121	175	74	Rounded	Rim	Session2	0.077	433429	297	0.07	4171	60	1.77	1.7	0.22521	2.08	0.012	5.171	17.8027	1.8	0.56550	1.8	0.356	0.15	3.08	2957	67	67	2882	83	83	2971	35	35	2976	34	2829	160	380	96.2	3.1
CI-214_32	2122	99	65	Rounded	Core	Session2	0.123	267053	171	0.14	1155	110	1.66	1.6	0.22636	2.23	0.022	4.690	19.0141	1.6	0.60329	1.6	0.001	0.16	2.62	3001	72	72	3036	79	79	3037	30	30	3043	28	3037	146	398	101.2	0.3
CI-214_31	2123	281	71	Rounded	Core	Session2	0.122	292059	203	0.29	1411	123	1.79	1.7	0.23356	2.88	0.055	6.531	18.0076	2.1	0.55218	1.8	-0.109	0.15	2.59	3045	92	92	2829	81	81	2982	40	40	2954	35	2844	137	376	92.9	6.0
CI-214_30	2124	94	75	Rounded	Core	Session2	0.008	294248	253	0.03	4652	56	1.74	1.8	0.22872	2.78	0.030	61.118	18.9660	1.8	0.56878	1.9	-0.104	0.18	4.08	3009	89	89	2895	92	92	2986	35	35	2979	31	2955	246	468	96.2	3.4
CI-214_29	2125	233	77	Prismatic	Core	Session2	-0.001	503273	343	0.04	6375	51	1.80	2.0	0.23241	2.68	0.018	19.736	18.0209	1.8	0.55998	2.0	0.005	0.16	3.48	3034	84	84	2857	94	94	2983	35	35	2977	33	2930	189	406	94.2	4.5
CI-214_35	2125	233	77	Prismatic	Rim	Session2	0.152	479047	320	0.03	7564	36	1.80	1.9	0.22234	2.91	0.005	6.284	16.9798	2.1	0.54055	1.9	0.070	0.14	3.87	2965	98	98	2780	86	86	2925	42	42	2908	38	2652	191	379	93.8	5.7
CI-214_36	2125	233	77	Prismatic	Rim	Session2	0.061	274441	209	0.11	-1410	-84	1.98	1.5	0.22497	1.40	0.016	4.105	15.9225	1.8	0.50283	1.4	0.183	0.14	2.45	3006	45	45	2622	63	63	2864	34	34	2816	34	2680	122	353	87.2	10.0
CI-214_23	2126	153	84	Rounded	Core	Session2	0.011	640389	439	0.08	10729	44	1.72	2.0	0.24312	2.40	0.052	14.355	19.8381	2.0	0.58462	2.0	0.270	0.18	2.70	3115	79	79	2960	95	95	3075	39	39	3076	38	3437	194	515	95.0	4.0
CI-214_28	2126	153	84	Rounded	Rim	Session2	0.763	213690	143	0.12	5405	23	2.38	1.84	0.23544	2.48	0.040	8.618	17.8604	1.8	0.54403	1.7	-0.043	0.31	3.34	3059	81	81	2795	76	76	2975	35	35	2948	32	5403	320	711	91.4	7.1
CI-214_24	2127	100	59	Rounded	Core	Session2	0.054	554214	340	0.01	4079	107	1.78	2.2	0.23282	3.40	0.004	10.278	18.0661	2.7	0.55664	2.5	0.148	0.30	9.24	3038	110	110	2845	116	116	2999	48	48	2974	50	5133	806	991	93.6	5.2
CI-214_23	2128	202	73	Prismatic	Core	Session2	0.034	265100	177	0.44	3843	48	1.81	1.9	0.22168	2.35	0.092	7.477	17.1007	1.6	0.55390	1.9	0.042	0.15	2.14	2965	75	75	2833	89	89	2934	32	32	2930	29	2899	115	374	95.5	3.6
CI-214_21	2129	104	42	Rounded	Core	Session2	0.585	313465	87	1.32	2277	30	1.79	2.3	0.22486	2.68	0.054	3.782	17.7028	2.4	0.56028	2.2	0.377	0.18	2.04	2881	84	84	2857	102	102	2960	45	45	2969	46	3324	125	424	95.8	3.7
CI-214_20	2130	120	84	Rounded	Core	Session2	0.073	218930	141	0.23	5904	31	1.69	1.7	0.23159	2.17	0.303	3.310	19.0945	1.7	0.59083	1.7	0.219	0.16	2.01	3039	69	69	2986	80	80	3039	33	33	3042	32	2935	110	377	98.2	1.9
CI-214_25	2131	154	65	Prismatic	Core	Session2	0.216	119984	90	1.31	2012	41	2.07	2.9	0.21978	2.42	0.293	3.790	15.2509	2.9	0.49726	2.9	0.607	0.19	4.33	2957	81	81	2583	124	124	2804	59	59	2855	53	3423	267	488	87.3	8.5
CI-214_26	2132	98	66	Rounded	Core	Session2	0.252	291757	200	0.13	7088	38	1.78	1.7	0.22382	2.39	0.034	6.229	17.4174	1.8																					

[illegible][illegible]

[illegible]

Supplementary Table S5: U-Pb reference materials (sample CJ-211)

LEGA, Universidade de Brasília						Data for Tera-Wasserburg plot				Data for Wetherill plot				Dates																			
Identifier	Comments	f206c	206Pb	Uppm	Th/U	206Pb/204 1s%	238U/206l 1s%	207Pb/204 1s%	208Pb/204 1s%	207Pb/235 1s%	206Pb/236 1s%	Rho	208Pb/231 1s%	207Pb/204 2s (abs)	2ssys (abs)	206Pb/231 2s (abs)	2ssys (abs)	207Pb/235 2s (abs)	2ssys (abs)	208Pb/231 2s (abs)	2ssys (abs)	% conc											
GJ1-2	Z_GJ1	0.680195	107528	303	0.03	-837.88	-7.49788	10.25	0.5	0.06070	0.85	0.004618	6.487592	0.8245	0.8	0.09815	0.5	0.17	0.027607	6.401145	604	36	36	603	5	5	609	7	7	541.0114	68.90422	98.12872	99.1
GJ1-3	Z_GJ1	0.43985	103149	285	0.03	-1037.15	-5.92624	10.32	0.5	0.05952	0.87	0.005244	5.805653	0.8039	0.8	0.09737	0.5	0.20	0.032997	6.015424	563	40	40	599	6	6	598	8	8	653.1302	78.28037	115.1597	100.2
GJ1-5	Z_GJ1	0.474857	107228	303	0.03	-1007.61	-6.1863	10.25	0.5	0.06012	0.82	0.004952	6.03731	0.8175	0.8	0.09800	0.5	0.20	0.030207	6.033354	580	37	37	603	5	5	605	7	7	597.961	72.32079	106.2231	99.7
GJ1-7	Z_GJ1	-0.1393	107575	313	0.03	-766.955	-7.78002	10.25	0.5	0.06032	0.86	0.005367	6.693024	0.8175	0.8	0.09805	0.5	0.15	0.032987	6.532784	587	37	37	603	6	6	605	7	7	643.6936	83.35554	117.503	99.6
GJ1-8	Z_GJ1	-0.29825	99501	270	0.03	-691.825	-7.64481	10.30	0.5	0.06030	0.89	0.005017	7.002866	0.8137	0.9	0.09742	0.5	0.21	0.028662	7.034384	588	38	38	599	5	6	602	8	8	584.7399	83.10472	113.0772	99.5
GJ1-9	Z_GJ1	-0.16884	99919	284	0.03	-778.424	-6.93804	10.30	0.5	0.06058	0.93	0.005272	6.718968	0.8183	0.9	0.09762	0.5	0.11	0.031378	6.777846	591	40	40	600	6	6	605	8	8	613.5371	82.77552	114.6082	99.2
GJ1-10	Z_GJ1	-0.0564	95834	268	0.03	-759.835	-6.72515	10.25	0.5	0.05977	0.94	0.005236	6.541601	0.8098	0.9	0.09806	0.5	0.18	0.031125	6.505592	564	40	40	603	6	6	601	8	8	609.0914	78.65021	111.1003	100.3
GJ1-11	Z_GJ1	-0.06216	95811	281	0.03	-754.837	-7.09651	10.35	0.5	0.06053	0.87	0.005754	6.128283	0.8140	0.8	0.09711	0.5	0.22	0.034797	5.923641	590	38	38	597	6	6	603	7	7	680.04	79.93829	118.5825	99.0
GJ1-13	Z_GJ1	0.210144	97687	286	0.03	-958.14	-5.6131	10.26	0.5	0.06037	0.81	0.005759	6.058007	0.8155	0.7	0.09799	0.5	0.16	0.032491	5.666733	592	36	36	603	6	6	604	6	6	643.6378	72.95285	110.9251	99.8
GJ1-14	Z_GJ1	0.092459	98994	292	0.03	-1020.76	-5.48791	10.28	0.5	0.05970	0.80	0.005341	5.748625	0.8121	0.8	0.09797	0.5	0.30	0.032936	6.063123	570	36	36	602	6	6	602	7	7	650.7342	78.42675	114.8889	100.1
GJ1-15	Z_GJ1	0.371906	99732	294	0.03	-1031.63	-5.58629	10.21	0.5	0.05974	0.84	0.004936	6.279253	0.8168	0.8	0.09844	0.5	0.15	0.028697	6.474688	568	37	37	605	5	5	604	7	7	561.4862	72.66968	102.8964	100.1
GJ1-16	Z_GJ1	-0.07075	101570	307	0.03	-668.567	-8.46086	10.21	0.5	0.05973	0.85	0.005217	6.251413	0.8132	0.8	0.09832	0.5	0.22	0.031197	6.239974	575	37	37	604	5	6	604	7	7	610.4609	75.65257	109.1579	100.1
GJ1-17	Z_GJ1	-0.11722	99661	300	0.03	-791.264	-6.23082	10.19	0.5	0.05976	0.88	0.007188	27.68157	0.8169	0.8	0.09884	0.5	0.12	0.032661	6.50503	586	36	36	607	6	6	605	7	7	636.2581	81.95106	115.7668	100.4
GJ1-18	Z_GJ1	-0.23031	89089	264	0.03	-701.251	-6.60487	10.33	0.5	0.06045	0.88	0.005705	6.525472	0.8148	0.8	0.09733	0.5	0.08	0.031543	6.360044	593	39	39	599	6	6	603	7	7	617.2986	78.04536	111.5125	99.3
GJ1-19	Z_GJ1	0.394532	92004	275	0.03	-559.623	-9.43451	10.29	0.5	0.05998	0.80	0.004953	6.340926	0.8158	0.8	0.09766	0.5	0.35	0.028067	6.155129	588	35	35	601	6	6	604	7	7	551.0941	67.62729	98.28112	99.5
GJ1-20	Z_GJ1	-0.0534	99241	306	0.03	-858.916	-6.19449	10.34	0.5	0.06039	0.92	0.004595	6.724649	0.8130	0.9	0.09745	0.5	0.52	0.026731	6.778836	587	41	41	599	6	6	602	8	8	524.752	70.76355	97.97109	99.5
GJ1-21	Z_GJ1	-0.02011	95209	295	0.03	-909.609	-6.01581	10.28	0.6	0.06059	0.92	0.006745	14.9926	0.8181	0.9	0.09783	0.5	0.17	0.034006	5.591224	591	40	40	602	6	6	606	8	8	665.9865	73.47459	112.5771	99.3
GJ1-23	Z_GJ1	0.176012	91584	283	0.03	-1021.04	-4.97606	10.33	0.5	0.06014	0.87	0.00479	7.550648	0.8107	0.9	0.09726	0.6	0.29	0.02621	7.466433	574	38	38	598	6	6	601	8	8	519.5572	75.1813	99.61675	99.6
GJ1-24	Z_GJ1	0.108763	94844	295	0.03	-1059.92	-4.97242	10.27	0.5	0.06020	0.84	0.005781	8.94399	0.8175	0.8	0.09797	0.5	0.20	0.030675	6.080088	576	37	37	602	6	6	605	7	7	600.3553	72.35885	105.8418	99.6
GJ1-25	Z_GJ1	-0.02063	92543	288	0.03	-978.972	-4.97242	10.28	0.5	0.06011	0.88	0.00571	5.831051	0.8154	0.8	0.09792	0.5	0.21	0.032975	5.74073	577	40	40	602	6	6	603	8	8	645.1408	73.50198	110.945	99.8
91500-1	Z_91500	0.36698	27238	42	0.54	-264.096	-5.76049	5.68	0.9	0.07836	1.65	0.085081	2.570042	1.9218	1.5	0.18043	0.9	0.16	0.059631	2.402047	1066	68	68	1068	17	17	1079	20	20	1169.965	55.29642	159.3253	99.0
91500-2	Z_91500	0.076221	26744	41	0.54	-231.591	-6.54562	5.69	0.9	0.07997	1.77	0.087027	2.645295	1.9481	1.4	0.18054	0.9	-0.07	0.060445	2.491046	1085	73	73	1068	18	18	1083	19	19	1179.963	57.03322	159.1804	98.6
91500-3	Z_91500	0.475814	27542	42	0.53	-241.975	-8.6217	5.60	0.9	0.07544	1.63	0.087653	2.409095	1.8838	1.4	0.18264	0.9	0.50	0.062513	2.352009	981	70	70	1079	18	18	1062	19	19	1224.563	56.4227	165.615	101.6
91500-4	Z_91500	0.517324	27082	42	0.54	-205.53	-7.03305	5.69	0.9	0.07635	1.81	0.088244	2.603441	1.8638	1.5	0.17918	0.9	-0.09	0.060514	2.419494	991	77	77	1061	17	17	1052	20	20	1181.585	55.56526	159.085	100.8
91500-5	Z_91500	1.242089	26367	42	0.54	-189.684	-7.49313	5.82	0.9	0.07243	1.80	0.089176	2.70721	1.7301	1.5	0.17593	0.9	-0.09	0.060054	2.586983	895	77	77	1043	18	18	1007	20	20	1177.438	59.77474	161.4469	103.6
91500-6	Z_91500	0.749351	26568	42	0.53	-222.426	-6.44864	5.69	0.9	0.07622	1.71	0.086089	2.592116	1.8755	1.5	0.17897	0.9	0.00	0.05955	2.401934	1017	71	71	1061	17	17	1058	20	20	1163.488	54.38815	156.7103	100.2
91500-7	Z_91500	1.050467	26808	43	0.53	-233.7	-6.65603	5.65	0.9	0.07731	1.82	0.08877	2.662575	1.8760	1.5	0.18081	0.9	-0.12	0.061774	2.465498	1017	77	77	1069	18	18	1066	20	20	1210.192	58.4708	164.6627	100.3
91500-8	Z_91500	0.07136	26881	43	0.53	-260.549	-6.14722	5.62	0.9	0.07723	1.68	0.083788	2.577091	1.9024	1.4	0.18058	0.9	0.02	0.05759	2.397713	1030	71	71	1068	18	18	1073	19	19	1126.431	52.51	151.5411	99.6
91500-9	Z_91500	-0.08141	26512	42	0.54	-285.719	-5.31602	5.66	0.9	0.07488	1.81	0.086487	2.363856	1.8386	1.5	0.18107	0.9	-0.03	0.059413	2.327157	967	72	72	1071	18	18	1052	19	19	1161.26	52.66337	156.0378	101.8
91500-10	Z_91500	1.669145	26194	42	0.54	-282.439	-5.50059	5.69	0.9	0.07674	1.71	0.089016	2.547824	1.8802	1.5	0.17949	0.9	-0.02	0.059847	2.365916	1031	71	71	1062	17	17	1060	21	21	1179.138	55.36059	160.0545	100.2
91500-11	Z_91500	2.096473	25985	42	0.53	-288.261	-5.29205	5.68	1.0	0.07681	1.63	0.091518	2.58842	1.8998	1.5	0.18115	0.9	0.05	0.062977	2.568893	1021	70	70	1071									

Supplementary Table S6: U-Pb reference materials (sample PJ-1)

LEGGA, Universidade de Brasília				Data for Tera-Wasserburg plot				Data for Wetherill plot				Dates																					
Identifier	Comments	T206c	206Pb	Uppm	Th/U	206Pb/204 1s%	238U/206Pb 1s%	207Pb/206 1s%	208Pb/206 1s%	207Pb/235 1s%	206Pb/235 1s%	Rho	208Pb/231 1s%	207Pb/206 2s (abs)	2ssys (abs)	206Pb/231 2s (abs)	2ssys (abs)	207Pb/235 2s (abs)	2ssys (abs)	208Pb/231 2s (abs)	2ssys (abs)	% conc											
GJ-1.FIN2_Z_GJ1		0.025529	145141	292	0.03	-2519.15	-4.57021	10.42	0.8	0.06027	1.34	0.005055	26.098	0.8124	1.1	0.09718	0.8	-0.06	0.033435	9.13188	566	59	59	598	9	9	602	10	10	657.9372	74.08986	118.0496	99.3
GJ-2.FIN2_Z_GJ1		0.361126	141207	278	0.03	-2345.65	-5.58843	10.39	0.9	0.05858	1.45	0.014498	75.33142	0.7940	1.1	0.09749	0.8	-0.17	0.031661	9.61834	562	577	64	599	10	10	593	9	9	623.5777	79.27385	117.6967	101.1
GJ-3.FIN2_Z_GJ1		0.036282	142756	286	0.03	-2366.58	-5.17355	10.43	0.8	0.06065	1.43	0.003628	7.55945	0.8102	1.1	0.09693	0.8	-0.14	0.030848	9.354399	564	63	63	596	9	9	600	9	10	607.3935	72.50796	111.5644	99.3
GJ-4.FIN2_Z_GJ1		0.176666	146007	293	0.03	-2591.55	-4.78752	10.37	0.8	0.06004	1.41	0.008506	50.84929	0.8082	1.1	0.09738	0.8	-0.12	0.037629	14.5028	556	64	64	599	9	9	599	10	10	656.1374	90.0454	103.3101	99.9
GJ-5.FIN2_Z_GJ1		0.110803	144900	290	0.03	-2634.23	-4.32269	10.35	0.8	0.06029	1.38	0.003481	5.621825	0.8190	1.1	0.09780	0.8	-0.01	0.028406	8.92256	576	58	58	601	9	9	605	9	10	561.7002	59.67156	98.75218	99.3
GJ-6.FIN2_Z_GJ1		0.021426	145832	292	0.03	-3778.91	-3.71642	10.24	0.8	0.05972	1.37	0.00863	35.27884	0.8137	1.1	0.09861	0.8	-0.02	0.043252	15.02144	545	58	58	606	9	9	603	9	10	748.6567	129.8037	147.4122	100.6
GJ-7.FIN2_Z_GJ1		0.143073	141572	282	0.03	-3455.81	-4.23313	10.24	0.8	0.06071	1.33	0.005429	21.58027	0.8290	1.1	0.09882	0.7	-0.02	0.032711	9.612742	581	58	58	607	9	9	611	9	10	642.3024	80.71956	119.9269	99.4
GJ-8.FIN2_Z_GJ1		0.326186	141782	288	0.03	-6904.95	-3.69171	10.29	0.8	0.06001	1.36	0.003358	5.749329	0.8184	1.1	0.09841	0.8	0.03	0.028698	8.829192	578	58	58	605	9	9	605	10	10	567.5077	58.59114	98.80767	100.0
GJ-9.FIN2_Z_GJ1		0.333167	141160	288	0.03	-6996.84	-3.46199	10.31	0.8	0.06013	1.31	0.004047	15.10726	0.8160	1.1	0.09816	0.8	0.03	0.028691	10.31088	560	59	59	603	9	9	604	10	11	543.6183	71.47556	98.6852	99.8
GJ-10.FIN2_Z_GJ1		-0.05405	139482	285	0.03	-2741.18	-3.96273	10.22	0.8	0.05978	1.34	0.004607	20.42878	0.8214	1.1	0.09870	0.8	-0.02	0.033939	10.39245	549	59	59	606	9	9	607	9	10	663.0428	96.60646	132.4464	100.0
GJ-11.FIN2_Z_GJ1		0.048725	138259	288	0.03	-2388.02	-4.81387	10.38	0.8	0.06100	1.43	0.003514	9.530057	0.8229	1.1	0.09747	0.8	-0.08	0.027357	9.545608	586	63	63	599	9	9	607	10	10	539.9661	67.2332	100.7526	98.7
GJ-12.FIN2_Z_GJ1		-0.02845	136531	287	0.03	-3043.34	-0.40695	10.35	0.8	0.05959	1.47	0.003894	14.59686	0.8128	1.4	0.09786	0.8	-0.01	0.030711	9.707776	530	61	61	602	9	9	597	10	10	604.0537	77.92058	114.4312	100.8
GJ-13.FIN2_Z_GJ1		-0.03419	137614	287	0.03	-2823.13	-4.1535	10.33	0.8	0.05976	1.43	0.003904	12.29063	0.8121	1.3	0.09776	0.8	0.05	0.029778	9.963342	535	62	62	601	9	9	601	11	11	585.1759	79.88156	114.0194	100.0
GJ-14.FIN2_Z_GJ1		-0.12736	136161	290	0.03	-3244.34	-4.91444	10.31	0.9	0.06034	1.60	0.004447	12.38353	0.8220	1.3	0.09844	0.9	-0.02	0.031335	9.553514	556	67	67	605	10	10	606	11	12	616.3623	76.63358	114.7218	99.8
GJ-15.FIN2_Z_GJ1		0.077964	138573	294	0.03	-3279.1	-3.74826	10.30	0.9	0.06087	1.41	0.004848	11.39248	0.8247	1.1	0.09840	0.9	0.00	0.036915	10.23073	581	62	62	605	10	10	608	9	10	719.6321	101.2735	140.8346	99.4
GJ-16.FIN2_Z_GJ1		0.2292	135978	296	0.03	-2563.66	-4.9667	10.34	0.8	0.06136	1.49	0.007207	31.07095	0.8239	1.2	0.09713	0.8	0.00	0.035044	12.06925	589	63	63	597	9	9	607	11	11	676.5549	123.4294	152.7418	98.3
GJ-17.FIN2_Z_GJ1		0.258333	136688	298	0.03	-2501.36	-4.88419	10.40	0.8	0.06041	1.44	0.008982	55.14767	0.8183	1.2	0.09719	0.8	-0.10	0.036617	24.1565	571	63	63	598	9	9	603	10	11	558.1309	77.89533	81.50522	99.1
GJ-18.FIN2_Z_GJ1		0.254898	124962	275	0.03	-3919.81	-3.60465	10.34	0.8	0.06071	1.54	0.00582	22.82348	0.8206	1.4	0.09786	0.8	0.03	0.030777	10.41508	562	64	64	602	9	9	605	12	12	602.7342	67.68977	119.9928	98.4
GJ-19.FIN2_Z_GJ1		0.004579	125200	277	0.03	-3713.73	-3.5593	10.43	0.8	0.06119	1.52	0.003405	6.788935	0.8231	1.3	0.09721	0.8	-0.03	0.027964	9.88183	578	66	66	598	9	9	607	11	11	559.6872	76.4215	110.0295	99.5
GJ-20.FIN2_Z_GJ1		0.378914	138499	307	0.03	-7911.74	-19.7885	10.30	0.9	0.06046	1.36	0.004263	13.14989	0.8226	1.1	0.09850	0.9	-0.01	0.032307	9.587871	577	63	63	605	10	10	607	10	10	634.7626	79.87667	119.0492	99.7
GJ-21.FIN2_Z_GJ1		0.25976	135928	302	0.03	-6460.11	-3.60881	10.28	0.8	0.05899	1.32	0.004407	16.70113	0.8028	1.2	0.09819	0.8	-0.01	0.03187	9.6668	526	58	58	603	9	9	596	10	10	626.0115	80.51022	118.819	101.2
GJ-22.FIN2_Z_GJ1		0.193456	124734	285	0.03	-4085.48	-3.60387	10.33	0.8	0.06063	1.51	0.004264	12.5253	0.8173	1.2	0.09782	0.8	-0.08	0.031667	9.643019	561	63	63	601	9	9	604	11	11	622.1971	79.18999	117.2129	99.6
GJ-23.FIN2_Z_GJ1		0.444714	121861	274	0.03	-3652.22	-6.10383	10.35	0.8	0.06027	1.61	0.005192	23.9859	0.8168	1.3	0.09783	0.8	0.38	0.030439	10.05179	562	68	68	601	9	9	603	11	12	597.7463	82.78814	117.1074	99.7
GJ-24.FIN2_Z_GJ1		0.166203	122368	279	0.03	-3081.6	-4.12047	10.22	0.8	0.05916	1.32	0.007157	51.78439	0.8084	1.1	0.09867	0.8	0.00	0.030702	9.897147	534	60	60	606	9	9	600	9	10	603.0787	81.73225	117.4811	101.1
GJ-25.FIN2_Z_GJ1		0.201817	119061	276	0.03	-3251	-3.83853	10.39	0.8	0.05972	1.42	0.004525	14.89292	0.8066	1.1	0.09713	0.8	-0.11	0.033654	10.04803	555	60	60	597	9	9	598	9	10	638.9176	81.60894	115.4833	99.8
GJ-26.FIN2_Z_GJ1		-0.06988	122108	283	0.03	-2821.6	-3.87309	10.30	0.8	0.05931	1.42	0.004462	13.97217	0.8074	1.2	0.09805	0.8	0.00	0.030431	9.956928	533	62	62	603	9	9	598	10	11	597.5043	81.68561	116.6719	100.7
GJ-27.FIN2_Z_GJ1		0.245732	122216	287	0.03	-2853.45	-0.02797	10.40	0.8	0.05982	1.42	0.005907	26.4566	0.8073	1.2	0.09736	0.8	-0.03	0.038156	13.41507	563	66	66	599	9	9	598	10	11	688.5549	129.899	153.1787	100.0
GJ-28.FIN2_Z_GJ1		-0.16081	123924	292	0.03	-2637.13	-4.07307	10.26	0.8	0.06046	1.36	0.00563	25.41374	0.8213	1.0	0.09868	0.8	-0.09	0.036756	13.2461	569	60	60	606	9	9	608	9	10	738.8497	132.6063	157.1617	99.8
GJ-29.FIN2_Z_GJ1		-0.22587	116709	281	0.03	-2647.94	-3.54988	10.39	0.8	0.06062	1.47	0.016584	80.34233	0.8114	1.2	0.09713	0.7	-0.13	0.027552	9.6814	567	64	64	597	8	8	602	10	11	543.1682	70.23536	103.4718	99.3
GJ-30.FIN2_Z_GJ1		0.127238	118375	287	0.03	-4461.86	-3.32263	10.38	0.8	0.05908	1.47	0.003405	8.365249	0.7977	1.1	0.09745	0.8	-0.09	0.025484	10.11453	514	64	64	599	9	9	593	10	10	502.2717	71.24638	100.1635	101.0
GJ-31.FIN2_Z_GJ1		0.388742	117706	285	0.03	-5097.05	-4.58911	10.41	0.8	0.06000	1.45	0.003783	13.81815	0.8077	1.2	0.09758	0.9	-0.04	0.029176	9.466416	546	63	63	600	10	10	600	11	11	575.0006	70.95416	107.4592	100.1
GJ-32.FIN2_Z_GJ1		-0.01376	117924	284	0.03	-3204.58	-3.55326	10.20	0.8	0.06077	1.43	0.004576	16.22292	0.8315	1.2	0.09887	0.8	0.10	0.035831	10.3452	593	65	65	609	9	9	612	10	11	674.7445	88.06443	121.2621	99.5
GJ-33.FIN2_Z_GJ1		-0.01415	114560	283	0.03	-3129.47	-3.5996	10.37	0.8	0.06099	1.42	0.00551	28.42736	0.8249	1.1	0.09777	0.8	0.05	0.029661	10.43575	586	61	61	601	9	9	608	10	10	581.3716	86.20425	117.7574	98.8
GJ-34.FIN2_Z_GJ1		0.291276	114061	282	0.03	-4232.66	-3.69095	10.36	0.9	0.05968	1.48	0.006802	41.35624	0.8058	1.2	0.09774	0.9	0.27	0.03398	10.93443	524	65	65	601	10	10	597	11	11	661.4322	105.8728	139.3474	100.6
GJ-35.FIN2_Z_GJ1		0.160678	115966	291	0.03	-4077.84	-3.75032	10.40	0.9	0.06120	1.74	0.004114	9.973691	0.8260	1.3	0.09741	0.9	0.05	0.032099	10.59001	583	71	71	5									

91500-34.I_Z_91500	-0.94304	27011	38	0.83	-548.839	-4.37894	5.84	1.0	0.07789	2.40	0.088086	3.150265	1.8700	2.1	0.17431	1.1	-0.06	0.053241	7.597459	1036	90	90	1034	21	21	1057	26	26	1054.08	57.49186	163.0338	97.8
PLES-1.FIN_Z_Plesovio	0.038277	159392	573	0.36	-2609.3	-4.6988	18.60	0.7	0.05295	1.09	0.040605	2.357951	0.4007	1.0	0.05420	0.7	0.08	0.017831	7.301343	297	52	52	340	5	5	342	5	6	357.0459	11.76905	51.66997	99.5
PLES-2.FIN_Z_Plesovio	-0.00368	186302	674	0.46	-3216.83	-4.28828	18.61	0.7	0.05216	1.17	0.047163	1.694806	0.3929	1.0	0.05419	0.7	-0.06	0.016534	7.265464	250	55	55	340	4	4	336	5	6	331.3558	9.842313	47.75159	101.3
PLES-3.FIN_Z_Plesovio	0.200997	131009	473	0.27	-2860.91	-4.27498	18.34	0.7	0.05359	1.34	0.027519	2.535015	0.4084	1.2	0.05484	0.7	0.06	0.016649	7.48419	305	59	59	344	5	5	347	7	7	333.4474	15.45677	49.46448	99.3
PLES-4.FIN_Z_Plesovio	-0.04728	132356	480	0.28	-2734.94	-4.36615	18.58	0.7	0.05341	1.25	0.028595	2.24099	0.4045	1.2	0.05433	0.7	0.12	0.017274	7.467563	295	58	58	341	5	5	344	7	7	345.8659	15.6673	51.2022	99.1
PLES-5.FIN_Z_Plesovio	0.536262	133434	496	0.29	-4362.28	-4.30043	18.72	0.7	0.05302	1.20	0.029728	2.606612	0.3989	1.1	0.05391	0.7	0.05	0.016827	7.466851	297	56	56	338	4	4	340	6	6	336.9869	15.2515	49.8875	99.5
PLES-6.FIN_Z_Plesovio	0.486951	127491	470	0.28	-3447.5	-4.51968	18.61	0.6	0.05342	1.16	0.038935	13.24264	0.4022	1.1	0.05401	0.6	0.19	0.018013	7.725863	308	54	54	339	4	4	342	6	6	360.271	21.44499	54.78499	99.0
PLES-7.FIN_Z_Plesovio	0.256333	126837	474	0.28	-1811.89	-5.87046	18.63	0.7	0.05468	1.59	0.029165	3.44881	0.4141	1.5	0.05410	0.7	0.12	0.016759	7.44742	328	67	67	340	5	5	350	8	9	335.6729	14.77204	49.59201	97.0
PLES-8.FIN_Z_Plesovio	-0.00079	133301	497	0.28	-2113.41	-4.74767	18.53	0.7	0.05256	1.27	0.029582	2.486774	0.3983	1.1	0.05451	0.7	0.03	0.017185	7.393338	284	58	58	342	5	5	340	6	6	344.1568	13.84954	50.45255	100.7
PLES-9.FIN_Z_Plesovio	-0.01223	130256	490	0.28	-2178.39	-4.49569	18.48	0.7	0.05342	1.49	0.029392	3.108502	0.4047	1.2	0.05452	0.7	-0.08	0.01705	7.395642	290	62	62	342	4	4	344	7	7	341.4695	13.78928	50.05303	99.5
PLES-10.FI_Z_Plesovio	-0.11652	128835	488	0.28	-1978.09	-4.87148	18.66	0.7	0.05377	1.40	0.032859	9.494605	0.4064	1.5	0.05406	0.6	0.11	0.016635	7.462888	301	61	61	339	4	4	345	8	8	333.1833	14.98568	49.27471	98.5
PLES-11.FI_Z_Plesovio	0.037626	133979	522	0.29	-3268.25	-4.03266	18.80	0.8	0.05317	1.28	0.030791	3.211582	0.3959	1.1	0.05352	0.7	0.01	0.016966	7.461826	307	62	62	336	5	5	338	6	6	339.7455	15.25295	50.21894	99.5
PLES-12.FI_Z_Plesovio	0.301911	134414	517	0.28	-3085.76	-4.56384	18.46	0.7	0.05382	1.21	0.031174	4.21026	0.4086	1.1	0.05452	0.7	0.11	0.017697	7.393614	315	55	55	342	5	5	347	6	7	354.299	14.25583	51.90932	98.6
PLES-13.FI_Z_Plesovio	0.054795	120758	458	0.30	-1969.31	-5.81152	18.55	0.7	0.05386	1.46	0.031823	8.072756	0.4085	1.3	0.05436	0.7	0.16	0.016922	7.478416	306	61	61	341	5	5	345	6	7	338.9323	15.58978	50.2463	98.8
PLES-15.FI_Z_Plesovio	0.164133	121826	483	0.29	-3294.41	-3.8473	18.83	0.7	0.05400	1.34	0.02972	2.025972	0.4058	1.5	0.05357	0.7	0.10	0.01656	7.375468	316	60	60	336	5	5	342	7	7	331.7841	12.9195	48.5325	98.3
PLES-16.FI_Z_Plesovio	0.124911	123575	499	0.29	-3267.75	-3.98265	18.78	0.7	0.05442	1.55	0.034791	8.366966	0.4086	1.4	0.05372	0.7	0.02	0.01762	7.75658	313	64	64	337	5	5	346	8	8	352.4839	21.43592	53.60753	97.3
PLES-17.FI_Z_Plesovio	0.422784	135582	544	0.29	-4128.76	-4.89091	18.54	0.7	0.05200	1.33	0.031115	5.534164	0.4004	1.3	0.05438	0.7	0.09	0.016585	7.423762	289	65	65	341	5	5	341	7	7	332.226	14.01698	48.68258	100.1
PLES-19.FI_Z_Plesovio	0.164139	128315	526	0.32	-3350.76	-3.94894	18.66	0.6	0.05289	1.25	0.034678	2.173848	0.4007	1.2	0.05395	0.6	-0.03	0.01679	7.36611	271	57	57	339	4	4	341	7	7	336.338	12.84533	49.08403	99.3
PLES-20.FI_Z_Plesovio	1.240391	124462	515	0.29	-3009.01	-4.55968	18.79	0.7	0.05416	1.68	0.042607	27.34377	0.4013	1.2	0.05367	0.6	0.12	0.017247	7.872881	304	53	53	337	4	4	342	6	7	344.9803	22.76266	52.9855	98.6
PLES-21.FI_Z_Plesovio	0.233191	153902	644	0.47	-4428.71	-4.12633	18.62	0.7	0.05294	1.21	0.047421	2.316223	0.3997	1.1	0.05426	0.7	-0.01	0.01613	7.337422	293	58	58	341	5	5	341	6	6	323.2473	11.62335	46.99528	100.0
PLES-22.FI_Z_Plesovio	0.440406	149552	625	0.48	-4134.6	-4.51128	18.48	0.6	0.05295	1.12	0.048878	1.585809	0.4031	1.1	0.05445	0.6	0.15	0.016464	7.279156	300	53	53	342	4	4	343	6	6	329.932	10.22588	47.61398	99.6
PLES-23.FI_Z_Plesovio	0.301095	129083	550	0.31	-3202.21	-4.34568	18.58	0.6	0.05341	1.15	0.036474	4.886475	0.4016	1.0	0.05419	0.6	0.11	0.017544	7.381555	301	53	53	340	4	4	342	6	6	351.2765	13.81749	51.35765	99.4
PLES-24.FI_Z_Plesovio	0.507972	119967	514	0.29	-3325.16	-4.03828	18.62	0.6	0.05332	1.36	0.032143	4.262593	0.4021	1.3	0.05416	0.6	0.02	0.016677	7.590402	290	59	59	340	4	4	342	7	7	333.9119	17.54858	50.0949	99.4
PLES-26.FI_Z_Plesovio	0.173053	154548	666	0.48	-2719.22	-5.03133	18.48	0.6	0.05290	1.18	0.050784	2.344035	0.4030	1.1	0.05448	0.6	0.07	0.016664	7.322169	282	57	57	342	4	4	343	6	6	333.8747	11.5853	48.39936	99.7
PLES-27.FI_Z_Plesovio	0.189194	151734	671	0.48	-6765.08	-3.57858	18.78	0.7	0.05337	1.18	0.052756	6.223036	0.3985	1.1	0.05368	0.7	0.01	0.016078	7.416658	297	54	54	337	5	5	340	6	6	322.1522	13.47295	47.30259	99.2
PLES-28.FI_Z_Plesovio	0.366523	130812	577	0.37	-5160.82	-3.73288	18.91	0.6	0.05420	1.11	0.038256	2.122496	0.4040	1.0	0.05330	0.6	-0.03	0.015699	7.304775	349	48	48	335	4	4	344	5	6	314.7079	10.4805	45.61973	97.3
PLES-29.FI_Z_Plesovio	0.443589	119378	533	0.29	-2896.77	-4.09373	18.64	0.7	0.05282	1.25	0.032223	7.015871	0.3968	1.1	0.05407	0.7	0.18	0.016776	7.506236	296	57	57	339	5	5	339	6	6	335.9354	16.02688	49.95154	100.1
PLES-30.FI_Z_Plesovio	0.042629	110981	505	0.28	-2623.06	-4.06581	18.92	0.7	0.05356	1.27	0.031651	6.594456	0.3990	1.3	0.05329	0.7	0.19	0.016031	7.50157	298	58	58	335	4	4	340	7	7	321.1552	15.24522	47.77579	98.5
PLES-32.FI_Z_Plesovio	-0.09977	114745	524	0.30	-3329.12	-3.68472	18.61	0.7	0.05296	1.20	0.029349	3.180033	0.4012	1.1	0.05407	0.7	0.05	0.015441	7.511169	287	58	58	339	4	4	342	6	6	309.4223	14.86268	46.0594	99.3
PLES-33.FI_Z_Plesovio	-0.14396	118437	551	0.30	-2176.46	-4.2767	18.80	0.7	0.05350	1.32	0.030476	3.018643	0.3985	1.2	0.05359	0.8	0.05	0.015852	7.572473	291	61	61	336	5	5	339	7	7	317.5406	16.41126	47.66213	99.1
PLES-34.FI_Z_Plesovio	-0.16995	111011	520	0.29	-2173.13	-3.46258	18.97	0.6	0.05423	1.12	0.029304	4.325802	0.4020	1.1	0.05301	0.6	0.12	0.015052	7.566422	356	51	51	333	4	4	342	6	6	301.6687	15.45883	45.1633	97.3

Supplementary Table S7: U-Pb reference materials (samples CJ-214 and CJ-215)

LEGGA, Universidade de Brasília				Data for Tera-Wasserburg plot				Data for Wetherill plot				Dates																				
Identifier	Comments	T206c	206Pb	Uppm	Th/U	206Pb/204 1s%	238U/206i 1s%	207Pb/204 1s%	208Pb/204 1s%	207Pb/235 1s%	206Pb/235 1s%	Rho	208Pb/231 1s%	207Pb/204 2s (abs)	2ssys (abs)	206Pb/231 2s (abs)	2ssys (abs)	207Pb/235 2s (abs)	2ssys (abs)	208Pb/231 2s (abs)	2ssys (abs)	% conc										
GJ1-2.FIN2_Z_GJ1	0.054483	118950	292	0.03	-272.866	-27.3868	10.33	0.5	0.06054	0.84	0.00503	8.307397	0.8179	0.8	0.09739	0.5	0.08	0.026923	7.801206	594	36	45	599	6	10	605	7	11	543.4861	85.49939	459.4434	99.0
GJ1-3.FIN2_Z_GJ1	0.023976	120019	294	0.03	-352.71	-19.048	10.27	0.6	0.06026	0.84	0.005744	6.144333	0.8152	0.8	0.09800	0.6	0.28	0.030974	6.012954	587	36	45	602	7	10	604	7	11	622.4631	75.18438	520.4682	99.8
GJ1-4.FIN2_Z_GJ1	-0.1192	119443	292	0.03	-306.372	-23.5496	10.28	0.5	0.05960	0.77	0.005474	6.048101	0.8085	0.7	0.09796	0.5	0.33	0.031045	5.919249	567	33	43	602	6	10	601	7	11	609.2141	71.68377	503.9299	100.3
GJ1-5.FIN2_Z_GJ1	-0.12059	118622	292	0.03	-291.582	-24.9958	10.30	0.6	0.06067	0.88	0.005848	6.01477	0.8183	0.8	0.09776	0.6	0.31	0.032457	5.978788	596	38	47	601	6	10	606	8	11	635.9349	75.31636	524.3001	99.1
GJ1-6.FIN2_Z_GJ1	0.483184	118697	289	0.03	-476.941	-13.5692	10.19	0.5	0.06071	0.83	0.005849	5.352254	0.8322	0.8	0.09873	0.5	0.08	0.03435	5.351718	608	35	44	607	6	10	613	7	11	673.9819	71.26858	553.1155	99.0
GJ1-7.FIN2_Z_GJ1	0.037668	120040	292	0.03	-536.397	-12.4631	10.20	0.5	0.05955	0.83	0.00702	27.1336	0.8118	0.7	0.09859	0.5	0.21	0.030251	6.717068	557	37	47	606	6	10	602	7	11	591.8837	78.13043	485.4169	100.7
GJ1-8.FIN2_Z_GJ1	0.009515	112434	279	0.03	-663.867	-9.23545	10.30	0.5	0.05977	0.84	0.004848	7.669243	0.8086	0.8	0.09778	0.6	0.26	0.026171	7.081265	573	36	45	601	6	10	600	7	11	513.2413	72.42554	427.4452	100.2
GJ1-9.FIN2_Z_GJ1	0.185293	115031	284	0.03	-659.08	-9.77166	10.24	0.6	0.05911	0.90	0.006709	20.35587	0.8034	0.8	0.09835	0.6	0.17	0.031526	6.266465	541	39	48	605	7	10	597	7	11	617.394	76.4185	508.0675	101.3
GJ1-10.FIN_Z_GJ1	-0.25191	111700	281	0.03	-670.741	-9.8987	10.37	0.5	0.05992	0.83	0.006042	8.810379	0.8022	0.8	0.09694	0.5	0.39	0.031423	5.851177	577	37	46	596	6	10	598	8	11	606.7417	68.74656	488.7881	99.8
GJ1-11.FIN_Z_GJ1	0.332036	113609	287	0.03	-676.272	-9.36174	10.41	0.5	0.06106	0.83	0.005168	7.235394	0.8183	0.8	0.09644	0.5	0.06	0.028949	6.380076	613	36	46	593	6	10	605	7	11	567.9876	71.94552	470.006	98.0
GJ1-14.FIN_Z_GJ1	0.25526	111209	280	0.03	-589.826	-11.0394	10.21	0.5	0.05967	0.87	0.006095	6.062906	0.8142	0.9	0.09851	0.5	0.18	0.034202	5.967232	560	38	47	605	6	10	603	8	11	685.9441	82.15573	572.9948	100.4
GJ1-15.FIN_Z_GJ1	0.158344	112849	285	0.03	-686.198	-9.25076	10.25	0.5	0.06009	0.90	0.005855	10.0072	0.8169	0.8	0.09832	0.5	0.09	0.031326	5.413832	572	40	49	604	6	10	605	7	11	616.0632	65.8084	504.9745	100.0
GJ1-17.FIN_Z_GJ1	0.147047	116811	296	0.03	-773.678	-8.69635	10.15	0.7	0.05976	0.85	0.008023	23.62745	0.8198	0.8	0.09903	0.6	0.04	0.037883	8.699219	572	36	45	608	7	11	606	7	11	689.6227	72.50742	350.8759	100.4
GJ1-19.FIN_Z_GJ1	-0.31113	110718	286	0.03	-760.111	-7.7006	10.32	0.5	0.05981	0.86	0.00539	6.024209	0.8082	0.8	0.09727	0.5	0.20	0.030395	6.052922	578	38	47	598	6	10	600	7	11	603.4284	72.73017	500.2241	99.8
GJ1-20.FIN_Z_GJ1	0.172622	106707	279	0.03	-702.077	-7.9967	10.38	0.5	0.06032	0.79	0.006131	5.601205	0.8133	0.8	0.09708	0.5	0.29	0.034837	5.674467	601	35	45	597	6	10	604	7	10	682.1746	76.41972	559.9364	98.9
GJ1-24.FIN_Z_GJ1	0.266993	106153	279	0.03	-693.774	-8.73312	10.33	0.6	0.06128	0.85	0.0051	6.622793	0.8303	0.8	0.09737	0.6	0.28	0.02952	6.397344	627	37	46	599	6	10	612	8	11	578.811	73.5373	479.1315	97.9
GJ1-25.FIN_Z_GJ1	0.312427	106713	283	0.03	-755.232	-7.71704	10.42	0.9	0.06066	0.94	0.006787	6.921587	0.8175	1.0	0.09733	0.6	0.22	0.037125	5.930875	599	39	47	599	7	11	604	9	12	724.5334	84.67961	594.1452	99.1
GJ1-33.FIN_Z_GJ1	-0.27155	105997	289	0.03	-693.027	-8.25924	10.34	0.5	0.05962	0.91	0.005639	5.706094	0.8018	0.8	0.09726	0.5	0.15	0.031989	5.720484	561	40	49	598	6	10	597	8	11	627.8227	71.18721	517.4818	100.3
GJ1-34.FIN_Z_GJ1	-0.02741	106375	286	0.03	-642.742	-9.31217	10.28	0.5	0.06023	0.84	0.005812	12.32994	0.8183	0.8	0.09786	0.5	0.29	0.031734	6.780429	589	36	45	602	6	10	605	7	11	601.5895	72.69179	447.5189	99.4
GJ1-36.FIN_Z_GJ1	0.237473	104887	287	0.03	-706.036	-14.041	10.39	0.6	0.05996	0.88	0.00614	11.22966	0.8083	0.9	0.09713	0.6	0.12	0.031564	6.176804	589	38	47	597	7	10	599	8	11	618.4233	75.29981	507.732	99.7
GJ1-37.FIN_Z_GJ1	0.301399	107780	291	0.03	-682.474	-8.70126	10.18	0.6	0.06095	0.86	0.00169	17.82245	0.8315	0.7	0.09894	0.6	0.15	0.009477	18.36659	613	38	47	608	7	10	614	7	11	182.4684	69.36601	170.3247	99.0
GJ1-39.FIN_Z_GJ1	-0.14823	102223	282	0.03	-653.784	-8.84264	10.26	0.5	0.06099	0.89	0.007565	28.22481	0.8326	0.9	0.09811	0.5	0.56	0.033676	6.591229	621	36	44	603	6	10	613	8	11	656.8719	85.85611	573.3407	98.4
GJ1-40.FIN_Z_GJ1	-0.11076	105873	290	0.03	-758.908	-7.45187	10.15	0.5	0.06065	0.91	0.005009	6.891308	0.8330	0.9	0.09907	0.5	0.03	0.028633	6.836358	593	39	48	609	6	10	613	8	11	560.6639	76.45161	466.9177	99.3
GJ1-41.FIN_Z_GJ1	-0.33354	110314	304	0.03	-859.222	-6.75837	10.16	0.5	0.05974	1.03	0.005802	6.083279	0.8223	1.0	0.09902	0.5	0.10	0.035495	5.754975	549	41	47	608	6	10	605	9	11	694.3138	79.23952	592.723	100.6
GJ1-42.FIN_Z_GJ1	0.167495	106932	298	0.03	-684.784	-8.74912	10.25	0.6	0.05980	0.85	0.006034	6.010876	0.8136	0.9	0.09835	0.6	0.37	0.035218	5.988208	574	37	46	605	6	10	603	8	11	696.3306	83.05732	577.2984	100.2
GJ1-48.FIN_Z_GJ1	0.348886	97174	282	0.03	-634.399	-12.4107	10.45	0.6	0.06034	0.87	0.004027	8.321469	0.8048	0.8	0.09655	0.6	-0.03	0.023072	8.213693	584	38	47	594	7	10	598	7	11	451.6295	74.29221	379.8829	99.4
GJ1-49.FIN_Z_GJ1	0.269425	101244	287	0.03	-770.541	-7.21018	10.17	0.6	0.05867	1.02	0.005302	5.986904	0.8079	1.0	0.09908	0.6	0.06	0.032382	6.02102	522	45	53	609	7	11	598	8	11	634.3615	75.82587	524.221	101.9
GJ1-51.FIN_Z_GJ1	-0.16972	97575	287	0.03	-645.935	-8.36159	10.40	0.5	0.06075	0.93	0.005539	8.781972	0.8154	0.9	0.09672	0.5	0.18	0.030955	6.44277	592	42	51	595	6	10	603	8	11	606.0023	77.22042	499.6728	98.6
GJ1-52.FIN_Z_GJ1	0.424773	99018	289	0.03	-597.524	-9.5057	10.32	0.6	0.06007	0.93	0.00571	5.8694	0.8091	0.9	0.09756	0.6	0.28	0.033594	5.924764	575	40	48	600	7	10	601	8	12	657.7424	76.99209	540.7528	99.8
GJ1-53.FIN_Z_GJ1	0.078561	100214	288	0.03	-606.094	-9.28572	10.20	0.5	0.05943	0.96	0.005744	6.06585	0.8095	0.9	0.09871	0.5	0.13	0.035412	5.925153	549	41	50	607	6	10	601	8	12	692.136	81.19614	570.2431	101.0
GJ1-54.FIN_Z_GJ1	-0.07105	97991	287	0.03	-628.624	-8.44262	10.37	0.5	0.06012	0.94	0.005924	5.786626	0.8074	0.9	0.09688	0.5	0.19	0.035193	5.911649	577	39	48	596	6	10	599	8	11	688.0718	80.34968	565.56	99.5
91500-1.FI_Z_91500	0.220157	34165	45	0.56	-127.222	-15.0293	5.48	0.8	0.07530	1.46	0.089514	2.292877	1.9188	1.3	0.18524	0.8	-0.08	0.056276	2.14429	1038	60	66	1094	16	21	1081	17	21	1103.001	46.09504	886.6064	101.2
91500-2.FI_Z_91500	-0.08273	33469	44	0.57	-113.616	-16.8567	5.61	0.9	0.07791	1.60	0.088385	2.596218	1.9393	1.3	0.18215	0.9	-0.04	0.053672	2.332222	1072	67	72	1077	18	22	1088	18	21	1052.819	47.88454	847.0174	99.0
91500-3.FI_Z_91500	0.212578	34121	45	0.57	-101.292	-19.8451	5.60	0.9	0.07621	1.72	0.090956	2.413055	1.8901	1.4	0.18256	0.9	-0.04	0.056099	2.327611	1007	72	76	1079	18	23	1067	19	23	1103.714	50.63856	897.5059	101.2
91500-4.FI_Z_91500	-1.27377	33631	45	0.56	-186.573	-9.69729	5.72	1.0	0.07405	1.73	0.088801	2.48865	1.8190	1.5	0.17924	0.9	-0.07	0.05445	2.36953	963	74	79	1061	18	23	1040	19	22	1067.512	49.32714	858.8415	102.1
91500-5.FI_Z_91																																

Supplementary Table S8: U-Pb in zircon reference materials (samples PJ-1, CJ-211, CJ-214 and CJ-215)

LEGA, Universidade de Brasília					Data for Tera-Wasserburg plot					Data for Wetherill plot					Dates																		
Identifier	Comments	F206c	206Pb	Uppm	Th/U	206Pb/204 1s%	238U/206Pb 1s%	207Pb/204 1s%	208Pb/204 1s%	207Pb/235 1s%	206Pb/235 1s%	Rho	208Pb/231 1s%	207Pb/204 2s (abs)	2ssys (abs)	206Pb/231 2s (abs)	2ssys (abs)	207Pb/235 2s (abs)	2ssys (abs)	208Pb/231 2s (abs)	2ssys (abs)	% conc											
GJ1_1	Z_GJ1	0.287419	82543	293	0.03	-1422.73	-28.083	10.22	1.7	0.06099	3.43	0.005727	7.571159	0.8248	2.4	0.09781	1.8	-0.29	0.030305	7.362471	546	150	150	601	20	607	22	22	620.6315	94.82449	127.5584	99.0	
GJ1_2	Z_GJ1	0.025968	81367	292	0.03	-1419.02	-24.5465	10.21	1.7	0.05949	2.97	0.005012	8.06274	0.8059	2.0	0.09785	1.7	-0.29	0.026271	7.564995	513	131	131	601	19	598	18	18	522.1008	78.0673	103.7682	100.6	
GJ1_3	Z_GJ1	0.500736	82198	295	0.03	-1686.68	-24.3386	10.19	1.5	0.05947	2.67	0.005428	8.281982	0.8091	2.0	0.09761	1.5	-0.15	0.029183	7.820908	526	118	118	600	17	600	18	18	578.7307	89.37404	117.126	100.1	
GJ1_4	Z_GJ1	0.560602	80312	290	0.03	-1247.36	-35.8279	10.16	1.9	0.05939	2.72	0.006173	7.308544	0.8131	2.0	0.09863	1.9	0.05	0.034184	7.509622	523	117	117	606	22	602	18	18	676.0423	99.75658	133.0231	100.6	
GJ1_5	Z_GJ1	-0.18286	79992	289	0.03	-1488.09	-25.4232	10.19	1.8	0.06088	2.77	0.007611	17.47329	0.8297	2.0	0.09817	1.8	-0.11	0.032701	8.204309	571	125	125	603	21	611	18	18	646.8508	103.2496	132.7052	98.7	
GJ1_6	Z_GJ1	0.299065	79175	288	0.03	-1826.45	-27.7541	10.25	2.0	0.05969	3.18	0.006058	9.316182	0.8039	1.9	0.09793	1.9	-0.36	0.031484	8.250378	512	136	136	602	22	597	17	17	645.4026	109.5289	140.4663	100.8	
GJ1_7	Z_GJ1	0.508448	78677	289	0.03	-2027.15	-28.5164	10.37	1.9	0.06056	3.13	0.006091	7.344703	0.8001	1.8	0.09673	1.9	-0.25	0.032928	7.17765	546	136	136	595	22	595	17	17	652.0396	91.98573	125.1753	99.9	
GJ1_8	Z_GJ1	0.22202	78139	287	0.03	-4216.69	-24.0244	10.20	1.6	0.06009	2.99	0.00576	11.22283	0.8155	2.1	0.09782	1.6	-0.30	0.028416	8.432759	533	133	133	601	18	18	603	19	563.4546	93.56753	118.986	99.7	
GJ1_9	Z_GJ1	0.174022	77563	287	0.03	-4682.53	-19.7171	10.29	1.9	0.05998	2.73	0.007298	11.74723	0.8094	1.8	0.09747	1.9	-0.06	0.036143	9.188262	539	124	124	599	21	600	17	17	712.1483	127.4955	157.1769	99.8	
GJ1_10	Z_GJ1	0.300595	76109	283	0.03	73641.57	32.25468	10.27	1.7	0.06324	3.29	0.006025	7.160655	0.8545	2.6	0.09731	1.7	-0.18	0.031355	6.96225	634	137	137	598	19	623	23	23	621.5828	85.17504	117.5702	96.0	
GJ1_11	Z_GJ1	0.518118	77471	287	0.03	45265.7	23.44659	10.18	1.8	0.06008	2.60	0.005979	7.917614	0.8223	2.1	0.09857	1.9	0.05	0.032422	7.488678	548	119	119	606	22	607	19	19	641.9152	94.66967	126.3945	99.8	
GJ1_12	Z_GJ1	0.582353	75417	276	0.03	2594.45	34.11239	10.08	1.9	0.06016	3.18	0.005808	8.60931	0.8274	2.3	0.09941	1.8	-0.18	0.031748	8.636872	524	145	145	610	21	609	22	22	627.978	106.4946	134.2124	100.2	
GJ1_13	Z_GJ1	0.77524	75410	273	0.03	2557.236	32.74186	10.11	1.8	0.05970	2.73	0.00603	8.627735	0.8196	2.0	0.09913	1.9	0.21	0.031557	8.292314	536	115	115	609	22	606	18	18	624.558	102.1985	130.806	100.5	
GJ1_14	Z_GJ1	0.531522	76393	282	0.03	2238.897	34.04978	10.16	1.9	0.05829	3.29	0.005908	8.50692	0.8115	2.0	0.09875	1.8	-0.01	0.032306	8.21174	542	157	157	607	21	601	18	18	639.075	103.1364	132.5124	100.9	
GJ1_15	Z_GJ1	0.49481	75321	285	0.03	2247.448	32.6235	10.29	2.0	0.05991	2.77	0.005517	10.79618	0.8110	1.8	0.09793	2.1	-0.14	0.026859	8.220052	533	128	128	602	24	601	16	16	533.1998	96.58999	111.2089	100.1	
GJ1_16	Z_GJ1	0.04228	72865	278	0.03	2367.999	35.12775	10.25	1.6	0.06036	2.41	0.009415	42.16485	0.8176	1.6	0.09742	1.6	-0.15	0.028769	6.296188	569	106	106	599	18	605	14	14	571.5787	71.16585	103.3011	98.9	
GJ1_17	Z_GJ1	-0.18906	73820	281	0.03	1963.134	39.04221	10.18	1.4	0.06104	2.80	0.022562	57.26824	0.8253	2.3	0.09776	1.4	0.01	0.055346	44.62573	577	123	123	601	16	612	22	22	605.1542	83.04414	83.95414	98.1	
GJ1_18	Z_GJ1	0.053723	75876	295	0.03	3609.863	29.12001	10.39	1.8	0.06006	3.07	0.008931	19.46469	0.8238	3.3	0.09649	1.8	-0.02	0.038411	9.88371	534	128	128	593	20	595	20	20	754.9555	41.6365	170.5074	99.7	
GJ1_19	Z_GJ1	0.379648	74742	292	0.03	944.2512	80.54061	10.34	1.7	0.06084	2.25	0.006524	8.126206	0.8180	1.8	0.09674	1.7	-0.05	0.033115	7.802889	593	97	97	595	19	605	17	17	677.2149	108.993	142.9748	98.3	
GJ1_20	Z_GJ1	0.399284	73772	293	0.03	2070.118	37.63779	10.45	1.7	0.06152	3.39	0.063882	89.84824	0.8208	2.7	0.09581	1.7	-0.12	0.032255	9.004161	550	119	119	589	19	605	24	24	637.4226	112.1707	139.2578	97.5	
GJ1_21	Z_GJ1	0.359727	76158	288	0.03	1782.255	40.65075	10.23	1.8	0.06073	3.20	0.006395	8.785217	0.8262	2.4	0.09806	1.8	-0.08	0.032415	7.875066	582	139	139	603	21	608	22	22	641.4563	99.59616	130.148	99.1	
GJ1_22	Z_GJ1	-0.12904	73488	285	0.03	559.4925	76.74602	10.09	1.5	0.05985	3.12	0.006459	9.548617	0.8241	2.4	0.09874	1.4	-0.28	0.032519	8.146775	521	134	134	607	17	607	22	22	643.2714	102.9603	132.7032	99.9	
GJ1_23	Z_GJ1	0.670908	76515	298	0.03	-92.1663	-598.67	10.17	1.9	0.05881	2.54	0.006107	9.948109	0.7938	2.0	0.09884	2.0	-0.16	0.032774	8.632402	529	110	110	607	23	592	16	16	647.744	110.0956	138.7773	102.6	
GJ1_24	Z_GJ1	0.55955	72991	290	0.03	-154.215	-190.052	10.26	1.6	0.05959	2.62	0.005302	9.711442	0.8093	2.1	0.09738	1.6	0.05	0.02624	8.347464	534	115	115	599	18	600	19	19	521.0942	86.00262	109.7938	98.8	
GJ1_25	Z_GJ1	0.494844	72495	286	0.03	-276.096	-115.789	10.14	1.5	0.06129	3.82	0.013682	60.06646	0.8296	2.5	0.09838	1.5	-0.24	0.030009	8.175679	610	162	162	605	18	617	26	26	594.5692	95.37498	122.7538	98.1	
GJ1_26	Z_GJ1	0.513633	72518	291	0.03	-619.343	-46.0805	10.18	1.8	0.05986	2.75	0.017321	67.26068	0.8063	1.9	0.09849	1.8	-0.02	0.029766	8.033972	536	121	121	605	21	599	17	17	589.9518	93.13773	120.7168	101.1	
91500_1	Z_91500	1.134743	24905	48	0.68	-346.955	-29.8785	5.37	0.7	0.07343	2.30	0.108766	2.478504	1.8781	2.0	0.18295	0.7	0.04	0.055283	2.611455	987	96	96	1083	14	14	1074	29	29	1086.609	55.18361	150.4686	100.8
91500_2	Z_91500	-0.95732	24764	48	0.68	-565.901	-19.7627	5.41	0.8	0.07238	1.90	0.107516	3.0631	1.8555	1.8	0.18182	0.9	0.11	0.054199	3.468139	969	78	78	1077	18	18	1062	24	24	1065.107	71.85086	154.9126	101.4
91500_3	Z_91500	-0.81726	24290	47	0.68	-400.601	-29.9209	5.47	1.0	0.07459	2.08	0.100725	2.59015	1.9130	1.6	0.18070	1.1																

Plesovice_ Z_Plesovic	1.369135	78491	533	0.22	1876.575	40.7196	18.11	0.6	0.05156	1.19	0.033983	4.019949	0.3966	1.3	0.05432	0.5	0.28	0.01528	3.511083	252	56	56	341	4	4	339	7	7	306.3523	21.33085	45.54901	100.6
Plesovice_ Z_Plesovic	1.100801	65848	465	0.18	1992.902	37.52053	18.60	0.8	0.05372	2.06	0.03205	4.578493	0.4018	1.9	0.05312	0.8	0.02	0.017239	3.036744	327	83	83	334	5	5	342	11	11	345.323	20.77811	49.86171	97.5
Plesovice_ Z_Plesovic	0.222424	80241	557	0.23	2964.403	33.67022	18.28	0.8	0.05280	1.47	0.036453	2.782765	0.4019	1.3	0.05406	0.8	0.14	0.015628	3.097958	314	69	69	339	5	5	343	7	7	313.3176	19.2728	45.49555	99.0
Plesovice_ Z_Plesovic	0.184578	61364	431	0.17	1606.087	37.22014	18.37	0.9	0.05188	1.84	0.027984	3.80555	0.3989	1.6	0.05385	0.9	0.21	0.016343	3.416969	283	70	70	338	6	6	340	9	9	327.4935	22.19056	48.40677	99.3
Plesovice_ Z_Plesovic	-0.03324	87531	617	0.20	408.1751	122.4338	18.30	0.8	0.05217	1.73	0.034118	2.658103	0.3935	1.5	0.05401	0.8	0.00	0.016763	2.173507	266	80	80	339	5	5	336	8	8	335.9361	14.47327	46.42578	100.8
Plesovice_ Z_Plesovic	0.496372	60567	431	0.27	519.3408	57.37796	18.40	0.8	0.05293	1.57	0.033484	4.771835	0.4009	1.5	0.05372	0.8	0.00	0.011991	5.313897	303	73	73	337	5	5	342	8	8	240.7121	25.40473	40.60064	98.7
Plesovice_ Z_Plesovic	0.54901	81161	580	0.21	-211.379	-154.809	18.32	0.7	0.05154	1.75	0.035796	2.590613	0.3915	1.5	0.05396	0.7	-0.09	0.016726	2.245606	236	83	83	339	5	5	335	9	9	335.2067	14.93193	46.51118	101.1
Plesovice_ Z_Plesovic	0.281415	78768	555	0.23	-527.888	-55.59	18.05	0.7	0.05191	1.45	0.03863	2.47188	0.3995	1.3	0.05459	0.7	-0.05	0.017244	2.742734	263	66	66	343	5	5	341	7	7	345.4528	18.78843	49.11509	100.5
Plesovice_ Z_Plesovic	0.724248	60577	439	0.31	-62.7904	-437.302	18.54	0.8	0.05288	1.77	0.033327	3.708106	0.3977	1.7	0.05336	0.9	0.21	0.010536	4.934513	296	81	81	335	6	6	339	10	10	211.6891	20.78358	34.79156	98.8

Supplementary Table S11: Trace elements reference materials (sample CJ-211)

[illegible]

DUR-2	2096.75	353.12	-4.54	0.26	1.85	0.82	37.79	1.29	521.07	15.70	1022.54	0.15	0.15	0.05	4717.87	166.48	6704.07	224.04	565.96	38.51	2885.59	46.42	2778.3	11.97	240.2	1.11	354.87	12.26	32.28	1.02	38.82	5.77	36.28	1.20	105.21	3.77	12.21	0.73	65.93	2.57	7.36	0.35	0.12	0.25	0.02	0.03	0.89	0.20	384.82	8.52	26.82	0.60																																																																																																																																																																																																																																																																																																																																																																																																																																																																				
DUR-2	2091.40	841.28	-1.02	0.22	1.80	0.80	36.47	1.20	521.08	15.78	1042.64	44.25	0.12	0.04	487.90	166.48	6704.07	223.96	565.95	38.51	2885.59	35.27	2778.3	11.97	240.2	1.11	354.87	12.26	32.28	1.02	38.82	5.77	36.28	1.20	105.21	3.77	12.21	0.73	65.93	2.57	7.36	0.35	0.12	0.25	0.02	0.03	0.89	0.20	384.82	8.52	26.82	0.60																																																																																																																																																																																																																																																																																																																																																																																																																																																																				
DUR-3	2121.31	206.35	-0.34	0.21	0.36	0.78	36.40	1.54	510.58	38.02	1008.25	47.40	0.15	0.06	460.81	182.83	6516.30	224.24	564.57	21.84	1847.14	45.78	2818	14.02	246.5	1.24	326.10	11.24	31.84	1.27	6.50	36.20	0.95	10.14	5.12	12.32	0.67	63.80	2.13	11.78	0.29	0.02	0.03	1.04	0.09	295.50	7.12	17.52	0.67																																																																																																																																																																																																																																																																																																																																																																																																																																																																							
DUR-3	2084.15	841.28	-0.34	0.21	0.36	0.78	36.40	1.54	510.58	38.02	1008.25	47.40	0.15	0.06	460.81	182.83	6516.30	224.24	564.57	21.84	1847.14	45.78	2818	14.02	246.5	1.24	326.10	11.24	31.84	1.27	6.50	36.20	0.95	10.14	5.12	12.32	0.67	63.80	2.13	11.78	0.29	0.02	0.03	1.04	0.09	295.50	7.12	17.52	0.67																																																																																																																																																																																																																																																																																																																																																																																																																																																																							
DUR-3	2090.20	146.94	-0.34	0.22	0.86	0.83	36.03	1.50	527.17	19.11	1131.35	47.40	0.15	0.07	479.77	177.94	6816.76	184.74	572.82	21.84	1847.14	48.83	26.29	17.9	21.4	0.00	318.33	11.54	31.82	1.61	8.68	5.73	37.08	1.24	10.69	4.87	12.52	0.75	63.80	2.21	6.99	0.38	0.08	0.03	0.00	0.00	0.00	0.00	1.08	0.14	284.54	9.87	16.46	0.70																																																																																																																																																																																																																																																																																																																																																																																																																																																																		
DUR-3	2090.20	146.94	-0.34	0.22	0.86	0.83	36.03	1.50	527.17	19.11	1131.35	47.40	0.15	0.07	479.77	177.94	6816.76	184.74	572.82	21.84	1847.14	48.83	26.29	17.9	21.4	0.00	318.33	11.54	31.82	1.61	8.68	5.73	37.08	1.24	10.69	4.87	12.52	0.75	63.80	2.21	6.99	0.38	0.08	0.03	0.00	0.00	0.00	0.00	1.08	0.14	284.54	9.87	16.46	0.70																																																																																																																																																																																																																																																																																																																																																																																																																																																																		
DUR-7	2082.57	402.60	-0.12	0.19	-2.40	0.75	37.36	1.40	500.05	15.81	1113.51	41.05	0.25	0.16	475.88	178.8	6763.50	234.68	568.18	21.84	1847.14	48.83	26.29	17.9	21.4	0.00	318.33	11.54	31.82	1.61	8.68	5.73	37.08	1.24	10.69	4.87	12.52	0.75	63.80	2.21	6.99	0.38	0.08	0.03	0.00	0.00	0.00	0.00	1.08	0.14	284.54	9.87	16.46	0.70																																																																																																																																																																																																																																																																																																																																																																																																																																																																		
DUR-7	2082.57	402.60	-0.12	0.19	-2.40	0.75	37.36	1.40	500.05	15.81	1113.51	41.05	0.25	0.16	475.88	178.8	6763.50	234.68	568.18	21.84	1847.14	48.83	26.29	17.9	21.4	0.00	318.33	11.54	31.82	1.61	8.68	5.73	37.08	1.24	10.69	4.87	12.52	0.75	63.80	2.21	6.99	0.38	0.08	0.03	0.00	0.00	0.00	0.00	1.08	0.14	284.54	9.87	16.46	0.70																																																																																																																																																																																																																																																																																																																																																																																																																																																																		
DUR-7	2086.61	141.20	-0.18	0.35	1.47	0.78	34.70	1.30	531.40	21.11	1135.52	47.68	0.15	0.06	4828.78	198.89	6816.76	234.61	574.88	21.84	1847.14	48.83	26.29	17.9	21.4	0.00	318.33	11.54	31.82	1.61	8.68	5.73	37.08	1.24	10.69	4.87	12.52	0.75	63.80	2.21	6.99	0.38	0.08	0.03	0.00	0.00	0.00	0.00	1.08	0.14	284.54	9.87	16.46	0.70																																																																																																																																																																																																																																																																																																																																																																																																																																																																		
DUR-7	2086.61	141.20	-0.18	0.35	1.47	0.78	34.70	1.30	531.40	21.11	1135.52	47.68	0.15	0.06	4828.78	198.89	6816.76	234.61	574.88	21.84	1847.14	48.83	26.29	17.9	21.4	0.00	318.33	11.54	31.82	1.61	8.68	5.73	37.08	1.24	10.69	4.87	12.52	0.75	63.80	2.21	6.99	0.38	0.08	0.03	0.00	0.00	0.00	0.00	1.08	0.14	284.54	9.87	16.46	0.70																																																																																																																																																																																																																																																																																																																																																																																																																																																																		
DUR-7	2088.97	21.72	-0.82	0.31	1.84	0.90	35.93	1.22	520.31	17.34	1090.98	46.08	0.14	0.04	450.12	148.16	6402.25	215.55	550.55	38.58	2888.98	17772.38	36.71	286.53	9.7	22.59	0.72	215.92	8.9	31.89	1.23	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.88	1.21	81.

Supplementary Table S9: LA-ICP-MS working parameters

Laboratory and Sample Preparation	
Laboratory name	Laboratório de Geocronologia e Geoquímica Isotópica, Instituto de Geociências, Universidade de Brasília (UnB)
Sample type/mineral	Zircon
Sample preparation	Conventional mineral separation, 0.5 cm resin mount, 1 µm polish to finish
Imaging	BSE, SEM Quanta 450, 10 nA, 20kV, 13.8 mm working distance
Laser ablation system	
Make, Model and type	Teledyne Iridia
Ablation cell and volume	Cobalt
Laser wavelength (nm)	193 nm
Pulse width (ns)	< 5 ns
Fluence (J cm ⁻²)	2.0 J cm ⁻²
Repetition rate (Hz)	20 Hz
Spot size	25 µm
Sampling mode / pattern	
Carrier gas	100% He, Ar make-up gas combined using a Y-piece along the sample transport line close to the torch.
Pre-ablation laser warm-up (background collection)	10 s
Ablation duration (s)	20 s
Wash-out delay	15 s
Ablation pit depth / ablation rate	~10 µm pit depth
Cell carrier gas flow (l min ⁻¹)	0.60 l min ⁻¹ He (0.300 + 0.300)
ICP-MS Instrument	
Make, Model and type	Thermo-Fischer, ElementXR, SC-ICP-MS
Sample introduction	Ablation aerosol
RF power (W)	1200 W
Make-up gas flow (l min ⁻¹)	0.9 l min ⁻¹
Detection system	SEM+Faraday
Masses measured	202, 204, 206, 207, 208, 232, 238
Integration time per peak/dwell times (ms); quadrupole settling time between mass jumps	202, 204, 232: 6 ms; 206: 11 ms; 207: 24 ms; 208: 7 ms; 238: 15 ms.
Acquisition mode	E-scan (peak jumping)
Total integration time per output data point (s)	82 ms per sweep
Dead time (ns)	N.A.
Data processing	
Gas blank	10 s
Calibration strategy	GJ1 used as primary reference material, 91500 and Plešovice used as secondary/validation
Reference Material info	GJ1 (Jackson et al. 2004, Horstwood et al. 2016); Plešovice (Sláma et al. 2008); 91500 (Wiedenbeck et al. 1995)
Data processing package used / Correction for LIEF	Iolite v.4.0 (Paton et al., 2011) & VizualAge (Petrus and Kamber, 2012) using exponential plus linear modelling for LIEF correction
Mass discrimination	Standard-sample bracketing with 207Pb/206Pb and 206Pb/238U ratios normalized to reference material GJ1
Common-Pb correction, composition and uncertainty	none
Uncertainty level and propagation	Ages are quoted at 2s absolute, propagation is by quadratic addition. Excess variance and age uncertainty of reference material are propagated where appropriate.

Supplementary Table 1.2: U-Pb in zircon (Sample CJ-2028)

LEIGA, Universidad de Brasília										Data for Tera-Wasserburg plot										Data for Wetherill plot										Dates											
Identif.	Grain	Comment	206Pb	U ppm	Th ppm	Th/U	U initial	Th initial	Th/U initial	206Pb/204Pb	1σ	206Pb/204	1σ	208Pb/232	1σ	207Pb/235	1σ	Rho	208Pb/232	1σ	207Pb/235	1σ	207Pb/26	2σ (abs)	Zsys (abs)	208Pb/232	2σ (abs)	Zsys (abs)	207Pb/232	2σ (abs)	Zsys (abs)	208Pb/232	2σ (abs)	Zsys (abs)	Concordia	% conc	Alpha dose × 10E14				
CJ202-107 T20	CJ2028	0.03642	15350	11	7	0.67	16.7	8.3	0.50	720.3	47.9	2.37	2.3	0.20232	2.28	0.127152	0.60991	11.694	2.8	4.81396	2.9	0.880	0.111288	7.260024	2827	72	75	2306	108	11	2586	65	66	2707	24	2191.784	327.987	2956.314	13.3	81.6	1.1
CJ202-111 T21	CJ2028	0.025435	15928	175	143	0.82	279.2	166.2	0.60	4697.8	83.7	1.80	0.6	0.21964	0.56	0.13153	1.524051	16.9025	0.8	0.55866	0.6	0.638	0.121144	1.513852	2876	18	26	2835	28	38	2598	15	17	2935	15	2328.721	50.1858	2881	2.64	95.9	0.9
CJ202-12 T21	CJ2028	0.060606	178655	107	51	0.48	164.9	58.3	0.35	83.74	216.3	1.98	1.0	0.19244	0.90	0.076003	1.852137	13.2852	1.8	0.50524	1.0	0.862	0.111661	2.186176	2760	30	36	2635	43	50	2696	36	37	2714	35	2137.432	68.48267	2636.937	2.53	95.5	10.7
CJ202-13 T21	CJ2028	0.029597	297461	178	145	0.82	268.1	165.1	0.62	1850.3	136.5	2.09	0.9	0.17698	0.82	0.12356	3.040908	11.7494	1.4	0.48014	0.9	0.819	0.097686	1.84141	2622	27	34	2527	37	44	2582	36	28	2599	26	1882.86	66.38083	2242.796	2.39	96.4	18.1
CJ202-14 T24	CJ2028	0.047959	501723	334	167	0.50	494.9	188.4	0.38	-2611.3	-143.7	2.28	1.1	0.16443	0.85	0.072052	2.280363	10.9414	1.6	0.44139	1.0	0.880	0.081479	1.617235	2498	29	35	2356	41	47	2434	30	31	2474	29	1582.65	49.28921	3922.399	1.43	94.3	30.3
CJ202-15 T24	CJ2028	0.031403	169169	236	185	0.50	274.6	208.3	0.36	1696.9	251.6	1.89	0.4	0.21521	0.6	0.096913	1.930203	15.7254	1.2	0.53024	0.4	0.672	0.091299	1.630781	2944	12	23	2742	19	32	2859	12	21	2943	12	1765.987	45.0017	2087.596	4.23	93.1	38.7
CJ202-16 T216	CJ2028	0.034796	307202	184	126	0.69	292.4	146.5	0.50	83.0	2365.5	1.79	0.8	0.22019	0.87	0.100103	1.584452	16.9956	0.8	0.55966	0.8	0.275	0.088358	1.511057	2798	28	34	2864	36	45	2933	15	17	2930	15	170.657	50.2769	2900.126	2.48	96.2	20.7
CJ202-17 T217	CJ2028	0.043817	574287	299	91	0.31	467.8	105.5	0.23	1284.1	323.2	1.89	0.9	0.21608	0.45	0.04153	1.256061	15.9534	1.0	0.53033	0.9	0.898	0.079716	1.626463	2950	15	24	2742	41	48	2872	19	21	2945	12	1549.9	37.68581	1957.559	6.68	92.9	30.3
CJ202-18 T218	CJ2028	0.021455	224417	119	71	0.60	187.6	82.0	0.44	384.84	56.1	1.86	0.7	0.20957	0.61	0.058748	1.358992	15.5883	1.0	0.53758	0.7	0.808	0.078508	1.640401	2900	20	27	2772	33	42	2850	19	21	2948	18	1526.91	48.14057	1859.78	3.24	95.6	12.8
CJ202-19 T219	CJ2028	0.04022	338879	172	127	0.74	273.7	146.9	0.54	42438.8	27.7	1.79	0.7	0.21866	0.55	0.104416	2.073787	16.9814	1.0	0.55978	0.7	0.783	0.078693	1.603049	2969	18	26	2855	31	42	2932	18	20	2954	16	1530.814	59.37179	1892.784	2.66	96.5	15.9
CJ202-20 T220	CJ2028	0.08016	258447	234	74	0.32	318.3	81.2	0.26	17936.6	41.7	2.94	1.1	0.21992	1.12	0.049751	3.022625	5.5863	1.0	0.34015	0.6	0.897	0.049286	2.575987	1948	40	46	1887	24	31	1913	18	20	1905	15	972.1755	49.0309	3233.146	1.49	96.9	15.9
CJ202-22 T222	CJ2028	0.095859	248816	221	89	0.40	301.3	98.3	0.33	611.7	302.2	3.01	0.8	0.11984	0.82	0.063008	3.064142	5.5025	0.9	0.33307	0.8	0.536	0.051603	1.774486	1950	29	36	1853	26	32	1930	15	17	1898	15	1016.694	53.16287	1335.441	2.4	95.0	15.4
CJ202-23 T23	CJ2028	0.037926	916175	531	53	0.10	840.8	61.5	0.07	-3557.3	-223.3	1.85	0.9	0.21324	0.92	0.015255	1.678425	15.7591	1.1	0.53997	0.9	0.715	0.085785	2.369498	2928	30	36	2783	39	47	2861	21	23	2877	20	1662.399	75.60025	2100.829	2.92	95.0	51.7
CJ202-24 T24	CJ2028	0.031996	920231	504	53	0.11	799.4	61.4	0.08	1862.4	434.1	1.81	0.7	0.21543	0.78	0.014129	2.394976	16.4006	0.6	0.52565	0.7	0.451	0.09899	2.847049	2948	25	31	2836	34	43	2900	12	15	2903	11	1906.129	103.7622	2442.113	2.25	96.3	48.4
CJ202-25 T225	CJ2028	0.1339	248382	144	60	0.42	220.3	68.6	0.31	67568.3	46.4	1.94	1.3	0.18636	0.62	0.098979	2.519756	13.3754	1.4	0.51929	1.3	0.898	0.393393	1.215383	2708	21	29	2694	57	62	2704	28	29	2712	18	6694.111	244.5947	7553.558	0.538	99.5	15.9
CJ202-27 T227	CJ2028	0.18583	73034	38	16	0.44	59.9	19.0	0.32	429.5	353.8	1.75	0.7	0.22205	0.76	0.038787	2.638973	17.4905	1.1	0.57117	0.7	0.509	0.385046	2.813133	2993	24	31	2912	33	43	2960	22	24	2956	12	6559.591	317.2127	6943.711	1.62	91.3	46.2
CJ202-28 T228	CJ2028	0.028103	251420	137	103	0.75	212.4	119.2	0.55	2121.4	101.7	1.85	0.7	0.21741	0.69	0.013745	1.99423	16.3354	1.3	0.53920	0.8	0.818	0.074061	1.458921	2958	29	35	2799	36	45	2894	25	27	2928	25	4891.721	126.6335	5278.838	0.58	94.0	15.5
CJ202-29 T229	CJ2028	0.03043	134760	79	39	0.50	120.7	45.0	0.37	6243.8	39.5	1.99	1.0	0.18421	0.88	0.072219	1.820503	12.8742	1.0	0.50385	0.9	0.530	0.204684	2.452198	2688	29	35	2629	41	48	2669	18	20	2672	19	3758.124	167.5843	4294.915	1.5	97.8	7.7
CJ202-31 T231	CJ2028	0.00677	689149	451	55	0.12	692.8	62.5	0.09	-59105.8	-28.5	2.15	0.7	0.18993	0.87	0.016879	1.752537	12.2489	0.7	0.46630	0.7	0.390	0.119455	2.51012	2740	28	34	2467	27	36	2623	13	16	2617	13	2279.785	93.3737	2767.088	6.13	90.1	41.2
CJ202-32 T232	CJ2028	0.018688	320271	142	5	0.04	226.5	6.0	0.03	134403.1	34.6	1.69	1.0	0.22136	0.49	0.088197	1.623266	18.3911	0.9	0.59389	1.0	0.874	0.12287	4.991543	2989	16	25	3004	48	56	3009	18	20	3012	12	2331.009	220.9142	2823.972	0.215	100.5	19.9
CJ202-33 T233	CJ2028	0.012265	645488	348	101	0.28	564.8	116.9	0.21	20387.7	41.2	2.00	0.6	0.21186	0.48	0.042096	2.904989	14.8205	0.6	0.50037	0.6	0.654	0.110708	1.304048	2918	16	25	2615	26	36	2803	11	14	2831	10	2117.914	62.25717	2518.505	0.705	100.6	36.1
CJ202-34 T234	CJ2028	0.070366	514295	269	160	0.59	425.1	184.6	0.45	-4557.9	-69.4	1.85	0.6	0.21301	0.51	0.073787	1.729316	16.1696	0.8	0.54231	0.6	0.752	0.113876	1.729316	2927	16	25	2792	27	38	2885	16	27	2878	25	2142.65	51.7231	2591.399	2.58	95.4	29.1
CJ202-35 T235	CJ2028	0.184011	235862	112	36	0.32	178.2	42.1	0.24	-2782.3	-99.8	1.76	0.7	0.21536	0.80	0.045647	2.441946	17.1714	1.1	0.56941	0.7	0.650	0.112313	1.977232	2944	26	32	2905	32	42	2943	20	22	2945	21	2150.492	80.72504	2652.437	1.36	98.7	11.6
CJ202-36 T236	CJ2028	0.02																																							

CJ202-110 Z110	CJ202B	-0.01295	439218	292	65	0.22	446.9	74.4	0.17	-13412.2	-29.5	2.42	2.6	0.18883	1.40	0.030566	1.306063	11.3325	3.6	0.42708	2.5	0.980	0.131066	2.908115	2721	49	53	2284	96	98	2520	72	73	2897	20	2483.608	136.2216	3039.661	27.1	83.0	27.1
CJ202-112 Z112	CJ202B	0.01186	105017	58	37	0.63	89.2	41.9	0.47	-4888.8	-23.3	1.87	0.8	0.18355	0.99	0.087399	2.152007	13.5686	1.5	0.53227	1.0	0.536	0.154064	2.420606	2693	40	46	2750	43	51	2717	29	30	2723	27	2893.341	130.9746	3503.352	-1.36	102.1	5.9
CJ202-113 Z113	CJ202B	-0.10052	128406	73	30	0.41	111.7	34.0	0.30	-3219.0	-31.9	1.92	0.9	0.18359	0.83	0.057987	2.02839	13.1387	1.2	0.52151	0.9	0.737	0.157891	2.846818	2683	27	34	2705	38	46	2688	22	24	2686	21	2957.836	156.0124	3542.039	-0.619	100.8	7.0
CJ202-114 Z114	CJ202B	0.648495	88856	57	29	0.51	87.8	33.3	0.38	-3923.6	-44.0	2.20	1.6	0.18703	1.93	0.075101	3.079723	11.8123	3.0	0.45649	1.6	0.807	0.135465	3.453476	2707	62	65	2422	64	68	2580	55	56	2540	69	2563.478	167.6231	3146.176	7.75	89.5	5.7
CJ202-115 Z115	CJ202B	-0.61286	84949	62	28	0.45	87.4	31.2	0.36	-1653.6	-19.2	2.50	0.9	0.13890	1.21	0.068801	1.866471	7.7362	1.2	0.39983	0.8	0.455	0.128503	2.315815	2205	44	49	2167	30	37	2198	22	23	2193	20	2439.88	105.6447	2938.976	1.58	98.3	4.9
CJ202-116 Z116	CJ202B	-0.03101	477706	236	34	0.15	373.8	39.7	0.11	-1147.3	-239.0	1.82	0.9	0.21147	0.78	0.020455	2.399975	16.2634	1.4	0.55217	0.9	0.850	0.168748	1.896708	2922	21	26	2833	41	49	2890	27	29	2917	24	3149.786	110.9447	3787.883	2.6	97.0	23.2

Supplementary Table 1.3: U-Pb in zircon (Reference Materials for sample CJ-202A - Session 2)

LEGGA, Universidade de Brasília				Data for Tera-Wasserburg plot				Data for Wetherill plot				Dates																					
Identifier	Comment	T206c	206Pb	Uppm	Th/U	206Pb/204 1s%	238U/206Pb 1s%	207Pb/204 1s%	208Pb/204 1s%	207Pb/235 1s%	206Pb/238 1s%	Rho	208Pb/231 1s%	207Pb/204 2s (abs)	2ssys (abs)	206Pb/234 2s (abs)	2ssys (abs)	207Pb/235 2s (abs)	2ssys (abs)	208Pb/231 2s (abs)	2ssys (abs)	% conc											
GJ1_1	Z_GJ1	0.287419	82543	293	0.0	-1422.73	-28.083	10.22	1.7	0.06099	3.43	0.005727	7.571159	0.8248	2.4	0.09781	1.8	-0.29	0.030305	7.362471	546	150	150	601	20	20	607	22	22	620.6315	94.82449	127.5584	110.0
GJ1_2	Z_GJ1	0.025968	81367	292	0.0	-1419.02	-24.5465	10.21	1.7	0.05949	2.97	0.005012	7.564995	0.8059	2.0	0.09785	1.7	-0.29	0.026271	7.564995	513	131	131	601	19	19	598	18	18	522.1008	78.0673	103.7682	117.3
GJ1_3	Z_GJ1	0.500736	82198	295	0.0	-1686.68	-24.3386	10.19	1.5	0.05947	2.67	0.005428	8.281982	0.8091	2.0	0.09761	1.5	-0.15	0.029183	7.820908	526	118	118	600	17	17	600	18	18	578.7307	89.37404	117.126	114.2
GJ1_4	Z_GJ1	0.560602	80312	290	0.0	-1247.36	-35.8279	10.16	1.9	0.05939	2.72	0.006173	7.308544	0.8131	2.0	0.09863	1.9	0.05	0.034184	7.509622	523	117	117	606	22	22	602	18	18	676.0423	99.75658	133.0231	115.9
GJ1_5	Z_GJ1	-0.18286	79992	289	0.0	-1488.09	-25.4232	10.19	1.8	0.06088	2.77	0.007611	7.174329	0.8297	2.0	0.09817	1.8	-0.11	0.032701	8.204309	571	125	125	603	21	21	611	18	18	646.8508	103.2496	132.7052	105.6
GJ1_6	Z_GJ1	0.299065	79175	288	0.0	-1826.45	-27.7541	10.25	2.0	0.05969	3.18	0.006058	9.316182	0.8039	1.9	0.09793	1.9	-0.36	0.031484	8.250378	512	136	136	602	22	22	597	17	17	645.4026	109.5289	140.4663	117.5
GJ1_7	Z_GJ1	0.508448	78677	289	0.0	-2027.15	-28.5164	10.37	1.9	0.06056	3.13	0.006091	7.344703	0.8001	1.8	0.09673	1.9	-0.25	0.032928	7.17765	546	136	136	595	22	22	595	17	17	652.0396	91.98573	125.1753	108.9
GJ1_8	Z_GJ1	0.22202	78139	287	0.0	-4216.69	-24.0244	10.20	1.6	0.06009	2.99	0.00576	11.22283	0.8155	2.1	0.09782	1.6	-0.30	0.028416	8.432759	533	133	133	601	18	18	603	19	19	563.4546	93.56753	118.986	112.7
GJ1_9	Z_GJ1	0.174022	77563	287	0.0	-4682.53	-19.7171	10.29	1.9	0.05998	2.73	0.007298	11.74723	0.8094	1.8	0.09747	1.9	-0.06	0.036143	9.188262	539	124	124	599	21	21	600	17	17	712.1483	127.4955	157.1769	111.1
GJ1_10	Z_GJ1	0.300595	76109	283	0.0	-73641.57	32.25468	10.27	1.7	0.06324	3.29	0.006025	7.160655	0.8545	2.6	0.09731	1.7	-0.18	0.031355	6.96225	634	137	137	598	19	19	623	23	23	621.5828	85.17504	117.5702	94.3
GJ1_11	Z_GJ1	0.518118	77471	287	0.0	-45265.7	23.44659	10.18	1.8	0.06008	2.60	0.005979	7.917614	0.8223	2.1	0.09857	1.9	0.05	0.032422	7.488678	548	119	119	606	22	22	607	19	19	641.9152	94.66967	126.3945	110.5
GJ1_12	Z_GJ1	0.582353	75417	276	0.0	-2594.45	34.11239	10.08	1.9	0.06016	3.18	0.005808	8.60931	0.8274	2.3	0.09941	1.8	-0.18	0.031748	8.636872	524	145	145	610	21	21	609	22	22	627.978	106.4946	134.2124	116.5
GJ1_13	Z_GJ1	0.77524	75410	273	0.0	-2557.236	32.74186	10.11	1.8	0.05970	2.73	0.00603	8.627735	0.8196	2.0	0.09913	1.9	0.21	0.031557	8.292314	536	115	115	609	22	22	606	18	18	624.558	102.1985	130.806	113.6
GJ1_14	Z_GJ1	0.531522	76393	282	0.0	-2238.897	34.04978	10.16	1.9	0.05829	3.29	0.005908	8.50692	0.8115	2.0	0.09875	1.8	-0.01	0.032306	8.21174	542	157	157	607	21	21	601	18	18	639.075	103.1364	132.5124	111.8
GJ1_15	Z_GJ1	0.49481	75321	285	0.0	-1247.448	32.6235	10.29	2.0	0.05991	2.77	0.005517	10.79618	0.8110	1.8	0.09793	2.1	-0.14	0.026859	8.220052	533	128	128	602	24	24	601	16	16	533.1998	86.58999	111.2089	112.8
GJ1_16	Z_GJ1	0.04228	72865	278	0.0	-2367.999	35.12775	10.25	1.6	0.06036	2.41	0.009415	42.16485	0.8176	1.6	0.09742	1.6	-0.15	0.028769	6.296188	569	106	106	599	18	18	605	14	14	571.5787	17.16585	103.3011	105.4
GJ1_17	Z_GJ1	-0.18906	73820	281	0.0	-1963.134	39.04221	10.18	1.4	0.06104	2.80	0.002562	57.26824	0.8253	2.3	0.09776	1.4	0.01	0.055346	44.62573	577	123	123	601	16	16	612	22	22	605.1542	83.04414	83.95414	104.1
GJ1_18	Z_GJ1	0.053723	75876	295	0.0	-3609.863	29.12001	10.39	1.8	0.06006	3.07	0.008931	19.46469	0.8238	3.3	0.09649	1.8	-0.02	0.038411	9.88371	534	128	128	593	20	20	595	18	18	754.9555	41.6365	170.5074	111.2
GJ1_19	Z_GJ1	0.379648	74742	292	0.0	-944.2512	80.54061	10.34	1.7	0.06084	2.25	0.006524	8.126206	0.8180	1.8	0.09674	1.7	-0.05	0.033115	7.802889	593	97	97	595	19	19	605	17	17	677.2149	108.993	142.9748	100.3
GJ1_20	Z_GJ1	0.399284	73772	293	0.0	-2070.118	37.63779	10.45	1.7	0.06152	3.39	0.063882	89.84824	0.8208	2.7	0.09581	1.7	-0.12	0.032255	9.004161	550	119	119	589	19	19	605	24	24	637.4226	112.1707	139.2578	107.1
GJ1_21	Z_GJ1	0.359727	76158	288	0.0	-1782.255	40.65075	10.23	1.8	0.06073	3.20	0.006395	8.785217	0.8262	2.4	0.09806	1.8	-0.08	0.032415	8.175666	582	139	139	603	21	21	608	22	22	641.4563	99.59616	130.148	103.5
GJ1_22	Z_GJ1	-0.12904	73488	285	0.0	-559.4925	76.74602	10.09	1.5	0.05985	3.12	0.006459	9.548617	0.8241	2.4	0.09874	1.4	-0.28	0.032519	8.146775	521	134	134	607	17	17	607	22	22	643.2714	102.9603	132.7032	116.4
GJ1_23	Z_GJ1	0.670908	76515	298	0.0	-92.1663	-598.67	10.17	1.9	0.05881	2.54	0.006107	9.948109	0.7938	2.0	0.09884	2.0	-0.16	0.032774	8.632402	529	110	110	607	23	23	592	16	16	647.744	110.0956	138.7773	114.8
GJ1_24	Z_GJ1	0.55955	72991	290	0.0	-154.215	-190.052	10.26	1.6	0.05959	2.62	0.005302	9.711442	0.8093	2.1	0.09738	1.6	0.05	0.02624	8.347464	534	115	115	599	18	18	600	19	19	521.0942	86.00262	109.7938	112.2
GJ1_25	Z_GJ1	0.494844	72495	286	0.0	-276.096	-115.789	10.14	1.5	0.06129	3.82	0.013682	60.06646	0.8296	2.5	0.09838	1.5	-0.24	0.030009	8.175679	610	162	162	605	18	18	617	26	26	594.5692	95.37498	122.7158	99.2
GJ1_26	Z_GJ1	0.513633	72518	291	0.0	-619.343	-46.0805	10.18	1.8	0.05986	2.75	0.017321	67.26068	0.8063	1.9	0.09849	1.8	-0.02	0.029766	8.033972	536	121	121	605	21	21	599	17	17	589.9518	93.13773	120.7638	112.8
91500_1	Z_91500	1.134743	24905	48	0.7	-346.955	-29.8785	5.37	0.7	0.07343	2.30	0.108766	2.478504	1.8781	2.0	0.18295	0.7	0.04	0.055283	2.611455	987	96	96	1083	14	14	1074	29	29	1086.609	55.18361	150.4686	109.7
91500_2	Z_91500	-0.95732	24764	48	0.7	-565.901	-19.7627	5.41	0.8	0.07328	1.90	0.107516	3.0631	1.8555	1.8	0.18182	0.9	0.11	0.054199	3.468139	969	78	78	1077	18	18	1062	24	24	1065.107	71.85086	154.9126	111.1
91500_3	Z_91500	-0.81726	24290	47	0.0	-400.601	-29.9209	5.47	1.0	0.07459	2.08	0.100725	2.59015	1.9130	1.6	0.18070	2.1	-0.12	0.050649	2.652883	1066	83	83	1070	21	21	1087	23	23	997.7538	51.62411	138.8631	100.4
91500_4	Z_91500	0.492709	23595	47	0.7	-451.207	-29.3328	5.59	1.0	0.07621	2.10	0.106889	3.155966	1.8937	1.7	0.17678	1.0	0.29	0.051484	3.087662	1069	86	86	1049	20	20	1076	22	22	1013.483	61.11019	144.6523	98.1
91500_5	Z_91500	0.8485795	25469	50	0.6	-862.125	-18.6593	5.47	1.1	0.07473	1.79	0.103833	5.882739	1.8734	1.8	0.18098	1.1	0.19	0.052052	3.258943	1039	70	70	1072	21	21	1073	26	26	1062.532	52.29666	146.6324	103.2
91500_6	Z_91500	0.812481	22862	47	0.6	-692.238	-25.3459	5.57	1.2	0.07834	2.92	0.107034	3.314561	1.9499	2.7	0.17750	1.1	0.07	0.054407	3.060116	1130	124	124	1053	22	22	1092	35	35	1069.743	63.57024	151.5894	93.1
91500_7	Z_91500	0.478486	24970	49	0.6	-502.97	-33.4959	5.49	1.4	0.07394	2.33	0.095807	2.919311	1.8766	2.0	0.17972	1.3	0.08	0.053476	3.183342	1001	94	94	1065	25	25	1068	27	27	1051.542	65.10993	150.3249	106.4
91500_8	Z_91500	-1.54337	21895	44	0.7	-1073.84	-15.0309	5.47	1.2	0.07432	2.89	0.105533	3.232419	1.8819	2.7	0.18117	1.2	0.24	0.053894	3.229704	996	110	110	1073	24	24	1067	33	33	1059.49	66.4881	151.7194	107.7
91500_9	Z_91500	1.529392	23892	47	0.7	-1308.26	-24.5606	5.48	1.1	0.070																							

Plesovice_Z_Plesovic	1.369135	78491	533	0.2	1876.575	40.7196	18.11	0.6	0.05156	1.19	0.033983	4.019949	0.3966	1.3	0.05432	0.5	0.28	0.01528	3.511083	252	56	56	341	4	4	339	7	7	306.3523	21.33085	45.54901	135.3
Plesovice_Z_Plesovic	1.100801	65848	465	0.2	1992.902	37.52053	18.60	0.8	0.05372	2.06	0.03205	4.578493	0.4018	1.9	0.05312	0.8	0.02	0.017239	3.036744	327	83	83	334	5	5	342	11	11	345.323	20.77811	49.86171	102.0
Plesovice_Z_Plesovic	0.222424	80241	557	0.2	2964.403	33.67022	18.28	0.8	0.05280	1.47	0.036453	2.782765	0.4019	1.3	0.05406	0.8	0.14	0.015628	3.097958	314	69	69	339	5	5	343	7	7	313.3176	19.2728	45.49555	108.1
Plesovice_Z_Plesovic	0.184578	61364	431	0.2	1606.087	37.22014	18.37	0.9	0.05188	1.84	0.027984	3.80555	0.3989	1.6	0.05385	0.9	0.21	0.016343	3.416969	283	70	70	338	6	6	340	9	9	327.4935	22.19056	48.40677	119.4
Plesovice_Z_Plesovic	-0.03324	87531	617	0.2	408.1751	122.4338	18.30	0.8	0.05217	1.73	0.034118	2.658103	0.3935	1.5	0.05401	0.8	0.00	0.016763	2.173507	266	80	80	339	5	5	336	8	8	335.9361	14.47327	46.42578	127.3
Plesovice_Z_Plesovic	0.496372	60567	431	0.3	519.3408	57.37796	18.40	0.8	0.05293	1.57	0.033484	4.771835	0.4009	1.5	0.05372	0.8	0.00	0.011991	5.313897	303	73	73	337	5	5	342	8	8	240.7121	25.40473	40.60064	111.2
Plesovice_Z_Plesovic	0.54901	81161	580	0.2	-211.379	-154.809	18.32	0.7	0.05154	1.75	0.035796	2.590613	0.3915	1.5	0.05396	0.7	-0.09	0.016726	2.245606	236	83	83	339	5	5	335	9	9	335.2067	14.93193	46.51118	143.3
Plesovice_Z_Plesovic	0.281415	78768	555	0.2	-527.888	-55.59	18.05	0.7	0.05191	1.45	0.03863	2.47188	0.3995	1.3	0.05459	0.7	-0.05	0.017244	2.742734	263	66	66	343	5	5	341	7	7	345.4528	18.78843	49.11509	130.5
Plesovice_Z_Plesovic	0.724248	60577	439	0.3	-62.7904	-437.302	18.54	0.8	0.05288	1.77	0.033327	3.708106	0.3977	1.7	0.05336	0.9	0.21	0.010536	4.934513	296	81	81	335	6	6	339	10	10	211.6891	20.78358	34.79156	113.3

Supplementary Table 1.4: U-Pb in zircon (Reference Materials for sample CJ-202A - Session 1)

LEGGA, Universidade de Brasília				Data for Tera-Wasserburg plot				Data for Wetherill plot				Dates																					
Identifier	Comment	T206c	206Pb	Uppm	Th/U	206Pb/204 1s%	238U/206Pb 1s%	207Pb/204 1s%	208Pb/204 1s%	207Pb/235 1s%	206Pb/238 1s%	Rho	208Pb/231 1s%	207Pb/204 2s (abs)	2ssys (abs)	206Pb/234 2s (abs)	2ssys (abs)	207Pb/235 2s (abs)	2ssys (abs)	208Pb/231 2s (abs)	2ssys (abs)	% conc											
GJ-1.FIN2_Z_GJ1		0.025529	145141	292	0.0	-2519.15	-4.57021	10.42	0.8	0.06027	1.34	0.005055	26.098	0.8124	1.1	0.09718	0.8	-0.06	0.033435	9.13188	566	59	59	598	9	9	602	10	10	657.9372	74.08986	118.0496	105.6
GJ-2.FIN2_Z_GJ1		0.361126	141207	278	0.0	-2345.65	-5.58843	10.39	0.9	0.05858	1.45	0.014498	75.33142	0.7940	1.1	0.09749	0.9	-0.17	0.031661	9.61834	506	64	64	599	10	10	593	9	9	623.5777	79.27385	117.6967	118.5
GJ-3.FIN2_Z_GJ1		0.036282	142756	286	0.0	-2366.58	-5.17355	10.43	0.8	0.06065	1.43	0.003628	7.55945	0.8102	1.1	0.09693	0.8	-0.14	0.030848	9.354399	564	63	63	596	9	9	600	9	9	607.3935	72.50796	111.5644	105.7
GJ-4.FIN2_Z_GJ1		0.176666	146007	293	0.0	-2591.55	-4.78752	10.37	0.8	0.06004	1.41	0.008506	50.84929	0.8082	1.1	0.09738	0.8	-0.12	0.037629	14.5028	556	64	64	599	9	9	599	10	10	656.1374	90.0454	103.3101	107.6
GJ-5.FIN2_Z_GJ1		0.110803	144900	290	0.0	-2634.23	-4.32269	10.35	0.8	0.06029	1.28	0.003481	5.621825	0.8190	1.1	0.09780	0.8	-0.01	0.028406	8.92256	576	58	58	601	9	9	605	9	9	561.7002	59.67156	98.75218	104.4
GJ-6.FIN2_Z_GJ1		0.021426	145832	292	0.0	-3778.91	-3.71642	10.24	0.8	0.05972	1.37	0.00863	35.27884	0.8137	1.1	0.09861	0.8	-0.02	0.043252	15.02144	545	58	58	606	9	9	603	9	9	748.6567	129.8037	147.3522	111.1
GJ-7.FIN2_Z_GJ1		0.143073	141572	282	0.0	-3455.81	-4.23313	10.24	0.8	0.06071	1.33	0.005429	21.58027	0.8290	1.1	0.09882	0.7	-0.02	0.032711	9.612742	581	58	58	607	9	9	611	9	9	642.3024	80.71956	119.9269	104.4
GJ-8.FIN2_Z_GJ1		0.326186	141782	288	0.0	-6904.95	-3.69171	10.29	0.8	0.06001	1.36	0.003358	5.749329	0.8184	1.1	0.09841	0.8	0.03	0.028698	8.829192	578	58	58	605	9	9	605	10	10	567.5077	58.59114	98.80767	104.6
GJ-9.FIN2_Z_GJ1		0.333167	141160	288	0.0	-6996.84	-3.46199	10.31	0.8	0.06013	1.31	0.004047	15.10726	0.8160	1.1	0.09816	0.8	0.03	0.028691	10.31088	560	59	59	603	9	9	604	10	10	543.6183	71.47556	98.6852	107.7
GJ-10.FIN2_Z_GJ1		-0.05405	139482	285	0.0	-2741.18	-3.96273	10.22	0.8	0.05978	1.34	0.004607	20.42878	0.8214	1.1	0.09870	0.8	-0.02	0.033939	10.39245	549	59	59	606	9	9	607	9	9	663.0428	96.60646	132.4464	110.4
GJ-11.FIN2_Z_GJ1		0.048725	138259	288	0.0	-2388.02	-4.81387	10.38	0.8	0.06100	1.43	0.003514	9.530057	0.8229	1.1	0.09747	0.8	-0.08	0.027357	9.545608	586	63	63	599	9	9	607	10	10	539.9661	67.2332	100.7526	102.3
GJ-12.FIN2_Z_GJ1		-0.02845	136531	287	0.0	-3043.34	-4.04695	10.35	0.8	0.05959	1.47	0.003894	14.59686	0.8128	1.4	0.09786	0.8	-0.01	0.030711	9.707776	530	61	61	602	9	9	597	10	10	604.0537	77.92058	114.4312	113.5
GJ-13.FIN2_Z_GJ1		-0.03419	137614	287	0.0	-2823.13	-4.1535	10.33	0.8	0.05976	1.43	0.003904	12.29063	0.8121	1.3	0.09776	0.8	0.05	0.029778	9.963342	535	62	62	601	9	9	601	11	11	585.1759	79.88156	114.0194	112.4
GJ-14.FIN2_Z_GJ1		-0.12736	136161	290	0.0	-3244.34	-4.91444	10.31	0.9	0.06034	1.60	0.004447	12.38353	0.8220	1.3	0.09844	0.9	-0.02	0.031335	9.553514	556	67	67	605	10	10	606	11	12	616.3623	76.63358	114.7218	108.7
GJ-15.FIN2_Z_GJ1		0.077964	138573	294	0.0	-3279.1	-3.74826	10.30	0.9	0.06087	1.41	0.004848	11.39248	0.8247	1.1	0.09840	0.9	0.00	0.036915	10.23073	581	62	62	605	10	10	608	9	9	719.6321	101.2735	140.8346	104.0
GJ-16.FIN2_Z_GJ1		0.2292	135978	296	0.0	-2563.66	-4.9667	10.43	0.8	0.06136	1.49	0.007207	31.07095	0.8239	1.2	0.09713	0.8	0.00	0.035044	12.06925	589	63	63	597	9	9	607	11	11	676.5549	123.4294	152.7418	101.4
GJ-17.FIN2_Z_GJ1		0.258333	136688	298	0.0	-2501.36	-4.88419	10.40	0.8	0.06041	1.44	0.008982	55.14767	0.8183	1.2	0.09719	0.8	-0.10	0.036617	24.1565	571	63	63	598	9	9	603	10	10	558.1309	77.89533	81.50522	104.7
GJ-18.FIN2_Z_GJ1		0.254898	124962	275	0.0	-3919.81	-3.60465	10.34	0.8	0.06071	1.54	0.00582	22.82348	0.8206	1.4	0.09786	0.8	0.03	0.030777	10.41508	562	64	64	602	9	9	605	12	12	602.7342	67.68977	119.9928	107.1
GJ-19.FIN2_Z_GJ1		0.004579	125200	277	0.0	-3713.73	-3.5593	10.43	0.8	0.06119	1.52	0.003405	6.788935	0.8231	1.3	0.09721	0.8	-0.03	0.027964	9.88183	578	66	66	598	9	9	607	11	11	559.6872	76.4215	110.0295	103.3
GJ-20.FIN2_Z_GJ1		0.378914	138499	307	0.0	-7911.74	-19.7885	10.30	0.9	0.06046	1.36	0.004263	13.14899	0.8226	1.1	0.09850	0.9	-0.01	0.032307	9.587871	577	63	63	605	10	10	607	10	10	634.7626	79.87667	119.0492	104.9
GJ-21.FIN2_Z_GJ1		0.25976	135928	302	0.0	-6460.11	-3.60881	10.28	0.8	0.05899	1.32	0.004407	16.70113	0.8028	1.2	0.09819	0.8	-0.01	0.03187	9.6668	526	58	58	603	9	9	596	10	10	626.0115	80.51022	118.819	114.6
GJ-22.FIN2_Z_GJ1		0.193456	124734	285	0.0	-4085.48	-3.60387	10.33	0.8	0.06063	1.51	0.004264	12.5253	0.8173	1.2	0.09782	0.8	-0.08	0.031667	9.643019	561	63	63	601	9	9	604	11	11	622.1971	79.18999	117.2129	107.2
GJ-23.FIN2_Z_GJ1		0.444714	121861	274	0.0	-3652.22	-6.10383	10.35	0.8	0.06027	1.61	0.005192	23.9859	0.8168	1.3	0.09783	0.8	0.38	0.030439	10.05179	562	68	68	601	9	9	603	11	12	597.7463	82.78814	117.1074	107.0
GJ-24.FIN2_Z_GJ1		0.166203	122368	279	0.0	-3081.6	-4.12047	10.22	0.8	0.05916	1.32	0.007157	51.78439	0.8084	1.1	0.09867	0.8	0.00	0.030702	9.897147	534	60	60	606	9	9	600	9	9	603.0787	81.73225	117.4811	113.5
GJ-25.FIN2_Z_GJ1		0.201817	119061	276	0.0	-3251	-3.83853	10.39	0.8	0.05972	1.42	0.004525	14.89292	0.8066	1.1	0.09713	0.8	-0.11	0.033654	10.04803	555	60	60	597	9	9	598	9	9	638.9176	81.60894	115.4833	107.6
GJ-26.FIN2_Z_GJ1		-0.06988	121108	283	0.0	-2821.6	-3.87309	10.30	0.8	0.05931	1.33	0.004462	13.97217	0.8074	1.2	0.09805	0.8	0.00	0.036915	9.596928	533	62	62	603	9	9	598	10	11	597.5043	81.68561	116.6719	113.0
GJ-27.FIN2_Z_GJ1		0.245732	122216	287	0.0	-2853.45	-4.02797	10.40	0.8	0.05982	1.42	0.005907	26.4566	0.8073	1.2	0.09736	0.8	-0.03	0.038156	13.41507	563	66	66	599	9	9	598	9	9	688.5549	129.899	153.1787	106.3
GJ-28.FIN2_Z_GJ1		-0.16081	123924	292	0.0	-2637.13	-4.07307	10.26	0.8	0.06046	1.36	0.00563	25.41374	0.8213	1.0	0.09868	0.8	-0.09	0.036756	13.2461	569	60	60	606	9	9	608	9	9	738.8497	132.6063	157.1617	106.5
GJ-29.FIN2_Z_GJ1		-0.22587	116709	281	0.0	-2647.94	-3.54988	10.39	0.8	0.06062	1.47	0.016584	80.34233	0.8114	1.2	0.09713	0.7	-0.13	0.027552	9.6814	567	64	64	597	8	8	602	10	11	543.1682	70.23536	100.4718	105.3
GJ-30.FIN2_Z_GJ1		0.127238	118375	287	0.0	-4461.86	-3.32263	10.38	0.8	0.05908	1.47	0.003105	8.365249	0.7977	1.1	0.09745	0.8	-0.09	0.025484	10.11453	514	64	64	599	9	9	593	10	10	502.2717	71.24638	100.1635	116.6
GJ-31.FIN2_Z_GJ1		0.388742	117706	285	0.0	-5097.05	-4.58911	10.48	0.8	0.06000	1.45	0.003783	11.38185	0.8077	1.2	0.09758	0.9	-0.04	0.029176	9.466416	546	63	63	600	10	10	600	11	11	575.0006	70.95416	107.4592	109.8
GJ-32.FIN2_Z_GJ1		-0.01376	117924	284	0.0	-3204.58	-3.55326	10.21	0.8	0.06077	1.43	0.004576	16.22292	0.8315	1.2	0.09887	0.8	0.10	0.035831	10.3452	593	65	65	608	9	9	612	10	10	674.7445	88.06443	121.2261	102.7
GJ-33.FIN2_Z_GJ1		-0.01415	114560	283	0.0	-3129.47	-3.5996	10.37	0.8	0.06099	1.42	0.00551	28.42736	0.8249	1.1	0.09777	0.8	0.05	0.029661	10.43575	586	61	61	601	9	9	608	10	10	581.3716	86.20425	117.7574	102.6
GJ-34.FIN2_Z_GJ1		0.291276	114061	282	0.0	-4232.66	-3.69095	10.36	0.9	0.05960	1.48	0.006802	41.35624	0.8058	1.2	0.09774	0.9	0.27	0.030398	10.93443	524	65	65	601	10	10	597	11	11	661.4322	101.8728	139.3474	114.7
GJ-35.FIN2_Z_GJ1		0.160678	115966	291	0.0	-4077.84	-3.75032	10.40	0.9	0.06128	1.74	0.004114	9.973691	0.8261	1.3	0.09741	0.9	0.05	0.032099	10.5													

91500-34.I_Z_91500	-0.94304	27011	38	0.8	-548.839	-4.37894	5.84	1.0	0.07789	2.40	0.088086	3.150265	1.8700	2.1	0.17431	1.1	-0.06	0.053241	7.597459	1036	90	90	1034	21	21	1057	26	26	1054.08	57.49186	163.0338	99.8
PLES-1.FIN_Z_Plesovic	0.038277	159392	573	0.4	-2609.3	-4.6988	18.60	0.7	0.05295	1.09	0.040605	2.357951	0.4007	1.0	0.05420	0.7	0.08	0.017831	7.301343	297	52	52	340	5	5	342	5	6	357.0459	11.76905	51.66997	114.6
PLES-2.FIN_Z_Plesovic	-0.00368	186302	674	0.5	-3216.83	-4.28828	18.61	0.7	0.05216	1.17	0.047163	1.694806	0.3929	1.0	0.05419	0.7	-0.06	0.016534	7.265464	250	55	55	340	4	4	336	5	6	331.3558	9.842313	47.75159	136.2
PLES-3.FIN_Z_Plesovic	0.200997	131009	473	0.3	-2860.91	-4.27498	18.34	0.7	0.05359	1.34	0.027519	2.535015	0.4084	1.2	0.05484	0.7	0.06	0.016649	7.48419	305	59	59	344	5	5	347	7	7	333.4474	15.45677	49.46448	112.9
PLES-4.FIN_Z_Plesovic	-0.04728	132356	480	0.3	-2734.94	-4.36615	18.58	0.7	0.05341	1.25	0.028595	2.24099	0.4045	1.2	0.05433	0.7	0.12	0.017274	7.467563	295	58	58	341	5	5	344	7	7	345.8659	15.6673	51.2022	115.5
PLES-5.FIN_Z_Plesovic	0.536262	133434	496	0.3	-4362.28	-4.30043	18.72	0.7	0.05302	1.20	0.029728	2.606612	0.3989	1.1	0.05391	0.7	0.05	0.016827	7.466851	297	56	56	338	4	4	340	6	6	336.9869	15.2515	49.8875	113.9
PLES-6.FIN_Z_Plesovic	0.486951	127491	470	0.3	-3447.5	-4.51968	18.61	0.6	0.05342	1.16	0.038935	13.24264	0.4022	1.1	0.05401	0.6	0.19	0.018013	7.725863	308	54	54	339	4	4	342	6	6	360.271	21.44499	54.78499	110.1
PLES-7.FIN_Z_Plesovic	0.256333	126837	474	0.3	-1811.89	-5.87046	18.63	0.7	0.05468	1.59	0.029165	3.44881	0.4141	1.5	0.05410	0.7	0.12	0.016759	7.44742	328	67	67	340	5	5	350	8	9	335.6729	14.77204	49.59201	103.5
PLES-8.FIN_Z_Plesovic	-0.00079	133301	497	0.3	-2113.41	-4.74767	18.53	0.7	0.05256	1.27	0.029582	2.486774	0.3983	1.1	0.05451	0.7	0.03	0.017185	7.393338	284	58	58	342	5	5	340	6	6	344.1568	13.84954	50.45255	120.5
PLES-9.FIN_Z_Plesovic	-0.01223	130256	490	0.3	-2178.39	-4.49569	18.48	0.7	0.05342	1.49	0.029392	3.108502	0.4047	1.2	0.05452	0.7	-0.08	0.01705	7.395642	290	62	62	342	4	4	344	7	7	341.4695	13.78928	50.05303	118.1
PLES-10.FI_Z_Plesovic	-0.11652	128835	488	0.3	-1978.09	-4.87148	18.66	0.7	0.05377	1.40	0.032859	9.494605	0.4064	1.5	0.05406	0.6	0.11	0.016635	7.462888	301	61	61	339	4	4	345	8	8	333.1833	14.98568	49.27471	112.7
PLES-11.FI_Z_Plesovic	0.037626	133979	522	0.3	-3268.25	-4.03266	18.80	0.8	0.05317	1.28	0.030791	3.211582	0.3959	1.1	0.05352	0.7	0.01	0.016966	7.461826	307	62	62	336	5	5	338	6	6	339.7455	15.25295	50.21894	109.6
PLES-12.FI_Z_Plesovic	0.301911	134414	517	0.3	-3085.76	-4.56384	18.46	0.7	0.05382	1.21	0.031174	4.21026	0.4086	1.1	0.05452	0.7	0.11	0.017697	7.393614	315	55	55	342	5	5	347	6	7	354.299	14.25583	51.90932	108.7
PLES-13.FI_Z_Plesovic	0.054795	120758	458	0.3	-1969.31	-5.81152	18.55	0.7	0.05386	1.46	0.031823	8.072756	0.4085	1.3	0.05436	0.7	0.16	0.016922	7.478416	306	61	61	341	5	5	345	6	7	338.9323	15.58978	50.2463	111.6
PLES-15.FI_Z_Plesovic	0.164133	121826	483	0.3	-3294.41	-3.8473	18.83	0.7	0.05400	1.34	0.02972	2.025972	0.4058	1.5	0.05357	0.7	0.10	0.01656	7.375468	316	60	60	336	5	5	342	7	7	331.7841	12.9195	48.5325	106.3
PLES-16.FI_Z_Plesovic	0.124911	123575	499	0.3	-3267.75	-3.98265	18.78	0.7	0.05442	1.55	0.034791	8.366966	0.4086	1.4	0.05372	0.7	0.02	0.01762	7.75658	313	64	64	337	5	5	346	8	8	352.4839	21.43592	53.60753	107.8
PLES-17.FI_Z_Plesovic	0.422784	135582	544	0.3	-4128.76	-4.89091	18.54	0.7	0.05200	1.33	0.031115	5.534164	0.4004	1.3	0.05438	0.7	0.09	0.016585	7.423762	289	65	65	341	5	5	341	7	7	332.226	14.01698	48.68258	118.2
PLES-19.FI_Z_Plesovic	0.164139	128315	526	0.3	-3350.76	-3.94894	18.66	0.6	0.05289	1.25	0.034678	2.173848	0.4007	1.2	0.05395	0.6	-0.03	0.01679	7.36611	271	57	57	339	4	4	341	7	7	336.338	12.84533	49.08403	124.8
PLES-20.FI_Z_Plesovic	1.240391	124462	515	0.3	-3009.01	-4.55968	18.79	0.7	0.05416	1.68	0.042607	27.34377	0.4013	1.2	0.05367	0.6	0.12	0.017247	7.872881	304	53	53	337	4	4	342	6	7	344.9803	22.76266	52.9855	110.9
PLES-21.FI_Z_Plesovic	0.233191	153902	644	0.5	-4428.71	-4.12633	18.62	0.7	0.05294	1.21	0.047421	2.316223	0.3997	1.1	0.05426	0.7	-0.01	0.01613	7.337422	293	58	58	341	5	5	341	6	6	323.2473	11.62335	46.99528	116.4
PLES-22.FI_Z_Plesovic	0.440406	149552	625	0.5	-4134.6	-4.51128	18.48	0.6	0.05295	1.12	0.048878	1.585809	0.4031	1.1	0.05445	0.6	0.15	0.016464	7.279156	300	53	53	342	4	4	343	6	6	329.932	10.22588	47.61398	113.8
PLES-23.FI_Z_Plesovic	0.301095	129083	550	0.3	-3202.21	-4.34568	18.58	0.6	0.05341	1.15	0.036474	4.886475	0.4016	1.0	0.05419	0.6	0.11	0.017544	7.381555	301	53	53	340	4	4	342	6	6	351.2765	13.81749	51.35765	113.0
PLES-24.FI_Z_Plesovic	0.507972	119967	514	0.3	-3325.16	-4.03828	18.62	0.6	0.05332	1.36	0.032143	4.262593	0.4021	1.3	0.05416	0.6	0.02	0.016677	7.590402	290	59	59	340	4	4	342	7	7	333.9119	17.54858	50.0949	117.1
PLES-26.FI_Z_Plesovic	0.173053	154548	666	0.5	-2719.22	-5.03133	18.48	0.6	0.05290	1.18	0.050784	2.344035	0.4030	1.1	0.05448	0.6	0.07	0.016664	7.322169	282	57	57	342	4	4	343	6	6	333.8747	11.5853	48.39936	121.4
PLES-27.FI_Z_Plesovic	0.189194	151734	671	0.5	-6765.08	-3.57858	18.78	0.7	0.05337	1.18	0.052756	6.223036	0.3985	1.1	0.05368	0.7	0.01	0.016078	7.416658	297	54	54	337	5	5	340	6	6	322.1522	13.47295	47.30259	113.5
PLES-28.FI_Z_Plesovic	0.366523	130812	577	0.4	-5160.82	-3.73288	18.91	0.6	0.05420	1.11	0.038256	2.122496	0.4040	1.0	0.05330	0.6	-0.03	0.015699	7.304775	349	48	48	335	4	4	344	5	6	314.7079	10.4805	45.61973	95.9
PLES-29.FI_Z_Plesovic	0.443589	119378	533	0.3	-2896.77	-4.09373	18.64	0.7	0.05282	1.25	0.032223	7.015871	0.3968	1.1	0.05407	0.7	0.18	0.016776	7.506236	296	57	57	339	5	5	339	6	6	335.9354	16.02688	49.95154	114.8
PLES-30.FI_Z_Plesovic	0.042629	110981	505	0.3	-2623.06	-4.06581	18.92	0.7	0.05356	1.27	0.031651	6.594456	0.3990	1.3	0.05329	0.7	0.19	0.016031	7.50157	298	58	58	335	4	4	340	7	7	321.1552	15.24522	47.77579	112.3
PLES-32.FI_Z_Plesovic	-0.09977	114745	524	0.3	-3329.12	-3.68472	18.61	0.7	0.05296	1.20	0.029349	3.180033	0.4012	1.1	0.05407	0.7	0.05	0.015441	7.511169	287	58	58	339	4	4	342	6	6	309.4223	14.86268	46.0594	118.2
PLES-33.FI_Z_Plesovic	-0.14396	118437	551	0.3	-2176.46	-4.2767	18.80	0.7	0.05350	1.32	0.030476	3.018643	0.3985	1.2	0.05359	0.8	0.05	0.015852	7.572473	291	61	61	336	5	5	339	7	7	317.5406	16.41126	47.66213	115.5
PLES-34.FI_Z_Plesovic	-0.16995	111011	520	0.3	-2173.13	-3.46258	18.97	0.6	0.05423	1.12	0.029304	4.325802	0.4020	1.1	0.05301	0.6	0.12	0.015052	7.566422	356	51	51	333	4	4	342	6	6	301.6687	15.45883	45.1633	93.6

Supplementary Table 1.5: U-Pb in zircon (Reference Materials for sample CJ-202B)

LEGGA, Universidade de Brasília					Data for Tera-Wasserburg plot					Data for Wetherill plot					Dates										% conc								
Identifier	Comment	f206c	206Pb	Uppm	Th/U	206Pb/204 1s%	238U/206l 1s%	208Pb/204 1s%	207Pb/204 1s%	206Pb/235 1s%	Rho	208Pb/231 1s%	207Pb/204 2s (abs)	2ssys (abs)	206Pb/231 2s (abs)	2ssys (abs)	207Pb/235 2s (abs)	2ssys (abs)	208Pb/231 2s (abs)	2ssys (abs)	% conc												
GJ1-1.FIN2_Z_GJ1		0.026449	102014	284	0.0	3159.32	41.69445	10.18	0.5	0.05989	0.95	0.004565	6.388482	0.8162	0.9	0.09836	0.5	0.14	0.030972	6.054683	592	42	50	605	5	9	605	8	9	614.7803	73.13707	789.7267	102.2
GJ1-2.FIN2_Z_GJ1		0.294263	101792	288	0.0	2841.252	33.05766	10.31	0.5	0.06054	0.87	0.00419	7.274275	0.8143	0.9	0.09710	0.5	0.21	0.029833	7.738149	616	38	46	597	5	8	604	8	9	591.5371	90.33174	754.0217	97.0
GJ1-3.FIN2_Z_GJ1		-0.01131	102901	290	0.0	1007.839	82.47773	10.20	0.4	0.06015	0.79	0.005706	5.803665	0.8165	0.7	0.09810	0.4	-0.01	0.031141	5.904541	603	34	42	603	5	8	606	6	7	618.1654	72.01071	782.1311	100.0
GJ1-5.FIN2_Z_GJ1		0.116154	100042	288	0.0	4323.034	36.37084	10.22	0.4	0.05974	1.01	0.006038	4.293914	0.8068	0.9	0.09793	0.4	0.16	0.030725	4.613293	586	43	50	602	5	8	602	9	10	610.6903	55.53099	779.4599	102.8
GJ1-6.FIN2_Z_GJ1		0.080087	100160	295	0.0	2912.141	39.41653	10.23	0.4	0.06054	0.85	0.006419	5.774858	0.8218	0.9	0.09784	0.4	-0.13	0.03089	5.406516	625	41	50	602	5	8	609	8	9	613.5418	65.31792	790.4183	96.3
GJ1-7.FIN2_Z_GJ1		0.122629	95478	279	0.0	-14998.5	-35.3266	10.23	0.5	0.05930	0.95	0.004501	8.561796	0.8041	0.8	0.09768	0.5	-0.06	0.03036	8.479009	570	43	50	601	5	9	599	8	9	601.3024	100.673	780.5597	105.4
GJ1-8.FIN2_Z_GJ1		0.536229	98147	282	0.0	-4020.88	-36.5967	10.23	0.4	0.06087	1.09	0.006725	5.186271	0.8306	0.9	0.09787	0.5	-0.24	0.030921	5.369643	624	46	52	602	5	8	614	8	9	614.1779	64.9177	792.6553	96.3
GJ1-9.FIN2_Z_GJ1		0.153078	102326	295	0.0	-47433.8	-46.9054	10.18	0.5	0.05982	1.02	0.005299	5.066731	0.8182	0.9	0.09815	0.5	0.07	0.030695	5.566521	598	42	48	604	5	9	608	7	8	609.6734	66.83639	795.9048	100.9
GJ1-10.FIN_Z_GJ1		0.101345	98571	286	0.0	-3293.18	-24.7614	10.24	0.4	0.06092	1.03	0.004003	8.522783	0.8135	0.8	0.09768	0.4	-0.11	0.030791	9.006486	628	45	52	601	4	8	604	7	9	609.268	108.0486	783.8642	95.7
GJ1-12.FIN_Z_GJ1		-0.01605	99044	286	0.0	-3954.59	-23.4301	10.19	0.5	0.06011	1.30	0.005433	5.87951	0.8179	1.2	0.09827	0.5	0.05	0.030757	6.164055	594	55	60	604	5	9	606	11	12	610.547	74.4631	787.0078	101.7
GJ1-13.FIN_Z_GJ1		0.027291	97968	286	0.0	-2514.35	-26.8912	10.26	0.4	0.05994	1.03	0.005409	5.193957	0.8090	1.0	0.09753	0.4	0.01	0.030728	6.020677	593	44	50	600	5	8	601	9	10	610.0619	72.5047	784.1046	101.2
GJ1-14.FIN_Z_GJ1		0.131867	98246	300	0.0	1087.786	64.41384	10.20	0.5	0.05972	1.16	0.005962	6.7451	0.8111	1.1	0.09811	0.5	0.32	0.030739	5.49685	594	55	61	603	6	9	602	10	10	610.5516	66.29532	783.851	101.6
GJ1-16.FIN_Z_GJ1		0.0428	85412	279	0.0	626.6076	120.4104	10.26	0.5	0.06058	0.95	0.001435	35.22706	0.8168	0.9	0.09754	0.5	0.09	0.030547	36.91146	630	47	55	600	5	9	608	9	11	565.0228	430.7205	872.1408	95.2
GJ1-18.FIN_Z_GJ1		-0.44155	97835	291	0.0	-16610.9	-24.8136	10.18	0.5	0.05977	1.07	0.005635	8.954207	0.8155	0.9	0.09838	0.5	0.02	0.03068	8.869227	586	46	53	605	6	9	605	8	9	608.6514	82.21115	772.4695	103.3
GJ1-19.FIN_Z_GJ1		-0.08335	98557	292	0.0	-7678.92	-26.1119	10.24	0.4	0.05942	1.38	0.005655	5.755965	0.8104	1.1	0.09772	0.4	0.12	0.03076	6.146095	598	59	64	601	5	8	602	10	11	610.6234	73.97768	778.9576	100.5
GJ1-20.FIN_Z_GJ1		0.039926	101798	291	0.0	2440.822	63.63182	10.26	0.6	0.06036	1.39	0.005232	6.4938	0.8095	1.1	0.09764	0.6	0.02	0.030737	6.932653	601	59	64	601	7	10	601	10	11	609.7322	82.87668	779.8791	99.8
GJ1-22.FIN_Z_GJ1		-0.27322	94584	287	0.0	63445.4	36.34633	10.22	0.5	0.06007	0.98	0.006732	19.96487	0.8174	0.9	0.09793	0.5	0.11	0.030319	6.508154	610	47	55	602	5	9	606	8	9	601.8294	76.86212	768.2513	98.7
GJ1-23.FIN_Z_GJ1		-0.04741	96575	292	0.0	10665.96	35.75398	10.23	0.6	0.05968	1.15	0.005516	8.26439	0.8088	1.1	0.09791	0.6	0.12	0.031924	7.728055	581	49	55	602	7	10	601	10	11	632.2187	96.68711	817.7322	103.6
GJ1-24.FIN_Z_GJ1		0.357585	91097	281	0.0	12277.93	27.14175	10.26	0.7	0.06074	0.98	0.003019	18.39051	0.8218	0.9	0.09770	0.7	0.28	0.029179	17.83722	622	43	50	601	8	10	609	8	9	568.251	203.3624	827.5788	96.6
PLES-2.FIN PLES		0.698009	114866	592	0.3	-3131.2	-469.393	18.75	0.5	0.05190	1.08	0.05781	1.511565	0.3839	1.1	0.05341	0.5	0.43	0.011882	2.129622	270	50	57	335	3	5	330	6	7	238.713	10.1072	299.0687	124.2
PLES-3.FIN PLES		0.099834	82987	450	0.2	-4722.73	-23.0968	18.69	0.4	0.05441	0.96	0.02377	3.255874	0.4030	0.9	0.05356	0.4	0.54	0.025231	3.789187	380	44	51	336	3	5	344	5	6	503.1931	37.64736	688.392	88.6
PLES-8.FIN PLES		0.650878	76791	439	0.2	832.9968	66.28501	18.69	0.6	0.05347	1.15	0.029081	2.62026	0.3986	1.1	0.05361	0.6	0.16	0.01889	2.602184	337	53	59	337	4	5	340	6	7	378.119	19.50151	490.4467	99.9
PLES-9.FIN PLES		0.581564	73033	397	0.2	-4216.65	-28.139	18.64	0.5	0.05249	1.35	0.02918	2.782298	0.3925	1.2	0.05373	0.5	0.02	0.015313	2.884303	304	57	63	337	4	5	336	7	8	307.0742	17.57352	393.3383	110.8
PLES-10.FI PLES		0.336577	68115	358	0.2	51466.96	106.7996	18.23	0.6	0.05372	1.23	0.027997	2.893932	0.4092	1.2	0.05496	0.6	0.08	0.014776	3.096096	345	58	65	345	4	6	348	7	7	296.3716	18.21795	380.5231	99.9
PLES-11.FI PLES		0.251275	66662	356	0.2	-1431.77	-38.9863	18.26	0.6	0.05375	1.45	0.028899	5.862724	0.4090	1.3	0.05472	0.6	-0.07	0.016783	3.407934	344	63	68	343	4	6	348	8	8	336.2474	22.71555	431.3738	99.9
PLES-12.FI PLES		0.216498	67035	368	0.2	-8180.43	-25.4172	18.49	0.8	0.05255	1.44	0.027962	3.574657	0.3945	1.2	0.05430	0.9	-0.11	0.017268	3.642619	291	67	72	341	6	7	337	7	7	345.8539	24.9893	444.1015	117.2
91500-5.FI_Z_91500		-0.63673	31856	50	0.7	5949.093	22.81145	5.61	0.8	0.07271	1.90	0.105004	2.372468	1.8069	1.5	0.17891	0.8	-0.15	0.066752	2.587649	981	75	79	1061	16	20	1045	20	21	1304.742	65.24006	1710.135	108.1
91500-7.FI_Z_91500		-0.20921	32282	50	0.7	-802.715	-29.3997	5.61	0.8	0.07474	2.07	0.106052	2.285169	1.8723	1.5	0.17893	0.8	-0.20	0.057457	2.048862	1057	76	79	1061	15	19	1069	20	21	1128.562	44.91613	1425.257	100.3
91500-8.FI_Z_91500		-0.2194	30391	49	0.7	-1087.4	-18.4746	5.74	0.9	0.07771	1.46	0.10693	2.379007	1.8775	1.2	0.17478	0.9	0.19	0.055703	2.767804	1124	58	63	1038	17	20	1071	17	18	1094.547	58.8434	1379.044	92.3
91500-9.FI_Z_91500		-0.16448	30283	57	0.7	-1038.93	-28.7931	5.67	1.0	0.07265	1.67	0.127596	17.96408	1.7655	1.5	0.17635	0.9	0.19	0.274434	3.665052	998	65	69	1047	18	21	1030	20	21	4871.642	302.5377	5384.714	104.8
91500-10.I_Z_91500		-0.30608	30545	58	0.7	-776.309	-22.8998	5.60	1.7	0.07172	1.99	0.101388	2.575276	1.7802	2.0	0.17882	1.2	0.25	0.27066	2.462223	948	88	92	1060	24	27	1034	26	27	4827.575	209.9102	5502.701	111.9
91500-11.I_Z_91500		1.978665	29773	47	0.7	-36.3887	-424.816	5.60	0.7	0.07699	2.15	0.106442	2.964152	1.8817	2.1	0.17891	0.7	0.17	0.057917	2.597924	1092	82	85	1061	13	17	1070	27	27	1136.941	57.44486	1438.551	97.2
91500-13.I_Z_91500		-0.78344	28866	47	0.7	-550.779	-24.2155	5.66	1.3	0.07544	2.18	0.10585	2.900339	1.8444	2.5	0.17701	1.1	0.38	0.054706	2.621792	1068	96	100	1050	21								

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CJ-202-106.FIN2	T202	Session 1	0.149861	898045	400	163	0.41	649	190	0.29	-13385.7	-8.1	2.01	1.2	0.24079	1.17	0.058619	5.13503	17.2941	1.8	0.51213	1.3	0.738	0.126481	7.603248	3100	37	37	2654	55	55	2925	32	33	2998	35	2388.668	121.7859	343.4481	10.4	85.6	44.1
CJ-202-107.FIN2	T203	Session 1	0.565821	1319962	679	654	0.96	1110	764	0.69	-7836.2	-17.7	2.42	0.8	0.24549	0.75	0.103258	2.038563	14.2547	1.0	0.41593	0.8	0.619	0.127451	7.252662	3142	24	24	2242	29	29	2761	17	19	2716	24	2419.415	64.70535	327.0757	21.4	71.4	85.1
CJ-202-108.FIN2	T204	Session 1	0.103704	1013128	356	334	0.94	598	393	0.66	-15879.1	-7.7	1.61	0.5	0.27264	0.72	0.082767	1.072154	23.6524	0.7	0.62251	0.6	0.222	0.164119	7.171206	3312	22	22	3117	28	28	3253	11	13	3239	13	3073.915	54.75401	416.4851	4.66	94.1	46.8
CJ-202-109.FIN2	T205	Session 1	1.01295	764397	299	308	1.03	493	360	0.73	-7015.9	-13.5	1.86	0.8	0.25513	1.15	0.158662	5.947379	19.4177	1.3	0.54360	0.8	0.416	0.155651	7.30528	3196	35	35	2798	35	35	3051	23	24	2991	26	2915.102	90.99888	391.4523	11.1	87.5	38.6
CJ-202-110.FIN2	T206	Session 1	0.156976	973018	387	257	0.66	633	300	0.47	-16363.0	-7.9	1.88	0.8	0.24526	1.05	0.075006	2.960654	18.3593	1.0	0.53454	0.8	0.213	0.138554	7.203038	3142	34	34	2756	35	35	3005	19	20	2962	19	2969.777	63.36479	395.8404	8.74	87.7	45.7
CJ-202-111.FIN2	T207	Session 1	0.050951	1138029	461	355	0.77	756	415	0.55	-22495.1	-6.2	1.84	0.8	0.24632	1.21	0.089962	2.525582	18.8863	1.1	0.54548	0.9	0.029	0.161374	7.139083	3163	41	41	2801	40	40	3028	19	21	2984	20	3058.005	87.1799	580.4006	9.34	86.5	56.0
CJ-202-112.FIN2	T208	Session 1	0.065903	342404	110	175	1.59	186	206	1.11	-7508.6	-5.3	1.48	1.3	0.28493	1.60	0.145084	1.380434	27.2730	1.2	0.69049	1.2	0.122	0.173012	7.2466	3364	51	51	3381	62	62	3390	22	23	3393	22	3219.091	83.23649	429.9333	0.288	100.5	16.5
CJ-202-113.FIN2	T209	Session 1	0.063027	933919	317	220	0.69	531	259	0.49	-17499.4	-5.9	1.61	0.8	0.27046	1.07	0.066577	1.861252	23.7423	0.9	0.62621	0.8	0.125	0.169587	7.176403	3291	34	34	3133	39	39	3251	16	18	3241	17	3162.187	57.14345	419.2588	4.34	95.2	39.5
CJ-202-114.FIN2	T210	Session 1	2.268322	1191542	619	587	0.95	1033	690	0.67	-3295.4	-36.4	2.36	1.1	0.26540	1.54	0.167095	4.734414	15.7381	1.4	0.42934	1.2	0.256	0.208026	8.366983	3267	50	50	2303	47	47	2854	25	26	2716	30	3747.478	283.8429	538.2985	25	70.5	80.5
CJ-202-115.FIN2	T211	Session 1	0.131877	939905	350	412	1.18	581	484	0.83	-18565.2	-6.3	1.73	0.7	0.25985	0.90	0.115858	2.047195	21.0072	0.8	0.58254	0.7	0.695	0.164633	7.168034	3233	28	28	2954	35	35	3134	14	16	3173	14	3076.818	52.63891	408.144	6.23	91.4	47.0
CJ-202-116.FIN2	T212	Session 1	0.182819	1049139	461	195	0.42	746	227	0.30	-18137.9	-8.2	2.04	0.9	0.23730	1.22	0.064017	3.228185	16.4935	1.4	0.49700	0.9	0.460	0.145339	7.328719	3076	39	39	2595	39	39	2891	26	27	2824	29	2738.088	64.43781	369.472	13.2	84.4	50.7
CJ-202-117.FIN2	T213	Session 1	0.534145	929514	410	110	0.27	651	127	0.20	-6751.1	-30.5	2.13	1.0	0.21660	1.25	0.033498	2.450801	14.3137	1.1	0.47311	1.0	0.208	0.186928	7.378162	2946	40	40	2495	41	41	2768	19	20	2725	21	3457.428	125.1888	468.1048	11.2	84.7	41.7
CJ-202-118.FIN2	T214	Session 1	0.195479	873107	344	418	1.21	571	490	0.86	-19556.1	-7.6	1.82	0.8	0.25869	0.82	0.141653	6.65502	20.0574	1.0	0.55475	0.8	0.460	0.165183	7.181662	3232	25	25	2844	35	35	3087	18	19	3078	20	3085.807	57.98918	410.1484	8.77	88.0	46.6
CJ-202-119.FIN2	T215	Session 1	0.138778	714138	323	152	0.47	519	177	0.34	-22395.6	-6.5	2.09	1.2	0.23988	1.07	0.07789	7.433441	15.7333	1.4	0.48866	1.1	0.608	0.118026	7.393704	3031	34	34	2562	49	49	2848	26	27	2863	28	2346.503	86.11296	313.9651	10.9	84.5	35.3
CJ-202-120.FIN2	T216	Session 1	0.070038	932003	393	265	0.68	642	310	0.48	-38089.8	-4.5	1.93	0.7	0.24371	0.90	0.068151	1.795515	17.7320	0.8	0.52119	0.7	0.094	0.151177	7.169911	3132	28	28	2704	29	29	2972	14	16	2922	15	2842.511	49.22752	378.1345	10.8	86.3	46.4
CJ-202A_1	T201	Session 2	-0.01254	67924	32	33	1.0	54	38	0.72	1617.7	51.0	1.37	2.7	0.28342	3.17	0.154114	3.428014	28.8795	1.9	0.73803	2.8	0.049	0.212112	3.235129	3350	101	101	3547	151	151	3443	37	37	3454	36	3876.935	226.3281	515.7605	-3.51	105.9	4.3
CJ-202A_2	T201	Session 2	0.001652	187337	126	8	0.1	207	10	0.05	3897.2	49.3	1.77	1.6	0.25611	2.79	0.011937	5.056438	20.1092	1.6	0.56234	1.8	-0.191	0.182442	5.107887	3204	83	83	2869	82	82	3090	32	32	3059	27	3354.09	313.1655	512.8647	8.35	89.6	13.3
CJ-202A_3	T213	Session 2	0.015694	562281	418	112	0.3	663	130	0.20	13428.0	41.8	2.04	1.5	0.21844	2.12	0.057278	7.481802	15.0103	2.0	0.48926	1.5	0.306	0.14314	3.107376	2948	66	66	2563	63	63	2807	38	38	2763	38	2725.72	145.21	341.9325	10.4	87.0	42.5
CJ-202A_4	T05	Session 2	0.055634	604430	409	18	0.0	641	71	0.03	32388.4	23.2	1.79	1.7	0.20781	2.42	0.006524	3.206009	16.1227	1.8	0.55682	1.6	-0.040	0.15106	3.083073	2859	79	79	2848	76	76	2877	33	33	2878	20	2834.828	162.5807	385.312	1.2	99.6	38.4
CJ-202A_5	T01	Session 2	0.01259	540036	292	492	1.7	492	581	1.18	15597.8	37.0	1.43	1.3	0.27718	1.16	0.278688	4.42759	27.0537	1.6	0.69651	1.3	0.572	0.186356	2.020386	3340	36	36	3403	68	68	3386	28	28	3384	30	3448.638	126.07	432.1572	-0.673	101.9	44.3
CJ-202A_6	T214	Session 2	0.094479	596232	378	268	0.7	626	314	0.50	18028.1	30.4	1.68	1.5	0.25885	1.53	0.111263	2.66754	21.5309	1.6	0.59171	1.5	0.479	0.164809	1.385292	3228	48	48	2991	72	72	3157	30	30	3166	31	3081.476	78.97275	385.8171	5.53	92.7	46.3
CJ-202A_7	T20	Session 2	0.026435	892981	265	37	0.1	419	43	0.10	10358.0	42.2	1.84	1.3	0.21516	1.86	0.040577	7.191618	16.3106	1.7	0.53911	1.3	0.324	0.195658	2.272687	2927	60	60	2776	59	59	2888	34	34	2878	32	3604.438	150.5792	464.0249	4.42	94.8	26.0
CJ-202A_8	T22	Session 2	0.154724	400792	305	17	0.1	476	20	0.04	10252.7	40.6	2.02	1.2	0.20389	1.55	0.013048	14.26717	14.1023	1.3	0.49200	1.2	0.245	0.150414	6.150508	2845	50	50	2578	50	50	2752	25	25	2734	24	2798.784	312.2573	458.9301	6.95	90.6	28.5
CJ-202A_9	T74	Session 2	0.590495	70831	36	39	1.1	62	47	0.76	4359.7	39.7	1.42	1.5	0.28840	4.16	0.161146	4.937372	27.9984	5.2	0.68326	2.5	0.644	0.192958	3.894835	3387	132	132	3352	135	135	3399	109	109	3407	102	3560.506	255.8847	504.8695	2.24	99.0	5.0
CJ-202A_10	T73	Session 2	0.249224	58661	26	30	1.1	45	36	0.79	3138	186.4	1.33	2.9	0.28211	2.95	0.156942	4.914695	29.6923	1.9	0.74252	2.5	0.338	0.202161	3.099969	3156	92	92	3622	169	169	3473	36	36	3475	36	3714.947	209.4821	494.2428	-3.08	107.9	3.7
CJ-202A_11	T70	Session 2	0.133818	321429	269	12	0.0	407	13	0.03	8959.2	38.0	2.29	2.0	0.18095	2.44	0.080643	7.531119	11.1526	2.5	0.43983	2.0	0.460	0.112622	4.902751	2611	80	80	2344	77	77	2531	45	45	2514	48	2499.892	225.0988	378.3866	7.77	89.1	23.2
CJ-202A_12	T215	Session 2	0.045795	311346	164	28	0.2	270	33	0.12	17351.2	28.3	1.47	1.9	0.25637	2.40	0.06025	13.11557	24.6495	2.8	0.68025	1.8	0.510	0.218823	2.685739	3205	75	75	3339	96	96	3281	54	54	3297	53	3990.769	195.1589	519.4253	-1.64	104.2	17.7
CJ-202A_13	T216	Session 2	0.07409	211331	123	30	0.2	203	35	0.17	9685.3	31.9	1.55	1.8	0.25422	2.00	0.054735	11.54775	23.0303	1.8	0.64798	1.9	0.432	0.18254	2.422265	3191	63	63	3211	93	93	3220	36	36	3229	34	3381.324	149.9688	436.6972	0.253	100.6	13.5
CJ-202A_14	T217	Session 2	0.061506	632807	373	17	0.0	618	20	0.03	16788.4	43.5	1.67	2.0	0.26034	2.49	0.058101	12.74226	21.9088	2.3	0.59885	2.0	0.433	0.226604	5.756812	3228	76	76	3018	97	97	3170	46	46	3168	45	4057.955	539.1487	716.9819	5.3	93.5	39.5
CJ-202A_15	T218	Session 2	1.904884	939413	559	523	0.9	925	613	0.66	4240.2	46.5	3.54	2.9	0.25748	1.97	0.149421	2.790864	10.5229	3.1	0.28867																					

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[S129_gpm.m](#) [S129_gpm.j](#) [Ca43_gpm.m](#) [Ca43_gpm.j](#) [Sc45_gpm](#) [Sc45_gpm](#) [T149_gpm.m](#) [T149_gpm.j](#) [V51_gpm.m](#) [V51_gpm.j](#) [S618_gpm.m](#) [S618_gpm.j](#) [Y89_gpm.m](#) [Y89_gpm.j](#) [N093_gpm](#) [N093_gpm](#) [La139_gpm.m](#) [La139_gpm.j](#) [Ca140_gpm](#) [Ca140_gpm](#) [P141_gpm.m](#) [P141_gpm.j](#) [N6146_gpm.m](#) [N6146_gpm.j](#) [Sm147_gpm.m](#) [Sm147_gpm.j](#) [Eu153_gpm.m](#) [Eu153_gpm.j](#) [Gd155_gpm.m](#) [Gd155_gpm.j](#) [Tb159_gpm](#) [Tb159_gpm](#) [Dy163_gpm.m](#) [Dy163_gpm.j](#) [Ho165_gpm](#) [Ho165_gpm](#) [Er166_gpm](#) [Er166_gpm](#) [Tm169_gpm](#) [Tm169_gpm](#) [Yb172_gpm](#) [Yb172_gpm](#) [Lu175_gpm](#) [Lu175_gpm](#) [Hf178_gpm](#) [Hf178_gpm](#) [Ta181_gpm](#) [Ta181_gpm](#) [Pb208_gpm](#) [Pb208_gpm](#) [Th232_gpm](#) [Th232_gpm](#) [U238_gpm.m](#) [U238_gpm.j](#) [Pu241_gpm](#)

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Si29 oom Si29 oom Ca43 oom Ca43 oom Sc45 oom Sc45 oom Ti49 oom Ti49 oom V51 oom V51 oom Sr88 oom Sr88 oom Y89 oom Y89 oom Nb93 oom Nb93 oom La139 oom La139 oom Ce140 oom Ce140 oom Pr141 oom Pr141 oom Nd146 oom Nd146 oom Sm147 oom Sm147 oom Eu153 oom Eu153 oom Gd155 oom Gd155 oom Tb159 oom Tb159 oom Dv163 oom Dv163 oom Ho165 oom Ho165 oom Er166 oom Er166 oom Tm169 oom Tm169 oom Yb172 oom Yb172 oom Lu175 oom Lu175 oom Hf178 oom Hf178 oom Ta181 oom Ta181 oom Pb208 oom Pb208 oom Th232 oom Th232 oom U238 oom U238 oom ZsElint

Dur-2	292041	441.12	-0.54	0.26	1.85	0.82	37.79	1.39	521.55	17.05	102.12	0.15	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-3	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-4	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-5	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-6	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-7	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-8	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-9	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-10	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-11	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-12	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-13	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-14	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-15	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-16	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-17	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-18	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-19	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-20	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-21	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-22	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-23	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-24	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36.38	1.10	101.241	3.77	12.11	4.47	65.53	2.57	7.36	0.33	0.17	0.25	0.03	0.03	0.93	0.10	29.842	0.02	56.82	0.60
DUR-25	25515	206.35	-0.12	0.22	1.77	0.80	36.67	1.20	520.58	15.56	114.64	0.44	0.15	0.05	47837.87	166.89	6709.40	273.05	565.95	151	18865.59	46.42	277.83	197	24.02	1.11	35.847	12.63	32.29	1.06	18.822	5.03	36																			

Supplementary Table 3.1: Raman data in zircon (Sample CJ-202A)

Sample	Comment	FWHM measured (cm-1)				FWHM corrected (cm-1)				Peak position (cm-1)				From LA-ICP-MS						From (1)						Isochron																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																											
		ER				ER				ER				U (ppm)		Th (ppm)		Da		Age		2s		eU		2s		DER		2s		TimeER		2s		TimeV2		DER/DV2		ER																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
		V2	V1	V3		V2	V1	V3		V2	V1	V3																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																									

Supplementary Table 3.2: Raman data in zircon (Sample CJ-202B)

Sample		Comment	FWHM measured (cm-1)					FWHM corrected (cm-1)					Peak position (cm-1)					From LA-ICP-MS										From (1)										Isochron									
			ER	V2	V1	V3		ER	V2	V1	V3		ER	V2	V1	V3		U	Zs	Th	Zs	Da	Age	Zs	eU	Zs		DER	Zs	TimeER	Zs	DV2	TimeV2	DER/DV2		Intercept	Zs	Zero-dam: Zs	Slope	Zs	Time	Zs	Age	408	45		
CJ-2028_45	Concordant		9.2	13.6	7.1	7.6	7.1	12.2	4.4	5.0	358.7	441.3	976.8	1009.5		131	26	103	21	1.49	2962	25	162	32	17.9	1.8	358	72	49.86	825	2.8		-0.5	1.26	3.96	0.21	0.128	0.014	408	45							
CJ-2028_50	Concordant		13.1	15.1	BDL	11.7	11.6	13.7	BDL	10.0	356.5	440.5	975.0	1009.3		113	23	73	15	1.11	2622	40	136	27	44.3	4.4	1051	210	60.92	1199	1.4																
CJ-2028_56	Concordant		11.1	12.6	BDL	8.1	9.3	11.0	BDL	5.7	354.9	438.9	974.6	1007.8		151	30	89	18	1.64	2944	26	180	36	30.8	3.1	553	110	41.72	622	1.4		-9	5.3	2.51	0.90	0.233	0.044	743	140							
CJ-2028_58	Concordant		7.3	8.8	5.7	4.3	4.6	6.6	2.3	0.0	359.2	442.2	977.8	1012.4		47	9.4	19	4	0.42	2505	47	181	31	3.5	0.4	207	41	10.46	515	3.0		-12.1	5.1	1.98	0.87	0.374	0.078	1193	249							
CJ-2028_60	Concordant		9.5	12.3	6.9	8.0	7.4	10.7	4.1	5.5	358.6	442.2	977.0	1010.2		117	23	95	19	1.33	2938	29	146	29	19.7	2.0	436	87	39.09	718	2.0																
CJ-2028_64	Discordant		20.2	25.6	BDL	15.1	19.2	24.8	BDL	13.8	354.3	440.0	970.9	1004.9		589	120	108	22	5.68	2850	24	644	130	89.5	8.9	449	90	139.54	580	1.6																
CJ-2028_66	Concordant		8.1	9.9	4.8	5.3	5.7	7.9	0.9	1.8	356.3	441.1	976.7	1010.9		66	13	25	5	0.58	2494	51	75	15	9.6	1.0	415	83	19.39	695	2.0																
CJ-2028_67	Concordant		10.6	13.3	BDL	7.2	8.8	11.6	BDL	4.5	355.6	439.6	974.2	1007.4		129	26	53	11	0.91	1971	57	149	30	27.8	2.8	604	120	46.83	843	1.7																
CJ-2028_68	Concordant		8.0	10.4	6.4	18.1	5.5	8.5	1.6	0.0	356.1	440.7	976.3	1008.9		75	15	32	3	0.76	2385	31	86	19	32.9	1.7	647	88	27.65	947	1.8																
CJ-2028_69	Concordant		8.5	10.3	5.9	6.6	6.2	8.4	2.6	0.8	357.7	440.7	976.3	1009.5		78	16	58	12	0.90	3031	31	96	19	12.6	1.3	424	85	23.27	649	1.8																
CJ-2028_72	Concordant		10.4	13.5	6.0	7.4	8.5	12.0	2.9	4.8	356.3	440.1	974.7	1007.7		164	33	89	18	1.77	2943	27	194	39	26.4	2.6	441	88	48.75	675	1.8																
CJ-2028_73	Discordant		12.0	14.2	8.9	9.1	10.4	12.8	6.7	7.0	354.7	439.2	972.9	1005.6		328	66	121	24	3.41	2944	25	373	75	37.4	3.7	323	65	54.33	390	1.5																
CJ-2028_74	Concordant		7.8	9.3	6.1	6.4	5.3	7.2	3.0	3.4	357.2	440.3	975.8	1009.0		51	10	25	5	0.51	2726	49	60	12	7.6	0.8	406	81	14.73	657	1.9																
CJ-2028_87	Concordant		12.6	16.9	7.3	9.5	11.0	15.7	4.6	7.5	358.1	441.7	976.2	1009.1		183	37	65	13	1.29	1999	35	207	41	40.8	4.1	635	130	74.94	968	1.8																
CJ-2028_96	Concordant		10.7	16.0	9.4	10.6	8.8	14.8	7.3	8.7	358.4	441.7	976.4	1009.4		201	40	196	39	2.50	3120	24	258	52	28.0	2.8	352	70	68.32	710	2.4																
CJ-2028_113	Concordant		8.1	9.9	6.6	6.8	5.7	7.9	3.7	4.0	359.6	442.8	978.1	1011.9		73	15	30	6	0.70	2683	34	84	17	10.0	1.0	384	77	19.20	612	1.5																
CJ-2028_116	Concordant		18.0	21.8	11.6	13.7	16.9	20.9	9.9	12.2	354.5	440.7	973.6	1006.3		236	47	34	7	2.32	2922	26	257	51	75.5	7.5	981	190	111.33	1163	1.9																
CJ-2028_15	Discordant		15.0	20.5	16.6	11.7	13.6	15.5	14.7	10.0	351.7	437.5	969.8	1002.6		362	72	80	36	3.87	2944	23	424	85	56.4	5.6	400	93	64.58	645	1.8																
CJ-2028_18	Concordant		9.5	12.3	8.0	7.9	7.4	10.6	5.4	5.5	354.8	438.2	973.5	1006.7		119	24	71	14	1.28	2900	27	142	28	19.7	2.0	47	89	38.93	734	2.0																
CJ-2028_27	Concordant		7.5	8.9	BDL	9.2	4.9	6.7	BDL	7.3	355.8	438.5	975.1	1011.4		38	8	16	3	0.40	2993	31	43	9	5.0	0.5	376	75	13.21	693.7	2.2																

Supplementary Table 3.3: Raman data in zircon Reference Materials

	FWHM measured (cm-1)					FWHM corrected (cm-1)					Peak position (cm-1)					From LA-ICP-MS		From (1)									
Sample	ER	V2	V1	V3		ER	V2	V1	V3		ER	V2	V1	V3		U	Th	eU	DER	TimeER	DV2	TimeV2	DV1	TimeV1	DV3	TimeV3	
91500_1		8.8	10.6	6.6	7.1		6.6	8.7	3.7	4.3		354.8	437.9	973.4	1006.6		51	34	62	1.53E+17	799	2.51E+17	1090	1.31E+17	570	1.35E+17	461
91500_2		8.9	10.6	6.6	7.2		6.7	8.7	3.7	4.5		354.7	437.9	973.4	1006.6		51	34	62	1.54E+17	808	2.53E+17	1099	1.28E+17	556	1.53E+17	523
BB_1		11.7	14.6	9.2	9.2		10.0	13.2	7.1	7.1		358.2	442.7	976.7	1009.5		311	77	345	3.52E+17	330	5.70E+17	442	3.71E+17	288	3.86E+17	236
BB_2		11.2	14.3	8.4	9.3		9.4	12.9	6.1	7.2		359.3	442.7	976.8	1009.7		311	77	345	3.18E+17	298	5.51E+17	428	3.02E+17	235	3.94E+17	241