



**UNIVERSIDADE DE BRASÍLIA
INSTITUTO DE GEOCIÊNCIAS
PROGRAMA DE PÓS-GRADUAÇÃO EM GEOLOGIA**

**MECANISMOS DE DEFORMAÇÃO NAS ZONAS
DE CISALHAMENTO ITAPETIM E TENDÓ,
PROVÍNCIA BORBOREMA, NE BRASIL**

RAYLLINE FERREIRA DA SILVA

Dissertação de Mestrado Nº 530

Orientador: Prof. Dr. Luis Gustavo Ferreira Viegas

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RAYLLINE FERREIRA DA SILVA

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RESUMO

As zonas de cisalhamento Itapetim (ZCI) e Tendó (ZCT) são estruturas subsidiárias do Domínio Central da Província Borborema, que se conectam à zona de cisalhamento Patos de direção E-W. As duas estruturas estão orientadas preferencialmente ao longo da direção NE-SW com cinemática predominantemente sinistral e deformam rochas associadas a ortognaisses e sequências supracrustais do Orógeno Cariris Velhos e intrusões graníticas relacionadas à orogênese brasileira. Esta pesquisa apresenta uma abordagem integrada que inclui mapeamento estrutural de campo, observações microestruturais, dados de orientações preferenciais cristalográficas e análises de química mineral, com o objetivo de investigar os mecanismos de deformação e os processos de localização da deformação da ZCI e ZCT. Em ambas as zonas de cisalhamento, predominam rochas miloníticas, com protomilonitos subordinados, enquanto bandas ultramiloníticas ocorrem localmente, paralelas à foliação milonítica. Na ZCI e na ZCT, os principais domínios microestruturais das rochas miloníticas são divididos em: i) porfiroclastos médios a grossos de K-feldspato ($d \sim 0.5$ mm a 2 cm) e de plagioclásio ($d \sim 250$ μ m), ii) fitas monominerálicas de quartzo (~ 200 μ m de espessura) e iii) agregados recristalizados quartzo-feldspáticos ($d \sim 25$ -300 μ m). Nas rochas ultramiloníticas, os domínios são individualizados principalmente em iv) porfiroclastos de feldspato ($d \sim 0.5$ mm a 2 cm) e em v) fitas de quartzo (~ 100 μ m de espessura) envoltos por um vi) matriz polifásica ($d \sim 5$ -20 μ m). Os dados de orientações preferenciais cristalográficas (OPCs) dos grãos de quartzo nas fitas monominerálicas de quartzo da ZCI indicam a ativação dos sistemas de deslizamentos romboédricos e basais do quartzo. Em contrapartida, os dados de OPCs da ZCT sugerem a ativação dos sistemas de deslizamento prismático e romboédrico dos grãos de quartzo. Nas bandas ultramiloníticas, ocorre a variação da composição química entre os porfiroclastos (An_{19-30}) e grãos recristalizados (An_{28-36}) de plagioclásio, o que sugere a presença de fluidos reativos durante o processo de localização da deformação na zona de cisalhamento. A localização da deformação em ambas as zonas de cisalhamento é principalmente acomodada por fluência de deslocamentos nos grãos de quartzo, acompanhada por transferência de massa difusiva que afetam cristais de feldspato, em temperaturas médias a altas ($\sim 520^\circ\text{C}$). O cisalhamento sinistral NE-SW dessas zonas de cisalhamento evidencia que a deformação plástica de médio a alto grau nessas estruturas foi desenvolvida como resultado de uma direção de encurtamento regional NNW-SSE. Este campo de deformação oblíquo, além de poder estar associado à movimentação sinistral da ZCI e ZCT, também estaria relacionado às estruturas regionais Patos e Pernambuco que apresentam cinemática destal. Com base nestas informações, o Domínio Central se comportou como um bloco dúctil durante o cisalhamento simples nas principais estruturas E-W formadoras do arcabouço tectônico da Província Borborema.

PALAVRAS-CHAVE: Província Borborema, Domínio central, zona de cisalhamento Itapetim, zona de cisalhamento Tendó, microestruturas, mecanismos de deformação

ABSTRACT

Itapetim Shear Zone (ISZ) and Tendó Shear Zone (TSZ) are subsidiary structures of the Central Domain of the Borborema Province, connecting to the E-W oriented Patos shear zone. Both structures are predominantly oriented along the NE-SW direction with dominant sinistral kinematics and deform rocks associated with orthogneisses and supracrustal sequences of the Cariris Velhos Orogen and granitoid intrusions related to the Brasiliano orogeny. An integrated approach, including field structural mapping, microstructural observations, crystallographic preferred orientation data, and mineral chemistry analyses, was employed to investigate the deformation mechanisms and the strain localization processes that operate in ISZ and TSZ. In both shear zones, mylonitic rocks predominate, with subordinate protomylonites, while ultramylonitic bands occur locally parallel to the mylonitic foliation. In the ISZ and TSZ, the primary microstructural domains of the mylonitic rocks are divided into: medium to coarse K-feldspar ($d \sim 0.5$ mm to 2 cm) and plagioclase ($d \sim 250$ μ m) porphyroclasts, monomineralic quartz ribbons (~ 200 μ m thick), and recrystallized quartzo-feldspathic aggregates ($d \sim 25$ -300 μ m); and for the ultramylonitic bands, the domains are primarily characterized by feldspar porphyroclasts ($d \sim 0.5$ mm to 2 cm) and quartz ribbons (~ 100 μ m thick) embedded in a polyphase matrix ($d \sim 5$ -20 μ m). Crystallographic preferred orientation (CPO) data of quartz grains in the monomineralic quartz ribbons of the ISZ indicate activation of rhombohedral and basal slip systems in quartz. In contrast, the CPO data of the TSZ suggest activation of prismatic and rhombohedral slip systems in quartz grains. In the ultramylonitic bands, variation in chemical composition between porphyroclasts (An_{19-30}) and recrystallized grains (An_{28-36}) of plagioclase suggests the presence of reactive fluids during the strain localization process within the shear zone. The strain localization in both shear zones is primarily accommodated by dislocation creep in quartz grains, accompanied by diffusion mass transfer affecting feldspar crystals, under medium- to high-temperatures ($\sim 520^\circ\text{C}$). The sinistral shear of these NE-SW shear zones indicates that the medium- to high-grade plastic strain in these structures resulted from a regional NNW-SSE shortening direction. This oblique strain field, in addition to would be associated with the sinistral motion of the ISZ and TSZ, would be related to the regional Patos and Pernambuco structures, which exhibit dextral kinematics. Based on this, the Central Domain behaved as a ductile block during simple shear within the major E-W structures forming the tectonic framework of the Borborema Province

KEYWORDS: Borborema Province, Central Domain, Itapetim shear zone, Tendó shear zone, microstructures, deformation mechanisms

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ESTRUTURAÇÃO DA DISSERTAÇÃO

Esta dissertação adota o formato de artigo científico, o qual será submetido para revisão e apresenta estruturação e formatação específica. O capítulo inicial, denominado Introdução, aborda a inserção da pesquisa realizada dentro do âmbito da geologia estrutural de zonas de cisalhamento litosféricas, destacando a relevância da área de estudo. O capítulo subsequente detalha o contexto geológico regional onde a área de estudo está inserida. O terceiro capítulo expõe a base teórica das técnicas analíticas empregadas na pesquisa. O quarto capítulo é composto pela compilação dos resultados obtidos neste estudo, organizados em forma de artigo que será submetido ao periódico *Journal of Structural Geology*. O quinto capítulo, Considerações Finais, discute de forma abrangente as contribuições deste trabalho para a compreensão da evolução tectônica das zonas de cisalhamento Itapetim e Tendó inseridas na Província Borborema. O sexto capítulo lista as referências bibliográficas utilizadas na dissertação e que não estão presentes nas referências do artigo no quarto capítulo.

CAPÍTULO 1

INTRODUÇÃO

1 INTRODUÇÃO

Zonas de cisalhamento são estruturas que acomodam taxas significativas de enfraquecimento reológico e são observadas ao longo de todo o perfil litosférico (Rutter et al., 2001). Quando nucleadas em níveis crustais intermediários, estas zonas são marcadas pelo desenvolvimento de tramas estruturais heterogêneas, os quais são observadas por meio da atividade combinada de mecanismos de deformação rúpteis e dúcteis. Além de localizar e registrar a evolução estrutural de cinturões orogênicos, as zonas de cisalhamento consistem em um dos principais condutos de circulação de fluidos (e.g., fluidos metamórficos, fluidos hidrotermais, magma) em diferentes profundidades crustais em decorrência de sua natureza reológica anisotrópica. A evolução textural e a distribuição da deformação no interior das zonas de cisalhamento são influenciadas diretamente por controles do ambiente (e.g. condições de pressão e temperatura, presença/ausência de fluidos, taxa de deformação) e por controles litológicos (e.g. composição do protólito, reações metamórficas; Rutter et al., 2001).

Nos níveis médios e inferiores da crosta continental, são predominantes os mecanismos de plasticidade cristalina ativados termicamente, que se enquadram no regime de deformação dúctil (Behrmann & Mainprice, 1987; Kenkmann & Dresen, 2002). Compreender tais mecanismos, particularmente em minerais fundamentais que constituem a crosta continental, é essencial para analisar o controle do estilo de deformação e para interpretar a história termomecânica das rochas deformadas. Assim, modelos reológicos da porção intermediária da crosta continental são tipicamente baseados na extrapolação de leis de fluxo experimental derivadas de quartzo e feldspato (e.g. Tullis, 2002; Tullis & Yund, 1985; Okudaira & Shigematsu, 2012). Essa abordagem teórica encontra aplicação prática em zonas de cisalhamento que deformam rochas quartzo-feldpáticas (e.g. granitoides) de maneira dúctil, as quais são um laboratório natural para a investigação da localização da deformação em níveis crustais intermediários a inferiores.

Na Província Borborema, as zonas de cisalhamento Itapetim (ZCI) e Tendó (ZCT) são estruturas subsidiárias do Domínio Central, que se conectam à zona de cisalhamento Patos de direção E-W (Vauchez et al., 1995; Van Schmus et al., 2008). As duas estruturas estão orientadas preferencialmente ao longo da direção NE-SW com cinemática

dominantemente sinistral. A ZCI e a ZCT contêm cerca de 50 e 25 km de extensão, respectivamente, e ambas afetam principalmente granitoides e sequências supracrustais (Coutinho, 1994; Archanjo et al., 2008). A ZCI exibe trama mesoscópica marcada pela presença de veios de quartzo auríferos que se localizam ao longo da parte central da zona de cisalhamento, paralelos à foliação milonítica (Coutinho, 1994; Maia, 2002; Almeida et al., 2024).

Poucos dados encontram-se publicados acerca dos mecanismos de deformação atuantes durante nucleação e localização da deformação da zona de cisalhamento Itapetim e da zona de cisalhamento Tendó. Além disso, a relação entre os mecanismos de deformação e interação com fluidos, atuantes durante a deformação é pouco conhecida para ambas as estruturas.

Neste trabalho, realizamos uma análise petroestrutural detalhada, baseada na análise microestrutural quantitativa e na química mineral dos milonitos e ultramilonitos das zonas de cisalhamento de Itapetim e Tendó. Utilizando uma abordagem integrada que inclui análise estrutural de campo, observações microestruturais detalhadas, estudos de orientações cristalográficas preferenciais e química mineral, temos como objetivo investigar os mecanismos de deformação e o comportamento dos processos cristal-plásticos dominantes durante a formação das zonas de cisalhamento de Itapetim (ZCI) e Tendó (ZCT). Este estudo contribui significativamente para a compreensão da evolução tectônica das zonas de cisalhamento de Itapetim e Tendó e elucida seu papel dentro do complexo quadro estrutural da Província da Borborema, no contexto da orogenia Brasileira-Pan Africana do Neoproterozoico.

CAPÍTULO 2

CONTEXTO GEOLÓGICO

2 CONTEXTO GEOLÓGICO

A Província Borborema, localizada no nordeste do Brasil, encontra-se na parte central (Figura 1a) do orógeno brasileiro-Pan-africano (ca. 650-500 Ma), limitada a sul pelo Cráton São Francisco (CSF), a oeste pela Bacia Parnaíba e de norte a leste pelas bacias costeiras do Atlântico (Brito Neves et al., 2000; Figura 1b). Esta faixa orogênica é resultante da aglutinação dos paleocontinentes São Francisco-Congo, e Amazônico-Oeste-Africano durante a amalgamação do Gondwana Ocidental no Neoproterozoico (Brito Neves et al., 2000). A província é constituída por um embasamento gnaíssico-migmatítico paleoproterozoico com núcleos arqueanos (Brito Neves, 2011; Dantas et al., 2013; Caxito et al., 2015; Santos et al., 2015, 2017a; Brito Neves et al., 2020), cobertos por sequências supracrustais de idade meso-neoproterozoica, e intrusões graníticas neoproterozoicas (Figura 1b). A Província Borborema apresenta uma estruturação regional formada por um sistema de zonas de cisalhamento de escala crustal, denominado de Sistema de Cisalhamento Borborema, que conectam domínios de distintas evoluções geológicas (Vauchez et al., 1995; Brito Neves et al., 2000).

O Domínio Central da Província Borborema, limitado a norte pela zona de cisalhamento Patos e a sul pela zona de cisalhamento Pernambuco (Van Schmus et al., 1995, Van Schmus et al., 2008), apresenta uma complexa rede de estruturas subsidiárias formada por zonas de cisalhamento anastomosadas de direção E-NE (Santos e Brito Neves, 1984, Santos et al., 1984, Corsini et al., 1991). Esses sistemas de zonas de cisalhamento desenvolveram-se sob condições metamórficas de baixa pressão e alta temperatura e fusão parcial, além de um abundante magmatismo granítico de idade brasileira (Van Schmus et al., 2008).

A zona de cisalhamento Itapetim (ZCI) e Tendó (ZCT) fazem parte do Domínio Central da Província Borborema e deformam rochas associadas a ortognaisses e sequências supracrustais do Orógeno Cariris Velhos (Santos, 1995; Ferreira & Santos, 2000; Kozuch, 2003; Santos et al., 2010; Guimaraes et al., 2012) e intrusões graníticas relacionadas à orogênese brasileira (Guimarães & Silva Filho, 2000; Archanjo et al., 2008; Viegas et al., 2022).

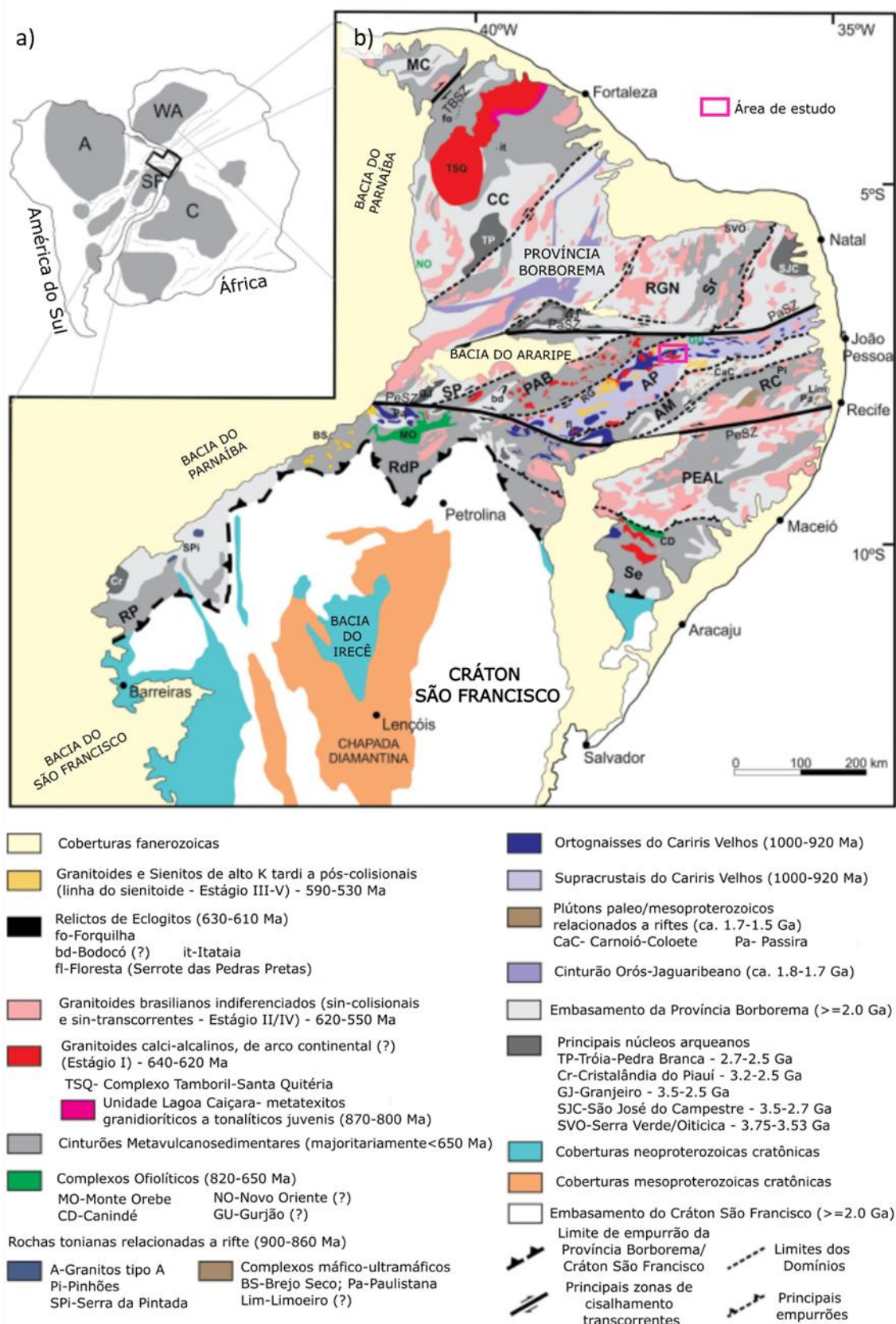


Figura 1: Arcabouço geológico simplificado da Província Borborema. A) Localização da Província Borborema na reconstrução esquemática dos continentes sul-americano e africano antes da fase drifte com crátons ilustrados em cinza (A – Cráton Amazônico, SF – Cráton São Francisco, C – Cráton do Congo e WA – Cráton Oeste Africano). B) Mapa simplificado da Província Borborema com as principais zonas de

cisalhamento (PeSZ – Zona de cisalhamento Pernambuco; PaSZ – Zona de cisalhamento Patos; TBSZ – Zona de cisalhamento Transbrasiliano) e as divisões de domínios e subdomínios: RP - Rio Preto, RdP - Riacho do Pontal, Se - Sergipano, PEAL - Pernambuco-Alagoas, RC - Rio Capibaribe, AM - Alto Moxotó, AP - Alto Pajeú, RG - Riacho Gravatá, PAB - Piancó-Alto Brígida, SP - São Pedro, MC - Medio Coreau, CC - Ceará Central, RGN - Rio Grande do Norte, Sr – Seridó; a área de estudo desta dissertação é destacada pelo retângulo rosa a sul da zona de cisalhamento Patos. Modificado de Caxito et al., (2020).

Os ortognaisses do Orógeno Cariris Velho são compostos por dois tipos principais: augen gnaisses (Complexo Recanto) e gnaisses com fácies migmatíticas (Complexo Riacho do Forno; Santos, 1995). A composição mineralógica desses complexos inclui microclínio, quartzo, plagioclásio, biotita, muscovita e minerais acessórios (titanita, apatita, alanita, zircão e granada rara; Santos, 1995; Santos et al., 2010). Estas rochas são classificadas principalmente como granodioritos e monzogranitos e menores ocorrências de metadioritos com hedenbergita (Santos, 1995; Santos et al., 2010). Há também muscovita±biotita sienogranitos com turmalina e granada como principais minerais acessórios (Brito Neves et al., 2005).

As sequências supracrustais do Orógeno Cariris Velhos são formadas pelos complexos Riacho Gravatá, Lagoa das Contendas e São Caetano (Santos et al., 2010). O Complexo Riacho Gravatá (ca. 920 Ma) é composto por uma espessa sequência metassedimentar-metavulcânica metamorfozada sob condições de baixo a médio grau metamórfico (Campos Neto et al., 1994; Bittar, 1998). Esta sequência inclui muscovita ± grafita biotita xisto, metagrauvacas, mármore, metatufos, metaultramáficas, metassiltitos e rochas metavulcânicas bimodais, predominantemente félsicas, com ocorrências locais de Formação Ferrífera Bandada (Campos Neto et al., 1994; Bittar, 1998). O Complexo Lago das Contendas compreende rochas metavulcânicas intermediárias a máficas, metatufos, metacherts, metagrauvacas e, localmente, mármore. O complexo São Caetano é formado por uma sequência de médio grau metamórfico de metagrauvacas, metapelitos, metapsamitos, mármore e rochas calcissilicáticas associadas a rochas metavulcânicas (Santos, 1995; Medeiros, 2004; Santos et al., 2010).

As principais intrusões graníticas neoproterozoicas na área de estudo são o Batólito Teixeira (Archanjo et al., 2008) e o Plúton Itapetim (Guimarães & Silva Filho, 2000; Viegas et al., 2022). O Batólito Teixeira, com orientação ENE, mede aproximadamente 80 km de comprimento e 10 km de largura, sendo composto principalmente por granito leucocrático a quartzo-sienito (Archanjo et al., 2008). O Plúton Itapetim é um monzogranito porfirítico de alto potássio e metaluminoso, de

natureza cálcio-alcalina, delimitado por duas zonas de cisalhamento dúcteis de tendência NE-SW sinistral, as zonas de cisalhamento de Itapetim e Taperoá (Guimarães & Silva Filho, 2000; Viegas et al., 2022).

CAPÍTULO 3

MATERIAIS E MÉTODOS

3 MATERIAIS E MÉTODOS

O desenvolvimento da presente dissertação compreendeu uma abordagem integrada da geologia estrutural de rochas deformadas em zonas de cisalhamento, envolvendo a combinação do mapeamento estrutural mesoscópico, observações microestruturais detalhadas, determinação de orientações cristalográficas preferenciais e química mineral.

3.1 Mapeamento estrutural de campo

O mapeamento estrutural de campo foi realizado para delimitação e caracterização do registro da deformação associada às zonas de cisalhamento Itapetim e Tendó. Nas proximidades das cidades Brejinho (PE), Desterro (PB), Maturéia (PB) e Teixeira (PB), foram cartografadas as principais estruturas, relações geométricas e critérios cinemáticos identificados entre as rochas miloníticas e encaixantes. Ao longo da extensão da ZCI e ZCT foram coletadas 46 amostras de rochas representativas da deformação local orientadas em relação à foliação e à lineação.

3.2 Descrição microestrutural

Para a análise petrográfica e microestrutural das rochas miloníticas representativas da ZCI e ZCT, foram confeccionadas 20 lâminas polidas, orientadas de acordo com a seção XZ do elipsoide de deformação (i.e., perpendicular à foliação (XY) e paralelas à lineação mineral (X)). As microestruturas de deformação foram investigadas através da microscopia de luz polarizada e da microscopia eletrônica de varredura (MEV), disponíveis, respectivamente, no Laboratório de Microscopia e no Laboratório de Geocronologia do Instituto de Geociências (UnB).

O estudo microestrutural envolveu a caracterização detalhada das relações geométricas, observadas entre os grãos deformados e recrystalizados, e a identificação dos domínios estruturais com base na intensidade de milonitização.

3.3 Determinação de orientações preferenciais cristalográficas

A coleta de dados de orientação cristalográfica de minerais é comumente realizada, nas Geociências, a partir da técnica de difração de elétrons retroespalhados (EBSD - *electron backscatter diffraction*; Prior et al., 1999, Mariani et al., 2008). O EBSD fornece dados mensuráveis de desorientações, de orientações cristalográficas e de geometria de borda de subgrãos e de grãos, os quais permitem a investigação de modelos microestruturais (Prior et al., 1999).

A técnica de EBSD se baseia na interação entre o feixe de elétrons incidente e a estrutura cristalográfica de uma amostra (Figura 2a; Prior et al., 1999). Em decorrência do diâmetro do feixe de elétrons ser maior do que o espaçamento atômico da amostra, os elétrons incidentes são espalhados em diversas direções. Aqueles elétrons retroespalhados que difratam, satisfazendo a lei de Bragg (Eq 1), descrevem uma trajetória cônica para cada plano da rede cristalina. A projeção dessa trajetória cônica (cones de Kossel) em uma tela de fósforo é representada como faixas ou linhas de difração, denominadas bandas de Kikuchi (Figura 2a). Uma rede de linhas de difração cria um padrão de difração de elétrons retroespalhados (EBSP – *electron backscattering pattern*) ou padrão Kikuchi (Figura 2b). As bandas que se cruzam produzem pontos luminosos no padrão de Kikuchi, que correspondem aos eixos das zonas, i.e., elementos de simetria da estrutura cristalina do mineral (Figura 2b). Através do processo de indexação, é possível identificar os elementos de simetria e determinar a orientação da estrutura cristalina em relação a um sistema de referência (Prior et al., 1999).

A lei de Bragg é descrita como:

$$n\lambda = 2d_{hkl} \sin \theta \text{ (Eq. 1)}$$

Onde,

n = ordem de reflexão;

λ = comprimento de onda ligada à tensão de aceleração dos elétrons

d_{hkl} = distância reticular (hkl)

θ = ângulo de Bragg

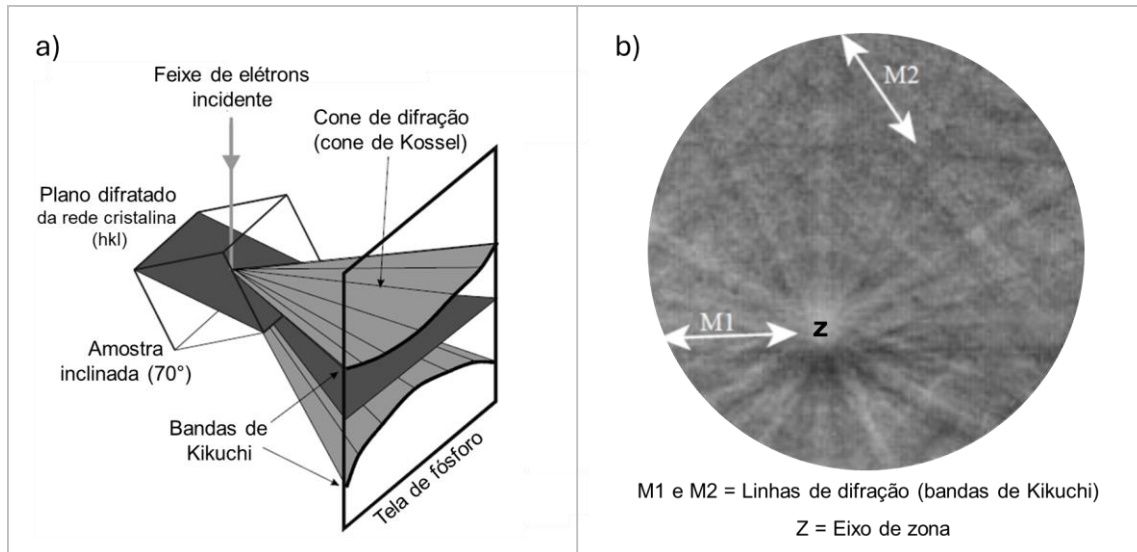


Figura 2: Ilustração esquemática da técnica de EBSD. A) Esquema tridimensional dos segmentos de cones de difração (cones de Kossel) para um plano da rede cristalina de uma amostra inclinada em 70° (Modificado de Prior et al., 1999). B) Padrão de difração de elétrons retroespalhados (EBSP) em tela de fosforo (Modificado de Prior et al., 1999).

Algumas das formas de representar os dados de EBSD obtidos incluem figuras de polo das orientações preferenciais cristalográficas e mapas e histogramas dos ângulos de desorientação (*misorientation*).

A figura de polo, neste caso, é tradicionalmente utilizada para representar os eixos e planos cristalográficos dos minerais em uma projeção bidimensional (Randle e Caul, 1996). Os eixos e polos dos planos cristalográficos são plotados em um estereograma de acordo com o sistema de coordenadas da amostra geológica, o qual corresponde a orientação da foliação e da lineação.

A desorientação é dada em ângulos e calculada a partir do ângulo de rotação necessário para que a orientação cristalográfica de um grão seja a mesma do grão adjacente. Os dados de desorientação podem ser representados através de mapas e por meio da distribuição estatísticas em histogramas. O mapa Mis2Mean exibe a desorientação entre cada orientação de pixel em relação a orientação média da fase mineral da área analisada. O histograma, além de exibir a frequência dos ângulos de desorientação, exibe as linhas da distribuição não correlacionada e da distribuição uniforme.

3.4 Química mineral

A caracterização química das principais fases envolvidas no processo deformacional fornece informações acerca das condições de reequilíbrio químico. Nesta pesquisa, as composições químicas de K-feldspato e plagioclásio, em diferentes domínios da ZCI e ZCT, foram quantificadas utilizando a Microsonda Eletrônica Jeol JXA-8230 (EPMA) do Laboratório de Microsonda Eletrônica do Instituto de Geociências (UnB). As análises foram realizadas com uma tensão de aceleração de 15-20 kV, corrente de 5 nA e diâmetro de feixe de 1 μm para o feldspato potássico e 5 μm para o plagioclásio.

CAPÍTULO 4

ARTIGO

4 HETEROGENEOUS STRAIN GRADIENTS ALONG THE MID-CRUSTAL, ITAPETIM AND TENDÓ SHEAR ZONES (NE BRAZIL)

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Abstract: The Itapetim Shear Zone (ISZ) and the Tendó Shear Zone (TSZ) are NE-SW trending, sinistral, high-grade structures that connect northeastward with the E-W Patos shear zone in the Borborema Province. These shear zones were investigated via field structural observations, microstructural analysis, crystallographic preferred orientations (CPO) and mineral chemistry in order to characterize the deformation mechanisms and strain localization processes. Both ISZ and TSZ are predominantly composed of granitic and orthogneissic mylonites and protomylonites, with localized ultramylonitic bands. Microstructural domains in the mylonitic rocks of both shear zones are defined by porphyroclasts, monomineralic quartz ribbons, and recrystallized aggregates of feldspar and quartz. In the ultramylonitic bands, a polyphase matrix is embedded/interlayered between these microstructural domains. In the ISZ, the quartz crystallographic fabrics indicate a transition in slip system activation, forming a gradient from prism $\langle a \rangle$ through rhombohedral $\langle a+c \rangle$ to basal $\langle a \rangle$, while in the TSZ, the dominant slip systems are prism $\langle a \rangle$ and rhomb $\langle a+c \rangle$. Strain localization in both zones is primarily accommodated by dislocation creep in quartz grains, coupled with diffusive mass transfer in the presence of fluids that affect feldspar crystals under medium- to high-temperature ($\sim 520^\circ\text{C}$). This temperature is consistent with the development of magmatic fabrics in nearby granite plutons. The strain compatibility between these NE-SW-trending, sinistral shear zones and the major E-W dextral lineaments was achieved through solid-state flow at high temperatures in the central domain of the Borborema Province.

Keywords: Borborema Province, Itapetim shear zone, Tendó shear zone, Central Domain, Dislocation creep, Diffusion creep

4.1 Introduction

Shear zones are structures that accommodate significant rates of rheological weakening and are observed throughout the entire lithospheric profile (Rutter et al., 2001;

Alsop & Holdsworth, 2004). In addition to localizing and recording the structural evolution of orogenic belts, shear zones are one of the main conduits for fluid circulation (e.g., metamorphic fluids, hydrothermal fluids, magma) at different crustal depths due to their anisotropic rheological nature (Handy et al., 2007; Bürgmann & Dresen, 2008; Bercovici and Ricard, 2012). The textural evolution and deformation distribution within shear zones are directly influenced by environmental controls (e.g., pressure and temperature conditions, presence/absence of fluids, strain rate) and lithological controls (e.g., protolith composition, metamorphic reactions; (Gonçalves et al., 2016; Pennacchioni & Mancktelow, 2018)).

In the middle/lower continental crust, thermally activated crystal-plastic mechanisms dominate, which typically correspond to the aseismic ductile flow that characterizes rock flow under viscous creep (Behrmann & Mainprice, 1987; Kenkmann & Dresen, 2002). Such mechanisms and processes are vital for the formation of thickened crust and represent the main mechanical control onto which flowing rock masses interact at plate boundaries (Montési, 2013; Kiss et al., 2019). Understanding these deformation mechanisms, especially in key minerals that make up the continental crust, such as quartz and feldspars, is essential for investigating the control of the deformational style and interpreting the thermomechanical history of deformed orogenic sections. Thus, rheological models of the intermediate portion of the continental crust are typically based on the extrapolation of experimental flow laws derived from quartz and feldspar (e.g., Tullis, 2002; Tullis & Yund, 1985; Okudaira & Shigematsu, 2012; (Mecklenburgh & Rutter, 2003; Rosenberg & Handy, 2005; Sly et al., 2023)). This theoretical approach finds practical application in shear zones that deform quartzo-feldspathic rocks (e.g., granitoids), which are a natural laboratory for investigating the localization of deformation at intermediate to lower crustal levels (Platt, 2015; Cawood & Platt, 2021).

The Itapetim Shear Zone (ISZ) and the Tendó Shear Zone (TSZ) are NE-SW trending, high-grade structures that connect northeastwards with the E-W Patos shear zone (Vauchez et al., 1995; Van Schmus et al., 2008). Together, these structures form a geometric and kinematically consistent array of shear zones that are associated with widespread Neoproterozoic granitic plutonism (Brito Neves et al., 2014). These geological features define what is known as the Borborema Province (Figure 1; Van Schmus et al., 2008). The NE-trending shear zones extend approximately 50 and 25 km,

respectively, and are both composed by protomylonites and mylonites in which crystal-plastic structures are widespread. Locally, the ISZ exhibits a mesoscopic fabric marked by the presence of auriferous quartz veins located along the central part of the shear zone, parallel to the mylonitic foliation (Coutinho, 1994; Maia, 2002; Almeida et al., 2024).

Several works have highlighted the kinematic consistency between the shear zone array of NE-SW and E-W shear zones (Corsini et al., 1991; Vauchez et al., 1995; Sial and Ferreira, 2016; Archanjo et al., 2021; Neves et al., 2021; Fossen et al., 2022). A major question remains as to the strain localization processes that operate in these shear zones. The co-existence of mylonites that grade into ultramylonites along the trend of the structure suggests that a deformation gradient is observed along the structures, calling for a long-strike variations in strain distribution following a NE-SW direction. The deformation mechanisms and strain localization processes in these shear zones are, however, poorly studied so far.

In this contribution, we conducted a detailed petrostructural study of the deformational and rheological conditions that operate at the Itapetim and Tendó shear zones. Based on an integrated approach that includes field structural analysis, detailed microstructural observations, crystallographic preferred orientations, and mineral chemistry studies, we aim to characterize the deformation mechanisms and strain localization processes observed in both shear zones, as a means of contributing to a better understanding of how strain gradients vary along mid-crustal shear zones. Our study helps elucidating the role of mid-crustal, ductile shear zones as planar anisotropies that accommodate heterogeneous strain gradients along their strike and also hint into the significance of these structures within the complex structural framework of the Borborema Province, in the context of the Neoproterozoic Brasiliano-Pan African orogeny.

4.2 Geological Setting

The Borborema Province (Figure 1), located in the northeast of Brazil, is situated in the central part of the Brasiliano-Pan-African orogeny (ca. 650-500 Ma), and exhibits a regional structural framework consisting of a crustal-scale shear zones system that connect domains of distinct geological histories (Vauchez et al., 1995; Brito Neves et al.,

2000). The Central Domain of the Borborema Province, bounded to the north by the Patos shear zone and to the south by the Pernambuco shear zone, exhibits a complex network of subsidiary structures formed by anastomosed E-NE-oriented shear zones (Santos & Brito Neves, 1984; Santos et al., 1984; Corsini et al., 1991). These shear zone systems developed under low-pressure and high-temperature metamorphic conditions, partial melting, and significant Brasiliano-aged granitic magmatism (Van Schmus et al., 2008).

The Itapetim Shear Zone (ISZ) and Tendó Shear Zone (TSZ) are part of the Central Domain of the Borborema Province and deform rocks associated with orthogneisses and supracrustal sequences of the Cariris Velhos Belt (Santos, 1995; Ferreira & Santos, 2000; Kozuch, 2003; Santos et al., 2010; Guimaraes et al., 2012) and granitic intrusions related to the Brasiliano orogeny (Guimarães & Silva Filho, 2000; Archanjo et al., 2008; Viegas et al., 2022; Figures 1 and 2).

The orthogneisses of the Cariris Velho Belt comprise two main types: augen gneisses (Recanto Complex) and gneisses with migmatitic facies (Riacho do Forno Complex; Santos, 1995). Their mineralogical composition includes microcline, quartz, plagioclase, biotite, muscovite, and accessory minerals (titanite, apatite, allanite, zircon, and rare garnet; Santos, 1995; Santos et al., 2010). These rocks are primarily classified as granodiorites and monzogranites (Santos, 1995; Santos et al., 2010). There are also muscovite±biotite syenogranites with tourmaline and garnet as the main accessory minerals (Brito Neves et al., 2005).

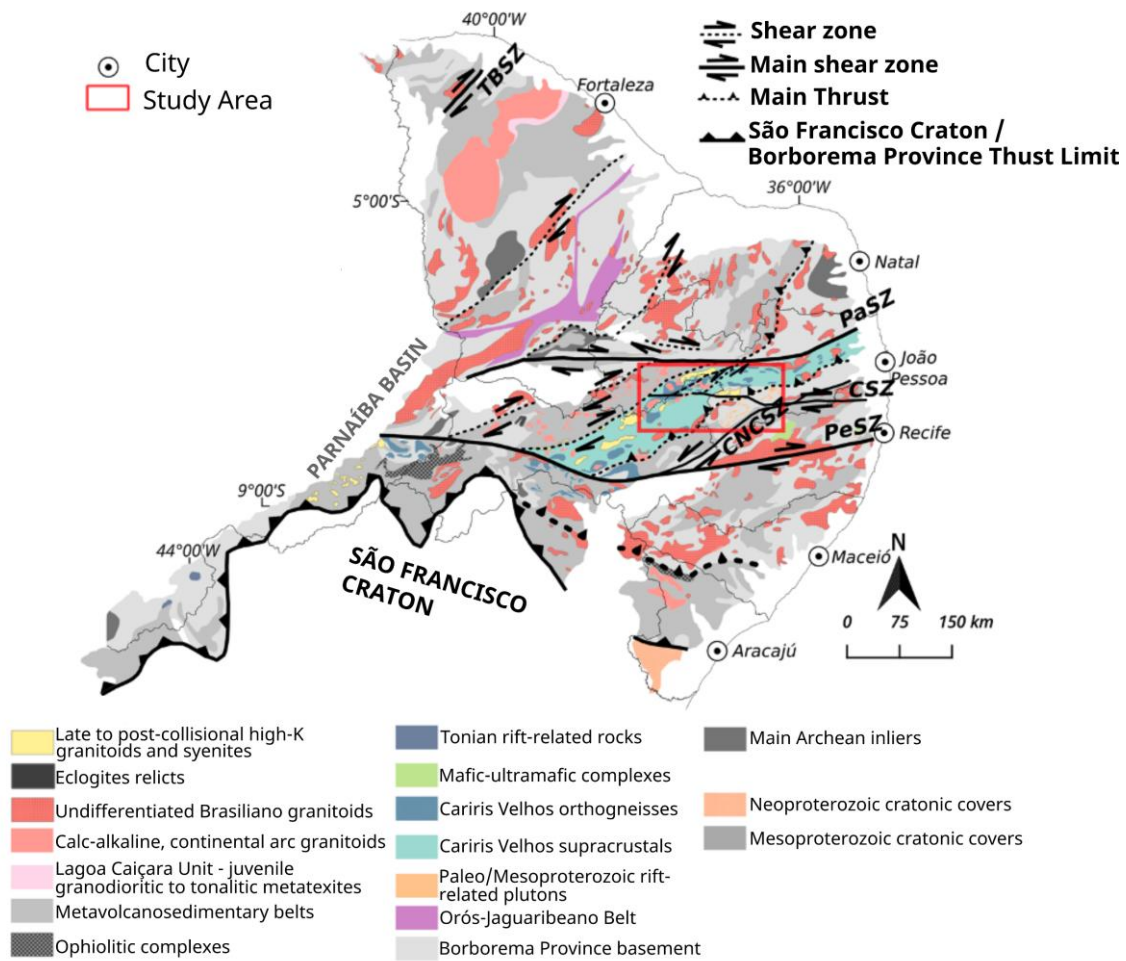


Figure 1: Map showing the arrangement of the major shear zones in the Borborema Province. PaSZ and PeSZ represent the Patos and Pernambuco shear zones, respectively, which bound the Central Domain. Others shear zones: TBSZ – Transbrasiliano shear zone, CNCSZ – Cruzeiro do Nordeste shear zone, CSZ – Congo shear zone. Modified from Brito Neves et al. (2014) and Caxito et al. (2020).

The supracrustal sequences of the Cariris Velhos Belt are formed by the Riacho Gravatá, Lagoa das Contendas, and São Caetano complexes (Santos et al., 2010). The Riacho Gravatá Complex consists of a thick metavolcano-metasedimentary sequence metamorphosed under low to medium-grade metamorphic conditions (Campos Neto et al., 1994; Bittar, 1998). This sequence includes muscovite $\pm$ graphite biotite schist, metagreywackes, marble, metatuffs, metaultramafics, metassiltites, and predominantly felsic bimodal metavolcanic rocks, with local occurrences of Banded Iron Formation (Campos Neto et al., 1994; Bittar, 1998). The Lagoa das Contendas Complex comprises intermediate to mafic metavolcanic rocks, metatuffs, metacherts, metagreywackes, and locally, marbles. The São Caetano Complex is formed by a medium-grade metamorphic sequence of metagreywackes, metapelites, metapsamites, marble, and calc-silicate rocks associated with metavolcanic rocks (Santos, 1995; Medeiros, 2004; Santos et al., 2010).

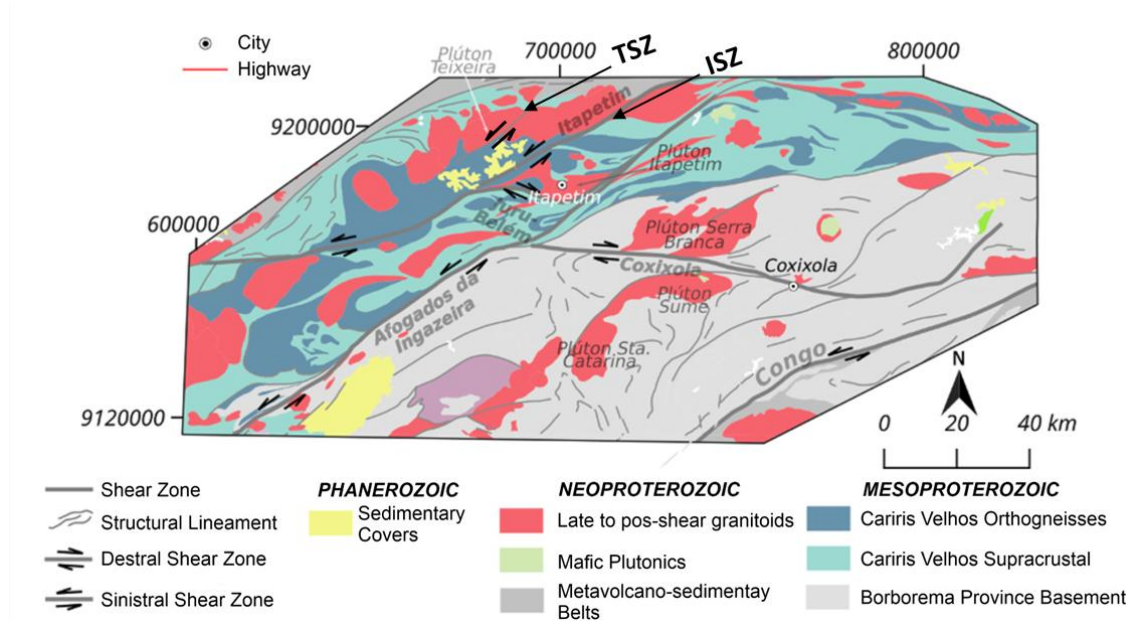


Figure 2: Western portion of the Central Domain of the Borborema Province, including the Itapetim Shear Zone (ISZ) and Tendó Shear Zone (TSZ) and associated intrusions. Modified from Hollanda et al 2011, Santos et al 2021 and Oliveira et al 2023.

The main Neoproterozoic granitic intrusions in the study area are the Teixeira Batholith (Archanjo et al., 2008) and the Itapetim Pluton (Guimarães & Silva Filho, 2000; Viegas et al., 2022). The Teixeira Batholith, oriented ENE, is approximately 80 km long and 10 km wide, primarily composed of leucocratic granite to quartz-syenite (Archanjo et al., 2008). The Itapetim Pluton is a high-K, metaluminous, calc-alkaline porphyritic monzogranite, bounded by two ductile shear zones with a NE-SW sinistral trend, the Itapetim and Taperoá shear zones (Guimarães & Silva Filho, 2000; Viegas et al., 2022).

4.3 Methods

4.3.1 Sample acquisition and microstructural analysis

Geological mapping was conducted to delineate and characterize the deformation record associated with the Itapetim and Tendó shear zones. Along the extents of the ISZ and TSZ, representative rock samples of the local deformation were collected (Figure 3). Oriented thin sections were cut in the XZ section of the deformation ellipsoid, perpendicular to the foliation (XY) and parallel to the mineral lineation (X). Deformation microstructures of the collected mylonitic rocks were investigated via optical and scanning electron microscopy (SEM).

4.3.2 *Electron backscatter diffraction (EBSD) analysis*

Crystallographic preferred orientations of recrystallized grains of quartz and feldspar were obtained through EBSD analysis of representative domains of the mylonitic and ultramylonitic microstructures. The EBSD analyses were conducted using a field emission scanning electron microscope (SEM, SU5000, Hitachi) equipped with a NordlysNano EBSD Detector at the Department of Earth and Environmental Sciences, Ludwig-Maximilians University, Munich. Images of deformation microstructures and recrystallized areas were captured using rectangular grids, with intervals ranging from 0.5 to 5 μm . The samples underwent mechanical polishing, followed by colloidal silica treatment to produce a damage-free surface. Subsequently, thin sections were carbon-coated and analyzed in a high-vacuum setting. Specific analytical parameters included an accelerating voltage of 20 kV, a 20-23 mm working distance, and a sample tilt of 70°. The EBSD data were processed using the MTEX package in MATLAB (Hielscher & Schaeben 2008), which facilitated the generation of pole figures, phase and crystallographic maps, and the analysis of misorientation angle distributions.

4.3.3 *Mineral chemistry*

The chemical compositions of k-feldspar and plagioclase (porphyroclasts and recrystallized grains) were determined using a Jeol JXA-8230 Electron Probe Microanalyzer (EPMA) at the Institute of Geosciences, University of Brasília. The analyses were carried out with an accelerating voltage of 15-20 kV, a current of 5 nA, and a beam diameter of 1 μm for k-feldspar and 5 μm for plagioclase.

4.4 Results

4.4.1 *Mesoscale fabrics*

4.4.1.1 Itapetim shear zone

The Itapetim shear zone (ISZ) is oriented in the NE-SW direction and deforms basement orthogneisses (Recanto Complex and Riacho do Forno Complex (Santos, 1995; Ferreira & Santos, 2000) and muscovite-biotite schists of the São Caetano Complex, as well as granitic plutons located in the vicinity of the structure (Itapetim Pluton and Teixeira Batholith (Guimarães & Silva Filho, 2000, Archanjo et al., 2008, Viegas et al., 2022; Figure 3). The ISZ has a length of about 50 km and a width ranging from 2 to 10 km, with the thickest part of the structure corresponding to the northeastern termination (~9 km), in which the structure branches out in a series of E-W and NW-SE splays (Figure 3).

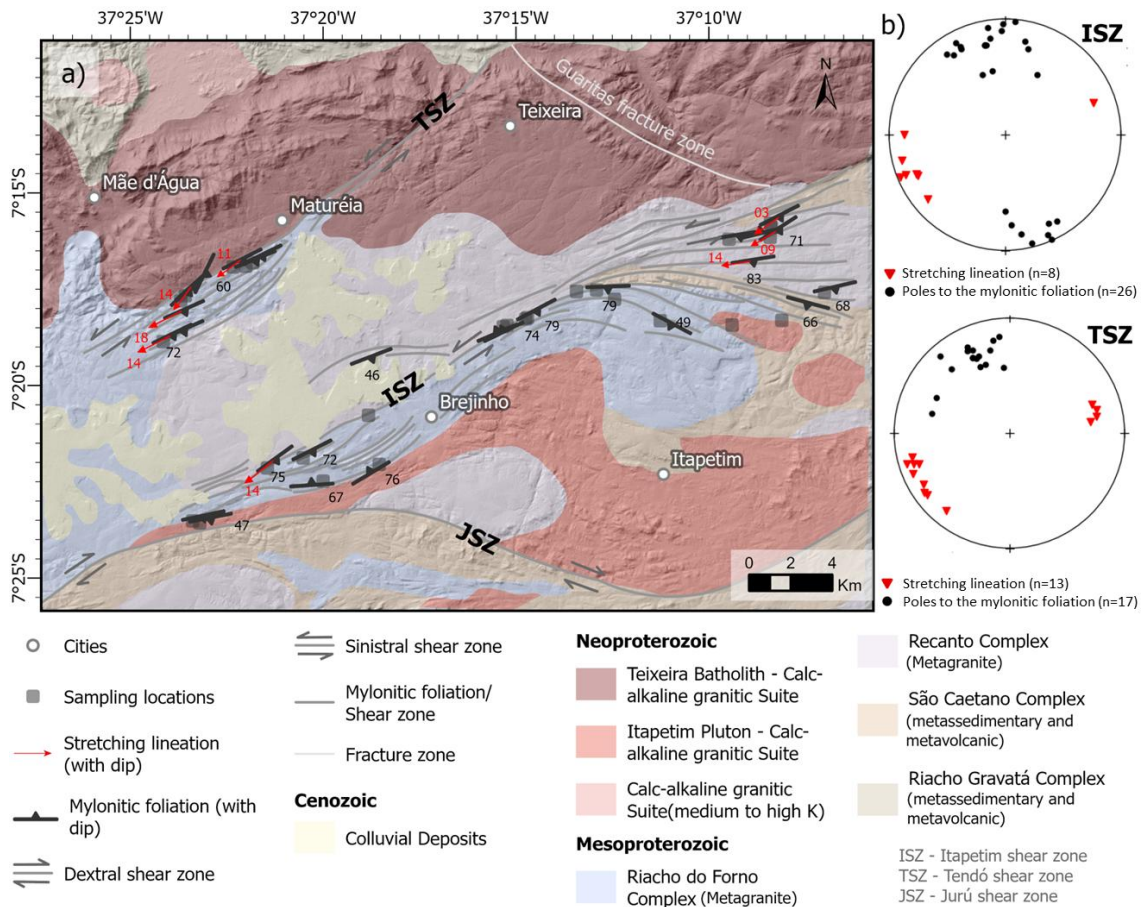


Figure 3: Geological map of the Itapetim shear zone (ISZ) and Tendó shear zone (TSZ). Modified from Pereira et al. (2020). b) Stereograms showing attitudes of the poles to the mylonitic foliation (black dots) and mineral stretching lineation (red triangles) of the ISZ and TSZ.

The ISZ is characterized by the predominance of granitic and orthogneissic mylonites and protomylonites, with ultramylonitic bands occurring locally (Figure 4a, b).

The main planar fabrics are defined by compositional layering and mylonitic foliation. The layers are characterized by the centimeter-scale alternation of biotite-rich and quartzo-feldspathic bands (Figure 4c). The mylonitic foliation is parallel to the compositional banding, oriented mainly in the NE-SW direction, pervasively developed, and dips steeply ($\sim 71^\circ$; Figure 3) to both SE and NW. The foliation is marked by the planar orientation of biotite lamellae and recrystallized aggregates of quartz and feldspar that surround centimeter-scale feldspar porphyroclasts (~ 1.5 cm; Figure 4d). The geometric relationship between the recrystallized aggregates and the porphyroclasts commonly presents sigmoidal shapes with evidence of sinistral shear sense (Figure 4d). Elongated quartz grains define a mineral stretching lineation that plunges shallowly to ($\sim 12^\circ$) to SW (Figure 3).

The ultramylonitic bands (~ 0.5 cm to 15 cm thick) occur parallel to the mylonitic foliation and are characterized by a predominance of a fine dark matrix (< 0.5 mm) in which mm- to cm-thick, sigmoidal porphyroclasts of feldspar and quartz are immersed (Figure 4a). Coarse-grained (≥ 1 cm) fragments of the host rock contained in the ultramylonite locally exhibit asymmetrical shapes that suggest a sinistral shear sense (Figure 4a).

Pegmatitic veins with a thickness ranging from centimeter to meter, mainly composed of K-feldspar, plagioclase, quartz and magnetite, intersect the main fabric of the rock predominantly along the N65E and N20W directions (Figure 4e). Near the edges of the pegmatitic veins, the adjacent mylonitic foliation is deflected in an anticlockwise direction. Millimeter to centimeter-thick quartz veins occur mainly parallel to the mylonitic foliation and at the center of ultramylonite bands (Figure 4b), and subordinate veins fill fractures that cut across the foliation and pegmatite veins (Figure 4f). Locally, in quartz veins parallel to the foliation, the presence of fine to medium-sized tourmaline crystals (~ 2 mm) is observed.

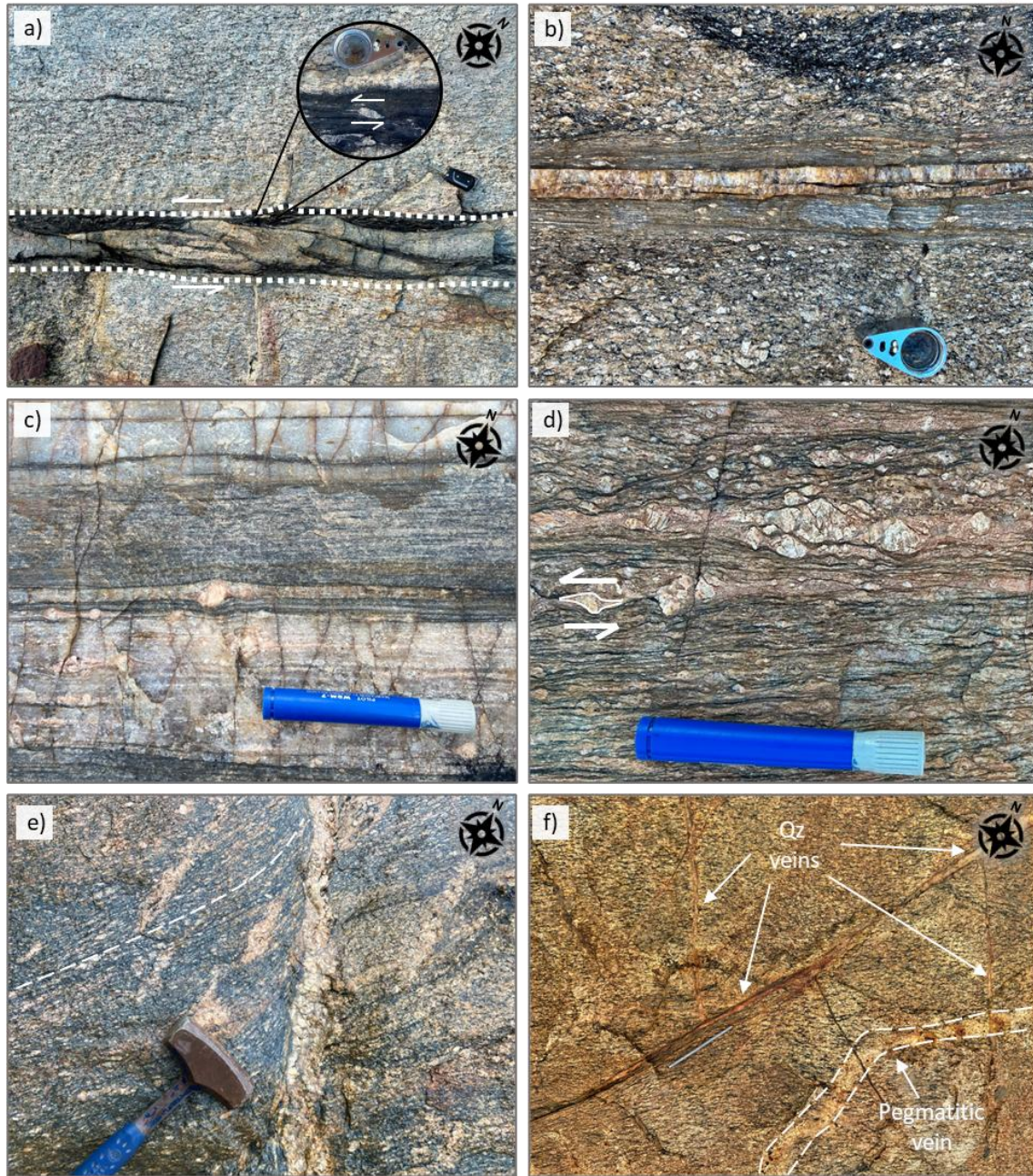


Figure 4: Field structures of the Itapetim shear zone. A) Dark-colored ultramylonitic band containing fragments of mylonitized orthogneiss; inset shows a sigmoidal quartz porphyroclast with sinistral shear sense; B) Ultramylonitic band developed at the margins of a cm-thick quartz vein parallel to the mylonitic foliation; C) Compositional banding defined by mafic bands predominantly composed by biotite, alternated with quartzo-feldspathic bands; D) Mylonitic foliation and recrystallized quartzo-feldspathic aggregates surrounding sigmoidal clasts of K-feldspar; clast asymmetry indicates sinistral shear sense; E) Pegmatitic vein (NNW-SSE) truncating the mylonitic foliation (NE-SW) and F) Quartz veins crosscutting pegmatite vein and the mylonitic foliation.

4.4.1.2 Tendó shear zone

The Tendó shear zone (TSZ) exhibits a NE-SW orientation, extending for approximately 25 km and reaching a maximum thickness of 2.5 km at its SW termination (Figure 3). The deformation associated with the Tendó shear zone affects the southwestern border of the Teixeira pluton and is also accommodated in orthogneisses of the Riacho do Forno Complex.

The NE termination of the TSZ, which cuts the Teixeira Batholith, was characterized by Archanjo et al. (2008) as displaying significant comminution of equigranular crystals of the granite, resulting in narrow and discontinuous bands of mylonite and ultramylonite (Figure 5a, b), as well as regions of intense fracturing. The ultramylonitic bands, approximately 15 cm thick, occur in abrupt contact with the apparently isotropic Teixeira Batholith (Figure 5a, b). The ultramylonites are characterized by a predominantly fine dark matrix (<0.5 mm), containing thin quartz ribbons and feldspar porphyroclasts (~2 mm; Figure 5a).

The southwestern segment of the TSZ exhibits a continuous distribution of mylonites, with localized occurrences of ultramylonites, along its length. The TSZ is characterized by a high-angle mylonitic foliation (~65°) trending NE-SW and a mineral stretching lineation with a dip of approximately 15° towards SW (Figure 3). The mylonitic foliation is distinguished by a planar orientation of phyllosilicates (biotite and muscovite) and exhibits millimetric intercalations of recrystallized, quartz-feldspathic bands (~2mm). The recrystallized aggregates encircle coarse feldspar porphyroclasts (~3cm) and medium-sized (0.5cm) quartz porphyroclasts (Figure 5c). The sigmoidal shapes of porphyroclasts exhibit a preferred sinistral shear sense. The ultramylonitic bands in this portion of the TSZ are approximately 7 cm thick and cut through orthogneisses of the Riacho do Forno Complex (Figure 5d). The ultramylonites are composed of a fine dark matrix (<0.5 mm), including feldspar clasts (~1 mm) and quartz-feldspar aggregates arranged in thin layers (<0.5 mm), parallel to the ultramylonite boundaries (Figure 5d).

Locally, there are occurrences of high-angle (82°) centimeter-scale shear zones that crosscut the main foliation in a NW-SE direction and exhibit dextral kinematics (Figure 5e). Similarly to what occurs in the Itapetim shear zone, centimeter to meter-scale

pegmatitic veins cut across the mylonitic foliation (Figure 5f), as well as millimeter to centimeter-scale quartz veins parallel to the main planar fabric.

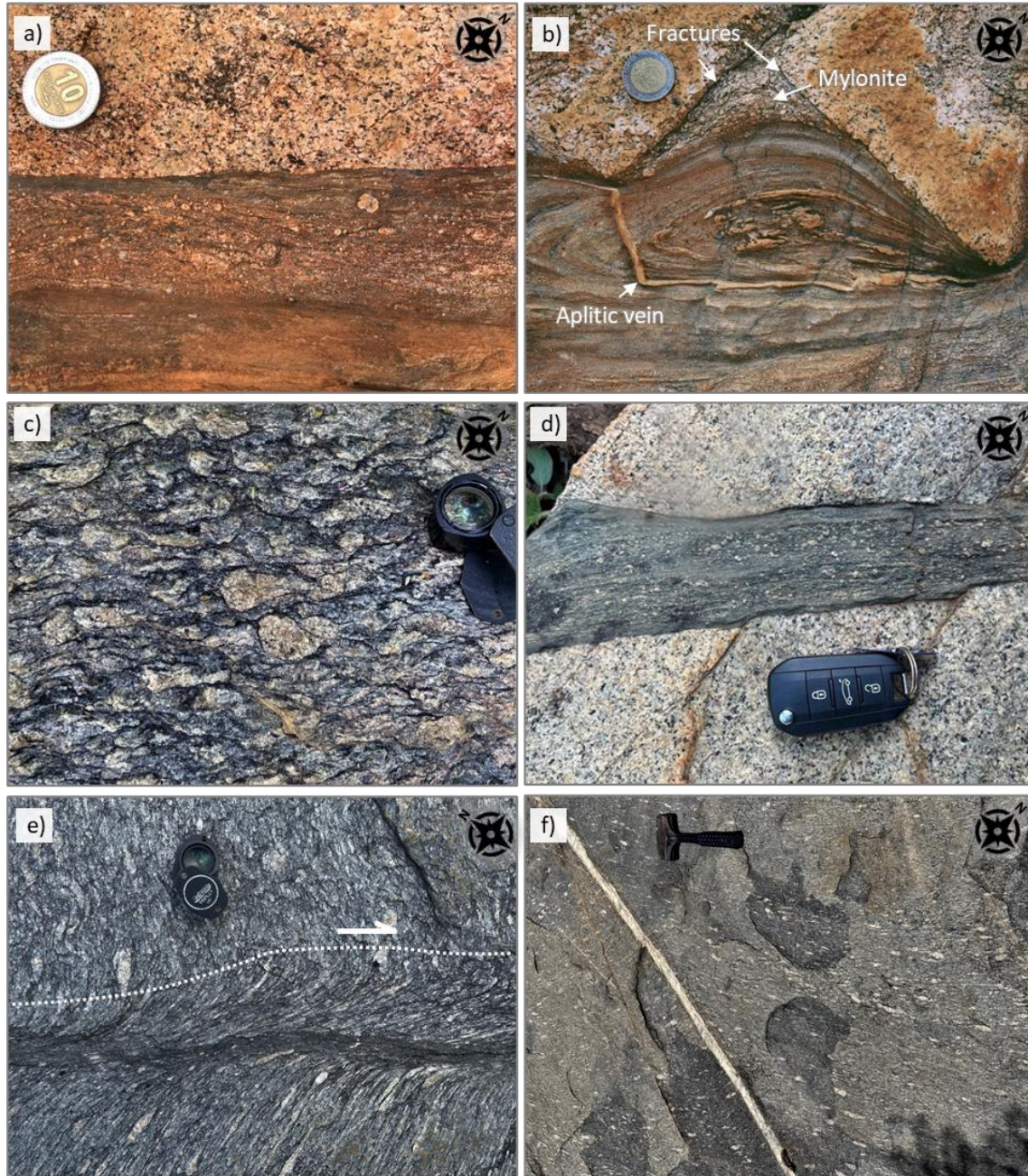


Figure 5: Field structures of the Tendó shear zone. A) Ultramylonitic bands in abrupt contact with apparently isotropic Teixeira Batholith. The ultramylonite develop cm-thick layers that are parallel to the NE-SW trend of the TSZ; B) Flow structures observed in ultramylonite at the contact with two fractured blocks of isotropic granite. Fine-grained mylonite is observed at the neck of the ultramylonite, in contact with the granitic, rigid blocks. Fine-grained aplitic veins are deformed within the ultramylonite band. C) Coarse feldspar porphyroclasts defining the mylonitic foliation in metagranite; D) ultramylonite crosscutting metagranite. The ultramylonitic band contains fine-grains of K-feldspar, plagioclase and quartz; E) NW-SE trending, dextral shear zone truncating the NE-SW oriented mylonitic foliation, and F) ESE-WNW pegmatitic vein cutting the mylonitic foliation.

4.4.2 *Microstructure*

4.4.2.1 Itapetim shear zone – granitoid mylonite

The mylonites of the Itapetim Shear Zone (ISZ) are composed of K-feldspar, plagioclase, quartz, biotite, and subordinately magnetite, tourmaline, epidote, apatite, and zircon. Along the area affected by the ISZ, three distinct microstructural domains were observed, which will be described separately:

- (I) Porphyroclasts of K-feldspar and plagioclase,
- (II) Monomineralic quartz ribbons,
- (III) Recrystallized aggregates of quartz and feldspar.

Domain I – Porphyroclasts of K-feldspar and plagioclase

K-feldspar porphyroclasts exhibit an elliptical to subelliptical morphology, varying in size from 0.5 mm to 2 cm. K-feldspar clasts present a characteristic chessboard twinning of microcline (Figure 6a), which is micropertitic. The flame-type perthite lamellae are subparallel to the cleavage plane and occur mainly near the clast boundaries (Figure 6a). The contacts of the clasts are lobate to serrated and have diffuse boundaries (Figure 6a). In protomylonites, some kink bands crossing K-feldspar clasts filled with fine recrystallized K-feldspar grains ($d \sim 20 \mu\text{m}$; Figure 6b). Both the limites of the kink bands and the grains filling them show diffuse boundaries. The thickness of these bands reaches up to $150 \mu\text{m}$ (Figure 6b).

Associated with the K-feldspar porphyroclasts is the presence of vermicular plagioclase and quartz intergrowths (i.e., myrmekite). The myrmekite is rounded in shape and predominantly occurs in contact with the boundaries of the K-feldspar porphyroclasts (Figure 6a, c). Only a few grains of myrmekite are included within the microcline clasts. Plagioclase porphyroclasts ($d \sim 250 \mu\text{m}$) are rare and only present in protomylonites. The plagioclase clasts display lobate contacts and curved/bent twins.

The main microstructures resulting from the solid-state deformation of K-feldspar and plagioclase porphyroclasts include undulatory extinction and curved/bent twins.

Domain II – Monomineralic quartz ribbons

Monomineralic quartz ribbons are a polycrystalline structure, elongated in the direction of the foliation, with a thickness of $\sim 200\ \mu\text{m}$ in mylonites (Figure 6d, e). The quartz grains are predominantly inequigranular, vary in size from ~ 30 to $\sim 500\ \mu\text{m}$, and exhibit lobate contacts (Figure 6d, e). Locally, more rectilinear contacts with equigranular grains and the formation of triple junctions are observed. In the protomylonites, elongated monocrystalline quartz crystals ($d \sim 1.5\ \text{mm}$) have an amoeboid shape, exhibit undulatory extinction, and intergranular fractures. In localized regions of the ISZ, quartz ribbons exhibit an oblique orientation relative to the main mylonitic foliation. The obliquity of these structures highlights the sinistral kinematics of the shear zone (Figure 6e).

Domain III – Recrystallized quartzo-feldspathic aggregates

Recrystallized aggregates are primarily composed of plagioclase and K-feldspar grains and, to a lesser extent, of interstitial quartz (Figure 6f). These recrystallized aggregates have sizes ranging from 25 to $300\ \mu\text{m}$, with lobate to rectilinear contacts and diffuse boundaries. The medium to coarse-grained recrystallized grains ($\sim 300\ \mu\text{m}$) exhibit undulatory extinction and deformation twinning. In the finer grains, there are few internal deformational features, yet they still display diffuse boundaries. Near myrmekite grains, the recrystallized aggregates contain some isolated quartz bubbles (Figure 6f).

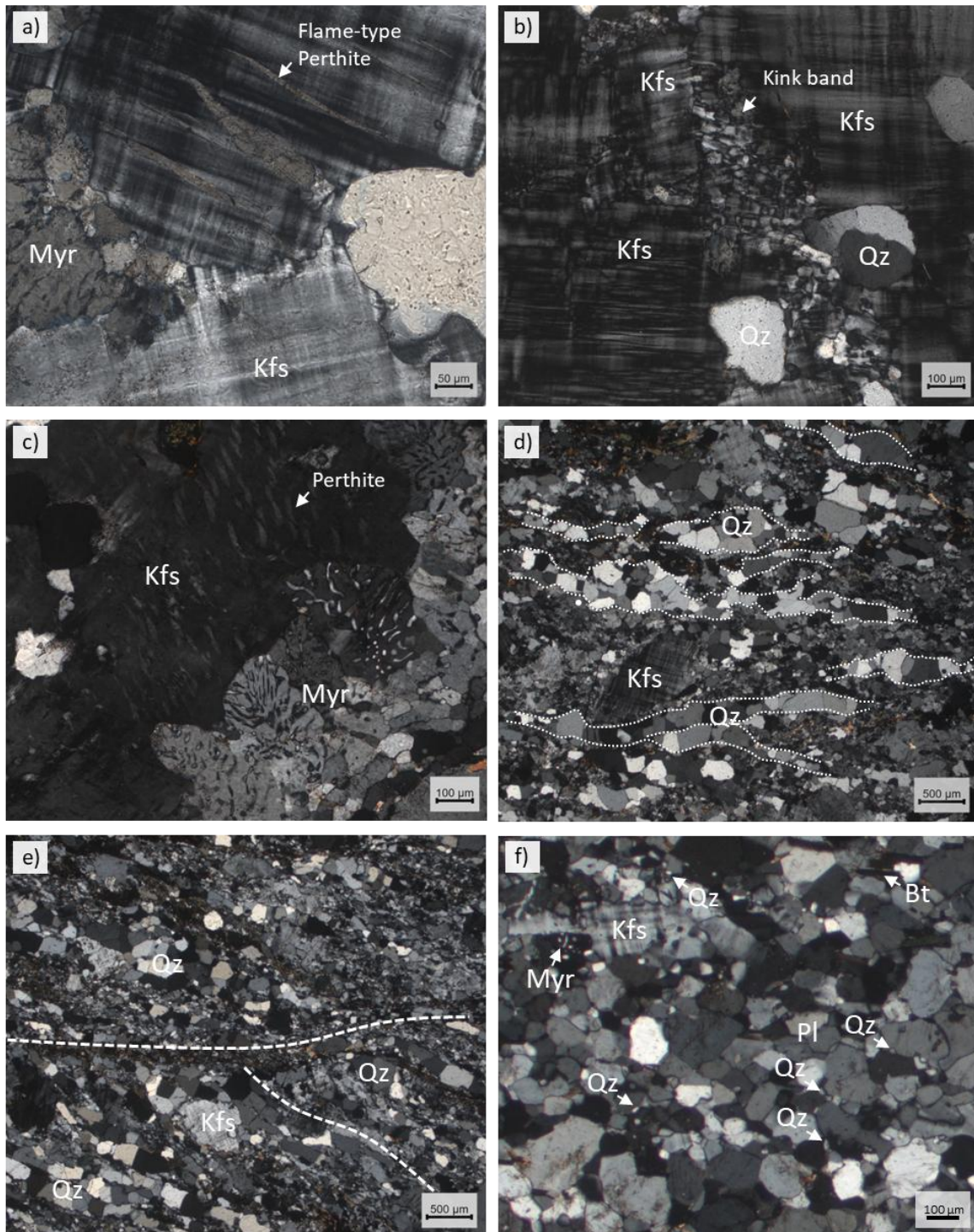


Figure 6: Mylonitic microstructures of the Itapetim shear zone. A) K-feldspar (Kfs) porphyroclasts with serrated boundaries in contact with myrmekite (Myr) grain; near the boundaries, flame-type perthite. B) Kink band in K-feldspar porphyroclast filled with recrystallized K-feldspar grains. C) Myrmekite grains at the edges of the K-feldspar porphyroclast. D) Polycrystalline quartz (Qz) ribbons. E) Quartz ribbons oriented in oblique direction relative to the main mylonitic foliation. F) Recrystallized plagioclase and K-feldspar aggregates with interstitial, fine-grained quartz at grain boundaries.

4.4.2.2 Itapetim shear zone – Ultramylonite

The ultramylonitic zones have abrupt contact with the adjacent mylonite (Figure 7a) and are composed of (I) porphyroclasts of K-feldspar, plagioclase, and quartz, (II) recrystallized aggregates of feldspar with interstitial quartz, (III) quartz ribbons, and (IV) a fine-grained polyphasic matrix of quartz, plagioclase, K-feldspar, biotite, titanite, and magnetite.

Domain I – Porphyroclasts

The K-feldspar porphyroclasts have a sub-elliptical geometry and range in size from ~500 μm to 2 cm (Figure 7b). The clast boundaries are lobate to serrated and slightly diffuse. The K-feldspar porphyroclasts exhibit undulatory extinction, and in the rare clasts where chessboard twinning is identifiable, these twins are slightly curved/bent. Some porphyroclasts contain asymmetric trails of recrystallized feldspar grains along their boundaries, suggesting sinistral kinematics.

Plagioclase and quartz porphyroclasts are rare in the ultramylonites. The plagioclase porphyroclasts are approximately 500 μm in size, sub-elliptical in shape, with lobate boundaries. The quartz porphyroclasts (~500 μm) have a sub-elliptical shape with flattened, recrystallized edges forming ribbons oriented parallel to the foliation (Figure 7b). The contacts between the quartz clasts and the new quartz grains are lobate and diffuse (Figure 7b). Intracrystalline fractures occur perpendicular to the longitudinal direction of the quartz clasts, without any opening or displacement (Figure 7b).

In the ultramylonites where the polyphasic matrix of type II, characterized in the topic of Domain IV of this section, predominates, the K-feldspar porphyroclasts are associated with myrmekites at their boundaries or are completely replaced by myrmekite aggregates (Figure 7c). Even in cases where K-feldspar is completely replaced by plagioclase and vermicular quartz, the sub-elliptical shape of the K-feldspar is preserved (Figure 7c).

Domain II – Recrystallized feldspar aggregates

This domain occurs only along the edges of the K-feldspar porphyroclasts associated with myrmekite and the type II ultramylonitic matrix (detailed in the domain IV). The recrystallized aggregates consist of plagioclase ranging from 5 μm to 50 μm and fine interstitial grains of quartz ($\sim 10 \mu\text{m}$) and K-feldspar ($\sim 30 \mu\text{m}$; Figure 7d). The contact between the plagioclase grains is straight and exhibits triple junctions. Fine quartz grains commonly occur between recrystallized plagioclase grains. In smaller proportions, recrystallized K-feldspar grains are present among the recrystallized plagioclase aggregates.

Domain III - Quartz ribbons

Discontinuous ribbons of recrystallized quartz grains are immersed in a polyphasic matrix and oriented according to the foliation (Figure 7e-g). The ribbons are approximately 100 μm thick and are composed of inequigranular quartz grains ($d \sim 10 \mu\text{m}$ to $\sim 150 \mu\text{m}$) with lobate and locally diffuse contacts. The recrystallized quartz ribbons are not entirely monomineralic; thin lamellae of biotite ($d \sim 50 \mu\text{m}$) and feldspar grains are locally present between the quartz grains. In the monomineralic regions of the quartz ribbons, the contact between the grains is straight and exhibits triple junctions.

Domain IV – Polyphasic Matrix

The fine-grained matrix of the ultramylonite can be divided in two types: I) A mixture of fine recrystallized plagioclase ($\sim 35\%$), quartz ($\sim 30\%$), and K-feldspar ($\sim 20\%$) aggregates with thin biotite lamellae ($\sim 14\%$) and, magnetite ($< 1\%$); and II) A biotite-rich layer primarily consisting of biotite lamellae ($\sim 70\%$) and subordinately of grains of quartz ($\sim 15\%$), plagioclase ($\sim 9\%$), K-feldspar ($\sim 4\%$), titanite ($< 1\%$), muscovite ($< 1\%$), and magnetite ($< 1\%$).

The quartz-feldspar mixture, which constitutes the type I matrix, has grain sizes ranging from $\sim 5 \mu\text{m}$ to $\sim 20 \mu\text{m}$ (Figure 7b, g). The contact between the grains is curved to straight, and in areas where straight edges predominate, the grains commonly exhibit triple junctions. Recrystallized K-feldspar grains have a sub-elliptical shape, with the direction of the long axis of the grain parallel to the mylonitic foliation. Biotite lamellae,

ranging from 5 μm to 100 μm in length, define the planes of the mylonitic foliation with spacings between the planes less than 25 μm .

The type II matrix is mainly composed of biotite lamellae ranging from 10 μm to 500 μm , oriented along two oblique directions relative to each other (Figure 7a, e, f). Between the biotite lamellae, there are isolated grains ($d \sim 5 \mu\text{m}$ to $\sim 100 \mu\text{m}$; Figure 7f) of quartz, feldspar, titanite, apatite and muscovite, as well as fine to medium-grained recrystallized quartz-feldspar aggregates ($d \sim 10 \mu\text{m}$ to $\sim 100 \mu\text{m}$; Figure 7e). This matrix surrounds the K-feldspar porphyroclasts, which are partially to fully replaced by myrmekite, and the quartz ribbons (Figure 7c, d).

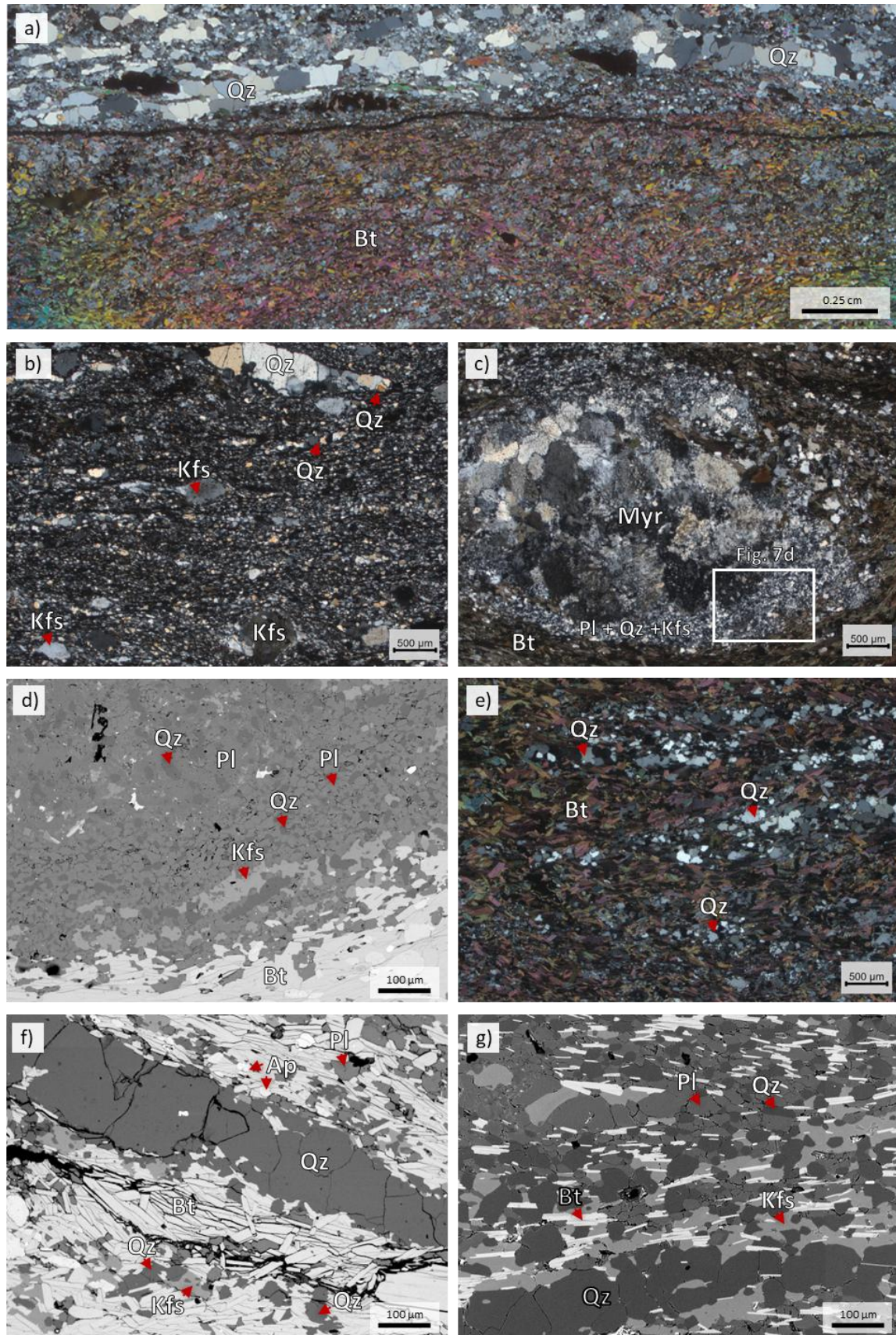


Figure 7: Main microstructures present in ultramylonites of the Itapetim shear zone. A) Abrupt contact between mylonite and ultramylonite. B) Porphyroclasts of K-feldspar and quartz immersed in type I matrix,

composed of fine grains of quartz, feldspar, and biotite. The quartz porphyroclast exhibits a flattened and recrystallized rim. C) K-feldspar porphyroclast completely replaced by plagioclase and vermicular quartz. Surrounding the porphyroclast are recrystallized aggregates of plagioclase with quartz and interstitial K-feldspar, detailed in D. D) Detail of the recrystallized aggregates of plagioclase with quartz and interstitial K-feldspar around the porphyroclast. E) Quartz ribbons immersed in type II matrix, formed by biotite and recrystallized grains of quartz and feldspar. F) Quartz ribbons with biotite lamellae in some interstices. The quartz ribbon is surrounded by type II matrix, essentially composed of biotite. G) Quartz ribbon with K-feldspar grain in the interstices. The ribbon is surrounded by type I matrix, composed of recrystallized grains of quartz and feldspar, and biotite lamellae.

4.4.2.3 Tendó shear zone – granitoid mylonite

The mylonites are primarily composed of quartz, K-feldspar, plagioclase, biotite, and muscovite. The structural fabric of the TSZ is defined by three distinct microstructural domains: (I) K-feldspar porphyroclasts, which are enveloped by (II) quartz ribbons, and (III) recrystallized aggregates of quartz and feldspar. Between these domains, oriented lamellae of biotite and muscovite mark the planes of the mylonitic foliation.

Domain I – K-feldspar porphyroclasts

K-feldspar (microcline) porphyroclasts are of medium to coarse grain size (~ 0.05 – 3 cm) and have lobate to serrated edges (Figure 8a, b). Inside the coarse clasts (~3 cm), bands composed by inequigranular, fine to medium-sized K-feldspar grains (~20 - 100 μm ; Figure 8a, b) are common. The K-feldspar clasts exhibit undulatory extinction, curved/bent twins and fine recrystallized grains (~20 μm) at the edges. In this domain, the fracturing/fragmentation of the porphyroclasts is rare.

Domain II – Monomineralic quartz ribbons.

The polycrystalline quartz ribbons have a thickness of ~500 μm and are continuous structures parallel to the foliation (Figure 8c). The recrystallized quartz grains are inequigranular, varying in size from ~20 to 1000 μm . The edges of the ribbon walls are lobate, and the internal grains of the ribbon exhibit lobate to amoeboid contacts (Figure 8c, d). Only in localized areas ribbons formed by equigranular grains (~100 μm) with a granoblastic texture are present. The coarse quartz grains often exhibit undulatory extinction and locally subgrains (Figure 8d).

Domain III – Recrystallized quartzo-feldspathic aggregates.

This microstructural domain is formed by recrystallized grains of K-feldspar, plagioclase, and quartz (Figure 8e). The recrystallized aggregates have equigranular domains ($\sim 70\text{ }\mu\text{m}$), but locally there are coarser recrystallized grains ($\sim 200\text{ }\mu\text{m}$). The contact between the grains is lobate to rectilinear. The grains of K-feldspar and plagioclase often exhibit deformed twins (Figure 8e).

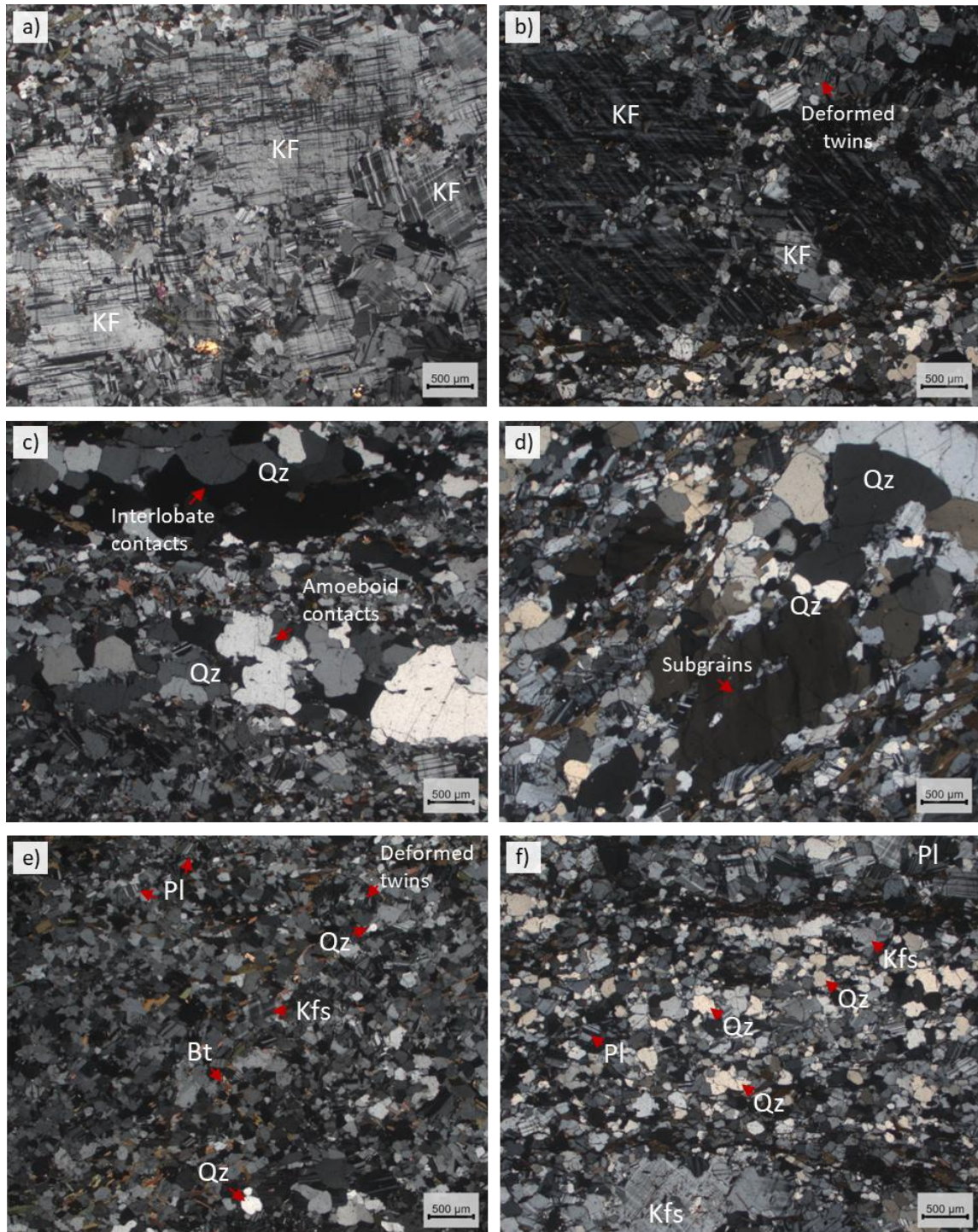


Figure 8: Mylonitic microstructures of the Tendó shear zone. A, B) K-feldspar porphyroclast with deformed twins and recrystallized bands. C) Monomineralic quartz ribbons with interlobate to amoeboid contacts. D) Monomineralic quartz ribbon with undulatory extinction and subgrains. E, F) Recrystallized aggregates of feldspar and quartz.

4.4.2.4 Tendó shear zone – Ultramylonite

The ultramylonitic band exhibits an abrupt contact with the deformed granitoid (Figure 9a). The wall of the ultramylonite is slightly undulating and features small recesses where the foliation is deflected (Figure 9b). The ultramylonite of the ZCT is composed of (I) feldspar porphyroclasts, (II) fine monomineralic ribbons of recrystallized quartz, and (III) a polyphasic matrix mainly consisting of quartz, feldspar, and biotite.

Domain I – Feldspar porphyroclasts

The K-feldspar and plagioclase porphyroclasts are about 150 μm in size and predominantly have a sub-elliptical shape (Figure 9b, c). The K-feldspar and plagioclase clasts display lobate to serrated edges and a preferred orientation parallel to the foliation. Some clasts show weak undulatory extinction.

Domain II – Monomineralic quartz ribbons

The monomineralic ribbons of recrystallized quartz have a thickness ranging from 30 to 150 μm and are oriented according to the foliation (Figure 9c, d). The contacts between the quartz grains are lobate, diffuse and are commonly oriented perpendicular to the ribbon walls. The quartz grains forming the ribbons are inequigranular, with sizes varying between 30 μm and 100 μm .

Domain III – Polyphasic Matrix

The matrix consists of fine grains of feldspar and quartz of about 20 μm intercalated with thin biotite lamellae (Figure 9d). The biotite lamellae (d ~40 μm) have a shape preferred orientation and define the foliation planes. Near the walls of the ultramylonite, the biotite lamellae are frequently deflected in areas where the feldspar porphyroclasts of the mylonitic granitoid protrude into the ultramylonitic band (Figure 9b).

In the analyzed ZCT-Ultra sample, there is a thin shear zone, oblique to the main ultramylonitic band, which cuts through the coarse protomylonitic granitoid (Figure 9a, e). The shear zone is 50 μm thick and is filled with fine ($d \sim 20 \mu\text{m}$) recrystallized grains of k-feldspar, plagioclase and quartz (Figure 9a, e).

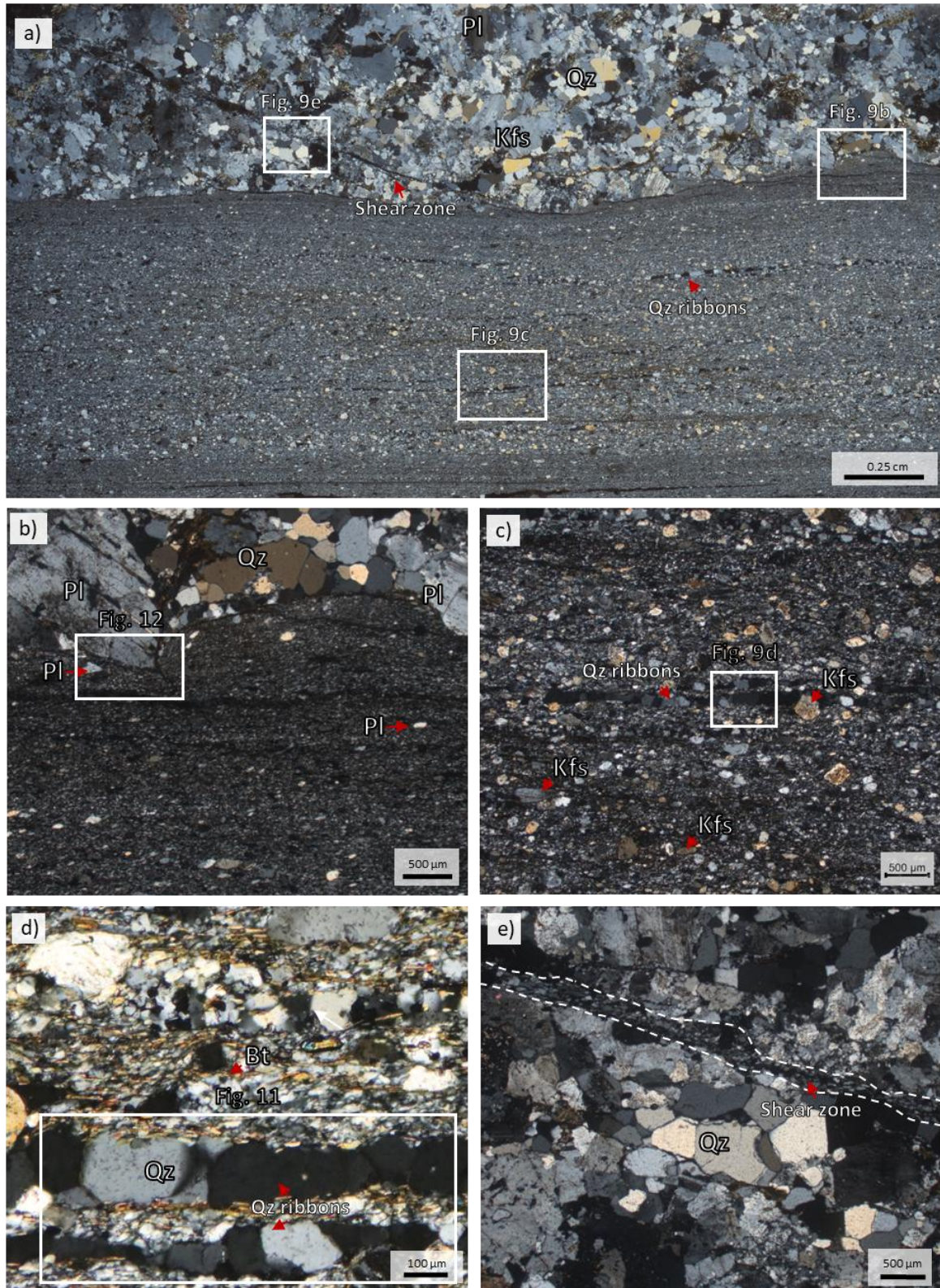


Figure 9: Microstructures of ultramylonites of the Tendó shear zone. A) Abrupt contact between ultramylonite and protomylonite of the Teixeira Batholith. A fine shear zone, obliquely oriented to the ultramylonite wall, crosscuts the protomylonitic granitoid. B) The wall of the ultramylonite features small recesses due to plagioclase porphyroclasts of the protomylonitic granitoid protruding into the ultramylonitic band. C) Porphyroclasts of K-feldspar and monomineralic quartz ribbons surrounded by a matrix composed of recrystallized grains of quartz, feldspar, and biotite lamellae. D) Quartz ribbons parallel to the mylonitic

foliation, embedded in a matrix of fine recrystallized grains of quartz and feldspar, with thin biotite lamellae exhibiting a shape preferred orientation. E) Fine shear zone crosscutting protomylonitic granitoid. The shear zone is filled with fine grains of quartz and feldspar.

4.4.3 *Crystallographic preferred orientations*

4.4.3.1 Itapetim shear zone - Mylonitic granitoid (Sample RS07A-2)

Figure 10 presents the results obtained by EBSD of a portion of the mylonitic granitoid near the contact with the ultramylonite (Figure 7a). The phase map (Figure 10a) shows large grains of quartz in ribbons alternating with recrystallized plagioclase grains.

Coarse-grained quartz ($d \sim 400 \mu\text{m}$) exhibits straight to curved boundaries and little intra-grain deformation, with subgrain boundaries being rare (red boundaries; Figure 10b). The quartz ribbons exhibit a weak CPO (J index ~ 1.41), with the poles of the (0001) planes concentrated near the Y position or aligned approximately 20° - 30° anticlockwise from the YZ plane (Figure 10d). Poles of the $(2\bar{1}\bar{1}0)$ planes show a discrete maximum $\sim 10^\circ$ - 20° anticlockwise from the XY plane (Figure 10d). Quartz misorientation angles exhibits peaks of correlated grains between 10° and 30° , which exceed the theoretical curve, and another peak at 60° , commonly associated with Dauphiné twinning (Figure 10f).

The domain of recrystallized plagioclase grains has an average grain size of $d = 28 \mu\text{m}$. In larger recrystallized plagioclase grains ($d \sim 100 \mu\text{m}$), there is an increase in internal deformation and the development of subgrain boundaries (Figure 10c). The CPO in recrystallized plagioclase grains is weak (J index ~ 2.61). The maxima of the poles to the (010) plane is concentrated near the great circle between the Z and X axes (Figure 10e). The (001) plane poles show a maximum concentration at approximately 10° anticlockwise from the Z axis, and the [100] axes are clustered in the intermediate region between the X and Y axes (Figure 10e). The histogram of misorientation angles of plagioclase grains shows a peak of correlated grains between 10° and 50° and another at 180° , associated with the albite twin law (Figure 10g).

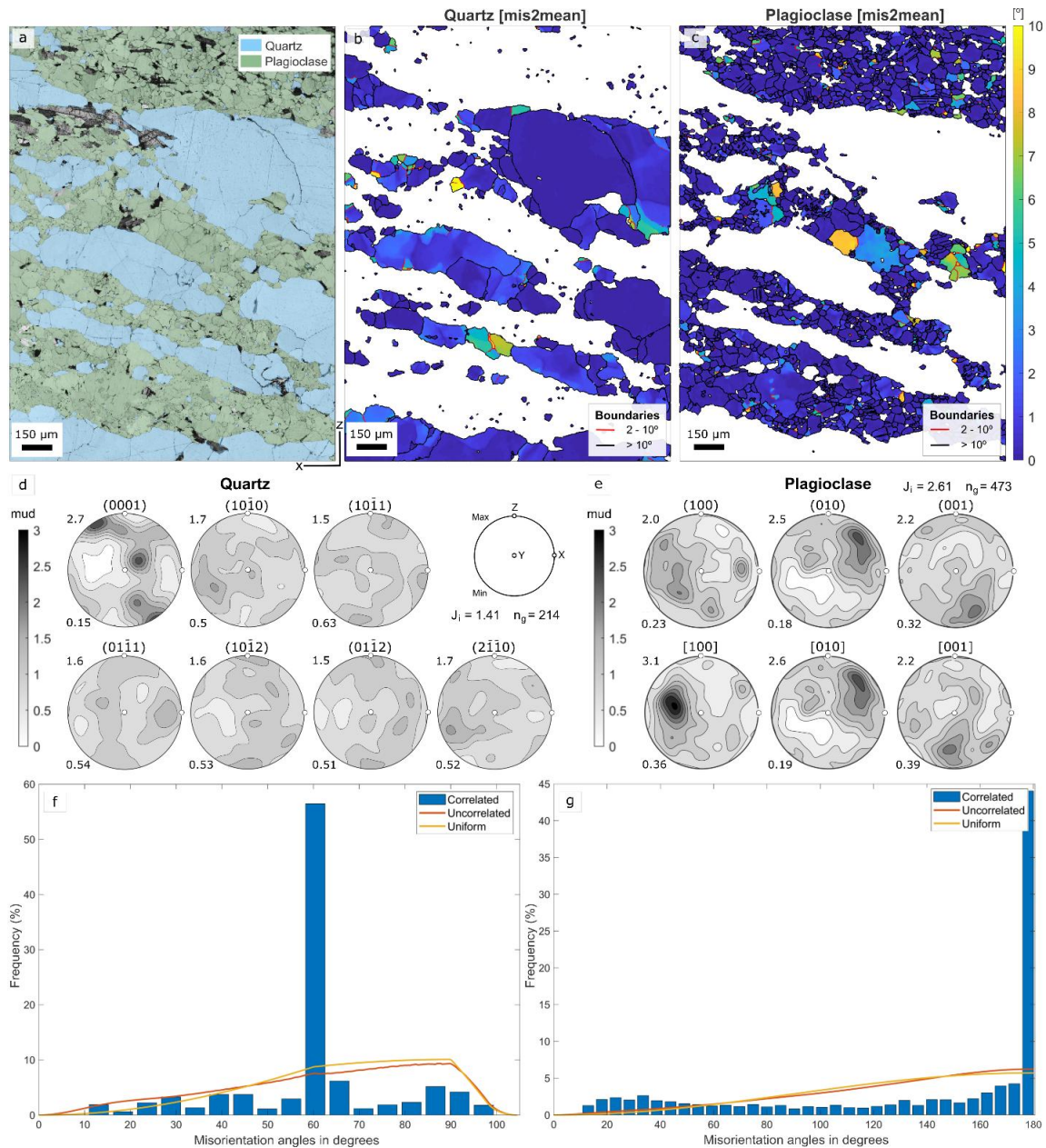


Figure 10: EBSD data of quartz ribbons and recrystallized plagioclase aggregates in mylonitic granitoid near the contact with the ultramylonitic band of the ISZ. A) Phase map identifying quartz and plagioclase. B, C) Maps of intragrain misorientation [mis2mean] of quartz and plagioclase, respectively. D, E) Pole figures showing the crystallographic orientation of quartz and plagioclase, respectively. mud, multiples of uniform distribution; J_i , J-index; n_g , number of grains. F, G) Histograms of misorientation angles of quartz and plagioclase grains, respectively.

4.4.3.2 Tendó shear zone - Ultramylonite (Sample ZCT-Ultra)

EBSD analyses were conducted on recrystallized quartz ribbons in ultramylonite (Figure 11), at the contact between the ultramylonite and a coarse plagioclase porphyroclast of the protomylonite (Figure 12), and in a fine-grained shear zone obliquely

oriented in relation to the main orientation of the ultramylonite bands, which crosscut the protomylonite of the Tendó shear zone (Figure 13).

The recrystallized quartz ribbons exhibit a mean size of 40 μm and are embedded in a fine-grained, polyphase matrix composed of plagioclase, K-feldspar and biotite (Figure 9d and Figure 11a). The recrystallized quartz grains exhibit little internal deformation. In the grains around 150 μm , a more pronounced development of subgrain boundaries is observed (Figure 11b). The CPO of the quartz grains is weak (J index ~ 1.63); the poles of the (0001) planes show a well-defined clustering near the Y-axis, and the poles of the $(2\bar{1}\bar{1}0)$ plane are concentrated along the great circle between the Z and X axes (Figure 11c). The misorientation angles of quartz grains show three peaks of correlated grains that exceed the theoretical curve, 0° - 10° , 15° - 30° , and 60° - 65° , the last peak is associated with Dauphiné twinning (Figure 11d).

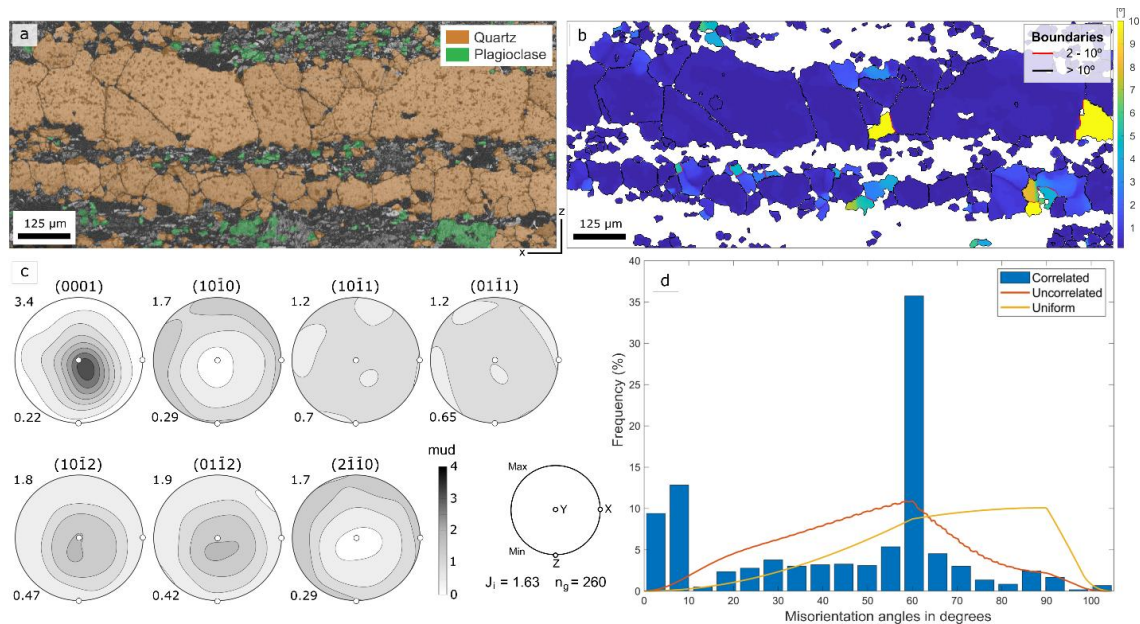


Figure 11: EBSD data of quartz ribbons in ultramylonitic band of the TSZ (location in Fig. 9d). A) Phase map highlighting the analyzed quartz ribbon and adjacent plagioclase grains. B) Map of intragrain misorientation [mis2mean] of quartz. C) Pole figures showing the crystallographic orientation of quartz. mud, multiples of uniform distribution; Ji, J-index; ng, number of grains. D) Histogram of misorientation angles of quartz grains.

The ultramylonites of the Tendó shear zone exhibit abrupt contacts with the adjacent rocks (Figure 9a, b). In the ZCT-Ultra sample, the phase map (Figure 12a) shows the plagioclase clast from the protomylonite in contact with fine grains of plagioclase, quartz, and K-feldspar from the ultramylonitic matrix. The plagioclase porphyroclast

from the protomylonite is coarse ($\sim 700\ \mu\text{m}$) and has serrated, fractured, and angular boundaries. The plagioclase clast shows slight internal deformation, with low-angle grain boundaries occurring locally (Figure 12b). At the contact between the plagioclase clast of the protomylonite and the ultramylonite, there is an aggregate of recrystallized K-feldspar grains (Figure 12a).

The polyphase ultramylonitic matrix is composed of biotite lamellae (not indexed in the EBSD results) and fine recrystallized grains of plagioclase, quartz, and K-feldspar with average sizes of $4.7\ \mu\text{m}$, $7.4\ \mu\text{m}$, and $4.5\ \mu\text{m}$, respectively. The phase contacts are curved, often exhibiting four grain junctions (Figure 12a). Most of the recrystallized grains in the matrix do not show internal deformation (Figure 12b, c, d). Plagioclase and K-feldspar grains exhibit a preferred shape orientation, with their long axes aligned at small angles to the foliation (Figure 12a). However, near the angular edge of the plagioclase clast from the protomylonite, there is a deflection of the ultramylonitic matrix, and the long axes of the plagioclase grains are oriented between 60° and 90° relative to the principal orientation of the ultramylonitic band (Figure 12a). Embedded in the polyphase matrix, there are plagioclase porphyroclasts of $\sim 150\ \mu\text{m}$ with serrated and fractured edges. The internal deformation in these porphyroclasts is more intense at the edges, with the presence of low-angle grain boundaries (Figure 12b).

The crystallographic orientation of plagioclase in the ultramylonitic matrix is moderate (J index ~ 3.61), with the maximum poles of the (010) plane concentrated in the XY plane and aligned near the Y position (Figure 12e). The poles of the (001) plane show low angles and are approximately 30° - 40° clockwise from the Z-axis; the poles of the [100] axis are clustered near the great circle, 20° - 35° from the X-axis (Figure 12e). The histogram of misorientation angles of plagioclase grains shows a small peak ($<3\%$ frequency) of correlated grains between 0° and 10° and another peak at 180° , associated with albite twin law, which exceed the theoretical curve (Figure 12h).

The crystallographic orientation of quartz is weak (J index ~ 1.22) and random (Figure 12f). The misorientation angles of quartz show peaks of correlated grains between 0° and 5° and another at 60° , corresponding to Dauphiné twinning (Figure 12i). The K-feldspar grains exhibit a weak CPO (J index ~ 1.43) with the maximum poles of the (010) plane in intermediate positions between Z and Y; the poles of the (001) plane show a slight maximum near the Y position, and the maximum poles of the [100] axis are aligned

with the X-axis (Figure 12g). The histogram of misorientation angles for K-feldspar shows peaks of correlated grains in the ranges of 0° - 10° , 25° - 30° , and 180° (Figure 12j).

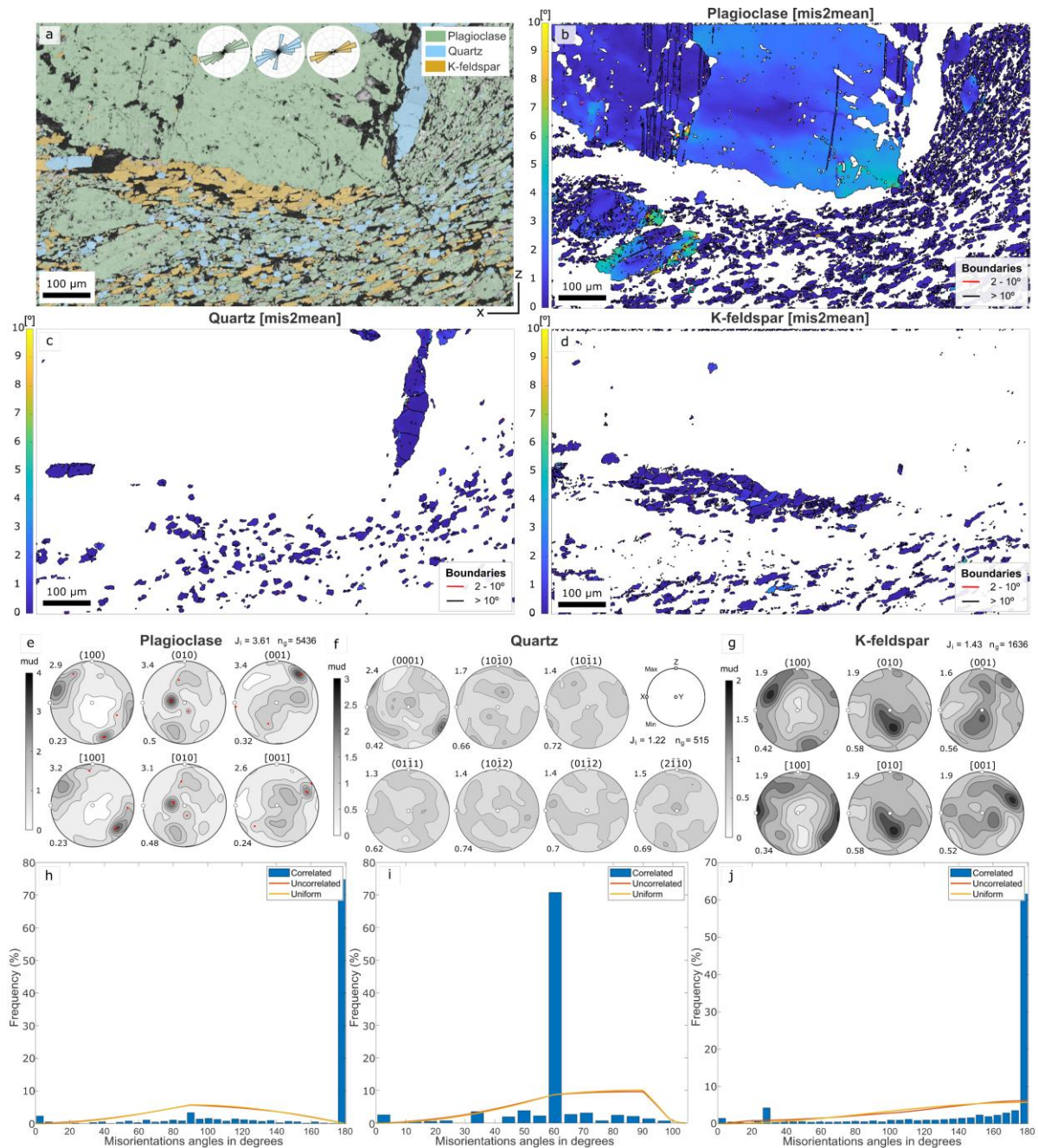


Figure 12: EBSD data of the contact between the ultramylonite and the coarse plagioclase clast of the protomylonite from the Tendó shear zone (location in Fig. 9b). A) Phase map identifying plagioclase clast from the protomylonite in contact with fine grains of plagioclase, quartz, and K-feldspar from the ultramylonitic matrix. Upper-center diagrams show the shape-preferred orientation of plagioclase, quartz and K-feldspar long axes. B, C, D) Maps of intragrain misorientation [mis2mean] of plagioclase, quartz and K-feldspar, respectively. E, F, G) Pole figures showing the crystallographic orientation of plagioclase, quartz and K-feldspar, respectively. mud, multiples of uniform distribution; Ji, J-index; ng, number of grains. H, I, J) Histograms of misorientation angles of plagioclase, quartz and K-feldspar grains, respectively.

The thin shear zone has an obliquity of 20° relative to the main direction of the ultramylonitic band (Figure 9a). One end of this thin structure starts at the contact between the ultramylonite and the protomylonite (Figure 9a) and extends throughout the protomylonite in the Tendó shear zone (Figure 9a, e and Figure 13a). The phase map shows that the shear zone is mainly composed of recrystallized K-feldspar grains with an average size of $15\ \mu\text{m}$, and to a lesser extent, quartz and plagioclase grains (Figure 13b). The analyzed area includes a portion of the contact with the protomylonite, where the plagioclase grains have an average size of approximately $150\ \mu\text{m}$.

The recrystallized K-feldspar grains predominant in the thin shear zone have two main shapes: some exhibit an elongated morphology, intermixed with mica grains (not indexed in the analysis), while others have a more isometric shape (Figure 13b). Elongated grains in contact with mica crystals have straight edges parallel to phyllosilicate orientations, while the contact between K-feldspar grains is sutured to curved. Isometric K-feldspar grains have predominantly curved edges and display four grain junctions, with sutured contacts occurring locally. The recrystallized K-feldspar grains show a preferential orientation slightly parallel to the edges of the shear zone (Figure 13b).

For the K-feldspar mineral phase, internal deformation is evident only in the protomylonitic region grains (Figure 13c). In plagioclase grains, internal deformation occurs with low intensity only at the edges of some plagioclase crystals from the protomylonite (Figure 13d). The crystallographic orientation of the recrystallized K-feldspar grains in the thin shear zone is moderate (J index ~ 6.77) and shows (010) plane pole maxima concentrated near the XY plane. The (001) plane poles and the [100] axis are randomly distributed (Figure 13e). The misorientation angle histogram of K-feldspar grains shows peaks of correlated grains (frequency $\sim 5\%$) that exceed the theoretical curve between 0 and 35° , at 45 - 50° , and at 180° , associated with twinning (Figure 13g).

Plagioclase grains from the protomylonite have a J-index of 15.6 , with (010) plane pole maxima concentrated at approximately ~ 15 - 25° counterclockwise from the XY plane. The (001) plane pole maxima are concentrated in the XY plane near the Y axis, while the [100] axis shows no defined distribution (Figure 13f). The misorientation

histogram shows only a low-frequency peak ($\sim 5\%$) between 0 and 10° and a peak at 180° corresponding to plagioclase twinning (Figure 13h).

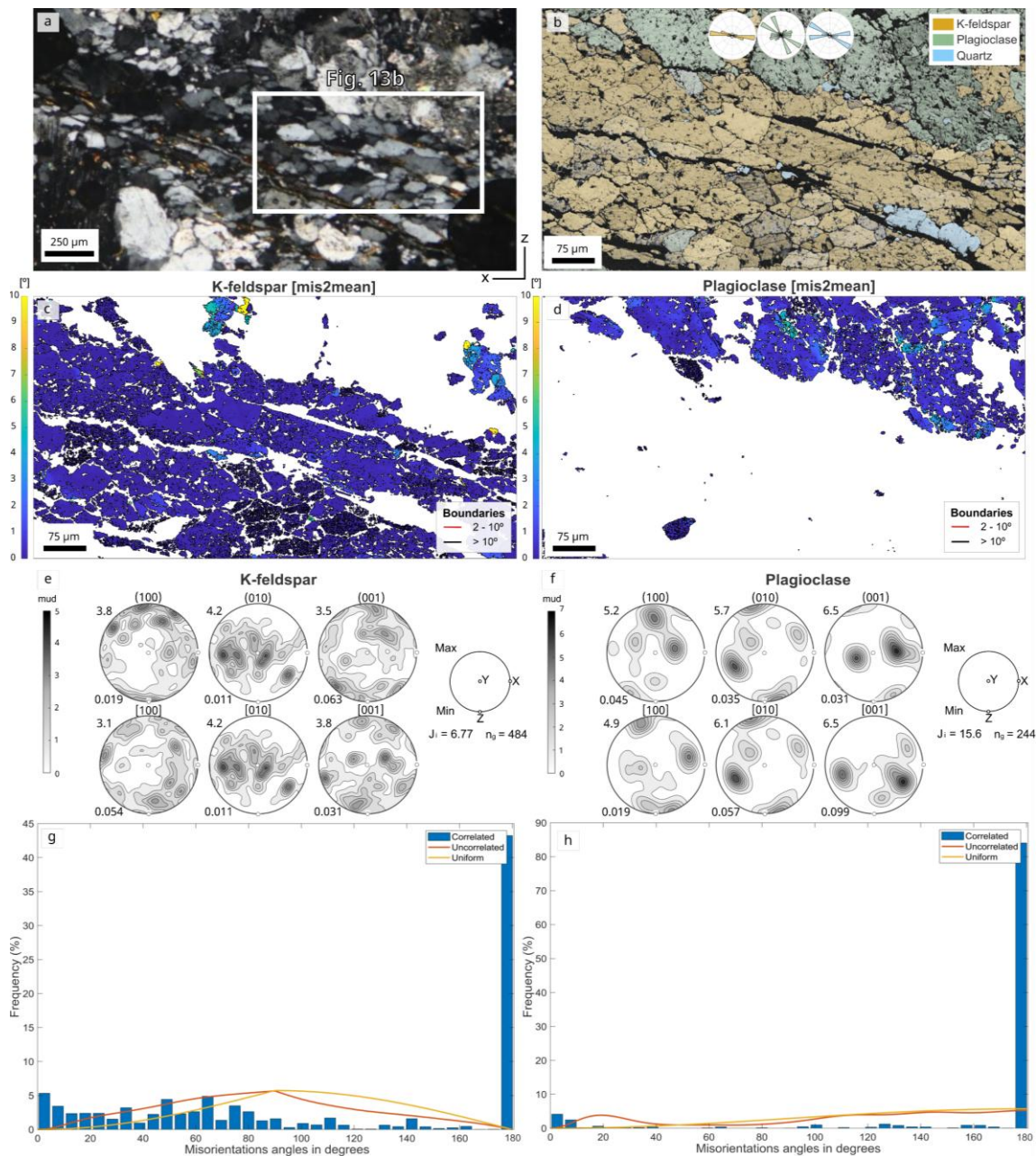


Figure 13: EBSD data from the fine shear zone that crosses the coarse protomylonite of the Tendó shear zone. A) Fine shear zone cutting through the protomylonite. The white rectangle marks the area where the EBSD analyses were performed. B) Phase map identifying the main minerals present in the fine shear zone, with K-feldspar being predominant, followed by plagioclase and quartz. The plagioclase grains at the top of the image belong to the protomylonite. Upper-center diagrams show the shape-preferred orientation of K-feldspar, plagioclase, and quartz long axes. C, D) Maps of intragrain misorientation [mis2mean] of K-feldspar and plagioclase, respectively. E, F) Pole figures showing the crystallographic orientation of K-feldspar and plagioclase, respectively. mud, multiples of uniform distribution; J_i , J-index; n_g , number of grains. G, H) Histograms of misorientation angles of K-feldspar and plagioclase, respectively.

4.4.4 Mineral chemistry

4.4.4.1 Itapetim Shear Zone

The chemical composition of the porphyroclasts and recrystallized aggregates of K-feldspar and plagioclase in the mylonites of the ISZ is shown in Figure 14a,b, and for the ultramylonites the data is presented in Figure 14c,d. In the mylonites, the composition of the K-feldspar porphyroclasts (microcline) varies between Or₈₉ and Or₉₈, and the plagioclase porphyroclasts between An₁₂ and An₃₀ (oligoclase). The chemical composition of the recrystallized K-feldspar grains tends to overlap with that of the porphyroclasts, ranging between Or₉₂ and Or₉₉; the recrystallized plagioclase grains have a composition of albite to oligoclase (An₈ to An₂₀).

In the ultramylonitic zones, the chemical composition of the porphyroclasts and recrystallized aggregates of K-feldspar shows Or content ranging from Or₉₁-Or₉₇ and Or₉₃-Or₉₉, respectively. The chemical composition of the porphyroclasts and recrystallized aggregates of plagioclase is slightly different; the porphyroclasts have an An content ranging from An₁₉ to An₃₀, while the recrystallized aggregates range from An₂₈ to An₃₆.

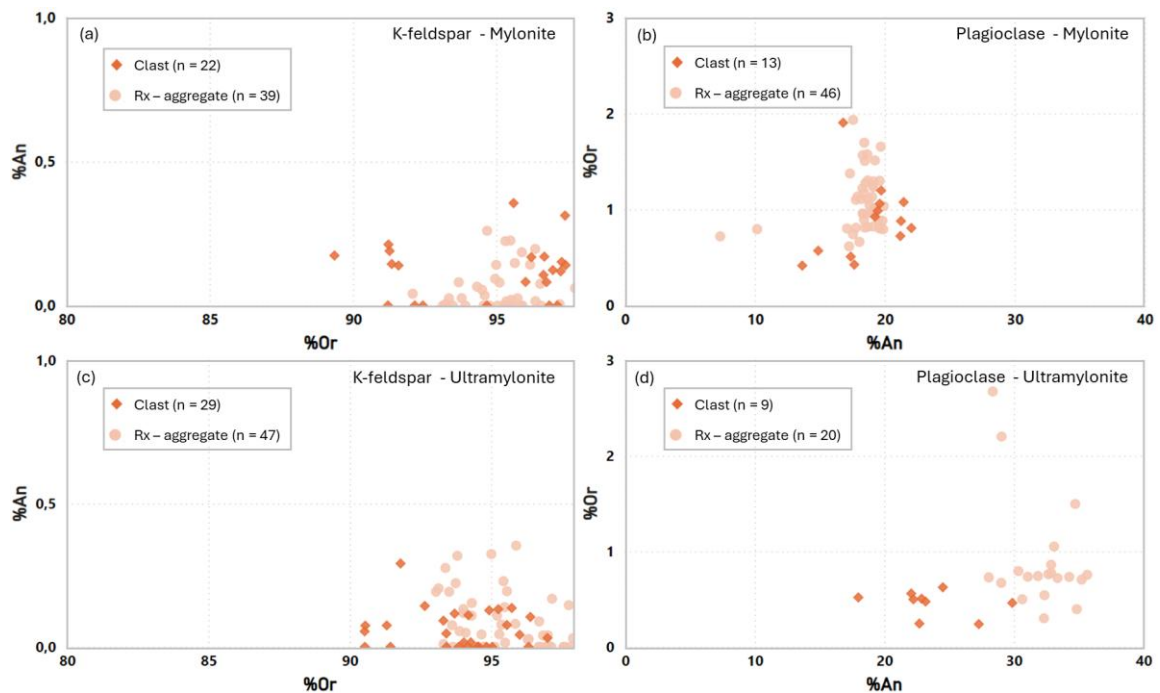


Figure 14: Chemical composition of K-feldspar and plagioclase porphyroclasts and recrystallized grains in: (a,b) mylonite and (c,d) ultramylonites of Itapetim Shear Zone.

4.4.4.2 Tendó Shear Zone

The chemical composition of the K-feldspar porphyroclasts and the recrystallized grains of K-feldspar and plagioclase in the TSZ is summarized in Figure 15. The K-feldspar porphyroclasts (microcline) vary in chemical composition between Or₉₀ and Or₉₇. The chemical composition of the recrystallized K-feldspar grains ranges between Or₉₂ and Or₉₈. The recrystallized aggregates of plagioclase have a composition of oligoclase and andesine, showing a chemical composition trend ranging from An₁₂ to An₃₆.

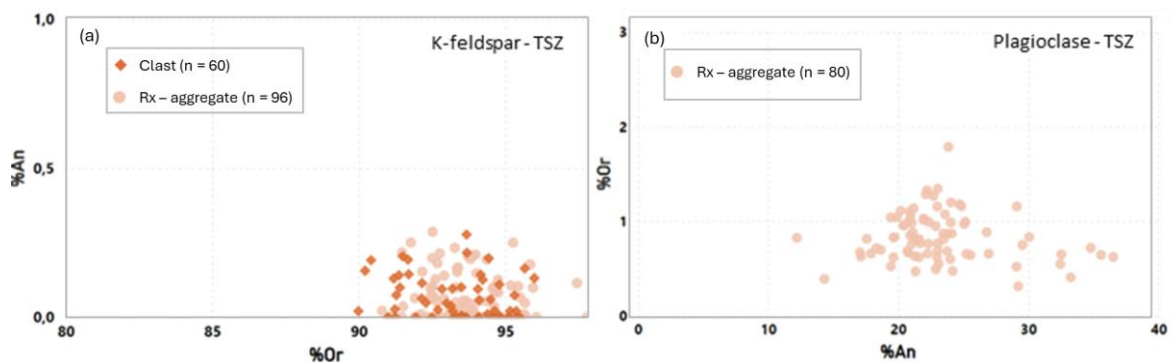


Figure 15 – Chemical composition of (a) K-feldspar and (b) plagioclase porphyroclasts and recrystallized grains of Tendó Shear Zone

4.5 Discussion

4.5.1 Deformation mechanisms

4.5.1.1 Itapetim shear zone

Quartz grains are concentrated in monomineralic quartz bands that are parallel to the shear plane and are not laterally connected to each other (Figure 6d). Microstructures such as undulatory extinction and lobate and diffuse contacts in the quartz ribbons indicate the operation of dislocation creep as the deformation mechanism (Hirth and Tullis, 1992). Although these microstructures are identified along the ISZ and suggest that quartz deformation was accompanied by dynamic recrystallization (Passchier & Trouw, 2005), several quartz grains have no internal deformation, possibly due to annealing (Trepmann et al., 2007). An example of this can be observed in the transition

region between the mylonite and ultramylonitic band (Figure 10), in which quartz grains show smooth grain boundary morphology in the ribbons. This is expected when the grains grow during static recrystallization (e.g., Culshaw & Fyson, 1984). In this contact region between mylonite and ultramylonite, microstructures and EBSD data, although revealing a low crystallographic preferred orientation (CPO) for the quartz grains in the mylonite, show that the c-axes of quartz are slightly concentrated at the edges of the pole figure and at intermediate angles near the Y-axis, forming a discrete girdle (Figure 10d). The CPO analysis suggests that during recrystallization of quartz grains, the prism $\langle a \rangle$ and rhombohedral $\langle a+c \rangle$ slip systems and, to a lesser extent, the basal $\langle a \rangle$ system were activated (Passchier & Trouw, 2005; Heilbronner & Tullis, 2006). The possible activation of these slip systems indicates low to medium deformation temperatures. Additionally, the asymmetric girdle geometry suggests the influence of a sinistral simple shear component, corroborated by other kinematic indicators such as oblique foliation (Figure 6e) and porphyroclast asymmetry (Figure 4d). In the quartz misorientation histogram, the peak at a 60° occurs due to Dauphiné twinning (Law, 1990; Lloyd, 2004). These twins are common in quartz in deformed rocks and possibly contribute to the mechanical weakening of quartz (Tullis, 1970). In the ultramylonites, quartz ribbons are immersed in a fine-grained polyphasic matrix and locally show diffuse contacts, indicating grain boundary migration; most of this domain is fully recovered and does not provide CPO information.

The feldspar porphyroclasts in the protomylonites are marked by the presence of kink bands filled with recrystallized grains (Figure 6b), and in rocks showing a higher degree of mylonitization (most of those in the ISZ), they exhibit an elliptical to subelliptical morphology concordant with the foliation (Figure 6d). In both cases, recrystallized grains concentrate at the edges. This highlights that feldspar recrystallization occurs primarily along kink bands and grain boundaries (Bell & Johnson, 1989). Along the boundaries of the kink band, subgrains and new grains show evidence of grain boundary migration, as indicated by diffuse contacts at both the kink boundaries and the new grains. Dislocation creep along these boundaries tends to follow regions of higher dislocation density (Tullis & Yund, 1985; Bell & Johnson, 1989). Overall, an initial phase of deformation partitioning is observed, forming kink bands in the host grains and consequently causing a faster reduction in their size. In rocks with a higher degree of mylonitization, the remaining feldspar porphyroclasts are those that show no evidence of

kink bands and are surrounded by recrystallized aggregates, suggesting that the clasts with more kink bands in the early stages of mylonitization were completely recrystallized into aggregates of new grains. Recrystallization of feldspar clast into aggregates in the mylonites does not show any change in chemical composition (Figure 14a, b), suggesting recrystallization occurred in the absence of fluids. In rocks with a higher degree of mylonitization, porphyroclasts are predominantly K-feldspar, and most of plagioclase and quartz grains have been completely recrystallized, indicating the more resistant rheological behavior of K-feldspar during deformation. Feldspar aggregates analyzed by EBSD (Figure 10), do not show a well-defined crystallographic fabric, due to the low CPO, possibly resulting from diffusion creep (Mansard et al., 2018).

Together with myrmekites, flame perthites occur along the edges of K-feldspar clasts, presenting similarities to those described by Pryer (1993) and Pryer & Robin (1995), which result from high stress along the edges of K-feldspar grains. In the ultramylonites where the matrix is predominantly composed of biotite, the K-feldspar porphyroclasts are completely replaced by myrmekite, and the plagioclase clasts show a chemical composition different from the recrystallized aggregates (Figure 14d). These characteristics suggest that fluid circulation may have acted in the reactions observed in the formation of the ultramylonite (Menegon et al., 2006; Ceccato et al., 2018).

4.5.1.2 Tendó shear zone

The Tendó shear zone, similar to the Itapetim shear zone, shows deformation partitioning throughout its evolution, characterized by rocks with varying degrees of mylonitization and the activation of multiple deformation mechanisms within specific microstructural domains.

The quartz ribbons in the mylonite and ultramylonite differ not only in thickness and length but also in their microstructure (Figure 8c, d and Figure 9c,d). In the mylonites, the quartz ribbons vary in size (~500 μm thick), with larger grains (> 500 μm) showing well-developed subgrains (Figure 8d), and locally exhibiting amoeboid contacts (Figure 8e). In the ultramylonites, the quartz ribbons are up to 150 μm thick, with lobate and diffuse contacts between the quartz grains, predominantly oriented perpendicular to the ribbon walls. In both mylonites and ultramylonites, the described microstructures indicate deformation accommodation through dislocation creep (Passchier & Trouw, 2005). In the

quartz ribbons of the ultramylonites, the quartz C-axes are mainly concentrated in the center of the pole figure (Y-axis), with a slight inclination at intermediate angles (Figure 11c). This fabric configuration suggests that, during quartz recrystallization, the prism $\langle a \rangle$ and rhombohedral $\langle a \rangle$ slip systems were activated (Passchier & Trouw, 2005; Heilbronner & Tullis, 2006), indicating deformation at medium to high temperatures (Stipp et al., 2002, 2010).

Exclusively in the ultramylonite, a fine-grained mineral phase mixture is developed, consisting of feldspar and quartz grains alternated with biotite lamellae (Figure 9 a-d). Figure 12 shows the EBSD data from an area analyzed at the contact between the polyphase matrix of the ultramylonite and a plagioclase clast from the protomylonite. The data reveals fracturing at the edges of the plagioclase clast, forming fragments approximately 150 μm in size. The aggregates of K-feldspar grains in contact with the plagioclase clast, without phase mixing (Figure 12a), suggest two possible interpretations: either they are recrystallized grains from an original coarse-grained K-feldspar crystal, or they result from fluid-assisted growth. The polyphase matrix near the edge of the plagioclase clast is mainly composed of plagioclase grains (Figure 12a), and the phase mixing is less homogeneous compared to the central portions of the ultramylonitic bands. The plagioclase grains show a weak orientation of (100) planes, while the quartz and K-feldspar grains do not exhibit a crystallographic preferred orientation. Due to the fine grain size ($< 10 \mu\text{m}$), it is likely that deformation in this domain was primarily accommodated through diffusion creep (Tullis and Yund, 1991).

In the thin shear zone truncating the granitic protomylonite (Figure 9a, e and Figure 13), the recrystallization of K-feldspar plays a crucial role during deformation. The elongated and straight geometry of K-feldspar grains in contact with mica lamellae suggests that phyllosilicate phases may have controlled the growth of these grains, indicating fluid-assisted growth (Platt, 2015). However, some grains display diffuse and serrated edges, which point to dynamic recrystallization through grain boundary migration. The other K-feldspar grains, not in direct contact with mica, exhibit an isometric geometry with diffuse and lobate edges, further indicating that deformation was accommodated through grain boundary migration (Hentschel et al., 2019). The poles of the crystallographic planes and axes of the recrystallized K-feldspar grains do not show a well-defined orientation (Figure 13e), with the misorientation angle peaks mainly

highlighting the twinning (Figure 13g). Such patterns further suggest that deformation within the thin shear zone is accommodated mainly by diffusion creep (Cross et al., 2020).

4.5.1.3 Tectonic implications

The Itapetim and Tendó shear zones occur as oblique, NE-SW-trending faults that connect with major E-W structures within the tectonic framework of the Borborema Province (Vauchez et al., 1995). Such anisotropies are associated with sinistral displacement and record a protracted chronological evolution, with ages spanning from ~ 615 Ma to ~ 570 Ma (Guimarães et al., 2011; Viegas et al., 2022; Araújo Neto et al., 2023). Recent geophysical models have proposed that the central part of the Borborema Province has accommodated ~ 200 km of dextral shear displacement during its main deformation phase (Fossen et al., 2022).

The data presented in this study provides evidence for the rheological behavior of the shear zones that form the interconnected, central block of the Borborema Province. Deformation mechanisms are mainly characterized by combined dislocation creep and diffusive mass transfer at medium- to high-temperature conditions. Furthermore, feldspar compositions suggest that reactive fluids may have had a role in localizing strain within the shear zones. Such patterns suggest that the NE-SW shear zones may constitute deformation transfer structures in which plastic strain was accommodated during E-W, dextral shearing of the block bounded by the Patos and Pernambuco lineaments (Corsini et al., 1991, 1998). Sinistral shear sense along the Itapetim and Tendó shear zones further suggests that medium- to high-grade plastic strain in these structures was developed as a result of a regional, NNW-SSE shortening direction combined with WSW-ENE extension. Such an oblique strain field would be responsible for sinistral motion in the Itapetim and Tendó shear zones, while the E-W, bounding Patos and Pernambuco faults would record dextral kinematics (Archanjo et al., 2021; Neves et al., 2021). Furthermore, the oblique extension associated with the sinistral kinematics of the Itapetim and Tendó shear zones is also associated with magmatic deformation of granitic plutons during cooling, i.e. the Itapetim pluton (Viegas et al., 2022).

Taken together, the combined dataset gathered in this study suggests that the central domain of the Borborema Province behaved as a ductile block during simple shear

in the main E-W structures of the Province. Such rheological contrasts may have been aided by the intrusion of granitoid plutons at the central domain, which contributed to maintain a hot, plastic rheology during shearing and allowed for a ductile extension component during contrasting shear kinematics within- and at the boundaries of the block. Nucleation of the Itapetim and Tendó shear zones with sinistral kinematics would be an asymmetrical response of a ductile layer to boundary simple shear during overall NNW-SSE oblique shortening. Such mechanical behavior of the crust has been modelled and proposed in crustal fragments in which magmatism and deformation are coeval (Vanderhaeghe, 2001, 2009; Rosenberg & Handy, 2005).

4.6 CONCLUSIONS

Field, microstructural, crystallographic and chemical data gathered in this study allow us to draw the following conclusions:

1. The Itapetim and Tendó shear zones localize strain mainly via dislocation creep in quartz grains, coupled with diffusive mass transfer in the presence of fluids that affect feldspar crystals.
2. Strain localization in the shear zones occurs under medium- to high-temperature ($\sim 520^{\circ}\text{C}$), which is consistent with the development of magmatic fabrics in adjacent granite plutons.
3. Strain compatibility between NE-SW-trending, sinistral shear zones and the major E-W, dextral lineaments was attained via solid-state flow at high-temperature in the central domain of the Borborema Province.

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CAPÍTULO 5

CONSIDERAÇÕES FINAIS

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Este estudo teve como objetivo realizar a caracterização estrutural e caracterizar os processos heterogêneos de localização da deformação ao longo das zonas de cisalhamento Itapetim e Tendó. A partir de uma abordagem integrada, que incluiu análise estrutural de campo, observações microestruturais detalhadas, estudos de orientações cristalográficas preferenciais e de química mineral, foi possível caracterizar os principais mecanismos de deformação e os processos de localização de deformação observados nessas zonas de cisalhamento. Esses resultados contribuem para uma melhor compreensão de como os gradientes de deformação variam ao longo de zonas de cisalhamento em níveis crustais médios.

As zonas de cisalhamento Itapetim e Tendó exibem orientação NE-SW e cinemática sinistral, com uma evidente partição do fluxo deformacional, marcada pela presença de milonitos e ultramilonitos ao longo das estruturas. A ZCI e ZCT localizaram a deformação principalmente a partir da fluência de deslocamentos em grãos de quartzo, combinado com a fluência difusiva que afeta os cristais de feldspato, em temperaturas médias a altas. A variação da composição química dos feldspatos nos ultramilonitos sugerem a presença de fluidos reativos, os quais podem ter influência direta na localização da deformação dentro das zonas de cisalhamento. Apesar das similaridades vistas em ambas as estruturas, os sistemas de deslizamento atuantes durante o processo de localização da deformação dos domínios das fitas de quartzo foram distintos, o que sugerem que foram ativados sob regimes termais diferentes. Na ZCI, ocorre a atuação dos sistemas de deslizamento romboédrico $\langle a \rangle$ e basal $\langle a \rangle$ nos grãos de quartzo, associados a temperaturas intermediárias; enquanto, na ZCT, ocorre a ativação dos sistemas de deslizamento prismático $\langle a \rangle$ e romboédrico $\langle a \rangle$ nos grãos de quartzo, relacionados a temperaturas mais elevadas.

No contexto regional, as zonas de cisalhamento Itapetim e Tendó ocorrem conectadas obliquamente a zona de cisalhamento Patos, a qual constitui uma das principais estruturas E-W que compõem o arcabouço estrutural da Província Borborema (Vauchez et al., 1995). O sentido de cisalhamento sinistral predominante ao longo da ZCI e ZCT aponta que a deformação plástica de médio a alto grau nessas estruturas foi desenvolvida como resultado de uma direção de encurtamento regional NNW-SSE. Este

campo de deformação oblíquo, além de estar associado à movimentação sinistral da ZCI e ZCT, estaria relacionado às estruturas regionais Patos e Pernambuco que apresentam cinemática destal. Em uma análise de escala regional, este estudo sugere que o Domínio Central da Província Borborema se comportou como um bloco dúctil durante o cisalhamento simples nas principais estruturas E-W formadoras do arcabouço tectônico da Província. Desta forma, a cinemática sinistral das zonas de cisalhamento Itapetim e Tendó seria em decorrência da assimetria da camada dúctil ao cisalhamento simples das estruturas adjacentes durante o encurtamento oblíquo geral NNW-SSE.

CAPÍTULO 6

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