GMG – 0332
Petrologia Metamórfica

Rochas de zonas de cisalhamento: cataclasitos, milonitos e rochas associadas

Zonas de cisalhamento: identificação

Os critérios para identificação de zonas de cisalhamento compreendem três categorias amplas:

1) Efeitos em unidades geológicas ou estratigráficas.

2) Efeitos em feições fisiográficas.

3) Feições intrínsecas às falhas.

1) Efeitos de falhamento nas unidades geológicas ou estratigráficas:

As falhas podem ser reconhecidas pela identificação de deslocamentos em estruturas-guia (camadas, diques, sills, etc)

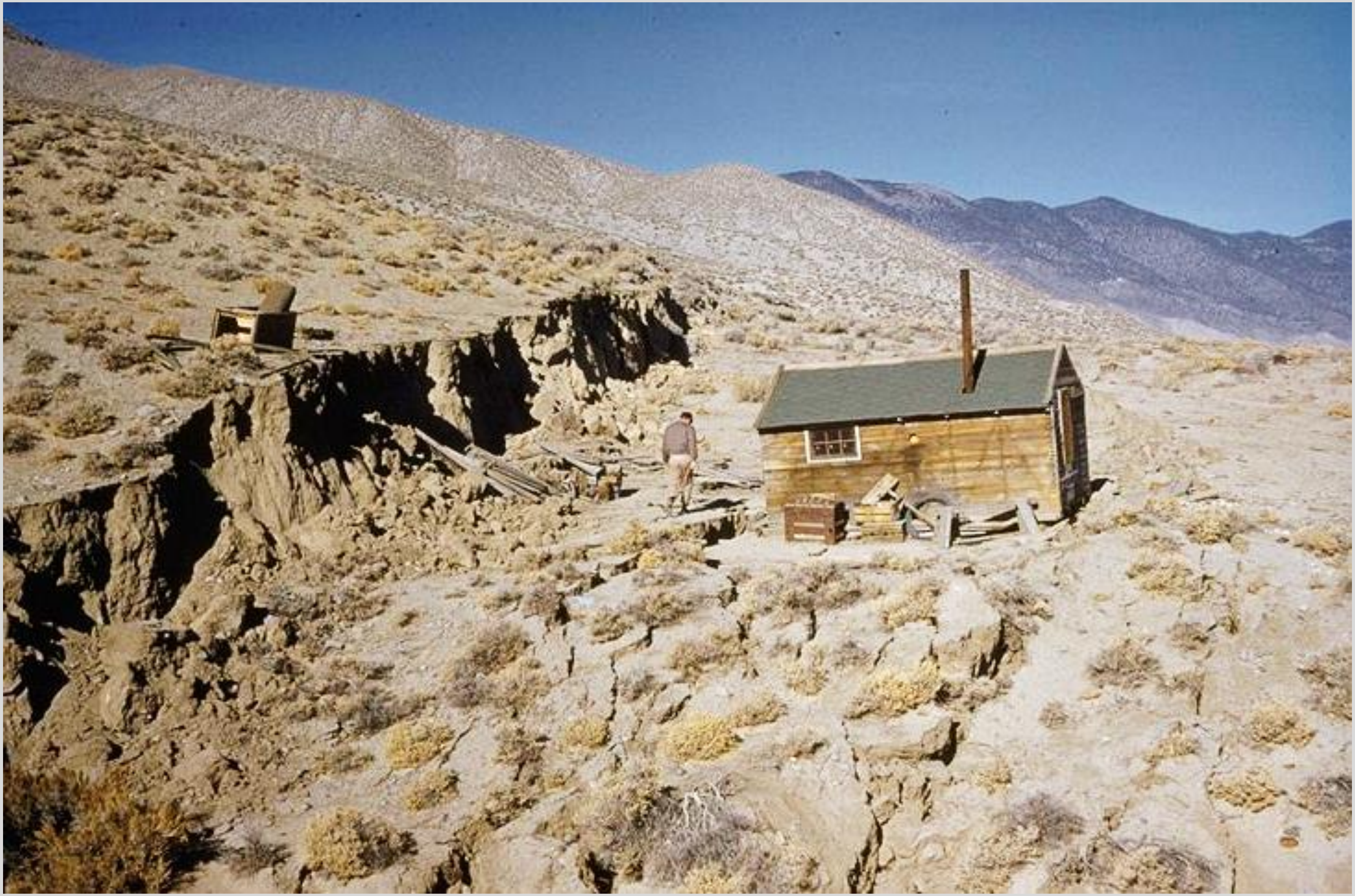
Falha direcional sinistral

Falhas: deslocamento de estruturas-guia

Falhas: deslocamento de estruturas-guia

http://www.tectonique.net/tectask/index.php?option=com_content&view=article&id=27:glacier-watch

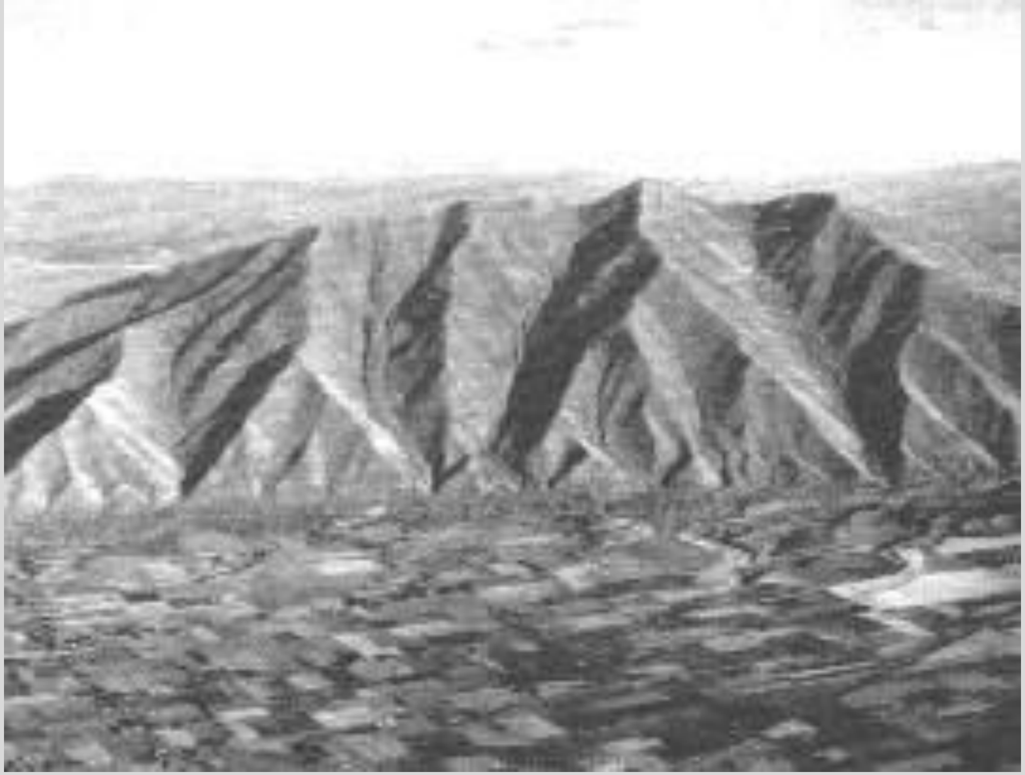
2) Efeitos na topografia



http://www.eerc.berkeley.edu/visual_resources/steinbrugge_collection.html

Falhas: efeitos na topografia

Wasatch range, Utah



http://www.slackpacker.com/faultedstructures.html

Falhas: efeitos na topografia

Falhas: efeitos na topografia

Falhas: identificação

3) Feições intrínsecas às falhas:

As falhas podem ser reconhecidas pelas microestruturas e estruturas desenvolvidas nas rochas como resultado de deformação intensa (cisalhamento simples, cisalhamento puro, achatamento, perda de volume).

Essas microestrutruas e estruturas dependem da taxa de deformação, das condições físicas em que a deformação ocorreu e das características dos protolitos e minerais envolvidos.

Zona de cisalhamento dúctil

http://www.tectonique.net/tectask/index.php?option=com_content&view=article&id=27:glacier-watch

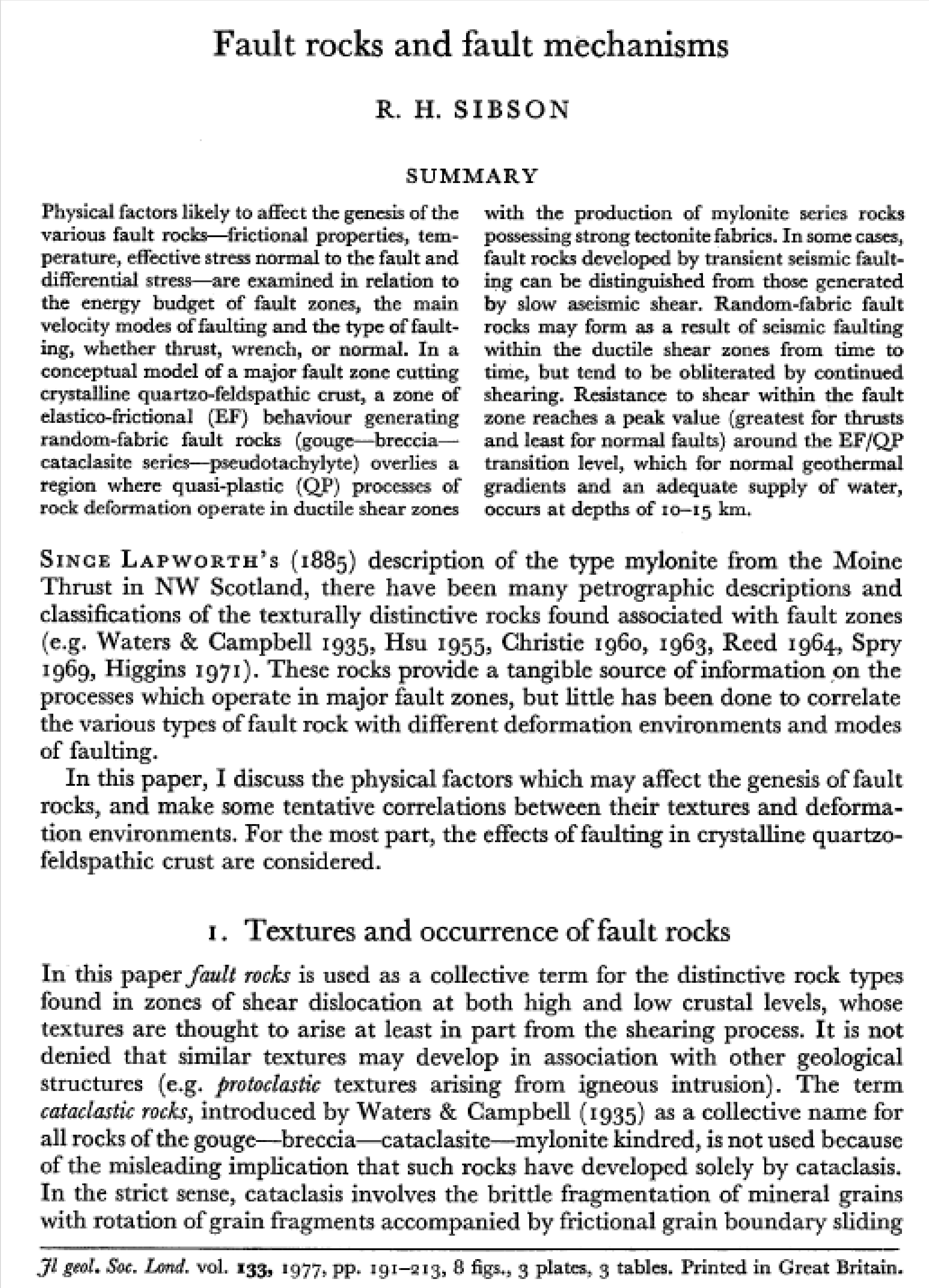
Cataclasitos e milonitos: rochas geradas em ambientes de alta tensão diferencial ($\sigma_1 - \sigma_3$), que promove intensa deformação (diagnósticos de falhas e zonas de cisalhamento).

Milonito (Lapworth, 1885) – do grego μύλος, *mylos*, moinho (= rocha moída).

Originalmente, acreditava-se que as rochas cataclásticas s.l. (milonitos) eram geradas predominantemente por cominuição mecânica, i.e. fragmentação de seus minerais constituintes nas zonas de falha.

Posteriormente, verificou-se que, na maioria dos casos, ocorria recristalização dinâmica.

(rochas cataclásticas s.l.; Waters & Campbell, 1935)



Fault rocks and fault mechanisms

R. H. SIBSON

SUMMARY

Physical factors likely to affect the genesis of the various fault rocks—frictional properties, temperature, effective stress normal to the fault and differential stress—are examined in relation to the energy budget of fault zones, the main velocity modes of faulting and the type of faulting, whether thrust, wrench, or normal. In a conceptual model of a major fault zone cutting crystalline quartzo-feldspathic crust, a zone of elastico-frictional (EF) behaviour generating random-fabric fault rocks (gouge—breccia—cataclasite series—pseudotachylyte) overlies a region where quasi-plastic (QP) processes of rock deformation operate in ductile shear zones with the production of mylonite series rocks possessing strong tectonite fabrics. In some cases, fault rocks developed by transient seismic faulting can be distinguished from those generated by slow aseismic shear. Random-fabric fault rocks may form as a result of seismic faulting within the ductile shear zones from time to time, but tend to be obliterated by continued shearing. Resistance to shear within the fault zone reaches a peak value (greatest for thrusts and least for normal faults) around the EF/QP transition level, which for normal geothermal gradients and an adequate supply of water, occurs at depths of 10–15 km.

SINCE LAPWORTH'S (1885) description of the type mylonite from the Moine Thrust in NW Scotland, there have been many petrographic descriptions and classifications of the texturally distinctive rocks found associated with fault zones (e.g. Waters & Campbell 1935, Hsu 1955, Christie 1960, 1963, Reed 1964, Spry 1969, Higgins 1971). These rocks provide a tangible source of information on the processes which operate in major fault zones, but little has been done to correlate the various types of fault rock with different deformation environments and modes of faulting.

In this paper, I discuss the physical factors which may affect the genesis of fault rocks, and make some tentative correlations between their textures and deformation environments. For the most part, the effects of faulting in crystalline quartzo-feldspathic crust are considered.

1. Textures and occurrence of fault rocks

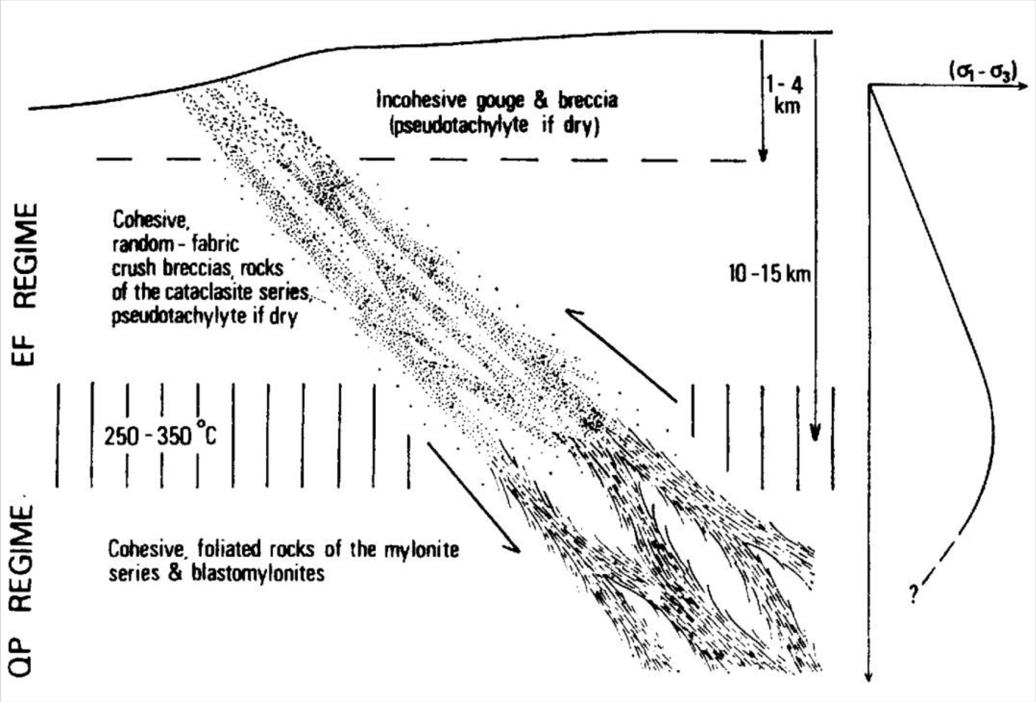
In this paper *fault rocks* is used as a collective term for the distinctive rock types found in zones of shear dislocation at both high and low crustal levels, whose textures are thought to arise at least in part from the shearing process. It is not denied that similar textures may develop in association with other geological structures (e.g. *protoclastic* textures arising from igneous intrusion). The term *cataclastic rocks*, introduced by Waters & Campbell (1935) as a collective name for all rocks of the gouge—breccia—cataclasite—mylonite kindred, is not used because of the misleading implication that such rocks have developed solely by cataclasis. In the strict sense, cataclasis involves the brittle fragmentation of mineral grains with rotation of grain fragments accompanied by frictional grain boundary sliding

Jl geol. Soc. Lond. vol. **133**, 1977, pp. 191–213, 8 figs., 3 plates, 3 tables. Printed in Great Britain.

Para tentar resolver o problema da gênese implícita no nome Sibson (1977), num trabalho considerado um clássico, propôs chamar o clã de rochas deformadas de *rochas de falha*.

Contudo, muitos autores consideram o termo falha restrito às zonas de cisalhamento rúptil e, assim, as ambiguidades genéticas continuam e não foram totalmente resolvidas até o momento.

Modelo conceitual de zonas de cisalhamento (Sibson, 1977)



Zona “elástico-friccional” – acima da transição para fácies xisto verde (~ 250-300 ^{o}C, $P_{lit} = P_{H2O}$) – minerais tem comportamento elástico, não são capazes de se deformar plasticamente e absorver as tensões: deformação “friccional” (rúptil, cataclase); são geradas brechas e cataclasitos;

Zona “quase-plástica” – a temperaturas maiores, os minerais (especialmente quartzo) se deformam plasticamente, dissipando as tensões; são gerados os milonitos.

Processos deformacionais em falhas e zonas de cisalhamento: condicionados por vários fatores

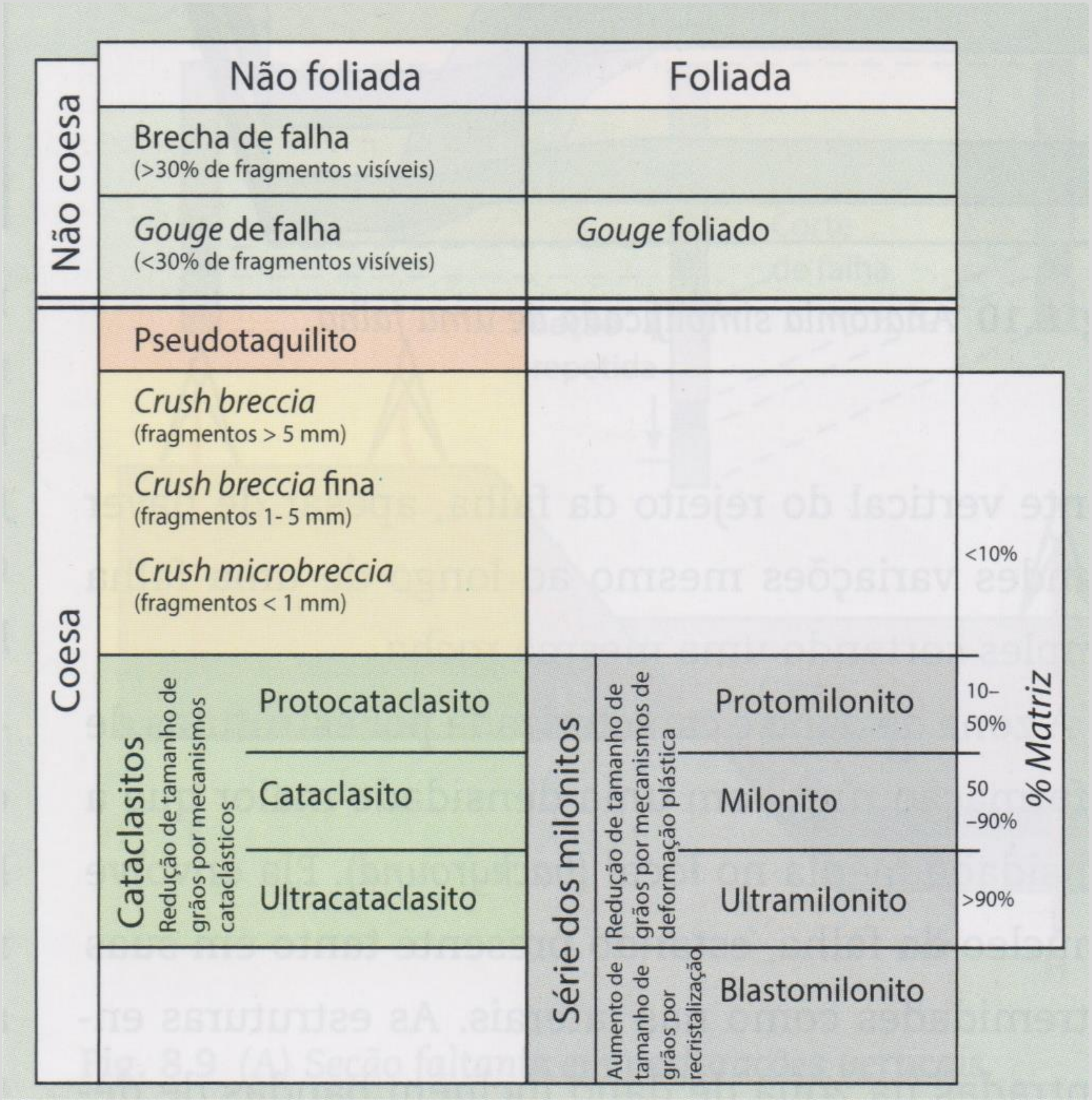
- Intrínsecos à rocha: composição mineralógica (litotipos), presença ou não e composição de fluido intergranular, granulação (absoluta, relativa), orientação dos minerais segundo retículo cristalino, porosidade e permeabilidade, texturas e estruturas pré-existentes;

- Externos: temperatura, gradiente geotérmico, pressão litostática, esforço diferencial, pressão de fluidos, taxa de deformação, orientação do campo de tensões.

Critérios para a classificação de rochas de falha segundo Sibson (1977):

- Coesão: se coesa ou não
- Estrutura: maciça x foliada
- Proporção matriz neoformada : porfiroclastos
- Presença de vidro = pseudotaquilito
- Crescimento de grãos intenso: blastomilonito

Classificação de Sibson (1977)



	Não foliada		Foliada		% Matriz
Não coesa	Brecha de falha (>30% de fragmentos visíveis)				
	Gouge de falha (<30% de fragmentos visíveis)		*Gouge* foliado		
Coesa	Pseudotaquilito				
	Crush breccia (fragmentos > 5 mm)				
	Crush breccia fina (fragmentos 1- 5 mm)				
	Crush microbreccia (fragmentos < 1 mm)				<10%
	Cataclasitos Redução de tamanho de grãos por mecanismos cataclásticos	Protocataclasito	Série dos milonitos Redução de tamanho de grãos por mecanismos de deformação plástica	Protomilonito	10–50%
		Cataclasito		Milonito	50 –90%
		Ultracataclasito		Ultramilonito	>90%
			Aumento de tamanho de grãos por recristalização	Blastomilonito	

Brecha de falha (>30% de fragmentos visíveis)

Farinha de falha (<30% de fragmentos visíveis)

Rochas friáveis (incoesas) formadas a profundidades entre 1 e 4 km.

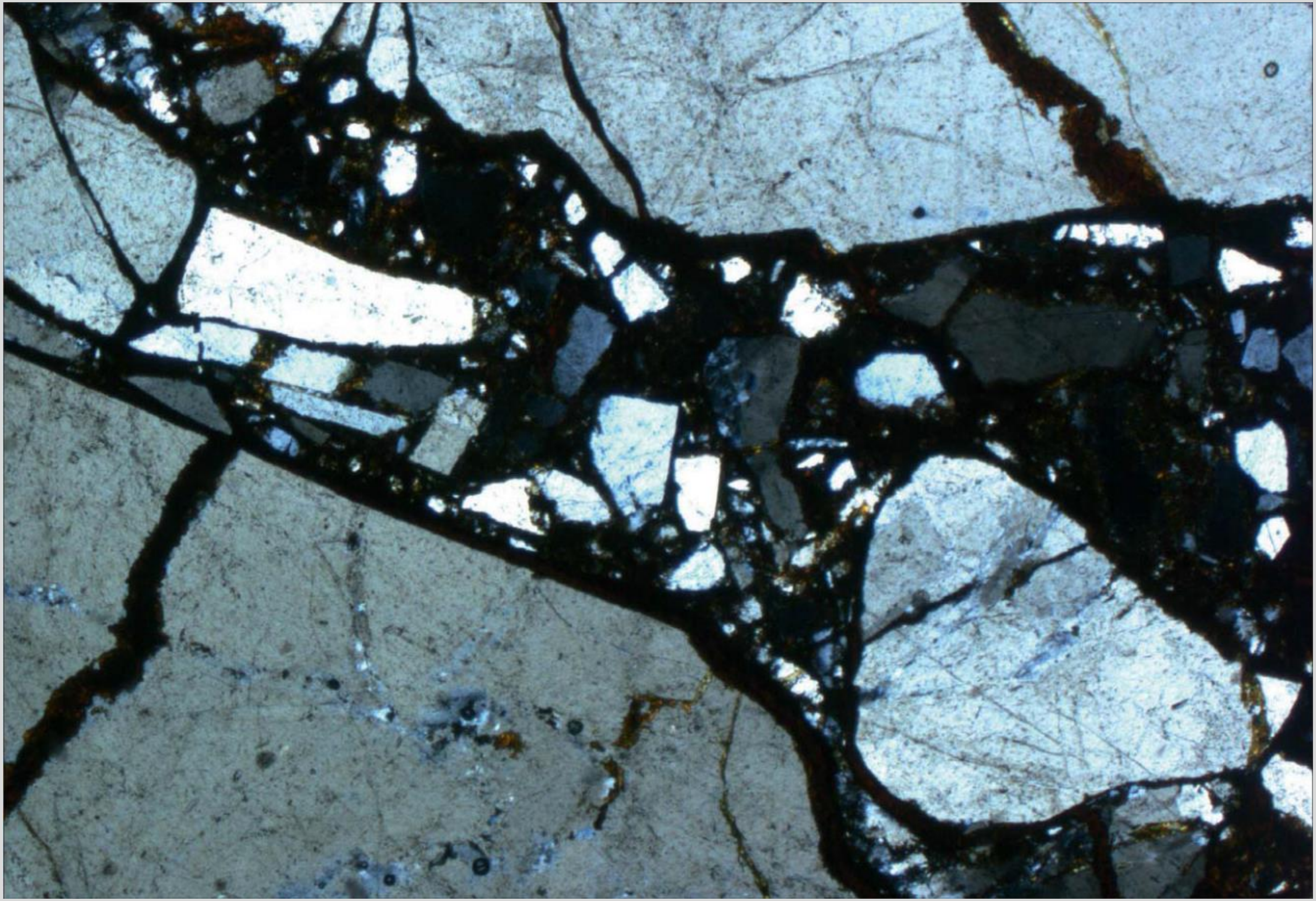
Efeitos de intemperismo dificultam sua identificação em campo.

Brecha de esmagamento:

rocha coesa com 0-10% de minerais neoformados (fragmentos > 5mm).

Microbrecha de esmagamento:

rocha coesa com 0-10% de minerais neoformados (fragmentos < 1mm).



Milonitos: tectonito “S-L”

Milonitos: tectonito “L”

Milonitos: tectonito "S"

Pseudotaquilito: 'fóssil' de atividade sísmica.

http://www.tectonique.net/tectask/index.php?option=com_content&view=article&id=27:glacier-watch

Pseudotaquilito: *preenchimento de falhas e veios*

Cráton São Francisco, Bahia

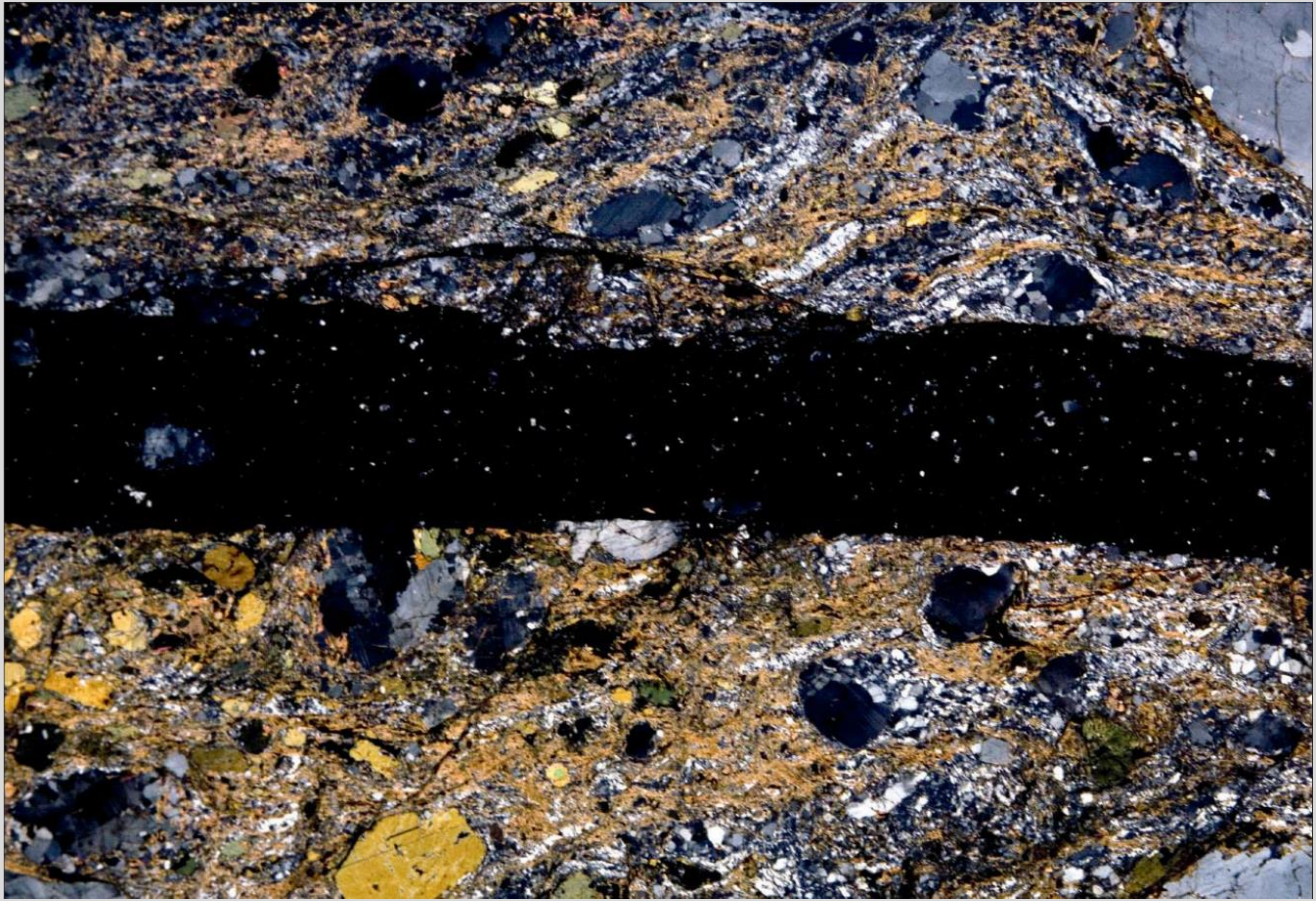
Pseudotaquilito: matriz de brecha de esmagamento

Cráton São Francisco, Bahia

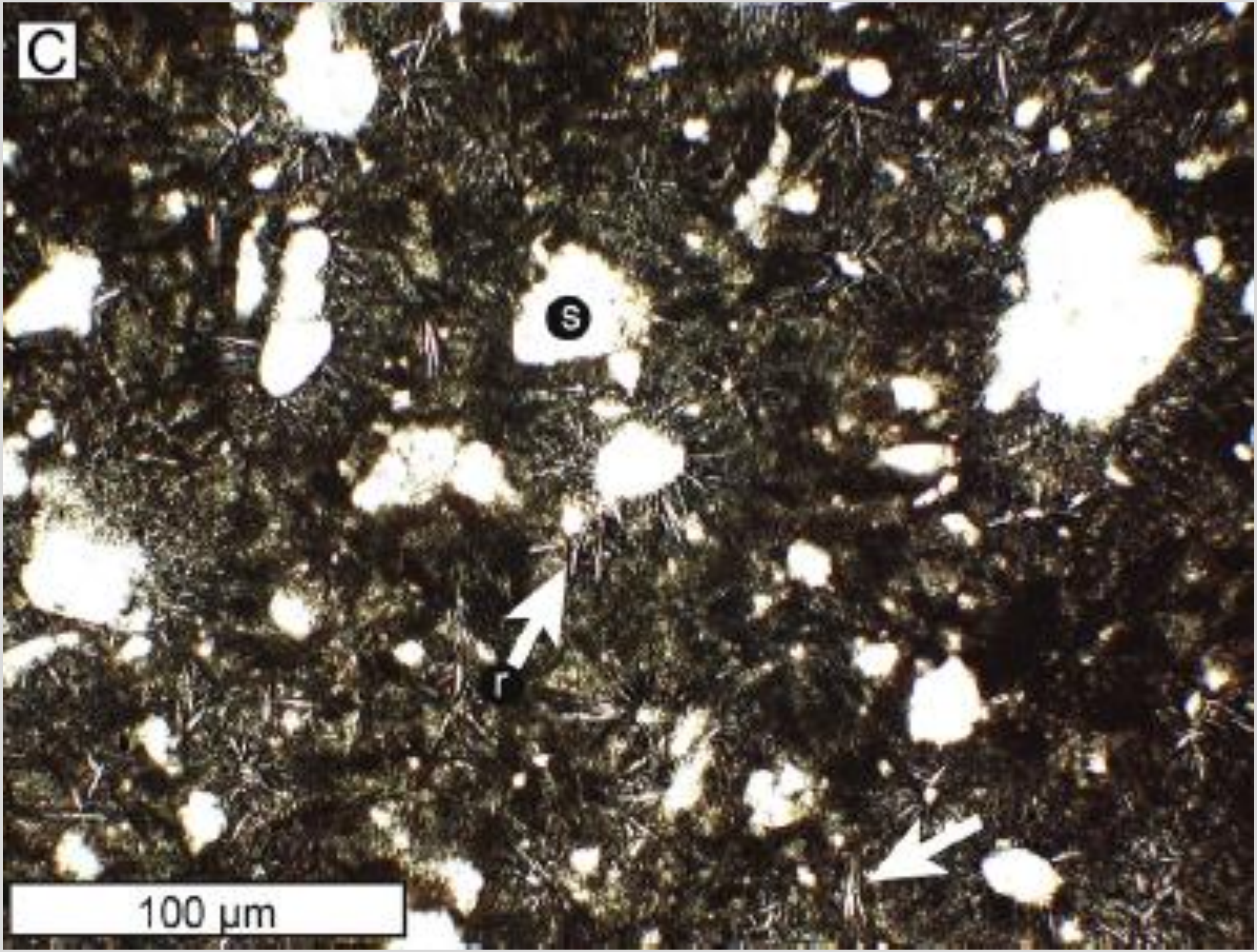
Pseudotaquilito: rede interconectada preenchendo veios, planos de falha e na matriz de brechas de esmagamento

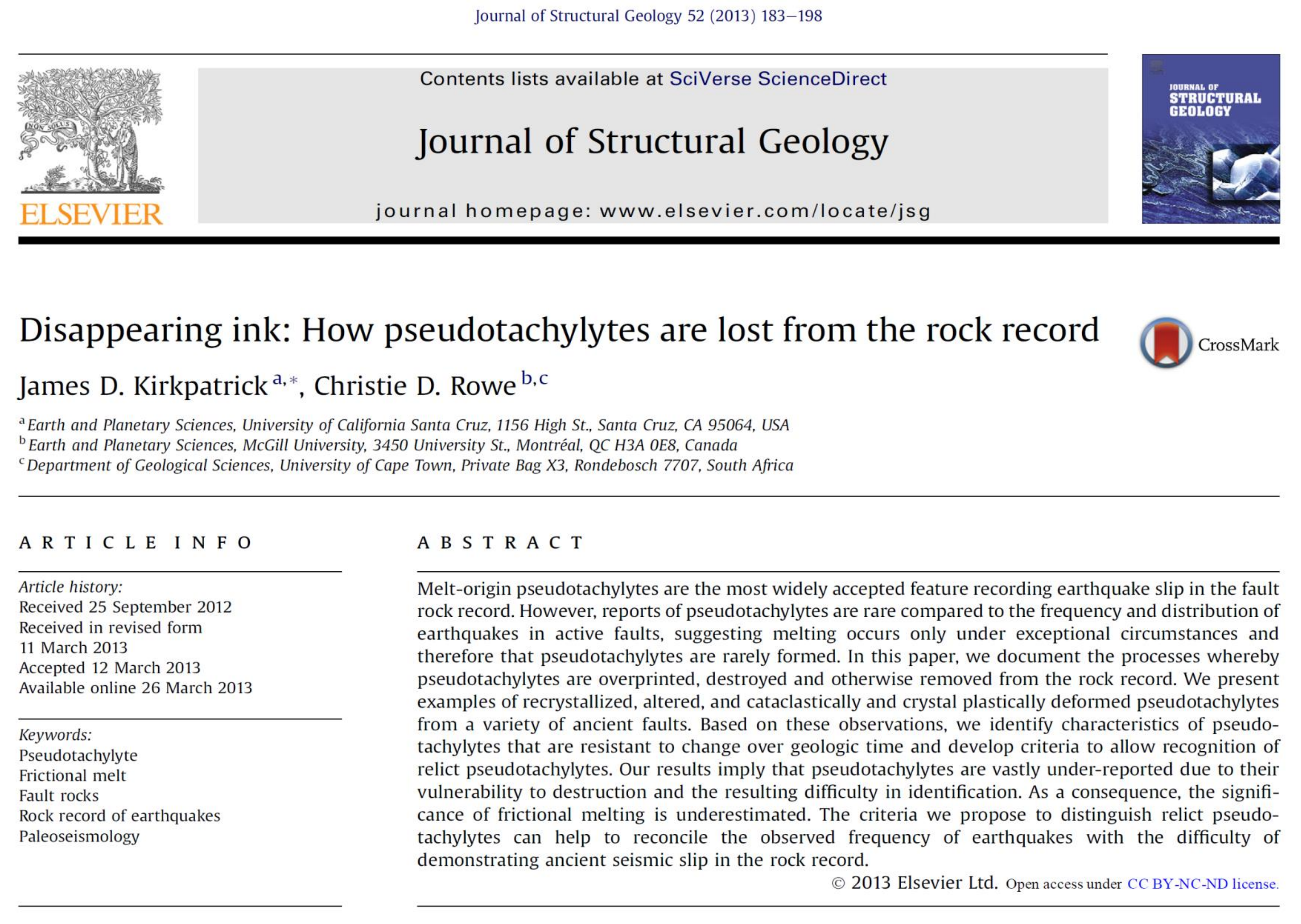
Cráton São Francisco, Bahia

Pseudotaquilito: escala microscópica



Pseudotaquilito: *escala microscópica*





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Disappearing ink: How pseudotachylytes are lost from the rock record

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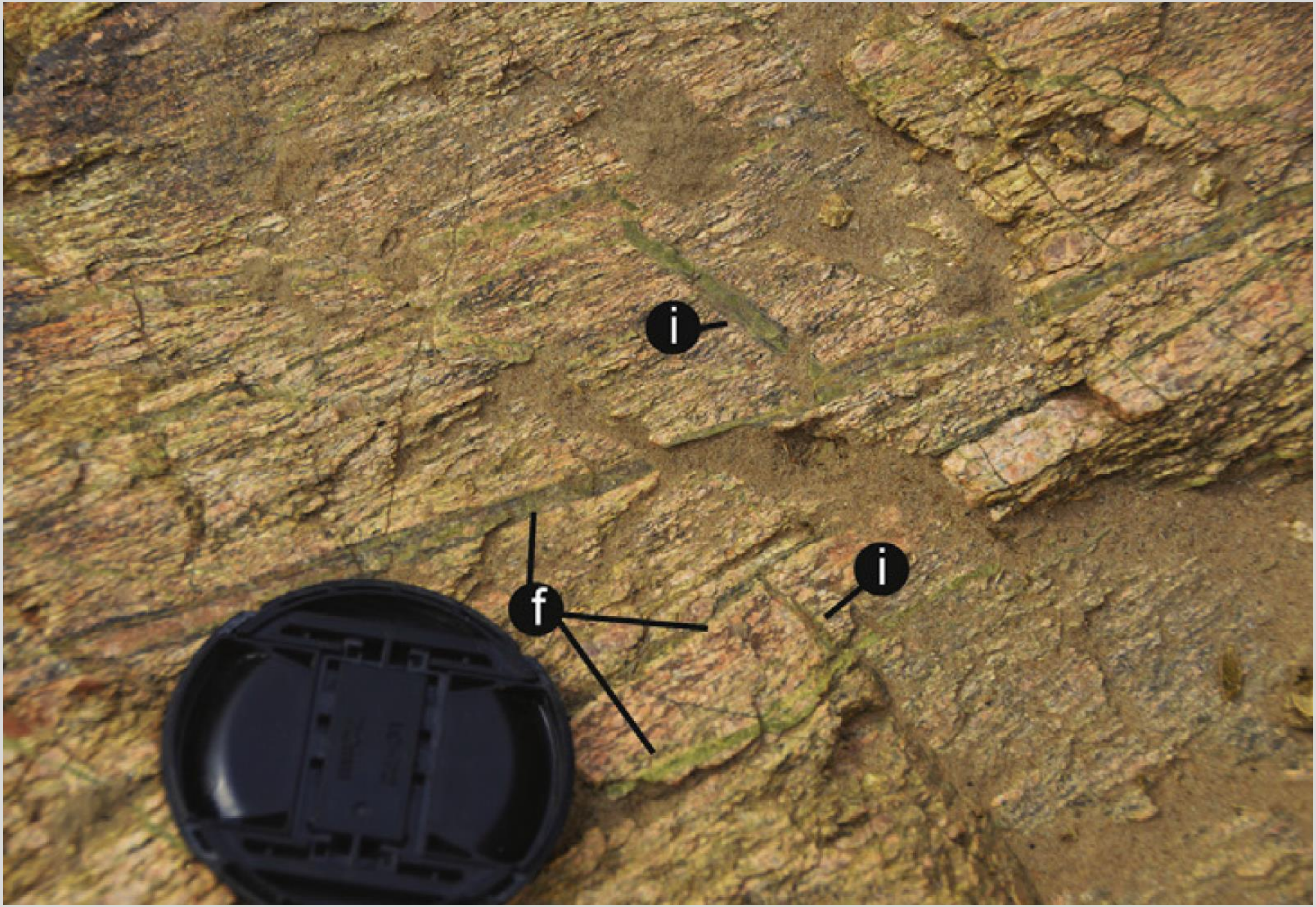
ABSTRACT

Melt-origin pseudotachylytes are the most widely accepted feature recording earthquake slip in the fault rock record. However, reports of pseudotachylytes are rare compared to the frequency and distribution of earthquakes in active faults, suggesting melting occurs only under exceptional circumstances and therefore that pseudotachylytes are rarely formed. In this paper, we document the processes whereby pseudotachylytes are overprinted, destroyed and otherwise removed from the rock record. We present examples of recrystallized, altered, and cataclastically and crystal plastically deformed pseudotachylytes from a variety of ancient faults. Based on these observations, we identify characteristics of pseudotachylytes that are resistant to change over geologic time and develop criteria to allow recognition of relict pseudotachylytes. Our results imply that pseudotachylytes are vastly under-reported due to their vulnerability to destruction and the resulting difficulty in identification. As a consequence, the significance of frictional melting is underestimated. The criteria we propose to distinguish relict pseudotachylytes can help to reconcile the observed frequency of earthquakes with the difficulty of demonstrating ancient seismic slip in the rock record.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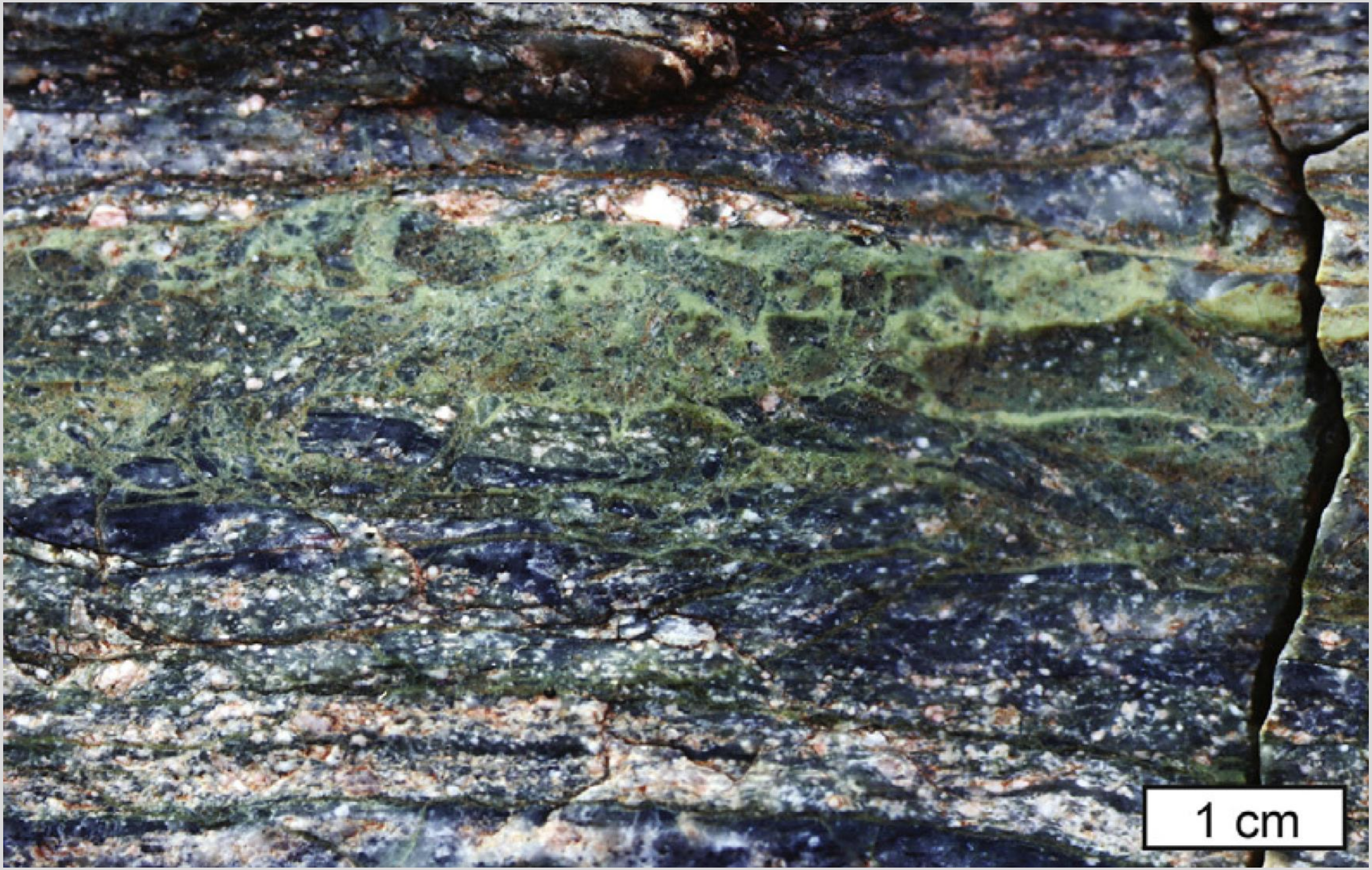
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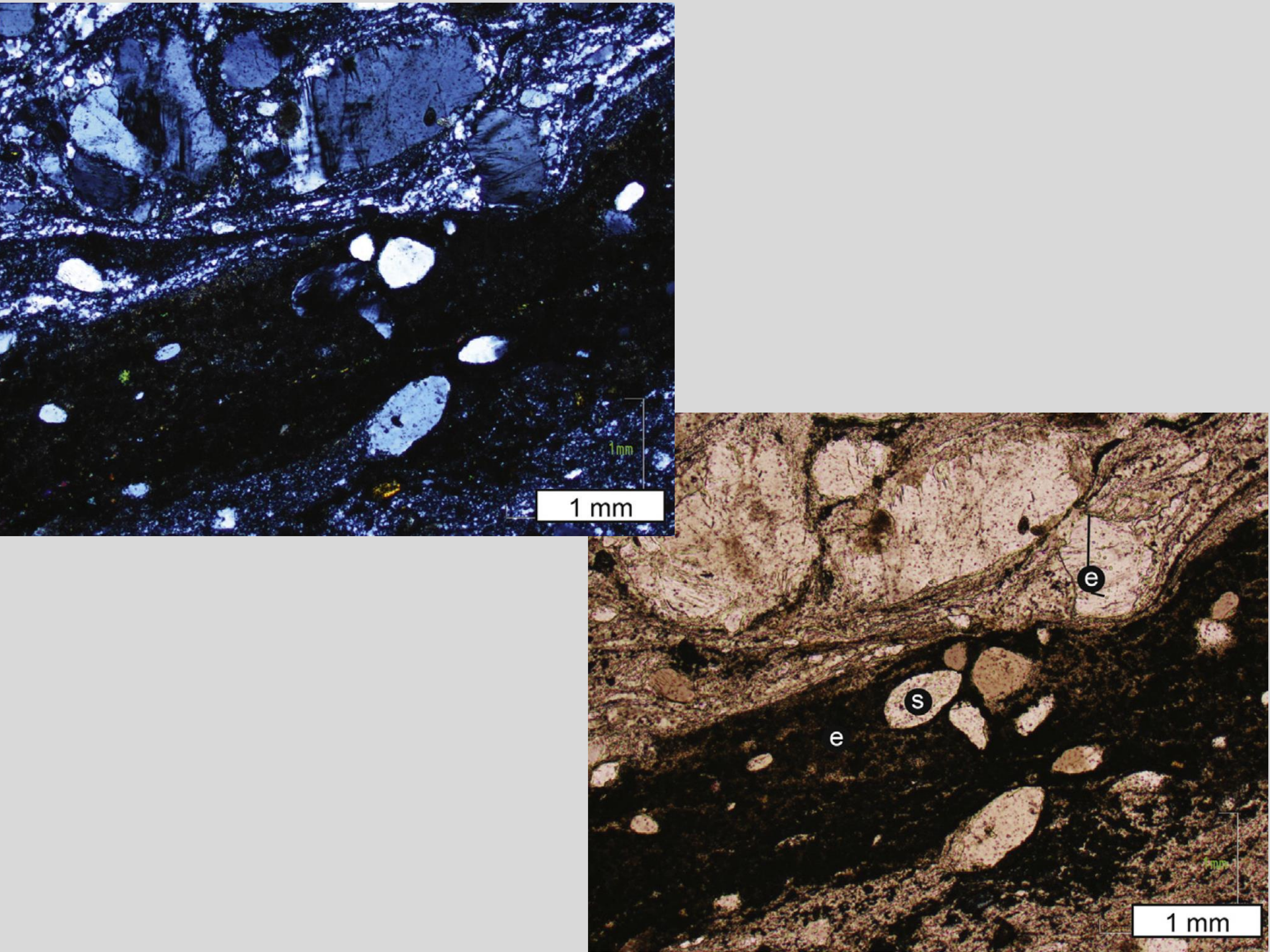
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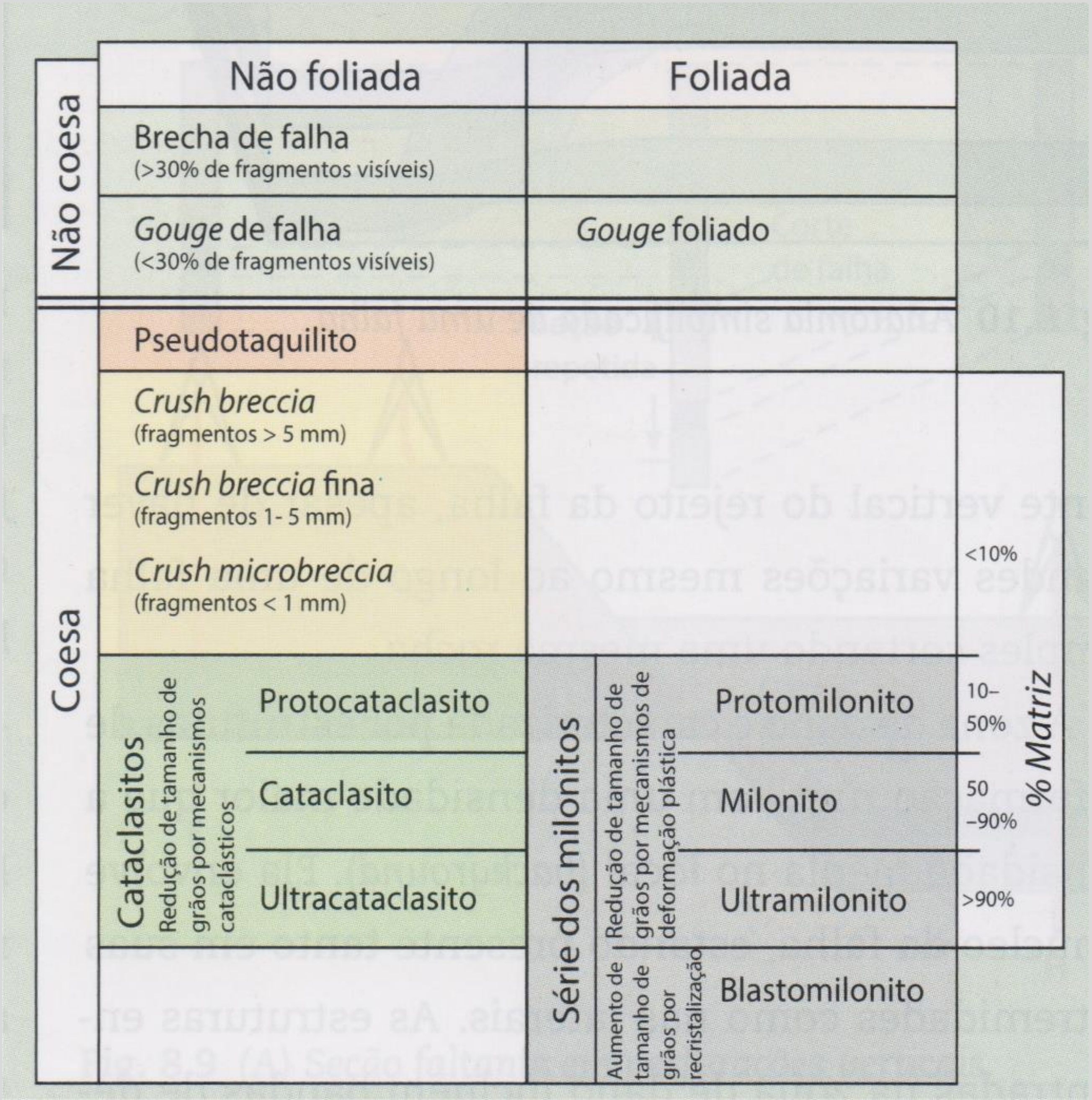
Classificação de Sibson (1977)



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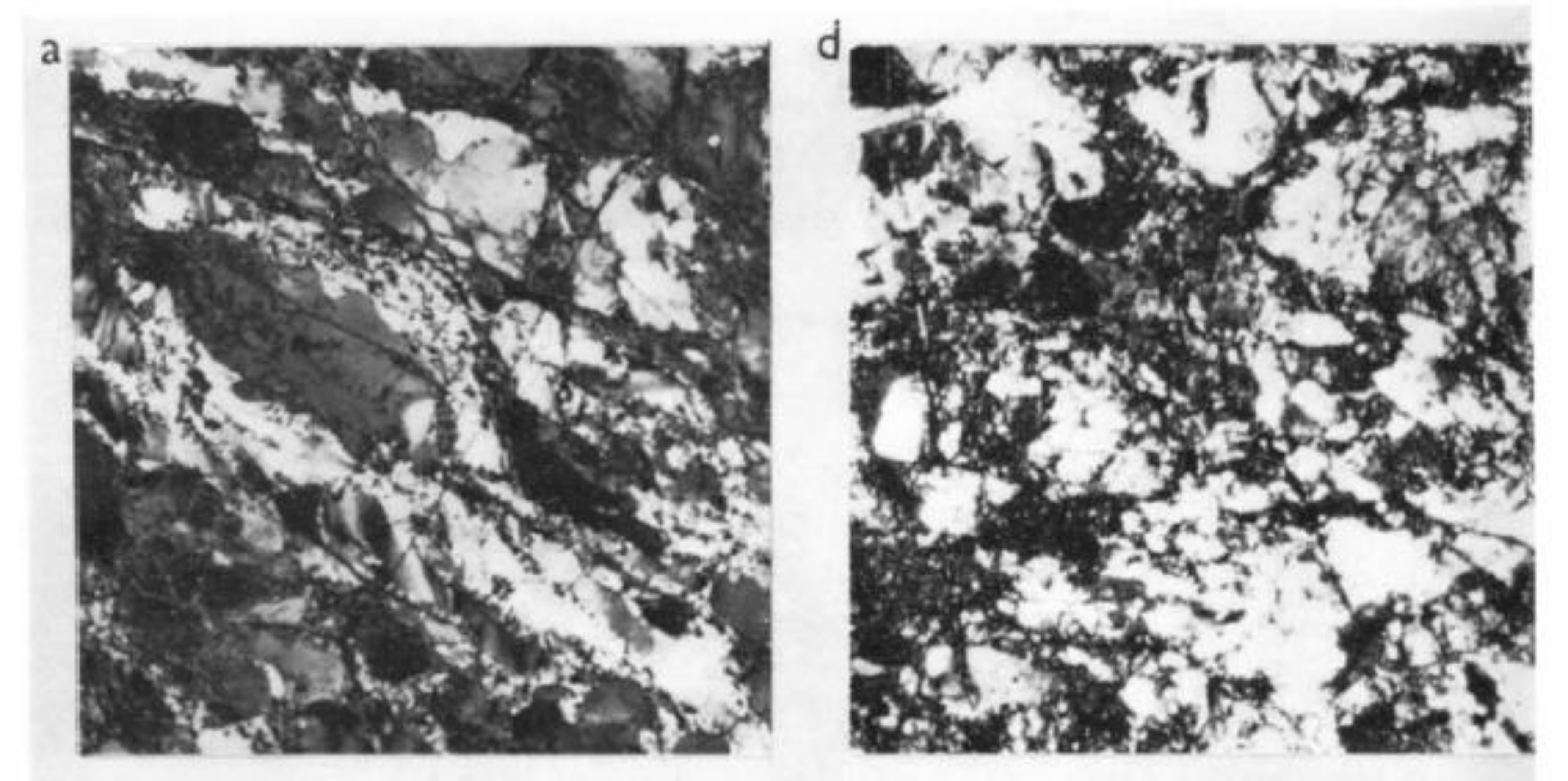
		Ultracataclasito		Ultramilonito	>90%
			Aumento de tamanho de grãos por recristalização	Blastomilonito	

Protomilonito e protocataclasito (Sibson 1977)

10-50% de minerais neoformados

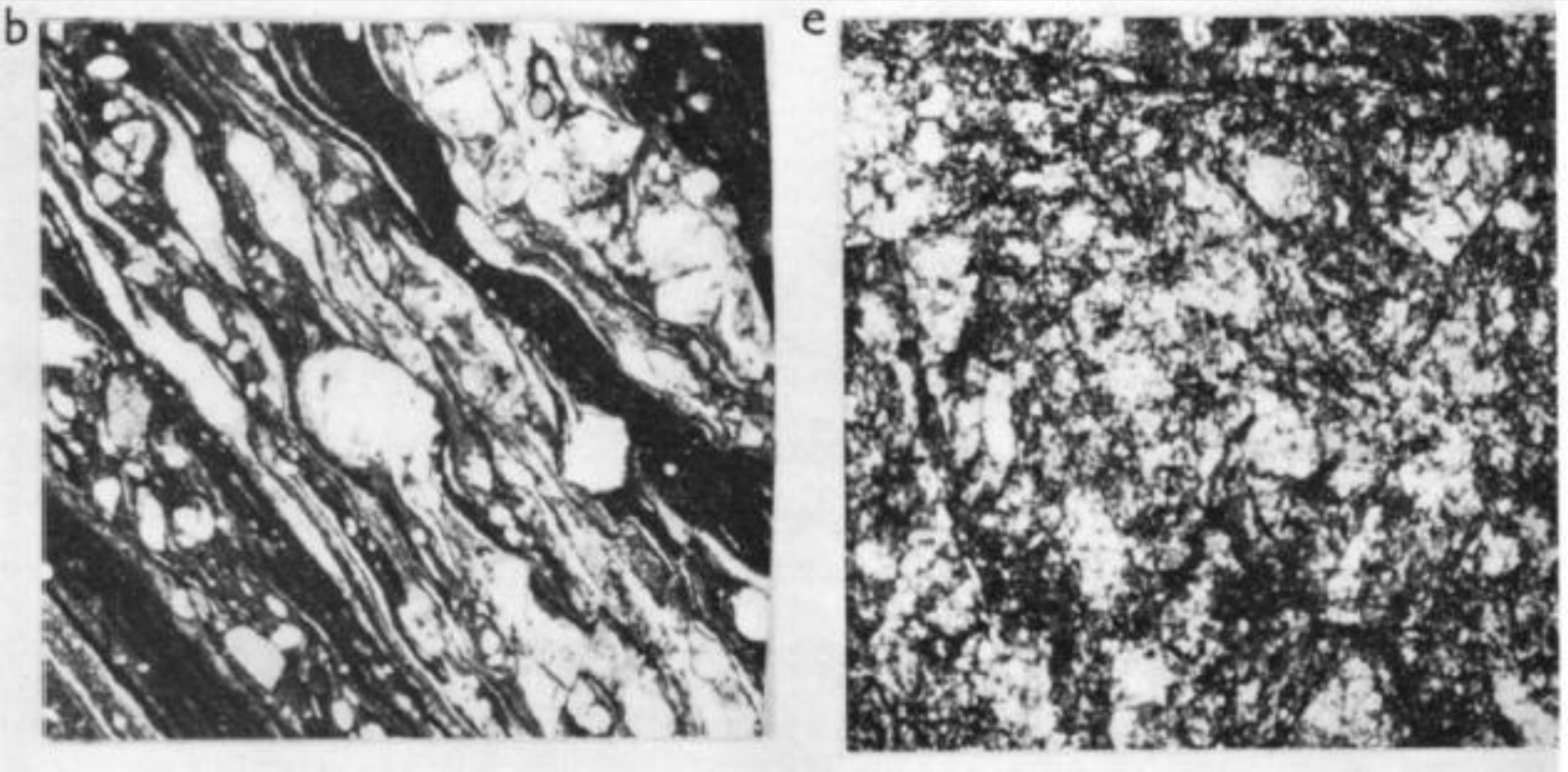


Protomilonito: rocha foliada

Protocataclasito: rocha maciça

Milonito e cataclasito (Sibson 1977)

50-90% de minerais neoformados

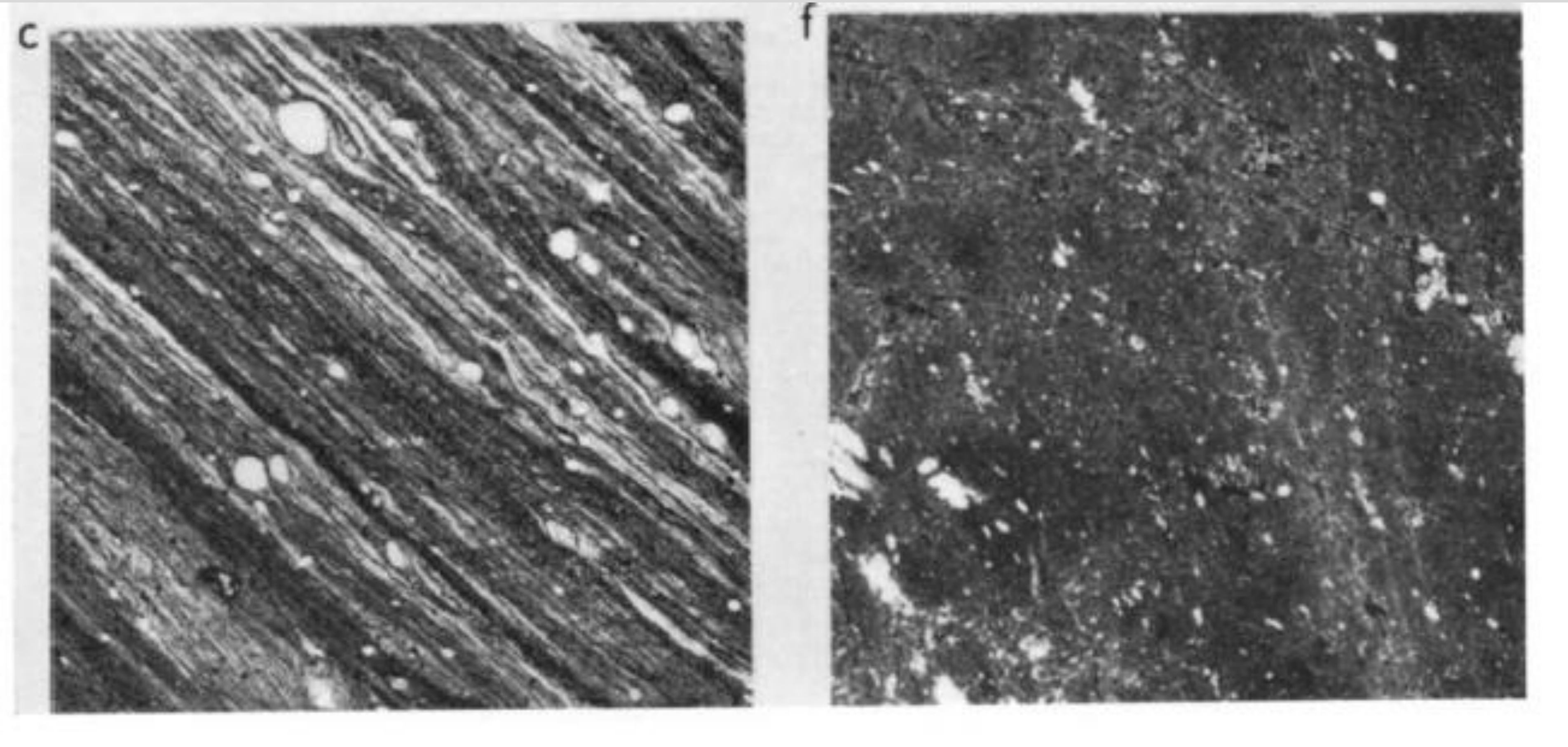


Milonito: rocha foliada

Cataclasito: rocha maciça

Ultramilonito e ultracataclasito (Sibson 1977)

>90% de minerais neoformados



Ultramilonito: rocha foliada

Ultracataclasito: rocha maciça

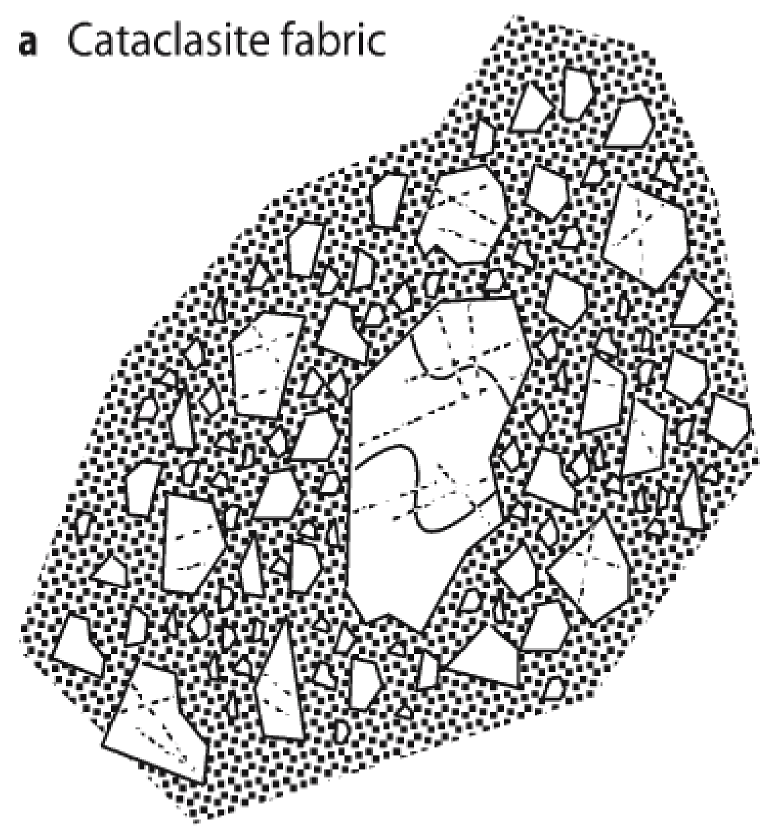
Filonito derivado de gnaisse: intensa transformação dos feldspatos em agregados ricos em sericita e epidoto

Rochas Cataclásticas:

Ocorrem em zonas que variam de poucos milímetros a quilômetros de espessura.

Em geral:

Quanto maior a espessura da zona de cataclasitos e menor a granulação da rocha, maior a quantidade de deslocamento acumulado na zona de falha.



Rochas Cataclásticas:

Rochas coesas: formadas a profundidades entre 4-10 km.

Distribuição de tamanho, forma e arranjo dos clastos apresenta geometria fractal.

Características de cataclasitos:

- -fragmentos angulosos;
- -dimensões dos clastos variadas;
- -fragmentos líticos, grãos minerais seccionados;
- -estrutura predominantemente maciça;
- -cimentação aumenta coesão: silicificação, carbonatação, epidotização, cloritização, etc.

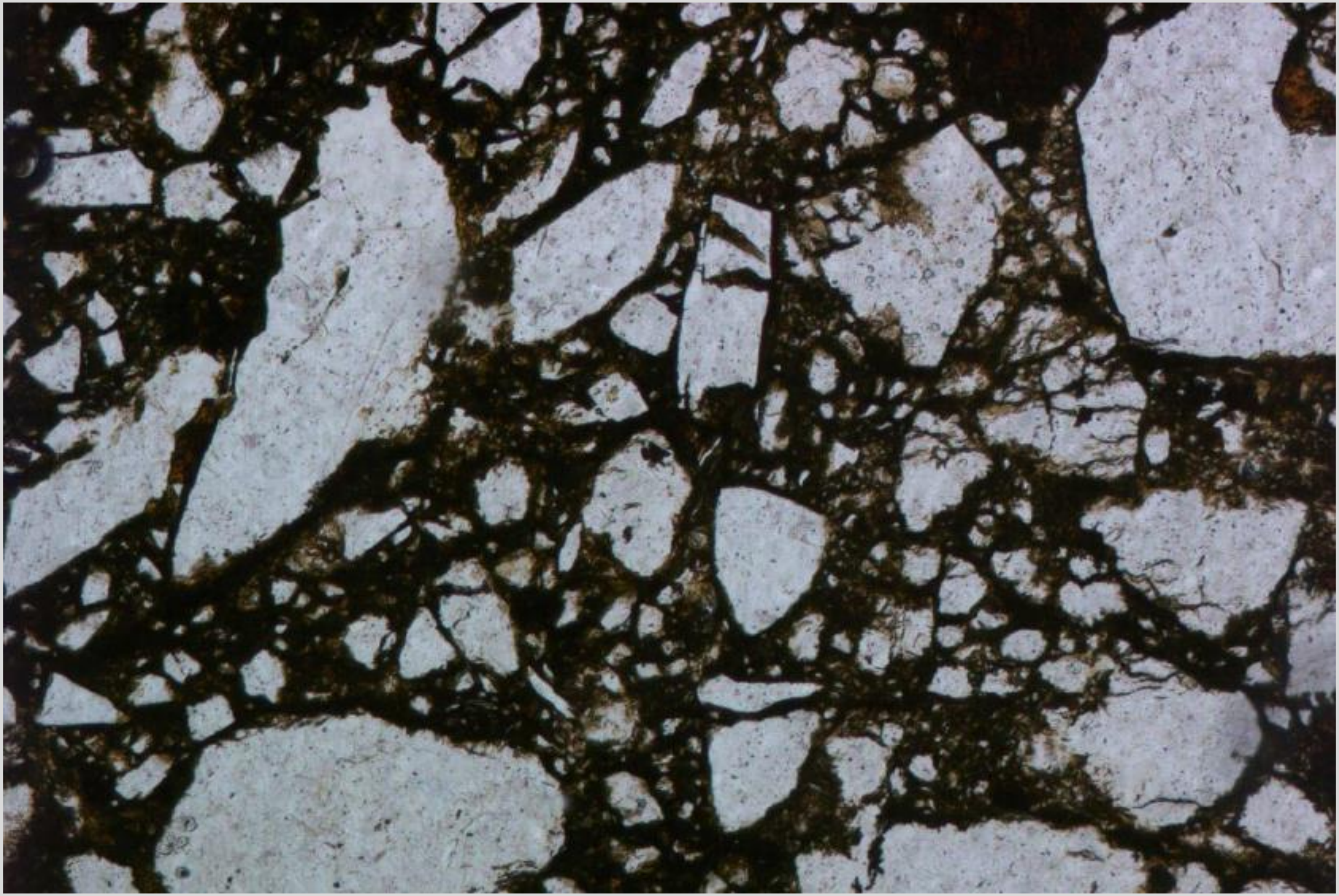
Geometria autossimilar: afloramento observado à distância

Brecha de esmagamento (rocha coesa, fragmentos > 5 mm) com matriz de cataclasito.

Geometria autossimilar: afloramento observado de perto

Brecha de esmagamento (rocha coesa, fragmentos > 5 mm) com matriz de cataclasito.

Geometria autossimilar:
Escala microscópica



Microbrecha de esmagamento (rocha coesa, fragmentos < 1 mm)

Processos de formação de rochas cataclásticas:

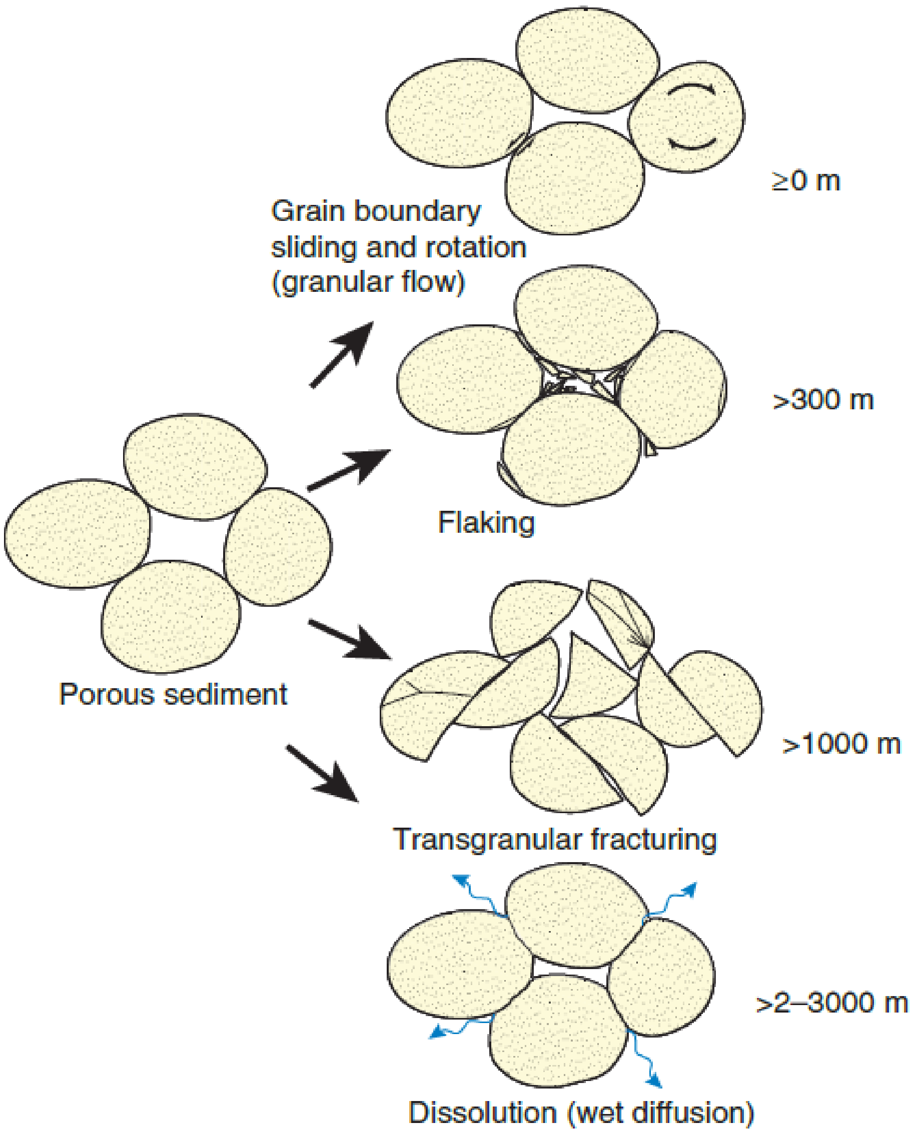
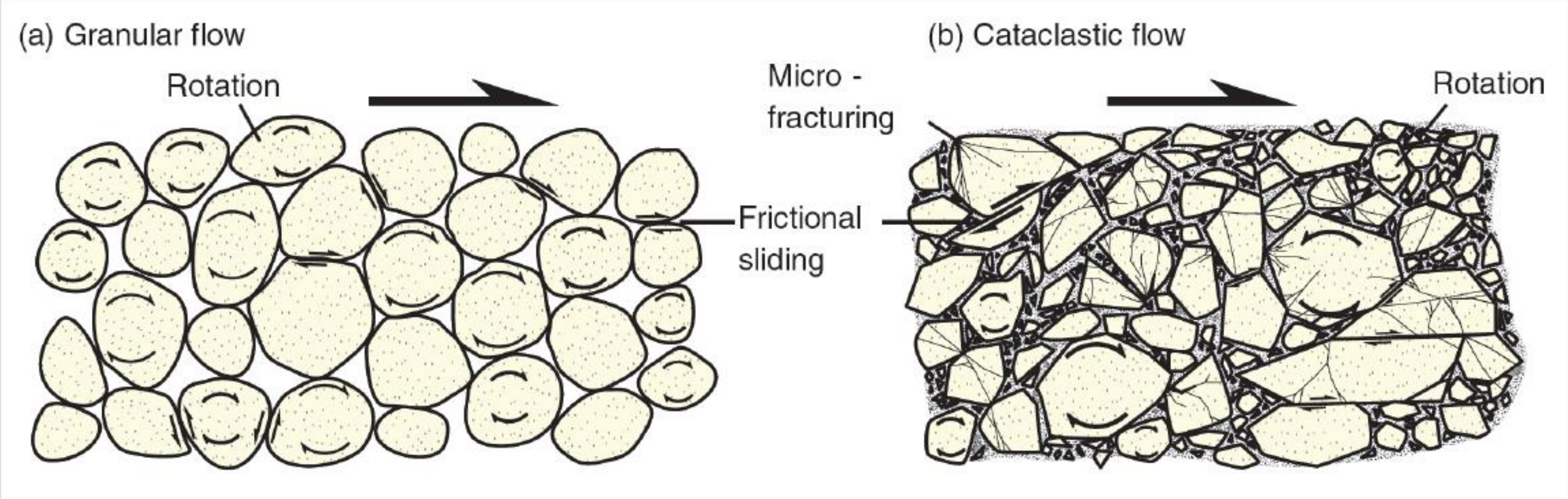


Figure 10.1 Deformation mechanisms operative at shallow depths. Very approximate depths are indicated.

Decréscimo de porosidade

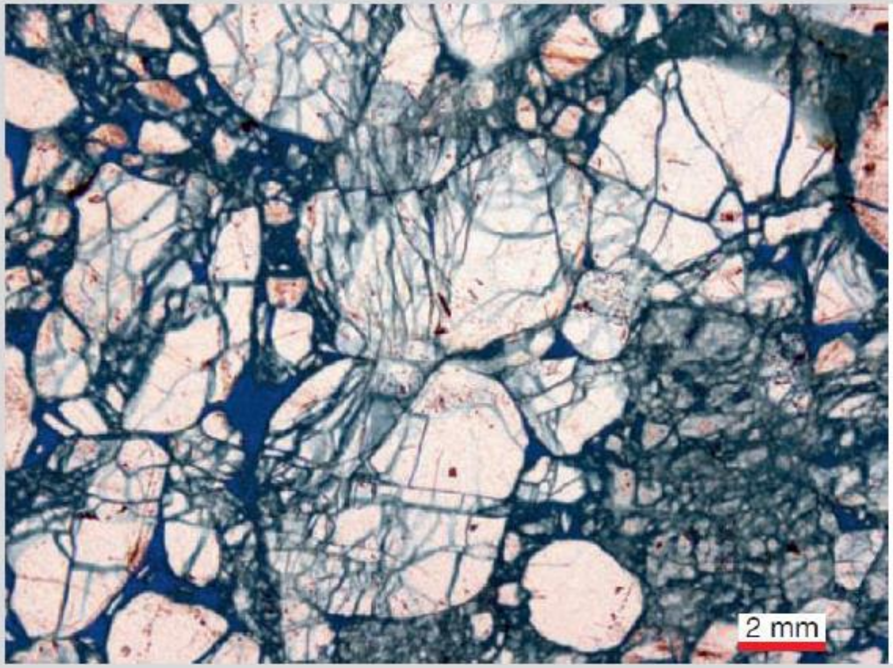
predomina fragmentação mecânica em temperaturas baixas (condições sub-xisto verde) e deformação predominantemente rúptil, em regiões rasas da crosta.



Rochas porosas

Rochas não porosas (coesas)

Brecha fina de esmagamento



Cataclasito

Rochas Miloníticas:

Formadas a profundidades maiores que 10-15 km (condições de metamorfismo ativo – fácies xisto-verde em diante).

São produtos de deformação dúctil, que ocorre na crosta em condições de temperatura superiores a 250-350°C.

Rochas miloníticas são tipicamente formadas por porfiroclastos em uma matriz muito fina derivada de redução da granulação por processos de recristalização.

Em milonitos: predomina deformação dúctil (aproximada pelo comportamento do quartzo).

Processos deformacionais:

- "*Pressure solution*" – dissolução das partes dos grãos expostas a pressão maior e reprecipitação do material dissolvido em zonas de pressão atenuada;

- Deformação intracristalina – controlada pela movimentação dos defeitos cristalinos (vacâncias, defeitos lineares e planares: deslocamento em cunha, helicoidais, etc);

- Geminação deformacional (carbonatos, plagioclásio, microclínio, etc) – importância menor.

- Geminação deformacional (carbonatos, plagioclásio, microclínio, etc) – importância menor.

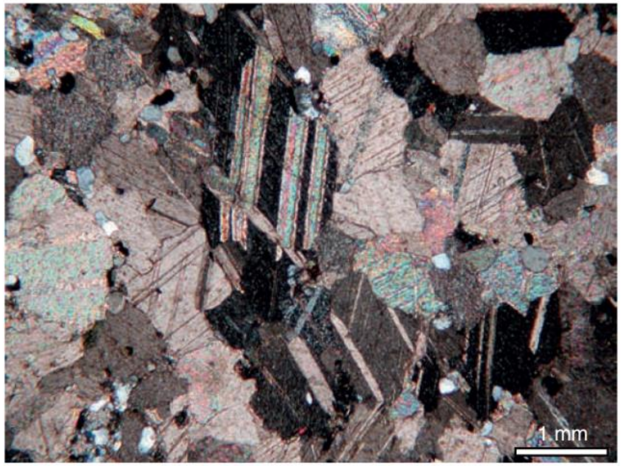


Figure 10.2 Deformation twins in an aggregate of calcite crystals.

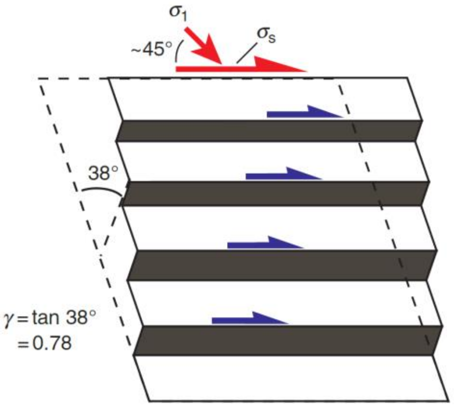
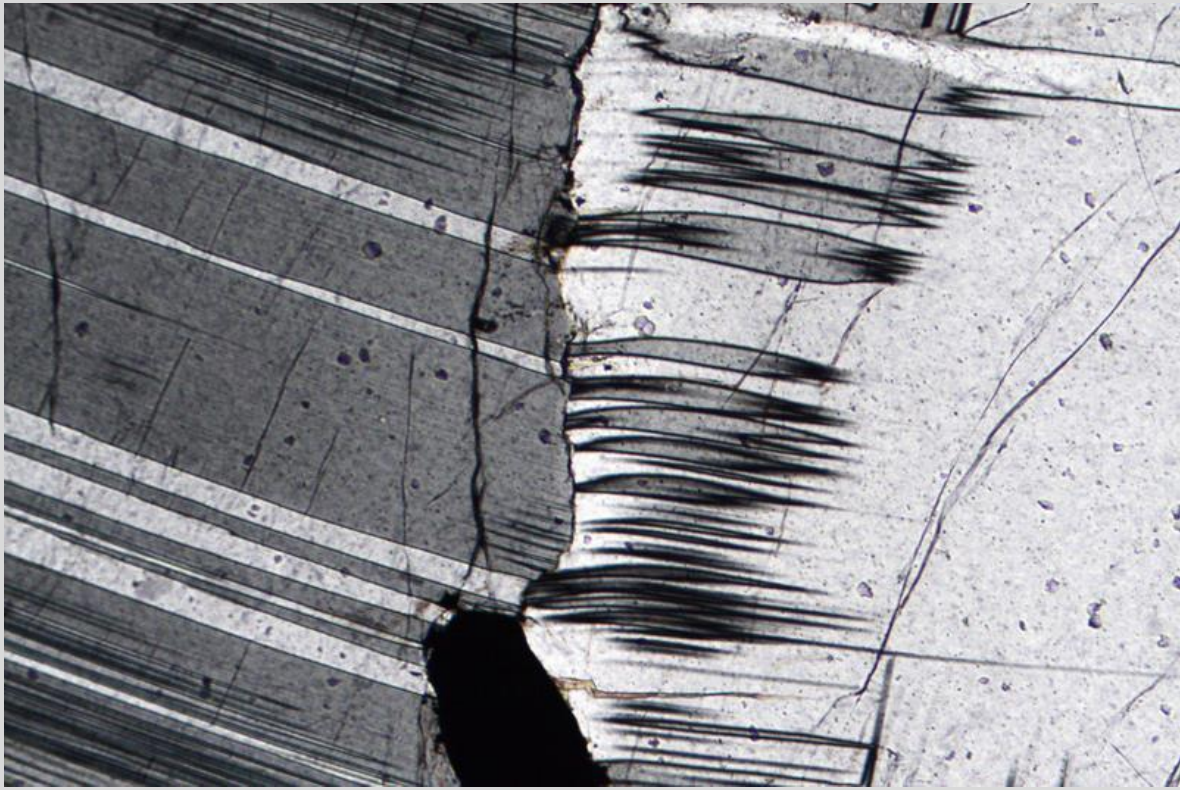


Figure 10.3 Deformation (glide) twins in a calcite crystal. Stress is ideally at 45° to the shear (glide) plane. Dark lamellae have been sheared (simple shear).



Deformação Intracristalina

Defeitos do retículo cristalino: pontuais – vacâncias iônicas, íons intersticiais

Transferência de massa por difusão

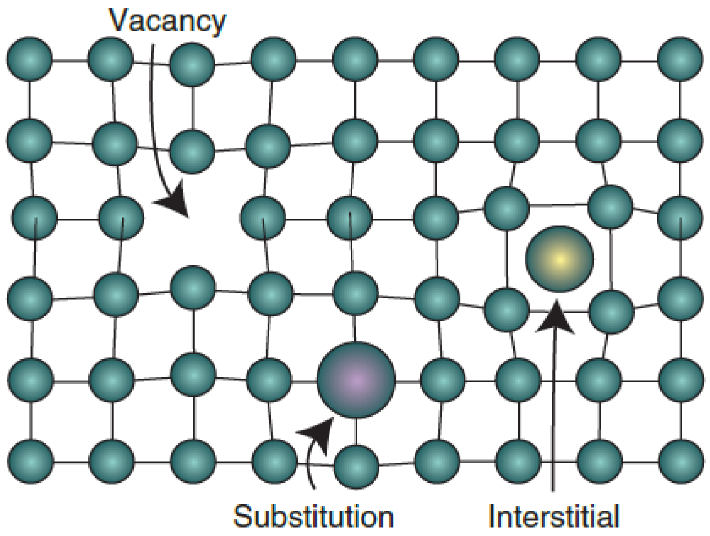


Figure 10.5 Point defects in a crystal lattice include vacancies (holes), substitutional impurities, and interstitial impurities. Vacancies represent the most important point defect in crystal-plastic flow.

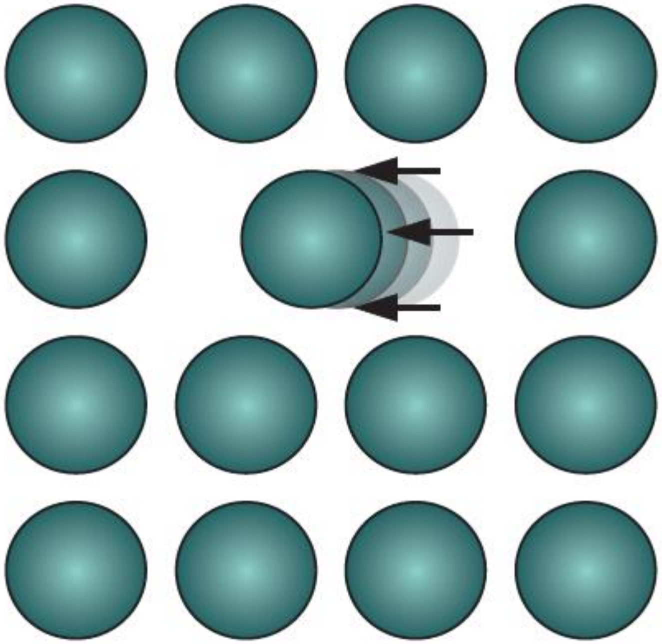
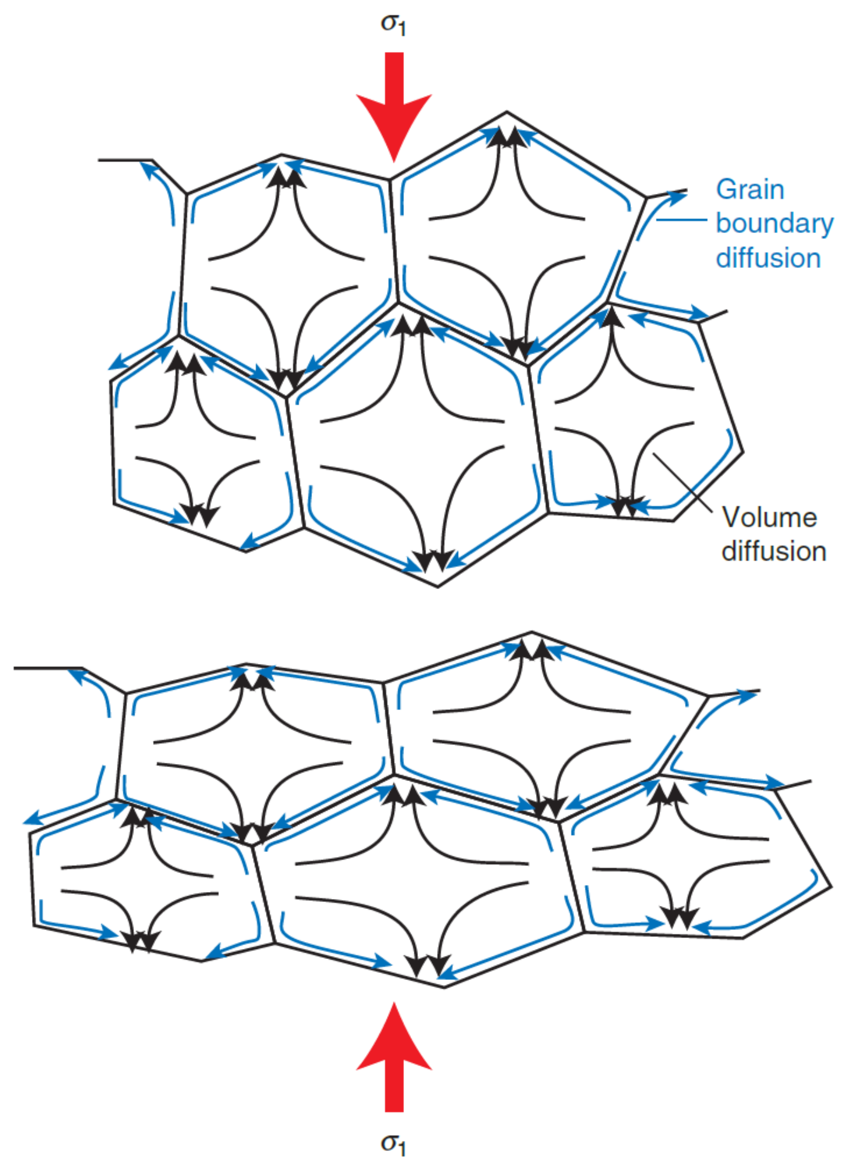


Figure 10.6 Migration of vacancies through an atomic lattice is called diffusion. A hole moves as it is replaced by a neighboring atom.

Diffusion creep – favorecido em temperaturas muito altas

Fossen (2010). Structural Geology



Migração das vacâncias em retículos cristalinos: difusão por fluência

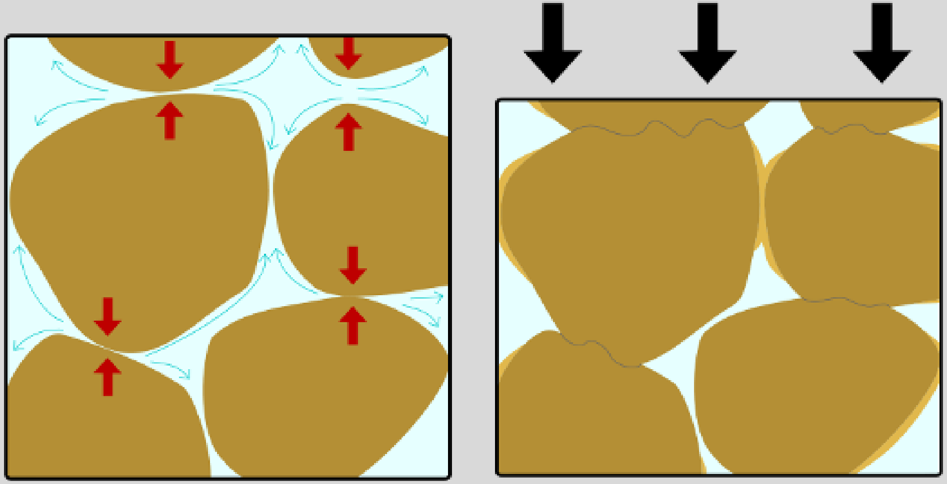
Difusão dentro dos grãos (difusão em volume)

Difusão ao longo dos limites de grãos

Em ambos os casos as vacâncias se movem em direção aos locais de maior esforço fazendo com que os grãos acumulem deformação (mudança de forma, desenvolvimento de foliação).

Fossen (2010). Structural Geology

“*Pressure solution*” – dissolução por pressão (= difusão por via úmida) : esquema e imagem de catodoluminescência

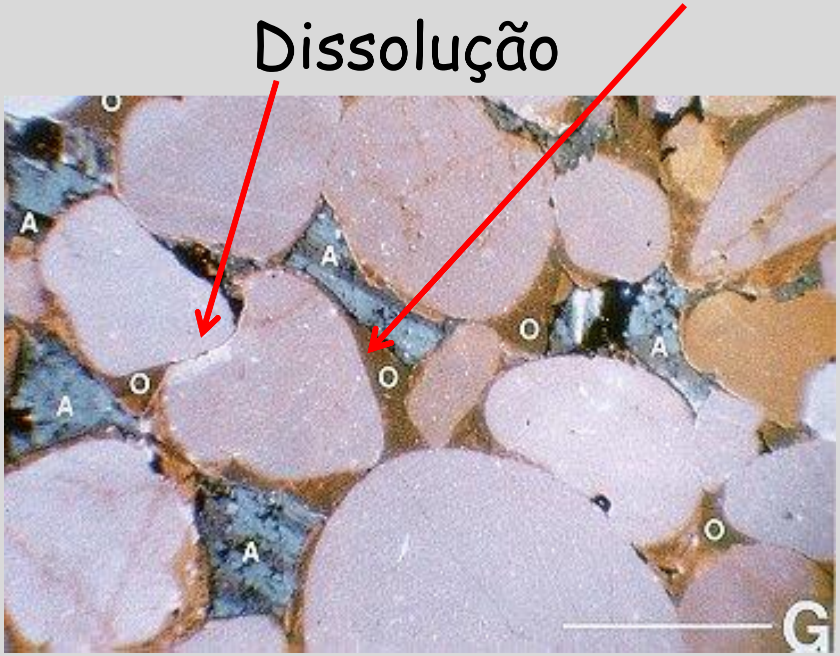


“*Pressure solution*”

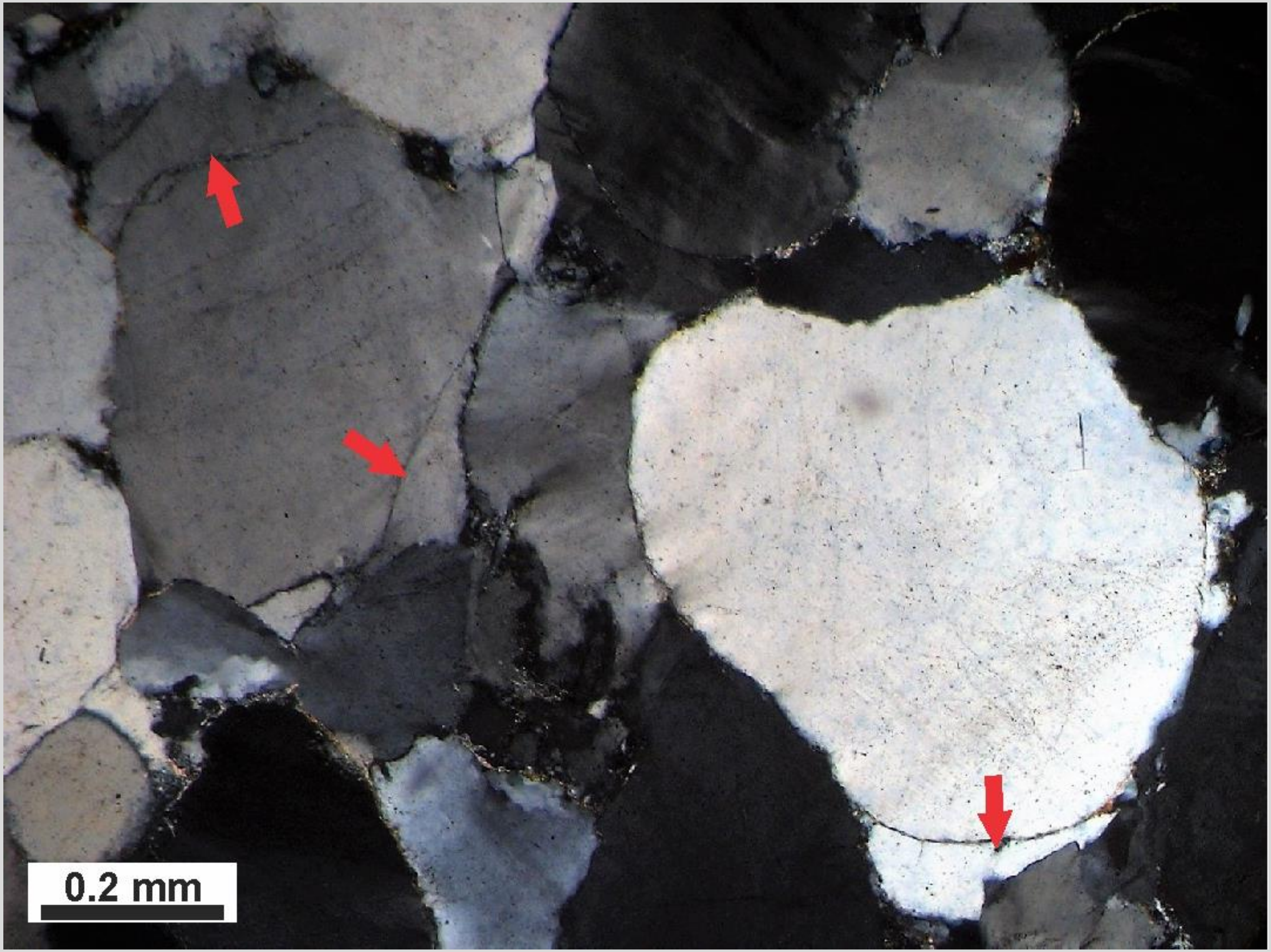
dissolução das partes dos grãos expostas a pressão maior e reprecipitação do material dissolvido em zonas de pressão atenuada.

Re-precipitação

Dissolução



"*Pressure solution*" – dissolução por pressão (= difusão por via úmida) : fotomicrografia



Deformação Intracristalina

Defeitos do retículo cristalino: lineares

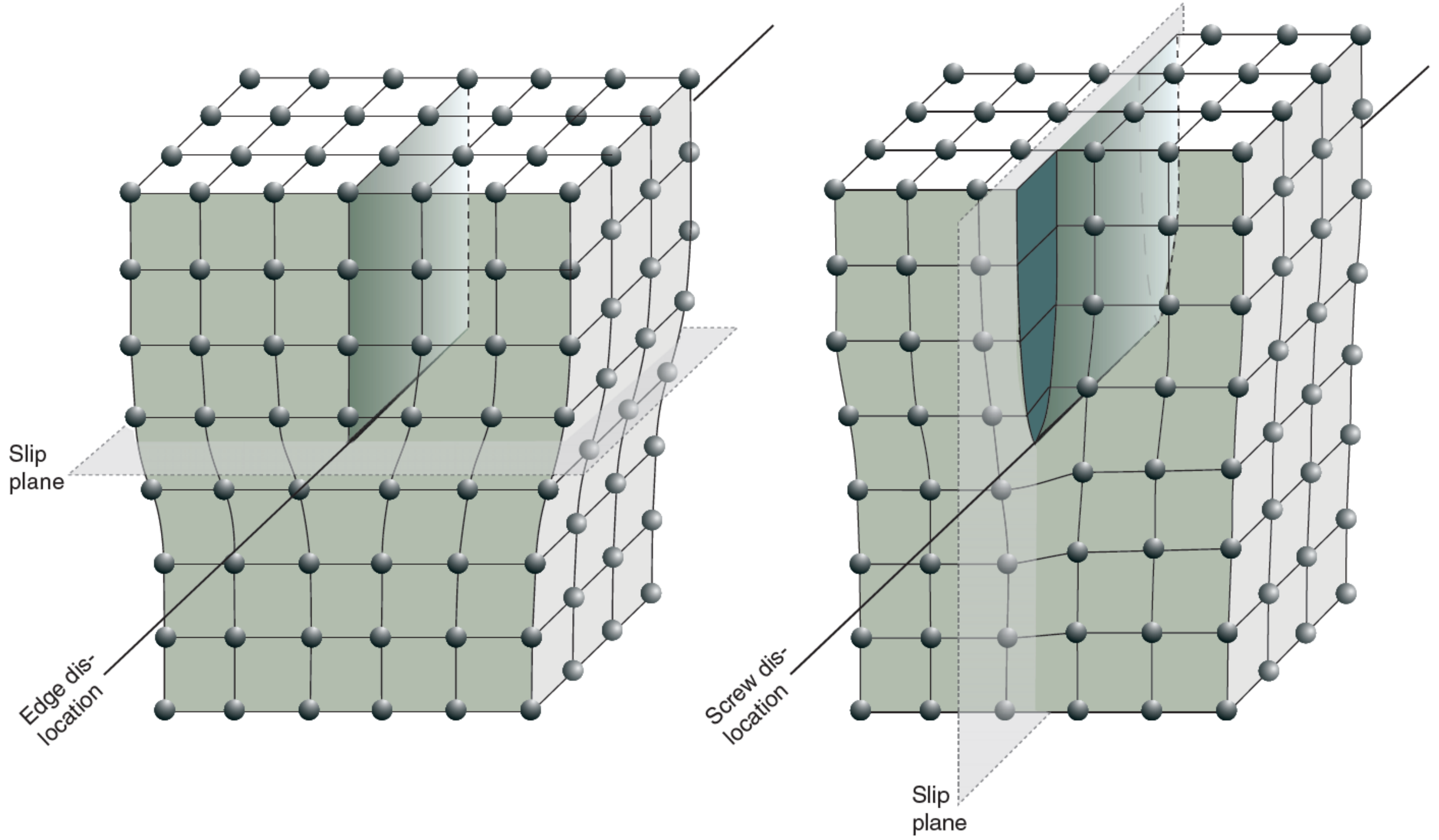


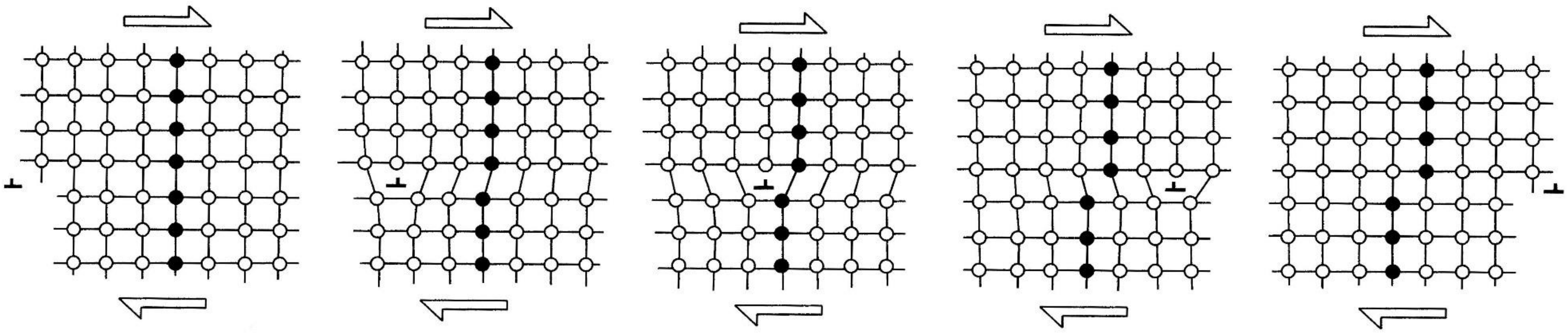
Figure 10.11 The two types of dislocations. An edge dislocation (left) occurs where an extra half-space of atoms interrupts the lattice, while a screw dislocation (right) involves twisting of the lattice.

Fossen (2010). Structural Geology

Deslocamento: linha móvel de defeitos

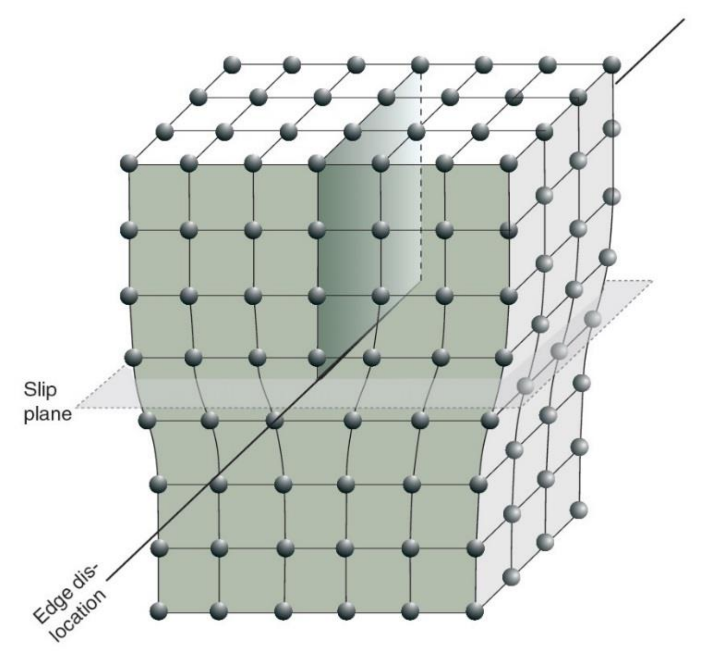
Produz deformação intracristalina por migração ou deslizamento

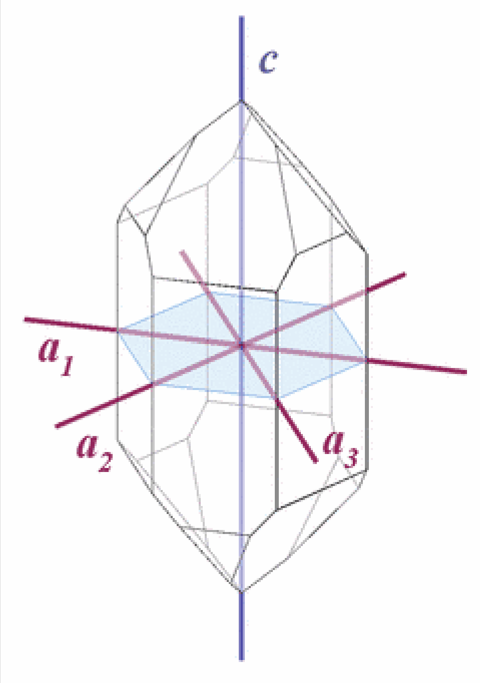
Movimentação de um deslocamento em linha através de um retículo cristalino

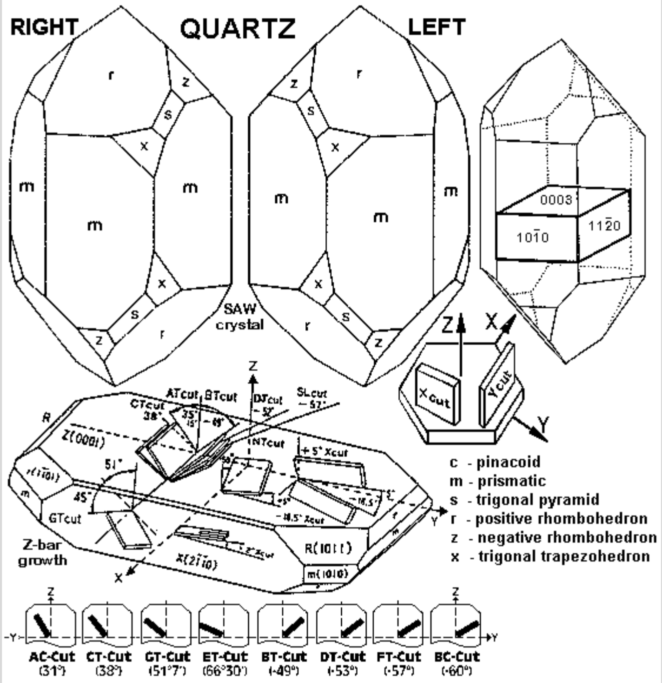


Migration of dislocation

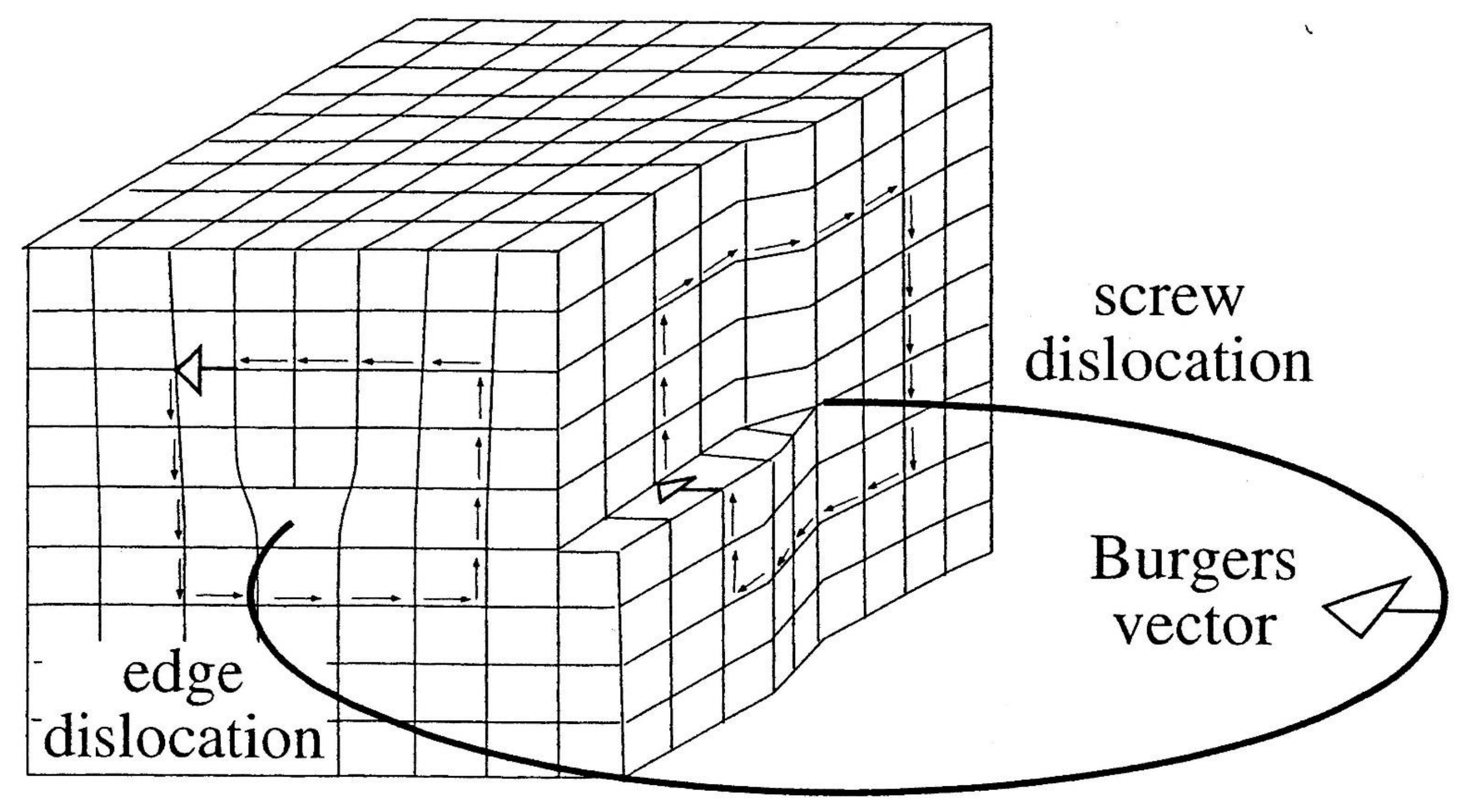
Crystal shape has changed without mechanical fracturing or loss of crystal structure







Movimentação combinada de deslocamentos em linha e em parafuso ao longo do retículo cristalino



Passchier & Trouw (2005). Microtectonics.

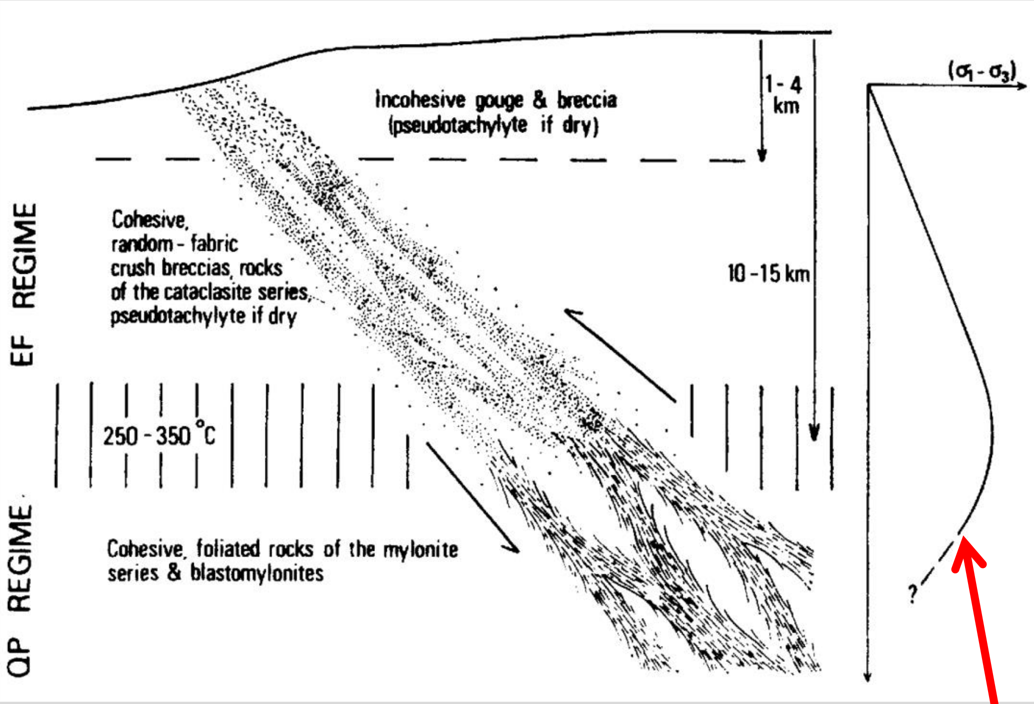
Fluência de deslocamentos (dislocation creep):

Conjunto de processos que abrange a formação, movimentação e destruição de deslocamentos em um cristal.

Processo de migração de um deslocamento em linha:

Deslizamento de deslocamento.

Fluência de deslocamentos (dislocation creep):



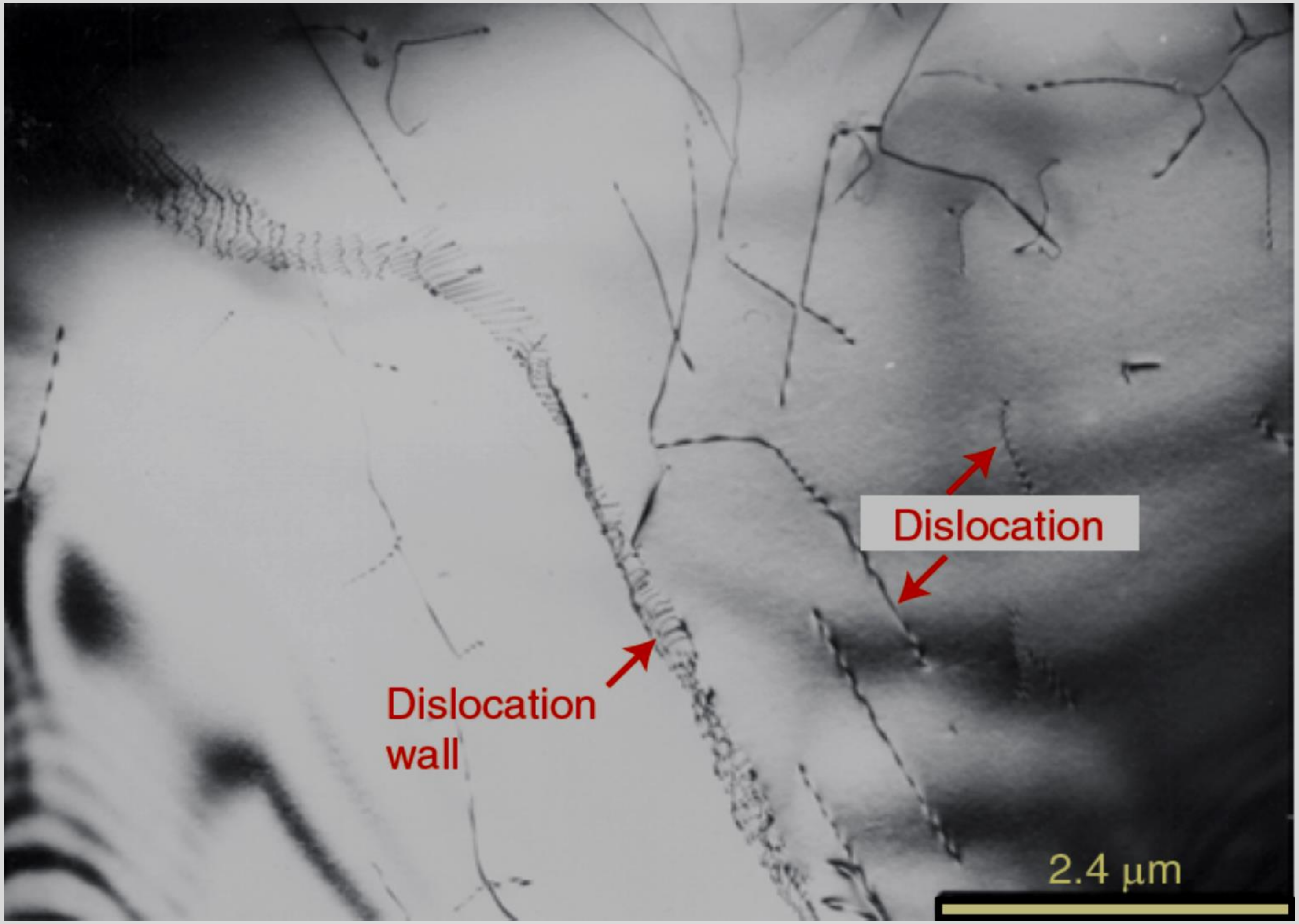
Zona "elástico-friccional" – acima da transição para fácies xisto verde (~ 250-300 °C, $P_{lit} = P_{H2O}$) – minerais tem comportamento elástico, não são capazes de se deformar plasticamente e absorver as tensões: deformação "friccional" (rúptil, cataclase); são geradas brechas e cataclasitos;

Zona "quase-plástica" – a temperaturas maiores, os minerais (especialmente quartzo) se deformam plasticamente, dissipando as tensões; são gerados os milonitos.

O processo de deslocamento se completa quando todo o cristal é atravessado, sem que ocorra ruptura da estrutura do cristal.

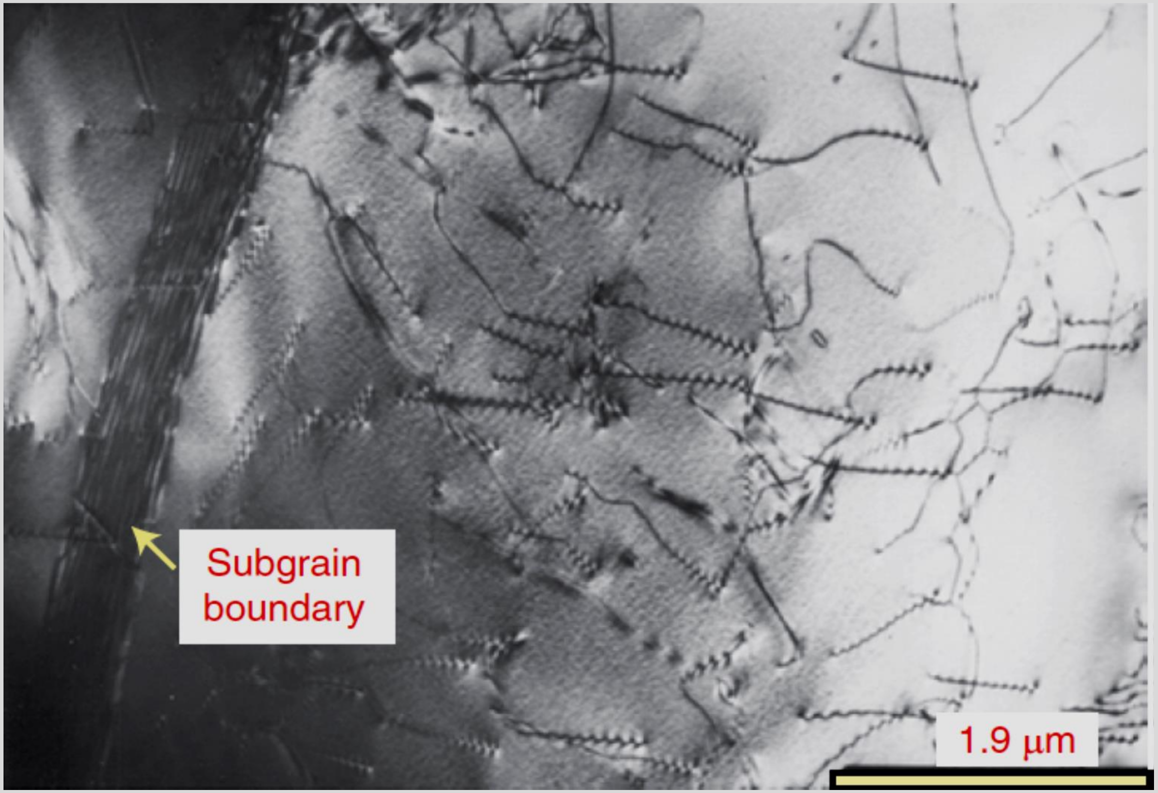
Esse processo permite que a deformação ocorra sob um esforço diferencial muito menor que o necessário para o fraturamento rúptil.

Deslocamentos vistos em imagem de microscópio eletrônico de transmissão.

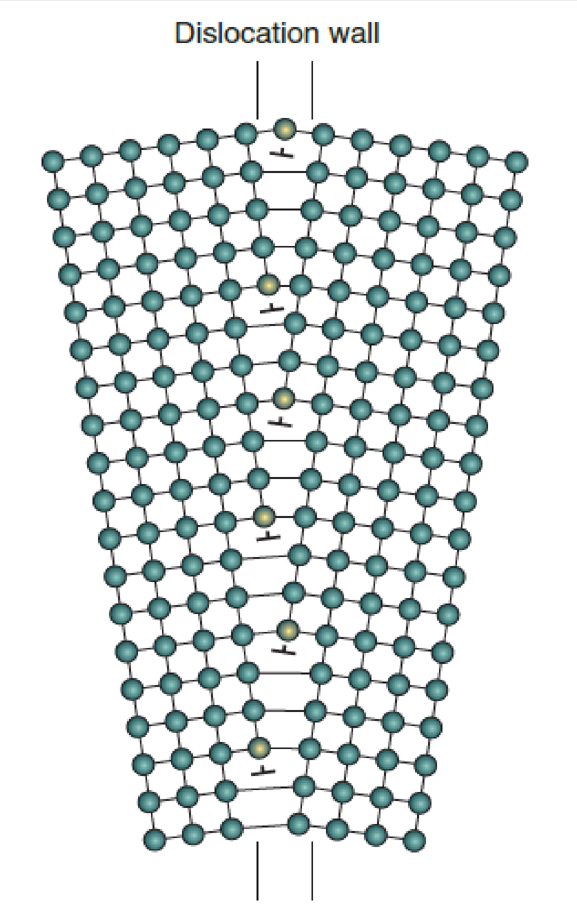


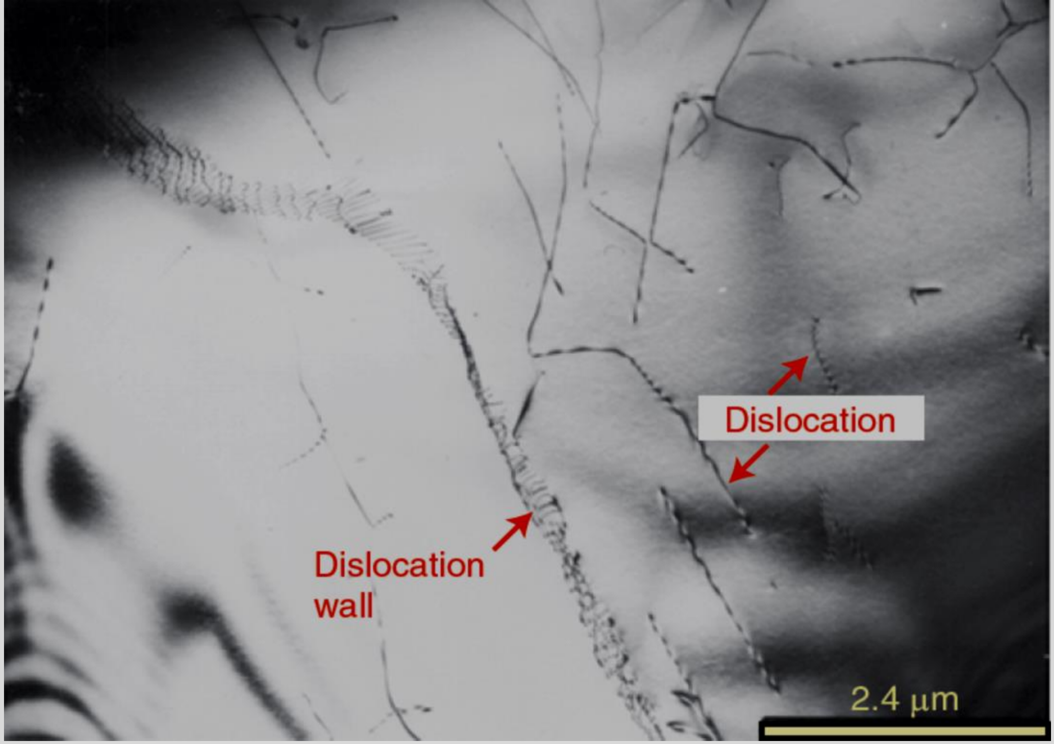
Recuperação da textura:

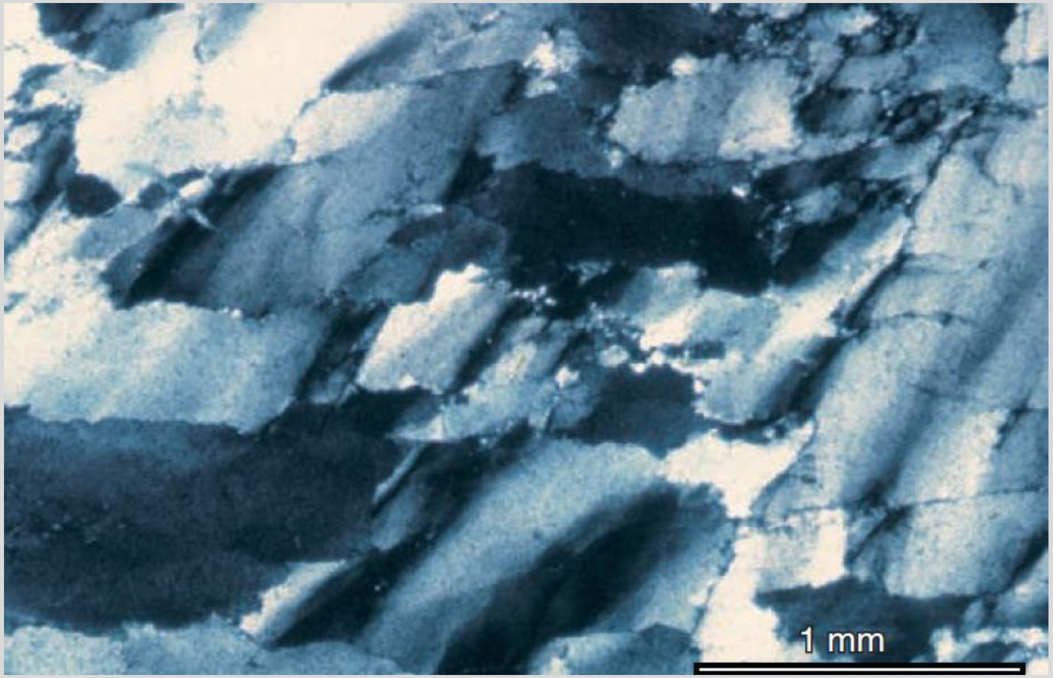
Engloba todos os processos que movem, anulam ou agrupam os deslocamentos em paredes que separam porções do grão original com orientações cristalográficas ligeiramente diferentes.



Fluência de deslocamentos reduz a energia interna de um grão mineral por meio de migração de deslocamentos para o limite de grão ou sua coleta no interior dos grãos.





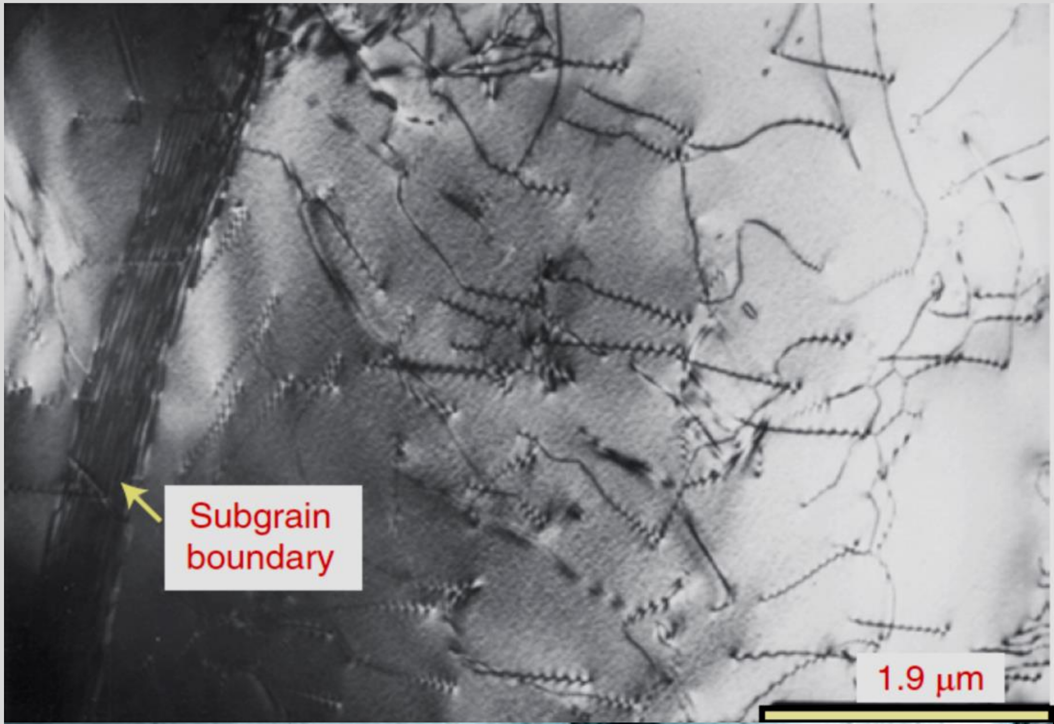


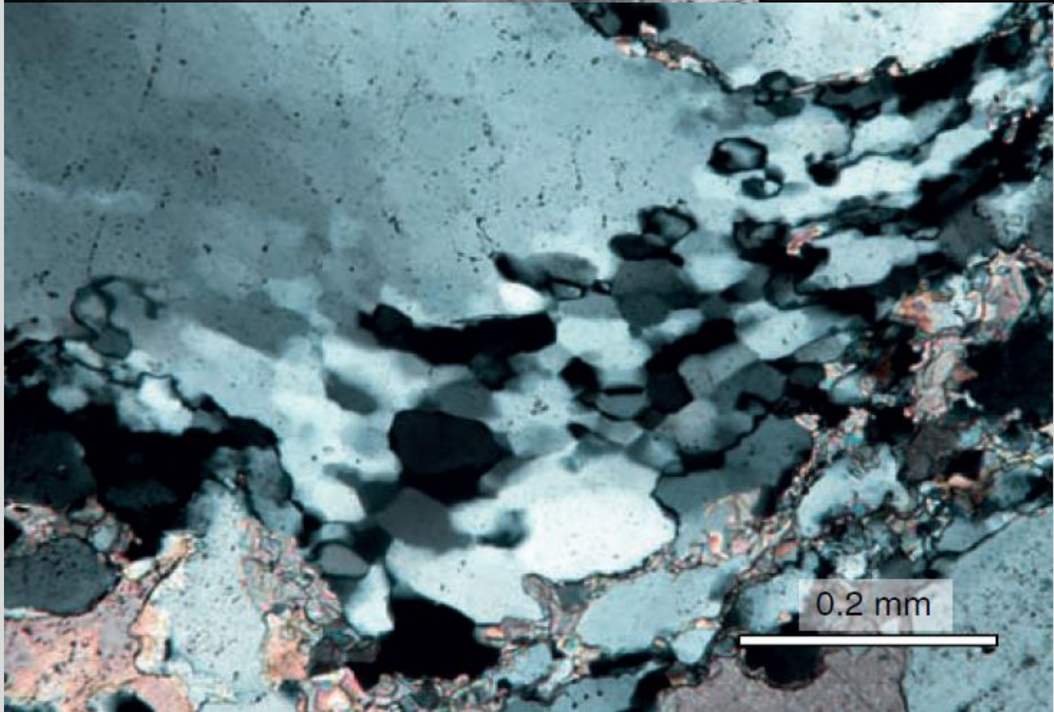
Os deslocamentos podem se reorganizar em paredes de deslocamentos.

(evidência microscópica: mudança de orientação cristalográfica)

Evolução no processo de migração de deslocamentos faz com que estes se arranjem em redes bem definidas, produzindo subgrãos.

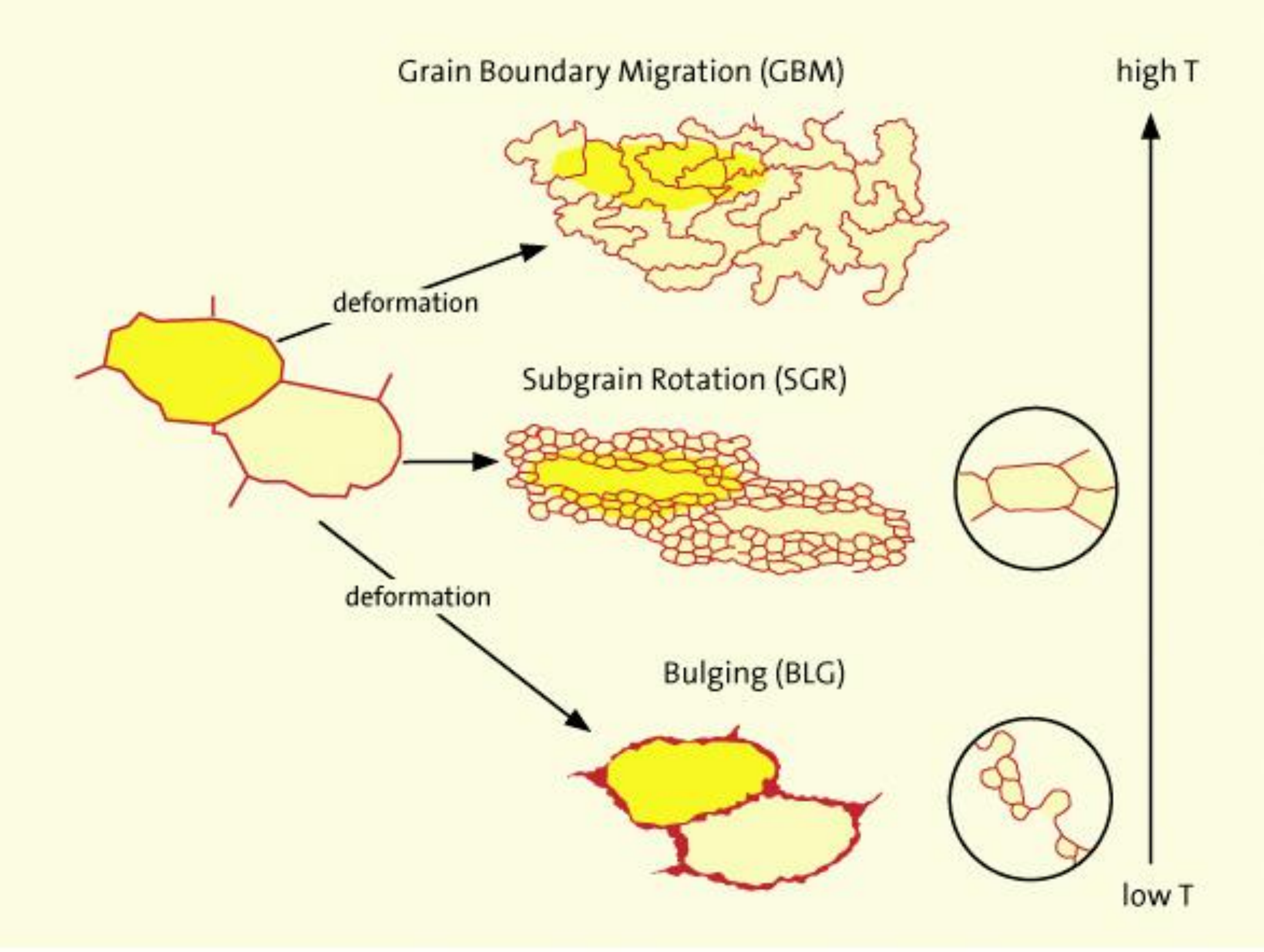
Bordas de subgrãos: desorientação ≤ 5° em relação aos domínios vizinhos.





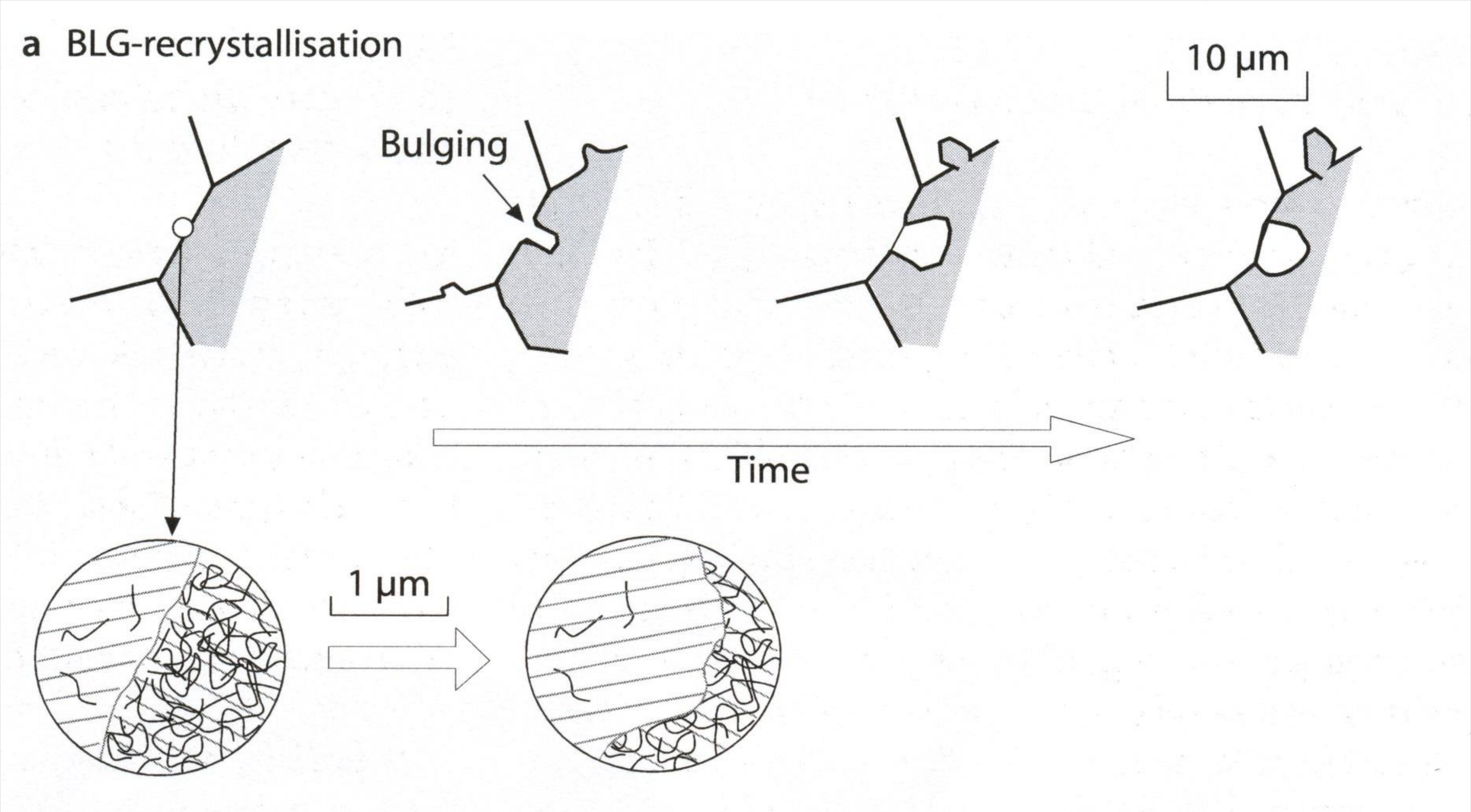
Recuperação: extinção ondulante irregular e lamelas de deformação.

Processos de recristalização dinâmica (Trouw et al. 2010):



Recristalização dinâmica: competem deformação e recristalização

Bulging recrystallization (baixa temperatura)

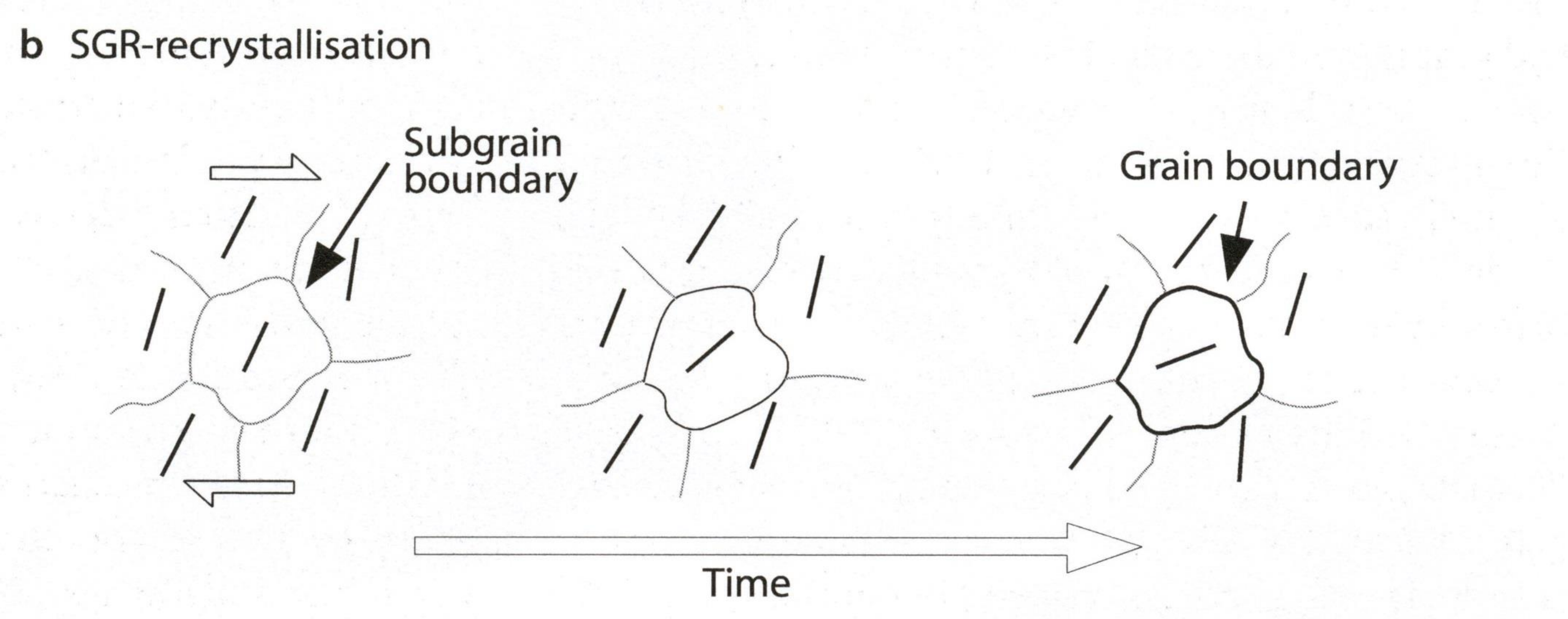


Recristalização dinâmica: competem deformação e recristalização

Bulging recrystallization (baixa temperatura)

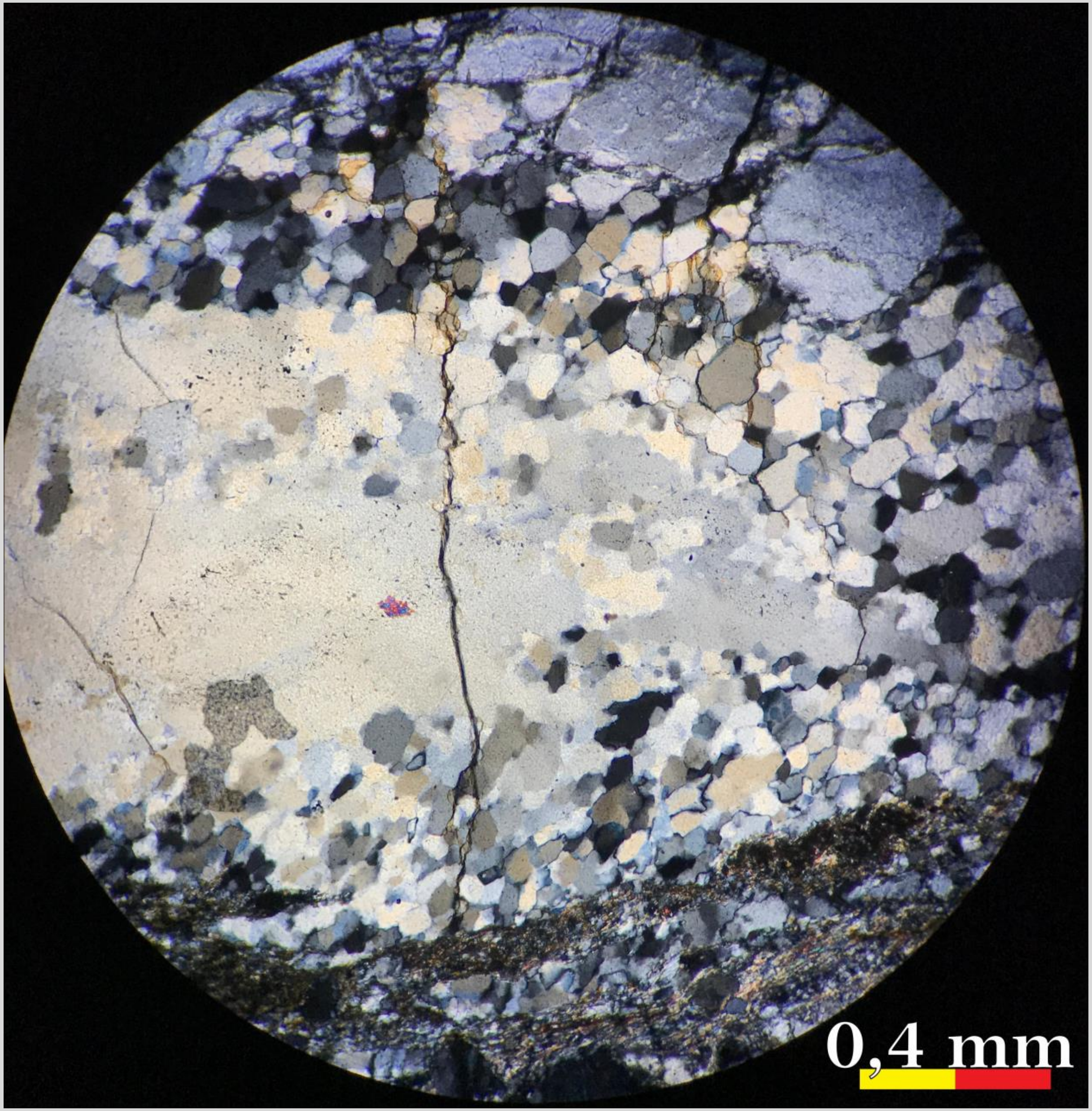
Recristalização dinâmica: competem deformação e recristalização

Rotação de subgrãos (temperatura intermediária)



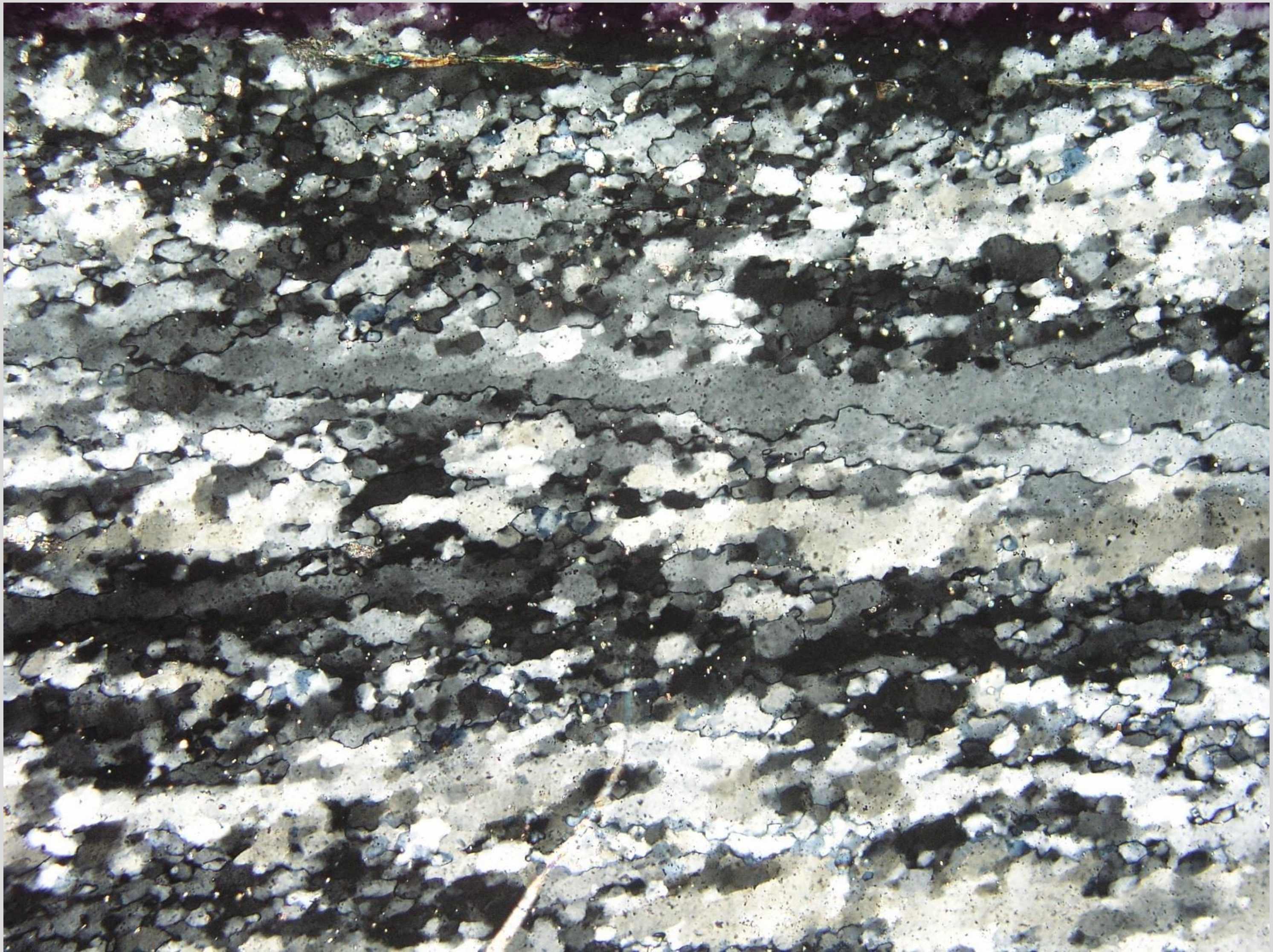
Recristalização dinâmica: competem deformação e recristalização

Rotação de subgrãos (temperatura intermediária)

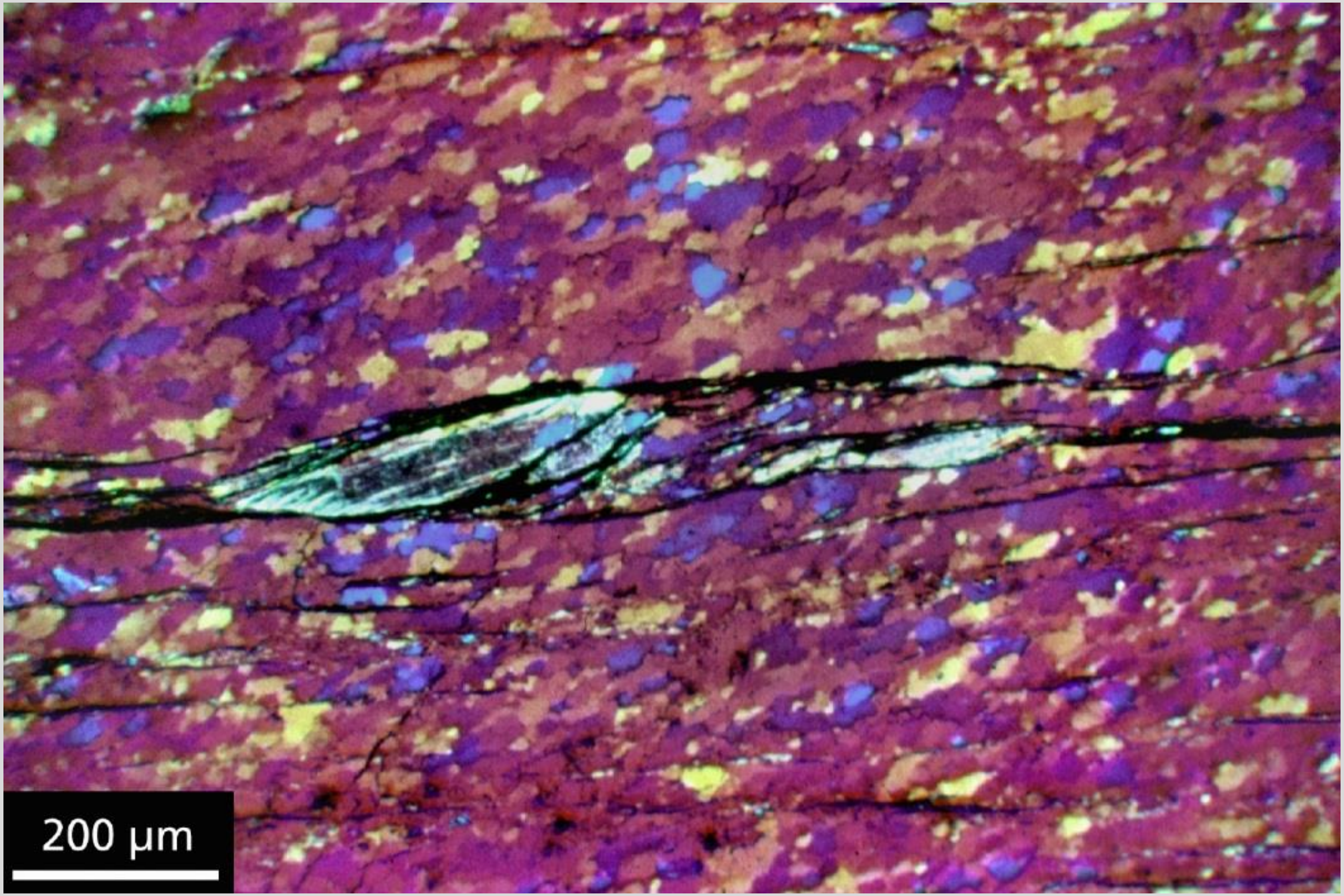


Recristalização dinâmica: competem deformação e recristalização

Rotação de subgrãos (temperatura intermediária)

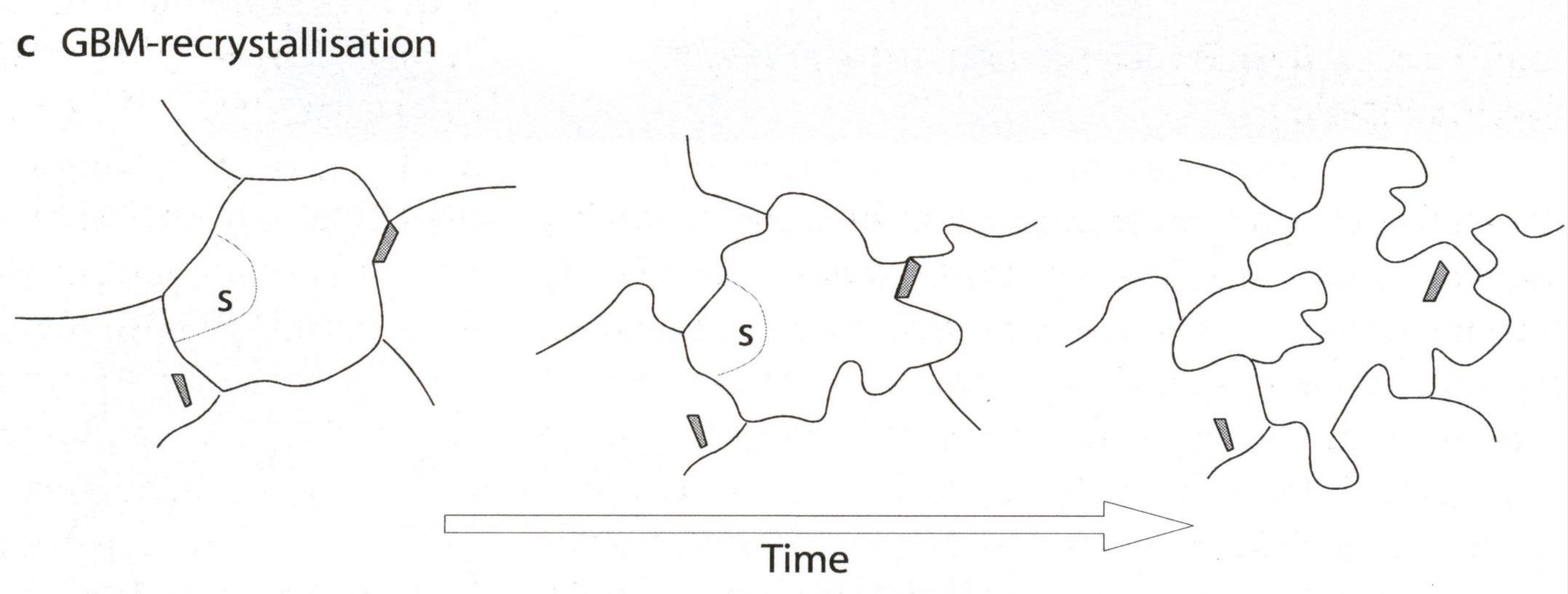


Milonito com foliação oblíqua (orientação preferencial de forma) definindo trama SC.



Recristalização dinâmica: competem deformação e recristalização

Migração de bordas de grãos (temperatura moderada a alta)



Recristalização dinâmica: competem deformação e recristalização

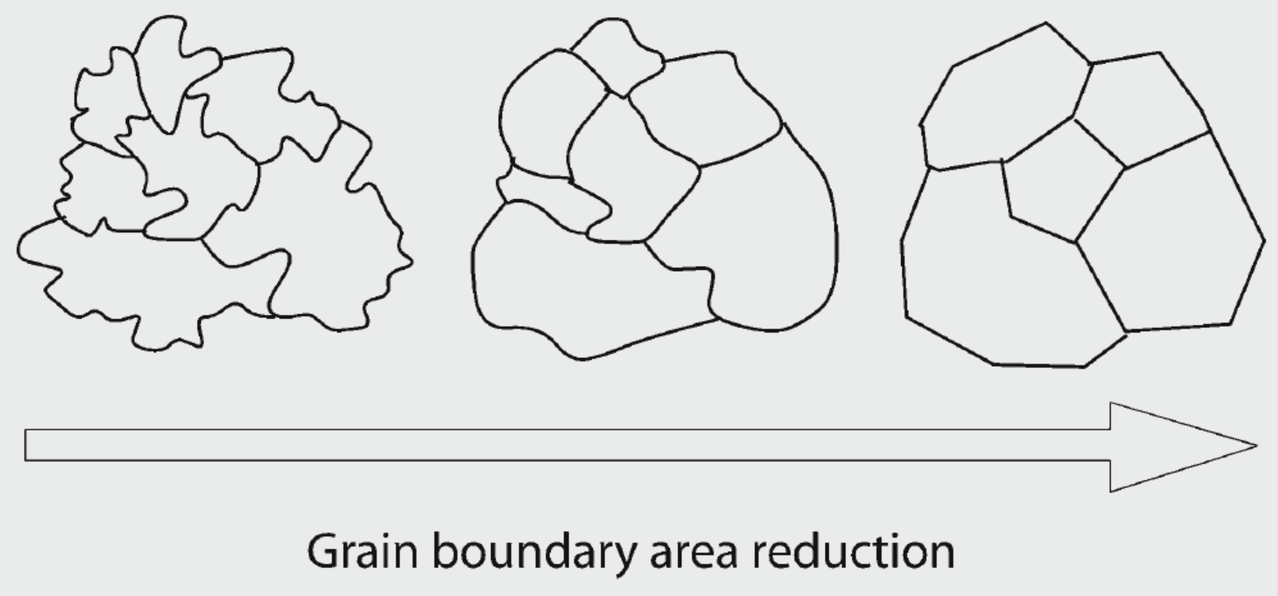
Migração de bordas de grãos (temperatura moderada a alta)

Textura poligonizada:

Além dos defeitos do retículo cristalino, bordas de grãos são considerados defeitos planares que contribuem para a energia interna livre de um volume de rocha.

Uma redução na área superficial total das bordas de grãos pode reduzir a energia interna livre de um agregado mineral.

Assim, bordas retas e grãos grossos são favorecidos de modo a reduzir a energia interna livre de um agregado.



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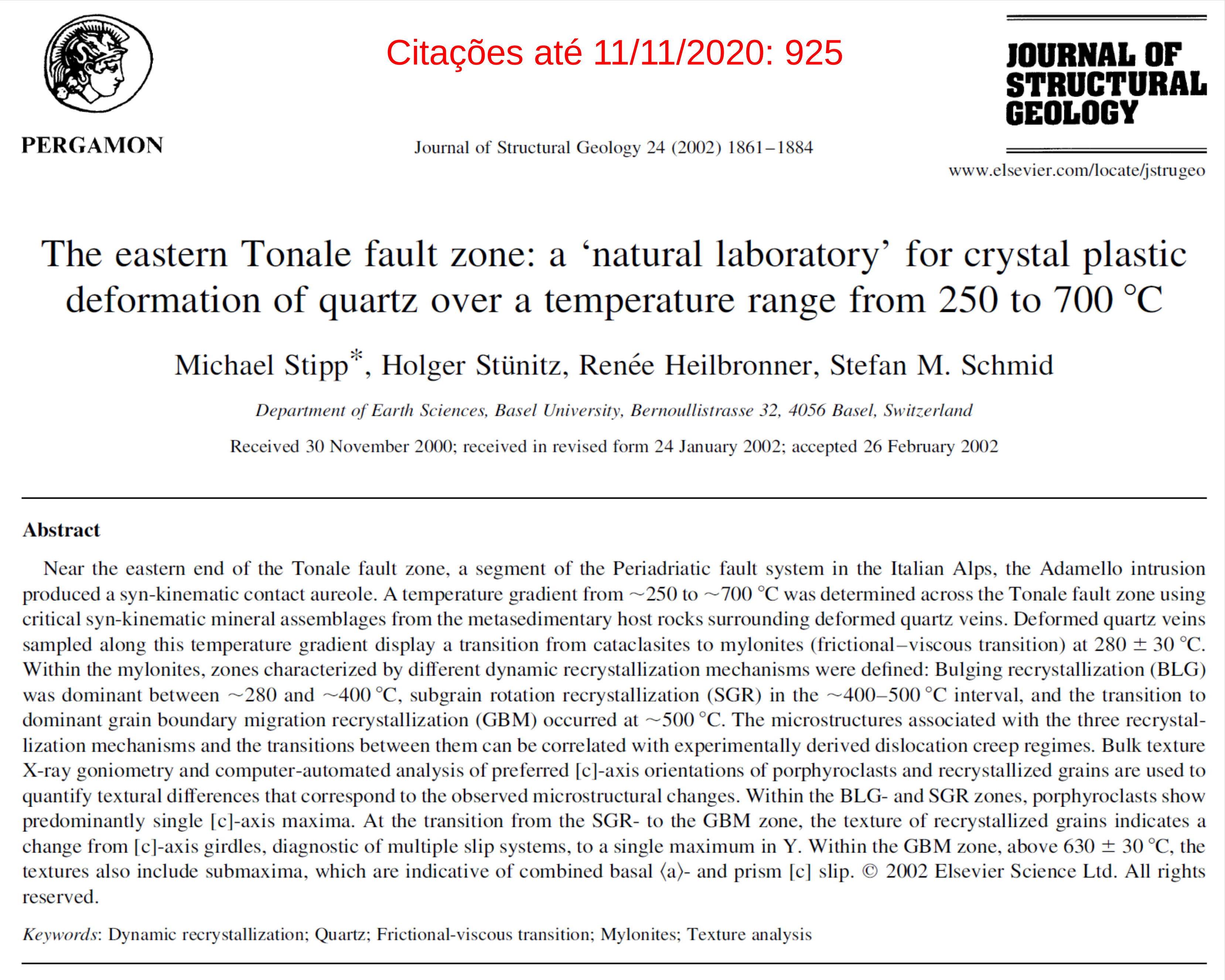

PERGAMON

Journal of Structural Geology 24 (2002) 1861–1884

JOURNAL OF STRUCTURAL GEOLOGY

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The eastern Tonale fault zone: a 'natural laboratory' for crystal plastic deformation of quartz over a temperature range from 250 to 700 °C

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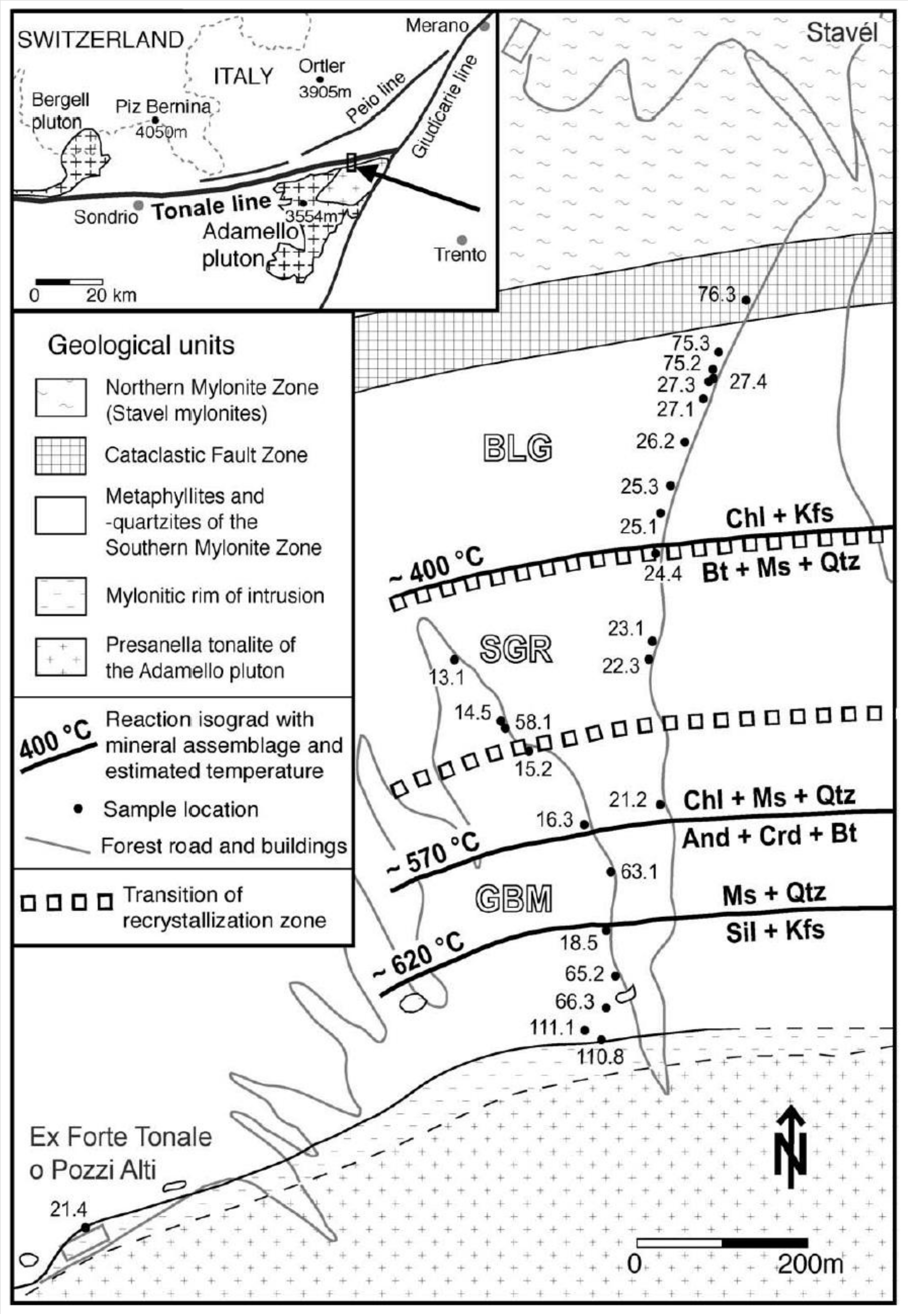
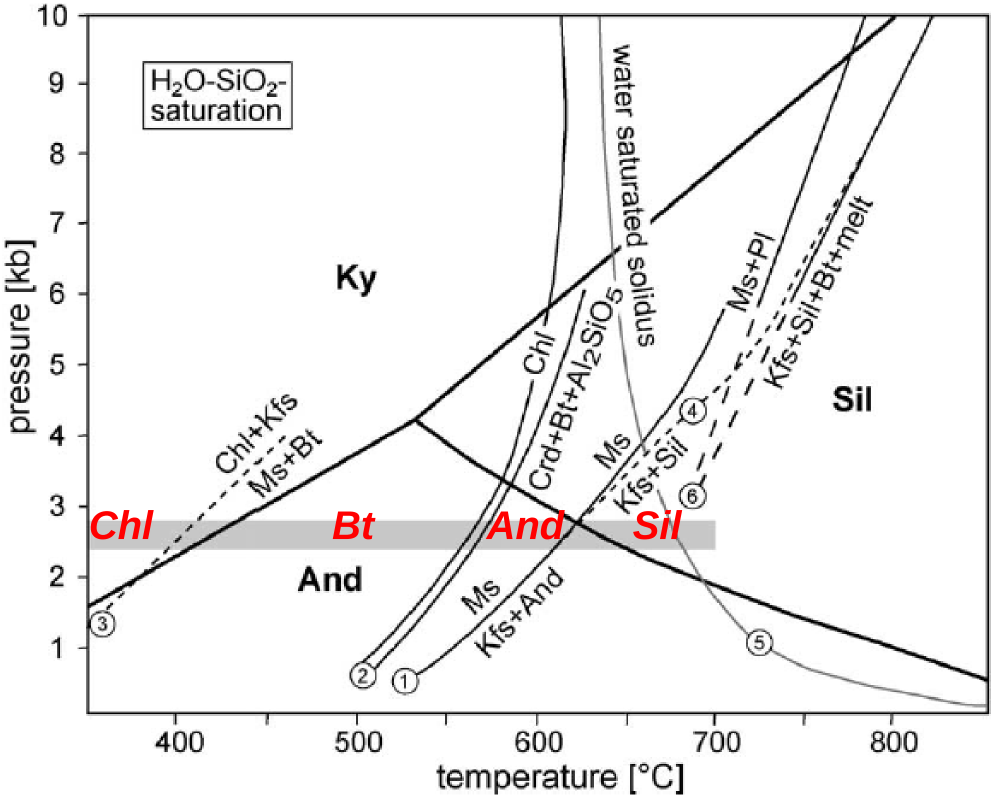
Abstract

Near the eastern end of the Tonale fault zone, a segment of the Periadriatic fault system in the Italian Alps, the Adamello intrusion produced a syn-kinematic contact aureole. A temperature gradient from ~250 to ~700 °C was determined across the Tonale fault zone using critical syn-kinematic mineral assemblages from the metasedimentary host rocks surrounding deformed quartz veins. Deformed quartz veins sampled along this temperature gradient display a transition from cataclasites to mylonites (frictional–viscous transition) at 280 ± 30 °C. Within the mylonites, zones characterized by different dynamic recrystallization mechanisms were defined: Bulging recrystallization (BLG) was dominant between ~280 and ~400 °C, subgrain rotation recrystallization (SGR) in the ~400–500 °C interval, and the transition to dominant grain boundary migration recrystallization (GBM) occurred at ~500 °C. The microstructures associated with the three recrystallization mechanisms and the transitions between them can be correlated with experimentally derived dislocation creep regimes. Bulk texture X-ray goniometry and computer-automated analysis of preferred [c]-axis orientations of porphyroclasts and recrystallized grains are used to quantify textural differences that correspond to the observed microstructural changes. Within the BLG- and SGR zones, porphyroclasts show predominantly single [c]-axis maxima. At the transition from the SGR- to the GBM zone, the texture of recrystallized grains indicates a change from [c]-axis girdles, diagnostic of multiple slip systems, to a single maximum in Y. Within the GBM zone, above 630 ± 30 °C, the textures also include submaxima, which are indicative of combined basal ⟨a⟩- and prism [c] slip.

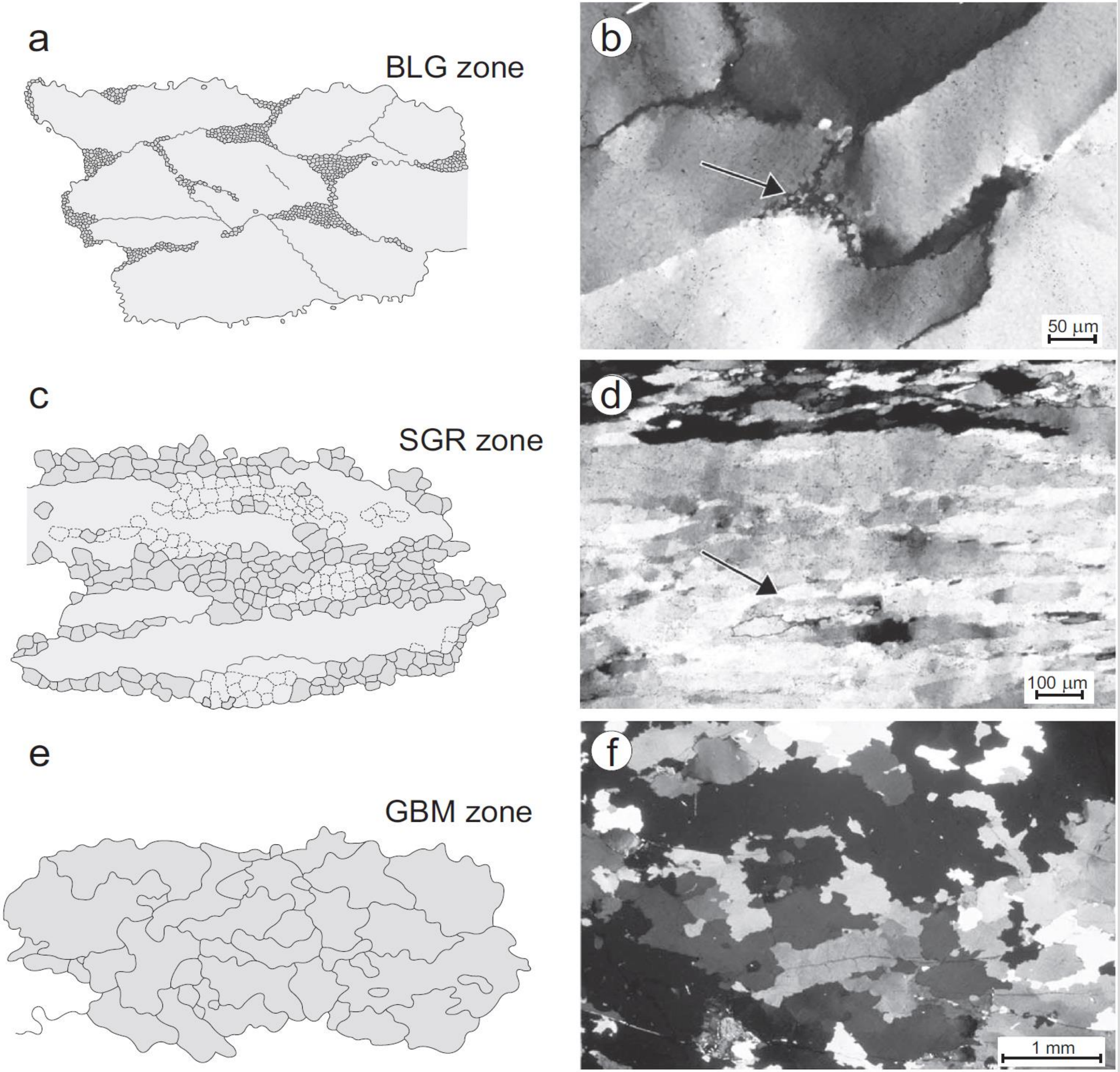
Keywords: Dynamic recrystallization; Quartz; Frictional-viscous transition; Mylonites; Texture analysis



M. Stipp et al. / Journal of Structural Geology 24 (2002) 1861–1884



Stipp et al. (2002a)



Stipp et al. (2002a)

280-400°C

400-500°C

>500°C

Tectonophysics 485 (2010) 193–214

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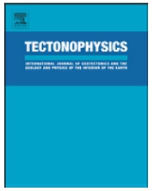

Quartz recrystallization regimes, *c*-axis texture transitions and fluid inclusion reequilibration in a prograde greenschist to amphibolite facies mylonite zone (Ribeira Shear Zone, SE Brazil)

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Rosa Maria da Silveira Bello [b], Kazuo Fuzikawa [c]

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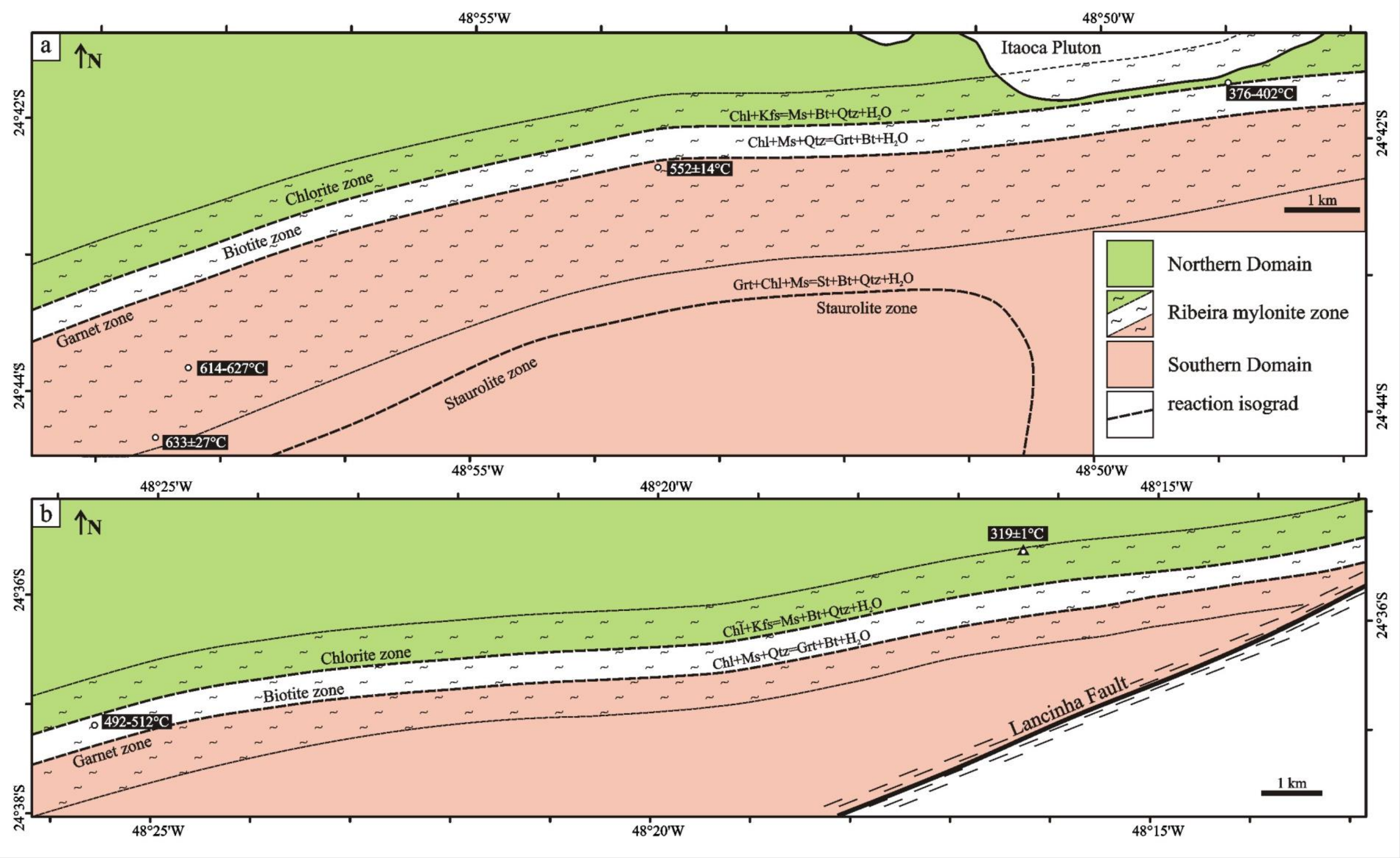
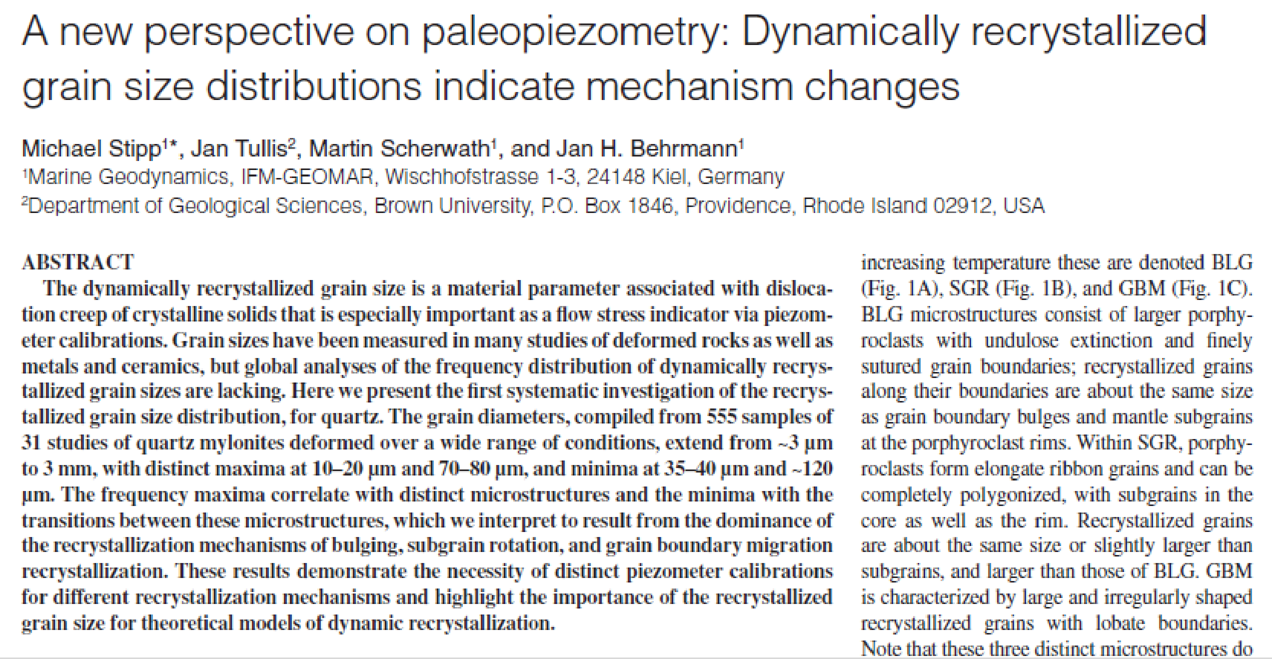
ABSTRACT

The crystal-plastic behavior of quartz mylonites from the Ribeira Shear Zone (SE Brazil), a major strike–slip structure that was active during a prograde metamorphic phase related to the Neoproterozoic Brasiliano–Pan African Orogeny, was investigated using a multi-method approach. Geothermobarometry results indicate deformational conditions ranging from ~300 to ~630 °C and 500–700 MPa. A strong correlation between mapped metamorphic zones and a dominance of different dynamic recrystallization mechanisms of quartz occurs within the mylonite zone. Bulging recrystallization (BLG) dominates within the chlorite zone between 300 and 410 °C, subgrain rotation recrystallization (SGR) operates within the biotite zone from 410 to 520 °C, and grain boundary migration recrystallization (GBM) dominates in the garnet zone above 520 °C. The development of quartz *c*-axis textures is mainly governed by temperature and dynamic recrystallization mechanisms. Textures from BLG zone mylonites are characterized by maxima around Z; SGR zone mylonites display single girdles or asymmetric type I crossed girdles; and GBM zone mylonites comprise maxima around *Y* and intermediate between *X* and *Z*. The scarcity or absence of water-bearing fluid inclusions in quartz mylonites from the SGR and GBM zones, which are dominated by carbonic inclusions, suggests water-deficient conditions, whereas BLG zone mylonites are dominated by water-bearing inclusions. This evidence indicates that water was available in the protoliths but has been eliminated with increasing deformation and deformation temperature. No effect of the water content variation on the quartz microstructural and recrystallized grain size evolution was detected, and little influence on *c*-axis texture development was observed. Most of the fluid inclusion densities were reequilibrated during the shear zone exhumation history, recording a decompression in the range of 300–500 MPa, while microstructural reequilibration effects related to the prograde metamorphism are largely preserved. Fluid inclusion microstructures and densities from two SGR zone samples preserved evidence for a near isothermal compression within the interior of the Ribeira Shear Zone during the prograde metamorphism.

Faleiros et al. (2010)



Mecanismo de recristalização *versus* granulação



A new perspective on paleopiezometry: Dynamically recrystallized grain size distributions indicate mechanism changes

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ABSTRACT

The dynamically recrystallized grain size is a material parameter associated with dislocation creep of crystalline solids that is especially important as a flow stress indicator via piezometer calibrations. Grain sizes have been measured in many studies of deformed rocks as well as metals and ceramics, but global analyses of the frequency distribution of dynamically recrystallized grain sizes are lacking. Here we present the first systematic investigation of the recrystallized grain size distribution, for quartz. The grain diameters, compiled from 555 samples of 31 studies of quartz mylonites deformed over a wide range of conditions, extend from ~3 µm to 3 mm, with distinct maxima at 10–20 µm and 70–80 µm, and minima at 35–40 µm and ~120 µm. The frequency maxima correlate with distinct microstructures and the minima with the transitions between these microstructures, which we interpret to result from the dominance of the recrystallization mechanisms of bulging, subgrain rotation, and grain boundary migration recrystallization. These results demonstrate the necessity of distinct piezometer calibrations for different recrystallization mechanisms and highlight the importance of the recrystallized grain size for theoretical models of dynamic recrystallization.

increasing temperature these are denoted BLG (Fig. 1A), SGR (Fig. 1B), and GBM (Fig. 1C). BLG microstructures consist of larger porphyroclasts with undulose extinction and finely sutured grain boundaries; recrystallized grains along their boundaries are about the same size as grain boundary bulges and mantle subgrains at the porphyroclast rims. Within SGR, porphyroclasts form elongate ribbon grains and can be completely polygonized, with subgrains in the core as well as the rim. Recrystallized grains are about the same size or slightly larger than subgrains, and larger than those of BLG. GBM is characterized by large and irregularly shaped recrystallized grains with lobate boundaries. Note that these three distinct microstructures do

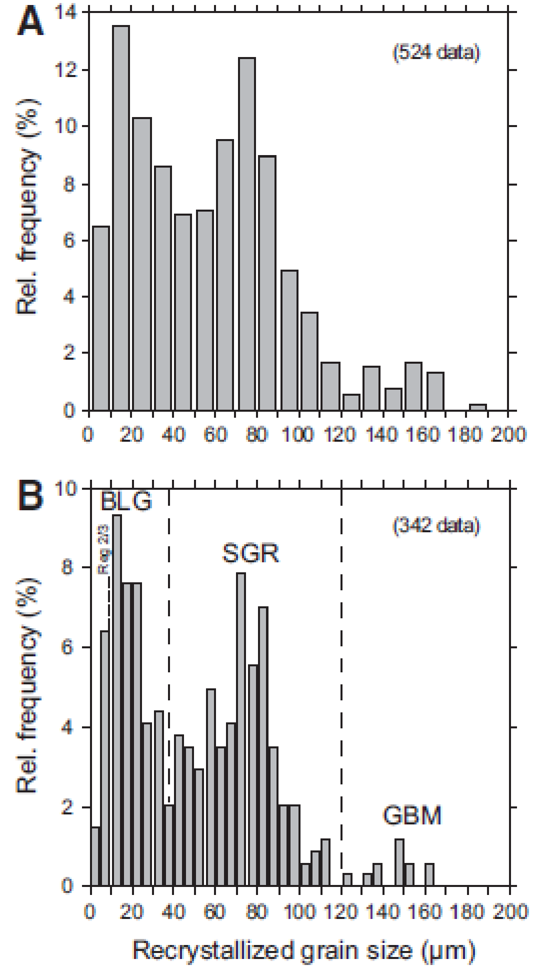
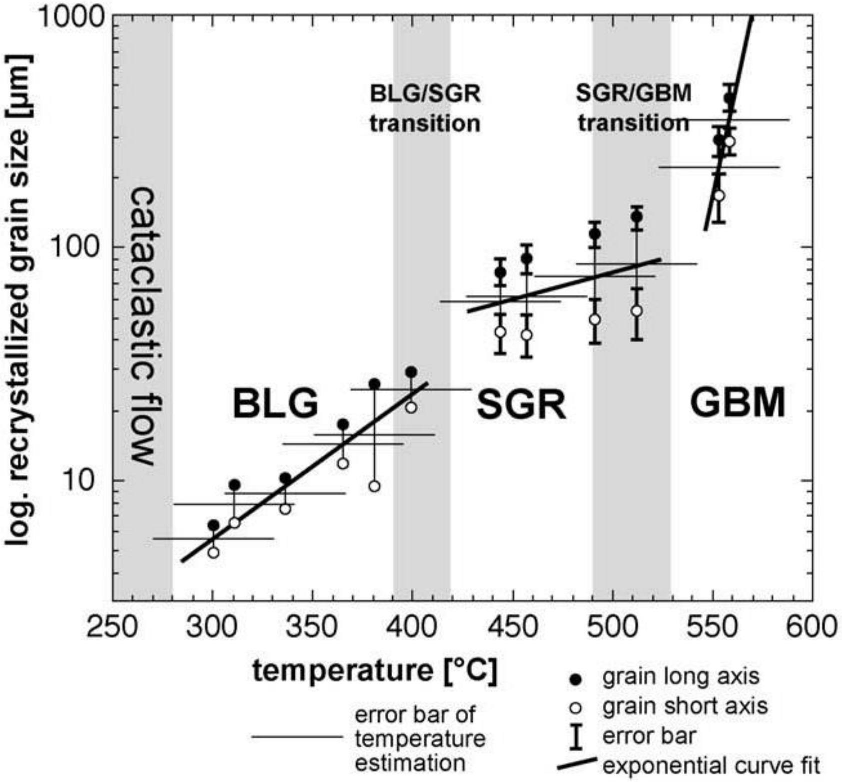


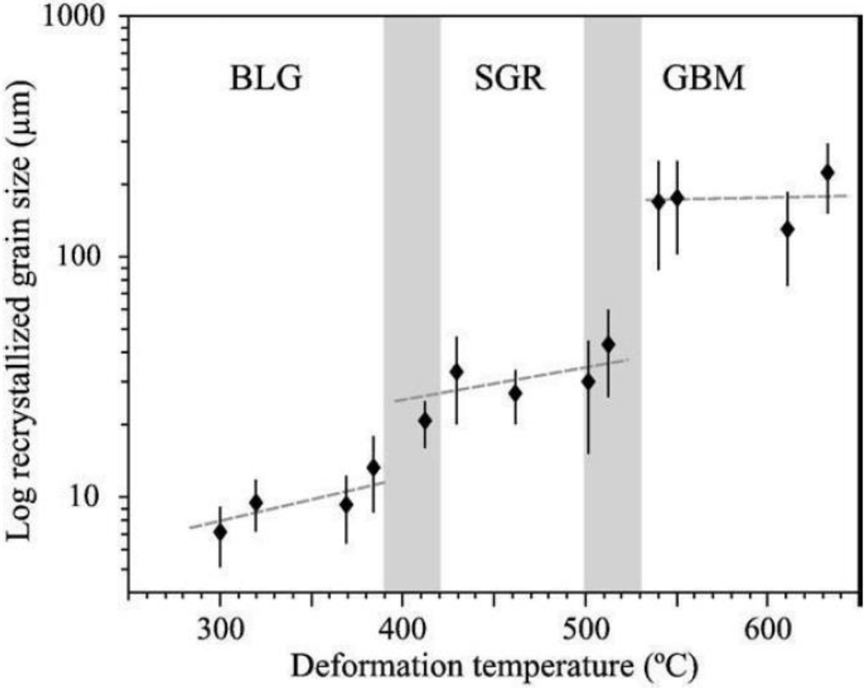
Figure 3. Recrystallized grain size fraction (<200 µm) of the natural samples. Note the different relative frequencies and bin sizes in the two diagrams. A: Grain size distribution for the complete data set (Fig. 2A) for sizes 0–200 µm. B: Grain size distribution for the refined data set (see text for further explanation). Ranges for BLG (bulging recrystallization), SGR (subgrain rotation recrystallization), and GBM (grain boundary migration recrystallization) microstructures (Stipp et al., 2002) and the experimental regime 2/3 transition (Reg 2/3; Stipp and Tullis, 2003) are indicated.

Mecanismo de recristalização *versus* granulação

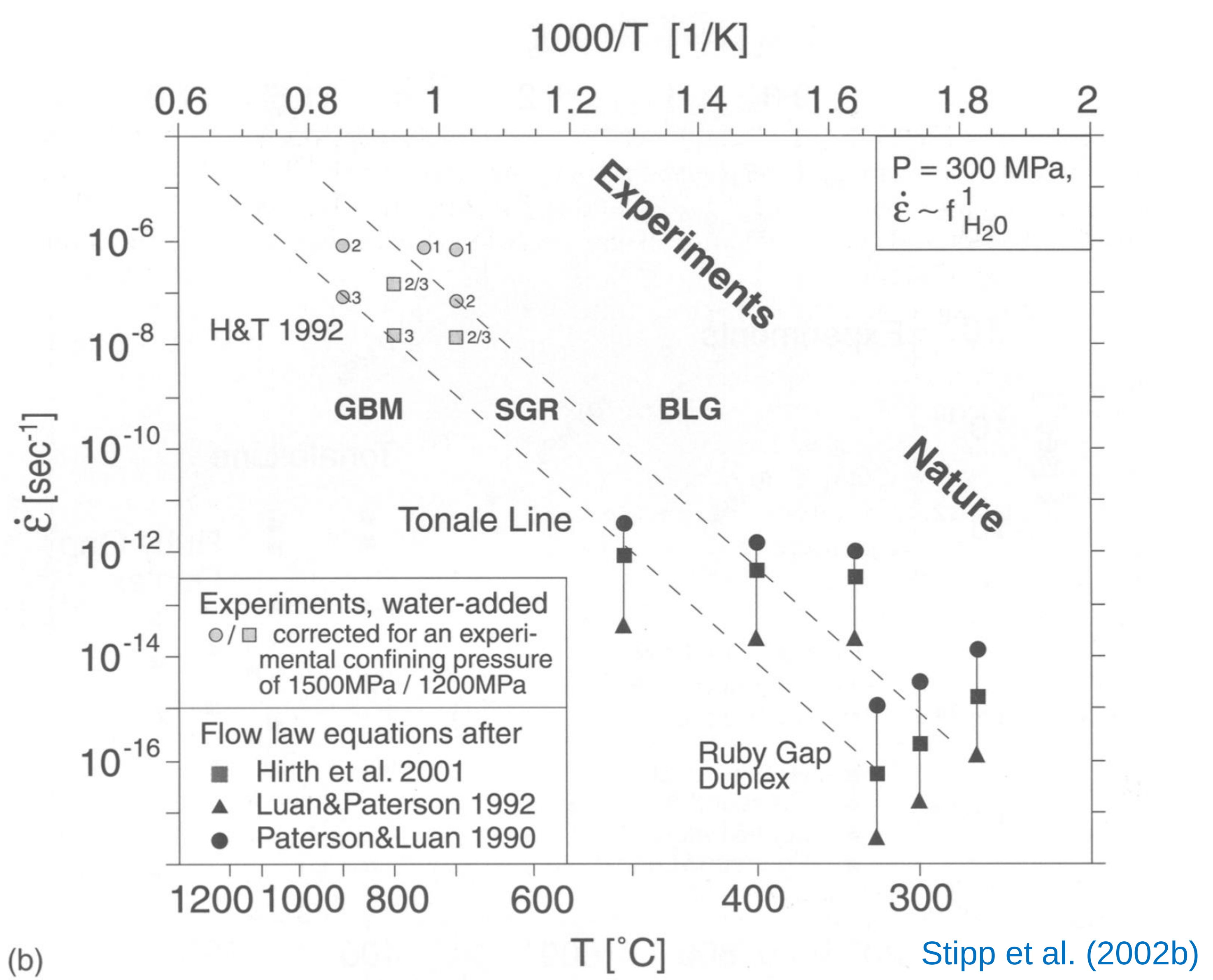
Stipp et al. (2002a)



Faleiros et al. (2010)



Mecanismo de recristalização *x temperatura x* taxa de deformação



Stipp et al. (2002b)

J. metamorphic Geol., 1996, **14,** 581–589

Prism- and basal-plane parallel subgrain boundaries in quartz: a microstructural geothermobarometer

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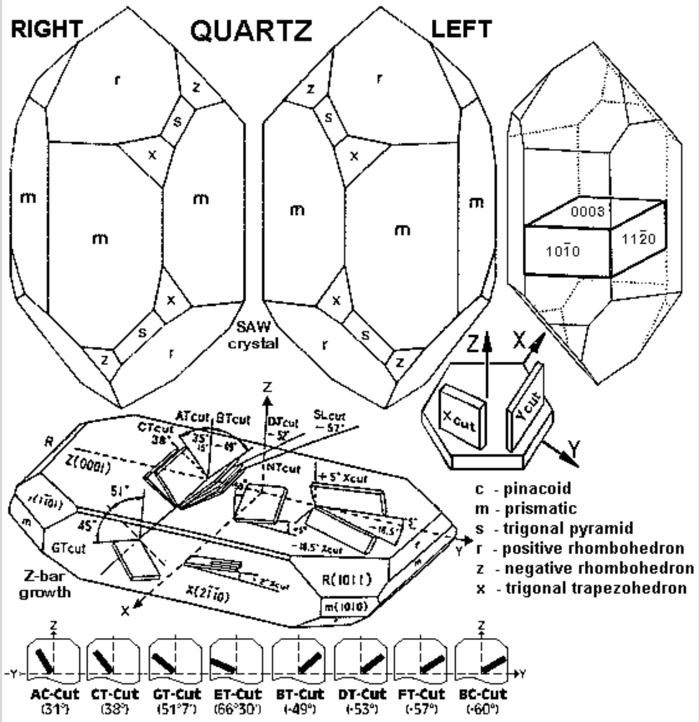
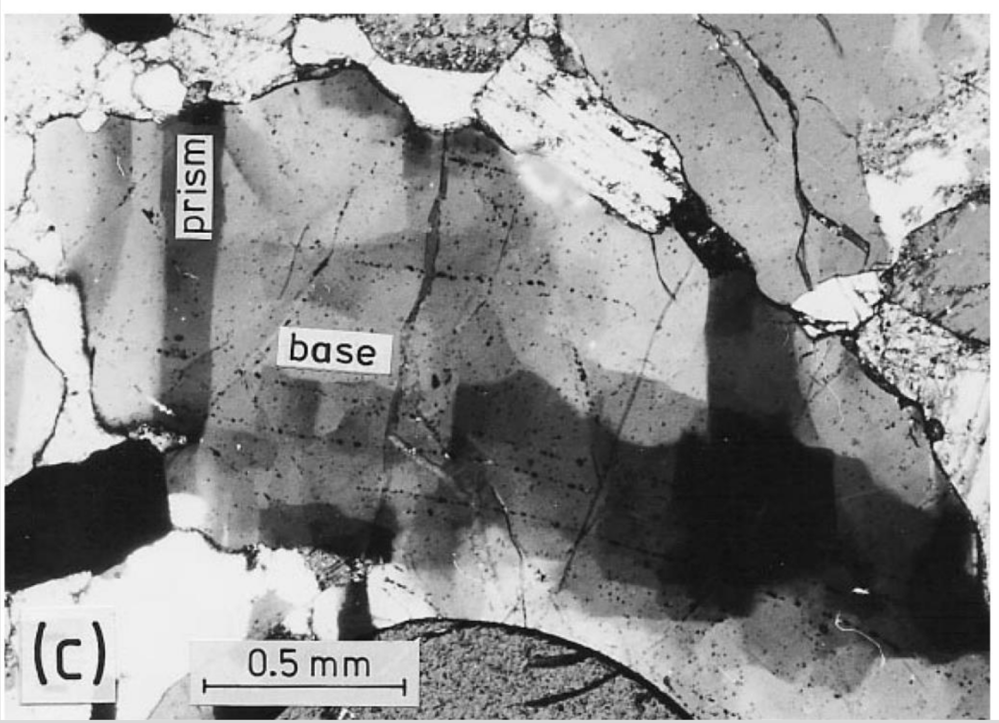
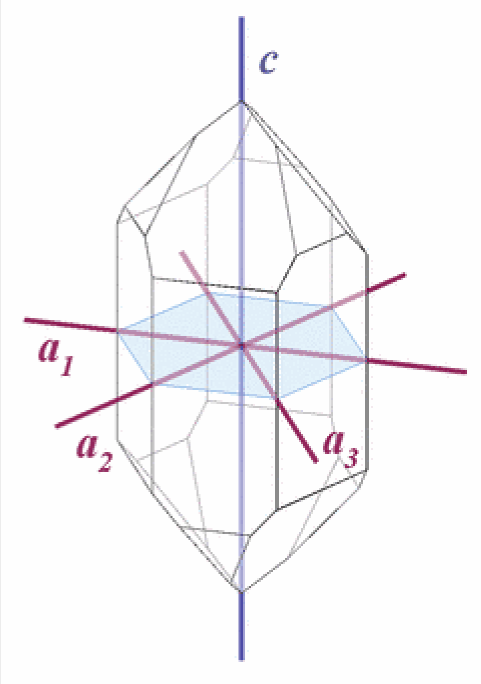
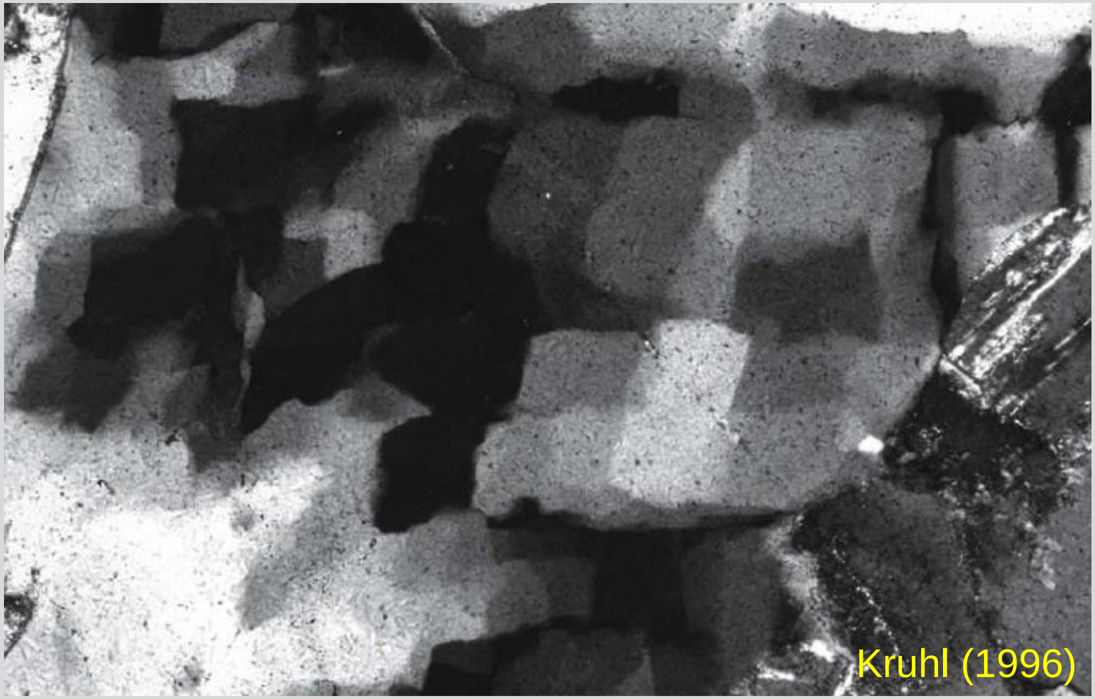
ABSTRACT Empirical data on quartz subgrain patterns from various metamorphic rocks show that, at least up to 10 kbar in the stability field of low-quartz, prismatic subgrain boundaries are dominant whereas basal subgrain boundaries are not developed. In the high-quartz stability field, both prismatic and basal subgrain boundaries occur and form typical rectangular ('chessboard') patterns. The likely reason behind the different occurrence of these subgrain patterns is that in high-quartz prismatic glide becomes as easy as, or probably even easier than, basal glide. The two types of subgrain patterns can be clearly distinguished by optical microscopy. Consequently, the occurrence of chessboard subgrain patterns in quartz represents a practicable geothermobarometer. The possibilities of its application are far reaching and include the specification of deformation conditions at high-grade metamorphism, the recognition of syntectonic intrusions and the distinction between pluton emplacement at lower and at higher crustal levels.

Key words: geothermobarometer; low- to high-quartz transition; quartz; subgrain boundaries.

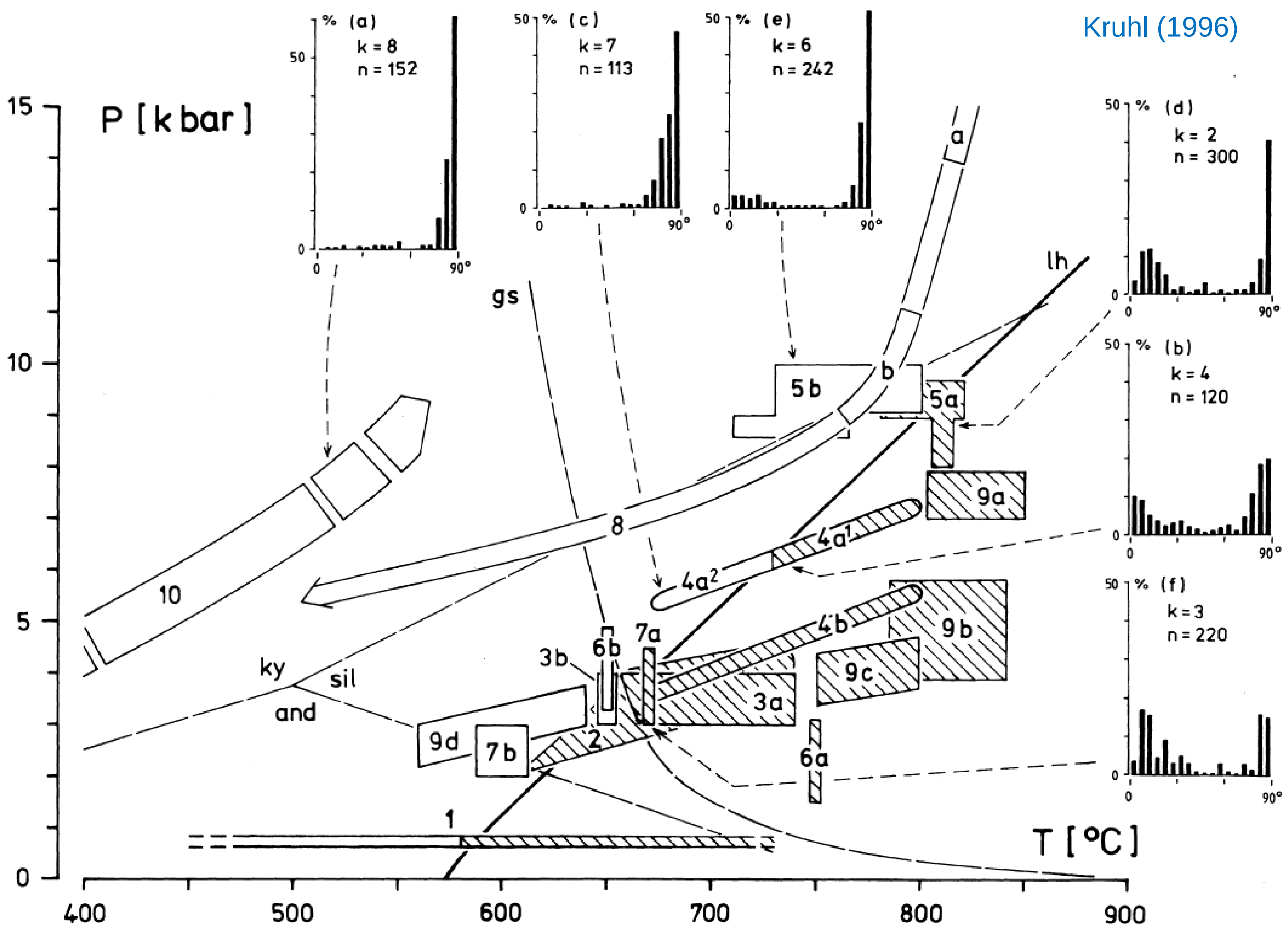

RIGHT
QUARTZ
LEFT
r
z
s
x
m
SAW crystal
0003
10$\bar{1}$0
11$\bar{2}$0
Z
X
Y
X cut
Y cut
ATcut
BTcut
CTcut 38°
DTcut -52°
SLcut -57°
Z(0001)
r(1$\bar{1}$01)
51°
45°
GTcut
INTcut
+5° Xcut
-18.5° Xcut
R(10$\bar{1}$1)
X(2$\bar{1}\bar{1}$0)
m(10$\bar{1}$0)
Z-bar growth
c - pinacoid
m - prismatic
s - trigonal pyramid
r - positive rhombohedron
z - negative rhombohedron
x - trigonal trapezohedron
AC-Cut (31°)
CT-Cut (38°)
GT-Cut (51°7')
ET-Cut (66°30')
BT-Cut (-49°)
DT-Cut (-53°)
FT-Cut (-57°)
BC-Cut (-60°)


prism
base
(c)
0.5 mm


c
a1
a2
a3

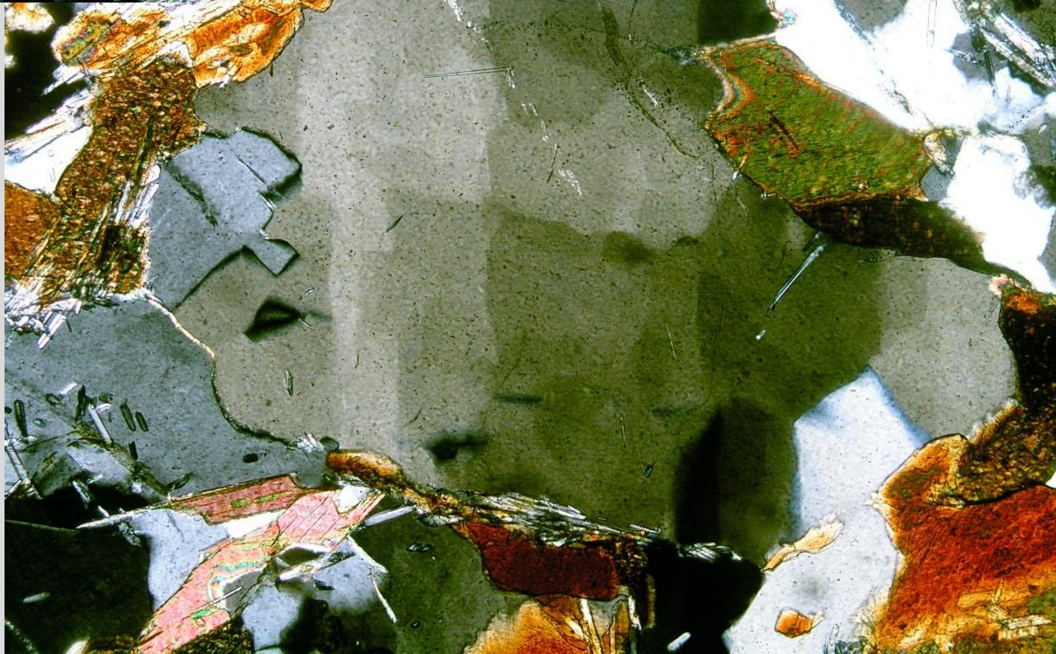


Kruhl (1996)


% (a)
k = 8
n = 152
50 % (c)
k = 7
n = 113
50 % (e)
k = 6
n = 242
50 % (d)
k = 2
n = 300
50 % (b)
k = 4
n = 120
50 % (f)
k = 3
n = 220
0
50
90°
15
10
5
0
P [kbar]
T [°C]
400
500
600
700
800
900
gs
lh
a
b
5b
5a
9a
9b
9c
9d
4a¹
4a²
4b
8
10
ky
sil
and
3a
3b
6a
6b
7a
7b
2
1

Kruhl (1996)

Bordas retangulares de grãos



Faleiros et al. (2016)

- Forte controle cristalográfico na migração de bordas de grãos.
- Alta mobilidade.
- Alta temperatura.

Feldspatos:

Comportamento rúptil até ~450°C

Extinção ondulante: T > 450°C

Recristalização dinâmica: T > 500°C (BLG)

Recristalização por rotação de subgrãos: 600-850°C

Recristalização por migração de bordas de grãos: T > 850°C

Feldspatos:

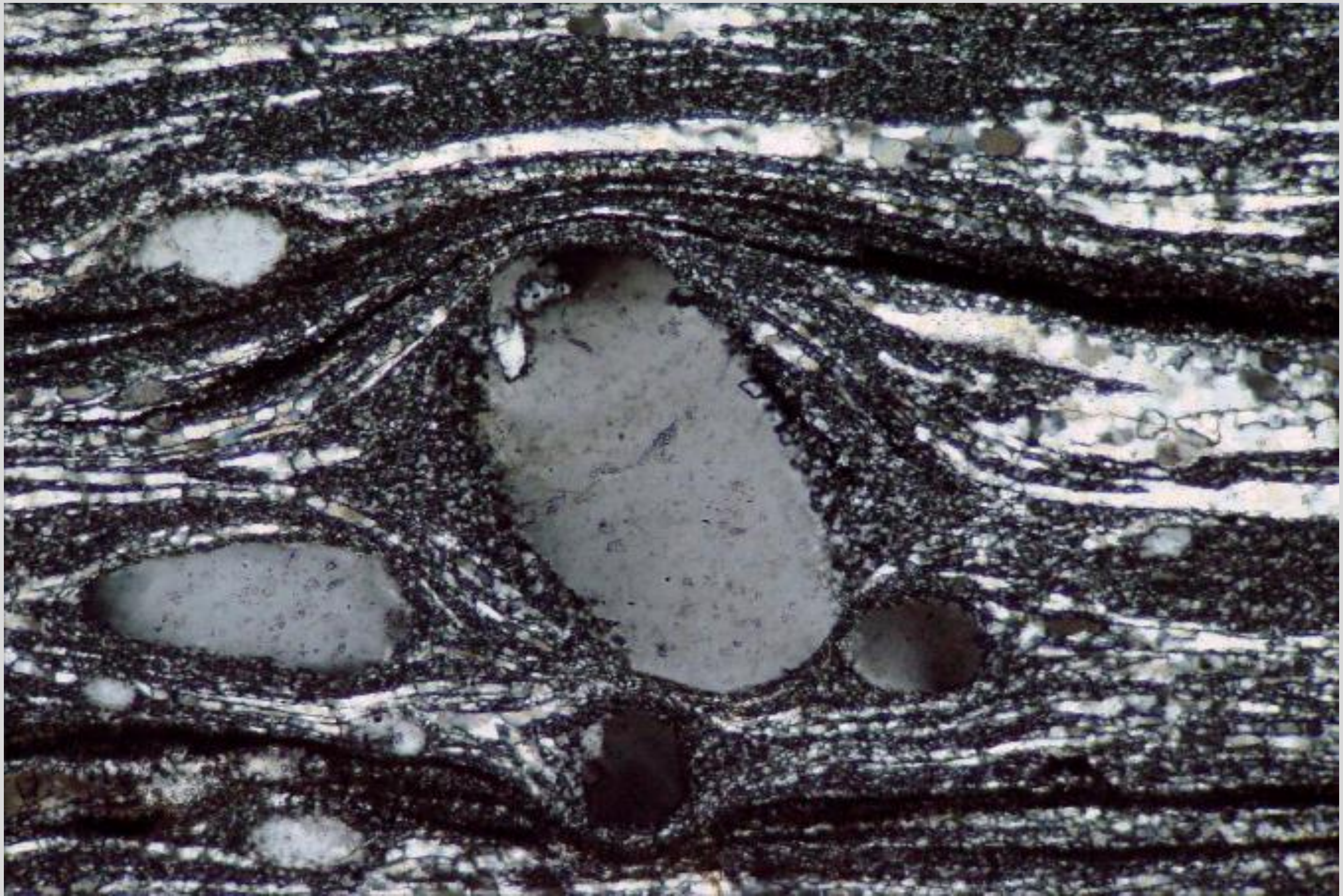
Comportamento rúptil até ~450°C

Extinção ondulante: T > 450°C

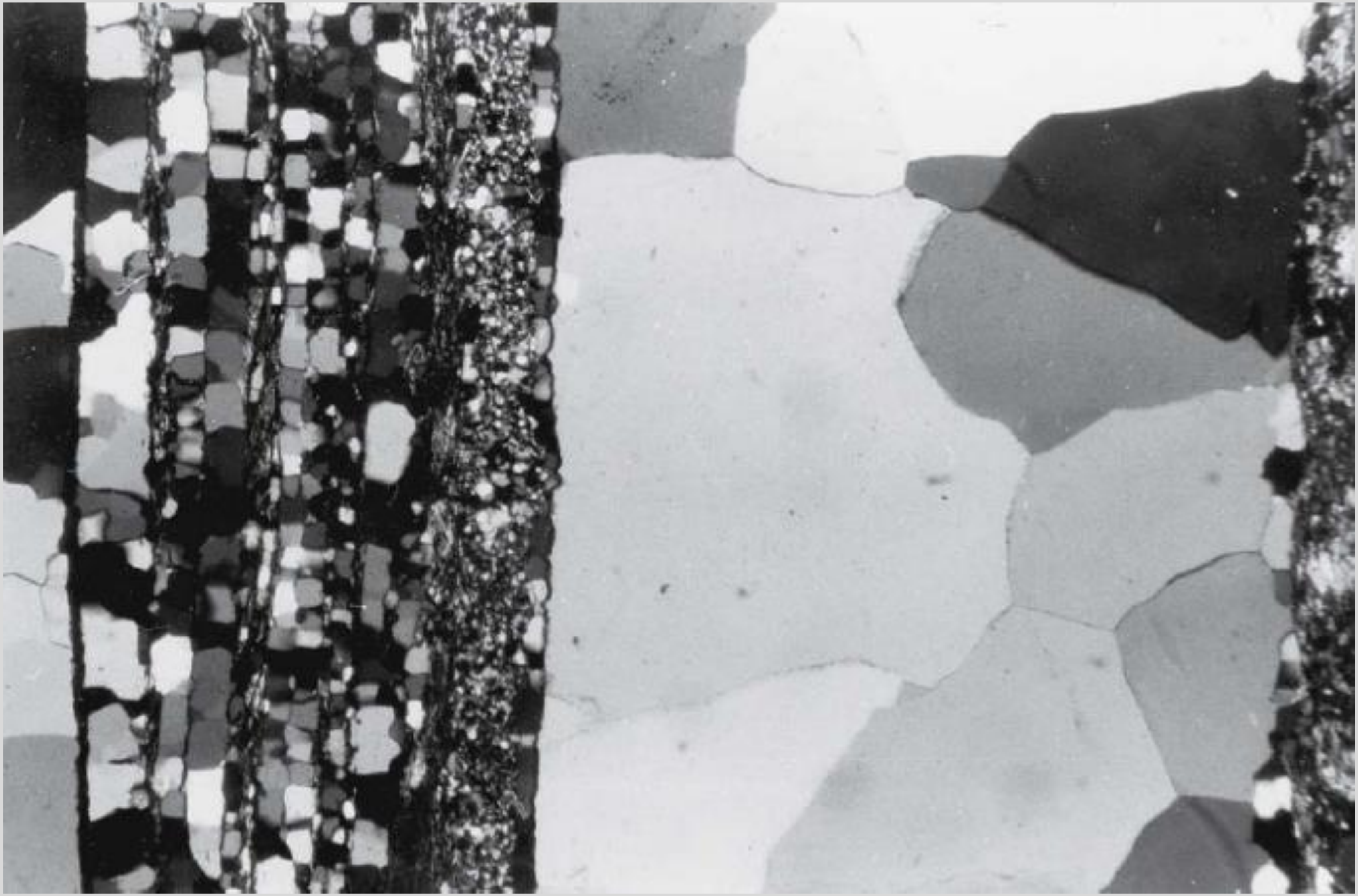
Recristalização dinâmica: T > 500°C (BLG)

Recristalização por rotação de subgrãos: 600-850°C

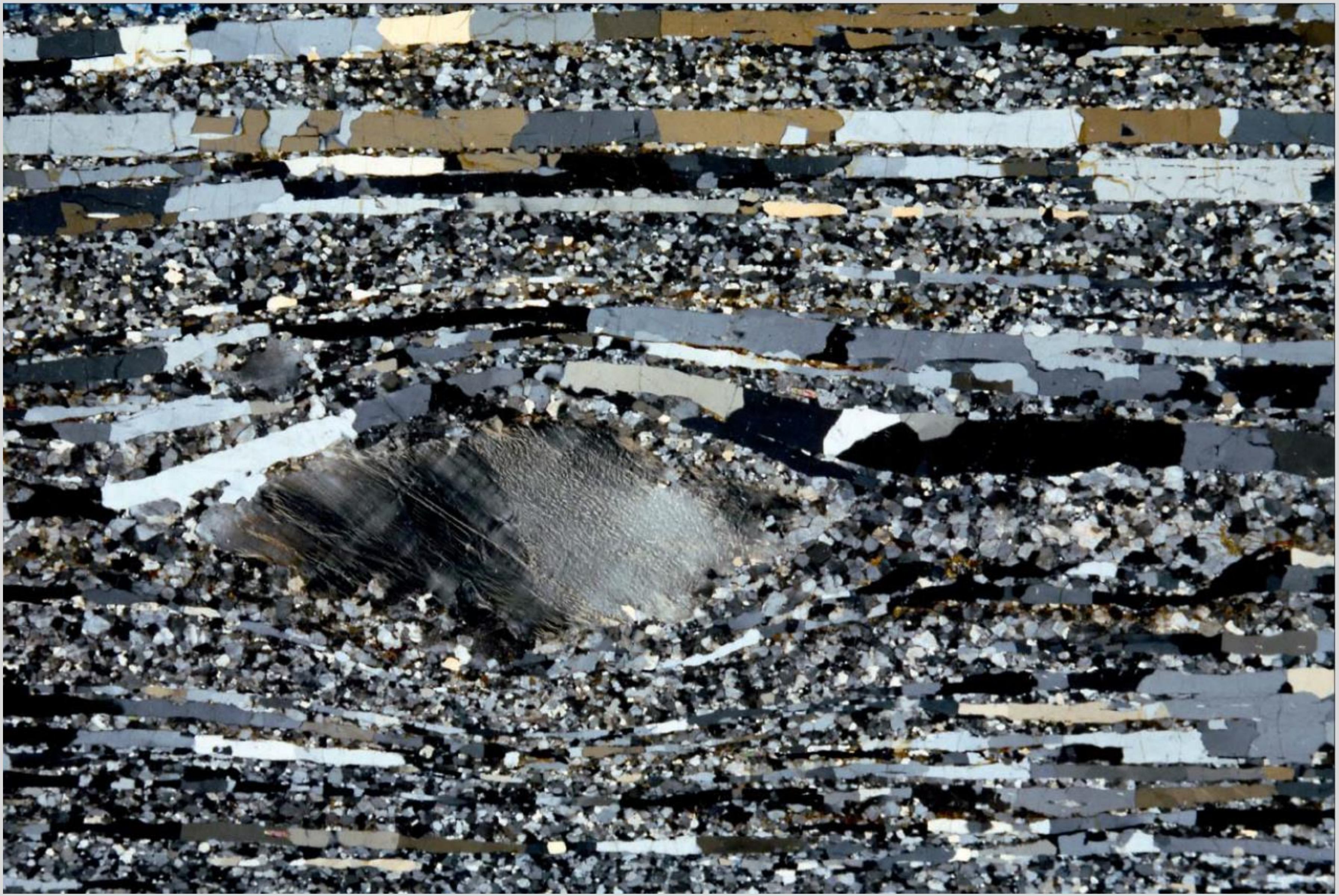
Recristalização por migração de bordas de grãos: T > 850°C



Quartzo versus feldspato



Quartzo versus feldspato (milonito de alta temperatura)

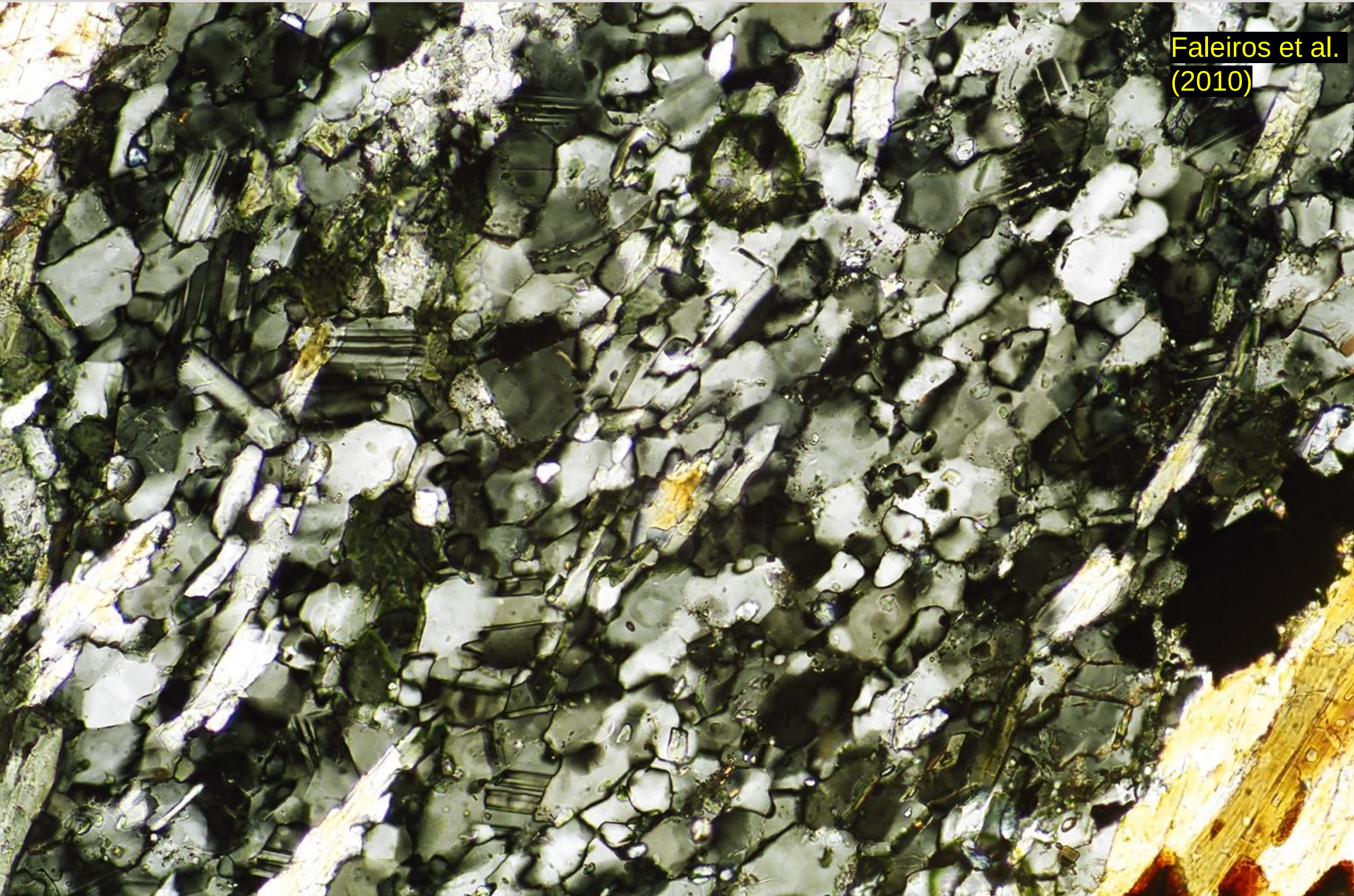


Ortopiroxênio recristalizado (milonito de alta temperatura)

Milonito máfico:
Porfiroclasto/blasto (núcleo de actinolita, borda de tschermakita)

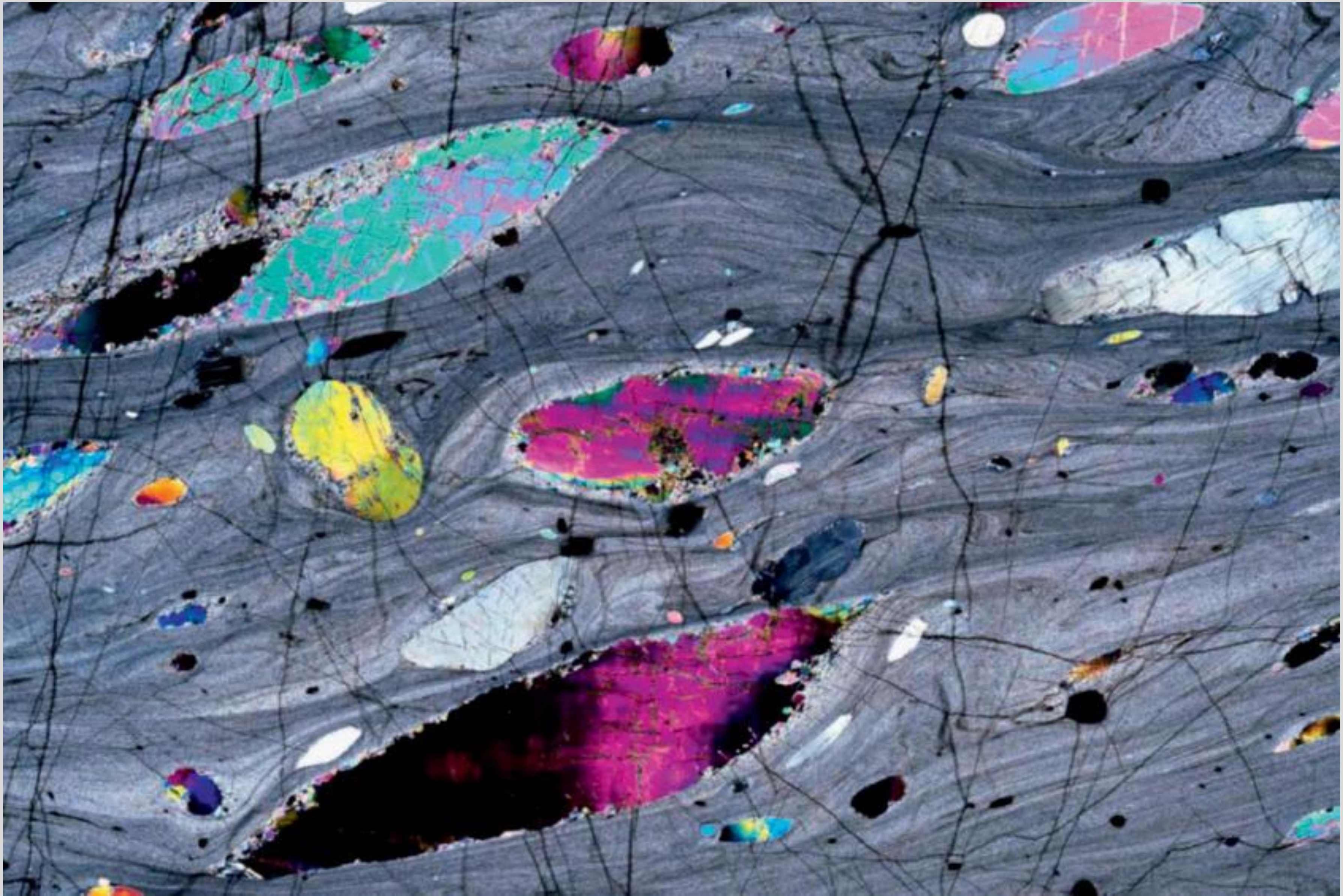
Faleiros et al. (2010)

Milonito máfico:
Matriz recristalizada com andesina + epidoto ± hornblenda

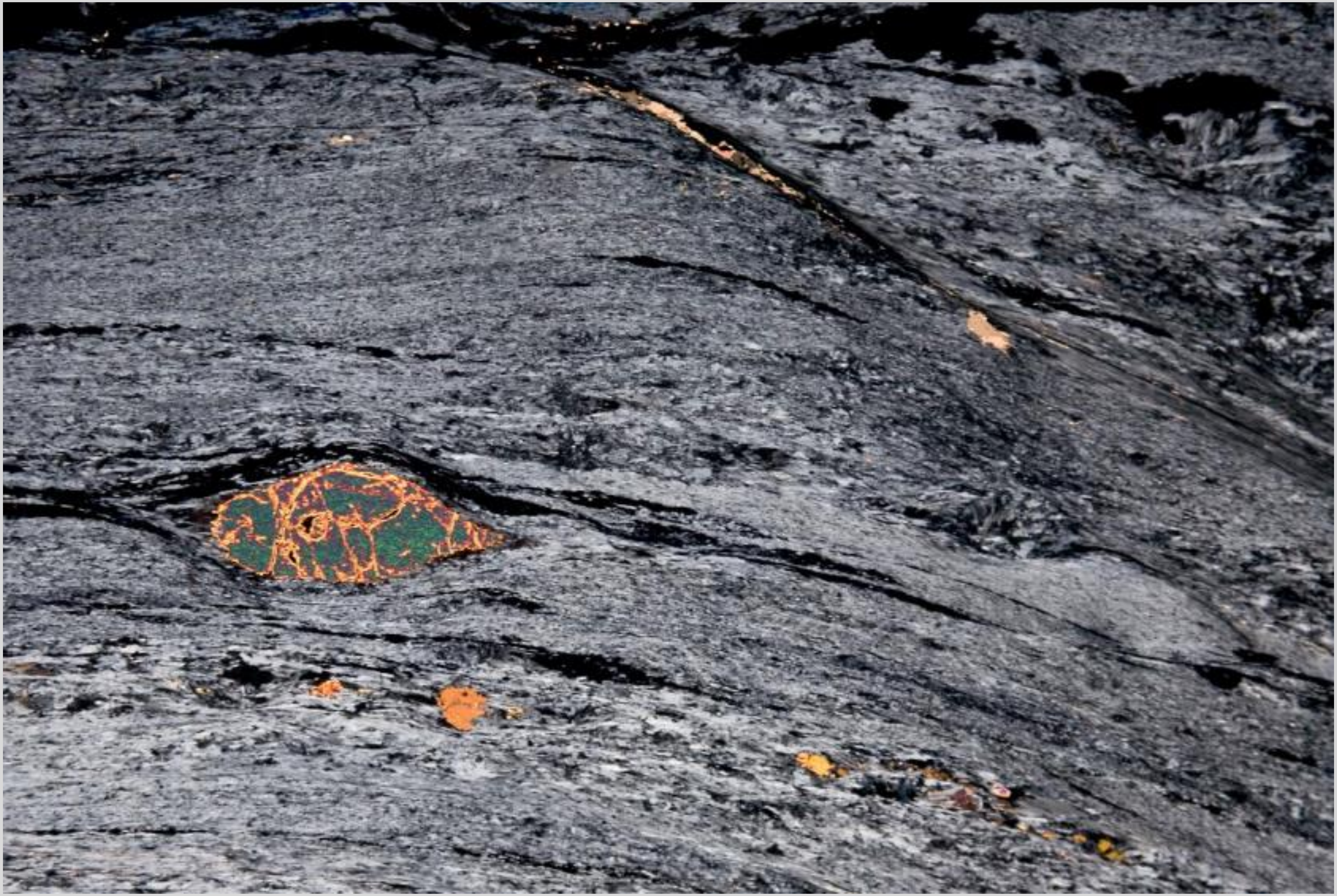


Faleiros et al. (2010)

Lherzolito milonitizado: porfiroclastos de Ol, Opx, Cpx, Spl em matriz muito fina com mesmos minerais + plagioclásio.

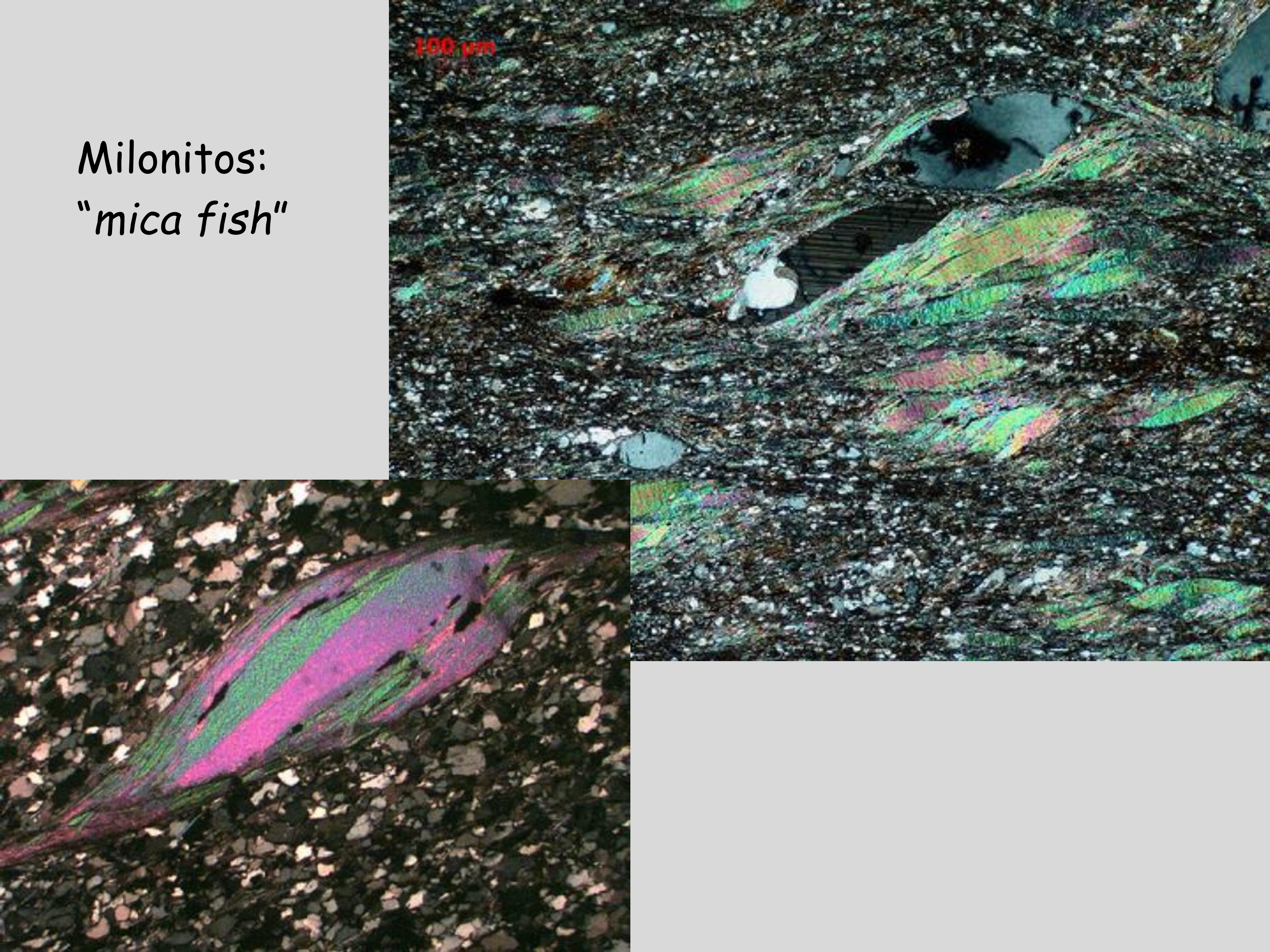


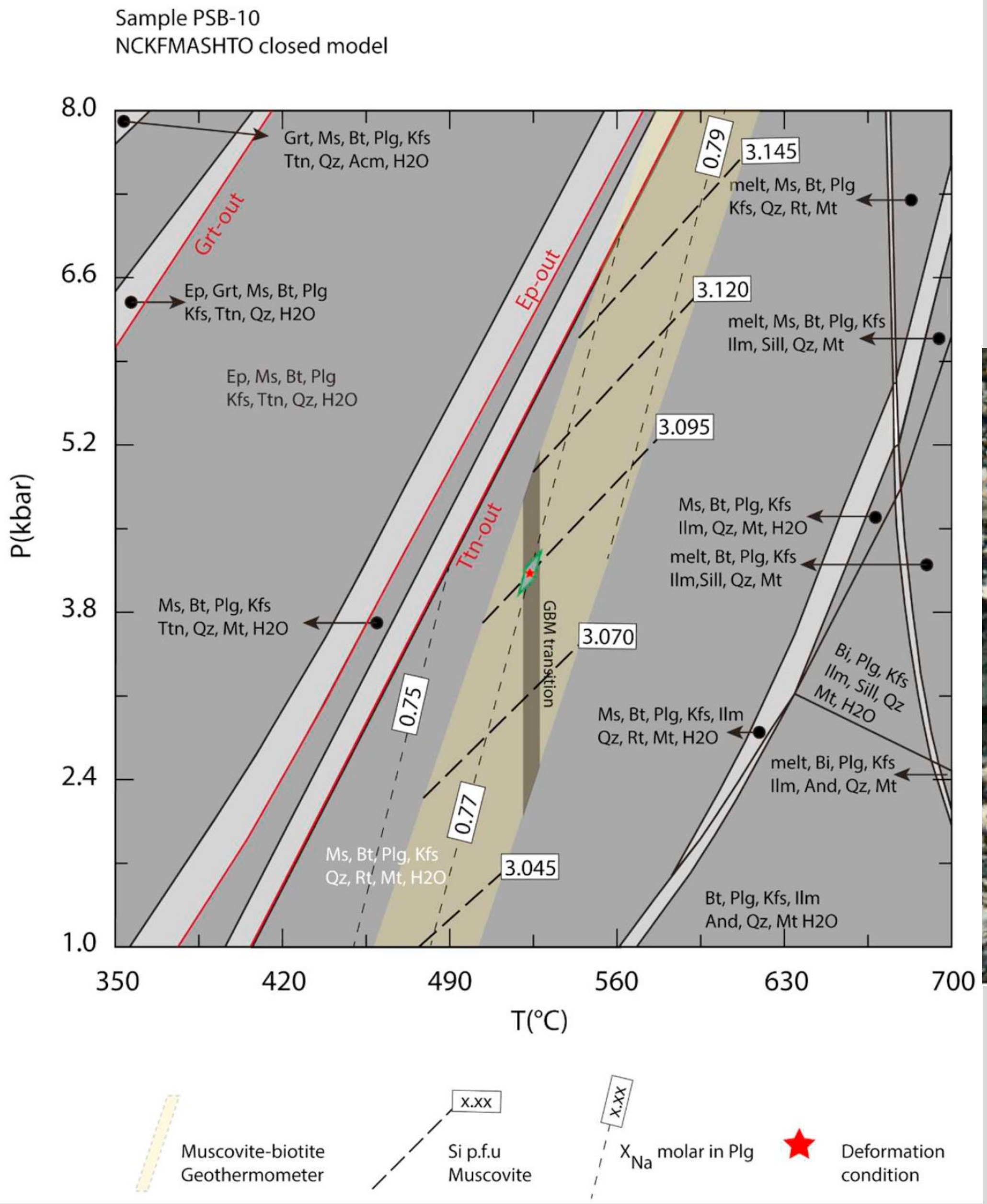
Serpentinito milonítico (porfiroclasto de titanoclinohumita)

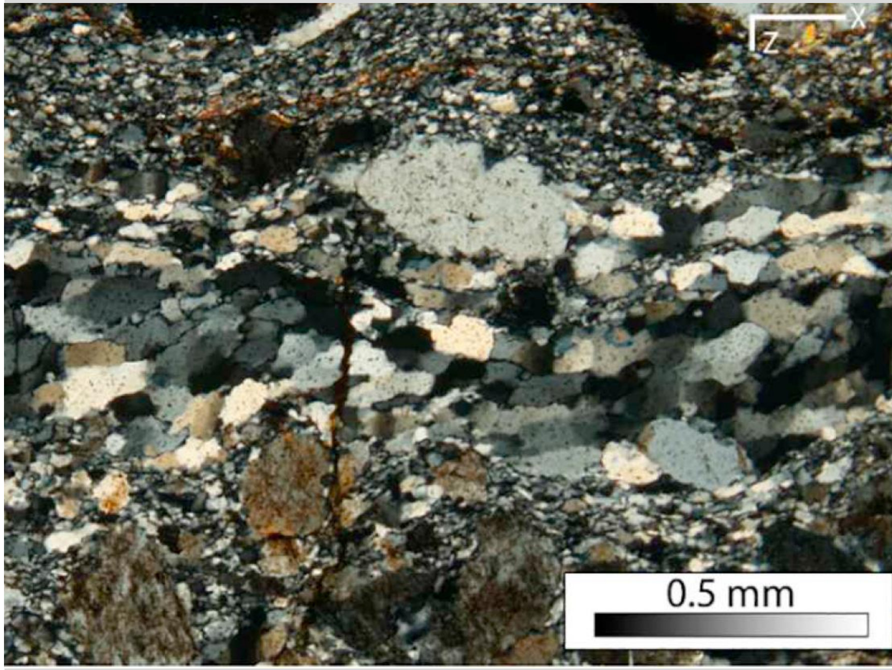


Milonitos: porfiroclastos

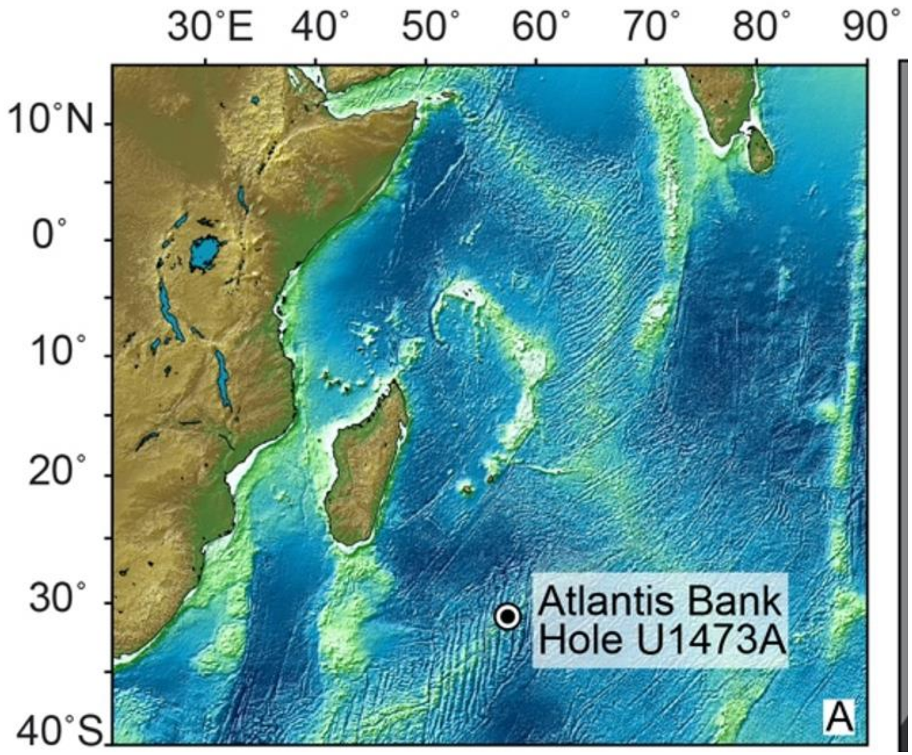
Milonitos:
"*mica fish*"







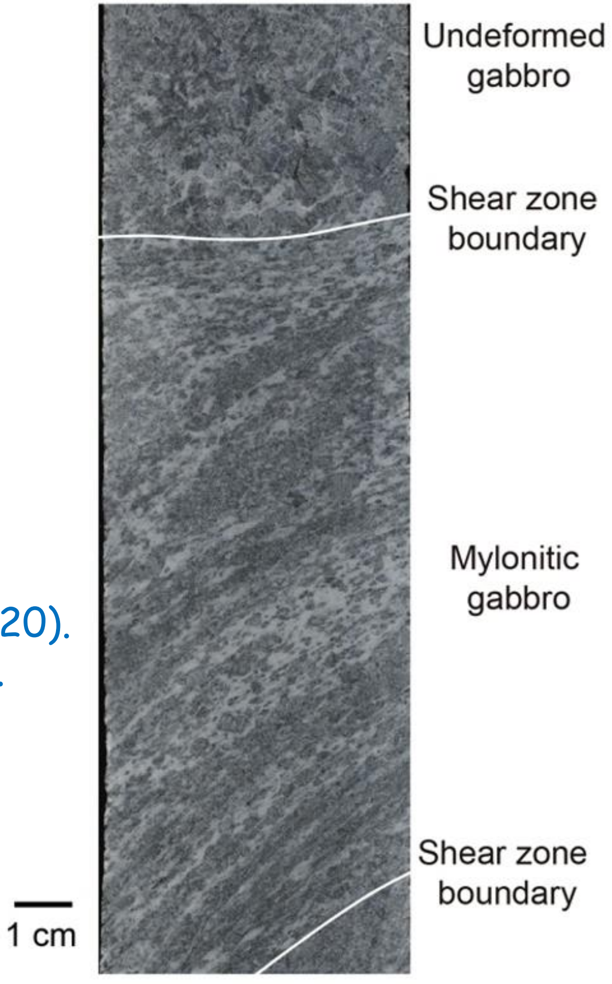
Ribeiro et al. (2019). Tectonophysics 751: 83-108.

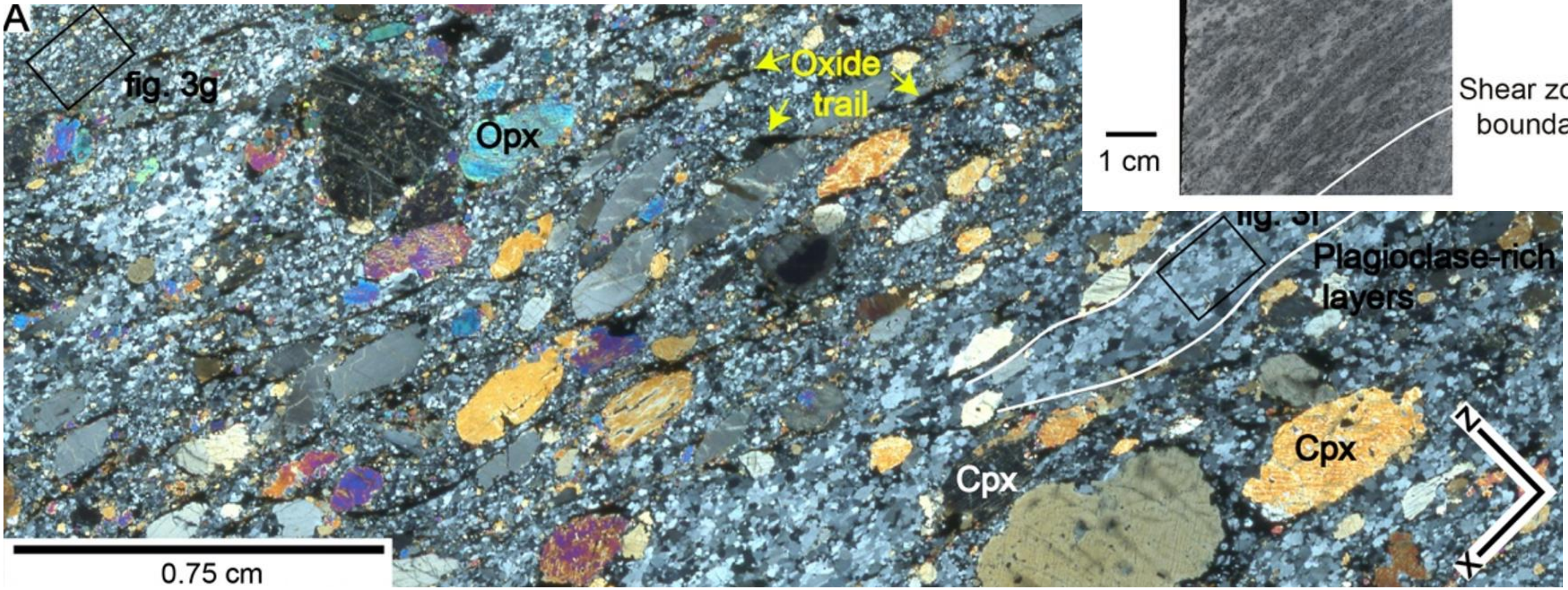


850-870 °C

2,5-2,8 kbar

Taufner et al. (2020). Lithos, submetido.





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