MICROSTRUCTURAL AND METAMORPHIC EVOLUTION OF THE PORTALEGRE SHEAR ZONE, NORTHEASTERN BRAZIL

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ABSTRACT MICROSTRUCTURAL AND METAMORPHIC EVOLUTION OF THE PORTALEGRE SHEAR ZONE, NORTHEASTERN BRAZIL At the end of the Brazilian/Panafrican thermal event, granitic emplacement followed by important shearing affected the Precambrian of northeastern Brazil. The uprising of the syntectonic granites required lateral-stress compensation as exemplified by the Portalegre Shear Zone (PSZ). Homogeneous porphyritic granites were sheared and a series of mylonitic microstructures are described, based on the occurrence of feldspar porphyroclasts and recrystallized minerals: coarse, middle banded and fine granitic mylonites, ultramylonites and cataclastic rocks. These microstructures show a history of cataclastic, crystallization, and recrystallization processes progressively developed during flattening and stretching. The last uprising stage involved tensional tectonics with retrograde metamorphism and fracture cleavage. The main compressional phase occurred between 450 and 350 °C and 2 to 5 kb, in upper greenschist facies conditions. Geometric and reaction softening related to H₂O, Mn, and Fe supply or release play an important role in the tectono-metamorphic development.

RESUMO EVOLUÇÃO MICROESTRUTURAL E METAMÓRFICA DA ZONA DE CISALHAMENTO DE PORTALEGRE, NORDESTE DO BRASIL Na fase final de posicionamento dos granitos Brasilanos/Pan-africanos de NE brasileiro, houve a superposição de um importante tectonismo em forma de zonas de cisalhamentos transcorrentes, afetando tanto rochas do Arqueano como do Proterozóico. O soerguimento dos granitos sintectônicos provocaram uma compensação lateral de tensão, como exemplifica a zona de Cisalhamento de Portalegre (ZCP). Foram estudados granitos cálcio-alcalinos porfiríticos homogêneos e descrita uma sucessão de texturas miloníticas superimpostas, sendo estas baseadas na ocorrência de porfiroclastos de feldspatos e na recristalizações de paragéneses minerais sintectônicas. São descritos milonitos graníticos grossos, médios e finos, ultramilonitos e cataclastos. Estas texturas mostram uma história envolvendo processos cataclásticos e de recristalização desenvolvidos progressivamente por achatamento e estiramento mineral. O último estágio envolveu uma tectônica tracional com paragéneses retrógradas e clivagem de fraturas. A principal fase compressiva ocorreu entre 450 e 350°C e 5 a 2 kb em condições de fácies xisto-verde superior. *Softening* geométrico e de reação relacionados ao suprimento ou perda de H₂O, Mn e Fe são fatores importantes no desenvolvimento tectono-metamórfico.

THE GEOLOGICAL FRAMEWORK The Precambrian terrains of northeastern Brazil show on a regional scale a prominent distribution of lineaments, some extending over 700 km. The Pernambuco and Patos Lineaments (Fig. 1) are the principal E-W shears. NE-SW lineaments deflected by the E-W system are also developed. The principal shear zones all have vertical shear planes with dextral transcurrent movement (Ebert 1962). The two main Patos and Pernambuco Lineaments define a central region called Zona Transversal by Ebert (*op. cit.*) (Fig. 1). This separates a northern and a southern block with the northern block subdivided into many NE-SW trending sub blocks.

Figure 1 – Geographical situation of the area. Compiled and modified from the Projeto Scheelita do Seridó (Lima et al. 1980, Schobbenhaus et al. 1981)

Figura 1 – Situação geográfica da área (compilado com modificações de Lima et al. 1980, Schobbenhaus et al. 1981)

The main shearing affected Archean and Proterozoic lithologies, during the Upper Proterozoic, with associated mylonites cutting or affecting widespread Panafrican/Brazilian granites (Neves 1975). However, it is not excluded that some of these Brazilian mylonites are a reactivation product of older shear zones.

Unconformable undeformed sediments of the Paraíba Basin (paleozoic) in the west, and the Potiguar Basin (Mesozoic) in the northeast, overlie the shear zones and give the upper time limit for the end of tectonism.

Sá & Hackspacher (1980), Agrawall (1981), and Hackspacher & Oliveira (1984) described a regional polyphase evolution based mainly on superposed structural patterns, with refolding and shearing of the precambrian lithologies. Sadowski (1982) estimated the dislocation of the Patos Lineament to be at least 40 km. This value probably represents the minimal displacement for the NE shear zones too.

The study of these shear zones focusses on a part Portalegre Shear Zone, where well exposed transversal and longitudinal outcrops, give a good overview (Figs. 1 and 2), recognizing an individual evolution related to the major Patos-Pernambuco shear system.

The PSZ comprises a NE-SW lineament situated in the north block and probably extending from the Rio do Peixe sedimentary basin to Felipe Guerra where it disappears under Cretaceous sediments of the Potiguar Basin. North of Portalegre, the mylonitic zone is more than 1.0 km wide, with gradational transition into the neighbouring lithologies. The reworked Archean basement (Caicó and São Vicente Group) near Riacho do Pontal and Mocambo is characterized by metasediments and intermediate to basic orthogneisses,

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affected by migmatization or granitization probably of Brazilian age. Proterozoic metasediments of the Seridó Group discordantly overlie the basal units. They are represented by paragneisses and marbles of the Jucurutu Formation, restricted to the southeast side of the PSZ near Viçosa and Bonito (Fig. 2). The Equador (basal) and Seridó (superior) formations are not present in the area. The NE trend of the Proterozoic lithologies is prominent in all sequences.

Foliated granites and late-intrusive metadiorites are the main lithologies in the researched area. The porphyritic granites appear on both sides of the shear zone, with a NE trend and vertical foliation. The localized metadiorite shows a similar trend and is intruded into the granites. Near Sucupira, large outcrops of an igneous breccia with xenoliths from the Seridó and basement groups confirm the chronological position of the granite.

Cretaceous sediments are found near Sucupira in a 6 km² "pull-apart graben", probably the root of a series of other similar tensional structures formed along the PSZ, between the Potiguar and the Araripe Basins. Tertiary sandstones of the Serra dos Martins Formation near Portalegre form a peneplain 200 m above the regional geomorphological surface. This surface is the result of a strong post-Tertiary erosion process during a long and old regional uplift.

THE MYLONITIC ROCKS In a regional tectono-metamorphic picture, the granites show the development of a S_4 foliation associated with the D_4 deformation phase (Hackspacher & Oliveira 1984), probably related to the syntectonic emplacement of these bodies. A lateral transition from the regional S_4 foliation to the mylonitic foliation (Sm, Sm') in the shear zone shows that the mylonitic overprint was a continuous and localized process at the end of the Brasiliano. It probably involved rapid mountain building and intrusion of plutonic bodies to upper crustal levels with simultaneous brittle-ductile shearing. Later, localized NW-SE undulations and an associated vertical crenulation-cleavage (S_5) show a slow tectonic overprint affecting the older lithologies, mainly in sub-horizontal layering.

This study is restricted to sheared porphyritic granites. The different mylonites described here depend mainly on the original composition and the texture produced during the mylonitization process. Its NE-SW vertical foliation (Sm, Sm') is formed by quartz recrystallization in ribbon form, new feldspathic crystals and mica recrystallization alternating with old feldspar porphyroclast bands. The mylonitic stretching lineation (Lm, Lm') is sub-horizontal with dips of 0-15° to NE or SW. It is defined by a quartz-feldspathic alternation and clasts with pressure shadows on the mylonitic foliation planes (Fig. 3). The larger the size and number of the clasts, the better and more developed the lineation is.

The term mylonite is used here in the sense of Sibson (1977) according to which 50-90% of the matrix is dynamically recrystallized, and ultramylonite when 90-100% is recrystallized. For blastomylonite we used the limit of grain growth (>0.1 mm) proposed by Takagi (1982, in Takagi 1986). Due to the great variety of textures it was necessary to subdivide the rocks into different types. The relation among feldspar-porphyroclast, recrystallized matrix, and its primary composition was used in this classification:

- Coarse granitic mylonite is composed of 20-50% clast in a dynamic recrystallized matrix.
- Banded granitic mylonite has less than 20% clast content which are strongly arranged in bands, alternating with recrystallized layers.
- Fine granitic mylonite consists of a dynamic recrystallized matrix in fine bands with sparse clasts (10%).
- Ultramylonite has less than 10% well-rounded feldspar clasts in a very fine recrystallized matrix.
- Granodioritic and basic mylonites show a greater quantity of hornblende clasts with less recrystallized quartz.
- Protomylonite is a particular group with less than 10% recrystallized material with a predominantly granitic texture.
- Cataclasite represents localized brittlely deformed granites or mylonites, with weak recrystallization along microfaults and fracture cleavage.

The coarse granitic mylonite (Fig. 4A,B,C) is undoubtedly the most important textural feature in the PSZ. It occurs along most of the shear, between Portalegre and Marrecas

Figure 2 – Geological map of part of the Portalegre Shear Zone. Modified cross-section from Hackspacher & Oliveira (1984)

Figura 2 – Mapa geológico de parte da zona de Cisalhamento de Portalegre (Perfil modificado de Hackspacher & Oliveira 1984)

(Fig. 2). It is characterized by a coarse pink mylonite of granitic composition, with K-feldspar, oligoclase, quartz, biotite and accessory titanite, zircon, and apatite. Coarse bands are formed by the alternation of feldspar-porphyroclast layers and quartz-feldspar matrix recrystallization around the older grains. The clasts, up to 3 cm in size, are composed of K-feldspar, oligoclase and sometimes biotite, titanite and zircon. The K-feldspar crystals are broken, locally myrmekitic and recrystallized, with initial formation of bands. The fine grained matrix formed by quartz, feldspar, and green biotite shows, under the microscope or in peels, a well-developed Sm foliation refolded and forming a new secondary Sm' plane that can also be mylonitic. This Sm' can be strongly developed near clasts (Fig. 3C). The textures of these lithologies can have sudden lateral variations NE and SW from Portalegre.

The banded pink granitic mylonite (Fig. 4D) is strongly foliated mainly between Viçosa and Riacho do Pontal, and in some other parts along the PSZ. The textures are defined by an alternation of mm-thick bands composed of coarse and fine recrystallized minerals with some porphyroclasts. The coarse bands are formed mainly by 50 to 150 μm recrystallized feldspar (K-feldspar and oligoclase) and quartz alternating with the fine bands. These fine bands are composed of a fine groundmass of 10-20 μm large quartz, K-feldspar, oligoclase, and green biotite. Titanite, garnets, zircon, and oxides are accessories. Feldspar clasts are reduced to less than 15% of the total volume by recrystallization. Disseminated garnets and oxides appear as reaction products from green biotites.

The fine granitic-mylonite (Fig. 3A) is formed in restricted parts of the SW side of the area by a quick transition between coarse mylonite and/or ultramylonites. The granitic composition is evidenced by feldspar clasts and recrystallized centimeter to millimeter bands of quartz, biotite, and feldspar. The fine mylonitic foliation Sm surrounds feldspar clasts and can be folded isoclinally on a millimeter scale or may form open folds on a meter scale. A new Sm'' mylonitic foliation is formed as an axial-plane foliation as similarly described by Bell & Hammond (1984). The Sm foliation is formed principally by recrystallized quartz-ribbon and stretched feldspar. When the Sm foliation is folded around clasts showing the new Sm' foliation in the pressure shadow region, it is possible to determine the sense of transport direction.

The ultramylonite (Fig. 4H) is characterized by a dark, fine foliated material with gradational transition between the lithologies described above. They form 0.3-2.0 m wide outcrops grading from fine to coarse granitic mylonites. Under the microscope small, 10-50 μm , grains of biotite and sericite alternate with fine quartz-feldspar layering to define Sm. Relict feldspar clasts are rare and never exceed 20% by volume. During a second deformation period, which is probably related to the formation of Sm', the Sm foliation and porphyroclasts rotated forming an asymmetrical pattern (Fig. 4H) where it is also possible to infer sense of transport direction. The clasts are thought to result of a very rapid rounding simultaneous with the recrystallization of the groundmass in Sm and Sm'.

Localized outcrops of granodioritic to dioritic mylonites are intercalated with the granites in the SW part of the area. Hand specimens suggest a plutonic medium-grained rock, but under the microscope mylonitic textures are clearly recognized. Fine plagioclase and amphibole clasts and sometimes K-feldspar are surrounded by a recrystallized matrix of quartz, mica, and epidote. It is suggested that the reduced quantity of quartz in the rock is the reason for the more competent behavior, compared with granitic mylonites.

Dark basic mylonites form a localized unit in the SW part to the area. They consist of rocks with quartz-amphibolitic composition without any apparent deformation. Under the microscope, the sheared Sm foliation is evident. An older,

probably S₄ foliation can be recognized locally with hornblende and plagioclase crystallization. The mylonitic foliation is evidenced by fragmentation of amphibole and feldspar in a newly formed biotite and oxide matrix. A secondary rotation and destabilization of Sm biotite, here also suggests an overprint of Sm'.

Protomylonite is used here for all lateral variation of mylonites to country rocks in which the texture from the primary rock is still recognizable (Spry 1969). Protomylonitic texture is very difficult to recognize in the field, it is often found in the transition zone to the country rock. Microstructures from granitic lithologies can show an initial formation of deformation bands, lamellae and myrmekitic reaction in K-feldspar, and an initial recrystallization of quartz in preferential bands.

Cataclastic rocks and pseudotachylyte (Fig. 3D) occur in NE and SW Portalegre, with brittle deformation superposed on mylonites. The brittle character and relationship with faulted rocks near Bonito suggest a connection with the Phanerozoic tectonics which formed the related "pull-apart" basin.

Deformation microstructures and textures The particular textures imprinted in the different parts of the mylonites show that the amount strain was very variable and heterogeneous through all the rock types. The associated minerals display a variable and different stage of deformation microstructures. For this reason each mineral will be treated separately.

QUARTZ MICROSTRUCTURES The development of the quartz microstructures will be related to the formation of the Sm and Sm', as defined above, in a progressive sequence. An anisotropy is formed by the alternation of feldspar and quartz bands. Related to Sm, a sequence of platy, dynamically recrystallized quartz-ribbons appear, probably due to flattening processes. Figure 4E shows a different distribution of the XY strain parameter from the neck region to the margin. The smallest grains in the neck region suffered, the most intense deformation. Statically recrystallized quartz grains are related to porphyroclast shadows (Fig. 4C) with formation of equidimensional strain-free grains. Association of these subgrains with the quartz-ribbons are difficult due to the possible relationship to Sm'.

The formation of the homogeneous Sm quartz-feldspathic bands (Fig. 3A) or layering with feldspar porphyroclasts produces the ideal anisotropy for a tectonic rotation superposed by the axial stress. The porphyroclasts serve as rotation axes for the folding of Sm. These clasts can also act as nuclei of folding in interlayered sequences on a mesoscopic scale. The sense of shear direction can in this case be defined by the asymmetry of the feldspar porphyroclasts (Passchier 1982, Simpson & Schmid 1983). Figure 4H shows a δ -porphyroclast system (sense Passchier & Simpson 1986). A reorientation of the quartz grains occurs associated with these folds and the displacement along Sm. In the hinge zone of folded Sm surfaces new Sm' grains are observed. The sheared Sm, in non-folded regions, shows similar preferred grain shaped quartz fabric oblique to the Sm surface, but is related to the same Sm'. This striking Sm' quartz is interpreted as dynamically recrystallized crystals caused by the dynamic rotation of subgrains and grains. The dynamic recrystallization is supposed to be related to the rotation of subgrains (Bell & Etheridge 1973, White 1975). This dynamically recrystallized quartz is thus probably the result of a progressive transformation of Sm ribbon quartz. Where Sm' is well developed, mainly in more homogeneous units, Sm will disappear. Subgrain development and undulatory extinction of these recrystallized grains are probably related to the decrease in temperature and the more brittle character of Sm'.

Figure 3 – A. Fine granitic mylonite with relict of the Sm foliation overprint by new Sm' quartz recrystallizations. Site 1. Crossed nicols. **B.** Feldspar clast with a myrmekite and a biotite front. Sm and Sm' are evident. Coarse granitic mylonite in XZ face. Site 9. Crossed nicols. **C.** Sphene crystal extended in stretching direction Lm. Coarse granitic mylonite, XZ face. Site 9. Crossed nicols. **D.** Microfaults associated with fracture cleavage Sm'' in coarse granitic mylonite. S, and Sm' are not visible. The fine-grained quartz resulted from hydrothermal processes during Sm''. XZ face. Site 6. Crossed nicols

Figura 3 – Fotomicrografias A. milonito granítico fino com relictos da foliação Sm sobreposta por nova Sm' de quartzo recrystalizado. Local 1, nicóis cruzados **B.** clasto feldspato com uma frente mirmequítica e formação de biotita no reverso. Sm e Sm' são evidentes. Milonito granítico grosseiro na face XZ. Local 9, nicóis cruzados. **C.** cristal de esfeno alongado na direção de estiramento Lm. milonito granítico grosso, face XZ. Local 9, nicóis cruzados. **D.** microfalhas associadas com fraturas de clivagem Sm'' em milonito granítico grosso. Sm e Sm' não são visíveis. O quartzo de granulação fina resultou de processos hidrotermais durante Sm''. Face XZ. Local 6, nicóis cruzados.

Figure 4 – A. Brittle deformation of K-feldspar from the coarse granitic mylonite. Exsolution lamellae are formed around the clast, parallel to oblique quartz crystals of the matrix. XZ-face. Site 6. Crossed nicols. **B.** Strong cataclastic feldspar clast with formation of tectonic microcline twinning on clast boundaries and progressive myrmekitization. Quartz is dynamic recrystallized in Sm. XZ-face in a coarse granitic mylonite. Site 5. Crossed nicols. **C.** Alternation of fine and coarse recrystallized bands quartz-feldspathic composition in middle banded granitic mylonite. Porphyroclasts show a intermediate stage of recrystallization. XZ-face. Site 10. Crossed nicols. **D.** Recrystallized plagioclase clast in a fine-grained quartz-feldspathic matrix of a banded granitic mylonite. XZ-face. Site 10. Crossed nicols. **E.** Dynamic recrystallization of quartz (Sm) between K-feldspar clast, in a fine granitic mylonite. Subgrain related to Sm' overprint on the left side. The feldspar clast is progressively transformed into biotite, quartz, oligoclase at the grain border. XZ-face. Site 6. Crossed nicols. **F.** K-feldspar clast of the coarse mylonite with myrmekite crystallization. Sm quartz layer shows oblique Sm' grains or subgrains. XZ-face. Site 6. Crossed nicols. **G.** Deformation bands and microcline twinning in a clast of the coarse granitic mylonite. Myrmekite formation begins to destroy the clast. XZ face. Site 6. Crossed nicols. **H.** Ultramylonite with fine Sm foliation deformed during Sm'. The porphyroclasts show a sinistral movement. XZ face. Site 6. Crossed nicols.

Figura 4 – Fotomicrografias A. deformação rúptil de K-feldspato de milonito granítico grosso. Lamelas de exsolução são formadas ao redor dos clastos, paralelas a oblíquas aos cristais de quartzo da matriz. Face XZ. Local 6, nicóis cruzados. **B.** Clasto de feldspato fortemente cataclástico com formação de geminação tectônica da microclina nas bordas do clasto e progressiva mirmequitização. Quartzo é de recrystalização dinâmica em Sm. Face XZ no milonito granítico grosso. Local 5, nicóis cruzados. **C.** Bandas recrystalizadas finas e grossas alternadas de composição quartzo-feldspática em milonito granítico medianamente bandado. Porfiroclasto mostram um estágio intermediário de recrystalização. Face XZ. Local 10, nicóis cruzados. **D.** Clasto de plagioclásio recrystalizado em uma matriz quartzo-feldspática de granulação fina de um milonito granítico bandado. Face XZ. Local 10, nicóis cruzados. **E.** Recrystalização dinâmica de quartzo (Sm) entre clasto de K-feldspato, em um milonito granítico de granulação fina. Subgrão relacionado à Sm' no lado esquerdo. O clasto de feldspato é progressivamente transformado em biotita, quartzo, oligoclásio na borda do grão. Face XZ. Local 6, nicóis cruzados. **F.** Clasto de K-feldspato do milonito grosso com cristalização de mirmequita. Banda de quartzo Sm mostra grãos ou subgrão de Sm' oblíquos. Face XZ, Local 6. **G.** Bandas deformadas e geminação da microclina em clasto de milonito granítico grosso. Começo de destruição do clasto devido à formação de mirmequita. Face XZ. Local 6, nicóis cruzados. **H.** Ultramilonito com foliação Sm fina deformada durante Sm'. Quartzo arredondado e porfiroclasto de feldspato mostram movimento sinistral. Face XZ. Local 6, nicóis cruzados.

Figura 5 – Trama do quartzo de milonitos. Local 6. Projeção estereográfica igual área no hemisfério inferior. A, B e C de platina universal; D e E são medições de intensidade relativa de raio-X (reflexo) obtidos em goniômetro de texturas A. Orientação preferencial do eixo C do quartzo em uma banda quartzo a de milonito grosso; B. Linhas de contorno de A; C. trama do eixo C do quartzo em um milonito grosso heterogêneo; D. orientação preferencial do eixo M_1 do quartzo; E. orientação preferencial do eixo $R_1 + R_2$ do quartzo; F. integração das principais linhas de contorno B, D, E e eixo M_2

CRYSTALLOGRAPHIC QUARTZ ORIENTATION This section describes complementary data on the degree of orientation of the crystallographic elements from the Sm and Sm' quartz crystals. The measurements were made in homogeneous and heterogeneous material from the fine granitic mylonite, since the other types did not show sufficiently large homogeneous areas for a precise statistical analysis. In homogeneous areas, the number of measurements were sufficient. On the other hand, the influence of Sm'' fracture cleavage in heterogeneous parts can make measurements impossible. On a homogeneous sample from the fine granitic mylonites with significant quartz layers it was possible to use Universal Stage methods for the basal and X-ray goniometer measurements for the pyramidal (reflex R) and prismatic (reflex M) crystallographic plane (Skrotzki & Hackspacher 1987).

The comparison of C-axis orientation in the homogeneous field can be seen in figure 5A and C. In both, a tendency towards the formation of small girdles around the Sm-surface can be seen. Using the simulation model for C-axis orientation of quartz by Lister *et al.* (1978), Model II with axial shortening explains the distribution in figure 5A and C. The M and R reflex obtained through the X-ray goniometer can be seen in figure 5D and E. For a combined observation, figure 5F gives the disposition of peaks C, M, and R subdivided in 1 and 2 in dependency on the crystallographic grouping. The R-peak concentration coincides with the Sm' pole maxima. The C-axis tend to form a little girdle near to the R-peaks. The M-peaks form a girdle around the C₁ and

C₂ maxima, as expected. A synoptic construction on the side shows two statistical quartz crystals with the rhomboedral crystallographic plane parallel to Sm'. For similar situations, Lister *et al.* (1978) proposed a (c + a) slip system. Bunge & Wenk (1977) and Christie (1963) attributed similar fabric patterns to low temperature and a-slip. Without neglecting the synchronous gliding from more than one crystallographic plane, we suggest a preferential crystal boundary rotation of the Sm quartz grain and subgrain, preferably around the rhomboedral R-axes, until it reaches the new Sm' position expressed in figure 5F. Consequently, the C-axes would form a narrow girdle around R-axes.

It was not possible to measure the orientation of Sm quartz, but there is a geometric possibility that quartz C-axes lying on Sm could rotate about 60 degrees around the R-axes, along the crystal boundaries, until the Sm' final position, oblique to Sm is reached. We suggest that, instead of rotating on c + a, the C-axes rotated around R.

FELDSPAR DEFORMATION MICROSTRUCTURES

The coarse mylonite to ultramylonite rock type of the area shows a progressive change from intracrystalline and cataclastic deformed feldspar in the coarse material, to crystallized recrystallized feldspar in the fine material. An intracrystalline deformation by cold deformation or cold working is observed as mechanical twinning, undulatory extinction, kink bands and deformation bands in feldspar clasts from the coarse and medium granitic mylonites. These structural features are recognized by White (1975) and

Figure 5 - Quartz fabric of the mylonites. Site 6. Lower hemisphere equal area stereographic projection. A, B, and C are universal stage measurements; D and E are X-ray relative intensity measurements (reflex) obtained with a texture goniometer. A. Preferred orientation of quartz C-axis from a quartz layer in the coarse mylonite; B. contours of A; C. quartz C-axis fabric in a heterogeneous coarse mylonite; D. preferred orientation of the quartz M₁ - axis; E. preferred orientation of the quartz R₁ + R₂ - axis; F. integration from main contours B, D, E, and M₂ - axis

Figura 5 - Evolução microestrutural progressiva na zona de cisalhamento de Portalegre (ver texto)

Williams & Gandais (1977) as deformation phenomena. Dislocations appear in preferred crystallographic direction on the feldspar, for example the (001)-plane in the plagioclase or pericline and albite twinning in the K-feldspar. Deformation bands and mechanical twinning can cross from one to other and terminate at the boundary of the clast. All the twins begin large at the edges and finish wedge-shaped in the middle of the clasts. Microcline twinning (Fig. 4B) is strongly developed on the longest side of the clast, related to the higher deformation rate (Starkey 1967, Vernon 1965) on that part. Another family of lenticular twins, recognized as mechanical by Vernon (1965), appears in low angle to the clast (Fig. 4A, E) as a continuity of exsolution described below. Cataclasis includes a brittle deformation affecting the K-feldspar or plagioclase in preferential parts with great mechanical distinction between matrix and clasts. Figure 4A and B show an extended K-feldspar clast lying in the main Sm foliation and oriented in the Lm stretching lineation. The assymetric distribution of microshears or cracks gives an idea of the progressive extension and rotation of the clast by a non-coaxial deformation during Sm'. The microfaults are still filled by quartz. This brittle deformation is described as the early mylonitic (Sm) mechanism acting in areas where cold working or recrystallization could not accomodate the strain rate imposed on the crystal. Associated microshears are thus probably an extension of deformation bands formed by primary pure shear process during the definition of the first assymetric Sm plane from the subsequent mylonite. With the increase of the strain rate, the feldspar began to crystallize recrystallize and change its chemistry. Recrystallizations are an end result in the dynamic recovery and dynamic recrystallization forming subgrain and grain in steady state (White 1976). New grains of feldspar should be nucleated in preferential regions (White *et al.* 1980).

EXSOLUTIONS Microperthitic oligoclase lamellae or antiperthitic K-feldspar lamellae occur in the oligoclase (Fig. 4A) and have been analyzed by microprobe (Table 1). The lamellae occur in most deformed parts of the feldspar porphyroclast, at about 45 degrees to the schistosity, with a strong relation to the Sm' rotational deformation. In figure 4A the lamellae are a prolongation of cleavage planes that cut the porphyroclast. Superposition of different lamellae can be attributed to reactivation processes. Exsolution of albite components in alkali-feldspar is probably related to deformation (Ramberg 1962, Spry 1969, Passchier 1982) mechanism. White (1975) and Vidal *et al.* (1980) also observed that chemical changes are linked more to deformation than recrystallization. The same situation is interpreted to have occurred here with the transition from lamellae to intracrystalline and cataclastic deformation. Perthitic lamellae are a low T phenomenon produced by diffusion (Passchier 1982). White (*op. cit.*) and Passchier (*op. cit.*) suggest a strain enhanced diffusion for this process.

MYRMEKITE A progressive crystallization from the border to the center (myrmekite) overprints the clasts and obliterates the lamellae from the microcline (Fig. 4F and 4G). This can be seen as a progression from intracrystalline deformation and lamellae formation to crystallization (Hamner 1982). With increasing strain rates and temperature, crystallization begins to transform the feldspar. This forms new phases such as oligoclase, K-feldspar, biotite, quartz, epidote, and secondary sericite. An interaction of metamorphism and structural processes is shown by the tendency to reduce the "free" energy formed during deformation by the crystallization of a new stable phase. This process of new grain formation is also related to deformation with increasing strain rate (Bhattacharyya 1971, Binns 1966, White 1975, Vidal *et al.* 1980). The crystallization of

myrmekite is clearly seen with scanning during the microprobe analysis (Fig. 6), forming a bulbous habit exhibiting markedly curved surfaces against the K-feldspar. The bulbs are formed by quartz blebs associated with oligoclase. These exsolutions form mainly on the clast boundaries, and in the intergranular position, between host grains, and sometimes in crystallized groundmass. Phillips & Garr (1973) related myrmekites on the margins of megacrysts to be the result of a chemical potencial promoting exsolution in the solid-state as function of grain boundary energy. Ashworth (1972) suggested that metasomatic processes could interact by diffusion through the matrix. The location of myrmekite at the clast margins may be explained by considering the distribution of pressure around preexisting porphyroclasts undergoing rotation and shearing during deformation (Ohta 1969). The increase of grain boundary energy and diffusion show an interesting parameter for myrmekite formation.

In figure 4E and 6 the biotite rims are normally situated at the outer part, far from the host grain, with myrmekite along the inner part of the new grain aggregate with bulbous in sense of the old grain. This myrmekite front is followed by formation of quartz and oligoclase rims sometimes with biotite and epidote intergrowths. The gradual development of fine oligoclase bands, biotite, and epidote around the older feldspar has its main way of formation in the myrmekite process. The grain mantle enhanced the deformation when compared to the core (White 1975, Vidal *et al.* 1980). This crystallization process must stop when the quantity of free Na+ decreases in the system, then only the recrystallization of K-feldspar will be possible.

OLIGOCLASE AND K-FELDSPAR CRYSTALLIZATION OR RECRYSTALLIZATION

Dynamic recrystallization and reaction enhanced ductility and diffusion processes during the Sm forming event follow the above described myrmekitic process. This enhanced ductility, mainly observed in the quartz component, is also found in the fine crystallized/recrystallized oligoclase bands which began to form between quartz and porphyroclast bands. These dynamic fine crystallized bands are related to higher stress in the system (White 1976). There must exist a difference in the behavior of fine and coarse recrystallization of the feldspar, which seems to be the primary heterogeneity between clast and fine recrystallized bands, and the consequent difference in energy involved in both systems. The progressive feldspar recrystallization will occur in strongly deformed parts of the crystal by the nucleation mechanism (Borges & White 1980, White 1975, Passchier 1985). Subgrain rotation and local grain boundary migration seem to be an important mechanism (Vernon 1965). In the PSZ, the fine banded oligoclase and K-feldspar appear to have been formed by nucleation aided by stress enhanced diffusion.

Mylonitic deformation. Discussion The progressive development from coarse to ultramylonites is associated with deformation processes controlled by mineralogical heterogeneities, in contrast with quartz/feldspar, associated with different strain rates. The behavior of the primary feldspar (50-60% by volume in the granites) must influence rotational processes (Debat *et al.* 1978). Also the degree of recrystallization depends on the porphyroclast concentration (Vidal *et al.* 1980) principally in the coarse mylonites. The continuous decrease of clast size in the other types must be influenced by a localized progressive strain rate increase. Progressive development of textures is related to heterogeneities parallel to the mylonitic foliation, as proposed by Lister & Williams (1983). With increasing temperature, strain rates, and confining pressure the granites began to deform by fragmentation and flattening of feldspar and

recrystallization of quartz. Rotation of porphyroclast was followed by dynamic recrystallization of feldspar on high concentrated extremities of the clasts (Vidal *et al.* op. cit) accompanying the quartz recrystallization with fabric development. The progressive deformation with increasing strain rate and mineral transformation changed the coarse mylonite to fine and ultramylonite types in similar PT conditions.

It was possible to reconstruct the deformation/crystallization/recrystallization sequence in the following way: firstly, cataclastic behavior with brittle failure and mechanical twinning in plagioclase and K-feldspar; followed by the formation of deformation bands and exsolution lamellae in K-feldspar and plagioclase clasts. The next deformation could now act on a pre-existing heterogeneity. Alternate bands of fine recrystallized quartz-feldspar and coarse feldspar show clast rotation indicating a non-coaxial deformation. The feldspar clasts played a very important role, as a resistance to the material transport along the Sm surface. The clasts acted as rotation axes perpendicular to the transport direction. The Sm foliation wraps around, and folds in, the new pressure shadow region; a new Sm' foliation appeared by recovery and recrystallization of the Sm' crystals. Mechanical microstructures such as deformation lamellae, twinning and exsolution were formed in feldspar; the next step was the formation of myrmekite and recrystallization in the fine and coarse bands. The anisotropy formed in the coarse mylonite increased until the formation of a millimeter to centimeter-thick banded mylonite. The fine K-feldspar, oligoclase, and quartz will continue in this condition during the transformation of the porphyroclast in coarse recrystallized bands. The shape of these bands seems to be related to protected bands recrystallized in coarse grains (50-400 μm) surrounded by fine quartz (10-40 μm) and feldspar (5-10 μm) matrix, predominantly at relatively low bulk strain. Grain formation must be due to interaction of migration and recovery processes to reduce the high dislocation rate caused by the main mylonitic event. Sheath-folds were preferentially formed in fine mylonite and ultramylonite by the heterogeneous progressive deformation during Sm'. Fold axes could rotate toward the direction of the mineral stretching or mineral flow. The possibility of contemporaneous stretching and formation of sheath-folds (Bell & Hammond 1984) is possible near Mocambo, where a 10 km long marble lense is included in the shear zone. Folds and stretching lineations parallel to the movement direction were formed here. In some parts it is possible to use the nomenclature S/C tectonite in reason of the evolution history between Sm and Sm' foliation. The latest tectonism along the PSZ tectonic evolution was the formation of a fracture cleavage Sm'' parallel to the older direction and strong crystallization of epidote and sericite. A sudden modification of the PT conditions accompanied the PSZ to a upper crustal level.

The progression Sm, Sm', Sm'' is similar to the sequence described by Wakefield (1977) through a gradation from mylonitic foliation to strain-slip cleavage to fracture-cleavage and finally to faults. By considering this system, a change from compressional to tensional tectonics must be accepted in this case.

METAMORPHISM Metamorphic relations between the regional and the main mylonitic phase are described by Hackspacher & Oliveira (1984). The conditions of the metamorphism during the mylonitic phase can be determined by the change in rheology and chemical composition of the minerals and also by the analysis of the new mineral associations.

The mineral stability can be determined by examining the transformation from the primary granitic assemblage to the

new one. S₄ biotites, primary K-feldspar, and plagioclase are transformed to new biotite, more sodic plagioclase, K-feldspar recrystallization with crystallographic and chemical modifications, garnet and epidote in the shear zone. There is a tendency to transform all the primary rock into a well foliated mylonite. Quartz reorientation, feldspar recrystallization, and new biotite formation are examples of adaptation of the mineral phases to the new thermodynamic conditions of mylonitization. Petrographic observations suggest the following sequence during the development of the mylonitic texture:

1. The formation of torsion perthite in the K-feldspar, followed by the formation of a plagioclase mantle or myrmekite structure around the microcline porphyroclasts.

2. Substitution of K-feldspar by the association biotite, plagioclase, quartz, and development of the mylonitic foliation Sm.

3. Formation of spessartine, epidote, and sericite during the late mylonitic deformation act Sm'.

Microprobe analysis were performed on the different mineral phases to define the thermodynamic conditions of the mylonitic event (Tab. 1).

The early process of redistribution of Na₂O, K₂O, and CaO between plagioclase and K-feldspar has three different expressions depending on the spread of the deformation. The perthite formation is associated with the deformation of the crystal and segregation of Na₂O and CaO in the dislocation planes, the albitic border is associated with granulation of the porphyroclast and formation of sub-grains. Finally, the formation of the perthite border would be a similar process of the albitic border, but with symplectic crystallization of the quartz. The microprobe analysis shows that the Na₂O and K₂O composition changed rapidly from the clast center to the recrystallized border. A scan profile across figure 4E shows a change of K₂O from 15.00 to 0.23% (Tab. 1 and Fig. 6) and a Na₂O increase from 0.72 to 8.26% in the same sense from a clast to a new grain. A similar picture was shown by the myrmekitic transformation. The transforming process by crystallization and recrystallization of the feldspar involved other phases. An example can be shown by figure 6 where K-feldspar clasts are transformed to oligoclase, quartz, biotite, and epidote.

The increase of biotite, recrystallized K-feldspar, and oligoclase, linked to the decrease of K-feldspar porphyroclasts and the change between K₂O and Na₂O by myrmekitic building suggest that the oligoclase crystallization was a continuous process from myrmekitization, documented by a change between K₂O (K-feldspar) and Na₂O (plagioclase), with development of strong textures from the PSZ in the upper greenschist condition. Hamner (1982) recognized in his study a similar situation with transformation of K-feldspar host to oligoclase and albite with mass transfer of Al, Ca and Si.

Using the two-feldspar geothermometry (Withney & Stormer 1977) we note the following temperature; 475° and 450°C for 5 and 2 kb, respectively, for the perthite (Tab. 1, samples 2 and 5) and albitic border (samples 1 and 4) and 420° and 400°C for 5 and 2 kb, respectively, for the myrmekitic border (samples 3 and 6). This structure would be the final expression of the alkali mobilization and could be related to the biotite formation. The syntectonic mica comes from the chemical modification of the S₄ biotite associated with the breakdown of the K-feldspar with a necessary supply of iron to justify the high Fe/Mg ratio of the new biotite (Tab. 1). The gliding reaction of the S₄ biotite to the new biotite would be:

Table 1 – Abundances of major elements and oxides in weight percent. Anorthit content in mole %. Coarse mylonites. Sample location in figure 2

Tabela 1 – Abundância dos óxidos dos elementos maiores (porcentagem em peso). Conteúdo de anortita em mole %. Milonitos grossos. Localização das amostras na figura 2

SAMPLE	MICROCLINE			PLAGIOCLASE			BIOTITE		GARNET	
	1	2	3	4	5	6	7	8	9	10
SiO ₂	64.39	63.44	62.99	65.21	64.84	65.25	37.21	38.12	36.44	36.66
TiO ₂	-			0.03	0.01		0.83	2.83	0.05	0.03
Al ₂ O ₃	19.86	20.16	19.91	21.27	22.89	23.03	17.76	18.39	22.52	22.50
FeO	0.02	0.03	0.01	0.30	0.03	0.04	29.58	25.34	18.28	18.38
MnO							0.42	0.34	23.91	24.46
MgO				0.09		0.02	6.28	5.05	0.21	0.22
CaO			0.01	3.02	1.57	1.61	0.09	0.11	1.64	1.39
Na ₂ O	0.72	0.90	0.62	8.26	8.79	8.12				
K ₂ O	15.41	15.12	15.44	0.23	0.10	0.09	6.99	8.13		
Total	100.40	99.65	98.97	98.41	98.28	98.16	99.16	98.31	103.06	103.65
		base (320)					base (220)		base (240)	
Si	11.81	11.74	11.69	11.44	11.51	11.45	5.30	5.55	5.82	5.83
Al	4.29	4.38	4.42	4.67	4.77	4.90	2.70	2.45	0.18	0.17
Al							0.63	0.87	4.06	4.05
Ti							0.10	0.32		
Fe ⁺⁺							3.92	3.25	2.44	2.43
Mn							0.06	10.05	3.23	3.29
Mg							1.50	1.16	0.05	0.06
Ca				0.61	0.298	0.32	0.02	0.02	0.28	0.24
Na	0.26	0.33	0.23	2.98	3.024	2.85				
K	3.61	3.56	3.71	0.04	0.020	0.02	1.42	1.60		
m Ab	6.7	0.08	5.8	82.1	8.9	0.10				
o										
l An	0	0	0	16.8	0.9	0.81				
e										
% O ₂	93.3	0.92	94.2	0.0	0.1	0.1				

The stability of iron-biotite was studied by Eugster & Wones (1962) in the field fO_2 -T. Considering a temperature of about 400°C inferred from the feldspar and iron, annite requires high conditions of oxidation controlled by the magnetite-hematite buffer.

Finally, the late metamorphic event is defined by the

crystallization of high Mn-Garnet (Tab. 1) with epidote and sericite. Petrographic observation shows the development of the spessartine on the K-feldspar crystal. It looks as if the garnet used the aluminium of feldspar with manganese supply to crystallize. A particular structure analyzed with the microprobe suggests the following reaction:

	K ₂ O	Na ₂ O	CaO	FeO
A	15.41	.72	0.00	0.02
B	0.23	8.26	3.02	0.3
C	8.13	0.00	0.11	25.34
D	3.96	0.04	0.05	8.22

	K ₂ O	Na ₂ O	CaO	FeO
A	9.66	0.62	0.00	0.00
B	0.00	0.01	0.00	0.00
C	0.12	8.51	1.51	0.00
D	0.10	8.79	1.57	0.00
E	15.12	0.90	0.00	0.00
F	1.33	4.70	0.93	0.00

Figure 6 – Location (A-D and A-F) and abundances of selected major elements oxides (K₂O, Na₂O, CaO and FeO) on different mineral phases of the coarse granitic mylonite. Microprobe analyses. Site 6 (Profile A-D on figure 4G, 7B and Table 1)

Figura 6 – Localização (A-D e A-F) e abundância dos óxidos de elementos maiores relacionados (K₂O, Na₂O, CaO e FeO) em diferentes fases minerais do milonito granítico grosso. Análises de microsonda. Local 6. (Perfil A-D na Prancha 2G, 5B e tabela 1)

Released potassium will be used together with plagioclase to form epidote, sericite, and albite (reaction 3).

The Fe/Mg partition between garnet and biotite (Ferry & Spear 1978) indicates a temperature between 350 and 400°C. This absolute value should be used with caution because of the high Mn content of the garnet; but this temperature is coherent with the temperature of crystallization of spessartine in high oxidation condition (Hsu 1968).

Applying the geobarometer plagioclase-garnet using the Ca repartition between the two phases (Ghent 1976), a stability pressure of 5.7kb was calculated and the metamorphism would be characterized by a geothermal gradient of 20°C/km. But the high content of Mn in garnet can disturb the Ca distribution and affect the barometric conclusions.

Considering a progressive evolution we can divide the mylonitic event into three thermal phases. The early phase at 450°C was responsible for the K-feldspar exsolution associated with the cataclastic effect on microcline crystal. The biotite crystallization in the mylonitic foliation occurred at 400°C with high oxygen fugacity, and iron and water supply. Finally, between 350 and 400°C with water and manganese supply, spessartine, epidote and sericite

crystallized, the final mylonitic texture should represent a stable condition occurring between 350-500°C and 2 to 5.0kb. It is suggested that there was an alternation of H₂O supply and release in the shear zone, related to an increase in local strain. A seismic pumping would concentrate water in this narrow shear zone which would act as a sink during stress increase (Sibson *et al.* 1975).

Considering a progressive evolution we can relate these mylonites to three similar deformation events with initial flattening and continuous shearing in a main shear zone followed by softening and metamorphism, as described below:

- Geometric softening related to deformation and continuous dynamic recrystallization of quartz with related cataclasis of K-feldspar porphyroclasts in a recrystallized matrix. The tendency of grain reduction must be a process of geometric or reaction softening (Williams & Dixon 1982) in an attempt to reach a strain free paragenesis.
- Reaction softening and metamorphic processes by the transformation of K-feldspar to biotite, oligoclase, and quartz through H₂O and Fe supply at 400°C. Sm and Sm' were formed.
- Reaction softening with metamorphic processes by transformation from K-feldspar to spessartine and quartz by release of H₂O between 350 and 400°C.
- Reaction softening with paragenesis related to Sm'' with sericite and epidote formation.
- At last, decreasing temperatures associated with brittle formation inhibited recovery and increased strain hardening (White *et al.* 1980).

The T decrease from the beginning to the end of the mylonitic event seems to indicate that the development of the brittle deformation happened during the uplift of the basement at the end of the Brasiliano.

Reaction enhanced ductility Considering the deformation induced reactions described above, a softening and reaction enhanced ductility is assumed to have occurred. It should be present in rocks undergoing deformation when grains are generated by metamorphic reaction, which may promote superplasticity in a mylonite (White & Knipe 1978). In this case, softening can be attributed to the entering of

release fluids by hydration or dehydration reactions of minerals which should result in a decrease or increase of pore fluid pressure in a closed system. The effect of deformation in terms of the mineralogy described previously has been to change an assemblage consisting dominantly of quartz and feldspar (mylonite) to one consisting dominantly of quartz and biotite (ultramylonite). During this deformation, chemical processes involving the addition of FeO, MnO, and H₂O are witnessed by the reaction from K-feldspar to Mn-biotite and Mn-garnet. SiO₂, K₂O, CaO, and Na₂O can be considered to be constant in the system after balancing the reactions.

DISCUSSION AND CONCLUSIONS The development of the PSZ shows a continuous history, related to regional processes, and phenomena restricted to the shear zone. At first, a lateral transition from the regional S₄ to the localized Sm foliation is recognized, probably related to regional modification in crustal level associated with lateral displacement along the PSZ. Regionally, all Precambrian lithologies are involved in the mylonitic processes, but only the homogeneous granitic body of Portalegre could offer a closed picture about the development of the PSZ.

The four principal textures found in the PSZ are characterized by a progressive development with a variable strain rate, and to different metamorphic conditions which produced the final heterogeneous textures (Fig. 7). Nevertheless, through marked differences in the textures it

has been possible to recognize a progressive deformation crystallization/recrystallization history as follows:

The primary porphyritic granite provides conditions for a differentiated behavior of phenocrysts and matrix submitted to a variable strain rate. In the first stage, a heterogeneous fabric began to form through banding parallel to the S₄ foliation. Flattening crashed the feldspars and deformed the quartz through intracrystalline processes producing extended ribbon quartz (Stage A).

A shearing process began to affect the material with variable responses of the mineralogical components. The feldspar clasts underwent perthitic or antiperthitic exsolution oblique to the Sm surface. Microcline twinning is interpreted as mechanically produced texture related to them. The fine grained matrix must have been recrystallized immediately in fine quartz-feldspathic layers. The quartz probably deformed and recrystallized during flow along Sm. A geometrical softening is thought to have occurred at this stage. Biotite formed at the expenses of the K-feldspar and was proportional to the strain rate. For that reason different strain rates are the principal causes for the final textures (Stage B).

A chemical transformation caused by high strain accumulation began to affect the clasts, and reaction softening acted in the system through reduction of grain size and metamorphic reactions. Myrmekite (oligoclase and quartz) formed at high and low pressure regions of the grains. Energies accumulated through twinning and reaction in the

Figure 7 – Progressive microstructural evolution of the Portalegre Shear Zone (see text)

Figura 7 – Evolução microestrutural progressiva da zona de Cisalhamento Portalegre (ver texto)

matrix were dissipated in the phases. Biotite formed behind the myrmekite front as forthcoming recrystallizations. H_2O and Fe entered into the system to form the biotite, associated with strain intensification. In regions with large stress accumulation the myrmekite was rapidly transformed into a fine recrystallization product; in protected regions, the feldspar crystallized coarsely (Stage C).

In a new progressive deformation folding of Sm quartz rich around porphyroclast formed an axial-plane parallel Sm' foliation. In some preferential regions, the rotation of clasts was the mechanism to form quartz layer folding. The formation of grains and subgrains (Sm') makes the C-axes distribution into a narrow circle around Z, when brought together with M and R reflex maximas, a rotational mechanism around R axes could be identified. It is suggested that for a definition of the crystallographic orientation of quartz, two or three crystallographic elements, must be measured. Sincronous with the quartz reorientation, feldspar began to rotate, as the matrix recrystallized (Stage D).

Next, localized breakdown of K-feldspar and Mn to spessartine garnets with liberation of quartz occurred. A water release probably occurred accompanying this

transformation. Simultaneously, feldspar clasts recrystallized and formed the coarser bands of the middle mylonite (Stage E).

Finally, fracture cleavage Sm'' was caused by uplift of the system to upper crustal levels, and production of epidote and sericite occurred.

The above considerations support the conclusion that the mylonitic textures developed at the end phase of the Brazilian granitic emplacement, probably by uprising and stress compensation through lateral shearing. The main metamorphic processes happened between 450-350°C with supply and release of water, and entering of Mn and Fe into the system.

Finally, a phanerozoic transtension system in the upper crust preceded the formation of "pull apart" basins.

Acknowledgments We thank Prof. Dr. K. Weber, Dr. A. Vollbrecht and Dr. W. Skrotzky from the Inst. für Geologie und Dynamik der Lithosphäre, Univ. Göttingen/FRG, for fruitful discussion; Dr. I. Davidson from the Universidade Federal da Bahia, for discussion and correction of the English text. This work has been supported by the Humboldt-Stiftung (Germany) and by CNPq/UFRN (Brazil).

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MANUSCRITO 450

Recebido em 14 de abril de 1987

Revisão recebida em 30 de setembro de 1988

Revisão aceita em 12 de dezembro de 1988

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