MINERAL DEFORMATION MECHANISMS IN GRANULITE FACIES, SIERRA DE VALLE FÉRTIL, SAN JUAN PROVINCE: EVELOPMENT CONDITIONS CONSTRAINED BY THE P-T METAMORPHIC PATH

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ABSTRACT

In the Sierra de Valle Fértil, evidence of granulite facies metamorphism have been preserved either in the constitutive associations as in deformation mechanisms in minerals from biotite-garnet and cordierite-sillimanite gneisses, cordierite and garnet-cordierite migmatites, metagabbros, metatonalites-metadiorites and mafic dikes. The main recognized deformation mechanisms are: 1) quartz: a) dynamic recrystallisation of quartz-feldspar boundaries, b) combination of basal <a> and prism [c] slip; 2) K-feldspar: grain boundary migration recrystallisation; 3) plagioclase: combination of grain boundary migration recrystallisation and subgrain rotation recrystallisation; 4) cordierite: subgrain rotation recrystallisation; 5) hornblende: grain boundary migration recrystallisation. Preliminary geothermometry on gabbroic rocks and the construction of an appropriated petrogenetic grid, allow us to establish temperatures in the range 800-850 C and pressures under 5 Kb for the metamorphic climax. Estimated metamorphic peak conditions, preliminary geothermobarometry on specific lithologic types and textural relationships, together indicate an counter-clockwise P-T path for the metamorphic evolution of the rocks of the area. Ductile deformation of phases resulting from anatexis linked to the metamorphic climax indicates that the higher-temperature ductile event recognized in the study area took place after the metamorphic peak. Evidence of ductile deformation of cordierite within its stability field and presence of chessboard extinction in quartz (only possible above the Qtz_{α}/Qtz_{β} transformation curve), both indicate temperatures above 700 C considering pressures greater than 5 Kb. Based on the established P-T trajectory and the characteristics described above, it can be concluded that deformation mechanisms affecting the Sierra de Valle Fértil rocks were developed entirely within the granulite facies field.

Keywords: *Sierra de Valle Fértil, Counter-clockwise P-T path, Deformation mechanisms, Granulite facies.*

RESUMEN: *Mecanismos de deformación en minerales en facies granulita, Sierra de Valle Fértil, provincia de San Juan: condiciones de desarro llo acotadas por la trayectoria P-T.* En la sierra de Valle Fértil han quedado preservadas evidencias de metamorfismo en facies granulita tanto en las asociaciones constitutivas, como en los mecanismos de deformación en minerales de gneises biotítico-granatíferos y cordierítico-sillimaníticos, migmatitas cordieríticas y granatífero-cordieríticas, metagabros, metatonalitas-metadioritas y diques máficos. Los principales mecanismos de deformación observados son los siguientes: 1) cuarzo: a) recristalización dinámica de los bordes de cuarzo-feldespato, b) combinación de deslizamiento basal y prismático; 2) feldespato potásico: recristalización por migración de borde de grano; 3) plagioclasa: recristalización por combinación de los mecanismos de migración de borde de grano y rotación de subgranos; 4) cordierita: recristalización por rotación de subgranos; 5) hornblenda: recristalización por migración de borde de grano. La geotermometría preliminar sobre rocas gábricas y la construcción de una grilla petrogenética apropiada, sugieren temperaturas en el rango 800-850 C y presiones inferiores a los 5 Kb para el climax metamórfico. La estimación de las condiciones del pico metamórfico, la geotermobarometría preliminar ensayada sobre tipos litológicos específicos y las relaciones texturales, indican en conjunto una trayectoria P-T antihoraria para la evolución metamórfica de las rocas del sector. La deformación dúctil de las fases producto de la anatexis asociada al climax metamórfico, indica que el evento dúctil de mayor temperatura reconocido en el área tuvo lugar con posterioridad al pico metamórfico. Las evidencias de deformación dúctil de la cordierita dentro de su campo de estabilidad y la presencia de texturas tipo "tablero de ajedrez" en cuarzo (sólo posibles por encima de la curva de transformación Qtz_{α}/Qtz_{β}), indican temperaturas superiores a los 700 C a presiones superiores a los 5 Kb. Considerando la trayectoria P-T obtenida y las características enumeradas previamente, puede establecerse que los mecanismos de deformación descriptos para las rocas de la Sierra de Valle Fértil se desarrollaron enteramente dentro del campo correspondiente a la facies granulita.

Palabras clave: *Fault rocks, Sierras de Buenos Aires, Cohesive breccias, Microbreccia.*

INTRODUCCIÓN

Evidence of granulite facies metamorphism are preserved in the constituting mineral associations and deformation mechanisms recognized in biotite-garnet and cordierite-sillimanite gneisses, cordierite and garnet-cordierite migmatites, metatonalites-metadiorites, metagabbros and mafic dikes, outcropping at the west-southwest of San Agustín del Valle Fértil locality (rectangle, Fig. 1a).

Numerous previous contributions dealing with the petrology, geochemistry, geochronology and structural-tectonics of the Sierras de Valle Fértil and La Huerta have been published, among others by Mirré (1971, 1976), Rabbia (1996), Vujovich *et al.* (1998), Pankhurst *et al.* (2000), Rapela *et al.* (2001), Castro de Machuca *et al.* (2002, 2005, 2007), Casquet *et al.* (2003), Murra (2004), Murra and Baldo (2004, 2006), Martino *et al.* (2004), Roesske *et al.* (2005). Nevertheless, specific geological information and microstructural-petrologic studies concerning deformational events and deformation mechanisms in the Sierra de Valle Fértil (Schneider *et al.* 2006, Delpino *et al.* 2006, Otamendi *et al.*, 2007), are very scarce.

This contribution focus mainly in the analysis of deformation mechanisms developed at high temperatures, due to the following reasons: 1) it provides an approximation to the metamorphic peak conditions attained by the rocks. This is one of the main problems to confront with when studying an area affected by several superimposed tectonometamorphic events, which very often lead to masking of progressive paragenesis due to retrograde processes; 2) most natural examples and experimental studies regarding deformation mechanisms in minerals, are related to deformation at low to medium grade metamorphism, those concerning deformation at high and very high grade metamorphic conditions being very scarce; 3) it constitutes an accessible and cheap tool, which in combination with textural and paragenetic analyses, allows to estimate (at least semi-quantitatively) the physical conditions prevailing during a deformation event (or events) affecting a given region.

The physical conditions leading to development of high-temperature deformation mechanisms are semi-quantitatively established through the analysis of the metamorphic evolution (P-T path) determined on the basis of paragenetic, textural and geothermobarometric studies. We also provide evidences and present a brief analysis of at least two overprinted retrograde events.

REGIONAL GEOLOGICAL SETTING

The Sierras Pampeanas tectono-stratigraphical province includes the Neoproterozoic and Lower Paleozoic metamorphic and igneous rocks of central Argentina. Despite the differences in lithology and age of igneous and metamorphic events within individual mountain blocks, a distinctive feature of the entire Sierras Pampeanas province is its exhumation prior to the deposition of the Upper Carboniferous to Permian continental sediments, collectively named the Paganzo Group (Bodenbender 1912 1922, Azcuy and Morelli 1970).

Based on the distribution of metamorphic and igneous rocks, the Sierras Pampeanas province was divided by Caminos (1979) into the western and eastern Sierras Pampeanas. Most authors have suggested Late Precambrian-Early Paleozoic ages for the Sierras Pampeanas basement and associated granitoids. The most recent geochronological studies (Sims *et al.* 1998, Rapela *et al.* 1998, Pankhurst *et al.* 1998, von Gosen *et al.* 2002, Sato *et al.* 2002, 2003), indicate that the majority of the geological events took place during the named Pampean and Famatinian Orogenic Cycles.

According to Rapela *et al.* (1998), Early Cambrian (≈530 Ma) reconstruction of the proto-Andean margin of South America is characterized by the formation of a passive margin sedimentary basin at the time oceanic crust subduction started, with development of an accretionary prism and a calcalkaline volcanic arc along the eastern edge of the Sierras Pampeanas. The subsequent closure of this ocean due to collision of a microcontinent (Pampean terrane) marked the onset of the Pampean Orogeny (Aceñolaza and Toselli 1976) during early Middle Cambrian times, followed by extensional collapse in the Late Cambrian at the end of the Pampean orogenic cy-cle. The Famatinian orogenic cycle, a major accretion and orogenic episode, started with subduction along the new Cambrian proto-Pacific margin (≈490 Ma; Pnkhurst and Rapela 1998, Dalla Salda *et al.* 1992). The subsequent and prolonged sequence of events, were grouped into the so called Famatinian Orogeny (Aceñolaza and Toselli 1976). The Famatinian belt is constituted by an Eopaleozoic continental magmatic arc associated to east-directed subduction linked to the approaching of a Laurentia-derived terrane [Cuyania (Ramos *et al.* 1998, Ramos 2004) and/or Precordillera terrain (Astini *et al.* 1995)]. This continent approach started in Mid-Cambrian times (Dalla Salda *et al.* 1992, Pankhurst *et al.* 1998) and ended with a continent-continent collision in Mid-Ordovician times (Dalla Salda *et al.* 1992, Ramos *et al.* 1998). The main Famatinian orogenic phase was followed by a period of extensional collapse and the emplacement of fracture-controlled, undeformed Devonian-Early Carboniferous granitoids (Brogioni 1993, Lira and Kirschbaum 1990, Pinotti *et al.* 1996, López de Luchi 1996, Llam-bías *et al.* 1998).

A new subduction episode developed to the west of the Precordillera, related to the collision of another terrane (Chilenia: Ramos *et al.* 1984, see also Astini 1996), was associated with the broadly coeval intrusion of within-plate plutons in the Gondwana foreland (Pankhurst and Rapela 1998).

GEOLOGY OF THE SIERRA DE VALLE FÉRTIL AREA

The Sierras de Valle Fértil and Sierra de

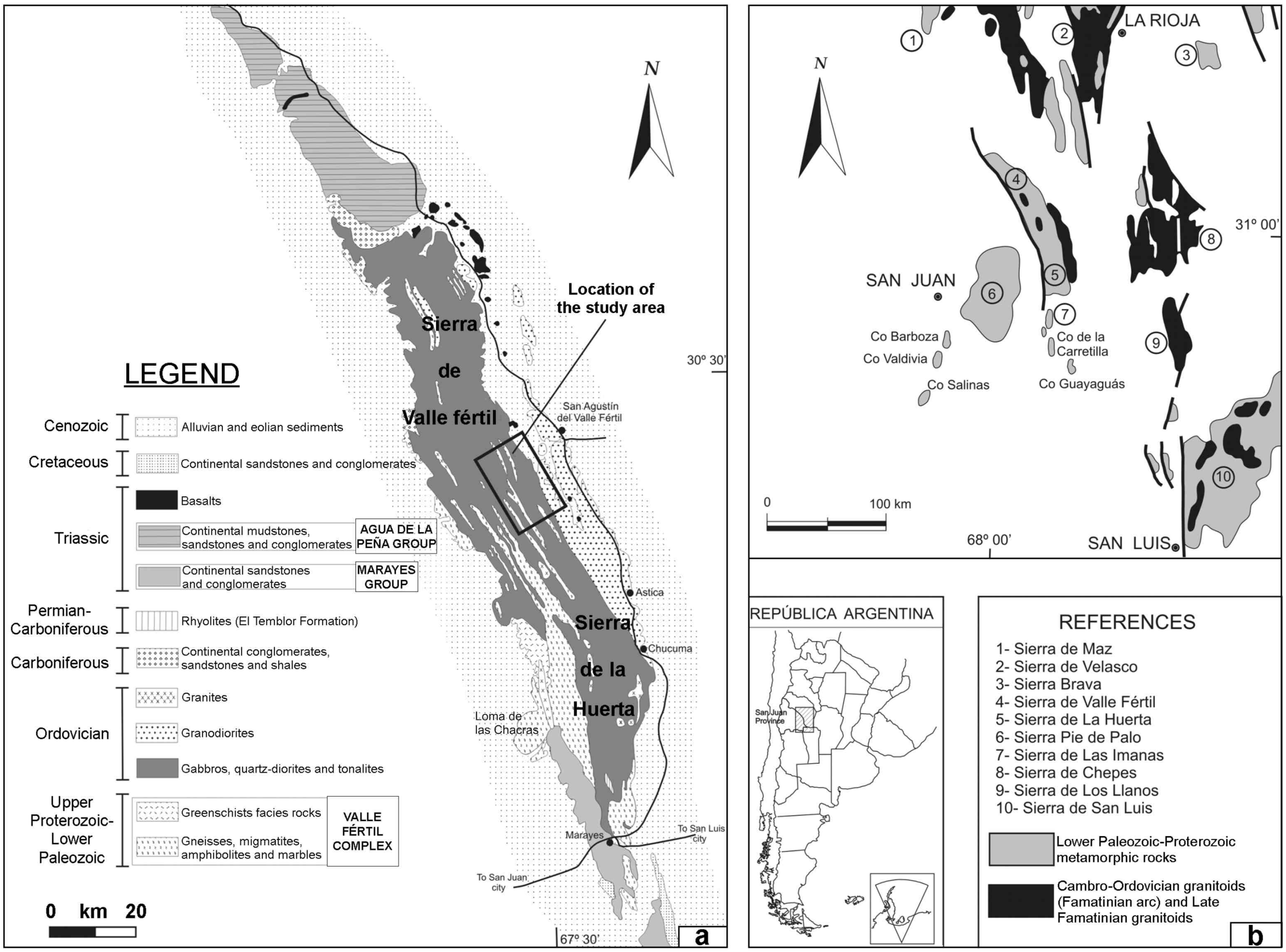

Figure 1: a) Location and geologic sketch map of the Valle Fértil-La Huerta ranges, San Juan province, Argentina (modified after Ragona *et al.* 1995). The rectangle delimits the working area; b) Partial regional view of the Sierras Pampeanas of central-west Argentina showing the location of the Valle Fértil-La Huerta ranges.

La Huerta (Fig. 1a), located between 30 11´ and 31 28´ S and 67 15´ and 67 55´ W, are part of the Western Sierras Pampeanas morphostructural unit (Fig. 1b). The limit between Sierra de Valle Fértil and Sierra de la Huerta is approximately located at the central inflexion of the mountain range (Fig. 1a).

The different litho-stratigraphic units that compose the igneous-metamorphic basement of the Sierra de Valle Fértil, were first outlined in the pioneer works of Villar Fabre (1962) and Mirré (1971, 1976) through detailed mapping of the area. The Valle Fértil Complex was defined by Cuerda *et al.* (1984). According to Rapela *et al.* (2001), the geology of the central and eastern sectors of the Sierra de Valle Fértil is dominated by a metaluminous sequence of hornblende-biotite diorites, tonalites and granodiorites, and suites of noritic and hornblende metagabbros emplaced in high-grade paragneisses, migmatites, amphibolites and marbles. The magmatic rocks are dominantly present in the eastern flank of the range. Schneider *et al.* (2006) indicates that a pre-Ordovician basement composed mainly of gneisses, amphibolites and marbles was intruded by tonalites-granodiorites to granite intrusives and metagabbro to metadioritic rocks in the Early Middle Ordovician (Famatinian Orogeny). Geochronological data obtained in the Sierras de Valle Fértil and La Huerta (Pankhurst *et al.* 1998, 2000, Pontoriero and Castro de Machuca 1999, Roeske *et al.* 2005) constrain the active magmatism to the interval between 500 and 460 Ma. U-Pb SHRIMP geochronological studies on migmatites from central-eastern Sierra of Valle Fértil provided ages between 466.5 ± 7.7 and 465.9 ± 4.4 Ma for the peak of the metamorphism, which occurred after the main intrusive period of the Famati-nian arc. Therefore, peak metamorphic temperatures and the attainment of anatectic conditions (Rapela *et al.* 2001) were approximately contemporaneous with plutonism (see also Otamendi *et al.* 2007).

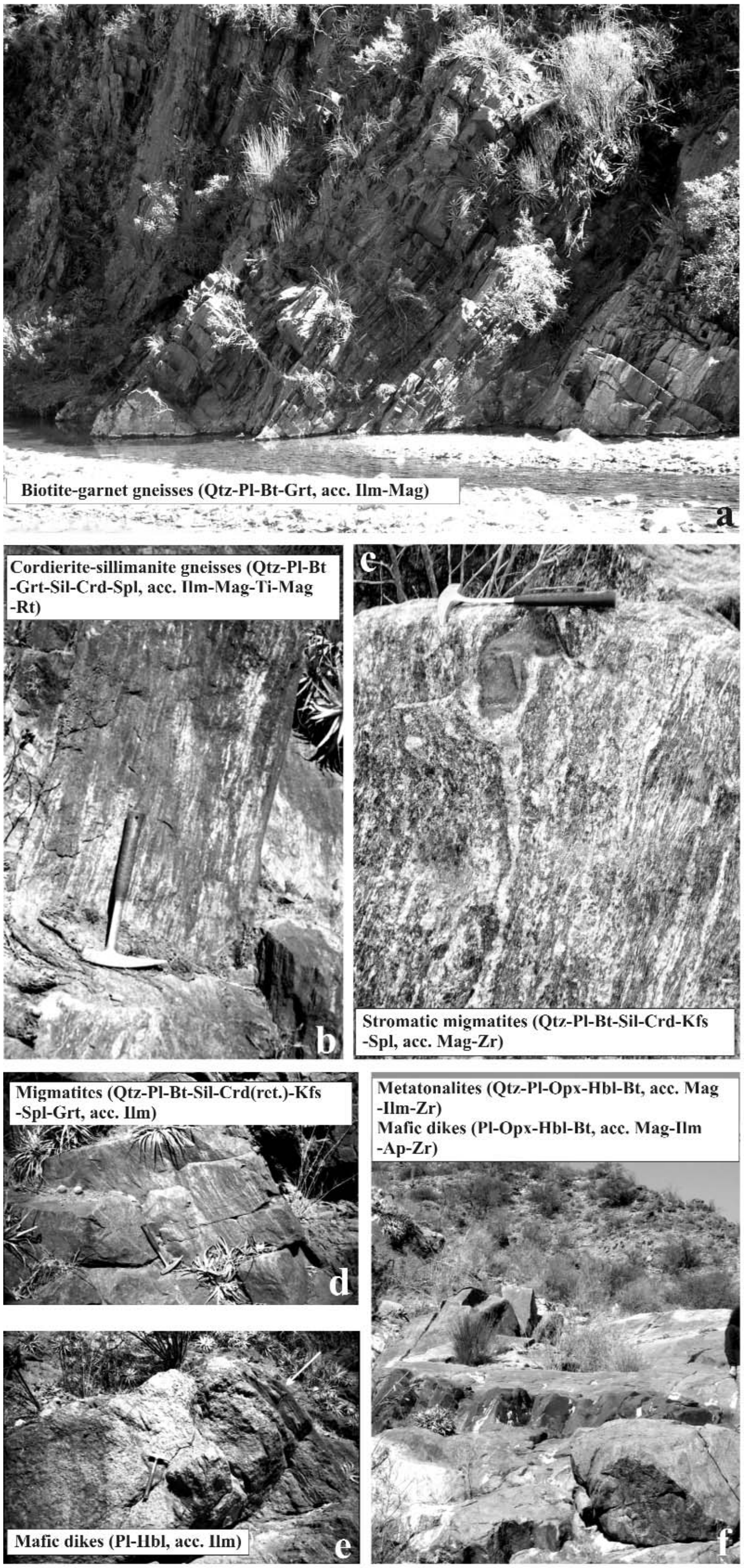

Figure 2: a-f) Field appearance of representative rock types used in this study, Sierra de Valle Fértil. Abbreviations after Bucher and Frey (1994).

PETROGRAPHY OF THE STUDIED ROCKS

Biotite-garnet gneisses

Bt-Grt gneisses are composed by the association Qtz-Pl-Bt-Grt-Ilm-Mag (abbreviations after Bucher and Frey 1994). Mesoscopically they appear as strongly foliated rocks showing dark biotite-bearing bands that anastomose around light quartz-feldspar-garnet microlithons (Fig. 2a). Under the microscope, quartz appears as large lenticular monocrystalline grains with lobate contacts with plagioclase and biotite. Very often, these coarse crystals enclose partially or completely feldspar or biotite grains (Fig. 3a). Internally, quartz crystals show development of large subgrains with square or rectangular shapes with chessboard extinctions indicating high-temperature ductile deformations (Fig. 3c). Quartz porphyroclasts also show, by sectors, development of low-amplitude bulging and recrystallisation at their margins and internal microfractures, which evidence overprinting of a lower-temperature event (Fig. 3a). Plagioclase appears as equidimensional porphyroclasts with irregular or elliptical shapes, surrounded by coarse-recrystallised aggregates of polygonal new-grains forming triple junctions at 120º (Fig. 3f). Relicts of former bigger porphyroclasts included in quartz, occur as lenses elongated parallel to foliation and with smooth boundaries with host quartz grains (Fig. 3a). Unrestricted quartz growth included also recrystallised polygonal aggregates of plagioclase (Fig. 3a, bottom right corner). Garnet appears as irregular or elliptical porphyroclasts. Former poikiloblastic growth of garnet from Qtz-Pl Bt Ilm/Mag is documented by a great number of preserved inclusions. Garnet shows fractures filled with biotite, which also crystallised and form their pressure shadows. Biotite appear as coarse crystals arranged in sub-parallel and anastomosing layers that wrap around garnet, plagioclase and quartz single porphyroclasts or polymineralic lenses defining foliation (Fig. 3c). Biotite crystals

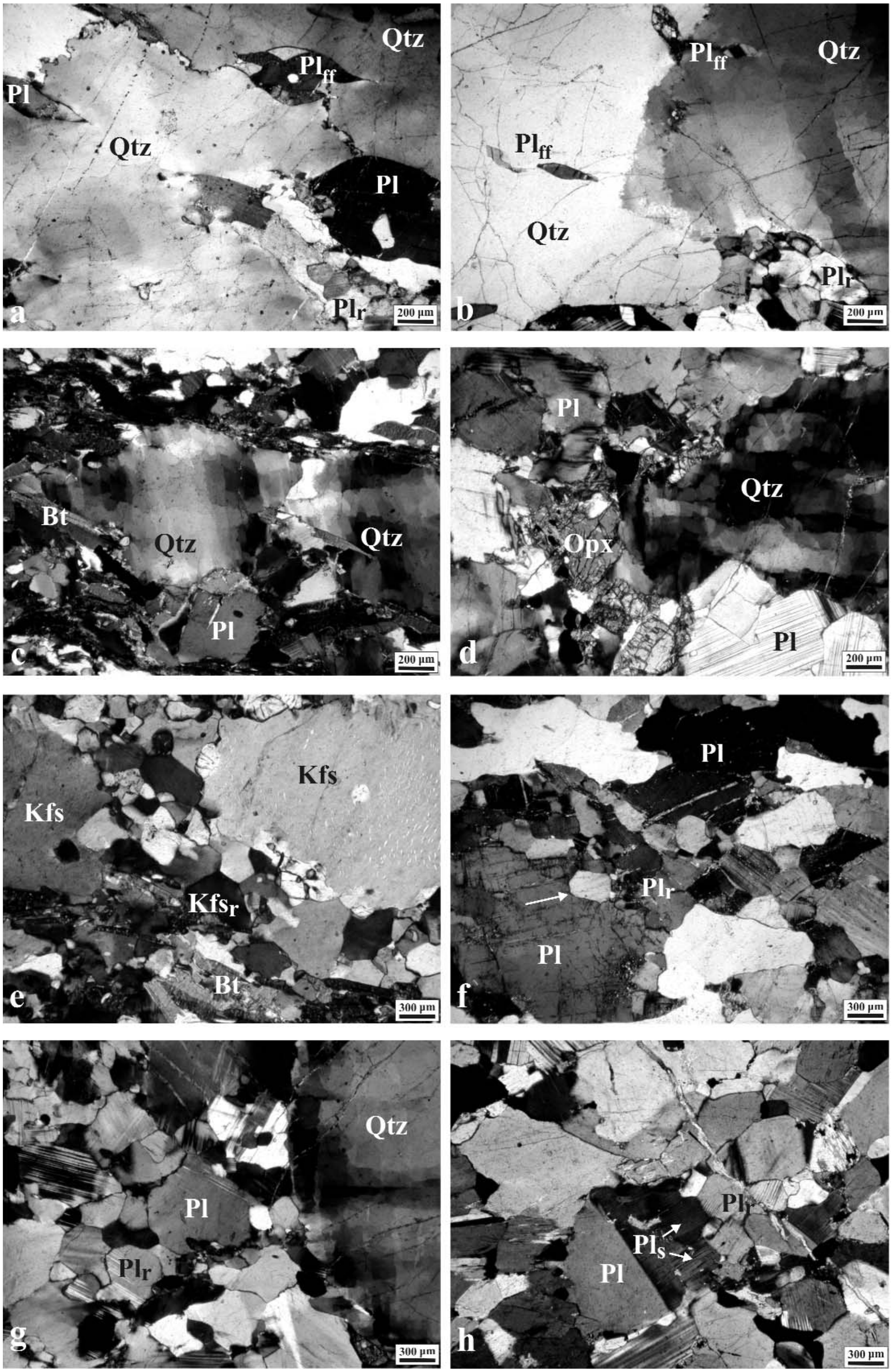

Figure 3: a, b) Dynamic recrystallisation of quartz-feldspar boundaries. Note the unrestricted growth of quartz (Qtz) not pinned by grain boundaries of the coexisting phases to which includes partially or totally. Observe the smoothly lobate contacts between quartz and feldspars (mainly plagioclase, Pl) and the lenticular or sigmoidal shapes of "feldspar fishes" (Plff) ; c, d) Chessboard extinction in quartz. Note the development of rectangular and square subgrains, due to activation of both basal <a> and prismatic <c> slip; e) Evidences of GBMR in perthitic k-feldspar. Observe equidimensional shapes of relict crystals (Kfs) with scarce intracrystalline strain and absence of subgrains. Pseudopolygonal recrystallised new-grains (Kfsr) with dissimilar sizes and triple junctions at 120 are conspicuous; f, g) Evidences of GBMR in plagioclase. Observe in f, the irregular shape of relict crystals (Pl) with scarce internal strain, absence of subgrains and recrystallised grains (Plr) contacting with the relicts through high-angle boundaries without mediation of subgrains (white arrow). In g, the disparity in size and the high mobility of the grain boundaries, is remarkable also in the recrystallised grains; h) Evidences of SRR in plagioclase. Note the development of polygonal subgrains (Pls, twinned crystals-centre) with shape and size similar to those of the new-grains (Plr) adjacent to the relict crystal boundaries. All photomicrographs with crossed-polarized light (XPL). Abbreviations after Bucher and Frey (1994).

show bending, interfingering (parallel to foliation) with the other relict phases and is one of the main phases forming their pressure shadows.

Cordierite-sillimanite gneisses

Field appearance of these rocks differs from that of the garnet-biotite gneisses due to the partial loss of the compositional foliation. Light irregular patches or ribbons elongated parallel to foliation stand out on a dark bottom (Fig. 2b). Microscopically, the following mineral association was identified: Qtz-Pl-Bt-Grt-Sil-Crd-Spl-Ilm-Mag-Ti-Mag-Rt. Light portions are composed of coarse-grained quartz, plagioclase and cordierite, plus very scarce biotite and sillimanite crystals. Dark portions are constituted by plagioclase, cordierite and garnet porphyroclasts, surrounded by coarse grained biotite and sillimanite crystals defining foliation. Quartz, plagioclase and biotite show the same characteristics as those observed in the previous sample. Within the light patches, cordierite forms anhedral to subhedral grains entirely surrounded by large quartz or quartz+plagioclase grains. These crystals show sometimes polygonal subgrains and, rarely, some new-grains. Very often it is pseudomorphically replaced by garnet in these sectors (Figs. 4f, 5b and 5c). In the dark portions, cordierite forms irregular or subhedral porphyroclasts of varied sizes, which do not show evidence of ductile internal deformation, except undulatory extinctions. Cordierite crystals show only incipient retrogression to green biotite and pinnitization at their margins. In the dark portions, sillimanite appear as coarse and thin prismatic crystals that wrap around garnet, plagioclase and cordierite porphyroclasts. In the light portions, fibrolite appear as replacement of cordierite crystals in association with the pseudomorphic replacement of this mineral by garnet (Fig. 5b). Coarse spinel is only recognized as inclusions within large cordierite crystals. Inclusions are isolated or associated to Ti-magnetite/ilmenite. Ten times smaller sized spinel inclusions were also recognized within poikiloblastic garnet, which also contains Ti-magnetite/ ilmenite inclusions and very small cordierite relicts.

Cordierite migmatites

These stromatic migmatites appear in the field as banded rocks with great amounts of leucosome segregates, arranged in thin lenses and veins defining a prominent layering. A subparallel foliation to this layering is recognized in the mesosome portions between segregated leucosomes. Mafic inclusions are surrounded by leucosome segregates, which extend parallel to foliation conforming tails (Fig. 2c). In thin sections the association Qtz-Pl-Bt-Sil-Crd-Kfs-Spl-Mag-Zr, was recognized. Quartz forms large ameboidal grains or monocrystalline ribbons that usually enclose -partially or entirely- cordierite, plagioclase and/or biotite crystals. Chessboard extinctions are commonly observed. Cordierite shows large equidimensional crystals with inclusions of quartz, biotite, spinel, Ilm/Ti-Mag and Zr. These crystals show, at their margins, subgrains and recrystallised polygonal grains meeting at 120º triple junctions (Figs. 4a y 4b). Cordierite grains are by sectors altered to fibrolitic sillimanite, which also appear at the margins of recrystallised grains. Very incipient pinnitization can also be observed. Biotite appears as irregular interstitial crystals of varied sizes or as inclusions in quartz, plagioclase, cordierite and k-feldspar. Sillimanite forms prismatic to acicular crystals, usually associated to biotite defining a rough foliation. As mentioned above, fibrolitic sillimanite partially replace cordierite crystals. Plagioclase grains form equidimensional porphyroclasts, surrounded by aggregates of subhedral to polygonal recrystallised grains meeting each other at triple junctions. Large K-feldspar crystals are dominant in the leucosome sectors. Coarse perthitic k-feldspar grains are more or less equidimensional or elongated parallel to the layering/ foliation and have ameboidal contours. K-feldspar crystals enclose relicts of plagioclase, biotite and quartz. Spinel has been recognized only as inclusions in cordierite.

Garnet-cordierite migmatites

At outcrop scale, these rocks show a greyish tonality and a well marked foliation enhanced by leucosomes forming thin ribbons or stretched lenses alternating with dark mesosome portions (Fig. 2d). The association Qtz-Pl-Bt-Sil-Crd-Kfs-Grt-Ilm is recognized in thin sections. This association do no differ from that of the stromatic migmatites, except for the presence of garnet, which is absent in the later rocks. However, there are some significant differences: 1) Stromatic migmatites and garnet migmatites both show evidence of a very high-temperature ductile event. However, relict migmatitic and ductile high-temperature event textures are better preserved in the former, whereas garnet migmatites have been stronger affected by a mylonitic medium-temperature ductile event that sensibly obliterate these previous textures; 2) Coarse sillimanite and biotite are much more abundant than in stromatic migmatites. Sillimanite forms coarse prismatic crystals that act as porphyroclasts, and thinner prismatic crystals which together with biotite, quartz and feldspars form folia that wrap around individual porphyroclasts or polymineralic lenses preserving evidence of the migmatitic (K-feldspar rich leucosomes) and higher ductile temperature event (large monocrystalline quartz with chessboard extinctions, feldspar surrounded by aggregates of large polygonal recrystallised grains) (Figs. 3e and 4e); 3) Cordierite appear as universally pinnitized porphyroclasts and partially replaced by biotite and sillimanite medium-sized crystals.

Metagabbros, metatonalites-metadiorites and mafic dikes

Metagabbros and metatonalites-metadiorites appear as irregular, medium sized

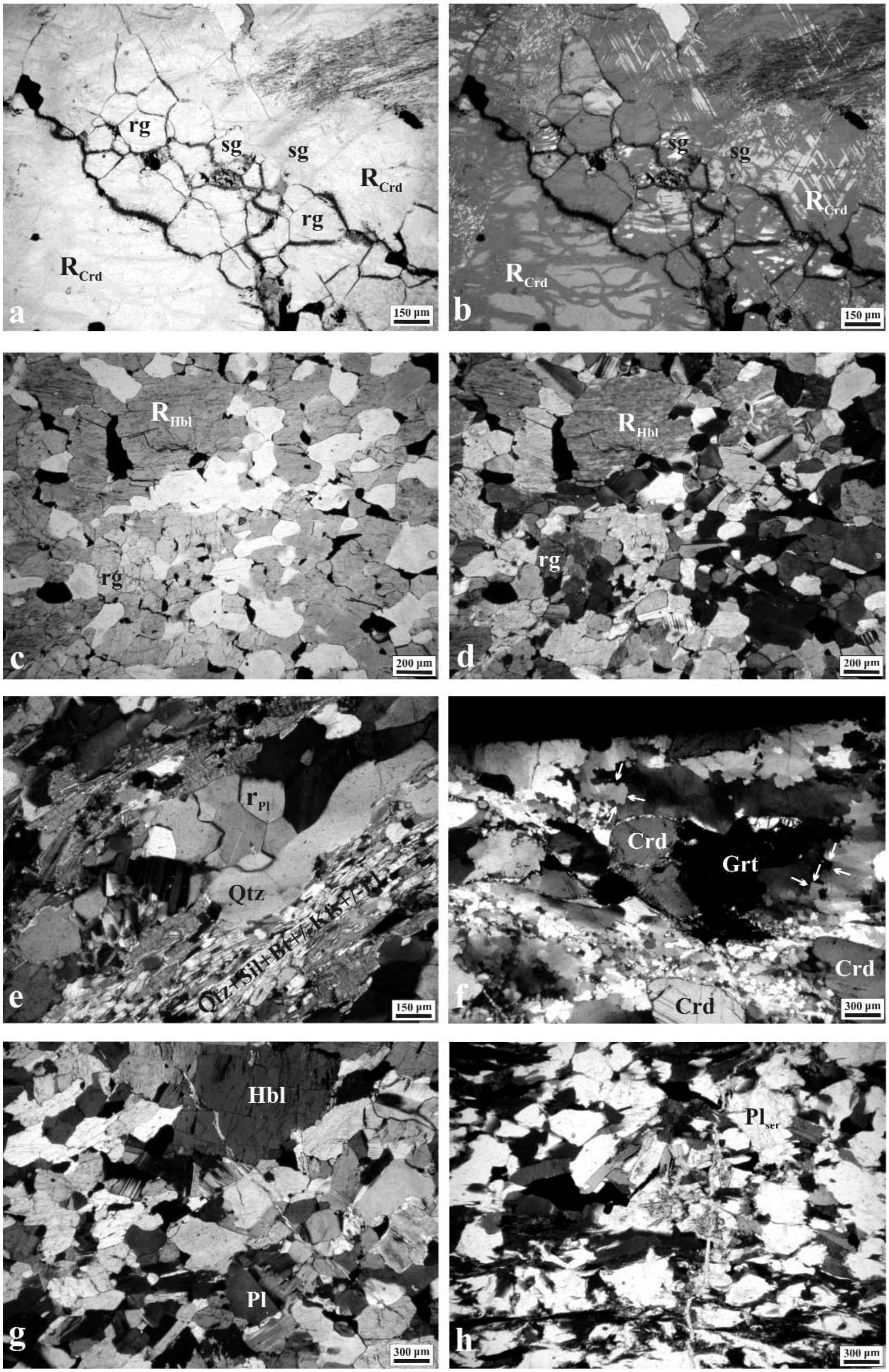

Figure 4: a, b) Evidences of SRR ductile deformation in cordierite. In b, as well as in a (photomicrograph with plane-polarized light (PPL) and gypsum plate to enhance the texture), note the presence of subgrains (sg) whose low-angle boundaries are invisible in PPL. In contrast, the high-angle boundaries of recrystallised grains (rg) are clearly visible. Also observe the similar shape and size of recrystallised grains and neighbouring subgrains. In b subgrains are also indicated by obliteration of twin planes in relict cordierite crystals (R_{Crd}), a typical feature of this phase; c, d) Evidences of ductile deformation in hornblende by GBMR. Note the irregular shape of relict crystals (R_{Hbl}), the grain boundary mobility evidenced by lobate contacts amongst Hbl-Hbl crystals and the absence of subgrains. Development of polygonal recrystallised grains with dissimilar sizes and triple joints at 120° (rg) is also seen; e, f) Evidences of the intermediate temperature ductile deformation event. Folia composed by Qtz-Sil-Bt Kfs Pl crosscut and obliterate textures of the higher temperature ductile event (rPl: polygonal recrystallised plagioclase and coarse quartz ribbons). In f observe superposition of the intermediate temperature event on big sized quartz grains, typical of the higher temperature event. Despite the intense obliteration, it is still possible to recognize the previously developed chessboard extinction (arrows); g, h) Evidences of the low temperature brittle deformation event. In g, intergranular mi-crofracture cuts trough both relict and recrystallised crys-tals. The microfracture is fi-lled by calcite. In h a microfracture is filled by calcite, epidote and chlorite. Close to the fracture, feldspars are strongly sericitized (Plser). Photomicrographs a, c and h: PPL; b: XPL and gypsum plate; d, e, f and g: XPL.

bodies, included in basement rocks being the present contacts tectonics. Most gabbros are strongly altered. However, deformation affected the bodies essentially at their margins and along narrow internal shear bands. Thus, magmatic layering and high-temperature subsolidus metamorphic textures (coronas and simplectic intergrowths), are preserved in the less deformed sectors of the bigger bodies. Grain size varies from coarse-grained in the central portions of the bodies to fine-grained towards to the contact with the basement the rocks. The metagabbros are composed by the association Ol-Pl-Opx-Cpx-Amp-Spl-Ilm-Mag. These coarse-grained rocks very often show alteration of olivine and pyroxenes to iddingsite, serpentine and chlorite, related to a low-temperature fragile event. Pyroxenes show sometimes small pseudopolygonal crystals indicating incipient recrystallisation. Clinopyroxene shows frequently exsolution lamellae of spinel and magnetite. Plagioclase appears as very large crystals, sometimes partially altered to sericite. Spinel constitutes large grains in the groundmass or forms simplectic intergrowth with magnetite or amphibole in the coronas developed around former magmatic phases. Metatonalite-metadiorite essentially differs from the metagabbros described above by its mineral constituents (Qtz-Pl±Opx Hbl±Bt±Cpx-Mag-Ilm). Abundance of felsic components like plagioclase and quartz increase significantly, whereas the main mafic components are represented by orthopyroxene and amphibole, with scarce biotite and -locally- clinopyroxene. Furthermore, coronas and simplectites are not present in these rocks. Another significant difference between these rocks and metagabbros, is the presence in the former rocks of clear evidences of high and medium-temperature ductile deformation events. Quartz and plagioclase show the same deformational textures like those previously described for the same phases in the basement rocks (compare quartz and feldspar deformation textures in figures 3b, 3d and 3g corresponding to metatonalites, with textures developed by the same phases in basement rocks showed in the rest of this figure). Mafic dikes are fine-grained (Figs. 2e and 2f) and cut across magmatic bodies in different directions. They are composed by the association Pl-Hbl± Opx±Bt±Cpx-Mag-Ilm-Ap-Py). Plagioclase and hornblende are largely the dominant constituents, being orthopyroxene, biotite or clinopyroxene subordinated and their occurrence usually related to their presence in the neighbouring host rock. Plagioclase and hornblende show por-phyroclasts surrounded by aggregates of polygonal recrystallised grains meeting at triple junctions denoting ductile recrystallisation of these phases (Figs. 3h, 4c, 4d and 4g).

EVIDENCE OF HIGH TEMPERATURE DEFORMATION MECHANISMS IN MINERALS

Quartz: The most frequently used reference for the estimation of the physical conditions prevailing during ductile deformation, are the textures developed in experimental studies on quartz. Textural modifications reflect changes in the operating deformation mechanism as a function mainly of variations in temperature, differential stress, strain, presence of fluids, etc. As a result, three different deformation regimes have been defined (Hirth and Tullis 1992). These deformation regimes in quartz, with some modifications, were extrapolated to the natural environment and semi-quantified by several workers (Dunlap *et al.* 1997, Stöckhert *et al.* 1999, Zulauf 2001, Stipp *et al.* 2002). The ductile deformation characteristics of this mineral at temperatures exceeding those of the regime 3 (the highest temperature regime, Hirth and Tullis 1992), were also considered by other authors (Blumenfeld *et al.* 1986, Mainprice *et al.* 1986, Kruhl 1996, Stipp *et al.* 2002).

Based on the preceding considerations, attention will be paid at first to the behaviour of quartz that presents two types of textures in the studied rocks:

1) Development of large crystals (frequently forming monocrystalline ribbons elongated parallel to foliation), by growth through grain boundary migration not-controlled (pinned) by other phases present. Well-equilibrated boundaries between quartz-quartz and quartz-feldspar grains, show smooth, curved or lobate shapes (Fig. 3a). Feldspar grains isolated within quartz crystals, show lenticular or sigmoidal shapes (Figs. 3a and 3b). These textures are characteristic of rocks deformed under granulite facies conditions, being migration assisted by grain boundary diffusional creep, the mechanism considered as responsible for their formation (Simpson and De Paor 1991, Martelat *et al.* 1999). This mechanism has been called "dynamic recrystallisation of quartz-feldspar boundaries" by Gower and Simpson (1992). Grain boundary migration results from diffusive mass transfer along phase boundaries, a process only possible at very high homologous temperatures ($T/T_{melting}$).

2) Chessboard extinction due to the presence of square or rectangular subgrains (Figs. 3c and 3d), which has been attributed to a combination of basal <a> and prism <c> slip (Blumenfeld *et al.* 1986, Mainprice *et al.* 1986). The operation of this slip systems combination, have been considered to occur at temperatures exceeding the Qtz_{α}/Qtz_{β} transition (Kruhl 1996, Stipp *et al.* 2002). As a reference, this transition takes place at around 660 ºC at 4Kb and 730º C at 7 Kb.

Feldspars: Regarding plastic deformation of feldspars, only the beginning of its ductile deformation has been constrained, although not accurately, to the range 400-500 ºC (see Passchier and Trouw 1996 and references therein).

Concerning deformation mechanisms, textural evidences suggest a general behaviour similar to quartz, although with regimes displaced towards higher temperatures. However, little is known about the limits of such regimes for feldspars. Therefore, it is interesting to evaluate the observed textures and consider the possible operating deformation mechanisms in areas where it is possible to constrain the metamorphic physical conditions by other means (for example, through deformation mechanisms developed in other phases during the same deformation event, determination of stability fields of specific mineral associations in equilibrium during this event, through geothermobarometry, etc). This could contribute to the establishment of such limits.

Perthitic k-feldspar shows more or less equidimensional relict grains with undulatory extinction, absence of subgrains, lobate boundaries and presence of bulging. It evidences recrystallisation with development of polygonal shaped new-grains with variable sizes, showing triple junctions at 120° (Fig. 3e). These features suggest recrystallisation by means of grain boundary migration (GBMR, see Passchier and Trouw 2005 and references therein).

Relict plagioclase grains are irregular and show embayments and recrystallisation to aggregates of polygonal new-grains contacting each other through rectilinear or lobate boundaries and forming 120° triple junctions (Fig. 3f).

The high mobility of grain boundaries evidenced by both relict (Fig. 3f) and recrystallised grains (Fig. 3g), as well as the recrystallisation characteristics itself, indicate that the dominant deformation mechanism was GBMR. However, in some sectors plagioclase also shows polygonal subgrains with sizes and appearance similar to contiguous recrystallised grains (Fig. 3h). Such features indicate that subgrain rotation recrystallisation mechanism (SRR), also contributed to the ductile deformation of this mineral.

Although, as were previously mentioned the transition between GBMR and SRR (see Passchier and Trouw 2005 and references therein) mechanisms has not been well established up to the present, Tullis and Yund (1985) noticed that feldspars in rocks belonging to the high amphibolite and granulite facies frequently show subgrains and, therefore, the SRR mechanism would be active under these conditions.

The observed differences in the rheological behaviour of k-feldspar and plagioclase (the first one evidencing only GBMR and the second a combination of GBMR and SRR), are consistent with the fact that the activation energy required by dynamic recrystallisation and dislocation glide is lower for plagioclase than for k-feldspar, at medium to high homologous temperatures (Fitz Gerald and Stunitz 1993, Schulman *et al.* 1996).

Cordierite: This mineral occurs as more or less equidimensional relict grains, subrounded or irregular, with development of subgrains and recrystallised grains at the margins. Recrystallisation gave place to aggregates of polygonal new-grains of similar sizes to those of the subgrains in the neighbouring relict crystals, forming triple junctions at 120° (Figs. 4a and 4b). These characteristics indicate recrystallisation by means of the SRR mechanism. It is very interesting the possibility to observe evidences of cordierite recrystallisation and be able to establish the probable operating deformation mechanism, since references about the ductile behaviour of this phase are very scarce in the literature.

Hornblende: This mineral shows evidence of recrystallisation and absence of brittle fracturing, indicating that it was also ductile deformed. Hornblende occurs as relict crystals with irregular shapes, without significant flattening or presence of subgrains. Recrystallisation has given place to arrangements of polygonal new-grains with varied sizes forming triple junctions at 120° (Figs. 4c and 4d). Such textural arrangement strongly suggests that GBMR was the dominant deformation mechanism.

LOWER TEMPERATURE OVERPRINTED EVENTS

Although the previous detailed analysis of deformation mechanisms document the occurrence of a ductile deformation event developed at high to very high temperatures, the studied rocks show also evidences of other superimposed events developed at lower temperatures, which will be briefly described in the next paragraphs.

At least two events have been documented, one ductile at intermediate temperatures and the other brittle at low temperatures.

Intermediate temperature event

It is characterized by development of a defined foliation that cut and obliterates textures resulting from the highest temperature event (Figs. 4e and 4f). The minimum temperatures of this event were determined by the fields of stability-instability of some phases and by the textures developed in quartz. At intermediate pressures the absence of muscovite and presence of stable sillimanite+k-feldspar (Fig. 4e), are typical of conditions exceeding the second sillimanite isograd (Ms+ Qtz $\rightleftarrows$Sil+Kfs+H_2O, Fig. 5). Quartz textures (amoeboid grains with large amplitude sutures and development of dissection microstructures, Fig. 4f) indicate that deformation conditions exceeded the transition between SRR and GBMR regimes (Stipp *et al.* 2002). Both characteristics are indicative of minimum temperatures in the order of 600 °C. This event could be correlated with the mylonitic event recognized by Castro de Machuca *et al.* (2007) on metagabbros from the SLH, which indicates temperatures around 650-700 ºC and pressures between 6 and 7 Kb. According to Murra and Baldo (2001), generalized mylonitization in the area would have begun at ca. 452-459 Ma and could be related to the later stages of the Famatinian orogeny.

Low temperature event

The brittle low temperature event is characterized by the presence of thin continuous intergranular microfractures, which cut through both relict and new-grains of recrystallised phases (Figs. 4g y 4h).

Depending on the lithology they are

affecting, microfractures can be filled with calcite (Fig. 4g), Fe-oxides, chlorite and/or epidote (Fig. 4h). This retrograde event is often associated to pervasive replacement of feldspars by sericite in the proximity of the microfractures (Fig. 4h). The described mineral association is indicative of deformation conditions within the field of low greenschist facies, at temperatures not exceeding 400°C.

PHYSICAL CONDITIONS OF DEVELOPMENT OF THE HIGH-TEMPERATURE DUCTILE EVENT

To analyze the physical conditions involved in the development of deformation mechanisms at high temperature, a diagram was constructed (Fig. 5) using the Perplex software (Connolly 1990, version 2006) and the thermodynamic database of Holland y Powell (1998, actualized version 2002). Based on the petrographic study, the following phases were considered for the system TKFMAS-HC: Rt-Ilm-Bt-Grt-hCrd-Opx-Spl-Kfs-Ms-Als-$Qtz_{\alpha-\beta}$-fluid (H_2O+CO_2). Isopleths of constant composition for garnet and biotite (Fig. 5) were calculated using the activity models of Holland and Powell (1998) and Powell and Holland (1999), respectively.

The most likely attained metamorphic peak conditions were established based on the following: 1) Stromatic migmatites in the region (Fig. 2c) comprise the mineral association Crd-Spl-Qtz, garnet absent. This association is typical of high grade metamorphism at intermediate to low pressures and is stable below the Grt+Sil+H_2O $\rightleftarrows$ hCrd+Spl+Qtz reaction (Fig. 5); 2) Preliminary geothermometric calculations on coronitic gabbros of the SVF (Cpx-Opx equilibrium) suggest maximum temperatures of the order of 850 °C (Schneider *et al.* 2006, Castro de Machuca *et al.* 2007). Considering this temperature as the thermal maximum reached by the rocks in the area of SVF, the association Crd-Spl-Qtz is stable only below pressures of around 4.7 Kb (Fig. 5); 3) Given that stromatic migmatites are the result of "in situ" partial melting, the lower temperature limit for the metamorphic peak, should be above the granite solidus. Curves corresponding to the solidus of an aplogranitic composition (Ebadi and Johannes 1991) and to ternary alkaline feldspars (Ab_{25-33}) in equilibrium with plagioclase An30 (Bohlen *et al.* 1995), both for low water activity conditions (XH_2O=0.25), are shown in Fig. 5. The curve of minimum melting temperature for the rocks of the study area should be located between these two extremes, most probably closer to the curve to the right because it takes into account the calcium content in plagioclase. The three formerly described characteristics fix a limit to the metamorphic peak temperature very probably in the range 800 to 850 °C and pressures below 5 Kb (shaded grey area, Fig. 5).

The preliminary geothermobarometric results applying both TWEEQU (Berman 1991, version 2001) and Perplex (Connolly 1991, version 2006) softwares to garnet-bearing gneisses and migmatites from the study area, indicate higher pressures and lower temperatures (circles and triangles, Fig. 5a) than the estimated for the metamorphic peak, and a CO_2-rich fluid phase composition (XCO_2= 0.75, the best fit between both formulations) (Fig. 5). Composition of the phases used in TWEEQU calculation, are showed in Table 1. These determinations would indicate that the P-T established values based on garnet-bearing rocks would represent the physical conditions prevailing during some stage of retrogression, but not those of the metamorphic peak. This interpretation is supported by the textural relationships. Cordierite and spinel-bearing stromatic migmatites are garnet free or, if present, garnet is the result of cordierite retrogradation. The pseudomorphic replacement of cordierite by garnet is accompanied by the formation of fibrolitic sillimanite and the replacement of ilmenite by rutile (Figs. 5a, 5b and 5c). These textural relationships indicate that the Grt+Sil+H_2O $\rightleftarrows$ hCrd+Spl+Qtz and Rt+Grt+Qtz+Sil+$H_2O$$\rightleftarrows$Ilm+hCrd reactions proceeded from the right to the left. Therefore, the metamorphic trajectory must be such that, beginning at the determined metamorphic peak conditions, it should evolve towards the stability field of the associations representative of higher pressures and lower temperatures located to the left side of both reactions (Fig. 5). The estimated peak metamorphic conditions, the preliminary geothermobaro-

TABLE 1: Representative phase chemical compositions used in TWEEQU calculation. MIJ0805: Garnet-cordierite migmatite. MIJ1505: Cordierite-sillimanite gneiss. MIJ1705: Garnet-biotite gneiss.

Mineral	Garnet			Plagioclase			Biotite		
Sample	MIJ0805	MIJ1505	MIJ1705	MIJ0805	MIJ1505	MIJ1705	MIJ0805	MIJ1505	MIJ1705
SiO_2	36,86	37,34	36,97	60,48	56,71	58,76	35,16	35,31	34,62
TiO_2	0,04	0,05	0,04	0,02	0,02	0,03	3,64	3,27	4,42
Al_2O_3	20,04	21,20	20,17	22,95	26,49	25,21	16,63	17,06	15,99
Cr_2O_3	0,09	0,06	0,06	0,02	0,02	0,01	0,07	0,03	0,04
Fe_2O_3	1,17	2,32	1,22	0,05	0,01	0,00	2,57	0,00	0,00
FeO	29,66	26,43	26,13	0,00	0,07	0,07	13,10	13,76	15,97
MnO	3,34	1,45	5,84	0,04	0,03	0,02	0,12	0,09	0,09
ZnO	0,00	0,00	0,00	0,07	0,04	0,00	0,00	0,00	0,00
MgO	6,29	8,40	5,89	0,00	0,00	0,01	12,65	14,33	12,50
CaO	0,72	1,35	1,70	4,21	8,25	7,06	0,07	0,09	0,06
Na_2O	0,00	0,00	0,00	9,79	6,46	6,82	0,00	0,13	0,08
K_2O	0,00	0,03	0,00	0,18	0,12	0,27	9,78	9,61	9,63
H_2O	0,00	0,00	0,00	0,00	0,00	0,00	3,83	3,90	3,81
Total	98,20	98,64	98,02	97,81	98,21	98,27	97,61	97,58	97,19

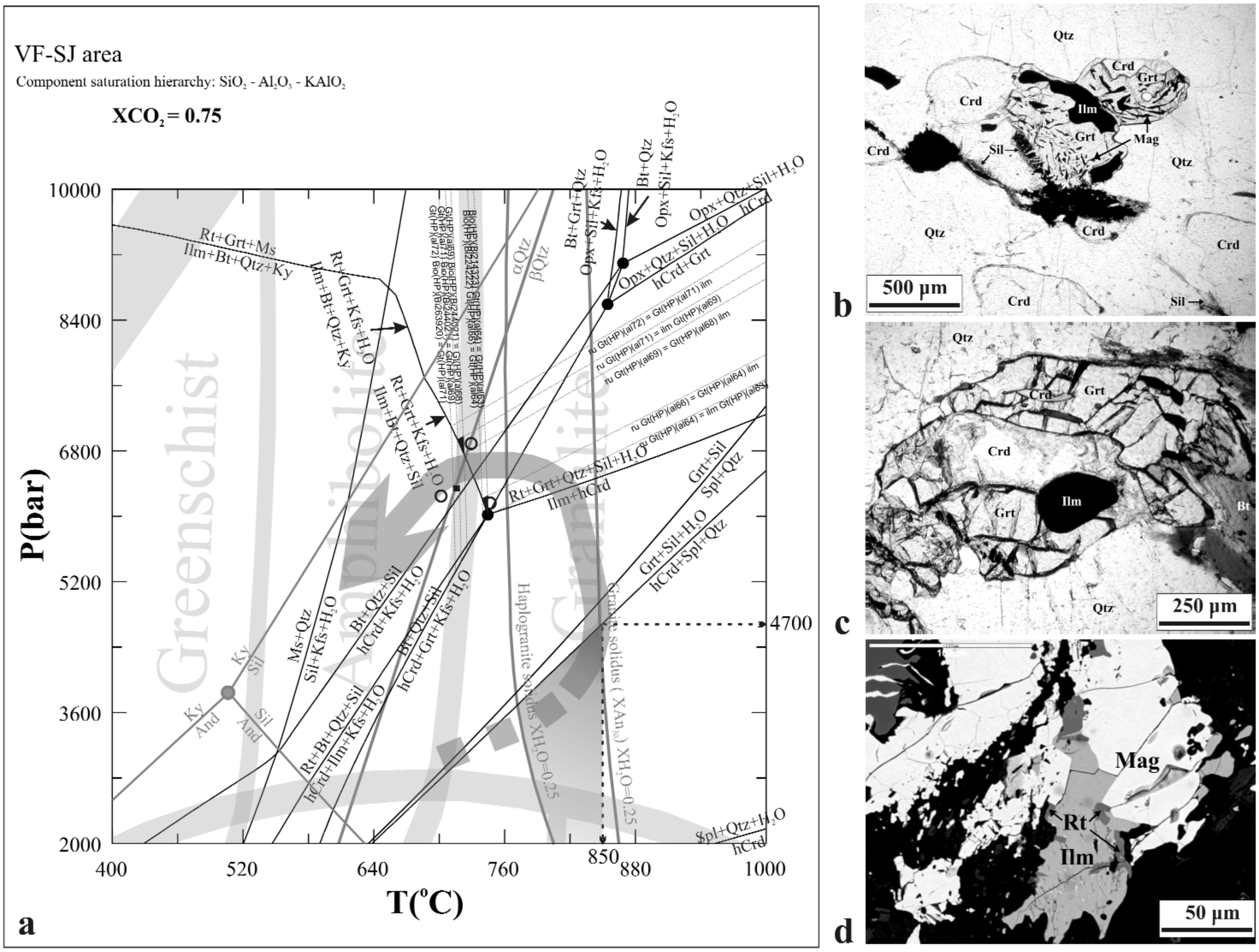

Figure 5: a) P-T diagram for the Sierra de Valle Fértil basement rocks. The grey field represents the most probable conditions attained by the rocks at the metamorphic peak. Empty circles represent the P-T values obtained with the TWEEQU program for rocks with the equilibrium association Qtz+Pl(an)+Kfs+Grt+Bt+Sil+fluid(H_2O+CO_2). Triangles and filled squares represent the P-T values established for the same rocks by means of isopleths of constant composition for garnet and biotite, calculated with the Perplex program. The grey arrow indicates the most probable metamorphic path, based on the analyses of paragenetic associations, textural relationships and geothermobarometry. b, c, d) Examples of the textural relationships that allow to constrain part of the metamorphic path. b and c: PPL photomicrographs showing details of cordierite pseudomorphic replacement by garnet and sillimanite (fibrolite). The replacement is associated to partial transformation of ilmenite into magnetite; d: SEM image showing in detail the transformation of ilmenite into rutile and magnetite.

metry on garnet-bearing rocks and the textural relationships, are characteristics that together suggest a counter-clockwise P-T path as the one shown in Fig. 5.

Both cordierite and k-feldspar (and probably the albitic plagioclase present in these rocks), are closely related to migmatization and were affected by ductile deformation after crystallisation. Therefore, the development of the observed deformation mechanisms must have occurred after the metamorphic peak (thermal maximum-anatexis). On the other hand, the lower temperature limit should not exceed the Qtz_{α}/Qtz_{β} curve (given presence of chessboard extinction in quartz) and the curve corresponding to the reaction Bt+Qtz+Sil ⇄ hCrd+Kfs +H_2O that defines the lower temperature stability limit for cordierite (this phase reflects ductile deformation within its stability field) (Fig. 5). This segment of the counter-clockwise trajectory is located above 700 °C at the considered pressures, i.e., entirely within the granulite facies field (Fig. 5).

DISCUSSION

Several peak metamorphic conditions and P-T trajectories have been proposed for different localities of the Famatinian arc. A low-pressure (< 3 Kb) contact aureole representing upper level exposures of the arc has been described in the Sierra de Chepes, located east of the Valle Fértil-La Huerta range (Dahlquist and Baldo 1996) (Fig. 1a). Peak metamorphic pressures in the range 5-7 Kb were recorded by Delpino *et al.* (2007) for the Pringles Metamorphic Complex (Sierra de San Luis) and Otamendi et al. (2007) for the Sierra de Valle Fértil-La Huerta, being backarc and deep arc the most probable geological settings proposed by these authors, respectively. These three localities have in common high to very high peak metamorphic temperatures attributable to magmatic heating and first stages of retrogression characterized by nearly isobaric cooling, within the context of a counter-clockwise metamorphic trajectory. On the contrary, a clockwise P-T metamorphic path was deduced from the study of metaigneous rocks from the Sierras de Las Imanas, located south of the Sierra de La Huerta (Murra and Baldo 2006). Neither textural nor petrological evidence for decompression have been found in the studied rocks from Sierra de Valle Fértil area (see also Otamendi *et al.* 2007). On the other hand, metamorphic pressures appreciably more higher have been recorded in the Loma de Las Chacras (Baldo *et al.* 2001, Vujovich 1994) (Fig. 1a). This difference in the levels of exposure of different parts of the Famatinian arc have been attributed by Otamendi et al. (2007) to a differential upward movement giving rise to higher rates of exhumation in the Lomas de Las Chacras than in the Sierras de Valle Fértil-La Huerta.

Otamendi *et al.* (2007) carried out a very detailed study of the metamorphic evolution of basement rocks of SVF-SLH and its correlations with other areas of the Famatinian orogen. These authors integrated petrographic and mineral chemical data from a sequence of migmatized pelites and quartz-feldspathic greywackes at SVF-SLH, in order to identify coexisting equilibrium assemblages and to constrain their P-T evolution. These authors also provide insights into two issues related to the evolution of the Famatinian supracrustal sedimentary rocks: the crustal levels they originally occupied and the evolutionary P-T path they followed as they were migmatized by the addition of magmatic heat. This information was used to establish the minimum thickness for the Famatinian arc crust and to provide constraints on geodynamic models accounting for the subduction-to-collision orogenesis that finished the former magmatic arc. Combining their results with those of other studies that have constrained the tectonic-thermal trajectories of metasedimentary and metaigneous rocks from distinct settings within the Famatinian arc, they presented an integrated view of the metamorphic evolution of the Famatinian magmatic belt from the backarc (Hauzenberger *et al.* 2001, Delpino *et al.* 2007) through the contact aureole of plutonic batholiths (Dahlquist and Baldo 1996, Murra and Baldo 2006) to the accretionary wedge (Vujovich 1994, Baldo *et al.* 2001).

The present study is a contribution for the elucidation of the tectonometamorphic evolution of a sector of the Famatinian belt. The proposed P-T metamorphic path fit very well with that presented by Otamendi *et al.* (2007), who also proposed a counter-clockwise trajectory for the basement rocks of the SVF and SLH. There is a total correspondence for the pressure and temperature conditions of retrogression related to an almost isobaric cooling following metamorphic peak. The only -small- difference between both models can be observed in the portion of the trajectory corresponding to the progressive stage. This difference is due to the fact that Otamendi *et al.* (2007) found spinel enclosed only in garnet, while we found coarse spinel inclusions in cordierite of garnet-absent migmatites and evidence of pseudomorphic replacement of cordierite (plus included spinel) by garnet in cordierite-sillimanite gneisses. This is the reason why our P-T path start at lower pressures so that the metamorphic peak falls within the stability field of the association Crd+Spl+Qtz, as was previously described.

CONCLUSIONS

1) At the metamorphic peak, temperature in the SVF reached 800 to 850 °C and pressures were below about 5 Kb.

2) Phase relations and geothermobarometry point to a counter-clockwise P-T path for the metamorphic evolution of the rocks in this region.

3) On the basis of paragenetic associations and deformation mechanisms in minerals, at least three overprinted deformation events can be differentiated in the rocks of the area, and their physical conditions of development constrained by the established P-T metamorphic path: a) a ductile event developed entirely within the granulite facies field, at temperatures exceeding 700 °C and in the probable range of pressures between 5 to 6 Kb; b) a ductile deformation event occurring under the conditions of medium to high amphibolite facies, at temperatures probably exceeding 600 °C and pressures in the interval 6-7 Kb; c) a brittle deformation event developed at low greenschist facies, probably at temperatures below 400 °C and pressures not determined with certainty until present.

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