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Kinematic evidence for cordierite porphyroblast growth in a contact aureole during progressive deformation; Shah-Kuh granitoid, NE Lut Block, Iran

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Abstract

The Shah-Kuh granitoid has intruded in the Triassic–Jurassic, pelitic and psammitic low-grade metamorphic rocks of the NE Lut Block, in Central Iran. Cordierite porphyroblasts are common in the southern pelitic sediments, but are rare in the northern psammitic rocks, in the contact aureole. Deformation fabrics in the contact aureole are well-preserved within the cordierite porphyroblasts. The relation of the cordierite porphyroblasts and deformation fabrics indicate that the time of growth has started and is synchronous with the first deformation phase and ends after the second deformation stage. The porphyroblasts are also generated in syn-intrusion ductile shear zones existing in the contact aureole and continue inside the Shah-Kuh granitoid. Shear zones in the contact aureole contain deformed cordierite porphyroblasts, with microstructures indicating clear shear sense. Structural analysis of various metamorphic rocks in the contact aureole of the Shah-kuh granitoid indicates a first stage, which is tight to the isoclinal folds, with well-developed axial-plane foliation, and a second stage of crenulation cleavage. Sequential growth of cordierite porphyroblasts preserved fabric from various stages of a progressive deformation in the granite contact aureole. It is concluded that the Shah-Kuh granitoid has intrusions synchronous with progressive deformation, cordierite porphyroblasts growth, and shear zone development in the contact aureole of the granitoid.

Keywords: Contact Aureole, Cordierite Porphyroblast, Deformation, Iran, Shah-Kuh.

Introduction

Metamorphism and deformation are intimately linked in orogenic belts, producing growth-foliation sequences (Williams, 1994). Interpretation of porphyroblast-matrix, microstructural relationships can provide relatively clear evidence of sequential porphyroblast growth in metamorphic sequences (Vernon, 1989). Vernon (2004) has discussed several cases of porphyroblastic minerals, preserving evidence of different stages of foliations. Kinematic evidence of porphyroblast growth during a progressive deformation, synchronous with prograde metamorphic reactions, especially with regard to development of foliations in a single rock has been studied previously in some areas (e.g., Bell & Rubenach, 1983).

We introduce fabrics in cordierite porphyroblasts in a contact aureole, which were growing during the intrusion of the Shah-kuh granitoid in low-grade metamorphic rocks of the Deh-Salm complex (Stöcklin, *et al.*, 1972) in SE Iran (Fig. 1). The NW–SE trending Deh-Salm metamorphic complex is a long border of mountains along the northeast of the Lut Block. This complex has been named the ‘metamorphic inlier’ and transported as a tectonic suspect terrain belonging to the Sanandaj-Sirjan metamorphic zone of SW Iran (Davoudzadeh & Soffel, 1981). The Deh-salm metamorphic complex has been divided into two, the lower amphibolite and upper green-schist units (Stöcklin, *et al.*, 1972; Berberian & Soheili, 1973).

The Shah-kuh granitoid has intruded into the upper green-schist unit of the Deh-Salm metamorphic complex. The Ar–Ar and K–Ar radiometric age determination suggests 163±3.5 Ma for Shah-kuh granitoid (Esmaeili, 2001). An obvious contact aureole is produced around this granitoid and a high population of cordierite porphyroblasts is generated in the southern contact, in the pelitic rocks, than in the northern psammitic sediments of the Deh-Salm metamorphic complex (Fig. 1).

In this study, the general characteristics of the deformation stages and the fabrics of the contact aureole are introduced. Evidence of growth time for cordierite porphyroblasts are displayed, based on their relation with the deformation stages occurring at the growth time in the area. Kinematic evidence of cordierite porphyroblast growth in syn-growth ductile shear zones in the contact aureole is also

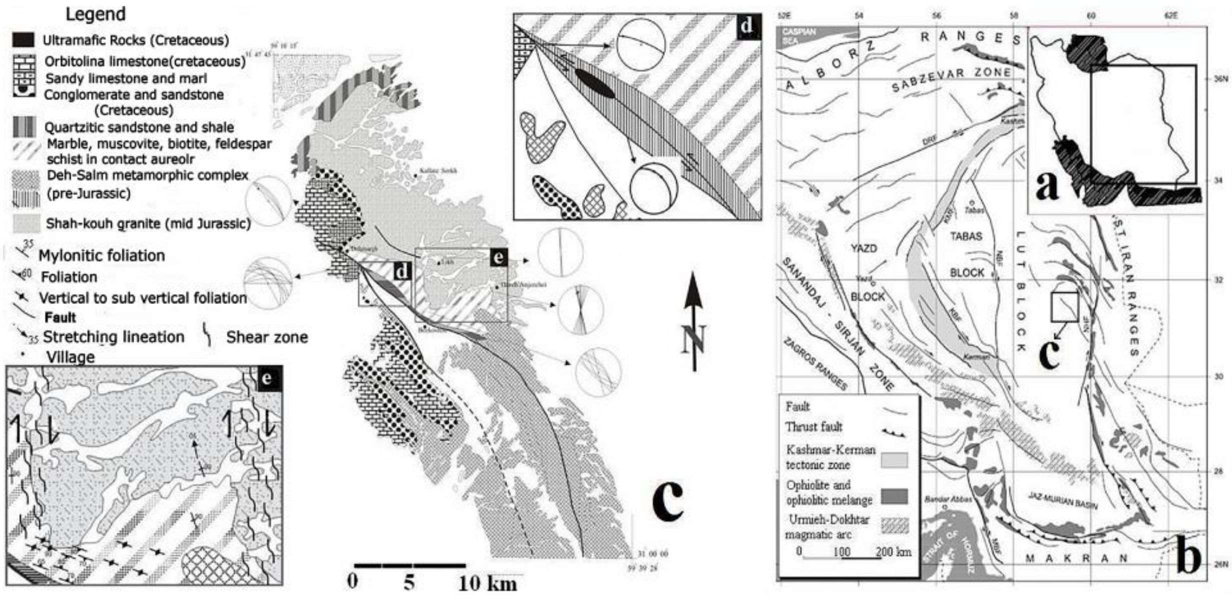

Figure 1. a) Location of the study area in east Iran; b)Central microplate of Iran containing three blocks of Yazd block to the west, Tabas Block to the east, and the Lut block in between Location of the study area in the northeast of the Lut Block is marked; c) Shah-kuh granitoid intruded in the Deh-Salam metamorphic complex with contact aureole. Stereographic projections show the geometry of the existing major structures in the study area. Location of shear zones and samples are determined; d) Location of marble and schist with exposed sheared ultramafic rock along the major strike-slip fault; d) N-S trending about the vertical dextral strike-slip shear zones in cordierite bearing contact aureole and granite

presented, and finally a tectonic setting of the Shah-Kuh granitoid in the NE Lut Block in Central Iran is discussed.

Geological setting

The Shah-Kuh granitoid intrudes into the Deh-Salm metamorphic complex exposed at the eastern border of the Lut Block. The Lut Block is the eastern block of the central microplate of Iran, consisting of the Yazd Block to the west, Lut Block to the east, with the Tabas Block in between (Fig. 1b). The Lut Block is composed of Paleozoic–Mesozoic, metamorphic, and abundant Tertiary volcanic rocks. The southern half of the Lut Block is largely covered by Quaternary sediments of Lut depressionThe central microplate of Iran has been proposed as a microcontinent surrounded by a Red Sea–type ocean during the Mesozoic. The remnants of ophiolites and colored mélanges have been exposed along the Neh Fault at the eastern border of the Lut Block. According to Crawford (1972) the Lut Block is an island of subcontinental size in the Tethys. Berberian (1973) argued that the Lut Block behaves as a rigid block and it is argued that the Lut Block has undergone an anticlockwise rigid-body rotation of up to 90 degrees during the Tertiary (Westphal *et al.,* 1986) and even more (Besse *et al.,* 2003), in response to the collision of India with Eurasia. Accordingly, the present eastern border of the Lut Block will have formed its southern to southwestern border before rotation - a border that belongs to the active margin of the subducted Neotethys (Dercourt *et al.,* 1986; 2000).

Therefore, the eastern border of the Lut Block represents the rotated southwestern prolongation of the Late Mesozoic Sanandaj–Sirjan metamorphic zone (Stöcklin, 1968).

According to Stöcklin *et al.* (1972), the intrusive rocks in the Lut Block belong to two suites. One comprises mostly of granites of the post-Early Jurassic age, including the Shah-Kuh granitoid in the eastern border of the Lut Block. The other suite consists of Granodiorites, Diorites, and the related Subvolcanics of the Middle or Late Tertiary age. The Deh-Salm metamorphic complex is exposed along about a 100-km long and 17-km wide area, extending to the northeast Lut Block in SE Central Iran (Fig. 1c). These metamorphic rocks were divided into two lower amphibolite facies consisting of carbonate and mafic volcanic rocks and the upper green-schist facies, which consists of graphitic shale and carbonates. No distinct fossils have been identified in these rock units except traces of crinoids. Deh-Salm metamorphic complex and Shah-Kuh granitoid were both overlain by a basal conglomerate of Cretaceous (Aptian) (Stöcklin, *et al.,* 1972) (Fig. 1c).

Shah-Kuh granitoid

The Shah-Kuh granitoid is exposed to the northeastern part of the Lut Block with a NW–SE elongated body, ~35 km in length and ~11 km in width, located 150 km south of Birjand and displays very clear intrusive contacts with the Triassic–Jurassic rocks. Along part of its western side, the pluton is transgressively covered by shallow, dipping basal conglomerates of the Lower Cretaceous. To the east, it disappears under extensive Quaternary sand deposits (Fig. 1c).

Shah-Kuh granitoid consists of three kinds of intrusive rocks, granodiorite, syenogranite, and microgranite, all cut by the NE–SW trending aplitic, dacitic, and andesitic dykes. Tourmaline–quartz veins are the younger intrusions cutting other rock types in the same orientation of dykes (Esmaeily, 2001). Minor fine-grained stocks, dykes, and quartz–tourmaline veins are also observed in places. The granodioritic unit, with compositions ranging from granodiorite to monzogranite, is exposed in the north and center of the pluton. A petrological and geochemical study of the Shah-Kuh pluton suggests that the granites forming the pluton correspond to a reduced I type (transitional to S-type), derived from a young crustal protolith (Esmaeily *et al.,* 2005).

Magmatic to submagmatic microstructures are observed in this granitoid. High temperature microstructures are present. It is generally assumed that the fabric formed while the granite was continuing to deform during emplacement, at temperatures close to the solidus (Esmaeily *et al.,* 2005). The Shah-Kuh pluton was subjected to an overall N–S to NNW–SSE stretching throughout its deformation during emplacement and ended, before full crystallization of the granite, in a regional shear zone. The shear zone is marked by the WNW–ESE alignment of mylonitic to submylonitic microstructures (Esmaeily *et al.,* 2007).

Contact aureole rocks to the north and west are mainly made of pale green to intense grass-green silty argillites and sandy shales, with several sandstone intercalations. The effect of contact metamorphism is mainly marked by rock-silicification in addition to a rather well-defined cleavage, which is re-crystallized close to the pluton, forming quartzites. In this part, rare cordierite porphyroblasts are identified. According to the geological map of the area (Behrouzi & Khan-Nazer, 1984), the sandstone unit is equivalent to the upper low-grade metamorphic unit of the Deh-Salm metamorphic complex, but no minerals of regional metamorphism have been identified.

The pelitic metamorphic rocks are dark-green hornfels, with cordierite and alusite in proximity of the contact. This formation extends to the south of Shah-Kuh for about 100 km (Fig. 1c) at a low metamorphic grade. The age of this formation is pre-Aptian, underlain by the orbitolina-bearing Cretaceous limestone. Metapelitic sediments along the southern contact of the Shah-Kuh granitoid contain abundant cordierite porphyroblasts. No cordierite porphyroblasts have been produced beyond the contact aureole by regional metamorphism in the Deh-salm metamorphic complex.

Structures in the contact aureole rocks

Structures in the aureole rocks are folds, faults, and shear zones. Folding is identified in different scales in the contact aureole rocks of the Shah-Kuh granitoid. Folds are well observed in the Deh-Salm metamorphic complex at the southern contact aureole of the granitoid (Fig. 1c). Folds in a mesoscopic scale are well developed in the Metapelitic rocks and are identified by well-developed axial plane schistosity. They appear mostly upright and in places with an overturned southwestern limb, tight to the isoclinals folds with attenuated long limbs and curved at the angular hinges (Fig. 2). Axial planes are mostly vertical or dip moderately to steeply at the NE and the axes mostly plunge shallowly to the NW. Boudinage and pinch-and-swell structures develop along the limbs of the folds. Foliation on the limbs of the folds is commonly parallel to the bedding. This axial plane foliation is a metamorphic structure as shown by syn-tectonic mineral growth. In the contact aureole of the granitoid, abundant cordierite and rarely any alusite porphyroblasts are generated and develop during this folding event (Fig. 3). The fabrics of these porphyroblasts display the timing of growth in relation to the dynamic activity in the region.

Faulting in the study area has contributed to the elongated, NW–SE trend of the outcrop pattern of the Shah-Kuh granitoid. Well-exposed major strike–slip faults with a dominant north-northwest

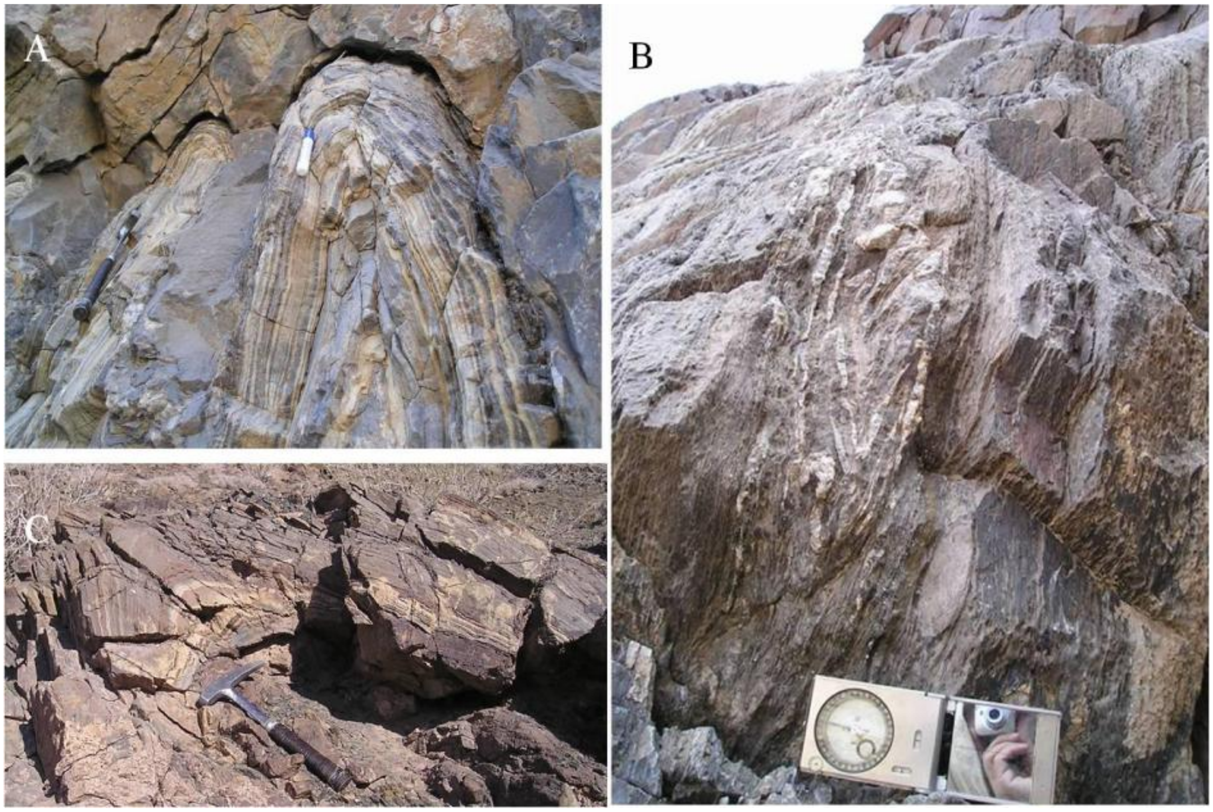

Figure 2. a) Tight to isoclinal first generation upright folds in marble, which is shallowly plunging to the northwest, and the axial plane steeply dips to the northeast in Deh-Salm metamorphic rocks; b) Overturned first generation folds in the quartz veins in Deh-Salm metamorphic rocks; c) Recumbent fold in Deh-Salm metamorphic rocks.

(NNW)-trend dip to the east-northeast (ENE) at the southern part of the Shah-Kuh granitoid (Fig. 1c).

These strike-slip faults have a large amount of left lateral displacement and are obviously displaced at the Cretaceous rocks, about 4 km at the southwestern part of the Shah-Kuh granitoid (Fig. 1c). Along one of the major faults, subparallel to the suture zone of the northern part of the study area (Fig.1b), the ultramafic rocks are exposed and strongly sheared. The foliation is about vertical and the sense of displacement is sinisteral (Fig. 4). To the north (Fig. 1b), ophiolites and ophiolitic mélanges are exposed along the same oriented major faults.

Fabrics of cordierite porphyroblasts

Six different stages can be postulated for the growth of cordierite porphyroblasts existing in the southern contact aureole. Each stage is described in detail and then fabrics of cordierite porphyroblasts are explained in the ductile shear zones existing in the contact aureole and continued into the Shah-Kuh granitoid (Fig.1c).

Stage 1. In this stage, the cordierite porphyroblasts contain sector trilling and twinning, and this, in particular, belongs to contact metamorphism and is normally not observed in regional metamorphic rocks (Kitamura and Yamada, 1987). Only the first generation foliation (S_1) exists in both matrix and cordierite porphyroblasts in the same orientation (Fig. 5A). Cordierite porphyroblasts are subparallel to the S_1 foliation or in special cases are post generated, and are not pre-generated in relation to S_1. In that case, a strain shadow could be produced on both sides of the porphyroblast (Fig. 5A).

Stage 2. In this stage the first generation foliation (S_1) is slightly crenulated and the fabric continuously exists in both the matrix and the porphyroblasts, in the same orientation (Fig. 5B). This indicates that the cordierite porphyroblasts have grown simultaneously with S_1 crenulation (syntectonic) or soon after crenulation.

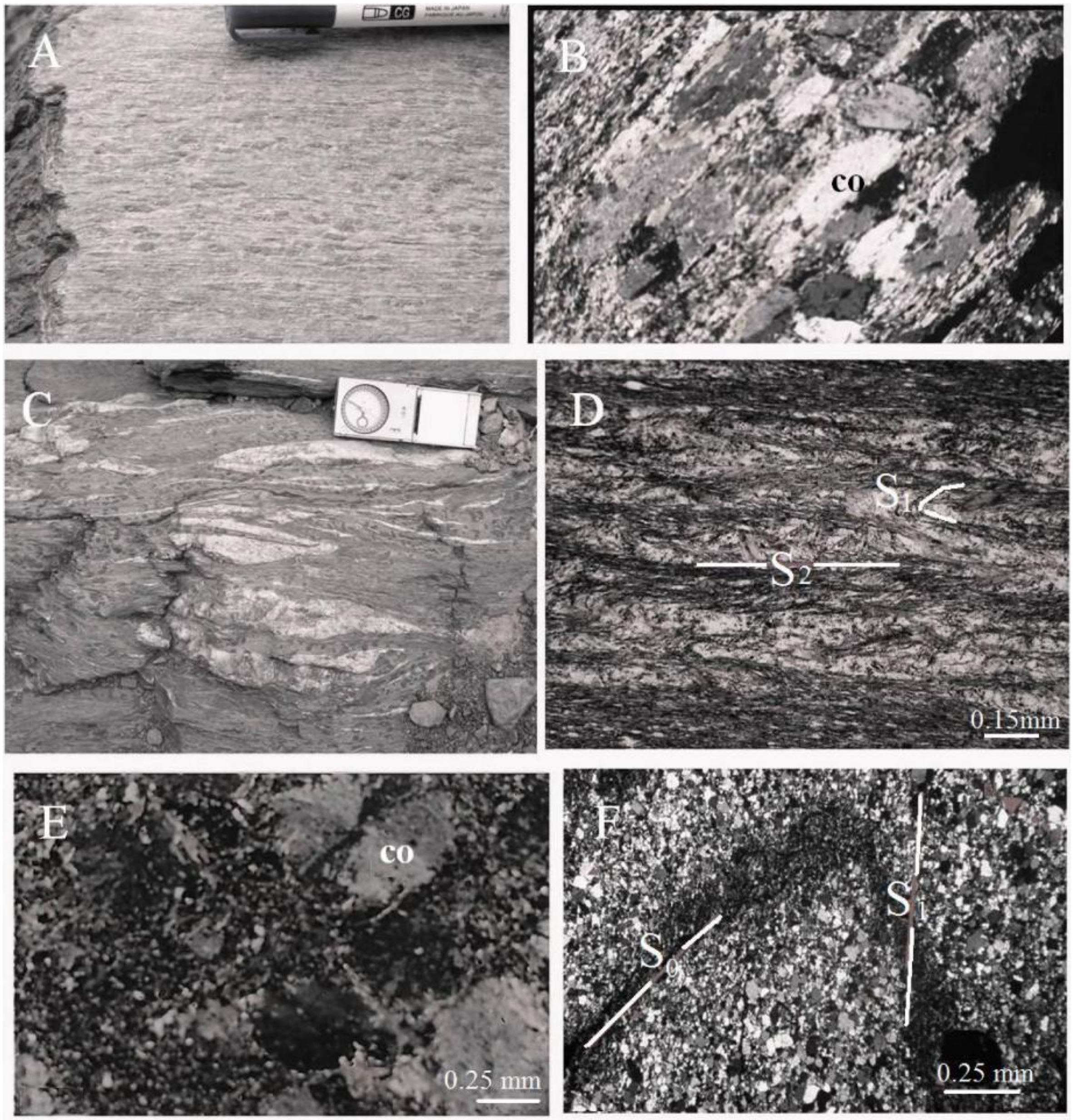

Figure 3. a) Cordierite porphyroblasts along the well-developed foliation in the pelitic rocks of the Deh-Salm metamorphic complex; b) Well-developed S_1 foliation in the pelitic rocks of the Deh-Salm metamorphic complex; c) Isoclinals flow folds in quartz veins with axial plane S_1 foliation; d) Crenulation foliation in schist; e) Cordierite porphyroblasts in the northern psammitic aureole; f) Folded bedding in quartz feldspathic schists. Axial plane S_1 foliation is identified by orientation of all grains in the rock.

Stage 3. In this stage the first generation foliation (S_1) is crenulated, the microlithons are separated from the second generation foliation domains, and the porphyroblast is generated inside the microlithon domain (Fig. 5C).

Stage 4. In this stage the cordierite porphyroblasts contain different internal foliation than that in the matrix. The first generation foliation (S_1) exists straight, with unique orientation inside the porphyroblasts. The second generation foliation in the matrix has been produced by crenulation of the first-stage foliation. The external second generation foliation (S_2) anastamoses the cordierite porphyroblasts producing strain shadows on both sides of the porphyroblasts (Fig. 6A).

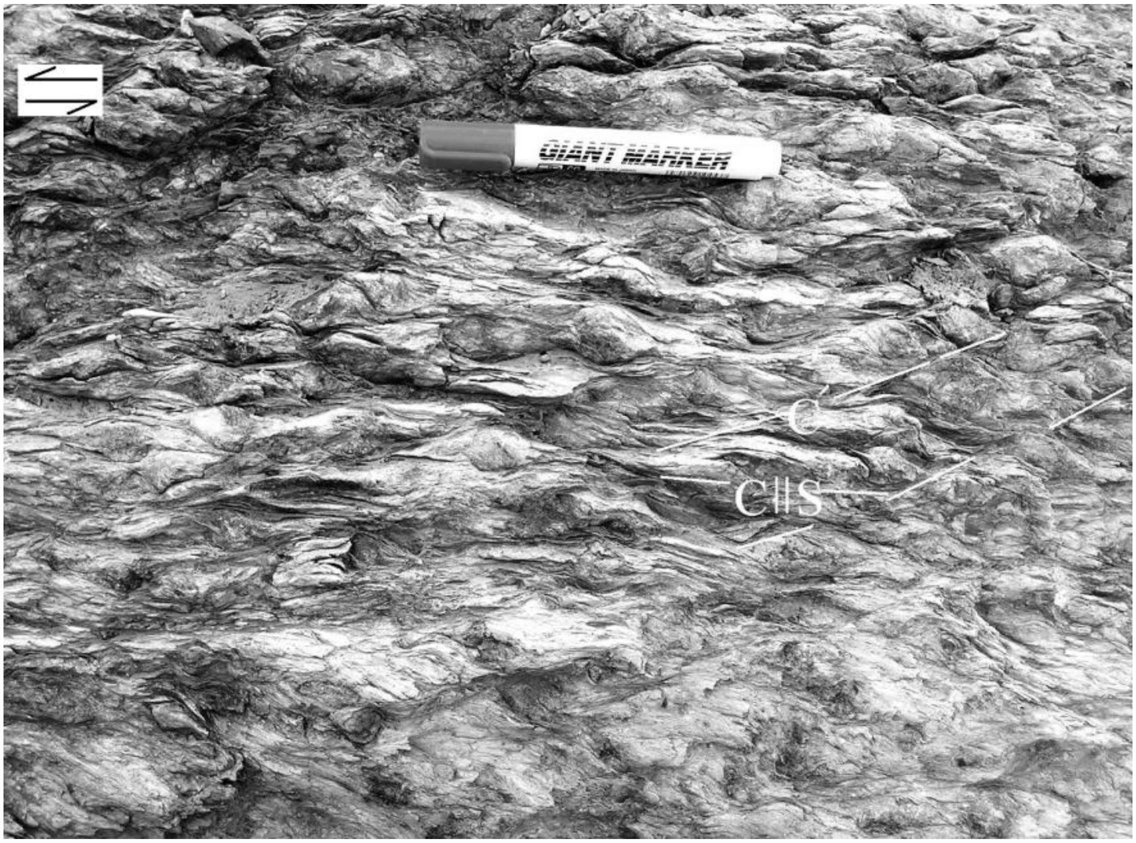

Figure 4. Shear-band structures in sheared ultramafic rock exposed along the major strike-slip fault

Therefore, the cordierite porphyroblasts contain S_1 internal foliation and S_2 is the external factor anastomosing them. This implies that the growth of the porphyroblasts occurs in the time interval between S_1 and S_2.

Stage 5. In this stage, the first generation foliation (S_1) is straight and in different orientations inside the porphyroblasts. The second generation foliation in the matrix anastamose the cordierite porphyroblasts producing strain shadows at both ends of the cordierite porphyroblasts (Fig. 6B). Therefore, the porphyroblasts are displaced from their original locations before the second generation foliation.

Stage 6. In this stage the first generation foliation (S_1) that has been crenulated producing both microlithons and second stage crenulation foliation occur inside the cordierite porphyroblasts at the same time as the matrix (Fig. 6C). This indicates that the porphyroblast growth is post S_2 (post tectonic).

Fabrics of cordierite porphyroblasts in ductile shear zones of contact aureole

Shearing fabrics are well-observed in the field study by strong subvertical mylonitic foliations and well-developed, gentle-to-subhorizontal stretching lineations in the ductile shear zones, both in granitoid and contact aureole rocks (Fig. 7). They were developed in two clear north–south (NS)-oriented, strike-slip shear zones at the southeastern contact aureole (Fig. 1c). Abundant shear sense indicators are observed in thin sections of the oriented samples, cut parallel to the stretching lineation and perpendicular to the mylonitic foliation. All shear sense indicators demonstrate a dextral sense of shear in shear zones. This is also well-clarified by the synshearing growth of cordierite porphyroblasts in the shear zones of the southern contact aureole (see below).

Shear zones in the contact aureole of the Shah-Kuh granitoid have developed in both the aureole and granite (Fig. 7). The shear zones are in the N-S orientation and are all strike-slip and vertical, with a dextral sense of shearing. Stretching lineation is almost horizontal, subparallel to the strike of the shear zones. Two distinct growth time stages are observed for cordierite porphyroblasts in these shear zones.

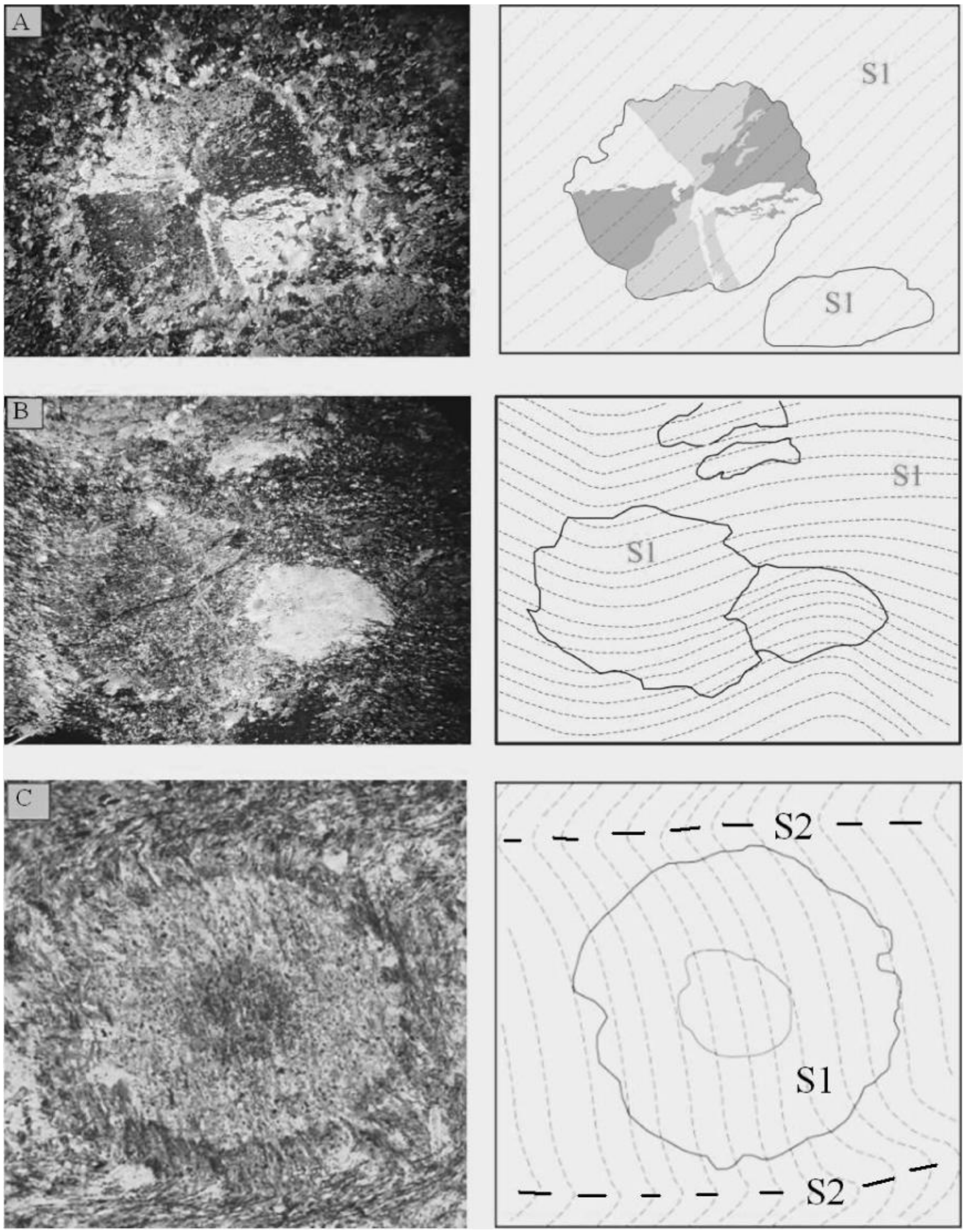

Figure 5. a) Cordierite porphyroblast containing sector trilling twins which are seen in the contact metamorphic rocks. S_1 is oriented from the right side of the upper part to the left side of the lower part in the figure and passes through the porphyroblast; b) Cordierite porphyroblasts have grown syn- or post crenulation of the S_1 foliation (XPL, X100); c) The figure shows a cordierite porphyroblast. Microlithons containing S_1 and cleavage domains are S_2 (PPL, X200).

Stage 1. In this stage cordierite porphyroblasts seem to be generated syn-kinematic with shearing. The S fabric is seen both inside and outside of the cordierite porphyroblasts, with no refraction. Cordierite porphyroblasts are elongated along the S fabric, indicating syn-shearing growth (Fig. 8A).

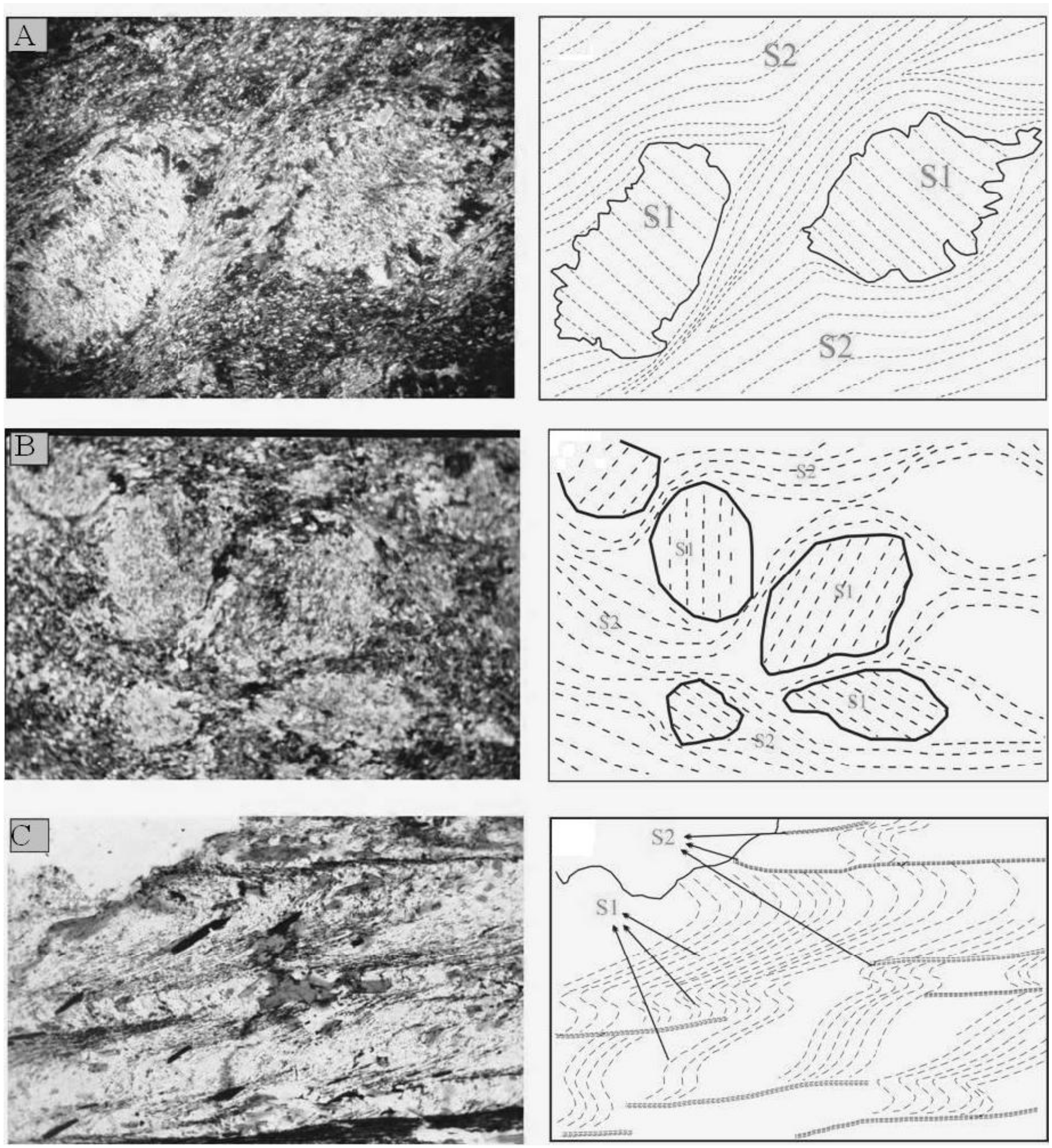

Figure 6. a) Internal foliation (S_1) is different from the external foliation (S_2), but the internal foliations in both cordierite porphyroblasts are in the same orientation. The strain shadows at both sides of the porphyroblasts indicate pre-deformation of the porphyroblasts when compared with the external foliation (XPL, X100); b) Cordierite that porphyroblasts containing S_1 have been rotated. S_2 is being generated in the matrix and anastamoses with the porphyroblasts (PPL, X100); c) S_1 crenulated with S_2 forms the internal foliation in a cordierite porphyroblast. Cordierite porphyroblasts are generated at the final stages of the formation of the second-stage crenulation foliation

Figure 7. a) Southern sector of the contact aureole of the Shah-Kuh granitoid. The width of the photo is about 80 m; b) Contact area of the granitoid. Foliation is developed subparallel to the contact line in both the granite and the aureole; c) Foliation in the granitoid is identified by alien black micas

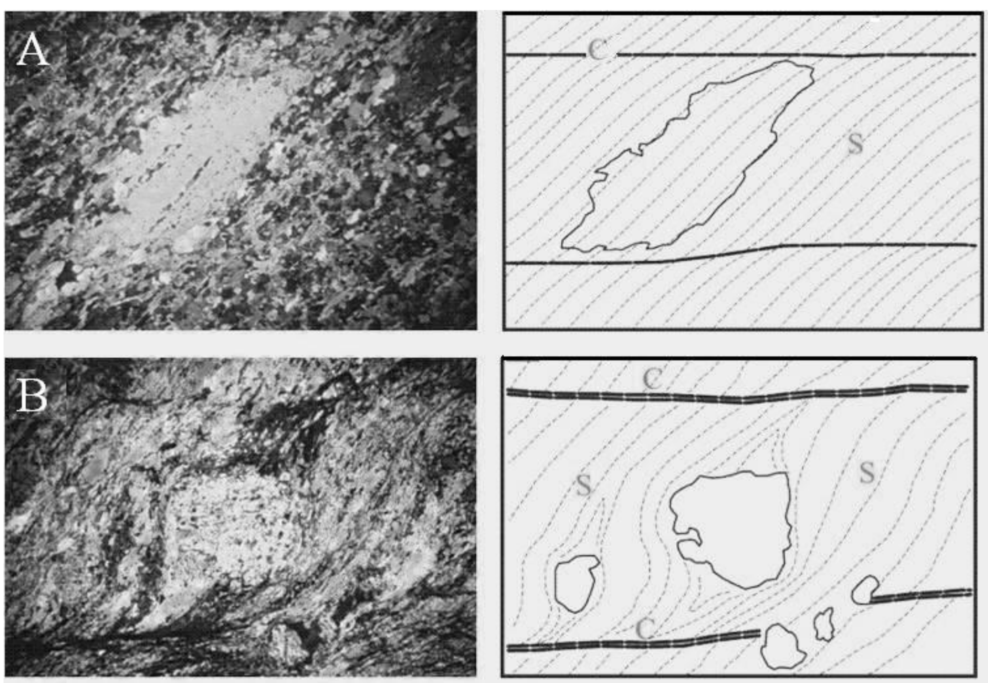

Figure 8. a) Cordierite porphyroblasts generated syn- growth in ductile shear zone. The S foliations of the shear zone are considered as continuous internal (Si) and external (Se) foliations (XPL, X100); b) Cordierite porphyroblast generated pre-syn shearing in the ductile shear zone. (Note the anastomosed porphyroblast by S foliation of the shear zone and strain shadow at both ends of the cordierite porphyroblast) (XPL, X100)

Stage 2. In this stage the cordierite porphyroblasts are anastomosed by the S foliation of ductile shearing and two distinct strain shadows exist at both ends of the porphyroblasts. Cordierites are not elongated along the S fabric, indicating that porphyroblast growth slightly predates the shearing process (Fig. 8B). Moscuvite fishes and elongated quartz fishes also indicate dextral shearing in the shear zones (Fig. 9).

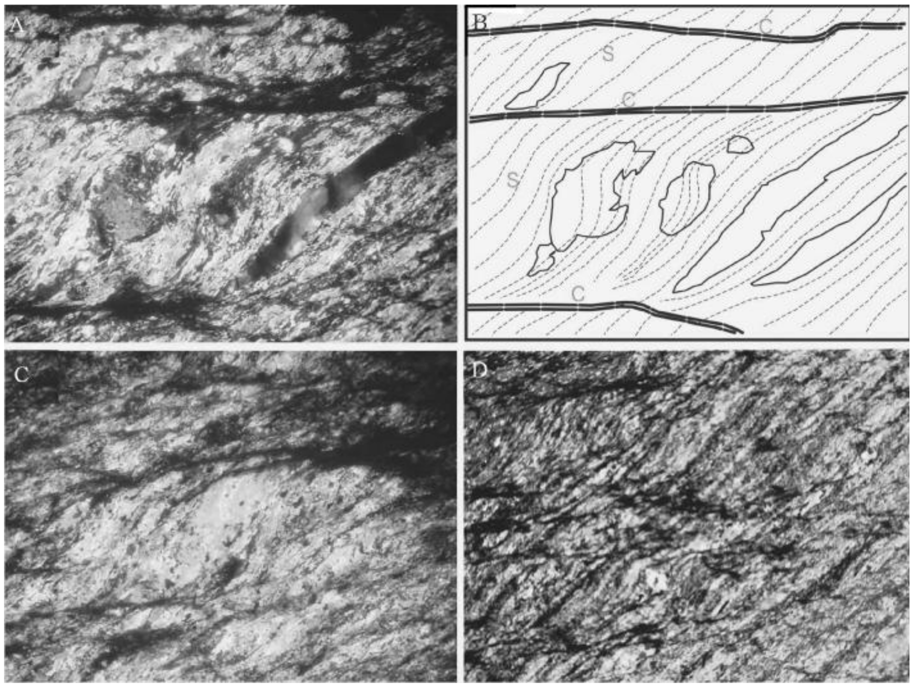

Figure 9. a) Shear band (S/C fabric) structure in the shear zone of the contact aureole. C fabrics are horizontal and S fabrics are oriented top right and down to the left side (PPL, X10). Note the end parts of the S fabrics that are turned toward the C fabrics at the contacts. Cordierite porphyroblasts and quartz ribbons are along the S fabric as a fish structure; b) Mica fishes clearly indicating right-lateral shear sense (PPL, X200)

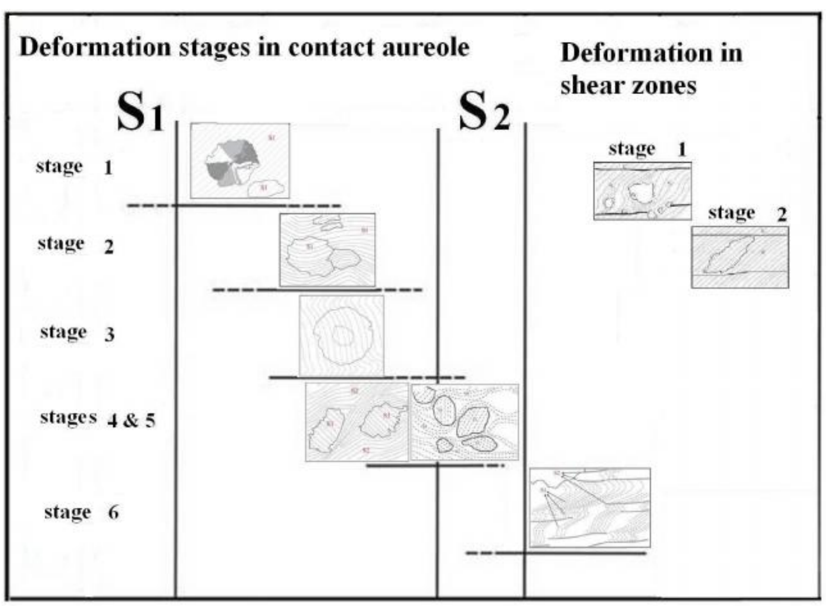

Figure 10. Deformation stages in the contact aureole (left) are displayed through six stages from pre-S_1 to post-S_2. Deformation in the ductile shear zones is presented in two pre- to syn- stages

Conclusions

The relations of cordierite porphyroblast growth with deformation fabrics were saved in various stages through contact metamorphism of the Shah-Kuh granitoid (Figs. 5, 6). They demonstrated both rates of growth and progressive deformation intervals. This indicated that generations of cordierite porphyroblasts existed syn- to post deformation in the contact aureole (Fig. 10). The youngest cordierite porphyroblasts grew after generations of second crenulation cleavage (Fig. 6C). The cordierite porphyroblasts in the ductile shear zones were also generated during shearing and this implied that the shear zones in the aureole were also produced synchronous with the intrusion of the Shah-Kuh granitoid.

We conclude that the Shah-Kuh granitoid was emplaced in the Neotethys-active continental margin during the Mid-Mesozoic along a major strike-slip fault, synchronous with progressive deformation and growth of cordierite porphyroblasts in the contact aureole.

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