Deformation path partitioning within the transpressional Khoy shear zone, Zagros orogen, NW Iran

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Abstract: Metamorphic-ophiolitic complex and various intrusive rocks in the Khoy area are located in a transpressed active continental margin. These complexes in the Zagros orogen were deformed during an oblique convergence scenario between the Arabian and West Alborz- Azerbaydjan blocks in NW Iran. The Khoy area contains both NW-SE striking dextral strike-slip and SW verging NE dipping ductile reverse shear fabrics. Ductile shear fabrics are overprinted by subsequent younger thrust and strike-slip fault systems. Abundant syn-tectonic granitoides were intruded in the Khoy area during convergent. Shear deformation fabrics are well identified in both deformed intrusive and metamorphic-ophiolite complex. The geometry and kinematics of shear fabrics indicate a deformation partitioning in both ductile and brittle conditions during a progressive transpression tectonic regime. [Hassan H.H, Ali S, Mohammad M, Mohsen P.K. **Deformation path partitioning within the transpressional Khoy shear zone, Zagros orogen, NW Iran**. *Life Sci J* 2013;10(4s):255-265] (ISSN: 1097-8135). http://www.lifesciencesite.com. 38

Keywords: Deformation partitioning, Khoy, Metamorphic-ophiolitic, NW Iran, Shear zone

1. Introduction

The Khoy shear zone (KSZ) is exposed 650 km west of Tehran and contains the Khoy metamorphic-ophiolitic complex in the Azarbaijan province of NW Iran (Fig 1). The NW-SE trending KSZ is the northwestern hinterland of the Zagros orogen (Sanandaj-Sirjan zone), (Stocklin, 1968; Berberian and King 1981; Alavi, 1994; Mohajjel et al., 2003) close to the border of Turkey in NW Iran. This shear zone consists of two different complexes: The Khoy metamorphic complex (KMC) and the Khoy ophiolite complex (KOC). Two opposite opinions exist about the nature of KMC. According to the SW vergence of the obducted KOC, it is believed that they are the result of sole metamorphism under the obducted ophiolites (Hassanipak and Ghazi, 2000). In contrast, others give documents and suggest that the KMC rocks were formed because of medium to high grade metamorphic condition during a regional metamorphism under KOC thrust sheet from the NE (Azizi et al., 2006).

The metamorphic complex of Khoy shear zone mostly exposed along the SW of the KOC. Stratigraphy, geochemistry, geochronology and petrology researches have been documented in the KMC and KOC by several studies (Hassanipak and Ghazi, 2000; Khalatbari jafari et al., 2003; Azizi et al., 2006; Monsef et al., 2010 ; Azizi et al., 2010). The present data suggest an origin of the Eastern Khoy Ophiolitic Complex peridotites from an ophiolitic mantle sequence, related to supra-subduction-zone contexts, thrusted over the continental margin during the collisional stage of a slow-spreading back-arc-basin center (Monsef et al., 2006). This study introduce the geometry and kinematic characteristics of deformed rocks in the Khoy area and covers the fabrics in KMC and KOC complexes to find out the structure, shear fabrics and shear sense indicators of the complexes. We believe that fabric study of the Khoy metamorphic-ophiolitic complex is necessary to get tectonic model of the Neo-Tethys closure in NW Iran.

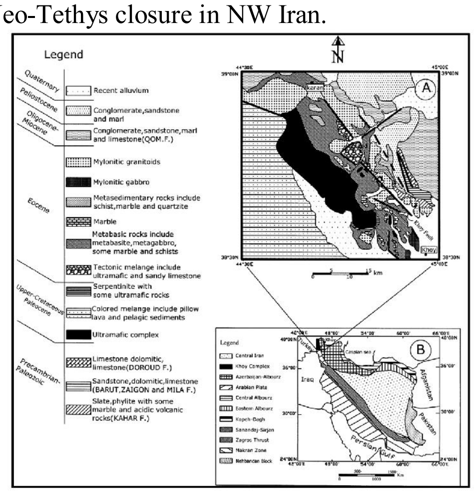

Fig.1.(A) Geological map of the region of Khoy (Azizi et al., 2006). (B) Tectonic map of Iran after Stocklin and Nabavi (1972)

2. Metamorphic-ophiolite complex

The metamorphic-ophiolite complex of the Khoy shear zone are bordered by Precambrian-Paleozoic non-metamorphic rocks to the northeast and Cretaceous ophiolites to the southwest (Fig 2). Upper Precambrian-lower Paleozoic rocks including Kahar, Baroot, Zaygon, Laloon and Mila Formations are overlain with Permian carbonates. The middle

Paleozoic units were not deposited in this area (Radfar and Amini, 1999). Late Cretaceous ophiolites are exposed in SW (Hassanipak and Ghazi, 2000). Oligocene-Miocene Qom Formation overlies metamorphic rocks along an unconformity and Neogene conglomerates occur in eastern part of the Khoy shear zone (Fig 1).

Metamorphic complex in the Khoy shear zone are mylonitic granite, meta-gabbros, meta-basite and meta-sedimentary rocks. Protolite of meta-basites are island arc toleiatic and calc-alkaline basalts and meta-sediments are pellitic with carbonate and detritic sediments including sandstone and conglomerate. The meta-basites include greenschists and amphibolites and, the meta-sedimentary rocks are micaschist, garnet-strotites and garnet sillimanites. Ro/Sr age dating of the metamorphic rocks indicates 146 Ma for the schists (Azizi et al., 2006). The greenschists of meta-basites contain epidote, chlorite, albite and iron oxide. The hornblende and plagioclase are abundant where the grade increases. In some cases, garnet is included in amphibolites and in other cases diopside is included containing 5% of the rock minerals. Metabasites in the metamorphic complex of the Khoy shear zone could be divided in 5 types of greenschist, epidote amphibolites, garnet amphibolites, garnet-diopside amphibolites and diopside amphibolites.

The ophiolite complexes in Khoy shear zone are mostly mylonitic and contain serpentine, gneiss, amphibolite, diorite, granite, lerzolite and harzborgite (Fig 2).

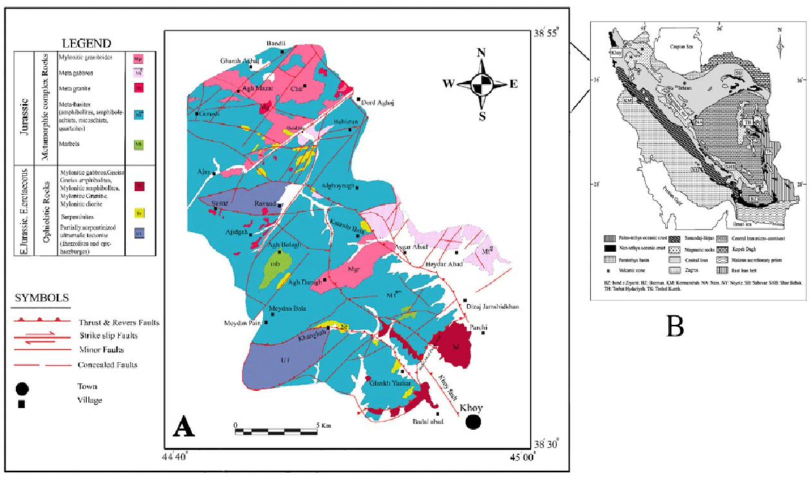

Fig. 2. (A). Geological map of Khoy shear zone. (B). Sedimentary-structural map of Iran after Aghanabati (2004).

3. Structure

Several fault-bend folds and thrusts crop out near the road cut to the Ajay and Khoy villages in the north and north west of Khoy city. The road cuts are oriented approximately perpendicular to the strike of the fault-bend fold structures and thrusts and present crosssectional views of these structures (Fig. 3). Two stages of folding occur in the metamorphic complex (Fig 4D). The first generation is the asymmetrical folds (F1) with NW-SE oriented axial plane moderately to steeply dipping to NE, parallel with strike of shear zones. They vary from gently or moderately inclined, based on their NW-trending NE-dipping axial planes (Fig 4H). The second generation folds are coaxial with the first generation folds.

Shear folds are found in lithologicl layering (Figs 4 C and G). These folds commonly reflect the overall sense of shear (Davis and Reynolds, 1994). Asymmetric folds are common in the KSZ that are found in the middle to deep levels of the crust (Hudleston and Platt, 2010). Axes of the sheath folds (Fig 4A) plunge to W-NW and are folded by non-cylindrical drag folds giving type three interference patterns. The asymmetric sheath folds plunge to (85-115) or (275-295). In planar outcrop faces, sheath folds in KSZ appear as elliptical eyes defined by rings of lithological layers (Fig 4E). Their long axis is generally parallel to the stretching lineation, and their shape reflects the sense of shear. They are formed by lateral variations in particle velocities within the flow regime, much like those that exist between the center of a flowing river and its banks (Davis and Reynolds, 1994). Type three interference pattern (Ramsay and Huber, 1983) that is produced during a coaxial progressive deformation and S and Z drag folds are observed in limbs of the sheath folds (Figs 4B and F).

Deformed boudins and flanking structures (Passchier, 2001) are found in mylonitic granitoides in SW Ajay village (Fig 5). Flanking- folds occur between dismembered boudins. Later layer-parallel shortening resulted in folded boudins. Fold hinge lines and neck lines of boudins plunge to east.

The NW-SE trending S1 foliation is the most abundant fabric in the KSZ. It is the axial plane foliation of F1 folds those were generated by folding of the primary bedding in rocks. The

S1 is a continuous foliation in schists and it is obvious with well-oriented micas. In amphibole-gneisses, oriented amphiboles, in marbles, oriented calcites and tremolite minerals and in quartzite, fine grain micas show a clear orientation (Figs 6C and D). The abundant NW-SE orientation of the S1 changes clockwise to NNE in north Badalabad, east Asgar Abad and south Ajay areas (Fig 6B). The S2 is a crenulation cleavage with NNW strike in schists and marbles (Figs 6 A and B) but it is observed as a mylonitic foliation in granite, diorite, gabbros and gneisses in the KSZ. The stretching lineation observed in most mylonitic igneous rocks and it is sub-parallel with the strike of the mylonitic foliation (Fig 7).

4. Microstructure

S-C structures (Berthier et al., 1979) are found in mesoscopic and microscopic scales in granite mylonite in north and northwest of the Khoy shear zone. It is also observed in metabasites and schists in different areas including Askarabad, Badalabad, Algoiroug, Khangah and Gorolbala areas. They indicate dextral shear displacement in NW-SE trending strike-slip shear zones. This fabric is seen as a conjugate set of two foliations which possibly were synchronously formed during a single progressive non-coaxial deformation event. The C planes are parallel to the bulk shear plane, while the S planes are assumed to be parallel to the XY plane of finite strain within the low strain domains between two consecutive high

strain domains (C planes). Hence, the obliquity of the S planes relative to the C planes directly reflects the orientation of the finite strain ellipsoid, making S-C fabrics a reliable shear sense indicator (Simpson and Schmid, 1983; Hanmer and Passchier, 1991) in the KSZ. C' planes, when present, also accommodate synthetic shear (Fig 8).

A variety of pull-apart microstructures occur in the granite mylonites in the Khoy shear zone within the Badalabad and north Khoy areas. The quartz porphyroclasts in the granite mylonite show varieties of micro-shear zones or micro-faults, which caused displacement of the porphyroclast fragments. Micro-faults make an angle of 35 with the C-type shear band cleavages. Two types of micro- faults are recognized. They include bookshelf structures (Etchecopar, 1977; Ramsay and Hubber, 1987) and pull-apart structures (Hippertt, 1993; Samanta et al., 2002). The book- shelf structures in the Quartz porphyroclasts show sets of parallel synthetic slips which are parallel to the regional dextral sense of shear. The fragments of quartz and feldspar porphyroclasts are separated during rotation and they form ''V'' pull-apart micro-structures (Fig 9A, B). The fracture angle varies from 10 to 35. Two types of ''V'' pull-apart geometry are recognized. Centrally located fractures produced parallel geometry (type I) pull-apart and off-centered fracture geometry (type II; Samanta et al., 2002). The ''V'' pull-apart is bled with one- grained muscovite and biotite which displays a strong preferred orientation.

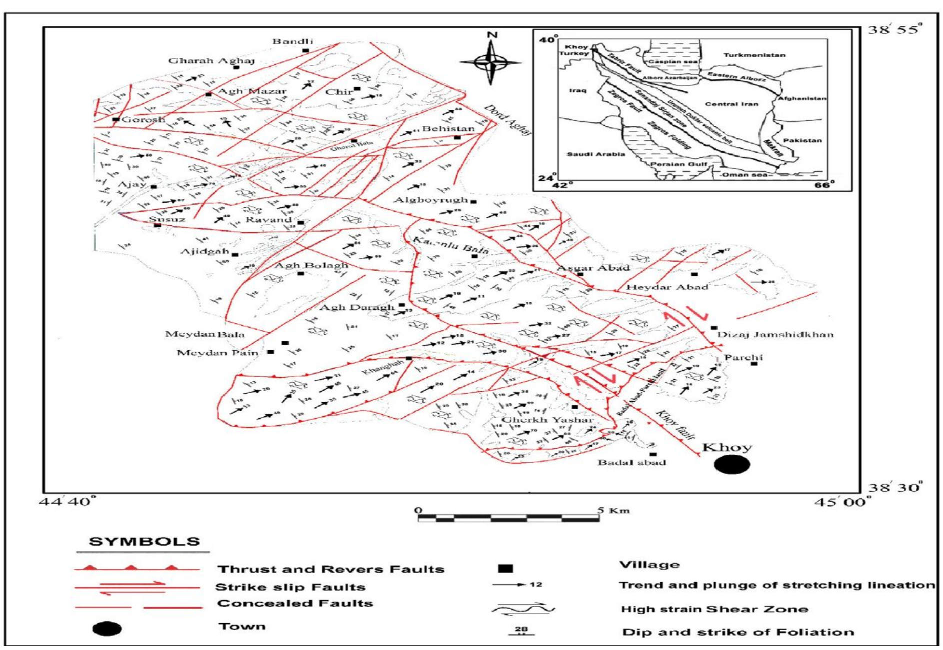

Fig. 3. Structural sketch map across the Khoy shear zone.

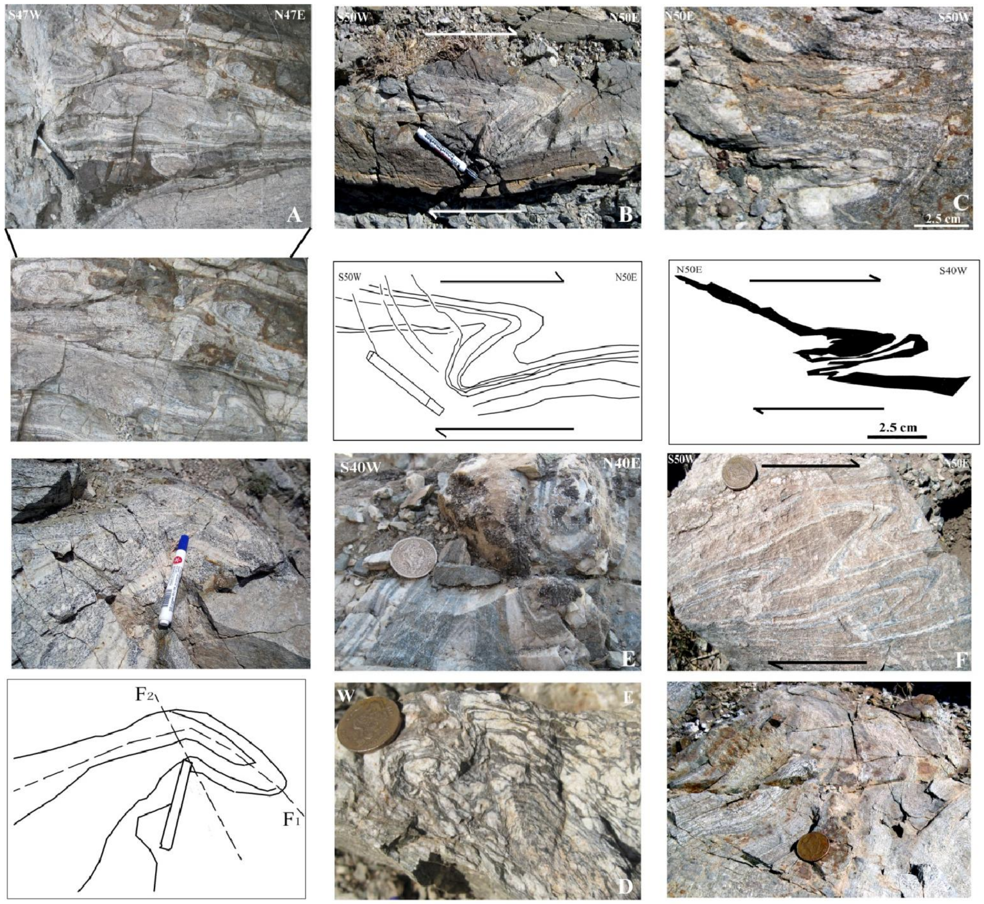

Fig. 4. Small-scale asymmetrical fold in the north of the khoy area. (A) Sheath fold in gneiss amphibolite, dextral shear sense. (B, F) Asymmetric folds in gneiss amphibolite, Dextral shear sense. (C, G) Asymmetric interfolial fold in K-feldspar vein mylonitic granite, reflecting the sense of displacement in a dextral shear zone. (D) The generations of the asymmetrical folds. (E) Eye-shaped fold, reflecting a curved fold axis, within banded gneiss. (H) asymmetrical fold in north the Badal Abad village.

In mylonitic granitoid rocks mono-crystalline quartz ribbons and poly-crystalline feldspar ribbons are produced by dynamic recrystallization. The quartz grains are strongly elongated and stretched, forming predominantly quartz ribbons in XZ sections. The ribbons show evidence of internal deformation like undulatory extinction and recrystallization. Recrystallized quartz ribbons anastamose around the feldspar porphyroclasts. The quarts ribbons are folded by the continued shear deformation and resulted in isoclinal micro-folds (Figs 10C and D). The axial planes of these isoclinal folds are parallel to the XY plane of the strain ellipsoid.

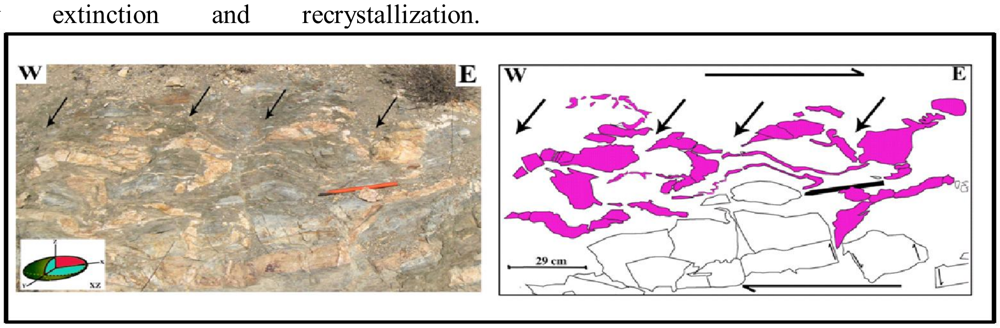

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Fig.5. Flanking folds and boudins in a dextral shear zone in the southwest Ajay area, Northwest Khoy. Black arrows indicate fractures about which flanking folds formed.

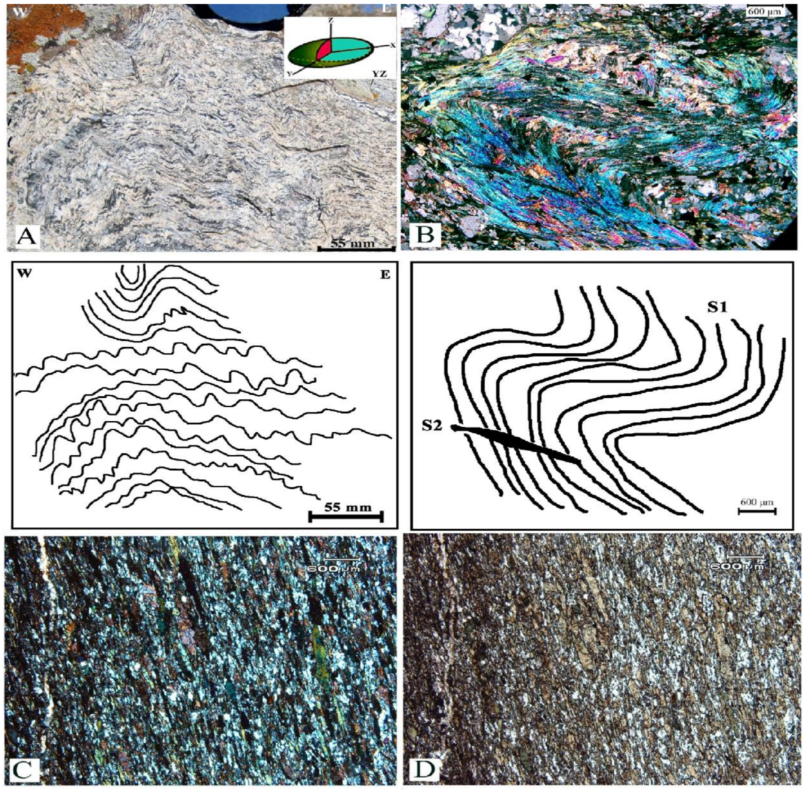

Fig.6. (A and B) The S2 is a crenulation cleavage with NNW strike in schists and marbles. (B) The abundant NW-SE orientation of the S1 changes clockwise to NNE in north Badalabad, east Asgarabad and south Ajay areas. (C and D) In amphibole-gneisses, oriented amphiboles, in marbles, oriented calcites and tremolite minerals and in quartzite, fine grain micas show a clear orientation. C, B:PPL, D:CPL.

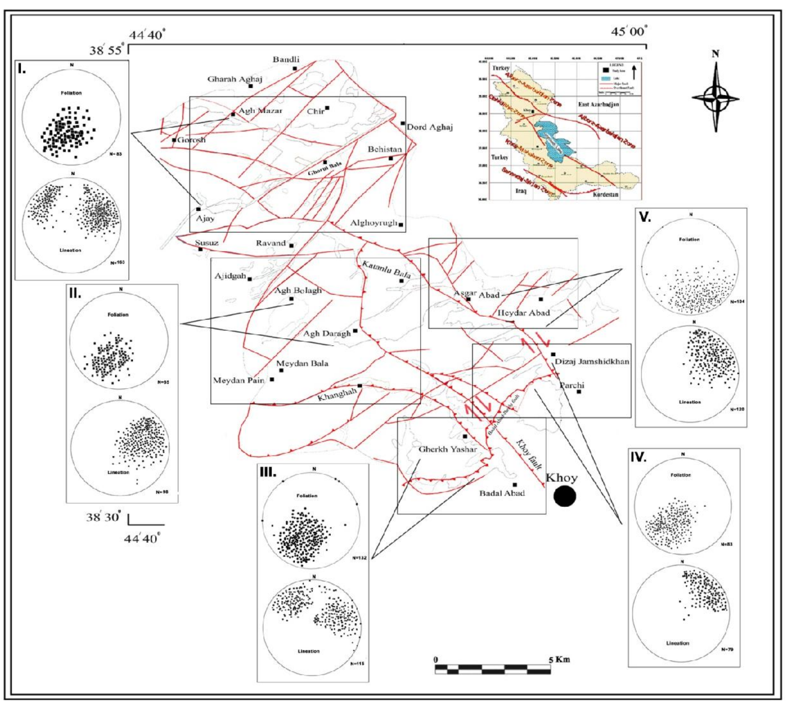

Fig. 7. Generalized structural map of the Khoy shear zone. Field measurements of the mylonitic foliations and lineations are presented in lower-hemisphere.

Mineral fish are rather abundant in the KSZ. Where the mineral fish touch the shear planes that bound them, the shear strain is maximum and equidistant from a pair of C-planes the shear strain is minimum. The C-planes are straight and envelope or are tangent to the mineral fish. These planes are defined by very fine-grained recrystallized minerals. The C-planes seem to be irregularly spaced (Figs 11 A, B). The reason is that quartz is the weaker phase in most deformed rocks, and special circumstances are needed to form quartz fish. Quartz fish either form by solution precipitation without internal deformation (Bestmann et al., 2000, 2004) or by intracrystalline slip with recovery and minor recrystallisation. The shape of group 2 fish is thought to evolve from group 1 by drag along zones of concentrated shear, localised along the upper and lower contacts (Ten Grotenhuis et al., 2003) .Mantled porphyroclasts of alkali feldspars with δ shape and quarter folds are observed in mylonitic gabbros in Badal Abad area (Figs 12A, B).

Different types of porphyroblasts with pre, syn and post tectonic growth exist in the metamorphic rocks. Two generation of garnet porphyroblasts are observed. The first generation garnets contain different curved and straight inclusions (Si). Biotite and quarts minerals occur in their strain shadows. Mylonitic foliaition turns around these pre to syn tectonic garnets. Post tectonic garnets occur in contact aureoles of the granites. These euhedral garnets have no strain shadows and are cutting the mylonitic foliation (Figs 13a-d). Pre- to syn tectonic garnet and staurolite porphyroblasts contain inclusions of quarts, iron oxide and biotite. The foliation inside the porphyroblasts (Si) observed straight or spiral continues with the external foliation (Se). Asymmetric strain shadows around the porphyroblasts indicate sense of shear (Figs 13e and f). Post tectonic euhedral biotite porphyroblasts are also found in schists (Figs 13g and h).

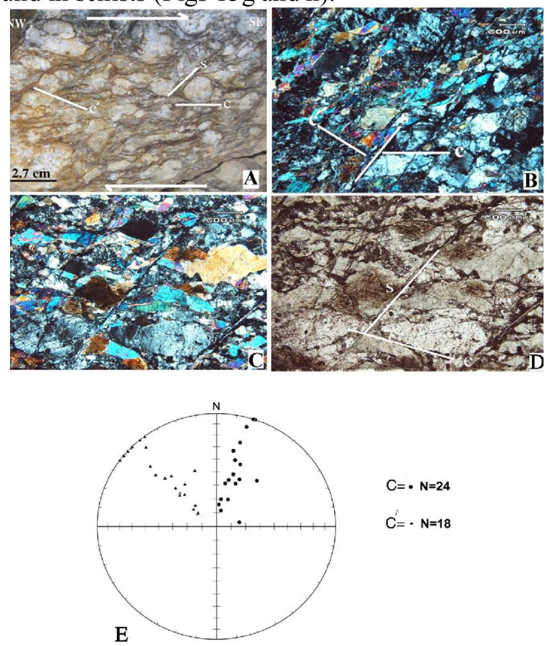

Fig. 8. S-C, C' structures of different scales observed on the XZ plane of finite strain. (A). S-C, C' structure in a granitic mylonite (KSZ, Ghorul Bala area, northwest Khoy). Note the decreasing angle between S and C towards the high strain domain on the top of photo. (B, D) and (C). S-C, C' structure in a granitic mylonite (Badal Abad area, north Khoy). The overall shear sense is dextral. C, B: PPL , D, C:PL.

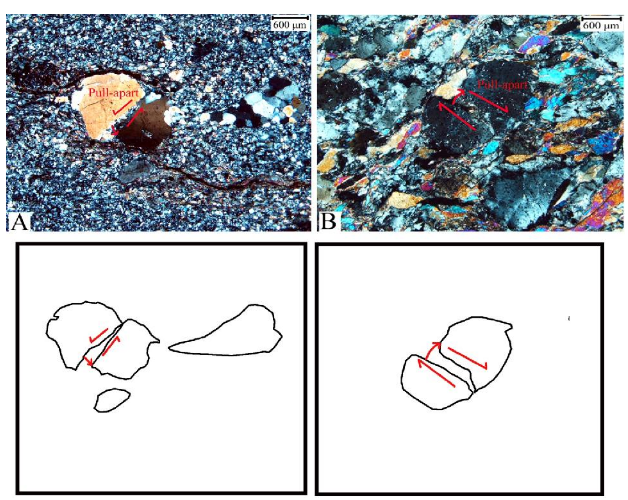

Fig.9. (A) and (B) Quartz and feldspar porphyroclasts in the granite mylonites transected by micro-faults and quartz fragments that are separated and rotated forming pull-apart structures.

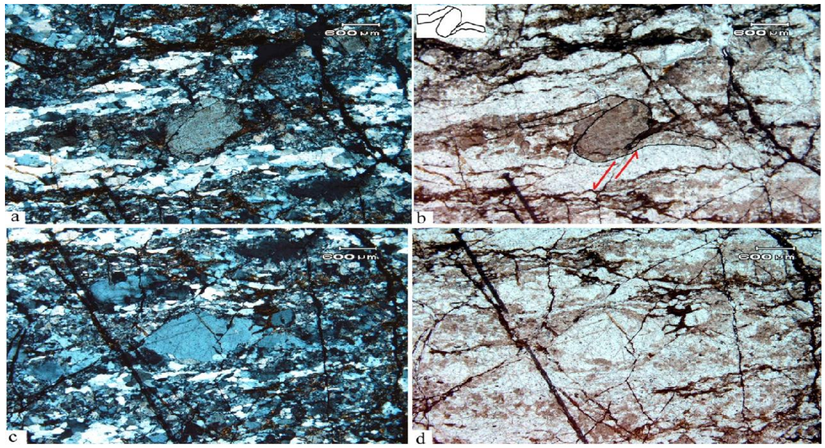

Fig.10.(a) and (b) Granitoid mylonite with a δ type mantled porphyroclast of K-feldspar (centre) in a matrix of recrystallised quartz. A mantle of recrystallised feldspar with isolated polycrystalline quartz ribbons surrounds the porphyroclast. Elongated and dynamically recrystallized quartz ribbons in a strongly deformed granite mylonite. (c) and (d) The quarts ribbons are folded by the continued shear deformation and resulted in isoclinal micro-folds. Section parallel to the aggregate lineation and normal to the foliation. Dextral shear sense. a, c: PPL , b, d:CPL.

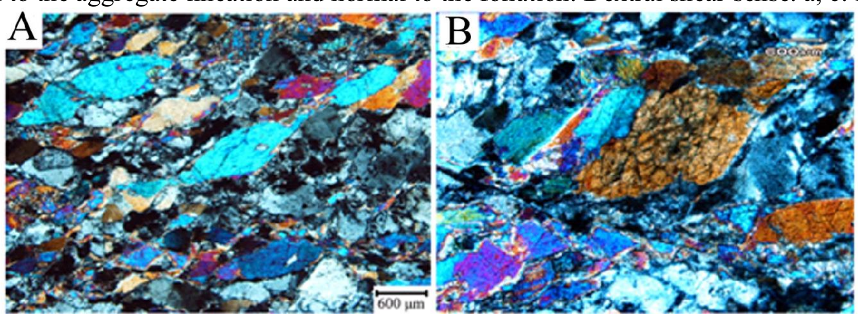

Fig11. Mineral fish are rather abundant in the KSZ. (A, B) The C-planes seem to be irregularly spaced. Mantled porphyroclasts of alkali feldspars with δ shape and quarter folds are observed in mylonitic gabbros in Badal Abad area. A, B: PPL.

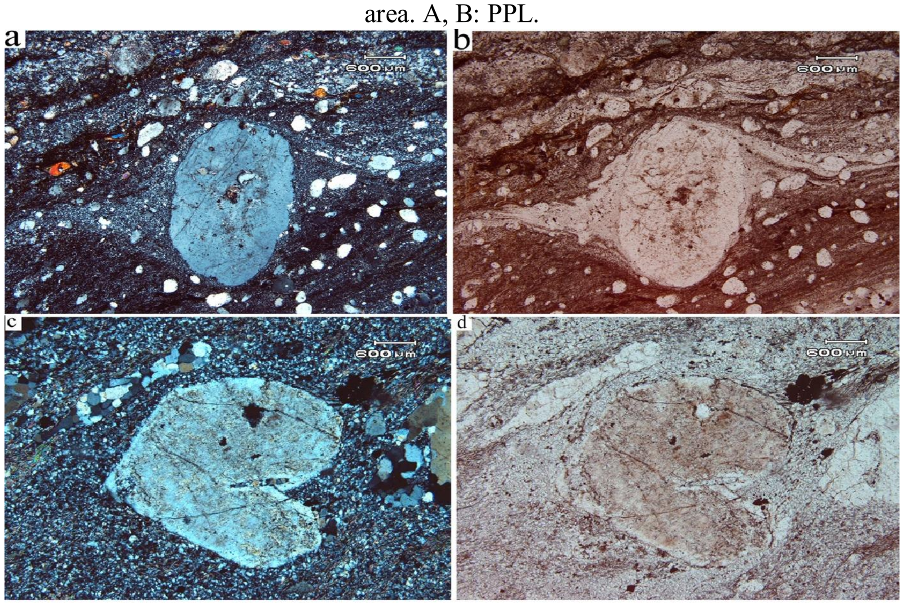

Fig12.(a) and (b) Gabbro mylonite with δ -type mantled porphyroclast of K-feldspar in the Badal Abad area, North Khoy. (c) and (d) Granitoid rock with K-feldspar porphyroclast in the Ajay area, northwestern Iran. Above the porphyroclast, the quartz vein were boudinaged. Shear sense, independently determined from mantled porphyroclast is sinistral in this field of view. a, c:PPL, b, d: CPL

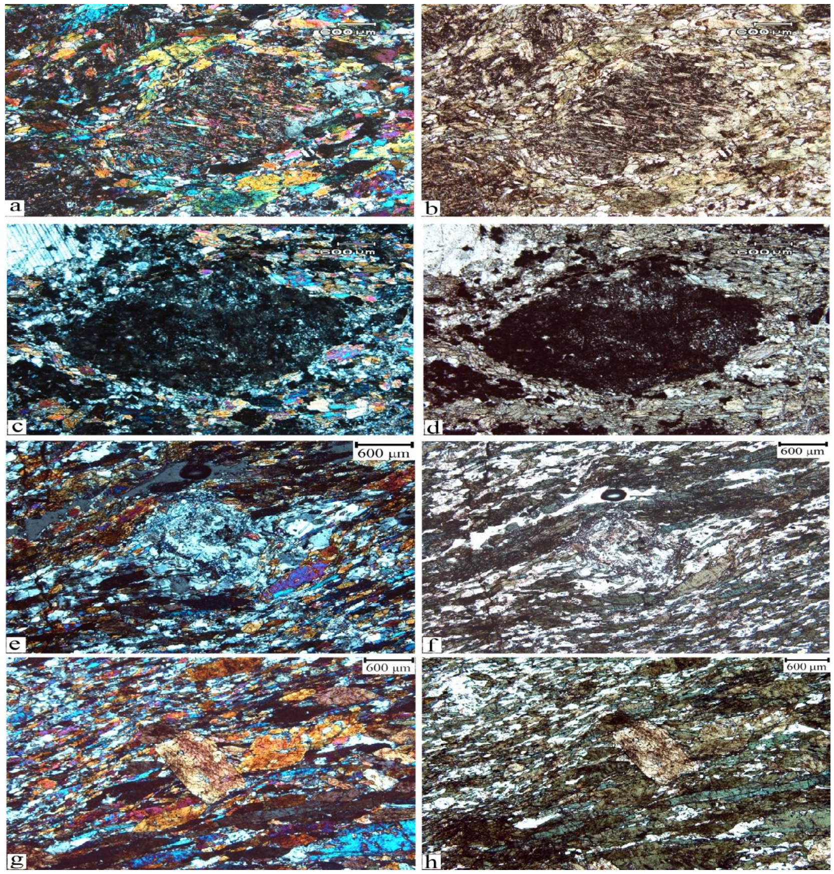

Fig. 13. Different types of porphyroblasts with pre, syn and post tectonic growth exist in the metamorphic rocks. (a-d) These euhedral garnets have no strain shadows and are cutting the mylonitic foliation. (e and f) Asymmetric strain shadows around the porphyroblasts indicate sense of shear. Post tectonic euhedral biotite porphyroblasts are also found in schists (g and h). a, c, e, g:PPL , b, d, f, h: CPL

Two types of symplectites are observed in the granitic rocks. A dominant graphic type intergrowth of quartz with alkali feldspar and quartz with plagioclase are seen in granite dykes that were intruded in metabasites. It is proposed that the granite dykes are result of melted metabasites in the area. Quarts occur inside the plagioclase minerals (Figs 14a and b). Coronas of garnet surrounded by biotite are observed in Ajay area west of Khoy city (Figs 14c and d).

5-Tectono-Metamorphic evolution of the KSZ

The estimated pressure during high-grade metamorphism is 6–7.5 kb corresponding to depths of 20–25 km. It is hardly possible that this pressure could be produced by just the weight of obducted oceanic crust having a maximum thickness of 10 km. Azizi et al. (2006) infer that neither the granitoids heat nor the KOC nappes were responsible for the metamorphism existing in the Khoy shear zone. Azizi et al. (2006) suggested that thickening of the crust during continental collision of the Arabian plate and Azerbaijan–Albourz block increased the thermal gradient. As a result, metamorphism of the rocks took place. Khalatbari-Jafari et al. (2003) suggest that, during the Late Cretaceous, northward subduction of the Neo-Tethys oceanic crust produced an island arc in the KSZ. To the north of the arc, a back arc basin opened and during the Late Cretaceous–Palaeocene, a passive continental margin (Arabian plate) collided with this island arc. Deformation of the back arc basin was accompanied by formation of a tectonic mélange between the island arc and Azerbaijan–Albourz block probably in the Late Eocene. The immature oceanic crust of the back arc basin was obducted to the southwest over the island arc. The obducted sheets of ophiolite almost completely overrode the island arc. During this tectonic event, volcanic and sedimentary rocks of the island arc complex were metamorphosed. The metamorphism and deformation triggered the formation of anatectic granite. The metamorphic grade increases northward towards the suture (tectonic melange), where amphibolite facies are exposed. In the Early Oligocene, the metamorphic rocks were exhumed to the surface (Azizi et al., 2006) (Fig 15).

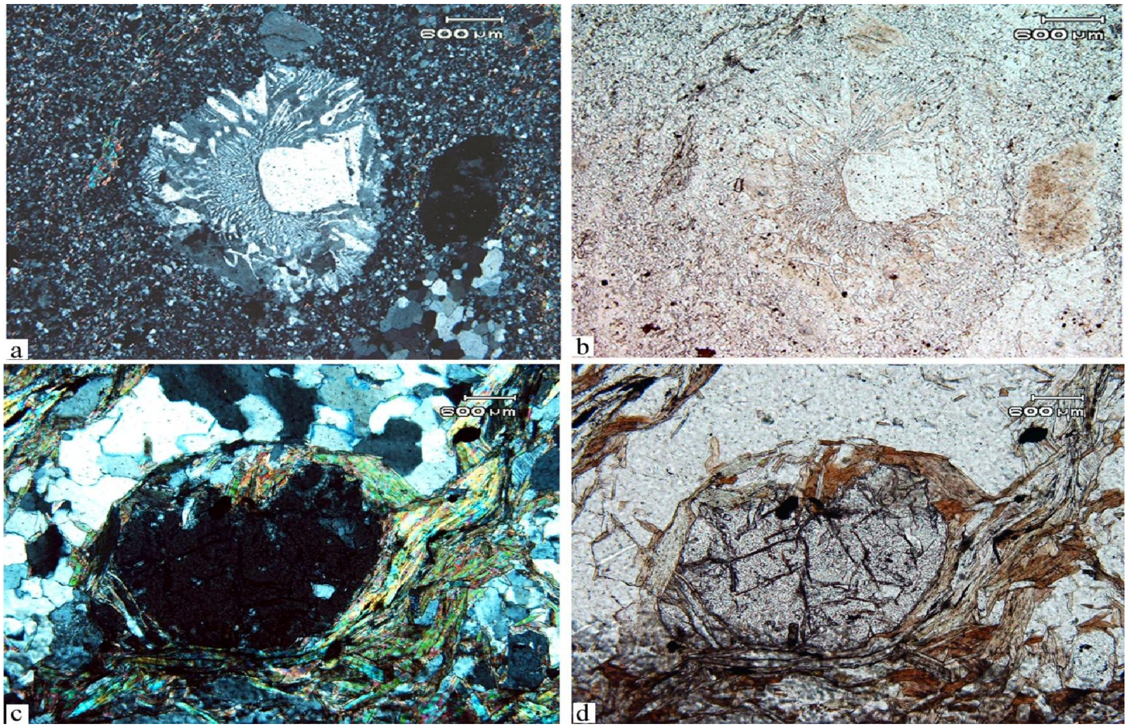

Fig. 13. Two types of symplectites are observed in the granitic rocks. (a, b) A dominant graphic type intergrowth of quartz with alkali feldspar and quartz with plagioclase are seen in granite dykes that were intruded in metabasites. Quarts occur inside the plagioclase minerals. (c and d) Coronas of garnet surrounded by biotite are observed in Ajay area west of KSZ.

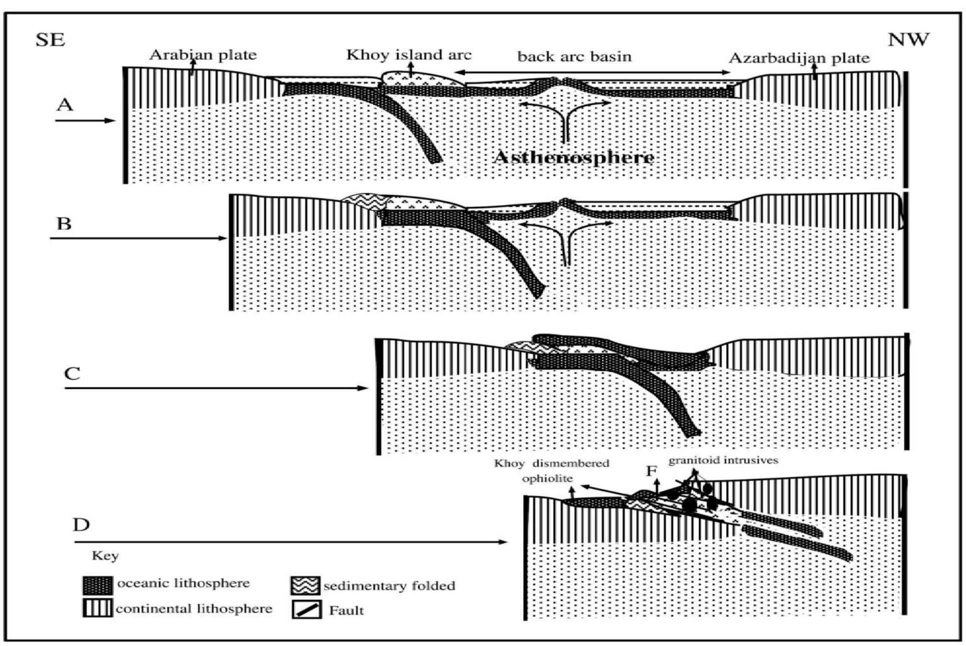

Fig. 15. Tectonic evolution of the Khoy region; (A) generation of island arc and back arc basins in the Late Cretaceous; (B) collision of the Arabian plate passive continental margin with an island arc probably during Late Cretaceous–Palaeocene; (C) consumption of the back arc basin and obduction of ophiolites over the island arc probably during the Eocene; (D) metamorphism of the island arc components and intrusion of granitoids during the Late Eocene (Azizi et al., 2006).

6. Discussion and Conclusions

Structural analyses in the Khoy Shear Zone (KSZ) indicate that they consist of NW-SE oriented various metamorphic rocks. They contain NW-SE trending moderate to steeply dipping mylonitic foliation to the NE. Stretching lineation plunge shallowly to moderately towards NE. Thrust faults are oriented the same as mylonitic foliation. Ductile fabrics are superimposed by brittle structures. Orientatios of the structures indicate that the main stress trend is NE-SW. Four deformation stages (D_1-D_4) identified in KSZ (Fig 16). The first two stages are ductile that superimposed by the tow other ductile-brittle stages.

Shear sense indicators such as S/C fabrics, shear bands, shear folds, book-shelf structures, fishes and mantled porphyroclasts indicate that the KSZ deformed via dextral transpression tectonic regime. The Khoy area contains both NW-SE striking dextral strike-slip and SW verging NE dipping ductile reverse shear fabrics. Ductile shear fabrics are overprinted by subsequent younger both thrust and strike-slip fault systems. Abundant syn-tectonic granitoides were intruded in the Khoy area during convergent. Shear deformation fabrics are well identified in both deformed intrusive and metamorphic-ophiolite complex. The geometry and kinematics of shear fabrics indicate a deformation partitioning in both ductile and brittle conditions during a progressive transpression tectonic regime (Fig 17). The KSZ deformed during an oblique convergence scenario between the Arabian and West Alborz- Azerbaydjan blocks in NW Iran.

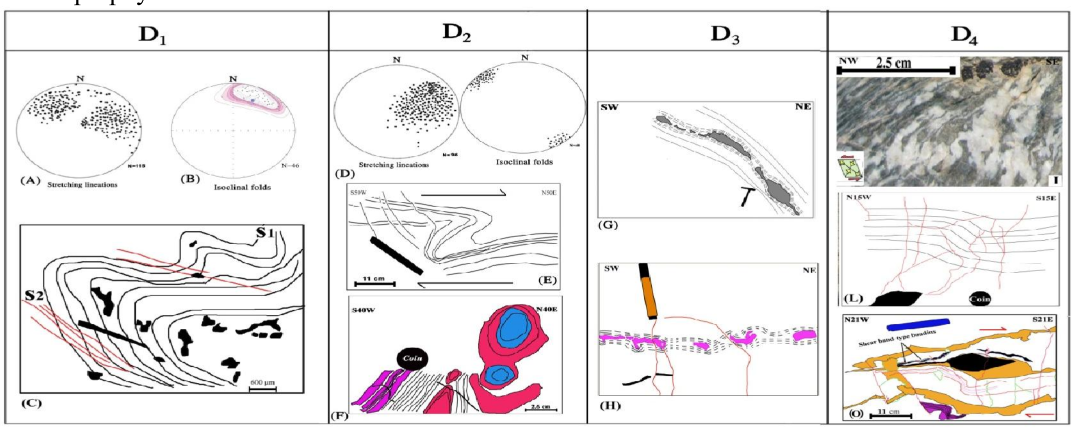

Fig.16.Summary of structures measured (stereoplots) and observed (drawings) in the field for deformation stages D_1 (A-C), D_2 (D-F), D_3 (G-H) and D_4 (I-O).

7.Acknowledgements

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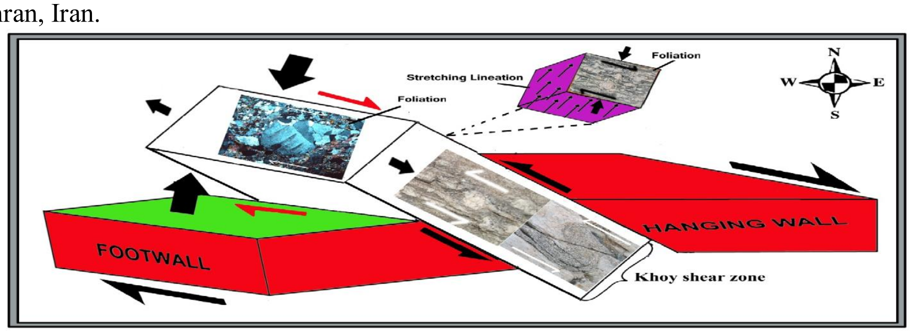

Fig. 17. Three-dimensional model proposed for the triclinic strain of the KSZ. The overall dextral kinematics reflects conditions observed at KSZ . The footwall and hanging wall are shown in white and the shear zone is in red. In XZ sections, parallel to the mineral stretching lineation, we observe. The obliquity is resolved in a strike-slip and a dip-slip component. In addition, in YZ sections perpendicular to the regional thrust transport direction, we observe both sinistral and dextral kinematics on similar types of structures to those described within the XZ sections. The coexisting opposing senses of shear in the YZ sections occur on all scales and are documented by many types of kinematic indicator. The geometry and kinematics of shear fabrics indicate a deformation partitioning in both ductile and brittle conditions during a progressive transpression tectonic regime. The KSZ deformed during an oblique convergence scenario between the Arabian and West Alborz- Azerbaydjan blocks in NW Iran

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