# The field and microstructural study of Malayer plutonic rocks,west of Iran

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(*received: 11/01/2010 ; accepted: 18/10/2010*)

**Abstract**
A detail field and microscopic characteristics of Malayer Plutonic Rocks (162-187Ma), west of Iran, are discussed in details to evaluate relationships between deformation and pluton emplacement. The studied rocks were injected into the slate, phyllite and schists of so called "Hamadan phyllites and slates" in the Sanandaj-Sirjan zone. Studies have shown that there is a continuity from magmatic to solid-state deformation and latter deformation overprint the magmatic structures. The brittle deformation such as deformed granite sheets, (sub)mylonites and migmatites occurred in the region is subjected to tectonic forces after cooling the pluton and imply the persistency of regional deformation. The continuity from liquid to solid state deformation suggests a syntectonic emplacement of pluton. These features display a shearing deformation in the pluton. Porphyroclasts in the sheared rocks show dextral shear sense. Overall microtectonic features show that the pluton was emplaced synchronously with respect to the regional scale deformation in the high-strain environment.

**Keywords**: *Granite, Microstructures, Malayer, Sanandaj-Sirjan, Iran*

## Introduction
Different viewpoints of analyses can be used in order to investigation of tectonic structure and evolution of the crust and lithosphere. Regional field and petrofabric studies generally provide insight into the geometry and kinematics of deformed parts of the crust and upper mantle (Schmid *et al.*, 1987). Petrofabric analysis mainly focuses on micro-scale microstructures in thin sections and field observations deal with deformation zones, such as faults or ductile shear zones (Imber *et al.*, 2001).

Studies show that in many convergent orogenic belts (such as Zagros orogenic belt), spatial and temporal relationships between granite and regional tectonic structures suggest ascent and emplacement during compaction rather than during extension (Hutton 1997; Brown and Solar 1998). Moreover, a close relationship has been established between granitic plutons, shear zone systems and transpressive convergent zones (D'Lemos *et al*., 1992; Ingram and Hutton 1994; Brown and Solar 1998; Mohajjel and fergusson 2000; Greiling and Verma, 2001; Romeo *et al*., 2006; Tiago *et al*., 2008). Correlating granite emplacement and deformation with regional tectonic events is a challenge because granitic rocks do not always develop mesoscopic scale deformation fabrics. Microstructural studies of granites can help to identify magmatic or solid-state deformation fabrics (e.g. Simpson 1985; Paterson *et al*., 1989; Bouchez *et al*., 1990), on the basis of which granite can be interpreted as deformed. In itself, this cannot lead to infer the relationship between a regional deformation event and development of a fabric in granite. Additional information is required, in particular on the orientation and spatial distribution of these fabrics and their relationship with host rocks of the granite pluton in question (Mamtani & Greiling 2005).

Although there are voluminous occurrences of the plutonic bodies in the Sanandaj–Sirjan Zone (SSZ) (Fig 1a), but their microstructural studies are rare (e.g. Hosseinpour *et al*., 2002; Ghalamghash *et al*., 2009). The SSZ in the west Iran is an elongated tectonic zone that is one of the most Iranian complicated and active zones. The SSZ represents a separable tectonomagmatic and metamorphic unit displaying a complex polyphase deformation history (e.g. Baharifar *et al*., 2004; Berberian & Alavi-Tehrani, 1977; Poshtkoohi, 2009). It consists of numerous plutonic bodies including deformed granitoids that are aligned along NW-SE direction

(Fig. 1a). These granitoids are related to magmatic events of subduction environment (e.g., Valizadeh & Cantagrel 1975; Berberian and Berberian 1981; Masoudi *et al*., 2002; Sepahi 2008; Mazhari *et al*., 2009; Shahbazi *et al*., 2010). They are closely associated with metapelitic rocks which were also strongly deformed under polyphase deformation (e.g. Baharifar *et al*., 2004; Poshtkoohi, 2009).

The Malayer Plutonic Rocks (MPR), located in the northern part of the zone, is emplaced within "Hamadan phyllites and slates" and represents a partial melted intrusion with both felsic and mafic components. The MPR have range in composition from gabbro-diorite and tonalite to leucogranite .

The presence of mafic bodies (e.g. diorite and gabbro) and mafic microgranular enclaves (MME) in the most plutonic complexes of the SSZ demonstrated that magmatism in this zone is genetically linked to the underplating of basic magma in the subcontinental mantle lithosphere (Sepahi, 2008). This process was developed probably as a result of subduction of the Neotethys oceanic crust beneath the Iranian plate. Delamination of lower crust in the Turkish-Iranian plateau is the most promising mechanism to induce extensive lower crustal melting including amphibolite and producing basaltic magma (Pearce *et al*., 1990; Maggi & Priestley, 2005, Shad Manaman & Shomali, 2010). This idea is supported by low velocity of seismic shear wave and high gravity (50 mgals at a wavelength of ~800 km) of long wavelength in the plateau (Hearn and Ni 1994; Maggi *et al*., 2002), which indicate an increase in mantle temperature beneath at least part of the plateau.

The magma was injected into the country rocks by a series of successive felsic and mafic inputs over the course of 162 to 187 million years (Ahadnejad *et al*. unpubl data). In this study, we employed the information from field-based and laboratory studies on macro and microstructure analyses, respectively. Field observations and petrofabric studies of well-exposed MPR could provide evidences for their formation and emplacement processes to depict regional crust evolution.

## Field observations

The MPR is located at the southeast of Malayer city, at the northern part of SSZ (Fig. 1b). It is a roped-shaped intrusive body which is emplaced in the high-strain shear zone (Ahadnejad *et al*. 2008). The majority of MPR consists of coarse-grained granitoids along with fine-grained aplitic dikes cutting through it, the gabbroic-dioritic rocks at the southernmost part of the pluton and subordinate monzonitic bodies (Fig. 1).

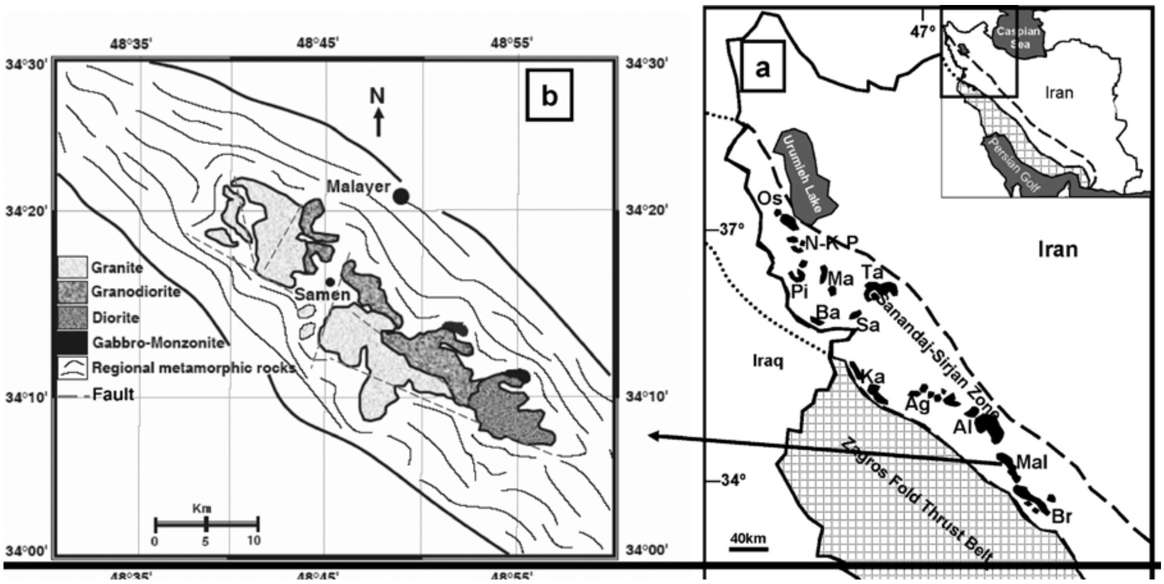


**Fig. 1: Geological sketch of the Malayer intrusive complex. a) The small map represents the position of the Malayer intrusive complex within the Sanandaj–Sirjam Zone. Black areas indicate the most important granite bodies: AS, Astaneh; BR, Brojerd; Mal, Malayer; AL, Alvand; AG, Almogholgh; BA, Baneh; DE, Delkeh; KA, Kamyaran; MA, Mahabad; N-K-P, Naqadeh–Khalifan–Pasveh; OS, Oshnavieh; PI, Piranshahr; SA, Saqqez; TA, Takab (modified from Emami *et al*. 1993). b) Geological map of Malayer plutonic rocks.**

The northernern side of the complex includes a composite alkali-, syeno- and monzogranite and pegmatite and aplitic dikes. With regards to the main body, the northern intrusives have the more differentiated (only granitic) composition. In northeastern part of granites, next to the granodiorite (tonalite), feldspars are preferentially oriented (Fig. 2a) which indicate a magmatic flow. Brittle structures including centimetre-scale shear-fractures to kilometre-scale fault zones are observed in the northern part of MPR. In the *Kamarboneh* village, local shear zone caused mylonitization (Fig. 2b).

Contacts between the rocks are gradational and locally digitate, however, between the pluton and the country rocks they are sharp, discordant and some times faulted with distinguishable contact metamorphism (Fig. 2c). The intrusions follow exactly the schistosity direction of surrounding metasedimentary country rocks (i.e. NW-SE). The contact between granodiorite and diorite is complex and commonly not distinguishable, rarely sharp and locally grades through a medium- to coarse -grained quartz-diorite, which contains some dioritic enclaves and metasedimentary xenoliths.

The enclaves are divided into two groups; microgranular and xenoliths and their contacts with the host rock are sharp to gradational. MME occasionally exibit apparent chilled margin. Gabbro-dioritic mega-enclaves of mantle origin occur near the *Arges-e-Olia* village. Their geochronology (Ahadnejad *et al*. unpubl. data) and field study showed that they are generally simultaneous with other plutonic rocks. Field observations of granodiorite show lenticular MME that is aligned sub-parallel to magmatic flow direction and reflect the intensity of flow in the host rock. MMEs are elongated in the corner (foliated) zone (Fig. 2d) and their elongation decreases toward the interior of the body, where they generally have circular shape (Fig. 2e). Metasedimentary xenoliths within granitoids have been observed at several places of the complex. Large angular milky quartz lumps, also occurring in the xenoliths (Fig. 2f). Surmicaceous enclaves and xenocrysts are not common in these mafic facies. Abundant metasedimentary enclaves in the felsic phases are considered as xenoliths entrapped during magma ascent. Enclaves are consisted of magmatic and metamorphic types. The MMEs have the dioritic to tonalitic composition and their contacts with granitic host rocks are gradational which interpreted as an evidence of hybridization and magma mixing/ mingling. The occurrences MMEs prepare a document for involving of mantle–derived component in production of rocks. This is confirmed by aboundant mafic synplutonic dikes that were penetrated into granitoids in the southern part of pluton. These features suggest that the granitic magmas might formed by variable degrees of mixing between mafic magmas and partial melts derived from older metasedimentary components, and so, they are hybrid products of mantle-derived magma and dominant crustal melt.

The coarse elongate andalusite is characteristic of studied granotids which showing a definite preferred orientation (Fig. 2g). The magmatic foliation wich is defined by biotite and feldspars follows the pluton margin and parallel to the field foliations of the country rocks (NW-SE). These orientations are in excellent agreement with those metasedimentary country rocks. Its intensity gradually decreases from the margin to the interior.The migmatitic granitoids can be seen in the local shear zones next to the *Darre Mianeh-e-Bala* village (Fig. 2h). Solid-state foliations in pluton were defined in the field by occasionally folding of earlier magmatic foliations (Fig. 3). Within the study area, pseudotachylite have been found in several locations (e.g. *Malicheh*, *Hji-Abad*, *Deh-e-Uness*, *Dareh Chenar*, and *Bid Kerih-e-Bala* villages). They are formed due to frictional melting of the wall rocks in the shear zones.

These features imply that the MPR experienced several deformation histories when it steel was molten and cools from the liquid (e.g. magmatic foliation) to solid state (e.g. folding of magmatic foliation). These deformations should be evidenced in the microscopic structures of the rocks.

For accurate interpretation of the internal structures of a pluton, a detailed study of its microstructures in order to define took place deformations in the magmatic, solid (high/low temperature), and mylonitic state is required. This study along with Anisotropy of Magnetic susceptibility (AMS) technique prepare good tool for examining mode of injection and emplacement mechanism. In this paper we report the petrofabrics results to determine whether the rocks affected by deformation and if it was during the solid state or with melt present? The AMS data under evaluation (not reported).

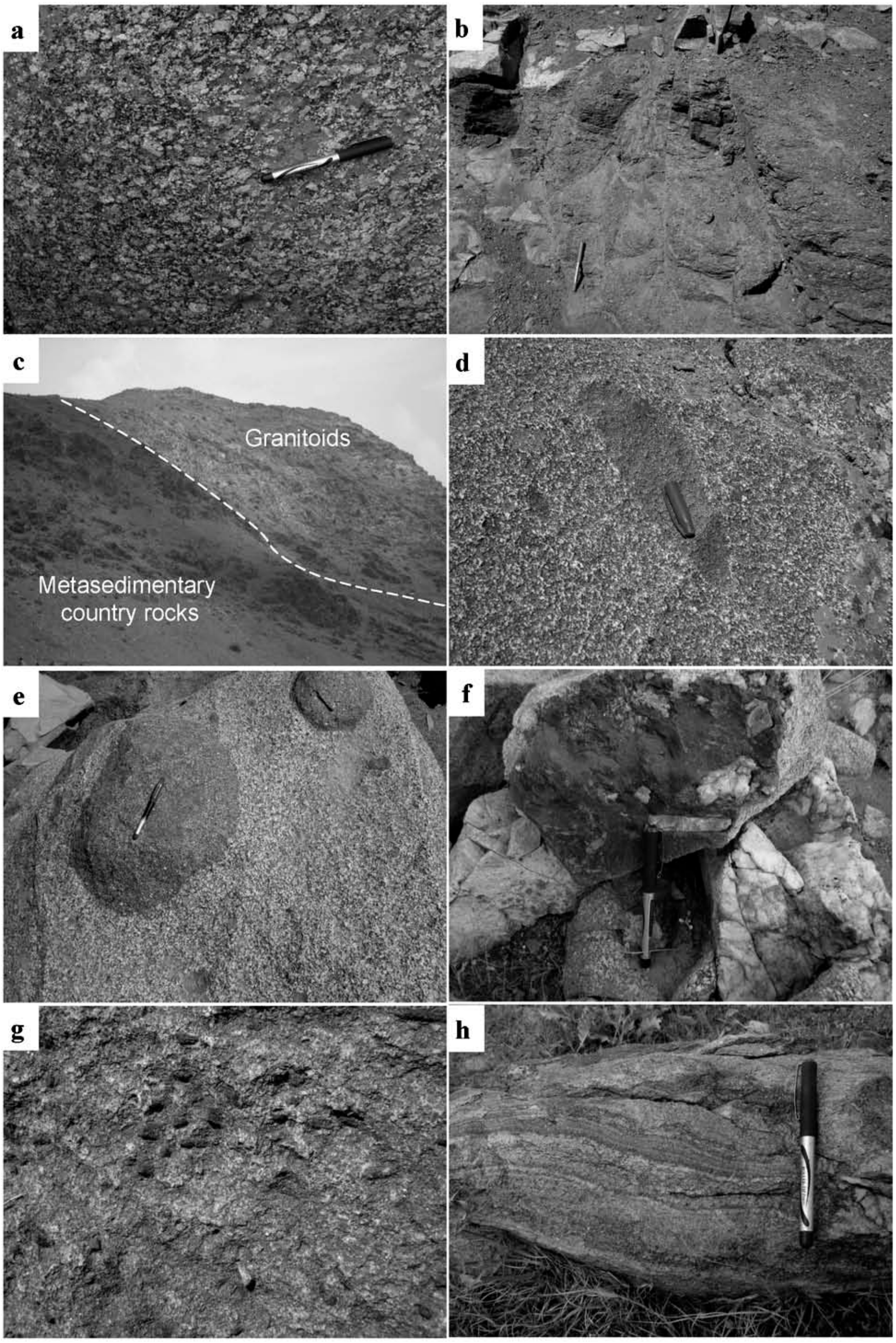


**Fig. 2: a) Preferentially orientation of feldspars define a magmatic flow. b) The mylonitization is common in the shear zones. c) Faulted contact between granitoids and metamorphic country rocks. d) Elongated MME in the corner (foliated) zone of pluton imply high strain in these parts. e) circular shape of MME in the interior part of pluton. f) Metasedimentary xenoliths containing angular milky quartz lumps. g) Preferentially orientation of andalusite show a magmatic flow in the contact of granitoids and country rocks.**

## Petrofabric studies

During cooling of a magma, minerals start to crystallize and record the strain conditions by deformation features. As crystallizing progress, the melt part decreases and continuous change of the proportion between melt and crystals, as well as the specific response of the various crystallized phases to deformation could reflect the whole range from magmatic to low-temperature solid-state fabrics.


**Fig. 3: The ductile deformation define by folding of the magmatic foliations**

More than 150 samples for a sequence rocks ranging from weakly deformed protolith to the ultramylonite were obtained for detailed petrographic and microstructural analysis. Among them, 90 oriented samples were selected from drilled cores. These cores were used for studying of microstructure and internal structures of pluton by using the Anisotropy of Magnetic Susceptibility (AMS). The geographic orientation, dip/dip direction were measured for these samples in the field.

**Granites:** They are medium- to coarse grained, located in the northern side of pluton and is composed of alkali, syeno and monzogranite. These rocks are white hypidiomorphic equigranular with alkali feldspar (orthoclase) phenocrysts up to 20 mm in length and generally contain turmaline.

These rocks show the transition from magmatic to cataclastic textures. The presence of preferentially oriented minerals suggests magmatic deformation and textures indicative of solid-state deformation include: slight fracturing of the feldspars, undulose extinction and deformation twins in plagioclase, recrystallized aggregates of feldspar and quartz, myrmekites in matrix, subgrain development on grain boundaries.

Polysynthetic deformation twins are aboundant in plagioclase grains. These multiple twins are formed through mechanical deformation under high temperature and shearing of the crystal lattice due to a series of dislocations (Wenk, 1969) (Fig. 4a). Patches of plagioclase have intergrown texture with quartz and display a myrmekitic texture. Deformation-induced myrmekites are developed around K-feldspar porphyroclasts as well. Exsolution, in the form of tartan twinning, is apparent in the orthoclase grains consertal textures are observable in many quartz and feldspar grains within the granite. Locally, bending of the twin planes plagioclase occurs due to plastic deformation (Fig. 4b). The preffered orientation of biotite locally shows a magmatic fabric in the biotite-granite near *Hossein Abad-Nazem village*.

**Granodiorite:** This facies includes granodiorite, diorite and tonalite. Their texture are mostly porphyritic to seriate. Biotite can be seen with naked-eye and grains often enclosing numerous small amphibole laths. No significant alteration products were observed in diorites. Quartz diorites and diorites include plagioclase, quartz, biotite, hornblende and very rare K-Feldspar. Plagioclase crystals are more developed in the granodiorite. Samples taken from the Malayer granodiorite include grey to black coarse-grained porphyritic biotite-hornblende granodiorite. Grains are being significantly more idiomorphic than those found in the granitic parts. As at granite, plagioclases have intergrown texture with vermicular quartz and show a myrmekitic texture. The plagioclase is sericitized and chlorite occurs along hornblende and biotite cleavage.

These rocks show submagmatic and (sub)mylonitic deformations. The submagmatic deformations are characterized by inclusions quartz grains in K-feldspar and myrmekites bordering ductilely deformed feldspars. Quartz crystals locally show weakly serrated grain boundaries and ductile bending which indicated by undulose extinction and form weak deformation bands (Fig. 4c). These fabrics indicate a weak deformation under sub-solidus conditions (Tullis and Yund 1987). The mylonitic portion records the highest shear strain in the rock in which al1 minerals have undergone a strict reduction in grain size by dynamic recrystallization.

**Gabbro-Diorite:** The gabbro-dioritic and monzo-syenitic bodies occur at the southeastern margin of pluton. The gabbro-dioritic bodies are condiser as mega enclaves that are entrapped by felsic magma during ascent and emplacement. They generally have hornblende, biotite and pyroxene as common mafic minerals and minor quartz and alkali feldspar.

Microstructural analysis reveals evidence for episodes of high temperature deformation as well as a low temperature event in this unit. The primary magmatic texture consists of euhedral plagioclase. Tightly packed of hornblende, plagioclase laths, and biotite define a magmatic foliation (Fig. 4d). The weak magmatic fabrics observed in this rocks are overprinted by soild state deformations. Intense subsolidus reworking starting at high temperatures is suggested by incipient subgrain formation in plagioclase (Fig. 4e). Dynamic recrystallization was followed by significant annealing as shown by quartz crystal aggregates with foam microstructure (Fig. 4f).

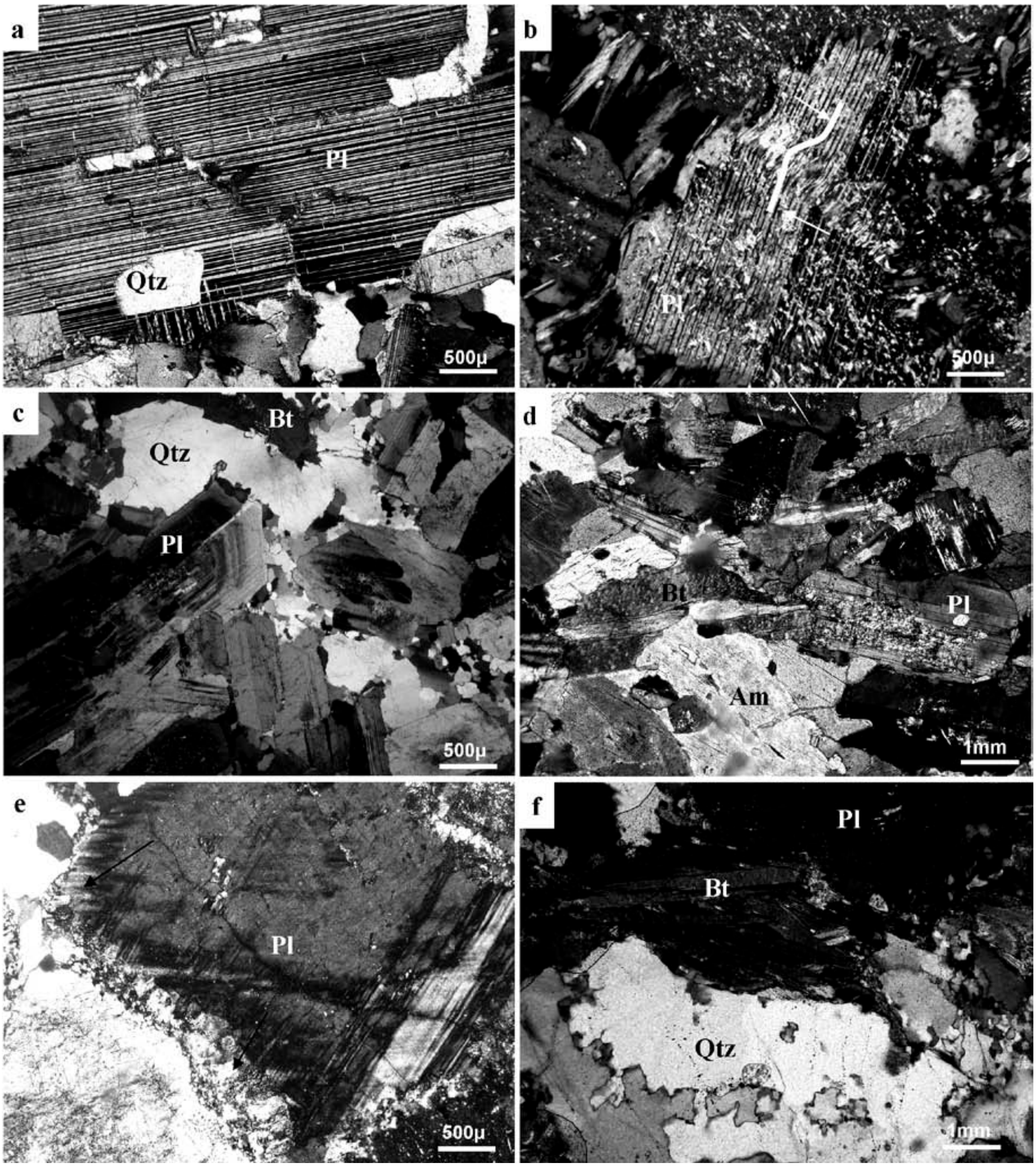


**Fig. 4: a) Mechanically twins in plagioclase. b) Bending of plagioclase display a plastic deformation of rock. c) Serrated grain boundaries and ductile bending of quartz. d) The magmatic texture of diorite formed by tightly packed of ornblende, plagioclase laths, and biotite. e) Subgrain formation in plagioclase at high temperature deformation. f) Annealing of quartz crystal aggregates**

The small bodies of monzonite to monzosyenite were exposed in the eastern margin of main mass. They represent globules of quenched, more basic magma mingled and modified by exchange with the host granitic magma. They are fine-grained, igneous-textured that are more basic (rarely including quartz) than their host rocks.

**Shear zones**

There are some local shear zones in the study area (Fig. 5) and faulting formed pseudotachylite within sheared rocks (Fig. 6a). These zones have variable size and trend, however, thy have mostly either a north-northeasterly or northeasterly trend. The studied shear zones are distinguished by the presence of (a) mylonitized rocks (b) typical penetrative S-C band structure (c) and local retrograde metamorphism. Generally, the rocks in this zones are strongly altered, silicified, and migmatized.

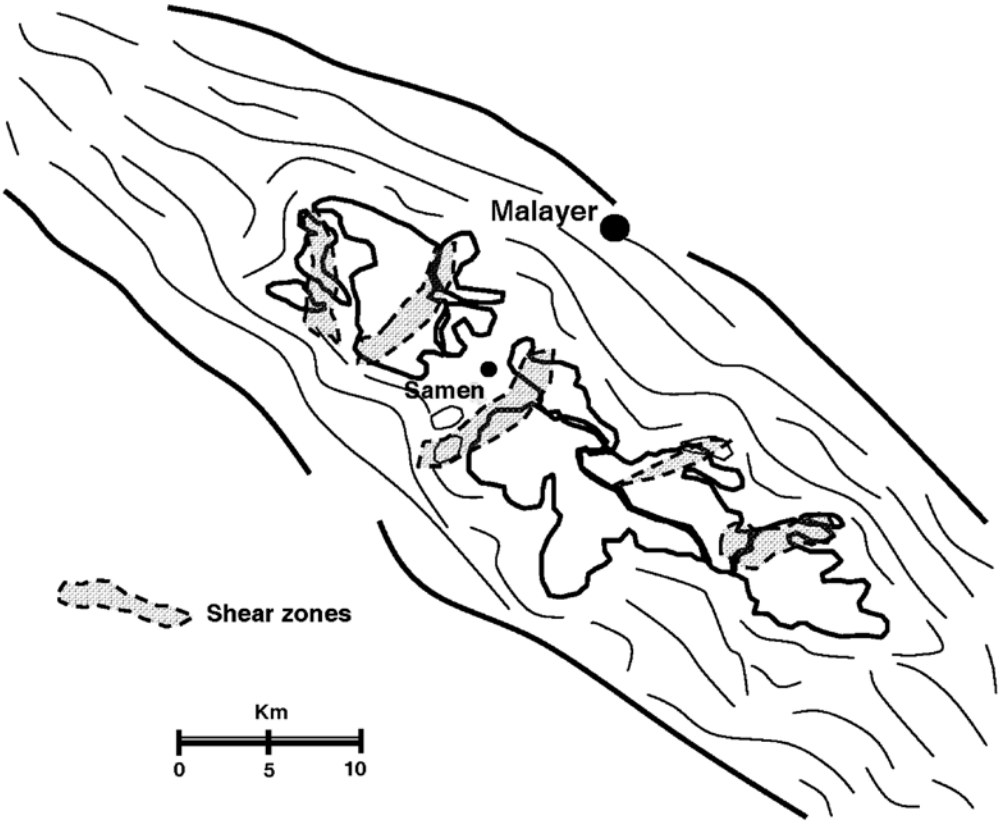


**Fig. 5: Local shear zones in the study area**

**a) Mylonites:**

The mylonitization is associated with local shear zones and evidenced by dynamic recrystallization of both plagioclase and K-feldspar producing a porphyroclastic fabric and mylonitic foliation. The mylonitic foliation is defined by compositional layering of alternating feldspar-rich layers and quartz ribbons (Fig. 6b). In the mylonitized rocks, two quartz populations can be distinguished (a) isolated quartz grains embedded in a matrix of feldspar and mica. Individual quartz grains usually show convex grain boundaries in contact with feldspars (Fig. 6c). (b) Quartz ribbons often consisting of extremely large grains with long axes up to several millimeters. They are pobably formed as crack-seal veins parallel to the mylonitic foliation (Fig. 6d).

**b) S-C structures and porphyroclast system**

Within the shear zone, the granite exhibits excellent S-C fabrics (Berthe *et al*. 1979) (Fig. 7a). The C-planes are well-defined planar discontinuities with marked offset of the finite strain foliations (S-planes) which are defined by preferred dimensional elongation of the component minerals including deformed K-feldspar aggregates, quartz ribbons and micas, as well as by the elongation of the microgranitoid enclaves.

Porphyroclasts of relatively strong minerals in mylonites commonly have an internal monoclinic shape symmetry defined by tails of dynamically recrystallized material. The geometry of a porphyroclast and its tails, called a ‘porhyroclast system’, can serve as a valuable indicator of the sense of vorticity (Passchiera and Simpson 1986). A porphyroclast system in a mylonite develops when the relatively weak dynamically recrystallized grain aggregate in the porphyroclast mantle changes its shape due to non-coaxial flow in the adjacent matrix. In the local shear zones of the study area, the porphyroclast system are commom and generally show dextral shear sense (Fig. 7b).

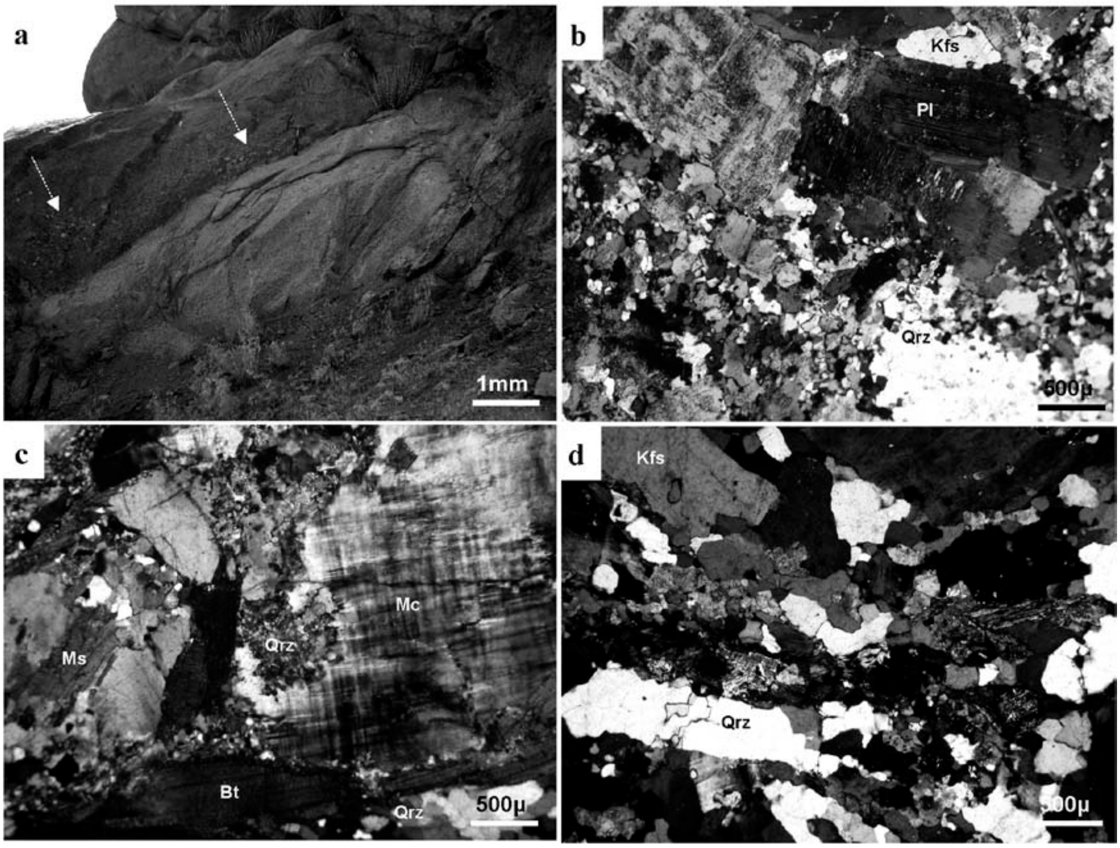


**Fig. 6: Pseudotachylite in the fault plane next to *Dareh Chenar* village. b) mylonitic foliation is defined by compositional layering of alternating feldspar-rich layers and quartz ribbons. c) The convex quartz grain boundaries in contact with feldspars. d) The quartz grains in the mylonites deformed in plastic manner and form ribbons.**

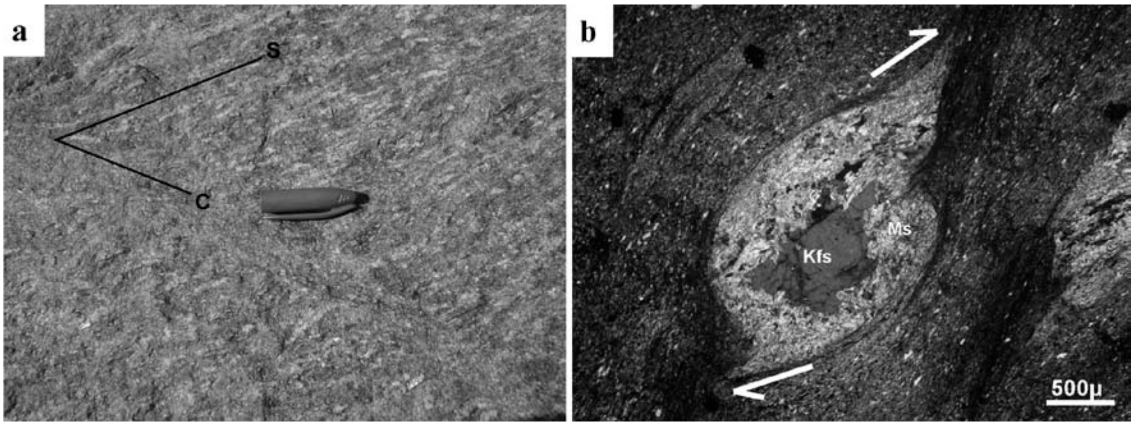


**Fig. 7: a) An example of S-C relations developed in the granodiorite next to the *Qal'e Nagdali* village. b) Stair-stepped tails of feldspar porphyroclasts in a ultramylonite which show dextral shear sense.**

## c) Retrograde metamorphism

The retrograde metamorphism of sheared rocks includes: saussuritization of calcic plagioclase (Fig. 8a), alteration of K-feldspars to white mica (Fig. 8b), albitization of microcline and calcic plagioclase, alteration of hornblende to epidote, chlorite, actinolite and biotite along with precipitating of Fe-bearing opaque minerals (Fig 8c), and finally alteration of andalusite to sheet silicates and kaolinite (Fig 8d).

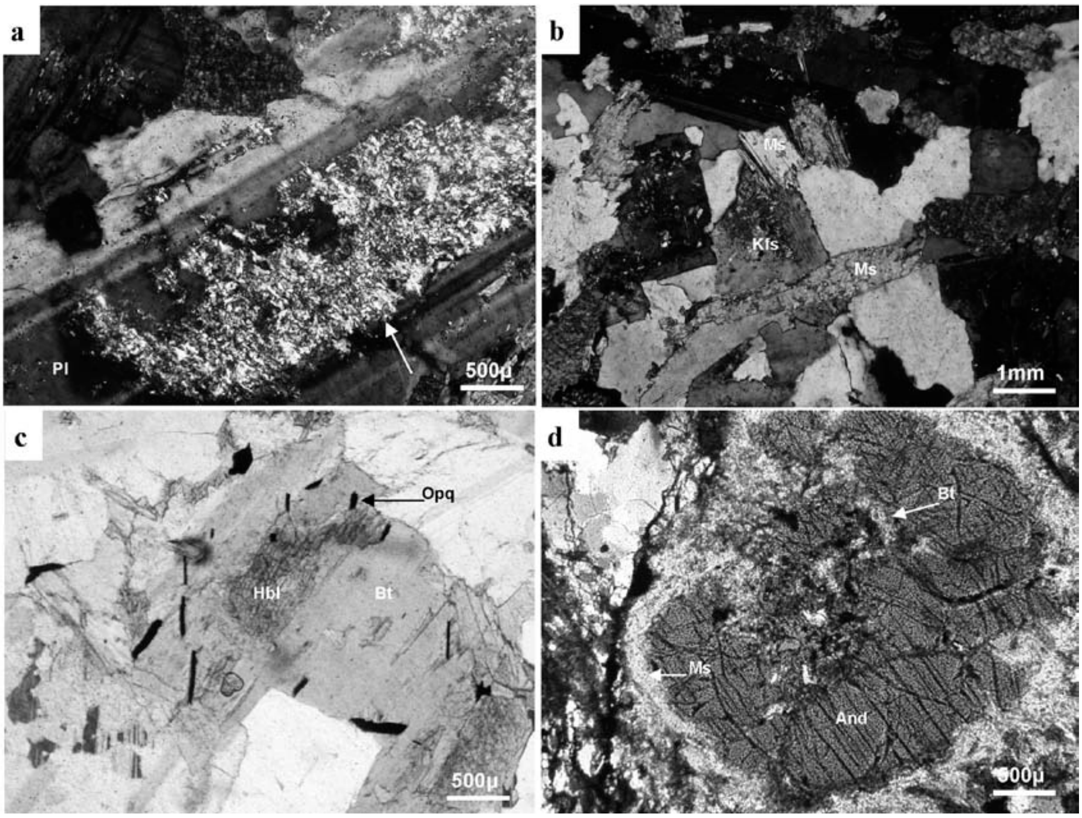


**Fig. 8: The retrograde metamorphism of sheared rocks: a) saussuritization of calcic plagioclase. b) alteration of K-feldspars to white mica. c) alteration of hornblende to biotite and Fe-bearing opaque minerals. d) The andalusite altered to sheet silicates and kaolinite.**

## Discussion and Results

The MPR is preserved transition from magmatic fabric, high temperature solid-state to low temperature solid-state, which followed by brittle deformation after cooling. This feature is typical of syntectonic intrusions. The syntectonic plutons might reflect different kinds of fabrics responding in part to the internal forces and partly to the regional kinematics during cooling and solidification of magma (Hutton 1988). As it turns out such differentiation seems to be insignificant, because resulting fabrics in plutons are due to the interaction of the buoyancy of the ascending magma and the regional strain field (Saint Blanquat and Tikoff 1997; Steenken *et al*. 2000). Concerning deformation, the MPR generally is homogenous in the central part and deformation intensity increases toward the pluton's margins. The magmatic structures are generally overprinted by mild to moderate solid-state and/or brittle deformation. In the field scale, there is a gradual decrease in the intensity of foliation in the pluton from the margin to the interior which is inferred as synmagmatic deformation during emplacement. The good agreement of magmatic and solid-state foliations suggests that the tectonic forces responsible for generating the magmatic fabric in the pluton continued to influence these rocks after crystallization. Furthermore, the present concordance of metamorphic foliations, magmatic foliations, and solid state fabrics suggests that the tectonic regime was active late in the evolution of the complex. This nature and the continuous passage from magmatic to solid-state deformation have been suggested to result from deformation of pluton as they crystallize by tectonic shortening (Castro 1987), granitoids that intruded active shear zones (Guineberteau *et al*. 1987), or simply from the ascent of a diapir with a solid external carapace (Cruden 1990).

The results obtained from field and microscopic studies show signs of continental margin setting that was tectonically active.

## Acknowledgements

This research is supported by the *Iran National*

*Science Foundation*, Grant No. 86103/32.

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