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New Constraints on Deformation History of the Zagros Hinterland: Evidences from Calcite Twin Morphology and Geothermometery in Sargaz Complex, Sanandaj-Sirjan Zone, SE Iran

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Abstract

In order to investigate deformation history preserved in the calcite twins in the hinterland of Zagros, several samples have been collected from calcschists of the Paleozoic Sargaz complex in the Faryab area, SE Iran. These samples are related to F_1-recumbent folding and thrust shear zones. The twin width is about 1 and 3.8 μm (thin-twin regime); the twin strain amounts 5 and 10%; twin intensity is about 24.8 and 72.2 twins.mm^{-1}. Based on the upper crust frictional stress equilibrium hypothesis, calculated differential stress values, of about 200 MPa, suggest that twinning occurred at depth about 7-8 ± 1 Km. Together with twin morphology which indicates that twinning developed under low T conditions (between 160 and 230°C), this suggest that twinning occurred at lower temperature and shallower depth than the reported greenschist facies. Calcite C-axis fabrics therefore show a low - temperature, post-tectonic (post F_1-folding) pattern. The results of Calcite C-axis fabrics reveal that the compressional stress axes are oriented NE-SW. Based on the age of samples together with timing of twinning relative to F_1-folding and thrusting, this regional compressional stress is likely related to oblique subduction of NeoTethys beneath Central Iran in Middle Triassic. All of results support that twinning developed as a late, post-metamorphism deformational event and reveal that the Paleozoic Sargaz complex is jacked-up by underplating process toward the lower-temperatures and shallower depths during the oblique subduction of Neo-Tethys beneath Central Iran.

Keywords: Calcite twin; Sanandaj-Sirjan zone; Iran

Introduction

Mechanical e-twinning of calcite is the dominant mode of crystal-plastic deformation in coarse-grained limestones and marbles deformed at temperatures below about 400°C [30]. Twins have been widely used as

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indicators of deformation history since Weiss [31]. Turner [32] developed a dynamic method to determine stress axes from a population of e- lamellae in deformed calcite rocks. This method has been modified and refined in order to determine the principal direction and/or magnitudes of paleo-stress [14, 21,22,18,19,16].

Twin lamellae in a calcite grain are produced by simple shear parallel to the glide direction *g* in the *ge* plane as shown in Figure 1. Different type of e- lamellae can be distinguished in naturally and experimentally deformed rocks [33]. Thickness of twins is a first criterion. Although twinning occurrence has only a small sensitivity to temperature, strain rate and confining pressure, twins have a spectrum of morphology that is related to temperature. Thin twins appear as thin black lines at low temperature (<200°C); above approximately 200°C, curved twins, twinned twins and completely twinned grains indicate the progressive importance of other crystalline slip systems (e.g., e gliding, twinning by simple shear parallel to the g in the ge plane) [Fig. 1], and larger intracrystalline strain are possible. At ca 250°C and above ancient straight twin lamellae are modified into irregular geometries by recrystallization and grain–boundary migration (Fig. 2) [4].

The very thin e-lamellae without microscopically visible twinned calcite (< 1 µm), termed microtwins by Groshong, [9] could on first sight be mistaken as cleavage planes. Thick twins (about 1-5 µm) are unmistakably recognizable as e-twins in thin section [4]. Laboratory and field observations reveal that the thickness of twins is mainly a function of deformation temperature [10,24,6]. The purpose of this paper is to make use of this property to study the conditions of deformation of the Paleozoic Sargaz complex outcropped in the Faryab area (Sanandaj-Sirjan zone, SE Iran) using twins morphology and geothermometry, and therefore to bring constraints on the tectonic evolution of the hinterland of Zagros orogenic belt.

Geological Setting

The Faryab area within the SE Sanandaj–Sirjan metamorphic zone (internal part of the Zagros belt) records two fold events (Fig. 3). F_1- folding have appeared in gently inclined to recumbent style and include mesoscopic, macroscopic folds and axial planar schistosity. This generation is well documented in the Sargaz and thin units of Abshour complexes. Axial planar schistosity is commonly parallel to bedding. The axial planes of F_1- folds dip 10-30° to the NE and their axes plunge gently to the w. F_1- folds formed by flexural flow.(Fig. 4a,b) [24], and thrust faults developed along overturned limbs. Formation of thrust is a result of differential flow in a ductile mass forming F_1-folds, then shearing out of common limb between the antiform and synform forming these thrusts. At the southern edge of the central domain, these faults displaced large slices of calcschists and interbedded marbles (Fig. 4c,d and e). F_2 folds, which co-axially refold F_1-folds, are well exposed in the Pasefid, Zartorosht, and Zehmakan anticlines. F_2-folds axes are variable in orientation, trending in the range between S45W and N80W (Fig. 4f). In the eastern and central domains (Fig. 3), two outcrops show interference patterns of Z on S, M on S, and S on S, indicating coaxial refolding of F_1 by F_2 (hook shape interference pattern) (Fig. 4 j,h,i and j). The orientations of F_1 and F_2 fold axes are consistent with this pattern of refolding [25,26]. Normal faults in three major trends; N-S to N15E, N40-70E and N70W display latest deformation phase. Influences of normal faults caused to development of half graben in various scales (Fig. 5a,b). Intrusive of diabasic dikes in the planes parallel to

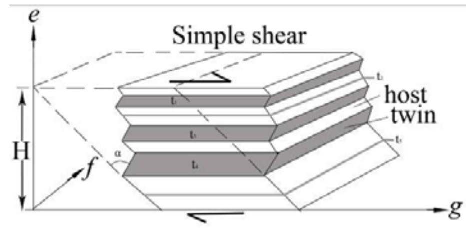

Figure 1. Geometry of twins in a calcite grain produced by simple shear [11]; (modified after [5]). The *f* axis is perpendicular to the *ge* plane. The dashed line outlines the original untwinned calcite grain. The shaded areas indicate the twinned lamellae, and the unshaded areas show the host portions. Here, α is the angle of the rotation of the grain edge from the host portion to the twinned lamellae and equals 38°17', according to Handing and Griggs [11], and H is the total thickness of the host and twins, t is the thickness of the twin [14].

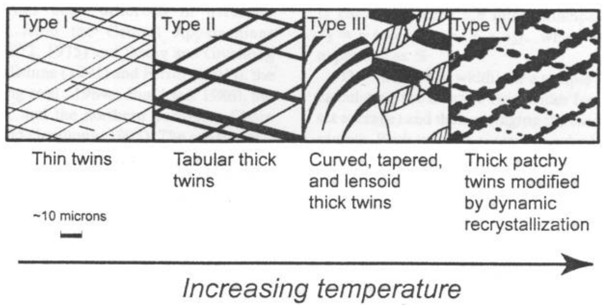

Figure 2. Schematic of influence of temperature on deformation by calcite twinning [4].

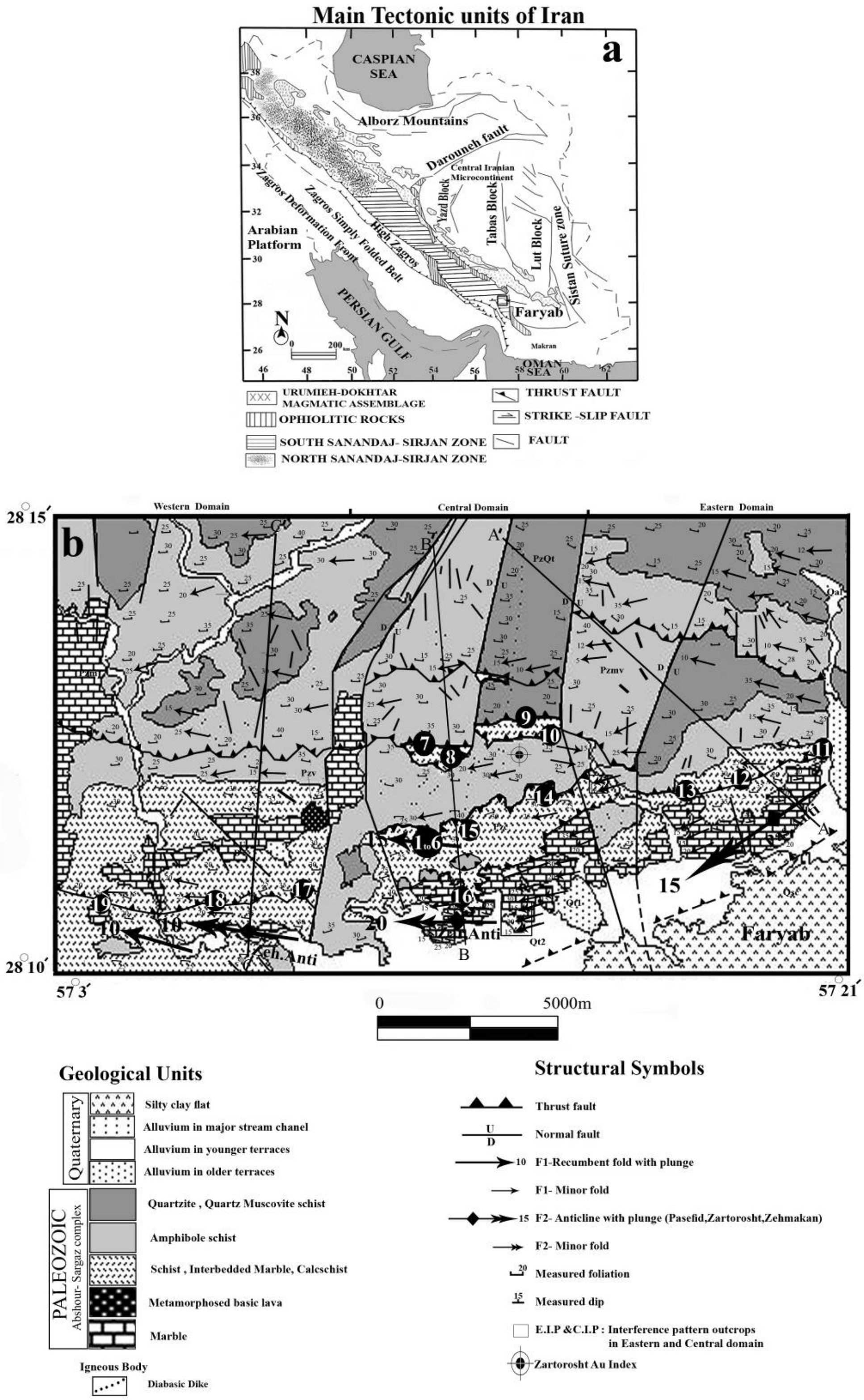

Figure 3. (a) Location of the study area. (b) Structural map of the Faryab area. 1 to 6 are the locations of samples collected from F_1-recumbent folding; 7 to 19 are the locations of samples collected from thrust shear zones. (c) A-A', B-B', C-C' are cross sections in the Eastern, Central and Western domains.

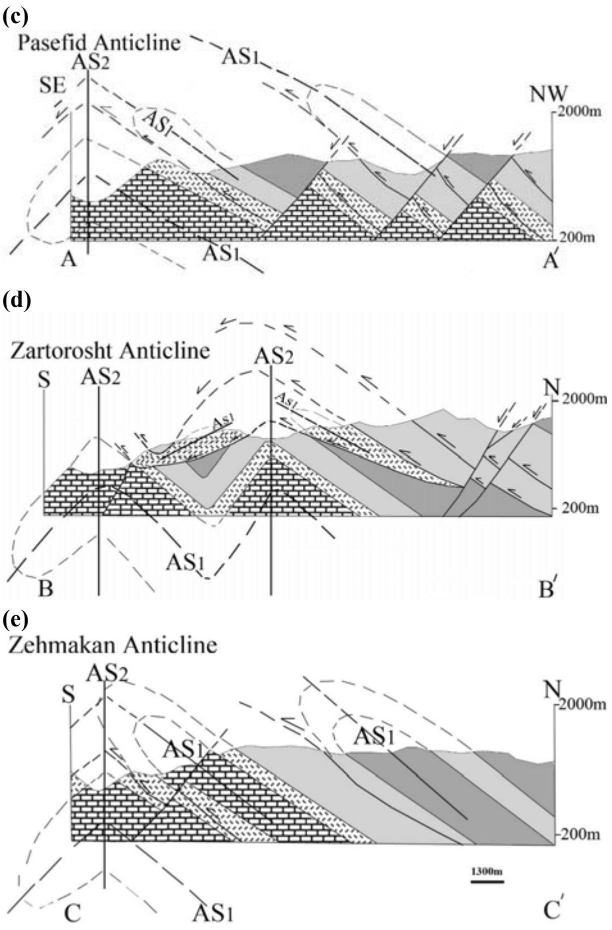

Figure 3. Continued.

normal faults cutting of dikes by later normal fault and construction of dropped area display influence and role of magmatism in development of normal faulting and diabasic intrusion. Isostatic, crustal thickness, residual gravity and earthquake intensity maps in the NE of Zagros confirms the presence of major deep structures in this region that these structures are mantle updoming [1,22,25,26,28]. Angular unconformity between the Paleozoic Sargaz complex and Lower Jurassic sedimentary-volcanic rocks reveal the imprint of early Cimmerian movements during the metamorphic deformation in the Paleozoic Sargaz complex by Middle Triassic times [2,26].

Sampling Method and Measurement Strategy

In order to constrain paleotemprature conditions of deformation in the hinterland of the Zagros belt based on analyses of calcite twins, 6 oriented samples from F_1-folds in the south of Zartorosht Au- Index in the central domain and 13 samples from thrust shear zones were collected from calcschists within the Sargaz complex. (Fig. 3). Oriented samples were chosen to reflect regional deformation patterns. For each sample, measurements twin set (classification of twins based on trend or width), twin width (thickness is measured as the the perpendicular distance between boundaries with the rotated to the vertical on a universal stage) and grain width (determined using the linear intercept method on optical thin section) were made using a U-stage from two perpendicular thin sections: one oriented normal to bedding and parallel to its strike, and the other normal to bedding and parallel to its dip. About 50 grains were measured in each thin section [5-9].

Results and Discussion

Morphological Features and Measurements of the Calcite Twins

The most common appearance of calcite twin lamellae in our samples is type II twins; additional types of twins were however also observed in these samples Type II show two twin sets which appear as thin or thick straight lines. The occurrence of this type is related to post-metamorphic events (Fig. 6a,b) [3,6]. The characteristics feature of type III are development of curved thick twins, twins within twins and completely twinned grains. This twin geometries suggest that twinning occurred as syn-metamorphic deformation (Fig. 6c,d). Type IV appeared in thick, patchy lines with sutured twin boundaries. This type generated from dynamic recrystallization (grain boundary migration). (Fig. 6e,f) [4,6]. In this study the calcite grains for twin measurements were randomly selected in thin sections. The grain size varied between 116 and 500µm. The mean of twin set is between 4 and 11sets, twin width varies between 1 and 3.8 µm and twin intensity ranges between 24.8 and 72.2 twins.mm^{-1}. Twin intensity is defined as the rate of change of the number of twin of a given twin set with respect to grain diameter measured normal to the trace of the twin lamellae [24].

Calcite twin data showed that twin width is dependent on both the temperature of deformation and strain ; furthermore, twin width and intensity can be used as indicators of the deformation conditions [6,7,8]. Calcite twin strain can accumulate by increasing the number of twins (increasing mean twin intensity), increasing the size of twins (increasing the mean twin width), or both [8]. In this study twin strain was calculated using Groshong's [9] equation. The shear strain equation can be rearranged as follows: γ =Tt2tan

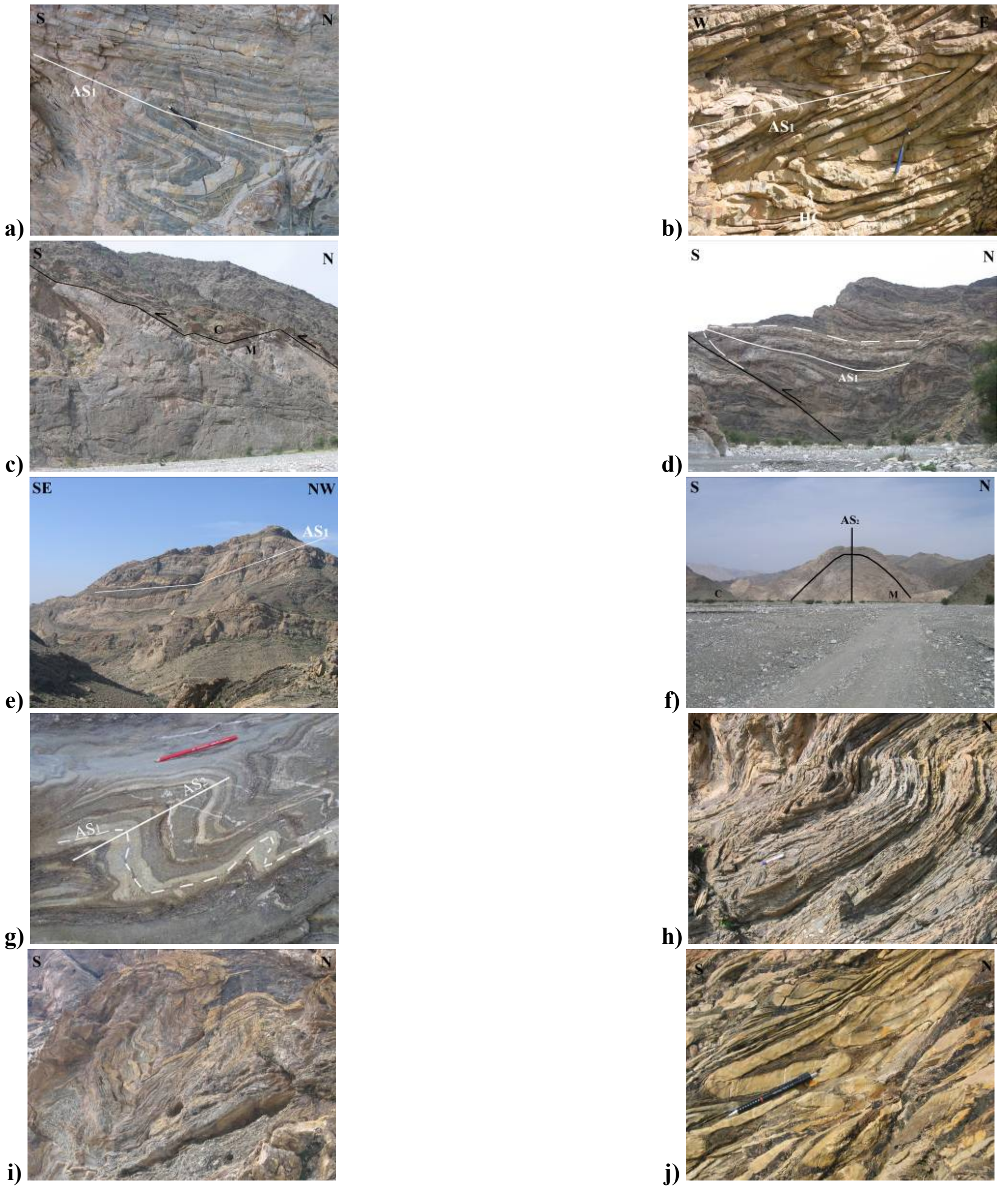

Figure 4. (a) Gentle inclined folding in thin layer units of Abshour complex near Pasefid and (b) Formation of gentle inclined folds under flexural flow conditions in calcschists unit of Sargaz complex. (SW of Zartorosht Au index). In this mechanism hinge collapsed (HC) [23] and axial surface schistosity have been developed. (c,d) Formation of thrust by differential flow in a ductile mass forming a fold, then shearing out of common limb between the antiform and synform forming a thrust. (e) At the southern edge of the central domain, thrust faults displaced large slices of calcschists and interbedded marbles. (f) Pasefide anticline F_2-fold in marble of Abshour complex.(g) Outcrop of refolding F_1-fold by Z-type F_2-fold. (h, i & j) Z on S, M on S and S on S patterns in outcrop of interference pattern in central domain (C.I.P in Fig. 3).

(α/2).[8], where γ = shear strain, T = twin intensity, t = twin width, α = angle of rotation of the grain edge from the untwinned to the twinned position, and is equal to 38°17' [9,11]. According to this equation, twin strain ranged from 5 to 10 %. Figure 7 illustrates the relationships between twin width and twin strain, twin intensity and twin strain, twin intensity and twin width, and the product of twin width and twin intensity and twin strain for each sample. Comparing the results of this study with those of Ferrill et al [8], it was determined that calcite twins in study area were produced at temperatures ranging between 160 and 230°C. Deformation of calcite at this temperature range occurs by formation of thin twins rather than by twin

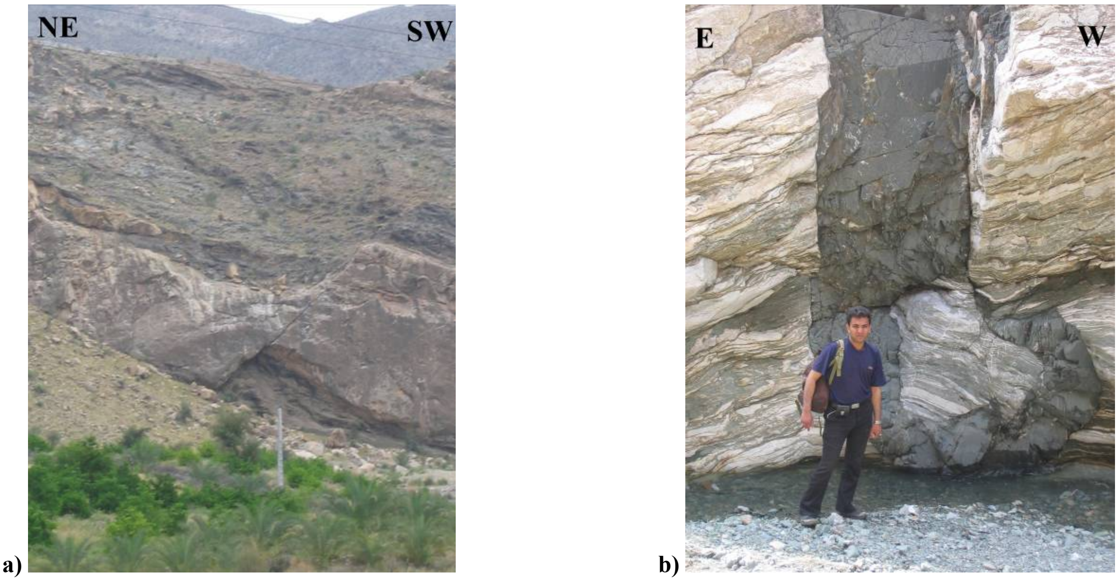

Figure 5. (a) Normal fault in marble of Abshour complex and calcschists of Sargaz complex (W of Zartorosht Au index).(b) Intrusive of diabasic dike in the calchschists of Sargaz complex.(NE of Zartorosht Au index)).

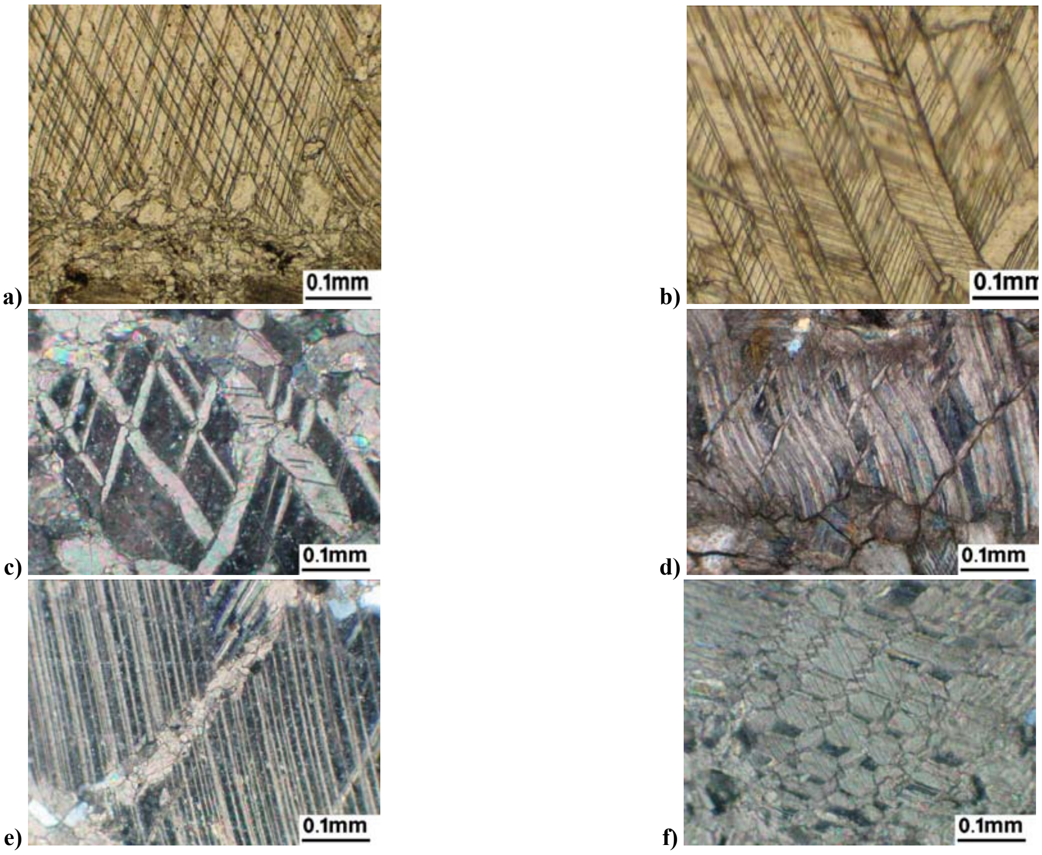

Figure 6. Colour microphotograph of several twins types. (a). type II, The most common appearance of twins in the samples. (b,c,d).type III which appear as two sets of curved thick twins, twins within twins and bent twins. (e,f). type IV. thick, patchy lines, sutured twin boundaries.

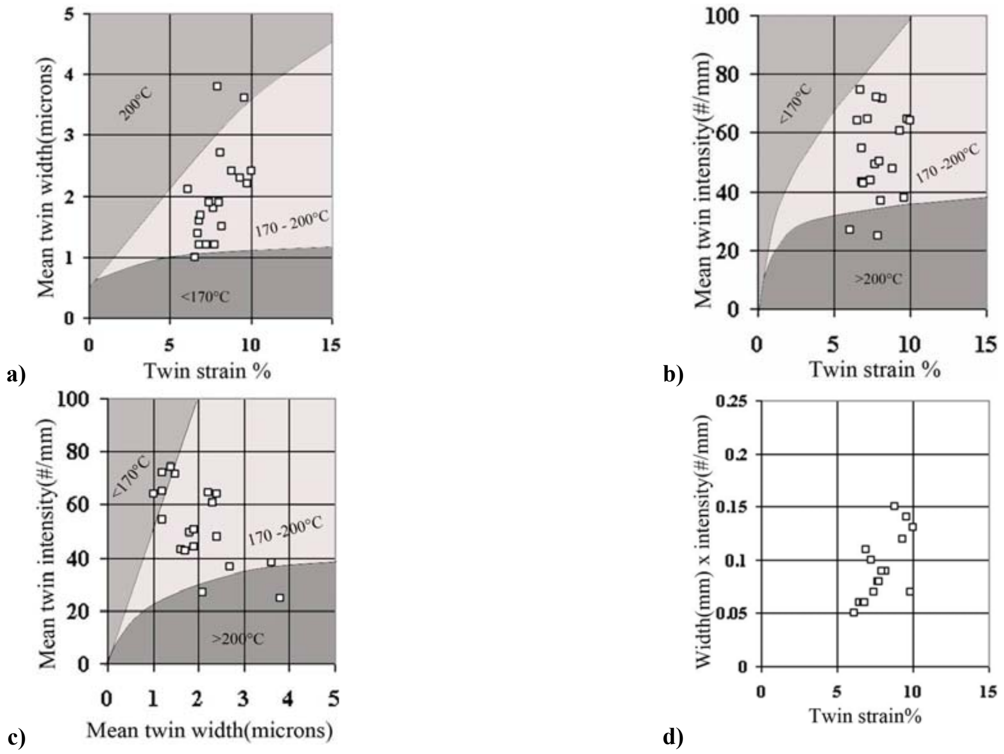

Figure 7. Graphs of twin parameters of samples collected from F_1-recumbent folding and thrusting in the Paleozoic Sargaz complex from the Faryab area, (a). Mean twin width versus twin strain, (b) mean twin intensity versus twin strain, (c) mean twin intensity versus mean twin width, (d) Product of mean twin width and mean twin intensity versus twin strain. (adapted from [6]).

enlargment or the formation of thick twins [8]. In our samples strain accumulation occurred by formation of new thin twin as type II and twins within twins (Fig. 6c). The calcite twin measurement data and results are summarized in Table 1.

For given stress and pore pressure regimes, it is possible to predict the maximum differential stress based on the frictional-failure equilibrium hypothesis and to compare this prediction with observed values. For a favourably oriented pre-existing cohesionless fault plane, the condition of reactivation, which therefore applies to a critically stressed crust, can be written as follows [13] $(\sigma_1 - P_f)/(\sigma_3 - P_f) = [(\mu^2 + 1)^{0.5} + \mu]^2$. This equation can be used to predict differential stress as a function of depth in crust at frictional equilibrium. For compressional settings [i.e., the largest principal stress σ_1 is horizontal, such that the states of stress are of strike-slip (σ_2 vertical) or reverse-type (σ_3 vertical) regimes], the following equations for strike-slip and reverse-type regimes have been considered: $\sigma_1 - \sigma_3 = 2\rho gz\,(\lambda - 1)(1 - [(\mu^2 + 1)^{0.5} + \mu]^2)/(1 + [(\mu^2 + 1)^{0.5} + \mu]^2)$ and $\sigma_1 - \sigma_3 = \rho gz\,(\lambda - 1)(1 - [(\mu^2 + 1)^{0.5} + \mu]^2)$. where $\lambda = P_f/\rho gz$. The value of λ is approximately 0.4 for hydrostatic conditions, 0.9 for near-lithostatic conditions, and exactly 0 for dry conditions. Figure 8 shows differential stress–depth curves that correspond to strike-slip (SS) and reverse faulting (C) regimes for values of λ of 0.38 (hydrostatic) and 0 (dry) and for values of the friction coefficient μ of 0.6 and 0.9 [17]. Based on the differential stresses related to F1 folding and thrusting, and assuming that the crust is close to frictional equilibrium, the depth of deformation for the samples analysed in the present study is estimated to be around 7–8 (± 1) km. These estimates of the magnitudes of differential stresses and depth of deformation are consistent with the tectonic setting of deformation of the Sargaz complex in the inner belt of the Zagros orogen. (Fig. 8) Together with twin morphology which indicates that twinning developed under low T condition (between 160 and 230°C) (Fig. 7). This suggest that twinning occurred at lower temperature and shallower depth than the reported greenschist facies.

Analysis of calcite C-axis fabrics therefore show a low–temperature, post-tectonic (post F_1-folding) pattern. The orientations of c-axes (Fig. 9) in samples from the Paleozoic Sargaz complex indicate post-tectonic (post-F_1-folding) Twinning [30,32]. These fabrics show a girdle with one or two unequal peripheral maxima with

Table 1. Results of calcite twin analysis. Samples 1-6 were collected from F_1-recumbent folding and 7-19 were collected from Thrust shear zones

Sample	Twin sets	Twin Intensity (#/mm)	Twin width (Microns)	Twin Intensity (#/mm)xWidth (mm)	Twin strain (√ J2%) Groshong (1976)	Temperature of deformation: T (°C) Ferril (2004)
1	10	60.7	2.3	0.12	9.3	170-200
2	10	43.2	1.6	0.06	6.8	170-200
3	9	36.8	2.7	0.09	8.1	170-200
4	8	49.4	1.8	0.08	7.7	170-200
5	11	50.3	1.9	0.09	8	170-200
6	8	71.4	1.5	0.09	8.2	<170
7	9	24.8	3.8	0.09	7.9	>200
8	8	26.8	2.1	0.05	6.1	>200
9	6	64.8	1.2	0.1	7.2	<170
10	7	64.7	2.2	0.07	9.8	170-200
11	7	38	3.6	0.14	9.6	170-200
12	9	64	2.4	0.13	10	170-200
13	7	48	2.4	0.15	8.8	170-200
14	7	42.6	1.7	0.11	6.9	170-200
15	8	43.9	1.9	0.07	7.4	170-200
16	4	64	1	0.06	6.5	<170
17	8	47.4	1.4	0.06	6.7	170-200
18	5	72.2	1.2	0.08	7.8	<170
19	5	54.5	1.2	0.06	6.8	170-200

monoclinic symmetry. In the samples from the thrust shear zones, these concentrations are very intense point maxima located anticlockwise of the normal to the shear plane; this obliquity or asymmetry in the low – temperature fabrics indicates non-coaxial deformation and a component of dextral shear along the thrust shear zones [20]. In thrust shear zones there are several shear sense indicators that absolutely reveal dextral shear within thrust shear zone (Fig. 10).

The stress system deduced from c-axis data is monoclinic, with σ_3 coinciding with the maximum for tension axes and σ_1 plotting close to the maximum for compression axes. The compression axes σ_1 trend NE–SW, with shallow plunges; the tension axes σ_3 trend NW–SE, with moderate plunges [25-27]. Based on the age of samples together with timing of twinning relative to F_1-folding and thrusting, this regional compressional stress can be likely related to oblique subduction of Neo-Tethys beneath Central Iran by Middle Triassic times [2,25,26,29]. All of results support that twinning developed as a late, post-metamorphic deformational event and reveal that the Paleozoic Sargaz complex is jacked- up (exhumed) toward the lower-temperatures and shallower depths (Fig. 11).

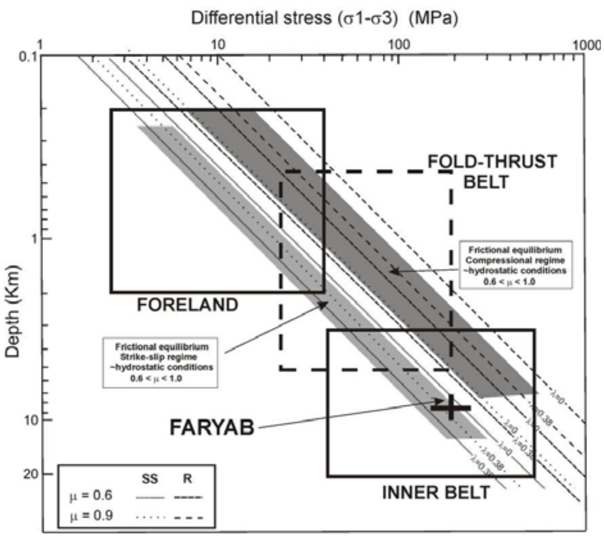

Figure 8. Values of differential stress derived from the relationship between paleopiezometry and depth (log-log). Dashed lines represent the stress-depth relationship predicted by Coulomb frictional-failure theory for coefficients of friction μ of 0.6 and 0.9, pore pressures of 0 (λ = 0) and hydrostatic (λ = 0.38), and various tectonic regimes (SS, strike slip; R, reverse) (adapted from [17]). Differential stress and depth of deformation are reported for the Faryab area.

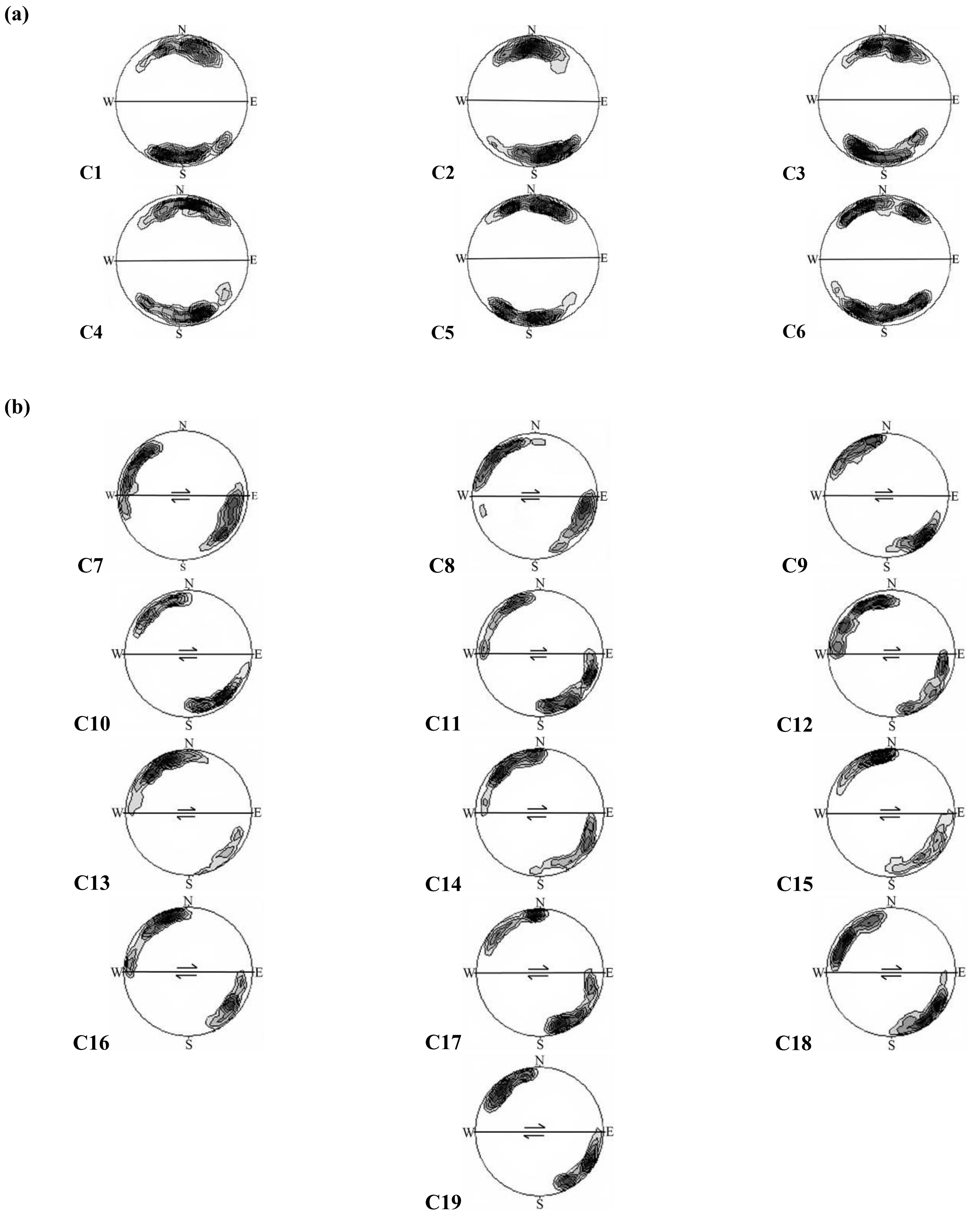

Figure 9. (a) Calcite c-axis fabrics of samples (1-6) from F_1-recumbent folding. (b) Calcite c-axis fabrics of samples (7-19) from thrust shear zones. In all these projections, the foliation is vertical. Concentration of C-axis in the 7-19 samples reveal a dextral shear sense on foliation plane [20]. 50 or more calcite c-axis orientation were measured in each sample.

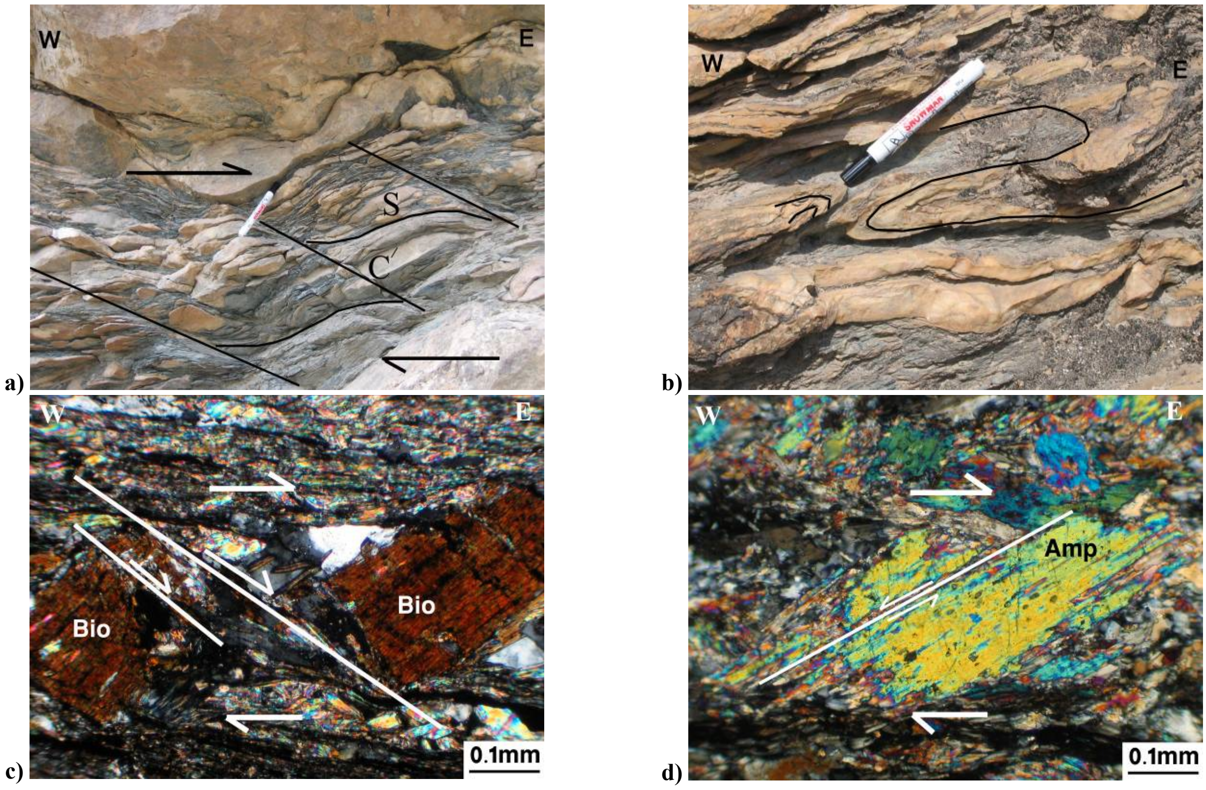

Figure 10. Microscopic examination of oriented thin sections of the samples and mesoscopic features collected from thrust shear zones indicates dextral shear for the strike-slip component in thrust shear zones. (a) The "V" pull-apart structures [12] in the biotite grains in the quartz-Muscovite schists (location,9 in fig3). (b) Development of antithetic fractures in the amphibole grain in the amphibole schists (location,10 in Fig. 3).(c) S-C, C′ shear band cleavages [3] in the calcschists of Sargaz complex. (d) Asymmetrical folds in the deformed marble (locations 11,12, 13 in Fig. 3) are the some of indicators for dextral shear sence within the thrust shear zones in the Faryab area.

Structural analysis established the deformation sequences in the Paleozoic Sargaz complex which is located in the Faryab area (South Sanandaj-Sirjan zone). This area was folded and thrusted by successive deformational events as a result of progressive tectonic evolution. Multiple folding in the Paleozoic Sargaz complex is consistent with style of deformation in the hinterland of orogenic belts. Axial planar schistosity is developed to F1. It is well developed in calcschists, greenschists and quartz-muscoviteschists. Schistosity appears with syn-tectonic mineral growth. The green-schist facies is developed due to compressional tectonic event that is related to subduction of the Neo-Tethys beneath central Iran. The vergence of F_1-recumbent folds and thrusting is consistent with the NE-SW direction of compressional stress axes.

The calculated values of twin width, 1 and 3.8 µm (thin-twin regime);twin strain,5 and 10%; twin intensity, 24.8 and 72.2 twins.mm^{-1}confirm that twins formed between 160 and 230°c. In addition, calcite C- axis fabrics therefore show a low – temperature, post tectonic (post F_1-folding) pattern. The orientations of c-axes in samples from the Paleozoic Sargaz complex indicate post-tectonic (post-folding) twinning. The direction of regional compressional stress deduced from c-axis fabric can be related to oblique subduction of Neo-Tethys beneath central Iran in Middle Triassic times. Based on the upper crust frictional stress equilibrium hypothesis, calculated differential stress values, of about 200 MPa,(based on Rowe and Rutter's [24] equation, $\sigma = -52 + 171.1 \text{ Log } d$, (d is twin intensity) and a standard error of 43 MPa, values of differential stress calculated in the present study are about 200 MPa), suggest that twinning occurred at depth about 7-8 ± 1 Km. Together with twin morphology which indicates that twinning developed under low T condition (between 160 and 230°C), this suggest that twinning occurred at lower temperature and shallower depth than the reported greenschist facies. These results reveal the jacking- up the Paleozoic Sargaz complex toward the lower- temperatures and shallower depth.

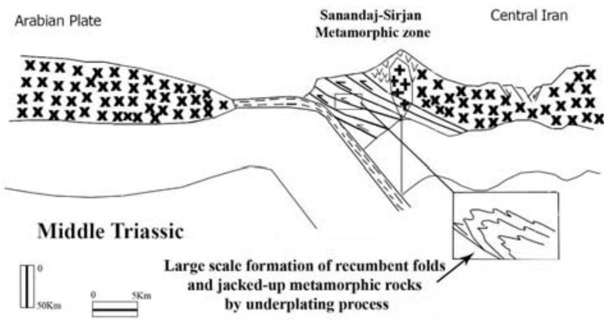

Figure 11. Deformation of Paleozoic units by underplating process in the oblique subduction of Neo Tethys beneach Central Iran by Middle Triassic.The results of calcite twins reveal that the Paleozoic Sargaz complex jacked-up and twinning occurred in shallower depts. (7-8)±1 Km and lower temperatures (160 and 230°C) than the reported greenschist facies [26].

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