Mesofracture Analysis of Azmur Anticline North Eastern Iraq

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ABSTRACT

Analysis of brittle failure structures carried out throughout a traverse across Azmur Anticline, NE Iraq. This includes widespread joints, mesofaults, planar and enechelon vein arrays and pressure solution surfaces (stylolite seams). The aim of this work is for unraveling the tectonic history and detecting tectonic episodes responded for the initiation and modification of such brittle failure structures.

Field observations and analysis revealed two subsequent compressive phases. The oldest trending ENE-WSW is normal to the Azmur fold axis, while the second is parallel to it. These directions ascertained by paleostress tensors deduced from slip analysis of striated mesofaults. Reorientation of stress regime from first compressive phase to the second has been attributed to the progressive oblique collision of Arabian and Eurasian plates. Furthermore, a final stretching phase in NE-SW direction had been deduced. This extensional phase which ought to the uplifting stage of fold structure is responsible for bedding parallel stylolite seams with vertical peaks, and normal slip faulting in the studied area.

تحليل تراكيب الكسور في طية ازمر شمال شرق العراق

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الملخص

أنجزت دراسة تراكيب التكسر الهش من خلال مسار مستعرض على طية ازمر – شمال شرق العراق. هدف هذه الدراسة هو توضيح التاريخ التكتوني من خلال استنباط الفترات التكتونية التي انشأت تراكيب التكسر الهش في المنطقة. تتألف هذه التراكيب من الفواصل كثيرة الانتشار، الفوالق المتواجدة على مقياس المكشف الصخري ، العروق واسطح الاذابة الضغطية (الستايلولايت). اظهر تحليل التراكب اعلاه طورين تكتونيين انضغاطيين متعاقبين، الأول يتجه شمال شرق – جنوب غرب وعمودي على محور الطية، بينما الثاني يوازي محور الطية. وتأكد حدوث هذين الطورين التكتونيين من خلال متجهات (تنسرات) الاجهاد القديم والمستنتجة من تحليل انزلاق الفوالق.

ان اعادة توجيه الحقل الاجهادي من الطور الانضغاطي الاول الى الطور الثاني يعود الى الاصطدام التقادمي المائل للطبقين العربي والاوراسي. فضلا عن ذلك فقد استنتج طور تمددي باتجاه شمال شرق – جنوب غرب. ان هذا الطور الناجم عن مرحلة رفع الطية ادى الى تكوين اسطح الاذابة الضغطية، ذات القمم الشاقولية الموازية لمستويات التطبق، فضلا عن تكوين فوالق اعتيادية في المنطقة.

INTRODUCTION

The present work aims to elucidate various modes of brittle failure structures developed within Azmur Anticline. So geometrical and kinematic analysis of these structures were performed, to understand the dynamic fashion according to the geotectonic scope of the region.

The investigated traverse that crosses Azmur Anticline located nearly (4)km. northeast Sulaimaniyah city, and restricted within lat. (35°40`00``) N and long. (45°25`00``) E. The elevation of highest point on the mountain exceeds (1700) m. above m.s.l. Its maximum width attains (4) km., and its axial trend approaches (35) km. (Fig. 1)

Azmur Anticline is one of the huge and numerous structures of the Imbricate partition of the Foreland Fold Belt of Zagros Collision Zone. (Numan, 1997; Jassim and Goff, 2006).

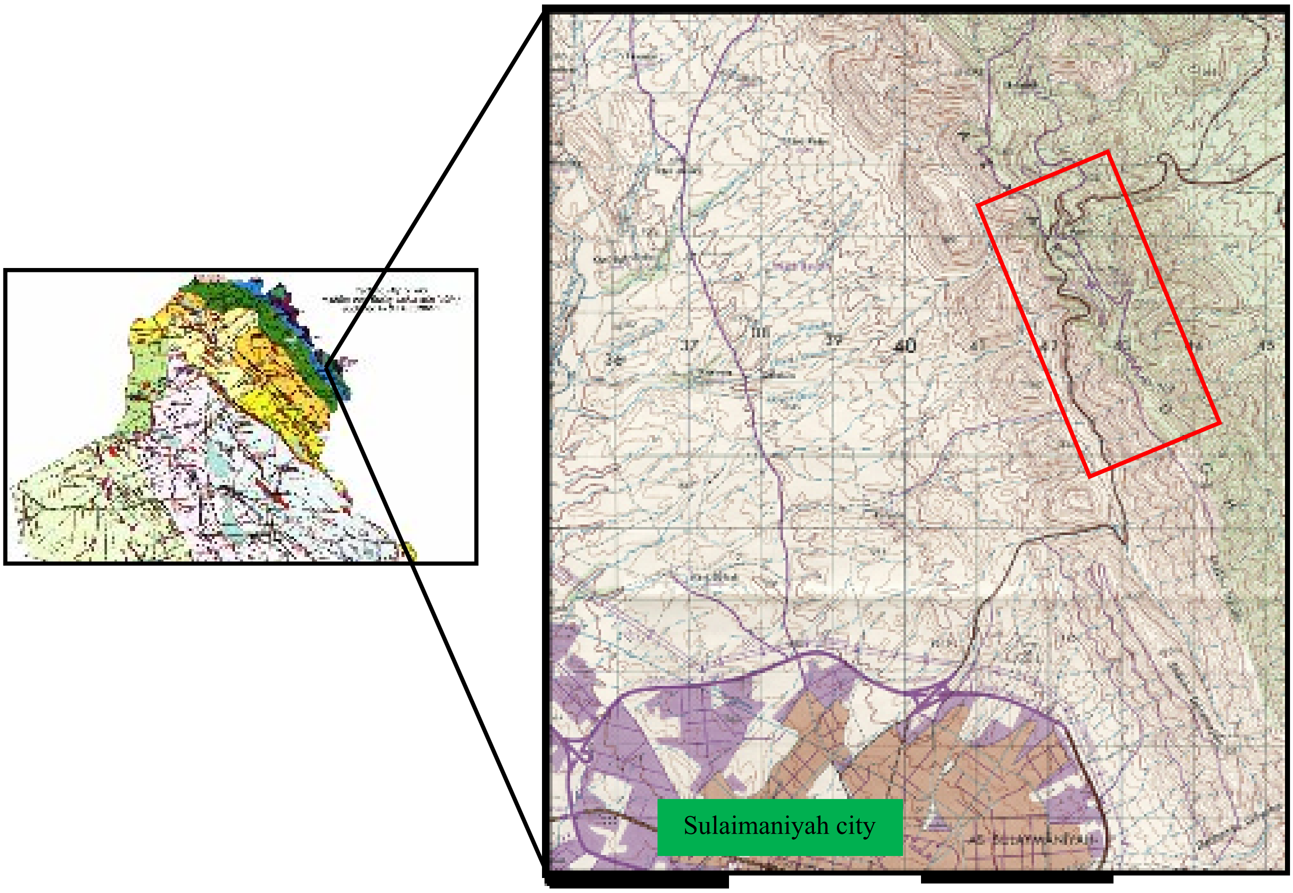


Fig. 1: Topographic map of Sulaimaniyah district showing the location of the study area.

It is a double plunging anticline trending NNW-SSE within Zagros range. It is generally asymmetric fold verging toward the SW, and its SW limb within the studied traverse is overturned. (Fig.2)

Geologically, the core of the Azmur Anticline exposes interbedded marl, limestone and dolomite layers of Balambo Fm. (Valanginian-Turonian). This formation is overlain by thin to moderately bedded white pelagic fine grained limestone with chert bands of Kometan Fm. (late Turonian-early campanian), that forms the carapace of the anticline. On the both flanks of the fold, scattered exposures of marl, marly limestone and limestone layers of Shiranish Fm. (Campanian), overlain by thin sandstone and shale beds changing upward to marl of Tanjero Fm. (Upper Campanian-Maastrichtian).

The area lacks any structural and tectonic analysis likelihood the present investigation. So the present investigation attempts to clarify the tectonic episodes that affected this area by using analysis of prevailed brittle type minor structures.

The benefit of minor structures (striated fault planes, vein arrays and brittle shear zones) in structural and tectonic investigations had become more interested worldwide. That is because the mesostructures can be interpretated more precisely, and their formation mechanism with respect to large scale structures can be resolved and used to decipher tectonic problems (Bles and Feuga, 1986; Jaroszwiski, 1984; Hancock, 1985; Suppe, 1985; Ramsey and Huber, 1987; Van der Pluijm and Marshak, 1997).

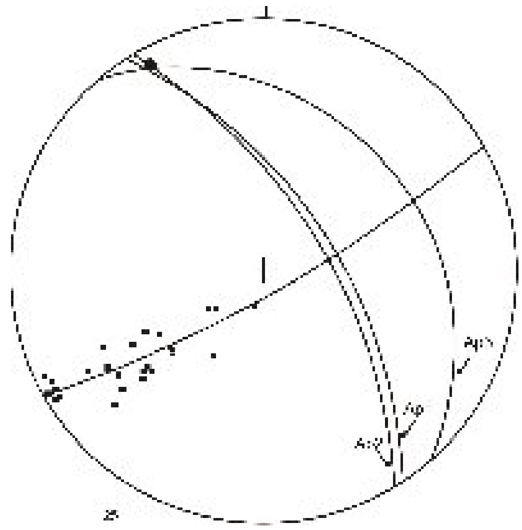


Fig. 2: Synoptic Pi-diagram of Azmur Anticline in the studied traverse (Ap is the axial plane of the fold).

Ap1: Between NE limb and vertical part of the SW limb.
Ap2: Between vertical and moderate parts of SW limb.
Ap3: Between moderate and shallow dipping parts of SW limb.

METHODOLOGY

The field work carried out in (25) measuring and description sites along a traverse that lies along the road cut across Azmur mountain. The measurements and notes taken at all sites including: attitudes of bedding, joints and mesofaults (with their striations pitches and movement sense); photographs and field sketches of pressure solution seams (stylolites) and planner and enechelon vein arrays.

The collected data were represented and analyzed stereographically as Pi-diagram for the main Azmur fold manually as well as by computer using Georient software (GEOrient © 9.2).

Fault slips data treated by using Tensor software (Delvaux and Sperner, 2003) based on improved dihedral method of (Angelier and Micheler, 1977). The paleostress tensors deduced by this analysis describe the orientations of maximum, intermediate and minimum principal stress axes, beside their ratios (R) that reflect the shapes of stress ellipsoids of these tensors.

High resolution camera photographs with their field sketches for microtectonic elements, such as stylolite seams, tabular and enechelon lenticular vein arrays, were taken and interpretated. This is to deduce the orientations of maximum and minimum principal compressive stresses (σ_1, σ_3) that are responsible for the development of such brittle structures. These representations and analyses helped to decipher various tectonic compressive episodes particularly where such structures associated with each other. This was achieved by determining the relative temporal relationships among them (i.e. using cross-cut and termination relationships).

Finally, the output of the kinematic analyses of various structural modes (mesofaults, stylolites, and vein arrays) unified to conclude the sequence of tectonic phases which architectured the study area in the view of geotectonic setting of the studied area.

ANALYSIS OF BRITTLE FAILURE STRUCTURES

The studied area characterized by a spectrum of brittle failure structures including joints, veins, pressure solution surfaces (stylolitic seams) and striated mesofaults. They are analyzed as follows:

1- Joint analysis

the systematic category of joints in the study area classified according to three mutually perpendicular tectonic axes (a, b, c) with (ab) defining bedding plane, (b) is strike direction, (a) is dip trend, and its normal c-axis. Such a traditional classification cited by (Turner and Wise, 1963), had been followed by many authors like (Hancock and Atiya, 1979; Hancock *et al.*, 1984; Hancock, 1985; Ramsay and Huber, 1987 and Al-Jumaily, 2004). According to this classification two orthogonal tension joint sets (ac) and (bc) and many shear systems were recognized (Fig. 3). The prevailed shear systems (hko) enclosing acute angles about (a) and (b) axes appear either as individual or conjugate sets. However, other shear systems like (hol) acute about (a) and (c) axes and (okl) acute about (b) and (c) axes were also recorded but with restricted distribution. It is worth to mention that many of these joints were acted as preexisting weakness planes for development of other brittle structure types in subsequent tectonic phases.

The kinematic analysis of the extensional and shear joint sets and systems in the study area revealed two subsequent compressive directions. An ENE-WSW compression normal to the general trend of the major anticline caused the development of (ac) tension set as well as (hko) and (hol) acute about (a) shear joint systems. The second compressive stress directed NNW-SSE parallel to the major anticlinal axis, was responsible for development of (bc) tension set, in addition to (hko) and (okl) acute about (b) shear systems. However, the (hol) acute about (c) shear joints seem to have been developed in response to ENE-WSW extensional phase associated with the final uplifting of the major fold.

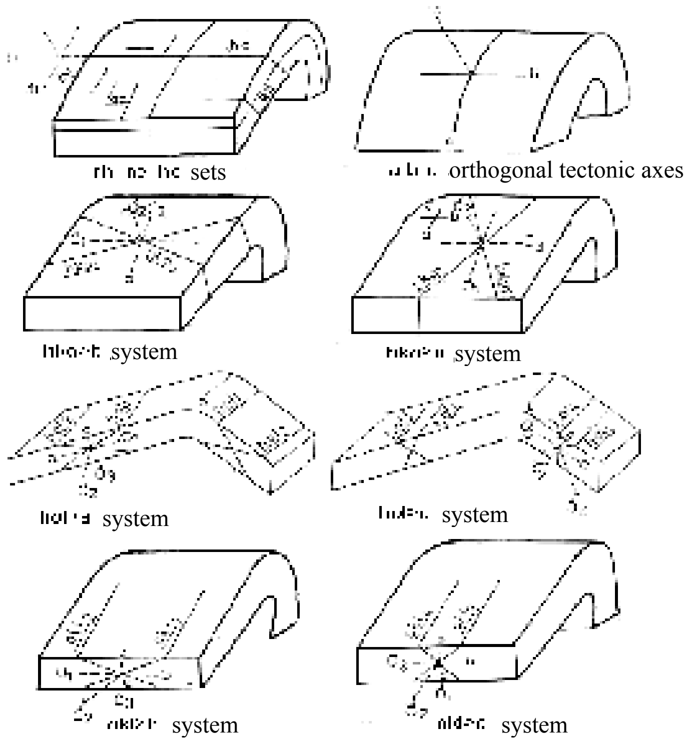


Fig. 3: Geometrical classification of joints with respect to three orthogonal tectonic axes (Hancock, 1985).

2- Vein analysis

veins are fractures filled with minerals precipitated from water solutions that passed through the fracture. Quartz or calcite form the most common vein filling, also other minerals do occur in veins, including numerous ore minerals. Some veins initiated as joints, whereas others initiated as shear ruptures or cracks formed adjacent to shear ruptures. Veins occur in all dimensions; some are narrow and short, others are wide tabular that reach a couple of meters across and many meters long. Groups of veins are called vein arrays and can have the following varieties (Van der Pluijm and Marshak, 1997 and Hobbs *et al.,* 1976):

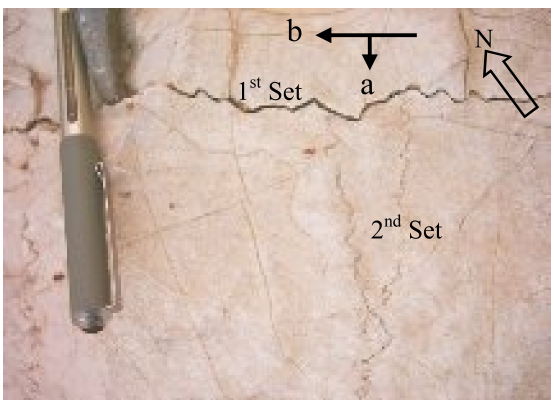
a- Planner systematic arrays: the competent veins are planner, mutually parallel and regularly spaced.
b- Nonsystematic arrays: veins tend to be nonplanner, and individual ones may vary in width.
c- Enechelon vein arrays: consist of short parallel veins lying between two parallel enveloping surfaces and are inclined at an angle to the surfaces.

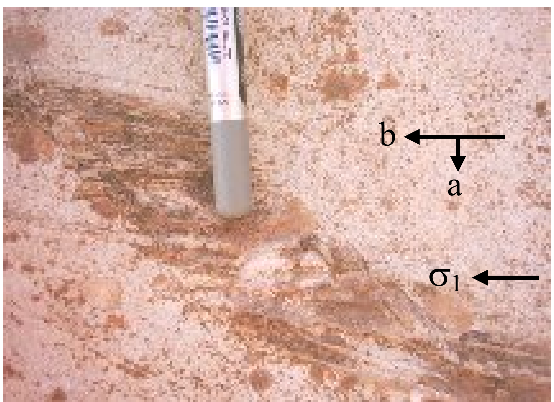
(Bles and Feuga, 1986) described the dilatational enechelon lenticular veins as tension gashes. They might be associated with stylolite seams, indicating the maximum principal stress direction, which is parallel to the long axes of such veins. The enechelon vein arrays may also present as single or conjugate sets. The boundary lines of tension gashes array usually parallel with the simple shear direction. Therefore, these arrays form brittle shear zones (Roering, 1968; Durney and Ramsay, 1973 and Ramsay, 1980).

The maximum principal stress σ_1 of the two conjugate vein arrays bisects the angle between them. The minimum principal stress σ_3 bisects the other angle between the conjugate sets and makes right angles with the long axes of lenticular veins, whereas σ_2 lies within the intersection zone of such conjugate sets (Hancock, 1982; Bles and Feuga, 1986; Ramsay and Huber, 1987; Van der Pluijm and Marshak, 1997).

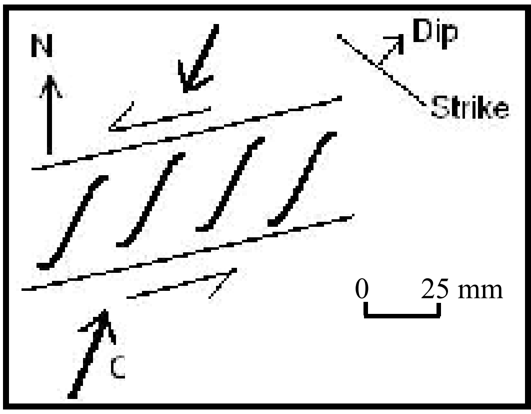
Both planner systematic and enechelon calcite vein arrays have been recognized in the study area. They are juxtaposed with stylolite seams. Two sets of planner systematic arrays occure; one of them accords with bedding strike direction (bc), whereas the other being transverse to that direction. The trend of each coincides with the peaks of the contemporaneous stylolite seams (photo.1). It is inferred from the association of these structures that, the transverse planner vein arrays with their associated stylolite seams have been developed in response to the first tectonic compression direction (σ_1 trending ENE-WSW). Whereas the longitudinal planner vein arrays and the stylolite seams associated with them, have been formed due to the second tectonic compressive direction (σ_1 trending NNW-SSE).

Individual as well as conjugate arrays of enechelon veins (tension gashes) were registered in the limestone beds of Kometan Fm. at both limbs of the major anticline. The border lines of some consist of stylolite seams. They are interpreted as brittle shear zones, in which stylolite peaks pointing in the same direction as the longitudinal axes of the enclosed lenticular veins (photo 2).

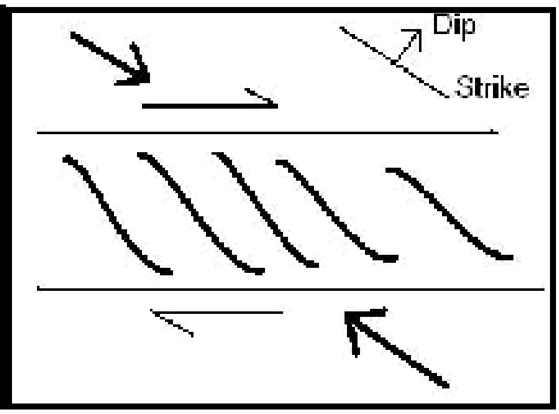




On bedding surfaces (ab) at the northeastern limb of the fold, three individual sets of these shear zones were observed at different sites. The first is a sinistral set at low angle with the dip direction (a) of bedding (sketch 1). Thus it belongs to the first compressive tectonic direction (σ_1 in ENE-WSW direction) as stated earlier. The other two sets forming acute angle with strike direction (b) of bedding, one of them, sinitral (photo 2), whereas the other is dextral (sketch 2). The σ_1 direction inferred from both sets indicates NNW-SSE direction which corresponds to the second tectonic compression direction. However, the first tectonic compressive direction (σ_1 in ENE-WSW direction) deduced also from two conjugate cross-cutting sets in the ac-section of bedding along the northeastern limb of the anticline. They enclose acute angle about c-axis, the sinistral set cutting across the dextral one (photo 3). The second tectonic compressive direction (σ_1 in NNW-SSE direction) is inferred also from two individual enechelon vein arrays occurring separately on (bc) sections of bedding at two locations on SW limb of the anticline. One of them is dextral set (photo 4), whereas the other is sinistral set (photo 5). The veins of the later set have sigmoidal shapes due to progressive shearing of the zone enclosing them.



Sketch 1



Sketch 2

A sinistral (sketch 1) and a dextral (sketch 2) brittle shear zones enclosing lenticular vein arrays at the NE limb of Azmur Anticline.

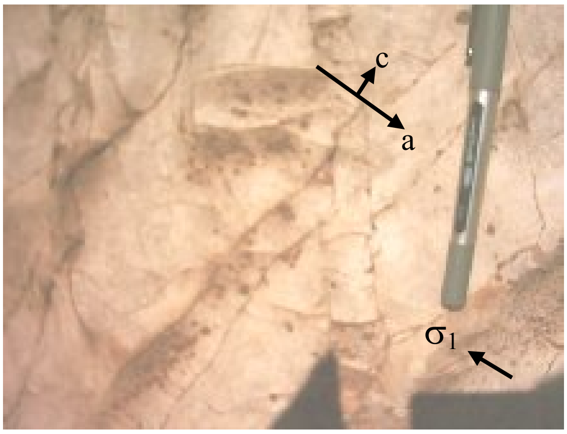


Photo 3: Two cross cutting shear zone inclosing vein arrays in (ac) section of kometan Fm. beds at the NE limb of Azmur Anticline.

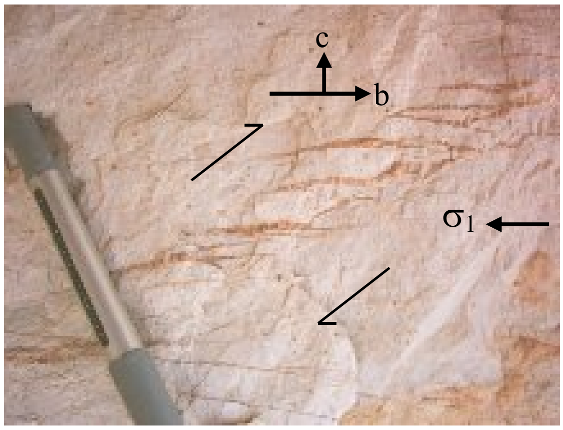


Photo 4: A dextral shear zone inclosing enechelon vein arrays in (bc) section of Kometan Fm. beds at the SW limb of Azmur Anticline.

3- Pressure – solution surfaces (stylolite seams):

Pressure solution surfaces (stylolite seams) are very irregular discontinuities with alternating peaks and hollows that correspond to each other on the two surfaces. Conical and cylindrical stylolites can be recognized by their appearance, the first is of tectonic origin, whereas the later thought to be of depositional (digenetic) origin. They develop mostly in calcareous but less common in sandstone. They might form in previously fractured or intact rocks, when compressed from opposite sides, so that they interpenetrate each other, as a result of dissolution of the rock matrix in the existence of solutions. The resulted discontinuity bears saw-like dentition, in which the peaks oriented parallel to the maximum principle stress orientation (Bles and Feuga, 1986; Suppe, 1985; Van der Pluijm and Marshak, 1997; Nicolas, 1987; Sinha-Roy, 2002 and Shadmon, 2008).

Stylolite peaks usually form perpendicular to their planes or seams (i.e. symmetrical stylolites). However, the peaks may also be oblique to their seams (i.e. asymmetrical stylolites) and hence they called slickolites (Nicolas, 1987).

Three categories of stylolite seams have been distinguished in the present study area. They are often associated with planner systematic vein arrays, or forming the border lines of the enechelon arrayed lenticular veins that alligned with the bedding strike (photo 2). Such association of both types of structures indicates dissolution of the rock constituent due to compressive stress and then precipitated in the open spaces as veins. Thus shortening of the rock body in a direction is complemented by its stretching at a nearly perpendicular direction (Suppe, 1985).

Photo (6) illustrates the conical type stylolite on the bedding surface within Kometan Fm. The two suborthogonal seams of stylolite, displayed on the northeastern limb of the anticline, are shown in photo (1). It is clear that the peaks of earlier set pointing along with dip direction (a) and terminated by a later set with peaks pointing in the strike direction of bedding. Both sets are associated with planner systematic vein arrays as mentioned earlier. Therefore, the earlier set is compatible with the first compressive tectonic direction (i.e. σ_1 in ENE-WSW direction). While the later set accords with the second compressive direction (i.e. σ_1 in NNW-SSE direction).

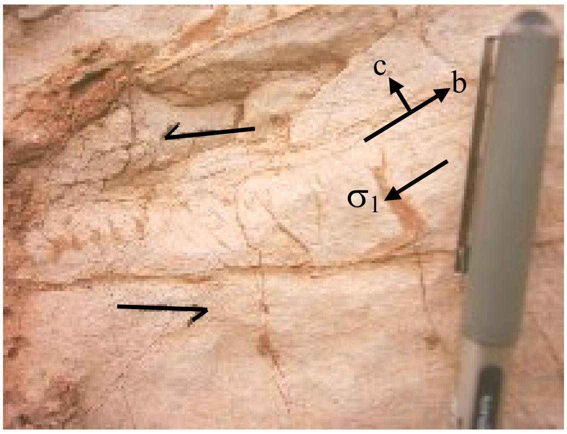


Photo 5: A sinistral shear zone inclosing enechelon vein array in (bc) section of Kometan Fm.beds at the SW limb of Azmur Anticline.

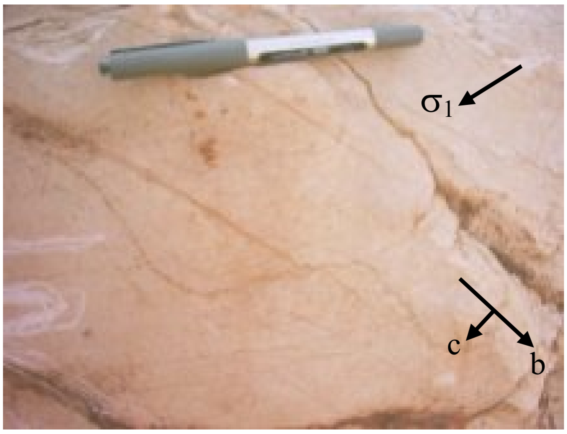


Photo 6: Conical type stylolite on bedding surface of Kometan Fm. at the NE limb of Azmur Anticline.

One of the stylolite seams attributed to the first compressive phase has been associated and displaced by a planar bedding parallel vein in Kometan Fm. at the northeastern limb of the anticline (photo 7).

The third set of stylolite seams observed along the bedding planes of Kometan Fm. at the northeastern limb of the fold. Their vertical peaks refer to the extension phase that accompanied with the final uplift of the folds (photo 8).

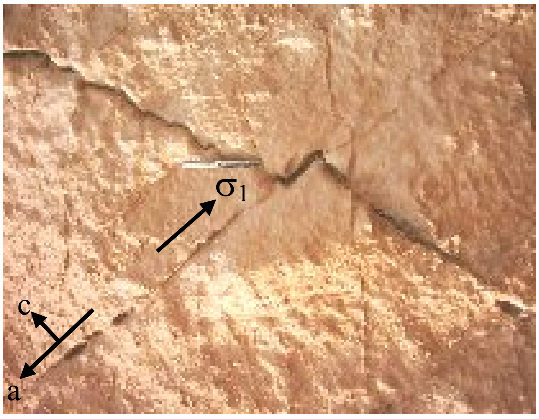


Photo 7: A seam of stylolite displaced by a bedding parallel planar vein in (ac) section of Kometan Fm. beds at the NE limb of Azmur Anticline.

Photo 8: Bedding parallel stylolite seam in the Kometan Fm. at the NE limb of Azmur Anticline.

4- Mesofaults

The striated mesofault assemblages gathered across the studied traverse at Azmur Anticline have different orientations with respect to the axis of their enclosing fold. Furthermore, their surface striations trending in various directions as well (Fig. 4). Accordingly, such an assemblage of mesofaults might be categorized kinematically into normal, reverse and strike slip displacements. Most of them associated with minor folds either as limb or hinge disturbing discontinuities on either limbs of such minor folds.

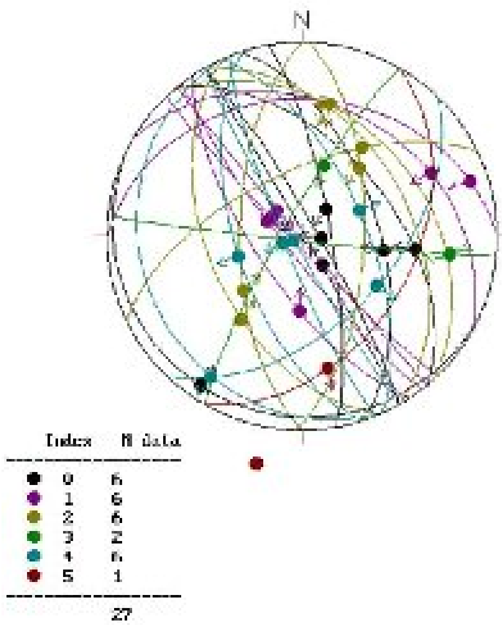


Fig. 4: Stereographic representation of mesofaults exposed at the both limbs of Azmur Anticline within studied traverse.

A series of synthetic and antithetic normal slip faults with limited displacements dissect thin-moderate beds of Kometan Fm. at the northeastern limb of Azmur Anticline (photo 9). These normal faults are striking generally subparallel to the anticline trend. Both groups of these faults either occupy or sub parallel the (hol) acute about (c) joints. Therefore, they might have been developed during the later layer parallel stretching episode directed ENE-WSW perpendicular to the trend of Azmur Anticline. Restriction of these normal mesofaults along the gentler relatively longer NE limb of this anticline is also documented in (Ramsay and Huber, 1987; Vander pluijm and Marshak, 1997). Such a stretching episode is due to the final uplift of folded strata in which the maximum principal stress axis (σ_1) is vertical. However, secondary extension along the fold was responsible for transverse normal slip mesofaults as a consequence for primary compressive folding stress regime.

A group of reverse slip mesofaults, subparallel in strike with the general trend of both major and minor folds, are disrupting either limbs or hinges of such folds. They occur as accommodating structures for space problem at the angular hinges of many minor folds as well as limb disturbing faults for others (photos 10, 11and 12). Therefore, the attitudes and orientations of slip vectors of such mesofaults accord with their position with such minor folds. Hence their inclinations vary from shallow to steep dip. Meanwhile, their striation pitches range from shallow to high angles. So they might be described as oblique slip faults in this respect. Some of these reverse slip mesofaults occupy and parallel with both (hol) acute about (a) and (c) joint systems in this area.

A preliminary kinematic interpretation of this group of reverse faults puts them in accord with a general ENE-WSW trending compressive phase responsible for folding as well. Further more, some minor strike slip faults, both dextral and sinistral, were observed along the investigated traverse. They follow or occupy either of (hko) acute about (a) and (b) joint systems as prexisting fractures for these faults. For instance, the trace of a sinistral one displayed on bedding surface (ab) of a limestone layer within Kometan Fm. at the northeastern limb of the anticline (photo 13). The mesofault itself is segmented into two pieces by a right bend or jog. The stepped or jogged (a rhomb shaped) zone of the fault is a releasing type, thus it filled with calcite crystals indicating stretch normal to the step segment of the fault. The rhomb shaped vein here termed “Lozenge” shape vein, and it resembles a small scale pull apart basin. The deduced σ_1 and σ_3 principal stress axes from this mesofault are conformable with local bedding strike and dip respectively.Therefore, this mesofault accords with the general second compressive NNW-SSE direction that acted sub parallel to the anticline trend.

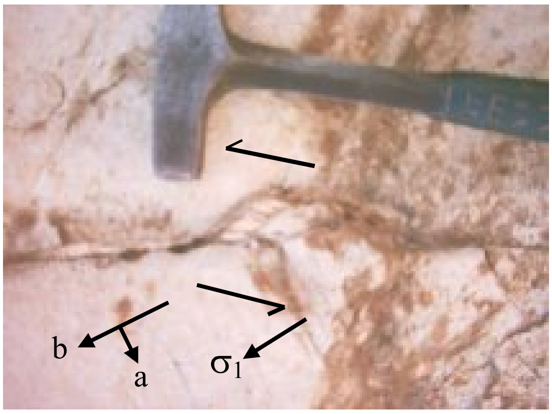
Photo 9: A series of step-like minor normal faults in the Kometan Fm. at the NE limb of Azmur Anticline.

Photo 10: A reverse fault disturbing the angular hinge of a minor fold at the NE limb of Azmur Anticline

Photo 11: A reverse slip mesofault in the Kometan Fm. at the SW limb of Azmur Anticline

Photo 12: A reverse slip mesofault in the Kometan Fm. at the NE limb of Azmur Anticline.

Photo 13: The trace of a Sinistral mesofault on bedding surface of Kometan Fm. at the NE limb of Azmur Anticline.



5- Fault-slip Analysis and Paleostress states

Using fault slip analysis to deduce paleostress states (orientations of principal stress axes and ratios) was the subject of interest of numerous workers throughout foregoing decades. Among them were (Mattauer, 1973; Angelier and Micheller, 1977; Angelier, 1979a; Petit et al., 1983; Bergerat, 1985; Angelier et al., 1995; Angelier, 1989; and Angelier, 1994).

Such an approach based on Bott's (1951) and Wallace's (1951) principle which states that slip on fault planes marked by striations are relicts of shear stress component of the tectonic stress regime responsible for movement on these faults. The inverse technique involves determination of maximum, intermediate and minimum principle stress orientations (σ_1, σ_2 and σ_3 respectively) from measurement of faults attitudes, pitches of their striations and their movement sense. This procedure can be performed by applying techniques cited by many authors. Among such techniques are the manual ones Arthaud, 1969; Etchecopar, 1984 and Powel, 1984). Furthermore, such principle stress orientations and ratios (R) can be resolved by applying automatic techniques (Etchecopar, 1984; Armijo et al., 1982; Angelier, 1990; Delvaux, 1993, 1997 and Delvaux and Sprener 2003). The stress ratios (R) [$R= (\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$] computed by these automatic methods, range in value between (0-1). (Delvaux,1997) combined the stress ratio values with the vertical attitudes of either principle stress axes to classify stress states accompanying frictional slip of various fault categories.

The collected fault slip data were analyzed automatically by applying Tensor software (Delvaux and Sperner, 2003) to decipher paleostress states acted in the investigated area, throughout its tectonic history. The first part of the software, named Dider program based on improved dihedra method of Angelier and Michler (1977), has sorted the assemblage data of mesofaults into five groups (sets). Each with specific reduced stress tensor parameters (i.e. three principal stress axes orientations σ_1, σ_2, σ_3, and their ratios R). The initial solution for each of sorted groups entered into the second part of the software, named Shear program. This part optimizes the initial solution for each set by applying the four dimensional dynamic rotational optimization, to establish the final stress state for each of such sets of mesofaults. The output tensor of each set consists of four parameters, the three principal stress orientations σ_1, σ_2 and σ_3, and their stress ratios (R). The program characterizes a tensor type for each resolved paleostress states according to Delvaux (1997) definition. That is beside the average deviation angle between the computed shear stress vector of the tensor and the actual slip lines on faults of the specified group. Each tensor also characterized by a quality rank index according to world stress map project.

The results of fault slip analysis in the study area postulated in the following states of paleostress (Table1):

1- ENE-WSW pure compressive state: represented by a subgroup of six reverse slip faults. It accords with the direct initial tectonic compressive phase responsible for early folding of Azmur Anticline (Fig.5). Three of this resolved subset classified as conjugate, thus they might be neoformed mesofaults induced by this tensor. Whereas the other three of the subset considered as activated, they might be preexisting joints that have been early formed by the same tensor. It is reasonable to realize this tensor as the horizontal component of oblique collision of Arabian plate against Eurasian plate. This state seems compatible with the kinematics of (hko) and (hol) acute about (a) shear joints. It is also responsible for development of stylolitic seams with peaks pointing normally to the general strike of bedding. Accordingly, the state seems conformable also with planar systematic veins transverse to bedding strike, as well as with the enechelon vein arrays enclosing acute bisectors transverse with bedding strike.
2- NE-SW pure compressive state: six reverse slip faults of the total assemblage attributed to this tensor (Fig. 6). It seems to be a subsequent for the former paleostress state, due to irregularities of the Arabian Plate boundary throughout its oblique collision with the Eurasian Plate. Three faults under this tensor considered as conjugate whereas the other three as activated. Thus the conjugate ones might had initiated as noeformed, whereas the others activated as preexisting fractures with respect to this tensor.
3- ENE-WSW strike slip compressive state: It is a substantial state of the first one in respect both has similar orientation of inclined maximum principal stress (Fig. 7). It consists of four conjugated and two activated mesofaults. This means that this state has setup four neoformed and activated two preexisting fractures by frictional sliding.
4- NW-SE pure strike slip state: it comprises only two activated mesofaults, their configurations seem that they were (hko) acute about (a) preexisting fractures that have been activated as strike slip movement under the present stress state (Fig. 8). This state is nearly compatible with the kinematics of (hko) acute about (b) joints and with stylolites with peaks pointing toward the general strike of bedding. It also conformable with planner systematic veins parallel with the bedding strike, and with the enechelon vein arrays with their long axes parallel to the bedding strike.

Table 1: Summarizes the parameters of paleostress tensors obtained from fault-slip analysis in the studied area.

al of lts	**Conjucated**	**Activated**	**Unactivated**	**Principle stress**			**Stress ratios**		**Average deviation angle α**	**Quality rank QRW**	**F N**
				σ_1	**σ_2**	**σ_3**	**$R=(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$**	**Stress types**			
	3	3	0	25/062	16/324	60/205	0.5	Pure compression	7.4	D	5
	3	3	0	01/221	01/311	89/086	0.48	Pure compression	14.35	D	6
	4	2	0	32/240	04/333	58/069	0.17	Strike-slip compression	10.13	D	7
	0	2	0	18/322	60/198	23/060	0.5	Pure strike-slip	23.9	E	8
	4	1	1	86/018	03/140	03/231	0.05	Radial extension	1.7	D	9

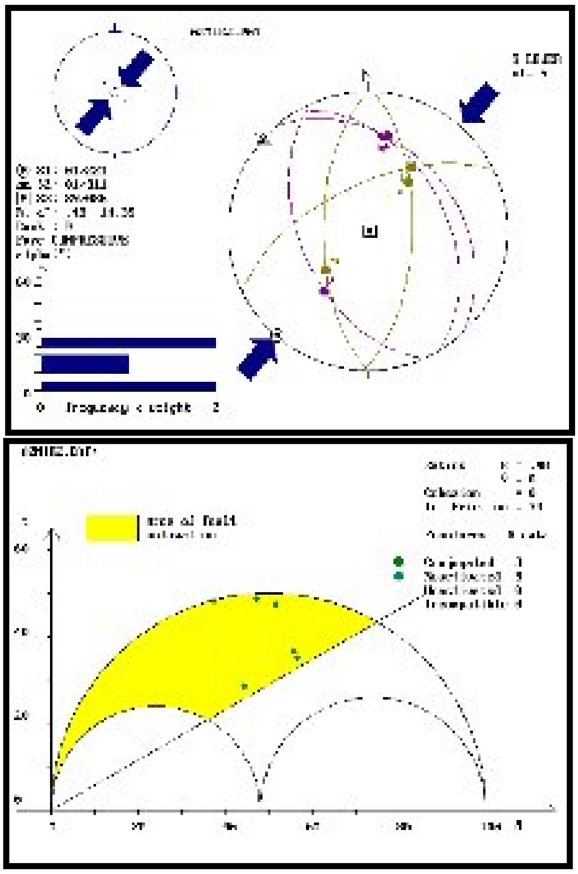


Fig. 5: Stereogram and Mohr diagram of ENE-WSW pure compressive paleostress state.

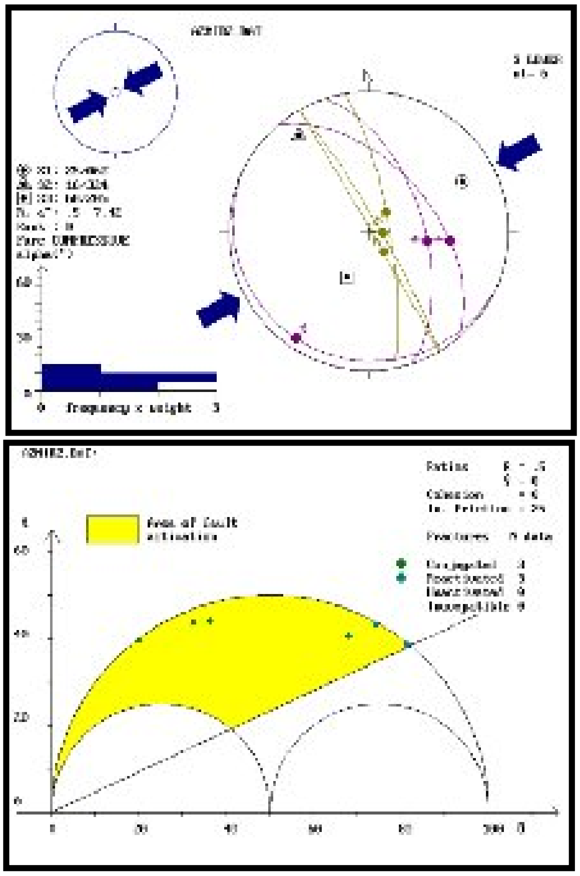


Fig. 6: Stereogram and Mohr diagram of NE-SW pure compressive paleostress state.

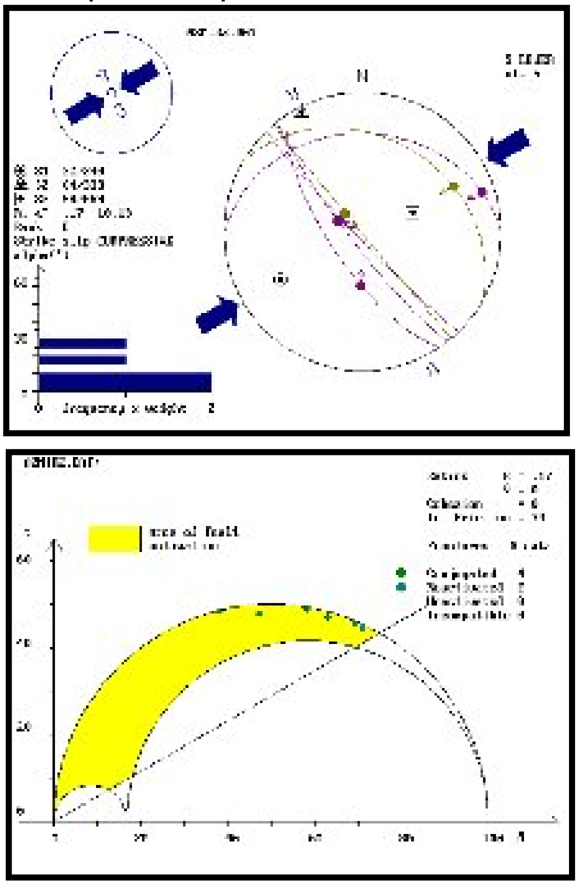


Fig. 7: Stereogram and Mohr diagram of ENE-WSW strike-slip compressive paleostress state.

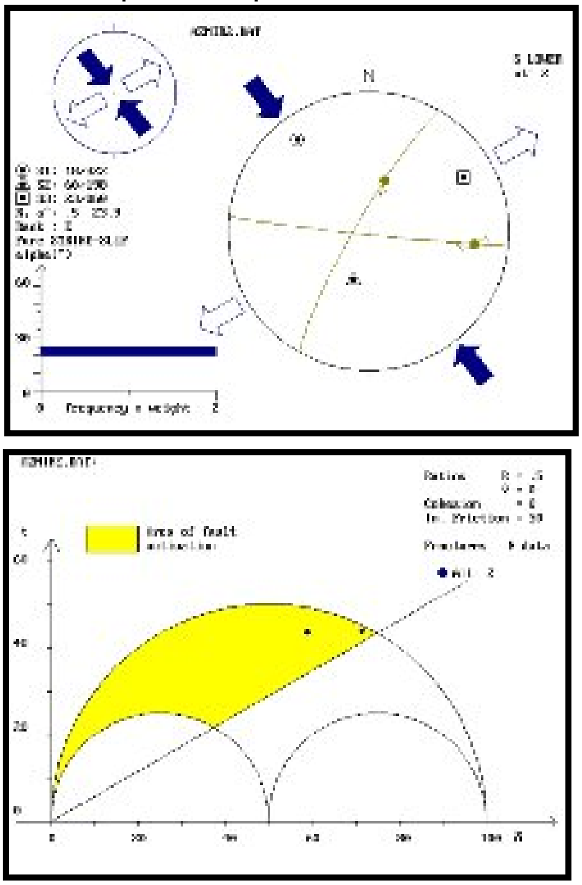


Fig. 8: Stereogram and Mohr diagram of NW-SE pure strike-slip paleostress state.

5- NE-SW radial extension state: it comprises four conjugated, one activated and one inactivated mesofaults (Fig. 9). The trend of later is transverse to others, hence it caused a radial character for this state. The transverse mesofault is due to extension parallel with fold axis that accompanied folding. The remaining subset represents layer parallel extension episode normal to fold axis which is typical to the final stage of folding that implies uplifting. It is compatible with bedding parallel stylolite seams having vertical pointing peaks.

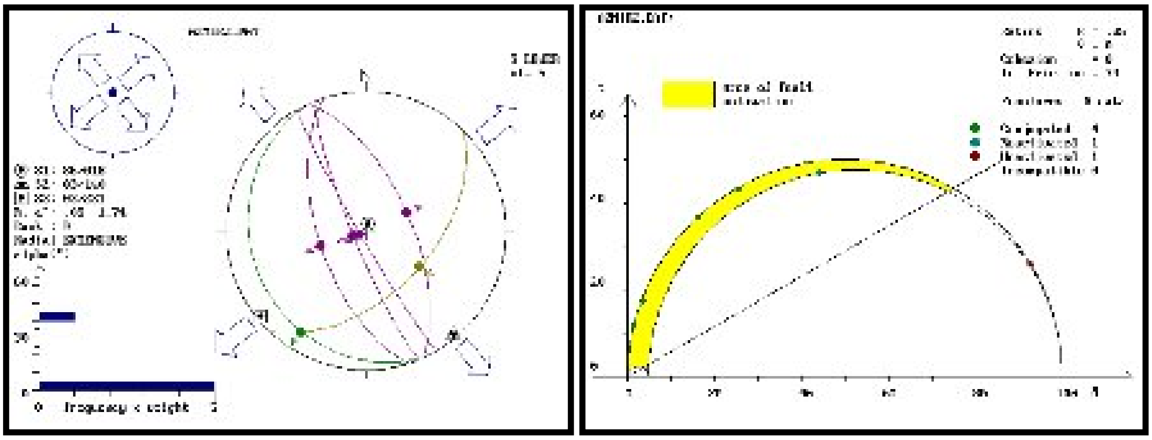


Fig. 9: Stereogram and Mohr-diagram of NE-SW radial extensive paleostress state.

DISCUSSION

The present investigation revealed two subsequent phases of deformation that have been architechared Azmur major fold. The first one directed ENE-WSW, which is tangential with bedding, is considered as the horizontal component of oblique collision of Arabian Plate against Eurasian. Folding of Azmur Anticline is ought to this compressive phase. The same phase also attributed for development of a spectrum of brittle failure structures in the competent units of the main anticline. Among these brittle structures are: widespread (ac) tension, (hko) and (hol) acute about (a) shear fractures, systematic planner veins transverse to fold trend, brittle shear zones enclosing enechelon lenticular vein arrays with their long axes trending transversely to the anticline axis, stylolite seams with peaks pointing across the trend of fold, and mesoscopic reverse slip and strike slip faults with their resolved maximum principle stress axis (σ_1) trending ENE-WSW direction.

However, this primary compressive phase consists of two substantially stress tensors as revealed by fault slip analysis (Table 1and Figs. 5,7). Both of them with inclined (σ_1) refering to development of these faults during folding, that implies the rotation of strata. Furthermore, another substantial stress tensor (NE-SW) within this primary compressive phase is deduced by analysis of a set of reverse slip faults (Table 1; Fig. 6). The (σ_1) attitude of this tensor is almost horizontal, meaning that this tensor had been started a bit after the initiation of folding.

The second compressive phase directed generally NW-SE led to initiation of (hko) acute about (b) shear fractures and reactivation of early formed (hko) shear fractures into dextral and sinistral strike slip mesofualts. The same compressive phase has also added planar systematic veins parallel with bedding strike, as well as stylolite seams with peaks along strike direction of bedding, and lenticular enechelon veins arranged as brittle shear zones enclosing acute angle about bedding strike.

This second compressive phase followed by a stretching episode directed subnormal to the axial trend of Azmur Anticline. This extension episode expressed in normal slip mesofualts trending parallel with the trend of the fold. It is also manifested in bedding parallel stylolite seams with their peaks pointing vertically upward. This stretching episode is due to the final uplift of the folds in the area.

The postulated two compressive tectonic phases in the present investigation via brittle failure structures analysis are the consequences of Alpine Orogeny. Such Orogeny accomplished by convergence of the irregular front of the Arabian Plate against Eurasian Plate since Cretaceous, then by their collision in Middle Eocene, and achieved its paroxysmal stage in Pliocene (Numan, 1997; 2000, 2001a and b; Sharland *et al.,* 2001; Jassim and Goff, 2006).

The varied orientations of compressive stress field (i.e. ENE-WSW, NE-SW and NW-SE) deduced in present work might be attributed to the oblique collision between the Arabian and Eurasian Plates with their frontal irregularities as well (Numan, 2000; Aswad, 1999).

However, three sequential compressive tectonic phases in a closely adjacent to the present investigation area were distinguished previously through superimposed folding together with the accompanying reverse and strike slip faults study (Al-Fadhli *et al.*, 1979, 1980). First and second phases of such a study were coaxial and operating in NE-SW direction, whereas the third phase operated normally to earlier ones. They (op.cit.) have referred their first two coaxial tectonic phases to the stress field resulted directly by continental collision between Arabian and Eurasian plates. While they have attributed their third phase to the reorientation of the first stress field in the region due to counter clockwise rotation of the Arabian plate with respect to the Eurasian plate.

Taha *et al.,* (1995) recognized also three tectonic phases by analyzing microtectonic elements at Dokan area. They considered the first two as successive compressive phases in NNE-SSW and EW directions respectively. However, they regarded the third phase as an extensional and in NW-SW direction. (Taha,1995) in another investigation has emphasized two tectonic phases, a compressive phase in NE-SW direction and an extensional phase at a transverse direction to the first.

The first tectonic compressive phase deciphered here is nearly compatible with the two succeeding coaxial compressive phases of (Al-Fadhli *et al.*, 1979, 1980) and with the first compressive phase of (Taha *et al.,* 1995 and Taha, 1995).

Meanwhile the second tectonic compressive phase of the present study accords with the third compressive phase of (Al-Fadhli *et al.,* 1979, 1980), and nearly with the second compressive phase of (Taha *et al.,* 1995). However, the extensional phase deduced here seams compatible with extensional phase concluded by the later authors at Dokan area and by (Taha, 1995) at Safin anticline of high folded zone, NE Iraq. The little discripancies in (σ_1) attitudes between this study and the other investigations mentioned above might be attributed to the folds' trend variations between the respectve areas of study.

(Numan and Al-Jumaily, 2007) deduced the same two tectonic compressive phases as a result of their paleostess analysis in the foreland fold belt in northern Iraq.

It is worth to mention here that Numan (2001a), who introduced two main phases of Alpine orogeny in northern Iraq at Cretaceous and Tertiary ends, separated by a regional and angular unconformity within the folded zone of northern Iraq. But the two tectonic compressive phases postulated here seem to be alternatively active throughout the progressive deformation from the end of Cretaceous to the end of Tertiary.

CONCLUSION

Mesoscopic fracture analysis at Azmur Anticline, NE Iraq revealed the following conclusions:

1- A widespread spectrum of brittle failure structures were distinguished throughout the studied traverse in Azmur Anticline. Joints represent the commonest among them, two orthogonal tension sets (ac and bc), as well as five shear systems were recognized. They are (hko) acute about (a) and (b), (hol) acute about (a) and (c), and (okl) acute about (c). Two stress regimes were derived from distribution of these sets and systems, which were compatible with those interpreted from other structures. One of these regimes lies normal, whereas the second parallel with the trend of major anticline.

2- Analysis of other brittle failure structures, known as kinematic indicators such as vein arrays, stylolite seams and striated mesofaults, revealed the prevalence of the same sub orthogonal compressive stress regimes throughout the study area. Two orthogonal sets of systematic planner vein arrays are associated with two orthogonal sets of stylolite seams. The same orthogonal stylolite seams also associated with the individual or conjugated sets of brittle shear zones enclosing enechelon arrays of lenticular veins.

3- Assemblage of striated mesofaults in the study area divided into normal, reverse and strike slip categories. Both synthetic and antithetic normal faults trending parallel to the axial trend of the fold were registered on the northeastern limb of Azmur Anticline. These normal faults reflect layer parallel stretching normal to the fold trend. Such a stretching episode is the result of final uplifting of the folds. This episode is compatible with vertical peakes of layer parallel stylolite seams. Reverse slip mesofaults are associated either with the angular hinges of minor folds or disrupting their limbs. Both dextral and sinistral strike slip mesofaults are conspicuous in the study area. The reverse slip and strike slip mesofaults are either neoformed with respect to a specific compressive stress state or as reactivation of preexisting fractures of an earlier compressive stress regime.

4- Paleostress analysis of striated fault slip data of study area revealed five paleostress states. Three of them which attributed to reverse slip faults, are compressive with their maximum principal stress axes trending in NE-SW and ENE-WSW directions. The later one is compatible with (hko and hol) shear fractures acute about (a). The fourth one is pure strike slip state with maximum principal stress axis (σ1) subparallel with the major Azmur fold trend. This state is compatible with (hko) shear fractures acute about (b). The fifth paleostress state is an extensional one, with its least principal stress axis (σ3) being horizontal and normal to the major fold trend. This state is compatible with the vertically pointing peaks of layer parallel stylolite seams, and resulted from final uplifting of folds.

5- The first four compressive and strike slip paleostress states could be reassembled, in analog with the trends of existing kinematic indicators (stylolite sets and enechelon vein arrays), into two subsequent tectonic compressive phases. The first being normal to Azmur fold trend, whereas the other is along the trend of this fold. One of these two orthogonal tectonic compressive phases which is normal to the fold trend represents the perpendicular horizontal copmponent of oblique collision between Arabia and Eurasia Plates. The other one represents the horizontal parallel component with respect to the boundary of such an oblique collision.

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