Determination of stress directions using section and surface criteria in fibrous gypsum veins samples North Muqdadia (Al-Sidoor)/ East Iraq

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Abstract

Many fibrous gypsum veins have been studied in Al-Sidoor area North Muqdadia city, East Iraq; the study used surface and section criteria for estimating the stress phases directions that the study area have been undergone. These veins grow in Injana Formation (Upper Miocene) which is conspicuous in the axial region of Southern Hemrin anticline; cropping out within horizontal beds of Sandstone, Marl and Siltstone. The study area effected by many tectonic events after the deposition of Injana and Muqdadia Formations in Late Miocene (8 Millions year. These tectonic events have recognized from the study of gypsum fibrous veins. Three types of veins measurement have achieved; the first one attains a general study on veins attitude; the second one studies plunge and azimuth of the fibers in the vein after the measuring of the attitude of the veins in the bed; and the third type studies of slip movement on vein surfaces. The first type gave one extension direction perpendicular to the veins planes, this extension plunges toward the Southwest. The second type indicates that the study area passed firstly by an extensive stage. The minimum stress axis ($\sigma3$) is plunged by an angle about 30º toward the Southwest. This stage followed by another extensive stage related to normal fault system, its minimum stress axis ($\sigma3$) is oriented Northwest-Southeast. After that the maximum principal stress axis ($\sigma1$) has been rotated from the vertical to the horizontal, then it suffered clock wise rotation from the direction Northwest-Southeast to North-South, then to Northeast-Southwest and finally to East-West. Win Tensor Method of Delvaux has examined the third type of measurement, on the paleostress reconstruction. Three stages have recognized; the older one is extensive stage. The plunge and azimuth of ($\sigma1$) are at 65/098; ($\sigma2$) at 24/295; and ($\sigma3$) at 06/202, the value of R is 0.67. The intermediate stage is compressive and $\sigma1$ at 12/001, $\sigma2$ at 05/092 and $\sigma3$ at 77/204, the value of R is 0.43, and the ounger stage is compressive and $\sigma1$ at 04/078, $\sigma2$ at 40/345 and $\sigma3$ at 50/173, the value of R is 0.45.

1. Introduction

Determination of extension directions is one of important subjects in structural geology. Vein's opening uses to determine the extension direction that affects any region. When the veins are fibrous and the opening is perpendicular to vein walls, the fibres grow perpendicular to vein walls, and the extension is pure dilation. When the opening direction is gradually changes from perpendicular to vein walls to oblique, the fibres become curved either in vein walls (antitaxial) or in vein centre (syntaxial) [1; 2]. These curved fibres give the progressive varying in the direction of the minimum principal stress $\sigma 3$ [2; 3; 4; 5]. Fibrous veins can record opening trajectories of veins in detail and reflect the different stages of displacement affected any region. The formation of fibrous veins in general is usually attributed to the crack seal mechanism of Ramsay (1980) [6]. Syntaxial veins have one single growth plane with a consistent position within the vein. Antitaxial veins have two simultaneous growth planes, located on the outer surfaces of the vein [7]. This definition avoids any ambiguity [8]. Antitaxial veins are normally very fibrous and the fibres are often curved and tend to accurately follow the opening trajectory [8]. They are common formed by calcite in dark shale [3; 9; 10; 11], but can also be composed of other minerals, such as quartz or gypsum [8].The fibrous veins bear some information on the stress stage from which they are derived. The events that affected our study area have been proved by three methods; the general method which depends on the strike and dip of veins; fibers curvature which depends on the measurement of the progressive varying of the plunging and azimuth of the fibres; and the slip data which depends on the orientation of the slip line and the shear sense on the vein plane.

Stress inversion procedures rely on Bott's (1959) [12] assumption that slip on a plane occurs in the direction of maximum resolved shear stress. Inversely, the stress state that produced the brittle microstructures can be partly reconstructed knowing the direction and sense of slip on variable oriented fault planes [13; 14; 15]. The fault planes in our study represented by the vein surfaces, the slip direction on the vein surface is inferred also from frictional grooves or slickenlines. The data used for the inversion are the strike and the dip of the vein plane, the orientation of the slip line and the shear sense on the vein surface. The inversion of fault-slip data gives the four parameters of the reduced stress tensor: the principal stress axes $\sigma 1$ (maximum compression), $\sigma 2$ (intermediate compression), $\sigma 3$ (minimum compression) and the Stress Ratio R= (σ2- σ3)/ (σ1- σ3) [16; 17; 18]. The index R' ranges from 0.0 to 3.0 and defines the stress regime completely and is a convenient for computing the mean regional stress regime from a series of individual stress tensors in a given area [19].

Vein surfaces could be containing several generations of striations indicating that more than one movement, which occurred after the pure dilation (the first step of opening), has affected the vein. We enquire the cross cutting relationship between them and compare that with the section and surface criteria proved by Petit, 1987[20] in fault plane and by Taha, 2010[21] in the sections and surfaces of the vein. Then we can establish the relative chronology of the paleostress stages affected a given area.

The attitudes of gypsum veins were recorded with three digits for strike direction and two digits for the amount of dip, which is clockwise to the strike e.g. 265/45˚. The exposed faces of the vein fronts were labeled in the field. The vein samples were then taken to the office for detailed examination.

2. Aim of the study

1) determine the extension directions from the fibres orientation in fibrous gypsum veins in the study area.

2) determine the stress phases using Win Tensor Method for the fault-slip data on vein surfaces as a fault plane.

3) examine the striations cross cutting for determining the relative chronology of the paleostress stages.

4) applying surfaces and sections criteria on samples of fibrous gypsum veins for determining the sense of displacement.

3. Geological setting

The study area is located about 125 km northeast of Baghdad in the core of the NW-SE trending Southern Hemrin Anticline in eastern Iraq (Fig. 1A). The dip of the northeastern limb of the Southern Hemrin Anticline is about 20˚ and the southwestern limb dips at about 60˚ (Fig. 1B).

This anticline is part of Makhul-Hemrin Subzone, which characterizes by long (over 100 km) prominent NW-SE trending anticlines. According to [22], these anticlines have been affected by decollement thrust faults during Alpine orogeny parallel to their axes that originate at detachment surfaces at the base of the saliferous beds of the Fatha Formation (Middle Miocene). Deformation along Zagros-Taurus folded belt is inhomogeneous due to the changes in the geometry of the edge of the Arabian plate along the collision zone with the Iranian and Turkish plates and due to the rotational movement within the Arabian plate itself [23].

The oldest formation exposed at the study area is the Upper Miocene detrital sediment of Injana Formation, which is about 600m thick and is composed of interbedded thin sandstone, marl and siltstone with fine grains in its lower part that gradually become coarser in its upper part, the sandstone layers are characterized by cross bedding structures [24; 25; 26]. Injana Formation is underlying by Fatha Formation, which is not out croup in the study area.

Overlying the Upper Miocene (Injana Formation) is the Muqdadia Formation of Late Miocene age [27]. The beds of the Muqdadia Formation are fining upward cycles of gravely sandstone, sandstone and red mudstone [22]. The size of the pebbles increase upwards, the thickness of the formation is about (1200-1300) m [28; 29]. Muqdadia Formation is overlain by the Bai-Hassan Formation of Upper Pliocene age. It crops out in the northeastern limb of the Southern Hemrin Anticline and is eroded from its southwestern limb. This formation is composed of conglomerates consisting of sub-rounded pebbles, cobbles, and boulders of quartz and limestone surrounded by a fine grained matrix of sandstone and limestone. The Bai-Hassan Formation covered by fine grain detrital sediments of Quaternary age [22].

According to Jassim and Goff, 2006[22], major thrusting occurred in Late Miocene-Pliocene time during collision of the Neo-Tethyan terrains and the Sanandaj-Sirjan Zone with the Arabian Plate. This event causes the uplift of the High Folded Zones. Southern Hemrin Anticline is one of the major structures occurred during or after the Late Miocene-Pliocene.

4. Fibrous gypsum veins features

Fibrous gypsum veins constitute the most prominent deformation feature in the core of the Southern Hemrin Anticline (Injana Formation). These veins are articulate in the axial region of the anticline, cropping out within horizontal beds of Sandstone, Marl and Siltstone. The veins are mostly oriented Northwest-Southeast and inclined about (60°) toward the NE, some of them are horizontal and they are rarely vertical (Fig. 2).

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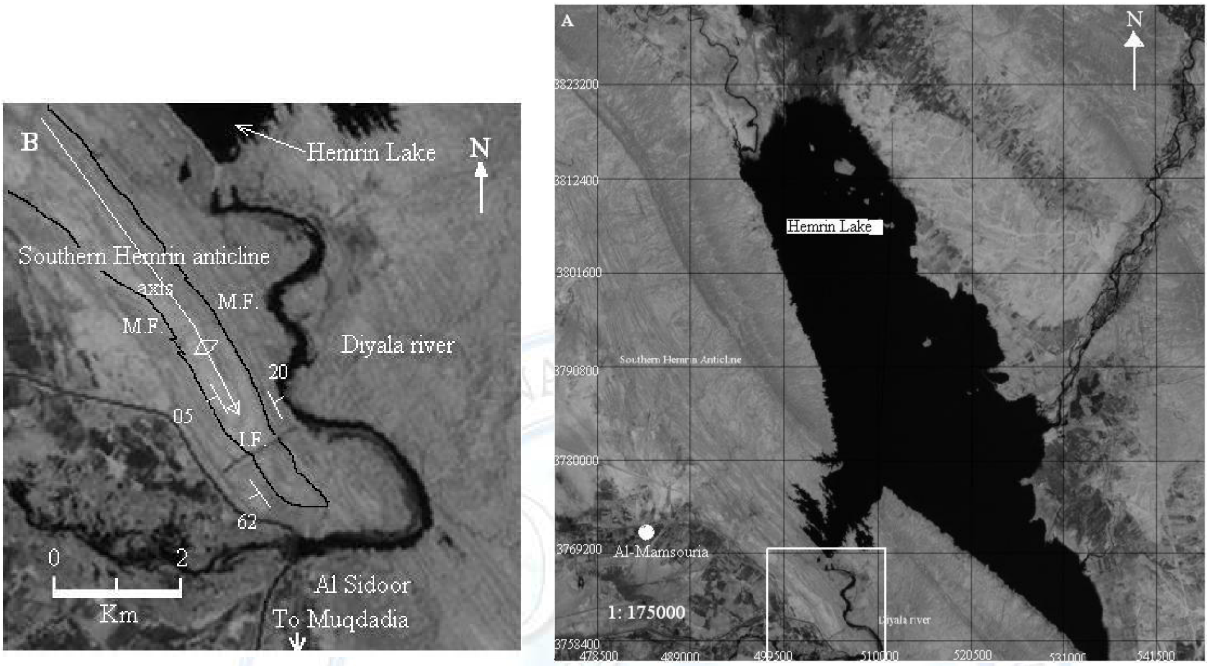


Fig.1.(A) Land Sat image 7 ETM 2002 , of the zone of Hemrin Lake, North Muqdadia city represents part of the eastern border of Southern Hemrin Anticline.(B) Enlargement of rectangle in (A), Showing the study area which occurs in the plunging zone of Southern Hemrin Anticline, I.F. and M.F. represent Injana and Muqdadia Formations respectively.

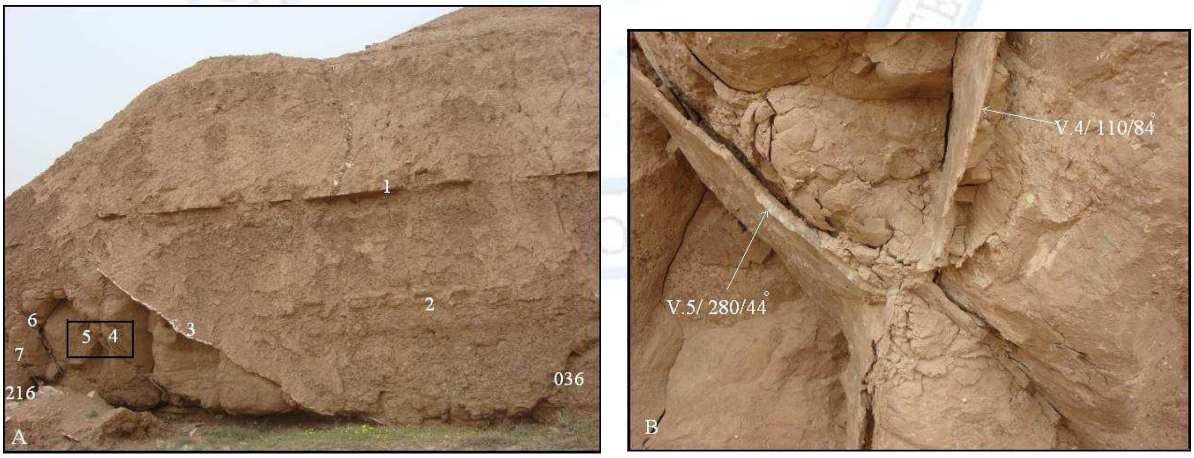


Fig.2. (A) Shows NE-SW section in subhorizontal beds of siltstone belong to Injana Formation (Upper Miocene age), contains seven fibrous gypsum veins (the maximum height of the section is about 11 metres). (B) Shows enlargement of two conjugate veins(4 and 5) in (A) affected by two stages of displacements; the first is an extensive stage, σ3 is North-South and the second is compressive, σ1 is East-West related to sinistral displacement (the height of the right rectangle is about 2 metres).

The veins range in length from several centimetres to some hundreds metres and in thickness from less than 2 millimetres to more than five centimetres. Some veins have constant thickness; others have thick middle section and thin tip. Many veins have changeable inclination angles related to their origin so that these veins may have developed from conjugate shear fractures. Fibrous appearance and milky white colour refer to satinspar gypsum. Curved fibres at the vein walls characterize the most of the veins in the study area and perpendicular to the vein suture line (parting), the vein fibres and the wall rock have different mineralogy, so their type is antitaxial [1]. The parting in most of the antitaxial veins is not at the center and generally lined by small grains of wall rock material. According to [8] the syntaxial veins are also existing but with less proportion. These veins have one single growth plane occurs within the vein. Other types of vein growth described by Durney and Ramsay (1973)[1] (i.e. composite and stretched)are rarely exist in the study area.

5. Veins measurements

The veins measurements have been achieved in the core of Southern Hemrin anticline, which formed of horizontal beds of Injana Formation. More than 56 fibrous gypsum veins have been measured in the study area, part of them (22 veins) have been effectuated a common measurement in the field like the strike and dip only without measuring the attitudes of the fibres in them. The others (34)veins have been effectuated a detail office study as a samples; by measuring, the fibres orientations; the striations orientations that occur on vein surfaces as a fault plane; determining the striations cross-cutting relationships; and determining the sense of displacement. Most of the 56 veins have the orientation NW-SE with mean inclination angle is about 60º to Northeast (Fig.3).

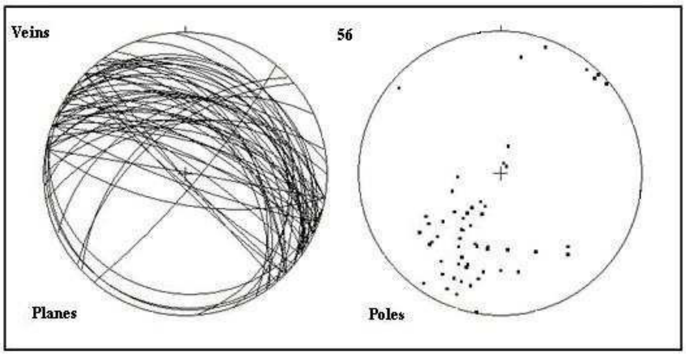


Fig.3. Equal area on lower hemisphere projection of 56 gypsum veins planes and poles.

The mean strike of the 22 veins is about 130-140, and the mean dip angle is 70-80º toward the northeast (Fig. 4). From the 22 veins, we can estimate roughly the direction of extension happened in the study area as we consider that the opening of them was perpendicular to veins planes, so it is NE-SW. The lacking of information of detail measurement in these veins causes the difficulty of exactly determining of the directions of extensions. Two methods used to represent the data obtained from the detail measurements of 34 vein's samples:

The first method depends on the projection of the plunge and azimuth of the fibres in vein samples as poles (Fig. 5). The number of vein samples was 29, part of them(13) have straight fibres with only one orientation, the others (16) have curved fibres with multiple orientations, so the total fibres orientations became 47 .The fibre orientation indicates the direction of the minimum principal stress σ3 (extension direction) [1].

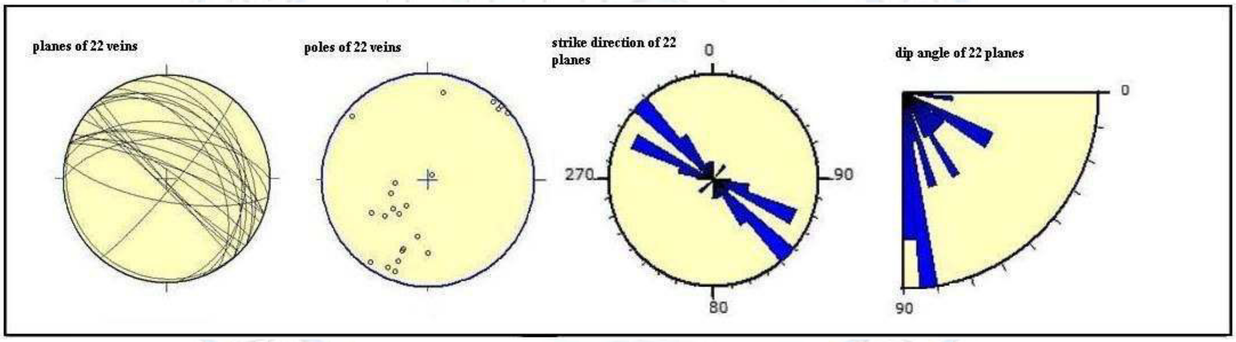


Fig.4. Shows equal area on lower hemisphere of the 22 veins, planes, poles, and rose diagram of strike direction and dip angle (explanation in the text).

The projection of the fibres poles in the study area shows three different zones, the first zone covers big number of the poles and indicates that the extension is plunged toward the SW; the second zone indicates that the extension is plunged toward the NE, and the third zone indicates that the extension is toward the NW. The opening of most of the veins started firstly perpendicular to vein plane and then it became oblique, so the fibres in most of the veins grew firstly perpendicular to vein walls and then they curved when they have affected by a second stage of opening. Therefore, the poles that plunge toward the southwest are probably represents the first stage of opening which is perpendicular to veins planes. The chronology of the others stages of opening are not easy to recognizing.

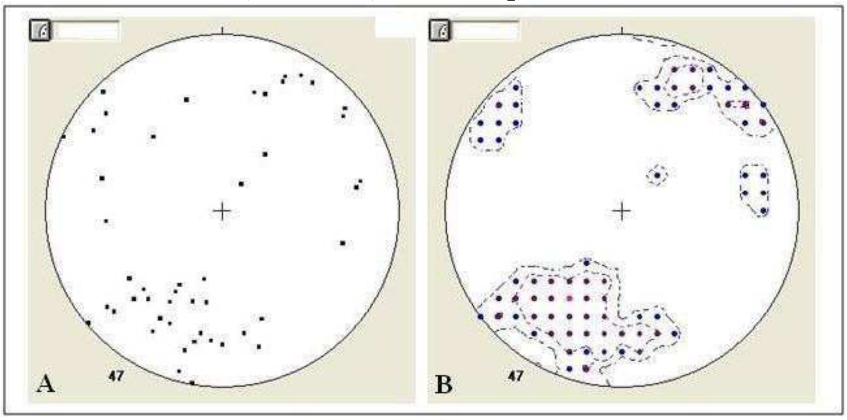


Fig.5. Equal area projection on lower hemisphere (A)shows fibres poles projection, (B) contours density of poles shows three zones, the first as a big one is plunged toward the SW, the second is plunged toward the NE, and the third is plunged toward the NW.

The second method depends on the paleostress reconstruction obtained from fault-slip data effectuated on vein's surfaces such as the orientation of the slip line and the shear sense, in addition to the dip angle and the dip direction of the vein. The total numbers of the well-striated vein samples with certain sense are 21. The vein samples that contain several generations of striations are 13.

Three phases or stages of stress have been diagnosed by using Win Tensor method [13], the first is characterized by extensive regime (Fig.6.a). The mean orientations (plunge and azimuth) of the principal stress axes are $\sigma 1$ at 65/098, $\sigma 2$ at 24/295 and $\sigma 3$ at 06/202.The values of R and R' are 0.67, 0.67 respectively that means the magnitude of $\sigma 2$ approaches to $\sigma 1$ and the magnitude of $\sigma 3$ is very small in comparison with others. The tensor of this stage indicates pure extensional regime.

The second phase is compressive (Fig.6.b) with mean orientations of principal stress axes are $\sigma 1$ at 12/001, $\sigma 2$ at 05/092 and $\sigma 3$ at 77/204. The values of R and R' are 0.43 and 2.43 respectively, that means the magnitude of $\sigma 2$ was in the midst between $\sigma 1$and $\sigma 3$. The tensor of this stage indicates pure compression regime related to strike slip and reverse faults.

The third phase is also compressive (Fig.6.c) with mean orientations of principal stress axes are $\sigma 1$ at 04/078, $\sigma 2$ at 40/345 and $\sigma 3$ at 50/173. The value of R and R' are 0.45 and 2.45, that means the magnitude of $\sigma 2$ was in the midst between $\sigma 1$and $\sigma 3$. The tensor of this stage indicates pure compression regime related to strike slip and reverse faults; the most of them are strike slip faults.

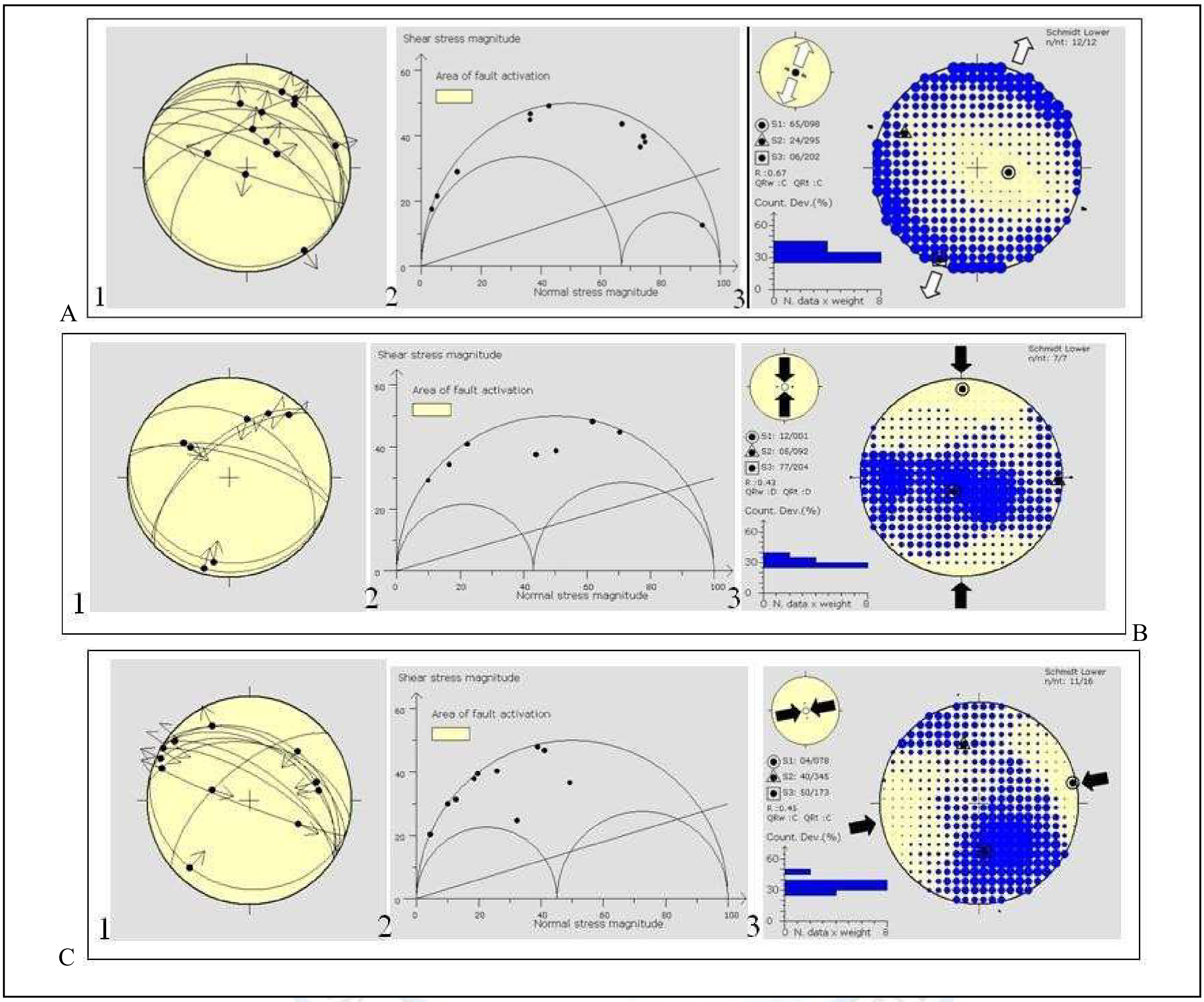


Fig.6. Win Tensor program shows three phases. A. Extensive phase with σ1is roughly vertical and σ3 horizontal has Northeast-Southwest orientation. B. Compressive phase with σ1is roughly horizontal North- South and σ3 roughly vertical has Northeast-Southwest orientation. C. compressive phase with σ1 horizontal oriented 078 and σ3 steeply inclined.1, is the veins planes projection, small arrow indicates the type of slip on vein's plane; 2 is Mohr circle, the dote indicates the position of the slip plane on Mohr circle; 3, shows the stress inversion method.

5. Surface and section criteria in vein samples.

Four samples have been chosen and detailed examination was carried out to identify the vein surface and vein section criteria. The integrated interpretation from the two types of criteria contributes towards characterization of the development history of the veins and determines the relative chronology of the formation stages.

5.1. Sample No: 1, Horizontal vein has a thickness of about 2.5cm; it consists of two parts which are separated clearly by a central line with subhorizontal fibres. In the middle of each part, the fibres are crystallized obliquely relative to vein walls by an angle about 60˚ toward the north. These fibres are curved at the walls and at the centre of the vein by an angle about 05˚ toward the north (Fig. 7). On the vein surfaces there are two types of striations, the first type are long and straight while the second type are short and toothy (Fig. 8). The second type of striation appears more clearly than the first.

From this example, we can imagine that the vein has undergone two opening stages the first gave the oblique fibres (60˚) to the vein's wall accompanied with the first striation and the second stage gave the subhorizontal fibres (05˚) associated with the teeth structure. The tectonic history of the vein indicates that the vein has undergone firstly an opening stage producing oblique fibres, which related to more dilation than shear displacement ($\sigma 1$ makes an angle equal to 30˚ with the horizontal and $\sigma 3$ parallels to the oblique fibres, which make an angle equal to 60˚). In the second stage the subhorizontal fibres formed which, indicates that the vein cannot extend vertically, so the vein has been used the vein walls and the vein centre as detachment surfaces for extending horizontally in the N-S direction producing subhorizontal fibres in vein centre and in vein walls.

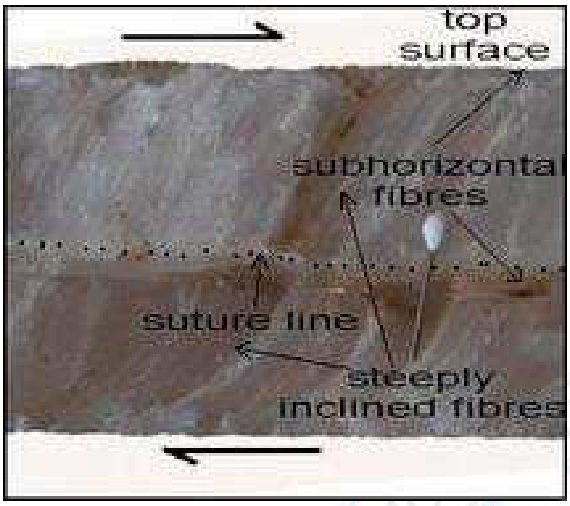


Fig. 7. Vertical section in horizontal vein sample No 1 shows the two parts of the vein divided by the suture line, the fibres in the middle of each part have high inclination angle with respect to vein walls (60˚) and in the vein walls and vein centre the fibers become subhorizontal (05˚), (pin length is 1cm).

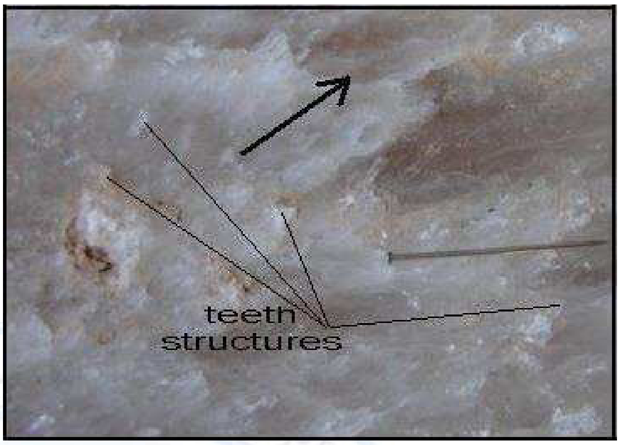


Fig. 8. Teeth structures appears on the top surface of sample No. 1 which, produced by the intersection of subhorizontal fibres (about 05˚) with vein surface, arrow indicates the sense of displacement of the top surface (pin length is 2.45 cm).

5.2. Sample No: 2, Oblique fibrous vein, its attitude is (265⁄45˚) and thickness is (1.8- 3.3) cm (Fig. 9). Two parts of fibrous crystallization are separated by suture line, which is not centrally located, this line is different from the fibrous crystallization by its brown to dark colour because of including of silt or mud material coming from the wall rock, and these two parts appear asymmetric in vein section (Fig. 10).

In the upper part of the vein section, (Fig. 10) straight and thin fibres with approximated thickness (0.5- 1) cm can be observed, this part contains a number of secondary wall-parallel fractures. Their fibres appear curved at the contact with the wall-parallel fractures and at the upper vein wall. In the lower part the fibres are started in growth vertically to the suture line then they become curved at about (7) mm from the lower vein wall, the thickness of the lower part is (1-2.3) cm, and dose not contain any secondary fracture.

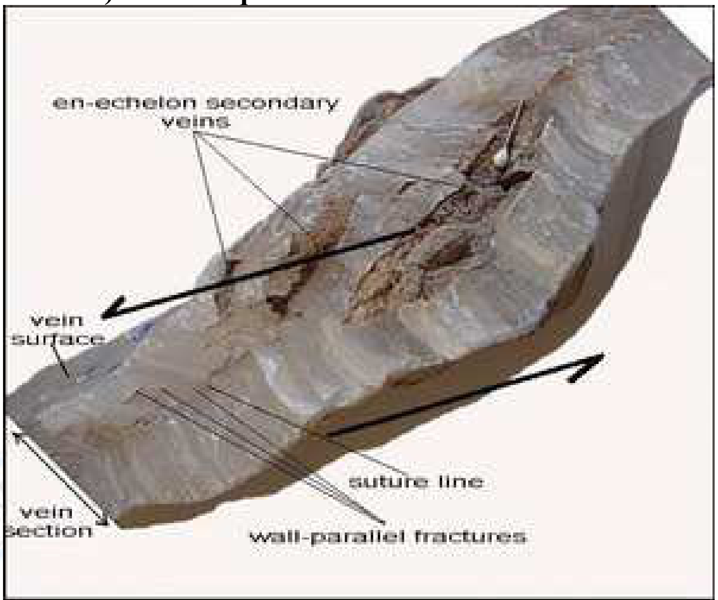


Fig. 9. Sample No 2, in which the secondary wall-parallel fractures in the middle of the photo have extended to the en-echelon secondary veins, these secondary veins cut the fibrous crystallization of the original vein and increase its thickness (pin length is 1cm).

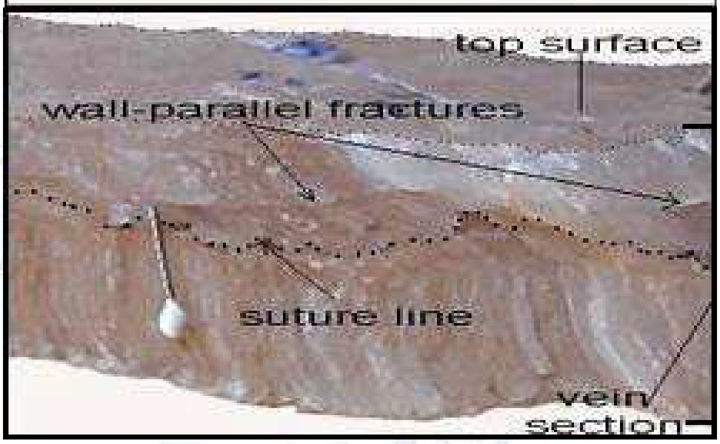


Fig. 10. Section in part of the sample No 2 which contains two parts with different fibres characters, the upper part has thin fibres which are affected by a number of secondary wall-parallel fractures. The lower part has relatively curved and thicker fibres; without wall-parallel fractures and they are asymmetric with the upper part, (pin length is 1 cm).

There are three secondary en echelon muddy veins, which vary clearly in size .The big one is filled by silt accompanied by fibrous gypsum ridges, the others filled by silt only. The secondary wall parallel fractures have been extend to the en echelon muddy veins, which cut the fibrous crystallization and increased the thickness of the original vein from (18)mm to (33)mm (Fig. 9). At vein surface, we observe a striation slightly oblique to vein strike by an angle equal to 15˚ E (Fig. 11).

Fig. 11. Part of the top surface of sample No 2 which contains striations that make 15˚E as pitch angle with the strike line of the vein(pin length is 1cm, the pin is parallel to striation).

From the three section's criteria such as the bent of the fibres at lower vein wall, the en- echelon secondary muddy veins and the secondary wall-parallel fractures, right lateral displacement has been determined; this displacement played an important role in the development of this vein. The history of the vein indicates that perpendicular fibres to vein walls have firstly created by pure dilation. Then the vein has been suffered right lateral displacement in E-W direction, which changes the extension direction from N-S to NE-SW and creates new oblique fibres, in the same time it fractures and curves the older fibres in the upper and lower parts respectively. The en-echelon secondary veins might be developed from the secondary wall-parallel fractures at the upper part of the vein. That happens by stress increasing in local zone in the vein, which increases the vein thickness in this zone.

5.3. Sample No: 3 Oblique fibrous vein, its attitude is (260⁄ 60˚) and thickness is (2.5-3) cm (Fig. 12). In vein section, the fibres have different inclination, so they make steep angle about (65˚) with the vein walls at zone A, and then these fibres are gradually curved and become horizontal and parallel to vein strike that at the vein walls. The fibres in zone B (near the suture line) have low and changeable inclination angle along the vein section which vary gradually from (15˚) at C to (40˚) at D, relative to the vein walls (Fig.12). Others section criteria have been shown, like thin secondary wall-parallel fractures, which bend the fibres and reduce their inclination angle; some sets of en- echelon fractures are observed with difficulty by naked eye; and a set of secondary veins filled by muddy material (Fig.13).

In vein surfaces (Fig. 14) there are two groups of striations, the older is very clear and perpendicular to vein strike this striation is also parallel to some surface criteria like tectonic tool mark and wavy structures axes (Fig. 15). The second group of striations is subperpendicular to the first (05°E as pitch angle) which is eventuated on one limb of the wave as striation and on the other as fibres growth (Fig. 16). The original vein surface appears very rough because of the genesis of secondary en-echelons veins under the vein walls, these secondary veins filled by muddy material have been increased the original vein thickness where they are exist (Figs. 12 and 13).

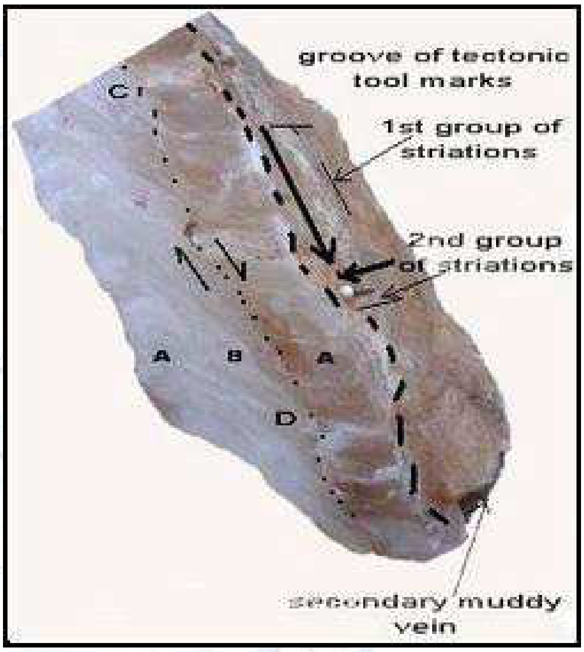


Fig.12. Sample No 3, the section of the sample shows two kinds of fibres inclination, the upper one and the lower one(A) have high inclination angle with respect to vein walls, in between them the fibres (B) have low inclination angle between (15° at C to 40° at D) relative to vein walls. The top surface (the right side) is very rough due to; the existence of two types of striations, the first is perpendicular to the strike line which, is associated with tectonic tool mark as surface criterion and the second is parallel to strike line; and the existence of some secondary muddy veins underneath the upper surface (pin length is 1cm).

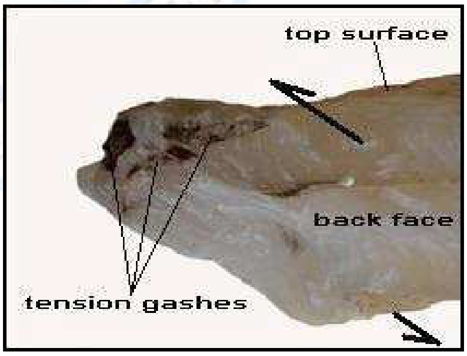
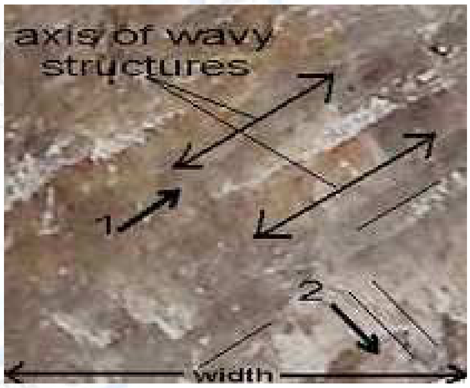


Fig.13. The back face of sample No 3, where the tension gashes at the top part of the sample have been developed by right lateral displacement but they appear as if it was developed by left lateral displacement(in contrary to the true case) because the sample is photographed from back side (pin length is 1cm).

Fig.14. Small area on the top surface of sample No 3 which shows the first group of striation perpendicular to vein strike, the arrow indicates the direction of displacement of the missing block (pin length is 1cm).

Fig.15. Groove of tectonic tool mark (1) appears on the top surface of sample No 3, has been affected by crystallization growth (2) at its upper limb, this groove is parallel to the first group of striation. The displacement of missing block is toward the left of the photo for the first displacement and toward the top for the second (pin length is 1cm).

Fig.16. Wavy structures appear on the bottom surface of sample No 3, which are parallel to the first displacement that has been affected by second displacement perpendicular to the axis of the waves. The second displacement induces striation and secondary fibres growth on the limbs of each wave, the displacement of the missing block is toward the upper right of the photo for the first generation and toward the bottom right of the photo for the second generation(the width of the photo is 3 cm).



From all these criteria, the history of the vein can be deduced; the oblique fibres (A) indicate that the vein has been opened firstly by normal displacement because the acute angle between the fibres and upper vein wall is toward the dip direction of the vein. This criterion coincides with others criteria like the secondary wall-parallel fractures and en-echelon fractures in vein section and the tectonic tool mark in vein surface. All these criteria refer to the normal displacement. The striation and fibres growth on the wavy structures on vein surface; the en echelon secondary veins; and the fibres curvature particularly close to vein walls, indicate the influence of right lateral displacement. From the striation and the fibres growth on the wavy structure and on the hard matter groove, the normal displacement appears prior to the right lateral displacement.

5.4. Sample No: 4, Oblique fibrous vein, has a Lozenge shape formed by conjugate shears fractures (Riedel system). The thickness of the vein is changeable, it reaches (2.5) cm in the middle of the vein and less than (0.5) cm in the lower tip. Shear displacement has occurred on f1 whose attitude is (105⁄ 16˚) and extension has occurred on f2 with horizontal attitude; f1 makes an angle equal to(6.5˚) with the mean plane of fracture(F) and f2 makes an angle equal to(13˚) with it. In vein section, the fibres inclined slightly from the vein walls they form small acute angle (13˚) with the upper wall in opposite direction to vein dip. There are three lozenge shapes (L1, L2and L3) filled by muddy material appear in the middle of vein section (Fig. 17). In lower vein surface, two sets of striations have been observed (Fig. 18), one of them is perpendicular to vein strike and the other is oblique to it. The oblique striation has a pitch angle equal to 65˚W, which forms a teeth structure and it appears posterior to the first. In upper surface, there are some non-fibrous crystals, which have been randomly distributed, these crystals are not affected by any displacement, and they appear without any striation.

From this example, we conclude that the vein has been opened by reverse displacement forming the fibres with weak inclination to vein wall and has produced the first set of striations. Then the vein was reopened by reverse displacement, which forms the muddy lozenges in the middle of the vein contemporaneous with the second set of striations. The existence of the non-fibrous crystals on the upper vein surface indicates that this surface was not restricted to the wall rock in the time of crystallization, the crystals have been grown freely in cavities, and then these crystals have not suffered any displacement.

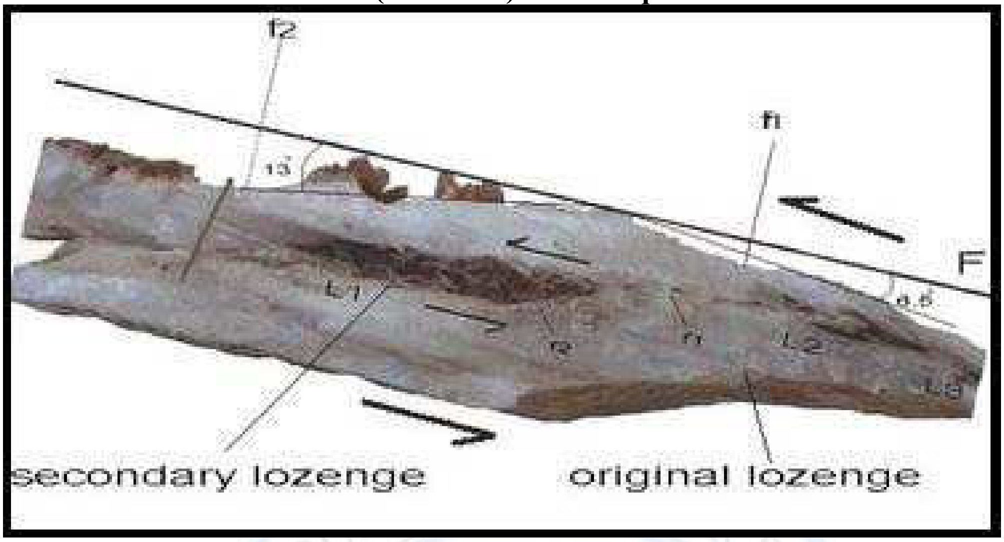


Fig.17. Section in sample No 4 shows fibrous vein has a lozenge shape produced by conjugate shear fractures (f1, f2), that in cross-section make angles 6.5°and 13°respectively with the mean plane of fracture (F). This vein is produced by reverse displacement, their fibres make acute angle with the upper wall (clear near the pin), and it contains secondary lozenges (L1, L2andL3) formed by secondary shear fractures (f1, f2), which filled by muddy material .These lozenges are produced by reversed sinistral displacement, (pin length is 21mm).

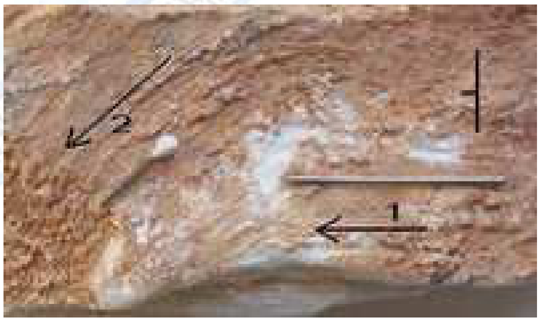


Fig.18. Two sets of striations appear on the bottom surface of sample No 4, the older is in the right of the photo which is perpendicular to veins strike, the other is oblique and has a pitch angle equal to(65°)W which form a teeth structure in the lower left corner (the small pin is 1cm length).

6. Discussion

The age of Muqdadia Formation has been dated by [27] as 8Ma old i.e. Late Miocene. Injana and Muqdadia Formations constitute the core of Southern Hemrin Anticline, so these formations have been suffered folding after their deposition that means the folding has been happened after the Late Miocene.

These Formations have been affected by an extension stage, which is characterized by the growth of gypsum fibrous veins; the general orientation of these veins is Northwest-Southeast, which is parallel to the axis of Southern Hemrin Anticline. The orientation of the maximum stress responsible for the folding is Northeast-Southwest, which is parallel to minimum stress responsible for the formation of the veins. That means the two stages of deformations (folding and veins formation) have been happened in different time. The veins in the study area appear clearly not affected by folding process, so these veins might be happened after the folding.

The fibres orientations in gypsum veins have been measured in the office in 29 samples, part of the veins shows straight fibres refers to single deformation stage and others show curved fibres, which refer to multiple deformation stages.

From the curved fibres, we can estimate the chronology of the opening stages; twelve veins exhibited two stages of deformation, the first stage is of perpendicular growth to vein walls, which, is related to pure dilation. The second growth is of oblique fibres, which have related to (6) dextral, (4) normal and (2) sinistral displacement .These veins have one single growth plane consists within the vein and they are probably syntaxial that all after the pure dilation (Figs. 19 A and B). Three veins show curved fibres, but here the fibres started in growth obliquely to the veins walls; the first underwent normal displacement followed by sinistral displacement; the second underwent dextral reverse displacement followed by reverse displacement; and the third underwent reverse displacement followed by sinistral reverse displacement. These veins have two simultaneous growth planes and are probably antitaxial.

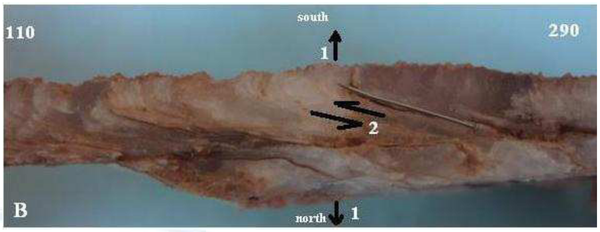


Fig.19. (A) Inclined vein in horizontal beds of Mudstone in Injana Formation, vein thickness is 2 cm. Pen for scale 14.5 cm.(B) Showing the horizontal top section of the vein. The vein underwent two stages of fibres growth, the first growth (adjacent to wall rock) is perpendicular to vein wall related to first stage of opening 1 which, is pure dilation . The second(in the middle of the vein) has inclined fibres (12°) from the vein wall and related to the second stage of opening 2 which is sinistral displacement, the vein appears as syntaxial .The white number(1,2) refers to the stages of opening and (110-290)refers to vein section direction. Pin for scale 25 mm.

The chronology of the development of the twelve veins is started by pure extension (σ3) is at 30º/ 205 and plunged, then succeeded by 1 stage of extension (σ3) oriented Northeast- Southwest and 2 stages of compressions, the first is oriented Northeast-Southwest and the second is East-West.

Moreover, from the three veins with curved and oblique fibres, three relative age chronology have been diagnosed. The first is extensive stage with σ3 plunges 40º toward Northwest followed by compressive stage with σ1 has oriented Northeast-Southwest, the second is compressive stage with σ1 has oriented Northwest-Southeast followed by another compressive stage with σ1 has oriented East-West, and the third is compressive stage with σ1 has oriented Northwest-Southeast followed by another compressive stage σ1has oriented Northeast-Southwest.

All the above fibres cases indicates that the study area passed firstly by pure dilation plunging 30º toward the Southwest followed by extensive stage related to normal fault system where σ3 is oriented Northwest-Southeast then σ1 has been rotated from vertical to horizontal. The direction of σ1 in the first stage of compression is Northwest-Southeast then it changed to North-South, then to Northeast-Southwest and finally the direction of σ1 rotates to East-West.

The striation cross cutting on the veins surfaces gave four cases. 1- Vein oriented 305/20º has been undergone two stages of displacement. The first is related to normal extension with σ3 oriented North-South, and the second is compressive stage related to dextral displacement with σ1 oriented East-West. 2- Vein oriented 290/44º has been undergone two stages of displacement. The first is related to pure dilation σ3 is plunge 46º toward Northwest, and the second is compressive stage related to sinistral displacement with σ1 oriented East-West (Figs. 19A and B). 3- Vein oriented 294/70º has been undergone two stages of displacement. The first is related to normal extension with σ3 oriented North-South, and the second is compressive stage related to dextral displacement with σ1 oriented East-West. 4- Vein oriented 305/40º has been undergone two stages of displacement. The first is related to reverse displacement with σ1 oriented North-South, and the second is compressive stage related to sinistral displacement with σ1 oriented East-West.

From these striation cross cutting we can estimate the chronology of the veins development as, the first displacement is related to normal fault system which process the North-South extension, then followed by North-South compression, and finally the East-West compression.

From the four vein samples, the directions of extension and compression in the study area have been estimated. Fibres attitude in vein section give the estimation of the direction of σ3 (i.e. the extension that the vein has been undergone). However, when the striations on vein surface have existed the direction of σ3 and σ1 could be more accurately determined. Sample No1 (Fig. 20) manifests two extension directions, the first is N-S direction where σ3 has steeply plunged (60°) toward the North. The second is subhorizontal where σ3 plunged (05 °)toward the North

Sample No 2 manifests two extension directions, the first has σ3 at 42°/168, the second direction has obtained from striation measurement on vein surface where σ3 at 38 °/207and σ1 at 20 °/090 (Fig. 20).

Sample No 3 exhibits three extension directions, obtained from the attitude of fibres in vein section, these extension directions are 05°/175, 20°/355 and 50°/355, the fourth direction is compressional, has obtained from the striation on vein surface where σ3 at 27 °/222 and σ1 at 14°/096 (Fig. 20).

Sample No 4 shows reverse displacement where, the directions of σ3 and σ1 are different from the previous samples. The older stage deduced from the striation on vein surface, gave σ3 at 80°/197 and σ1 at 10°/017, but the younger has been deduced from the striation on vein surface, gave σ3 at 80°/253 and σ1 at 10°/036 (Fig. 20).

The first three samples exhibit N-S extension due to normal displacement, which followed by E-W compression due to right lateral displacement.

The fourth sample exhibits two stages of compression (NNE-SSW and NE-SW) produced by reverse displacement.

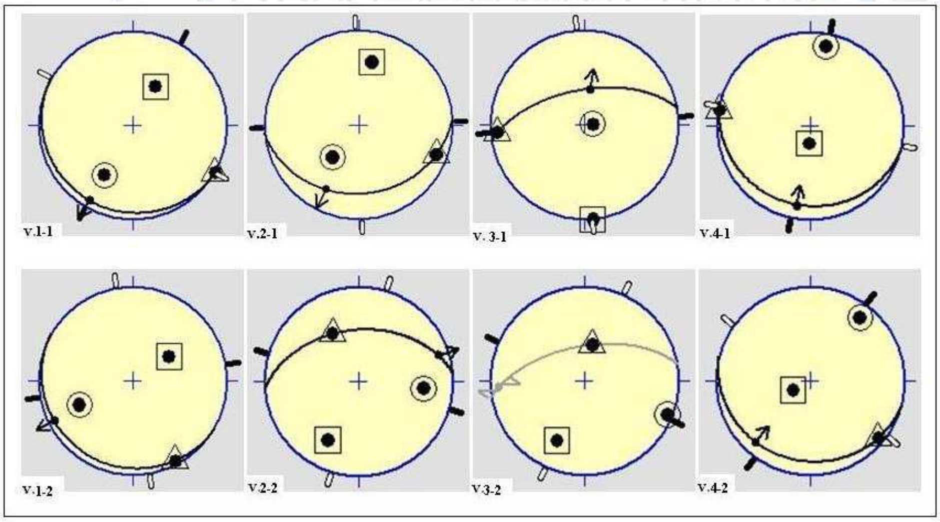


Fig.20. Equal-area lower- hemisphere projection of fibres and slickenside striae for four gypsum vein samples in the study area shows the directions of maximum principal stress σ1( ), the direction of intermediate principal stress σ2( ), the directions of minimum principal stress σ3 ( ), the great circles represent the vein's plane, and arrows indicate pitch angle of slickenside striae on vein plane. See text for further discussion.

After the folding of Southern Hemrin anticline during the Late Miocene-Pleistocene 8 Ma ago, the zone has been affected by an extension stage. Gypsum fibrous veins have been generated during this extension stage.

The study of the orientation of gypsum fibrous veins; the orientation of the fibres in the veins; the fault-slip data on vein surfaces; and the relative chronology of the age of displacements indicate that after the folding, the study area are affected by: Pure dilation perpendicular to vein planes, $\sigma 3$ plunged toward the Southwest, followed by another stage of extension related to normal fault system, $\sigma 3$ rotated toward the North-South, followed by compressive stage $\sigma 1$ is North-South, and finally $\sigma 1$ rotated to East-West.

Vein surface some time contains big and dispersed non-fibrous crystals that developed freely in void; therefore, they have not been affected by any striation. This case refers to pure dilation, but when the vein is stranded in hard rock, it cannot be extended perpendicularly to vein walls, so it extends parallel to vein walls, the new fibres grow parallel to vein walls in vein surface and/or in vein centre, this case refers to detachment displacement

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