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Tectonic significance of mesofracture systems associated with the Lebanese segment of the Dead Sea transform fault

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Abstract—A 3000 m Jurassic–Cretaceous–Palaeogene succession dominated by carbonates is deformed by NNE trending open folds of Palaeogene age. Conjugate wrench faults and a system of normal faults extend the fold belt axially and probably evolved during anticlockwise rotation in a transpressive regime related to the oblique convergence of the African and Arabian plates across the Lebanese segment of the Dead Sea transform fault. Three sets and four systems of conjugate mesoscopic fractures, symmetrically orientated with reference to bedding and the plunge of the fold in which they are contained, resulted in minor axial elongation. Pressure solution on surfaces striking parallel to the fold belt locally achieved up to 50% shortening.

The N30°E vertical Yammouné Fault Zone, which connects with the principal rift faults to the north and south, is accompanied by mesostructures which indicate that displacements were dominantly left-lateral and that the 1–2 km Zone is younger than the folds, possibly of Neogene age.

STATEMENT OF THE PROBLEM

QUENNELL (1958, 1959), Freund (1965) and Freund *et al.* (1970) claim on the basis of geological evidence that there has been substantial left-lateral displacement along the Dead Sea Rift, a fault zone reflecting the transform boundary separating the African, or a possible Sinai/Levantine plate, from the Arabian plate (McKenzie 1972, 1977, Dewey *et al.* 1973, Le Pichon *et al.* 1973). From the entrance to the Gulf of Aqaba, where the rift valley diverges from the obliquely spreading Red Sea boundary to the Tauride Belt in southeast Turkey, the 1100 km fault zone may be divided into seven segments; from south to north they are (Fig. 1) the Aqaba, Araba, Dead Sea–Jordan River, Lebanese, southern Gharb, northern Gharb and Kara Su segments. The slip vector on the three southern segments and the Gharb (Syrian) segments is parallel or sub-parallel to the fault zone, so that displacements are either transcurrent or transcurrent combined with subsidiary extension (Le Pichon *et al.* 1973). Across the Lebanese segment, which is oblique to the slip vector, it is likely that there was compression combined with left-lateral slip.

Freund *et al.* (1970) think that there has been about 105 km post-Turonian sinistral displacement along the three southern segments of the Rift Zone and that 60 km occurred after the Cretaceous but before the Miocene, that 40–45 km is post-Miocene, 10 km post late Pliocene and at least 150 m is late Quaternary. Across the Syrian segments they estimate 70 km sinistral offset of the Maestrichtian ophiolite masses and about 8 km offset of the Pliocene basalts at the Syrian–Lebanese frontier. They believe that 105 km of sinistral displacement together with a 6° anticlockwise rotation of the Arabian plate should give an overlap in the Lebanon of 55 km, but they reduce this to about 20–25 km by constructing a model (Freund *et al.* 1970, fig. 10) which allows for displacements on faults other than the Yammouné Fault, the principal fault in the Lebanon. In an earlier model Freund (1965) had envisaged that the overlap in the Lebanon would give rise to compression normal to

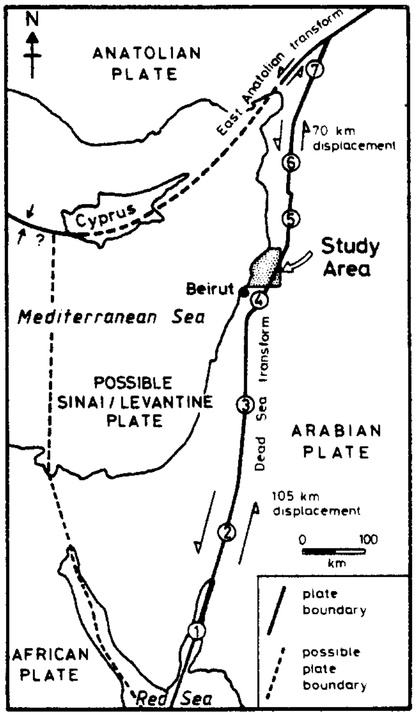

Fig. 1. Plate setting of the northern Lebanese segment of the Dead Sea transform. After Le Pichon *et al.* (1973, fig. 30A), Şengör (1979, fig. 1) and Freund *et al.* (1970, fig. 11). Segments of the Dead Sea transform fault are: (1) Aqaba, (2) Araba, (3) Dead Sea–Jordan River, (4) Lebanese, (5) southern Gharb, (6) northern Gharb, (7) Kara Su.

the boundary, and he noted that the folds in the Lebanon do not achieve a shortening in accord with an overlap of 20–25 km.

Accepting the broad outlines of Freund's model, there are at least two aspects of the structural evolution of the Lebanon which require explanation:

(a) The NNE trend of the folds which, although subparallel to the plate boundary, is markedly oblique to the direction of convergence.

(b) The shortening achieved by the folds is less than that which would be anticipated as a consequence of about 25 km of overlap.

This paper analyses planar mesoscopic structures in the northern part of the Lebanese segment of the Dead Sea transform in an attempt to solve some aspects of these two problems. The value of mesofractures in the analysis of major fault zones is demonstrated by Hancock & Kadhi (1978) in their study of the central Arabian graben system.

As a model for structural evolution between two obliquely convergent plates we adopt Harland's (1971) concept of tectonic transpression, in which folds are initiated approximately normal to the direction of closing, but with further convergence are tightened and rotated so that their axial traces become aligned subparallel to the plate margins. Rotation will be accompanied by axial elongation of the fold belt, and a transcurrent fault will develop only in the final stages of closing.

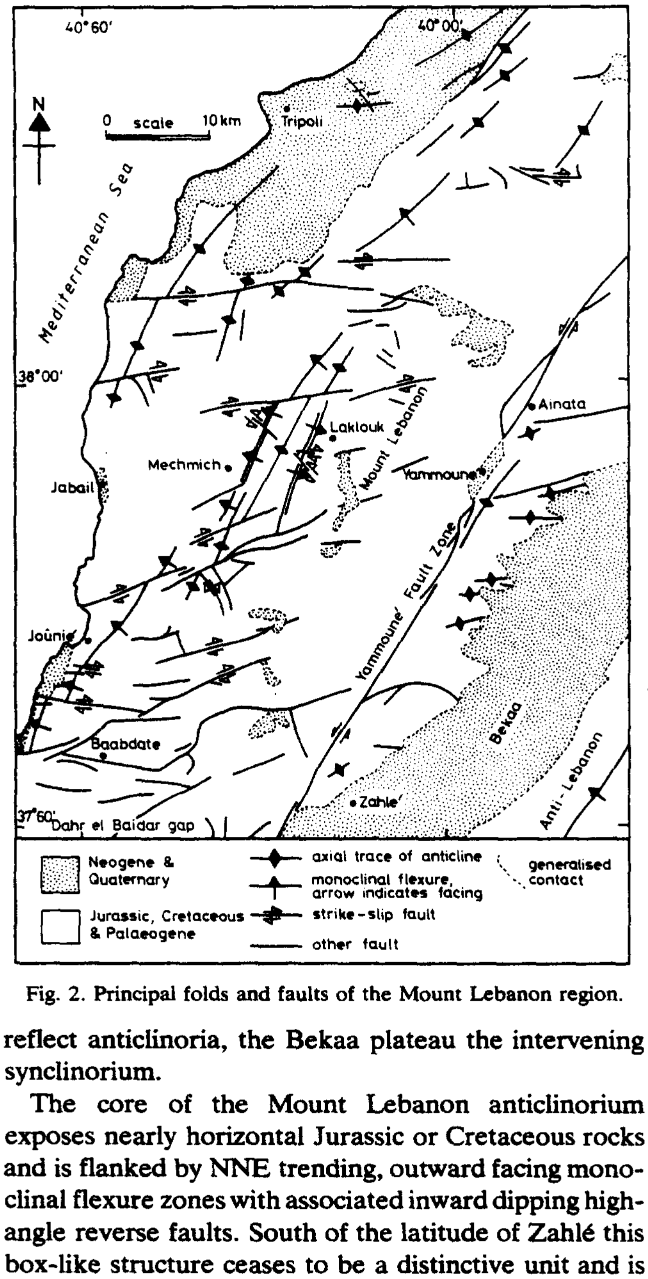

Fig. 2. Principal folds and faults of the Mount Lebanon region.

STRUCTURE OF NORTHERN LEBANON

Figure 2, which shows the principal structural elements of the northern Lebanon, is based on Dubertret's (1955) 1 : 200,000 map, the work of Renouard (1955), Wolfart (1967) and Beydoun (1977a, b), who review the geology of the Lebanon, and the authors' observations. The exposed sequence of folded rocks is about 3000 m thick and ranges from Middle Jurassic in the cores of anticlinoria to Eocene in the cores of synclinoria. It mainly comprises marine carbonates and marls but includes thin late Jurassic – early Cretaceous basalts and pyroclastics, and also up to 250 m of continental sandstones and clays of early Cretaceous age. Unconformities without significant angular discordances interrupt the sequence. The deformed succession is unconformably overlain by flat-lying to gently tilted Middle Miocene to Quaternary rocks. Adjacent to the Mediterranean they include marine limestones, marls and conglomerates but inland, where the unconformable cover is largely restricted to the Bekaa, the Neogene and Quaternary is mainly represented by continental conglomerates. The topography of the region is dominated by two NNE trending mountain ranges, Mount Lebanon rising to 3088 m and the Anti-Lebanon rising to 2815 m, they are separated by the Bekaa plateau at about 1100 m. As Freund (1965) remarks, it is significant that each unit is about 1000 m higher than its homologue to the south. The ranges reflect anticlinoria, the Bekaa plateau the intervening synclinorium.

The core of the Mount Lebanon anticlinorium exposes nearly horizontal Jurassic or Cretaceous rocks and is flanked by NNE trending, outward facing monoclinal flexure zones with associated inward dipping high-angle reverse faults. South of the latitude of Zahlé this box-like structure ceases to be a distinctive unit and is replaced by a broad region of flat-lying rocks cut by a system of E–W normal faults in the Dahr el Baidar gap. The region between the eastern monoclinal flexure and the Yammouné Fault is underlain by horizontal or gently tilted rocks, but between the Mediterranean and the western monocline there are several open, upright, gently plunging folds of parallel style, and on all scales from the metric to the kilometric (Fig. 2). The majority of folds trend NNE parallel to the anticlinorium, but to the east of Tripoli there are important NE trending folds.

The Mount Lebanon anticlinorium is divided into several compartments separated by narrow zones of E–W trending nearly vertical dextral faults, many of which display nearly horizontal groove or crystal fibre slickenside lineations. Across each fault zone the axial trace of the core of the anticlinorium and the western monocline flexure zone are displaced by up to 2 km. In addition, the width of the core, the steepness and width of the western monocline, and the number and shapes of

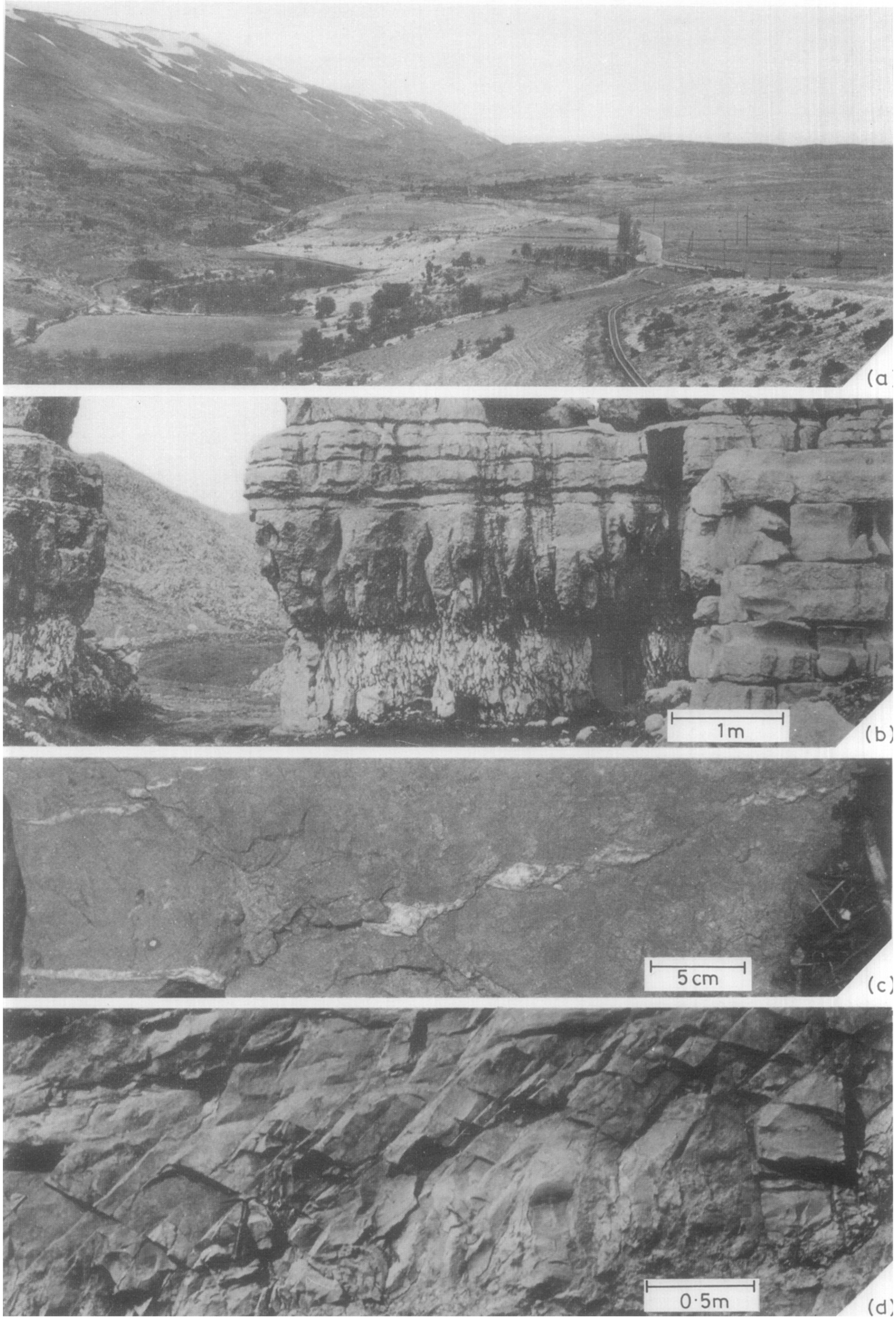

Fig. 3. (a) View NE near Ainata along the topographic trench following the Yammouné Fault Zone. The range on the left is the eastern flank of Mount Lebanon (African plate) and the plateau on the right belongs to the Arabian plate. (b) Horizontal Lower Cretaceous limestones near Laklouk. The upper part of the thick bed is cut by widely separated *bc* extension fissures while the lower division of the same bed is cut by closely-spaced *bc* pressure solution surfaces. (c) Bedding plane in Upper Jurassic limestone exposing an array of an échelon vein segments derived from a formerly continuous vein by pressure solution across *bc* surfaces oblique to the vein, Baabdate. (d) Conjugate *h0l* shear joints enclosing an acute angle about *a* and cutting gently inclined Upper Cretaceous limestones near Mechmich.

subsidiary folds in the west also vary from compartment to compartment. These relationships suggest that folding and dextral displacements were partly synchronous. A conjugate set of NW–SE trending sinistral faults comprises shorter fractures achieving smaller displacements than the E–W faults. The conjugate strike-slip fault system is symmetrically arranged about the trend of the anticlinorium. It resulted in axial elongation combined with a clockwise sense of rotation as a consequence of the dominance of the E–W dextral set. The E–W normal fault system of the Dahr el Baidar gap also achieved minor axial elongation of the fold belt.

In northern Lebanon the core of the Bekaa synclinorium is unconformably covered by nearly horizontal Neogene and Quaternary rocks. The western boundary of the synclinorium is the Yammouné Fault Zone, a structure reflected by a topographic trench 1–2 km wide (Fig. 3a). The Fault Zone, the only structure which is continuous throughout the length of the Lebanon, connects with the principal rift faults to the north and south and separates regions of contrasting structural style. The Bekaa synclinorium plunges gently south and contains folds which are gentler and of smaller amplitude than those of the Mount-Lebanon anticlinorium. The majority of the folds trend parallel to the length of the synclinorium, but in the plateau immediately to the east of the Yammouné Fault Zone gentle E–W trending folds are abundant (Fig. 2).

PLANAR MESOSTRUCTURES

The three-dimensional orientations and morphological characters of about 4000 planar mesoscopic structures were recorded at 152 stations, each of which was a structurally homogeneous domain of less than 10 m^2 area. The majority of the structures within the Mount Lebanon anticlinorium and on the western flank of the Bekaa synclinorium are orientated symmetrically with respect to sedimentary layering and the plunge of fold axes. Within the Yammouné Fault Zone many of them are also arranged in this way, but additionally there are structures whose arrangement or style is related to the presence of the Fault Zone. Accordingly, the regionally distributed mesostructures and the distinctive assemblage restricted to the fault zone are described separately.

Planar mesostructures in rocks external to the Yammouné Fault Zone

Because the majority of these structures are arranged symmetrically with reference to sedimentary layering and the plunge of fold axes, their geometry is most conveniently described with respect to a fabric axial cross, which at any point within a fold is orientated so that the *ab* plane is parallel to bedding with *b* parallel to the fold axis, and *c* is normal to the layers (Fig. 4). Structures containing two axes are said to be in *ab, ac* or *bc*, those containing one axis in *0kl*, *h0l* or *hk0*, and those oblique to all three axes in *hkl*. Intercepts on the *a, b* and *c* axes are denoted by *h, k* and *l*, respectively, parallelism to an axis being indicated by 0. As Fig. 5 illustrates, there are structures belonging to the single sets in *ab, bc* or *ac*, and the conjugate sets in *h0l* enclosing an acute angle about *a*, in *h0l* enclosing an acute angle about *c*, in *hk0* enclosing an acute angle about *a*, and in *0kl* enclosing an acute angle about *c*. The average number of sets per station is four; all, or the majority of which, belong to the symmetrical sets or systems, but at half the stations there is also a single set or a conjugate system in *hkl*. In the succeeding analysis of the sets or systems the following additional symbols are also used:

σ_1 — maximum principal stress;

σ_2 — intermediate principal stress;

σ_3 — minimum principal stress;

$(\sigma_1 - \sigma_3)$ — stress difference;

λ_e — $\frac{p}{\sigma_3}$, where p = fluid pressure;

2θ — conjugate shear angle.

Surfaces in *ab* include primary inter-layer bedding planes unmodified by tectonism, inter- and intra-layer stylolitic pressure solution surfaces and intra-layer extension joints (Figs. 5a & b). Many intra-layer extension joints are small fissures, probably related to recent unloading and denudation.

The majority of *bc* surfaces are joints or calcite veins, some of the latter containing crystal fibres orientated normal to vein margins. Both joints and veins are interpreted as extension fractures formed perpendicular to σ_3 (Fig. 5c), the veins probably being hydraulic fractures developed at a time when σ_3 was layer-parallel and normal to fold axes and the value of λ_e approached unity. Because the structures belong to a single set of extension fractures it is likely that $(\sigma_1 - \sigma_3)$ did not exceed four times the tensile strength of the limestones (Price 1977, Hancock & Kadhi 1978).

Some limestones above the level of the Middle Jurassic are cut by *bc* pressure solution surfaces indicative of layer-parallel compression normal to fold axes (Fig. 5d). About 95% are stylolitic, the remainder being planar. They are especially common in, or close to, the monoclinal flexure zones bounding the core of the Mount Lebanon anticlinorium. The juxtaposition of *bc* extension fractures and *bc* pressure solution surfaces in the same horizontal bed of Lower Cretaceous limestone at Laklouk, immediately east of the eastern monoclinal flexure zone, is particularly intriguing (Fig. 3b). The upper part of the bed is cut by relatively widely separated *bc* extension fractures, while the lower part contains closely-spaced *bc* pressure solution surfaces. The transition between the two assemblages is a 10 cm zone which is not coincident with a primary bedding plane. It is tempting to interpret the relationship as preserving the location of a former neutral surface separating an upper part of the layer which was being stretched parallel to *a*, from a lower part of the layer which was under compression.

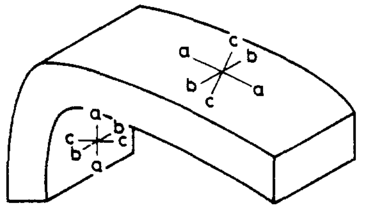

Fig. 4. Orientations of fabric axial crosses relative to the attitude of sedimentary layering and fold plunge.

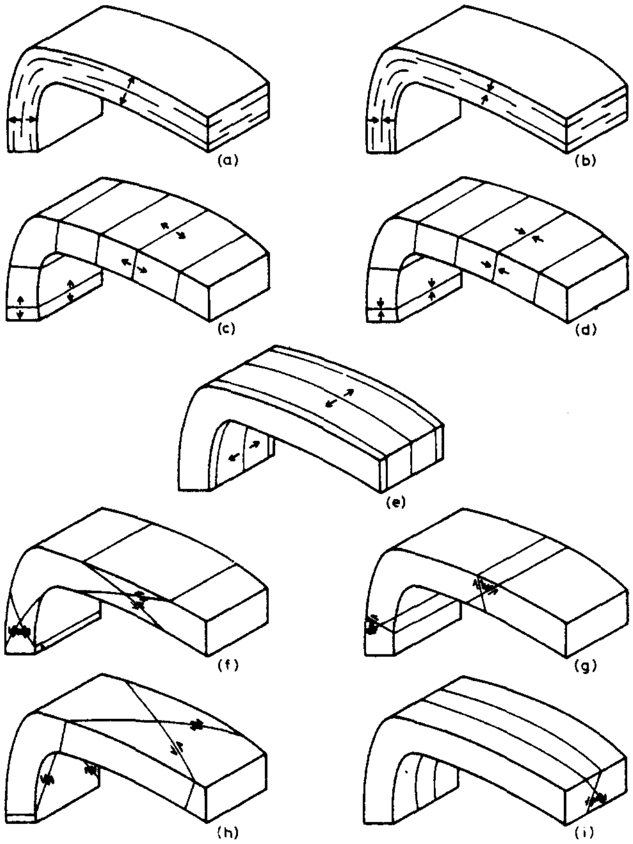

Fig. 5. Geometry of planar mesostructures orientated symmetrically with reference to sedimentary layering and fold axes. (a) *ab* extension fractures. (b) *ab* pressure solution surfaces. (c) *bc* extension fractures. (d) *bc* pressure solution surfaces. (e) *ac* extension fractures. (f) Conjugate *h0l* contraction faults and shears enclosing an acute angle about *a*. (g) Conjugate *h0l* extension faults and shears enclosing an acute angle about *c*. (h) Conjugate *hk0* shears enclosing an acute angle about *a*. (i) Conjugate *0kl* shears enclosing an acute angle about *c*.

Many *bc* pressure solution surfaces are sites of insoluble residue concentrations at which clastic calcite grains, fossils or ooids are abruptly truncated. Valuable mesoscopic strain markers are formerly continuous veins which are now divided into en échelon segments by *bc* pressure solution surfaces (Fig. 3c). A simple method of determining shortening from such an array of segments has been discussed already by the authors (Hancock & Atiya 1975). Employing their technique on the Lebanese examples shows that shortening parallel to *a* exceeded 50% in some zones of closely-spaced *bc* pressure solution surfaces. Outside regions of closely-spaced pressure solution surfaces the shortening achieved in this manner was probably less, but nevertheless it may have been substantial.

Throughout the region *ac* joints and non-fibrous calcite veins are abundant, although less well represented in the nearly horizontal limestones in the core of the anticlinorium. They are interpreted as extension fractures formed normal to σ_3 when it was orientated parallel to the fold axes (Fig. 5e). The observation that many *ac* surfaces are veins and the structure comprises a single set of extension fractures allows the inference that λ_e approached unity, and that $(\sigma_1 - \sigma_3)$ was less than four times the tensile strength of the limestones.

Conjugate *h0l* shears enclosing an acute angle about *a* (Fig. 5f) are especially well-developed in, and close to, the steep limbs of the western and eastern monoclinal flexures; 42% of sampled surfaces being joints, 30% mesofaults of 15 cm average displacement, and 28% veins. Most of the joints are restricted to single layers (Fig. 3d), while veins commonly comprise fibrous calcite giving a lineation normal to *b* within congruous accretion steps. Where conjugate mesofaults are equally developed they shorten layers parallel to *a*. Because the senses of displacement relative to the horizontal depend on the inclination of the layer in which the faults are contained they are most conveniently described using Norris' (1958) term contraction faults (Fig. 6a). According to whether displacements support or oppose the presumed sense of inter-layer shear they are synthetic or antithetic faults. Contraction faults in *h0l* are absent in the horizontal Jurassic limestones in the core of the Mount Lebanon anticlinorium, but they are well-developed in association with *bc* pressure solution surfaces in Cretaceous limestones in, or close to, the bounding monoclinal flexure zones.

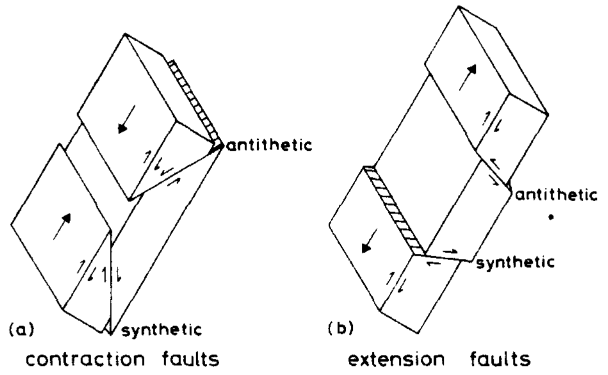

Fig. 6. Conjugate contraction and extension faults in *h0l*.

Many conjugate *h0l* sets at less than 45° to *a* are symmetrically orientated about the *a* direction (Fig. 7a) and thus, because it is reasonable to interpret them as conjugate shears, it follows that when they were initiated σ_1 was coincident with *a*, σ_2 with *b* and σ_3 with *c*. The average 2θ angle between conjugate symmetrical sets is 39°, indicating that when they were developed $(\sigma_1 - \sigma_3)$ was between four and eight times the tensile strength of the limestones. Because the 2θ angle is less than 45°, they may be regarded as paired extension fractures in the shear–extension fracture transition. Less commonly, conjugate *h0l* sets belonging to the system are asymmetrically arranged about the *a* direction. The acute bisectrix giving the orientation of σ_1 is always refracted 10 to 20° towards the horizontal (Fig. 7b). The average 2θ angle between asymmetric conjugate sets is

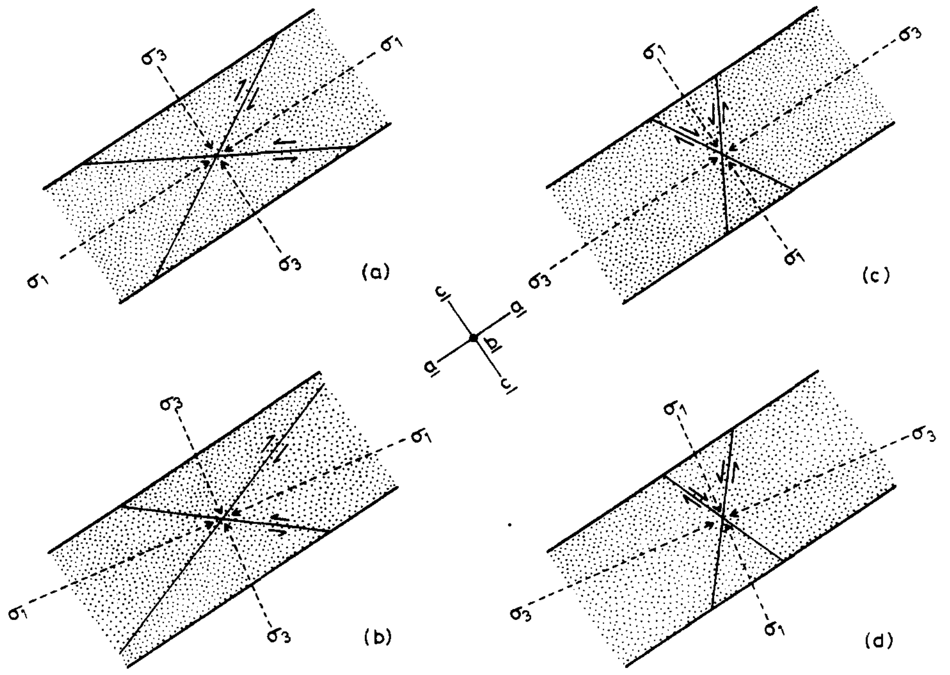

Fig. 7. Geometry of conjugate *h0l* shear fractures. (a) Symmetrically enclosing an acute angle about *a*. (b) Asymmetrically enclosing an acute angle about *a*. (c) Symmetrically enclosing an acute angle about *c*. (d) Asymmetrically enclosing an acute angle about *c*.

53°, suggesting that when they were formed the magnitude of $(\sigma_1 - \sigma_3)$ was greater than during the development of the symmetric sets and that they are shear fractures. It is possible that the asymmetric sets are younger than the symmetric sets and were initiated when, or shortly after, folds had locked and the σ_1/σ_2 plane was being progressively refracted towards the horizontal. The observation that 28% of *h0l* fractures enclosing an acute angle about *a* are veins indicates that λ_e commonly approached unity during their formation.

At stations where *h0l* surfaces enclosing less than 90° about *a* are present those enclosing less than 90° about *c* are absent. Structures in the latter system (Fig. 5g) are widely distributed, comprising joints, mesofaults of 12 cm average displacement and non-fibrous calcite veins. Mesofaults belonging to the system are extension faults in Norris' (1958) terminology (Fig. 6b). Where antithetic and synthetic sets are equally developed they elongate layers parallel to *a*. Although crystal fibre lineations and accretion steps are rarely associated with *h0l* extension faults they are commonly accompanied by a few cm of fault breccia or gouge. Conjugate *h0l* sets are arranged either symmetrically or asymmetrically about the *a* or *c* directions (Figs. 7c & d). During the development of the symmetrical sets σ_1 and σ_3 were orientated parallel to *c* and *a*, respectively (Fig. 7c), while during the formation of the asymmetric sets the σ_2/σ_3 plane was refracted by up to 15° towards the horizontal (Fig. 7d). The average 2θ angle enclosed by conjugate *h0l* surfaces in this system is 64°, suggesting that the value of $(\sigma_1 - \sigma_3)$ equalled or exceeded eight times the tensile strength of the limestones, and that the surfaces are shear planes. The smaller proportion of veins compared with the other *h0l* system may reflect lower fluid pressures during their development.

Sets of conjugate *hk0* surfaces enclosing an acute angle about *a* are widespread throughout the Mount Lebanon anticlinorium. Of the recorded surfaces, 75% are joints, 20% calcite veins, 5% mesofaults and 5% stylolitic pressure solution surfaces. Whereas joints are common everywhere, fibrous and non-fibrous veins are abundant only in the monoclinal flexure zones bounding the core of the anticlinorium. The crystal fibre lineation is commonly parallel to the bedding–vein intersect, but may lie a few degrees closer to the horizontal. Congruous accretion steps associated with fibrous veins indicate that shear was layer-parallel and involved the inward motion of the acute-angled wedge (Fig. 5h). The relative abundance of veins in *hk0* indicates that fluid pressures were relatively high at the time of their formation. The average displacement on *hk0* faults of mesoscale is about 20 cm. Relative to layers restored to the horizontal those trending NW–SE display sinistral displacements, while those trending WSW–ENE show dextral displacements. The development of conjugate *hk0* joints, veins and mesofaults occurred when σ_1 was parallel to *a* and σ_3 parallel to *b*. The average 2θ angle between conjugate *hk0* fractures is 61°, suggesting that they are shear planes formed when $(\sigma_1 - \sigma_3)$ equalled or exceeded eight times the tensile strength of limestones. Stylolitic pressure solution surfaces in *hk0* are spatially restricted to limestones in the Mechmich and Laklouk areas, adjacent to the western and eastern monoclinal flexure zones, respectively. Stylolitic lineations are normal to surfaces, and the segmentation of formerly continuous E–W veins shows shortening to have been up to 30%. Stylolitisation of *hk0* surfaces belonging to the dextral set is commoner than that of the sinistral set, and may be related to pressure solution having occurred across pre-existing fractures during wrench faulting.

Conjugate 0*kl* fractures (Fig. 5i) are largely restricted to the core of the Mount Lebanon anticlinorium, 50% of sampled surfaces being joints, 32% non-fibrous calcite veins and 18% mesofaults. Because 0*kl* mesofaults display normal displacements up to 20 cm, and the average 2θ angle between all varieties of conjugate 0*kl* fractures is 63°, the system is interpreted as comprising shear planes formed when $(\sigma_1 - \sigma_3)$ equalled or exceeded eight times the tensile strength of limestones, σ_1 was orientated normal or nearly normal to layering and σ_3 was nearly horizontal and parallel to fold axes. Where conjugate 0*kl* fractures are not precisely symmetrical with respect to *a*, *b* and *c*, the intersect between them generally lies closer to the horizontal than the *a* axis.

Of sampled surfaces in *hkl*, 75% are joints, 16% are faults and 9% are non-fibrous calcite veins, the majority being single surfaces or sets. Where conjugate sets are recognizable, mainly in gently inclined limestones external to the monoclinal flexure zones, they belong to one of four systems which, although asymmetric to *a* and *b*, are symmetric about *c*.

System 1: conjugate low-angle *hkl* contraction faults, joints and veins striking NE–SW.

System 2: conjugate low-angle *hkl* contraction faults, joints and veins striking N–S.

System 3: conjugate high-angle *hkl* extension faults, joints and veins striking NNE (intermediate in attitude between *h*0*l* extension faults and 0*kl* shears, but closer to the *h*0*l* system).

System 4: conjugate high-angle *hkl* extension faults, joints and veins striking WNW (intermediate in attitude between *h*0*l* extension faults and 0*kl* shears but closer to the *h*0*l* system).

The *hkl* systems indicate that although stresses were generally parallel or normal to layers they were not everywhere exactly parallel to *a* and *b*.

It is possible to erect a tentative mesofracture sequence using two types of criteria:

(a) A surface belonging to one set which is offset at a mesofault, vein or pressure solution surface belonging to another set is younger than the surface on which it is offset.

(b) The traces of younger joints terminate at those of older joints and, in general, younger joints are of smaller dimensions than older joints.

On the basis of these relationships it is possible to conclude that: (a) surfaces in some sets or systems are younger than those in others; (b) different styles of structure in a single set are not not necessarily of the same age; and (c) not all surfaces of a common style in a single set or system are of exactly the same age. Although each set or system evolved as a consequence of multiphase fracturing, the following generalized sequence applies to the principal surfaces at many stations.

(a) *h*0*l* contraction faults, *h*0*l* extension faults, *bc* pressure solution surfaces, *ac* and *hk*0 veins.
(b) *ac* and *hk*0 joints.
(c) *h*0*l* joints enclosing an acute angle about *a*, *h*0*l* joints enclosing an acute angle about *c*, 0*kl* joints.
(d) *bc* joints.
(e) *hkl* joints.
(f) *ab* joints.

Within any group, structures are either of approximately the same age (e.g. *bc* pressure solution surfaces and *h*0*l* contraction faults) or their inter-relationships are unknown because they do not occur in conjunction (e.g. *h*0*l* joints and 0*kl* joints). As might be anticipated, ductile or semi-brittle structures such as mesofaults, veins or pressure solution surfaces are older than brittle structures such as joints.

The structures discussed in this subsection occur only in rocks older than the Miocene. The Neogene–Quaternary cover succession, which rests unconformably on the deformed sequence, is cut by a few, commonly isolated, joints which cannot be matched with sets or systems in the deformed sequence. Thus the development of the main mesostructural assemblage probably occurred during the later stages of folding and immediately after folds had locked. It was probably complete by the Miocene.

Mesostructures in the Yammouné Fault Zone

The 1–2 km wide Fault Zone comprises nearly vertical N30°E trending faults and a distinctive assemblage of structures not represented outside the Zone. In the northern Lebanon the Zone separates the Mount Lebanon anticlinorium from the Bekaa synclinorium although both units are exposed in Cenomanian limestones. Many fault surfaces are lineated by horizontal or nearly horizontal slickenside grooves, indicating that a principal component of displacement was strike-slip. Fault-breccia in belts up to 200 m wide is associated with many of the fault planes. Parallel to the major N30°E fault planes there are numerous subsidiary sinistral strike-slip faults (Fig. 8). Within the Fault Zone at Yammouné there is a rhomb-shaped basin of Quaternary sediments about 7 km in length, its western margin coinciding with the northern extension of the principal fault and its eastern margin with the southern extension of the fault (Fig. 2). The rhomb shape of the basin and its relationship to the principal faults are not dissimilar to those of pull-apart basins (Quennell 1958, Crowell 1974) which develop where the trace of a major transcurrent fault is offset. In addition to N30°E trending faults the Zone also contains a system of NNW striking small-scale normal faults and conjugate joints, E–W approximately vertical, minor dextral strike-slip faults and a system of NE striking, high-angle reverse faults (Fig. 8). There are also some horizontally grooved NW striking faults of unknown sense of relative displacement.

Small folds of abnormal attitude also characterise the Fault Zone, being especially well-developed east of the fault near Zahlé. Axial traces trend NE with axial planes of less than 500 m separation being inclined 50–75° NW, and the steep limbs of some relatively tight folds being overturned by a few degrees. Within the Fault Zone near Ainata there are numerous NW trending open, upright

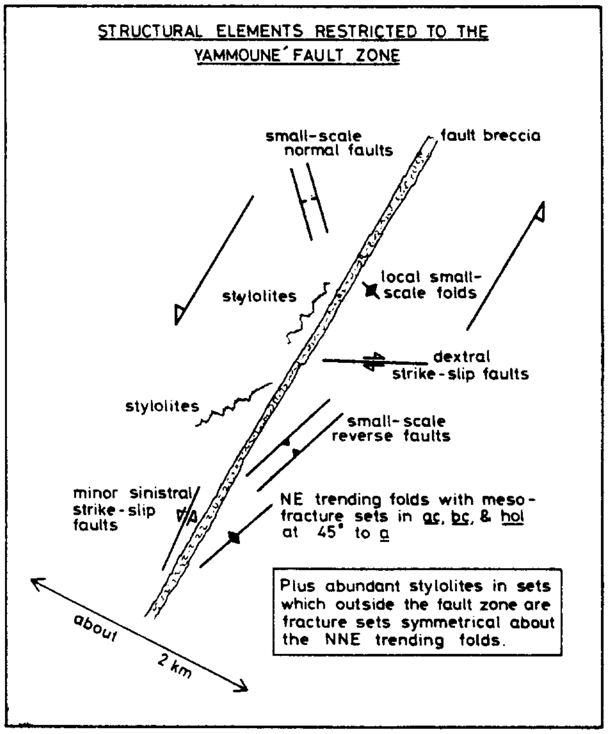

Fig. 8. Diagrammatic map illustrating the assemblage of structures which is distinctive of the Yammouné Fault Zone. The spatial distribution of features is entirely schematic and unrelated to the locations of individual elements on the ground.

folds with axial planes rarely more than 50 m apart. The NE trending folds are accompanied by mesofractures in *ac*, *bc* and *h0l* which are symmetrical with respect to the geometry of the fold in which they are contained.

The Fault Zone also contains abundant stylolitic surfaces, two vertical sets being especially important. One strikes NNE parallel to the Zone and comprises surfaces which increase in frequency towards the fault until there are about eight surfaces per m. The other set strikes NE–SW and is largely restricted to limestones west of the fault. This latter set strikes subparallel to the NE trending folds and reverse faults which deform the limestones to the east of the Fault Zone (Fig. 8). The NE trending stylolitic surfaces display a geometry relative to layering which is comparable with that of dextral *hk*0 fractures outside the Zone. These stylolites probably developed as a consequence of pressure solution across pre-existing *hk*0 fractures which were suitably orientated with respect to a secondary direction of compression within the Zone. Support for the idea that other stylolites within the Fault Zone may be located on the sites of pre-existing fractures is provided by the observation that many possess the geometry of sets or systems in *ac*, *bc*, *h*0*l* or 0*kl* with respect to folds of NNE trend. Furthermore, a higher proportion of *ac*, *bc*, *h*0*l* or 0*kl* surfaces within the Fault Zone are fibrous veins than outside the Zone. The greater abundance of stylolites and fibrous veins in the Zone is probably related to enhanced solution–deposition across, or on, pre-existing fractures during later shearing along the Zone.

The geometry of the total mesostructural assemblage in the Yammouné Fault Zone is consistent with its development within a major N30°E left-lateral transcurrent zone in which a primary shear couple generated a direction of secondary compression responsible for the stylolites, small-scale reverse faults and folds, and a direction of secondary extension responsible for the small-scale normal faults (Fig. 8).

DISCUSSION AND CONCLUSIONS

Many of the structural features of northern Lebanon are compatible with those which might evolve in a NNE trending transpressive regime combining approximately N–S convergence with left-lateral displacement. Each aspect predicted from Harland's (1971) model, and a partial solution to the apparent lack of shortening, is considered separately.

Anticlockwise rotation of the Lebanese fold belt

Because the motion of the Arabian plate was northward relative to the African/Sinai plate it is likely that the initial axial direction of the folds was approximately normal to the direction of convergence, but oblique to the trend of the zone. Continued closing probably tightened some folds, and also rotated them anticlockwise until their trend was subparallel to that of the zone. Structurally, such a rotation is difficult to demonstrate and possibly involved a substantial component of rigid rotation, however it may be significant that folds in the Tripoli region trend NE rather than NNE as elsewhere (Fig. 2). Rotation would have been less in the Tripoli region where the net displacement on the Lebanese segment is only 70–80 km compared with about 105 km in the south where axial traces are subparallel to the fault, and rotation would have been at a maximum. Support for a major component of rotation is provided by the work of Gregor *et al.* (1974) who demonstrate, using palaeomagnetic data from Upper Jurassic and Lower Cretaceous basalts, that there was a progressive 70° anticlockwise rotation of the Mount Lebanon region during the late Jurassic–Pliocene interval. They also argue that regions adjacent to the fault zone to the south of the Lebanon did not participate in this rotation. Such a conclusion is also in accord with the model adopted here.

Axial elongation of the Lebanese fold belt

Abundant structural evidence indicates that the fold belt has been axially elongated:

Conjugate wrench fault system. The system of conjugate wrench faults which developed symmetrically about axial traces resulted in the axial elongation of the Mount Lebanon anticlinorium combined with subsidiary clockwise rotation. Elongation was accompanied by complementary shortening at right angles to the fold belt. The feeble development of wrench faults in northwest Lebanon may be related to the possibility, discussed in the preceding subsection, that the NE trending folds of that region were not rotated through such a large angle as those of central and southern Lebanon. Where rotation was less it is to be expected that accompanying signs of axial elongation will also be less marked.

Normal fault system of the Dahr el Baidar gap. The normal fault system in the gap resulted in a minor component of axial elongation which was not accompanied by complementary shortening or significant rotation.

Mesofracture sets or systems in ac, hk0 or 0kl. The development of extension veins and joints in *ac* and conjugate mesofaults, shear joints and veins in *hk*0 and 0*kl* also achieved minor axial elongation which, during the formation of *hk*0 shears, was combined with shortening normal to the axial direction.

The Yammouné Fault as a late stage left-lateral zone

Because the nearly vertical, rectilinear Fault Zone separates the structures of the Mount Lebanon anticlinorium from those of the Bekaa synclinorium, the later displacements on it must post-date the folding. Its trace, reflected by a topographic trench crossing drainage divides and containing at least one sediment-filled pull-apart basin, also displays other features characteristic of large active strike-slip faults (see Allen 1965, Ambraseys 1978, Şengör 1979), suggesting that the Zone may be the principal active representative of the Dead Sea transform fault within the Lebanon. Additional support for the idea that the Fault Zone is younger than the folds is provided by the observation that many surfaces in sets, which external to the Zone consist of barren fractures, are stylolites or veins within the Zone. Such extensive modification of former fractures by solution-transfer and mineralisation probably occurred during the evolution of the Fault Zone which was superimposed on the older structures.

In the northern Lebanon it is difficult to match individual stratigraphic horizons or structures across the Fault Zone and hence a reliable estimate of displacement is difficult to achieve. The geometry of the distinctive structural assemblage which is restricted to the Fault Zone indicates that the sense of shear was left-lateral (Fig. 8). The Quaternary basin of Yammouné possesses a side length of about 7 km, and, if this basin is a pull-apart structure, its length may be approximately the same as the displacement on the Fault Zone. It is noteworthy that this value is approximately equal to the offset of Pliocene lavas at the Lebanese–Syrian border in the north. Considering that the major part of the displacement on the Lebanese segment of the Dead Sea Rift would be achieved during rotation of the fold belt early in the Cenozoic, it is not surprising that the slip on the fault cutting the folds is substantially less than the total displacement across the entire width of the segment.

Shortening across the Lebanese fold belt

Inspection of Renouard's (1955), Wolfart's (1967) and Beydoun's (1977a, b) structural profiles across the Lebanese fold belt shows that the shortening achieved by folding and faulting rarely exceeds 10%. As proposed earlier in this paper, some additional shortening will have resulted from the combined effects of the development of the conjugate wrench faults, *h*0*l* contraction faults and *hk*0 shear fractures. In addition, it is suggested that a significant component of shortening accompanied the development of the widespread *bc* pressure solution surfaces. Although it is unlikely that shortening values of 50% as determined near Baabdate (Fig. 3c) apply everywhere we believe that this mode of deformation may be responsible for substantial shortening undetected by earlier workers in the Lebanon. Regrettably, the security situation within the country rendered our return to investigate this aspect in detail somewhat impractical.

Conclusions

The planar mesoscopic structures and their relationships to the Mount Lebanon anticlinorium and Bekaa synclinorium are compatible with those which are likely to develop within a transpressive regime related to the oblique convergence of the Arabian and African/Sinai plates across a NNE trending boundary. Early formed folds possibly trended approximately E–W and were subsequently tightened and rotated into alignment with the margins of the zone, mainly during the late Palaeogene. Rotation was accompanied by inhomogeneous axial elongation as a consequence of the development of conjugate wrench faults, normal faults and mesofractures belonging to sets or systems in *ac*, *hk*0 or 0*kl*. At a late stage, probably during the Neogene, the left-lateral Yammouné Fault Zone cut the fold belt and generated a distinctive assemblage of neotectonic structures restricted to the Zone.

Pressure solution across surfaces striking parallel to the fold belt may have achieved substantial shortening, and may offer a partial solution to the problem of the apparent lack of evidence for telescoping within the Lebanese fold belt.

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