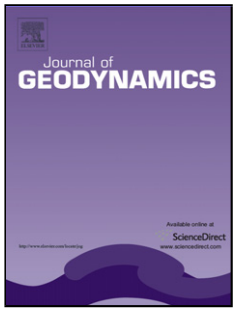
Basin tectonics during the Early Cretaceous in the Levant margin, Lebanon

C. Homberg, E. Barrier, M. Mroueh, W. Hamdan, F. Higazi



Title: Basin tectonics during the Early Cretaceous in the Levant margin, Lebanon

Authors: C. Homberg, E. Barrier, M. Mroueh, W. Hamdan, F. Higazi

PII: S0264-3707(08)00079-3
DOI: doi:10.1016/j.jog.2008.09.002
Reference: GEOD 866

To appear in: *Journal of Geodynamics*

Received date: 13-2-2008
Revised date: 5-9-2008
Accepted date: 5-9-2008

Please cite this article as: Homberg, C., Barrier, E., Mroueh, M., Hamdan, W., Higazi, F., Basin tectonics during the Early Cretaceous in the Levant margin, Lebanon, *Journal of Geodynamics* (2008), doi:10.1016/j.jog.2008.09.002

Basin tectonics during the Early Cretaceous in the Levant margin, Lebanon.

C. Homberg [1*]
E. Barrier [1]
M. Mroueh [2]
W. Hamdan [2]
F. Higazi [2]
1 : Université Pierre et Marie Curie, Laboratoire de Tectonique, UMR7072, Case 129, 4 place jussieu, 75252 Paris Cedex 05, France
2 : Université libanaise, Faculté d'Agronomie, B.P. 13-5368 Chourane, Beyrouth 1102-2040 Lebanon.
* corresponding author

ABSTRACT

We present new brittle tectonic data constraining the onset of formation of the eastern passive margin of the Levant basin (Eastern Mediterranean basin) in Lebanon. From the identification of syn-tectonic growth faults, we infer an extensional tectonic regime starting in the Early Cretaceous and ceasing during the Cenomanian. The related stress field had a NNE-SSW direction of extension. It produced WSW-ENE to WNW-ESE normal faults with offsets as large as several hundred meters. Late Jurassic volcanic activity preceded this rifting event and continued until the late Aptian. Thickness and facies variations of the Upper Cretaceous sequence indicate that this rifting event led to the development of an E-W basin in Lebanon. This basin deepens westward, with a possible offshore continuation. The significant obliquity between the ~NE-SW Early Mesozoic faults in southeastern corner of the Levant basin and ~E-W Early Cretaceous faults recognized in Lebanon indicates that the mechanisms driving the development of the Eastern Mediterranean basin drastically changed during the Mesozoic.

KEY WORDS : Levant basin, Eastern Mediterranean Basin, Neotethys, Early Cretaceous extension, rift tectonics, Lebanon.

1. Introduction

The Levant basin (LB), the easternmost part of the Eastern Mediterranean basin (EMB), is generally regarded as a basin that resulted from rifting. This is supported by crustal thinning from 30-35 km on the Africa and Arabia continents (Makris et al., 1988) to ~8km below the LB overlain by a 10-14 km thick sedimentary pile of probably Jurassic to Present age (Makris et al., 1983; Ginzburd and Ben-Avraham, 1987; Vidal et al., 2000; Ben-Avraham et al., 2002). However, several aspects of the history of the LB remain unsolved. First, the affinity of the crust below the LB is regarded either as highly stretched continental (Woddside et al., 1977; Hirsch et al., 1995; Robertson et al., 1996; Vidal et al., 2000) or as oceanic (Ginzburd and Ben-Avraham, 1987 and Garfunkel, 1998). Second, various ages for the opening of the basin have been proposed: from Triassic or Late Permian (Freund, 1975; Garfunkel, 1998 and Stampfli et al., 2002), Jurassic (Ginzburg and Guitzman, 1979) to Cretaceous (Dercourt et al., 1986). Third, some difficulties arise in reconciling the kinematic models that predicts a N-S opening of the basin (Dercourt et al., 1986; Stampfli et al., 2002) with tectonic structures such as Mesozoic NE-SW faults recognized in the LB and along its margins (Vidal et al., 2000).

These unsolved issues permit a variety of plate tectonic models of the western Neotethys. A major difficulty in getting relevant information on the LB is attenuation of seismic signals by Messinian evaporates, thus precluding good imaging of the underlying Mesozoic strata and structures and enhancing the uncertainties on the reflectors. This paper presents new observations in the Mesozoic sedimentary succession of the eastern passive margin of the LB, in Lebanon. After a review of the regional structures, we present arguments for an Early Cretaceous extensional tectonic event in Lebanon. Comparing published data and those of this paper, we then discuss the tectonic history and setting of the LB.

2. Geological frame of Lebanon

2. 1. Tectonic structures of Lebanon

The Levant margin is now the active left-lateral transform boundary between the Nubia and Arabia plates, namely the Dead Sea Fault System (DSFS). The DSFS developed during Late Cenozoic times with a roughly N-S direction and now connects the Red Sea Rift basin in the south to the Arabia-Eurasia-Nubia triple junction in the north (fig. 1). About 100 km of left-lateral slip have been suggested for the southern DSFS (Quennel, 1958; Freund et al., 1970).The main fault of the DSFS in Lebanon is the ~150 km-long left-lateral NNE-SSW Yammouneh fault. The N-S Roum fault and the NE-SW Rachaya and Sergaya faults are secondary faults, with more moderate offsets (Butler et al., 1988). The Meso-Cenozoic sequence is folded in three wide NNE-SSW folds that are, from west to east, the Mount Lebanon Anticline, the Bekaa syncline, and the Anti-Lebanon anticline (fig. 1). These folds are thought to have accommodated the shortening imposed by the obliquity of the Nubia-Arabia plate motion (e. g., DeMets, 1990; Jestin et al., 1994) relative to the strike of the Yanmouneh fault (Freund et al., 1970; Garfunkel, 1981; Butler et al., 1988). Local NE-SW and NW-SE faults also exist. They are thought to be minor dextral and sinistral faults, respectively, related to the transform tectonics (Hancook and Atiya, 1979). The Cenozoic tectonics exhumed and translated the Mesozoic structures away from their initial paleogeographic positions. Although strike-slip movements occurred on several faults in Lebanon, a large part of the northward translation was absorbed along the Yammouneh fault (Walley, 1998). Because most of our observations were done west of this fault, and thus in the 'Nubia attached' domain, integration of the Mesozoic structures in Lebanon in the geodynamic context of the opening of the EMB does not necessitate taking into account the Cenozoic movements.

2. 2. The Mesozoic sequence

The Mesozoic sequence in Lebanon crops out in the cores of the Mount Lebanon and Anti-Lebanon anticlines (fig. 1). The Jurassic and Lower Cretaceous sequences consist of shallow marine

carbonates or continental sandstones. The oldest outcropping levels are Lower to Middle Jurassic limestones or dolomites. They are overlain by a thick sandy sequence, the Chouf sandstones (called Grès de Base by previous authors). These fluvial deposits are Neocomian to Barremian in age (Dubertret, 1975); the first levels postdate the early Valanginian (Ferry, personal communication). The overlying Aptian and Albian formations are shallow marine carbonates, or locally sandstones and marls. They include a remarkable marker-bed that is the lagoonal Jezine Formation (previously known as Barre de Blanche), uppermost early Aptian in age. The alternation of shallow water carbonates and deeper marls of the Cenomanian and Turonian sequence precedes widespread marine flooding at Senonian time and deposition of chalky limestones. The pioneer Lebanese workers (e. g., Saint Marc, 1974; Dubertret, 1975) recognized that the Mesozoic sequence exhibits, at the Levant basin scale, a westward thickening and facies evolution from shallow marine sediments onshore to deep pelagic sediments offshore. This led some authors to propose that the present-day western limb of the Mount Lebanon anticline was the eastern margin of the Levant basin during the Mesozoic, trending, therefore, NNE-SSW (e. g., Walley, 1998). However, the Lower Cretaceous sequence also exhibits a N-S thickness variation. It is particularly spectacular for the Chouf sandstones, whose thickness reach 300m in Central Lebanon (Chouf area) and is reduced to a few tens of meters in northern Lebanon. The geometry and the opening direction of the Lebanese sector of the LB are thus difficult to establish solely on the basis of the sedimentological architecture. We thus sought out direct arguments for tectonic activity during Mesozoic times.

3. Early Cretaceous extensional tectonics

3. 1. Dating arguments and faulting

In order to constrain the Mesozoic tectonics in Lebanon, we examined the faults that cut the Mesozoic formations. Complete or partial sections of the Middle Jurassic to Cenomanian sequence are visible along the large valleys that incise the core of the Mount Lebanon anticline. Most faults in this area trend WSW-ENE to WNW-ESE as mapped in the 1/200 000 geological map of Dubertret (1955). They

100 are particularly well-developed in the Chouf area and are a few tens of kilometers long. These faults dip
101 either to the North or to the South, with a regular ~60° angle (Fig. 2). They offset vertically the Upper
102 Jurassic to Lower Cretaceous beds of several tens to hundreds of meters. Because the strata are sub-
103 horizontal, their offsets cannot result from a pure strike-slip fault movement. When the fault plane is
104 visible (~50% of the faults), the striae inclination is systematically close to 90°, indicating that faults are
105 dip-slip normal faults (fig. 3). It follows that most WSW-ENE to WNW-ESE faults cutting the Mesozoic
106 series were produced by an extensional event the age of which is now discussed.

107 When outcrop conditions allowed observation of the whole Lower to Middle Cretaceous sequence,
108 the Cenomanian beds sealed most of the normal faults, as illustrated in figure 2. A few faults enter into the
109 basal Cenomanian, which generally forms the top of the cross-sections. According to the geological maps
110 of Dubertert, these faults do not extend more than a few hundred meters from the Albian-Cenomanian
111 boundary. St-Marc (1970) showed that the first Cenomanian levels are in fact Late Albian in age.
112 Therefore, the extensional tectonics that produced the WSW-ENE to WNW-ESE normal faults ended just
113 prior to the Cenomanian. Our observations in the younger series confirm tectonic quiescence during the
114 Late Cretaceous. Some NE-SW and NW-SE faults, well developed in southern Lebanon, cut the Upper
115 Cretaceous and Eocene succession (fig. 1). Because our paper focuses on Mesozoic structures, we do not
116 further discuss these Cenozoic features.

117 In order to define the time span of this extensional tectonic event, the whole Mesozoic sedimentary
118 succession was examined for normal growth faults. The oldest such faults were observed in the Chouf
119 sandstones. Basaltic lenses interlayered in these fluviatile deposits indicate that volcanic activity
120 accompanied the extensional tectonics. The normal fault shown in figure 4 illustrates that normal faulting
121 continued during Aptian and Albian times. No growth faults were recognized in the Middle to Late
122 Jurassic levels. However, such structures may be difficult to document in this poorly bedded sequence.
123 We thus do not exclude normal faulting during Late Jurassic time, but believe that significant vertical
124 movements did not start not before Early Cretaceous. The widespread Late Oxfordian to Early (Mid?)

Kimmeridgian basalts and tuffs attest to a regional volcanic event that immediately pre-dates the Early Cretaceous phase of extensional tectonics. Extensional tectonics documented in Lebanon thus started in the Early Cretaceous and ended at in the late Albian (or early Cenomanian). The WSW-ENE to WNW-ESE orientation of the several kilometer long normal faults suggests a rough N-S direction of extension.

3.2. Stress field

Because the sole direction of normal faults does not necessarily indicate an accurate direction for the driving stresses, fault-slip data on meso-scale faults cutting the Lower Cretaceous and older formations at 29 sites were also measured. Fault-slip data were collected on faults with offsets of 1-100 mm and, when possible, on Early Cretaceous growth faults. The local stress states were inferred from the inversion of faults using the method of Angelier et al. (1990), which is based upon the Wallace–Bott hypothesis that faults slip in the direction of the resolved shear traction. This method allows the determination of the orientation of the three principal stresses, σ_1, σ_2 and σ_3, as well as a shape ratio between principal stress differences, without any assumption on material strength. The uncertainty on the stress axis orientation depends on the 3-D distribution of the fault-slip data. When fault-slip data are of various attitudes and include conjugate sets, the accuracy on the direction and plunge of the principal axes is ~10°.

The fault population includes strike-slip faults at all the visited sites and includes normal faults at 18 sites. Strike-slip faults were disregarded because their compatibility with Dead Sea Fault System tectonics suggests that they formed during the Cenozoic. The normal faults found at 18 sites typically strike between N060ºE and N140ºE (azimuthal range described in clockwise sense). Their dips generally exceed 55º, with 77% of them dipping between 60º and 85º. Fault inversion yields normal stress tensors in which the minimum and intermediate principal stresses are sub-horizontal and the maximum stress is sub-vertical. The rose diagram in figure 5 illustrates the azimuthal distribution of the minimum horizontal stress axis (σ_3). The azimuth of σ_3 spreads out the N029ºE arithmetic mean and lies between N152°E and N064°E. This range is rather large, but 71% of the stress states have a σ_3 direction between N160ºE and

N040ºE. The data are therefore quite consistent and indicate a NNE-SSW direction of extension. Data out of this range may reflect local stress deflections.

At five sites, we could establish that the calculated stress states are Early Cretaceous in age. At two of these, the fault population includes a majority of fault-slip data on Early Cretaceous growth faults with offsets in the range of meters. At the other three, faults were formed in the close vicinity of large-scale Early Cretaceous normal growth faults showing offsets of several or tens of meters. Because faulting generally implies a variety of fracture scales, we are confident that slip on these meso-scale faults reflects the same mechanisms as the large-scale faulting. For the remaining 13 sites, we could not establish with confidence the absolute age of the normal fault-slips. However, for three of them situated in highly dipping strata, the calculated stress states clearly predated the Neogene folding (fig. 5). Indeed, measurement of present-day stresses (e.g., Cornet et Burlet, 1992; Brudy et al., 1997) and paleostress reconstructions (e. g., Homberg et al., 2002) support the hypothesis that stresses follow the Anderson model in which two of the principal stresses are horizontal, the third one being vertical. For the three sites discussed above, this criterion is fulfilled when performing the stress inversion on faults with their backtilted attitude (faults rotated around the local strike of bedding by the amount of tilting). We attributed the calculated stress states in the remaining 13 sites to the Early Cretaceous extension, although we cannot firmly exclude that some of them may reflect a later tectonic event. However, because these 13 stress states together show a NNE-SSW direction of extension that is compatible with the strike of the large-scale WSW-ENE to WNW-ESE normal growth faults, we believe that they also reflect the driving mechanism of Early Cretaceous tectonics.

4. Discussion and conclusion

Our investigation of the Mesozoic structures indicates that a phase of extensional tectonics occurred in Lebanon during the Early Cretaceous. It started during the deposition of the Chouf sandstones, and thus during late Valanginian or Hautervivian times, and ceased during the Cenomanian. This NNE-

SSW extension produced WSW-ENE to WNW-ESE normal faults with length of several kilometers to several tens of kilometers and with offsets as large as several hundred meters. In view of these fault data, we interpret the regional northward thinning (and facies evolution) of the Lower Cretaceous sedimentary sequence as the result of the development of a roughly E-W striking basin in Lebanon. This interpretation differs from that of Walley (1998) who interpreted the westward thickening of the Mesozoic sequence near the coast line as a NNE-SSW structural grain, with no reference to specific faults. This interpretation seems no longer valid considering that the observed abrupt changes of the sequence thickness are controlled by E-W faults (fig. 4) and that the regional extensional direction trends NNE-SSW (fig. 5). The westward thickening implies rather that the E-W Lebanese basin continues and deepens westward, that is offshore through the Levant basin. The axis of the Lebanese basin was situated somewhere in central (or southern) Lebanon, most probably in the Chouf region. Here, the Lower Cretaceous succession reaches its maximum thickness of about 700 m and is offset by numerous normal growth faults. The northern margin of the basin was situated ~ 50km to the North, south of Tripoli, where fluvial and shallow marine sedimentation was strongly reduced and sometimes replaced by lavas flows. The southern margin is not visible due to later Paleogene deposits that cover southern Lebanon. Late Jurassic volcanic activity preceded the development of the basin and continued until the late Aptian. Quite remarkable is that Early Cretaceous tectonics produced a combination of WSW-ENE and WNW-ESE faults in Lebanon (fig. 1). Considering the mean NNE-SSW direction of extension inferred from the fault analysis, the WSW-ENE faults may reflect an earlier structural fabric. Such a fabric is well-developed eastward in Syria in the WNW-ESE Permian to Early Mesozoic Palmyride Trough (e. g., Brew et al., 2001).

As discussed above, the westward increase of the thickness of the Lower Cretaceous succession described by Walley (1998) suggests that the E-W Lebanese basin extends further offshore into the deep Levant basin (LB), although its structural continuity may have been slightly disrupted by offshore Cenozoic faulting. Extrapolating our investigation in Lebanon, the LB and more generally the Eastern Mediterranean Basin (EMB) registered a major extensional event during the Early Cretaceous. Although

the Early Cretaceous is marked by intense volcanism in Lebanon, our data do not allow us to decipher whether oceanic spreading occurred or not in the easternmost part of the EMB. On the other hand, they exclude that the EMB had already attained its present configuration during the Early Cretaceous time as claimed by Garfunkel (1998). Taking a full 0.5 cm/yr opening rate during the about 40 Myr of extension recorded in Lebanon, the EMB widened by 200km during the Early Cretaceous. This value is hypothetical and can be much smaller, especially if the basin did not reach the level of sea-floor spreading. Our data also suggest that the mechanisms driving the development of the EMB drastically changed during the Mesozoic (fig. 6). A WNW-ESE direction of opening during the Triassic and Jurassic was proposed by Garfunkel (1998) and Walley (1998), in the light of the NNE-SSW pre-Late Permian, Early to Middle Triassic, and Early to Middle Jurassic grabens onshore and offshore of Israel (see Cohen et al., 1990 for a review). This direction is almost perpendicular to the Early Cretaceous NNE-SSW extension documented in Lebanon, also recognized but with a N-S strike in Egypt (Hantar, 1990; Fawzy and Dahi, 1992). This change in the direction of opening, from a mean WNW-ESE to a NNE-SSW direction, occurred somewhere in the Late Jurassic. In addition to this polyphase development, the absence of significant Early Cretaceous faulting in the southern Levant margin (Israel-Jordan) could indicate that the locus of extension in the LB migrated northward.

Acknowledgements

This work was supported by the MEBE (Middle East Basins Evolution) Program and partially by the French and Lebanese CNRS, and the Lebanese University.

References

Angelier, J., 1990, Inversion of field data in fault tectonics to obtain the regional stress. III: A new rapid direct inversion method by analytical means: Geophysical Journal International, v. 103, 363-376, 1990.

224 Ben Avraham Z., Ginzburh, A., Makris, J., Eppelbaum, 2002, Crustal structure of the Levant Basin,
225 eastern Mediterranean: Tectonophysics, v. 346, 23-43.
226 Brew, G., Barazangi, M., Al-Maleh, A., K., Sawaf, T., 2000. Tectonic map and gelogic evolution of
227 Syria: GeoArabia, 6, 573-616.
228 Brudy, M., Zoback, M., D., Fuchs, K., Rumel, F., Baumgärtner, J., 1997, Estimation of the complete stress
229 tensors to 8km depth in the KTB scientific drill holes: implications for crustal strength: Journal of
230 Geophysical Research, v. 102, 18453-18475.
231 Buttler, R., W., H., Spencer, S., Griffiths, H., M., 1998, The structural response to evolving plate
232 kinematics during transpression: evolution of the Lebanese restraning bend of the Dead Sea Transform: *in*
233 Holdsworth, R. E., Strachan, R. A., Dewey, J.- F., eds., Continental Transpressional and Transtensional
234 Tectonics: Geological Society (London) Special Publication 135, 81-106.
235 Cohen, Z., Kaptsan, V., Flexer, A., 1990, The tectonic mosaic of the southern Levant: implications for
236 hydrocarbon prospects: Journal of Petroleum Geology, v. 13, 437-462.
237 Cornet F., H., Burlet, D., 1992, Stress field determinations in France by hydraulic tests in boreholes:
238 Journal of Geophysical Research, v. 97, 11829-11849.
239 Dercourt, J., Zonenshai,, L., P., Ricou, L., E., Kazmin, V., G., Le Pchon, X., Knipper, A., L.,
240 Grandjacquet, C., Sbortshikov, D., Westphal, M., Bazhenov, M., L., Laurer, J., P., Bijou-Duval, B., 1986,
241 Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias: Tectonophyscis, v.
242 123, 241-315.
243 Dubertret, L. and collaborators, 1955. Carte géologique du Liban au 1/200 000. République libanaise,
244 Ministère des Travaux publiques, Institut géographique nationnal.
245 Dubertret, L., 1975, Introduction à la carte géologique a 1/50 000e du Liban : Notes et Mémoires sur le
246 Moyent-Orient ; v. 13, 345-403.
247 Freund, R., Garfunkel, Z., Zak, I, Goldberg, M., Weissbrod, T., Derin, B., 1970, The shear along the Dead
248 Sea Rift: Philosophical Transactions of the Royal Society of London, v. 267, 107-130.

249 Freund, R., Goldberg, M., Weissbrod, T., Druckman, Y., Derin, B., 1975, The Triasic-Jurassic structure of
250 Israel and its relation to the origin of the eastern Mediterranean: Geological Survey of Israel, v. 65, 1-26.
251 Garfunkel, Z., 1998, Constrain on the origin and history of the Eastern Mediterranean basin:
252 Tectonophysics, v. 298, 5-35.
253 Garfunkel, Z., 1981, Internal structure of the Dead Sea leaky transform (rift) in relation to plate
254 kinematics: Tectonophysics, v. 80, 81-108.
255 Ginzburg, A., and Gvirtzman, G., 1979, Changes in the crust and in the sedimentary cover across the
256 transition from the Arabia platform to the Mediterranean basin: evidence form seismic refraction and
257 sedimentary studies in Israel and Sinai: Sedimentary Geology, v. 23, 19-36.
258 Ginzburg, A., and Ben-Avraham, Z., 1987, The deep structure of the central and southern Levant
259 continental margin: Annales Tectonicae, v. 1, 105-115.
260 Hancock, P., L., Atiya, M., S., 1979, Tectonic significance of mesofracture systems associated with the
261 Lebanese segment of the Dead Sea transform fault: Journal of Structural Geology, v. 1, 143-153.
262 Hirsch, F., Flexer, A., Rosenfeld, A., Yellin-Dror, A., 1995, Paliinspastic crustal setting of the Eastern
263 Mediterranean: Journal of Petroleum Geololgy, v. 18, 149-170.
264 Homberg, C., Bergerat, F., Philippe, Y., Lacombe, O., and Angelier, J., 2002, Structural inheritance and
265 cenozoic stress fields in the Jura fold-and-thrust belt (France): Tectonophysics, v. 327, 137-158, 2002.
266 Jestin, F., Huchon, P., Gaulier, J. M., 1994, The Somalia plate and the eastern Africa Rift System, present-
267 day kinematics: Geophysical Journal International, v. 116, 637-654.
268 Makris, J., Ben-Avraham, Z., Behle, A., Ginzburg, A., Giese, A., Steinmetz L., Whithmarsh, R., B.,
269 Eleftheriou, S., 1983, Seimic refraction profiles between Cyprus and Israel and their interpretations:
270 Geophysical Journal of the Royal Astronomical Society, v. 75, 575-591.
271 Makris, J., Rihm, R., Allam, A., 1988, Some geophysical aspects of the evolution and structure of the
272 crust in Egypt: *in* El-Gaby, S., Greiling, R., O., eds., The Pan-African belt of the Northeat Africa and

adjacent areas: International monograph series on interdisciplinary earth science and applications, 345-369.

Quennell, A., M., 1958, The structure and the evolution of the Dead Sea Rift: Quarterly Journal of the Geological Society of London, v. 64, 1-24.

Robertson, A.H.F., Dixon, J., E., Brown, S., Collins, A., Morris, A., Pickett, E., Sharp, I., and Ustaomer, T., 1996, Alternative tectonic models for the Late paleozoic-Early Tertairy development of the Tethys in the Eastern Mediterranean region: *in* Morris, A., and Tarling, D., H., eds., Paleomagnetism and tectoncs of the Mediterranean region: Geological Society (London) Special Publication 105, 239-263.

Saint-Marc, P., 1974, Etude stratigraphique et micropaléontologique de l'Albien, du Cénomanien et du Turonien du Liban : Notes Mém. Moyen-Orient, v. 8, 8-342.

Saint-Marc, P., 1970, Le Crétacé inférieur et moyen du bord occidental du Jabl Sannine (Liban) : Notes et Mém. Moyen Orient, v. 12, 217-226.

Stampfli, G., M, and Borel, G., D., 2002, A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrones: Earth and Planetary Science Letters, v. 196, 17-33.

Vidal, N., Alvarez-Marron, J., Klaeschen, D., 2000, Internal configuration of the Levantine Basin from seismic reflection data (Eastern Mediterranean). Earth and Planetary Science Letters, v. 180, 77-89.

Walley, C., 1998, Some outstanding issues in the geology of Lebanon and their importance in the tectonic evolution of the Levantine region: Tectonophysics, v. 298, 1, 37-62.

Woodside, J., M., 1977, Tectonic elements and crust of the eastern Mediterranean Sea. Marine Geophysical Researches, v. 3, 317-354.

Fig. 1. Kinematic frame of Lebanon A: Simplified tectonic map of the Eastern Mediterranean domains Ar, Eu, Nu: Arabia, Eurasia, Nubia plates. DSF; Dead Sea Fault. RS and CZ: Read Sea rift and Arabia-Eurasia collision zone. LV: Levant Basin. B: Main structures of Lebanon. YF, RoF, RaF, SF: Yamouneh, Roum, Rachaya, Sergaya fault. Be, Ba, Tr: cities of Beirut, Balbeck, Tripoli.

Fig. 2. Normal faults cutting the Jurassic to Lower Cretaceous sequences. See fig. 1 for location. The uppermost Albian beds seal the normal faults. Jf: Jezine formation.

Fig. 3. Early Cretaceous normal fault plane cutting the Jezine formation. Site of Kafer Hachno (see fig. 1 for location). The striae or slip vector (thin arrows) is aligned with the maximum dip. View is to the N°30°E. Meso-scale faults collected in this site and corresponding stress state are shown. Continuous lines: fault planes. Slickenside lineations in dots with double arrows for strike-slip motion and outward-directed single arrow for normal motion. Gray stars with 5, 4, 3 arms: σ_1, σ_2, and σ_3, respectively. Divergent large black arrows show directions of σ_3.

Fig. 4. Aptian-Albian growth fault. Inset shows how the growth fault split upward into two branches, the southern making of clockwise angle with the single deep fault. Jf: Jezine formation. See fig. 1 for location.

Fig. 5. Stress states during the Early Cretaceous extension in Lebanon.

Arrows indicate the direction of extension (σ_3) obtained from secondary fault inversion. Examples of fault-slip data and stress calculation are shown. In highly dipping strata, age of stress states relative to folding was obtained using the Anderson model in which two one of the principal stresses is vertical. Stress sates predate folding if this criterion is fulfilled when performing the stress inversion on faults with

318 their backtilted attitude. The rose diagram of the σ_3 direction is shown. CA: Chouf area. Same legend as in
319 fig. 3.
320
321 Fig. 6. Main extensional tectonic event in the polyphase Levant basin.

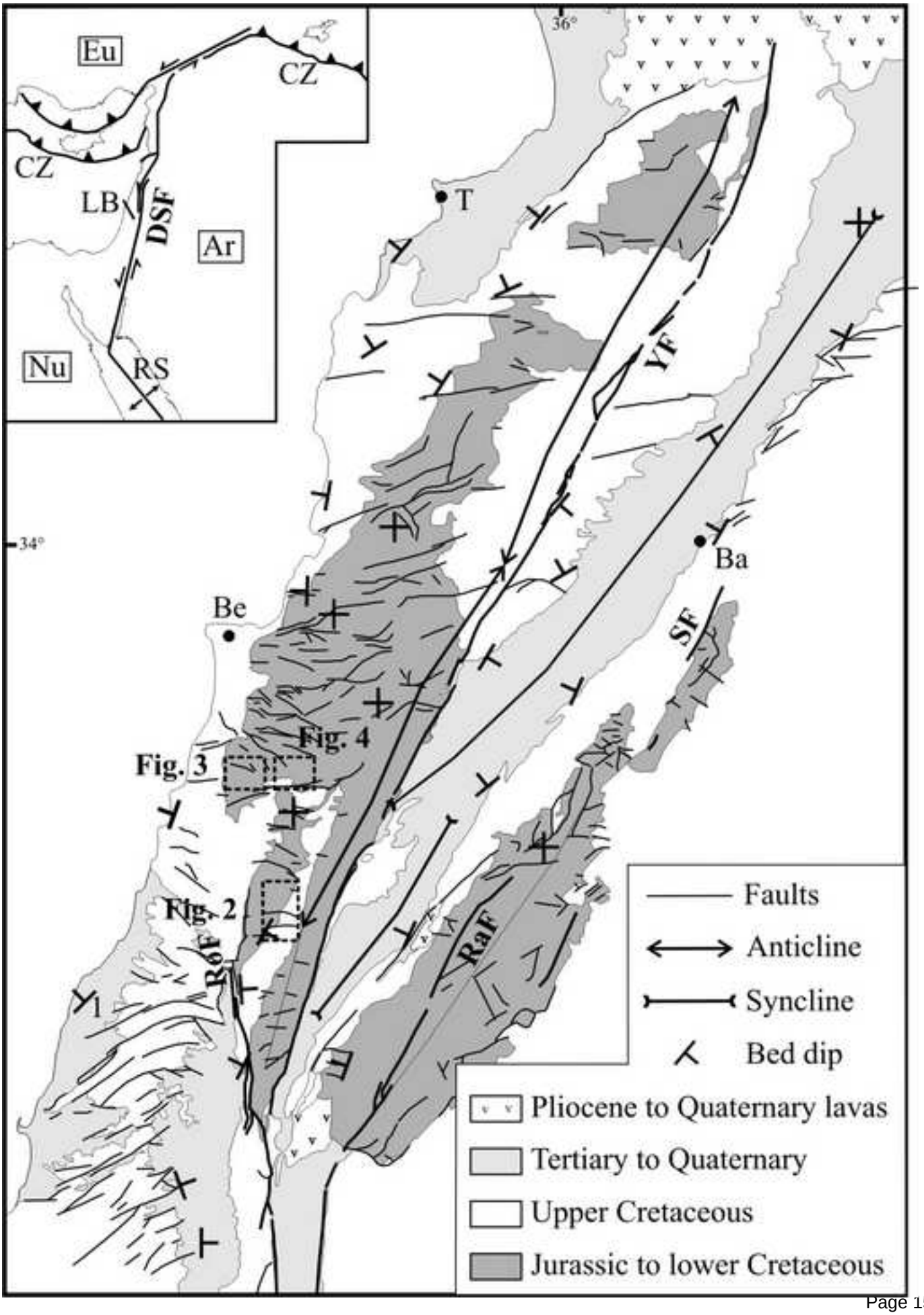


Figure2

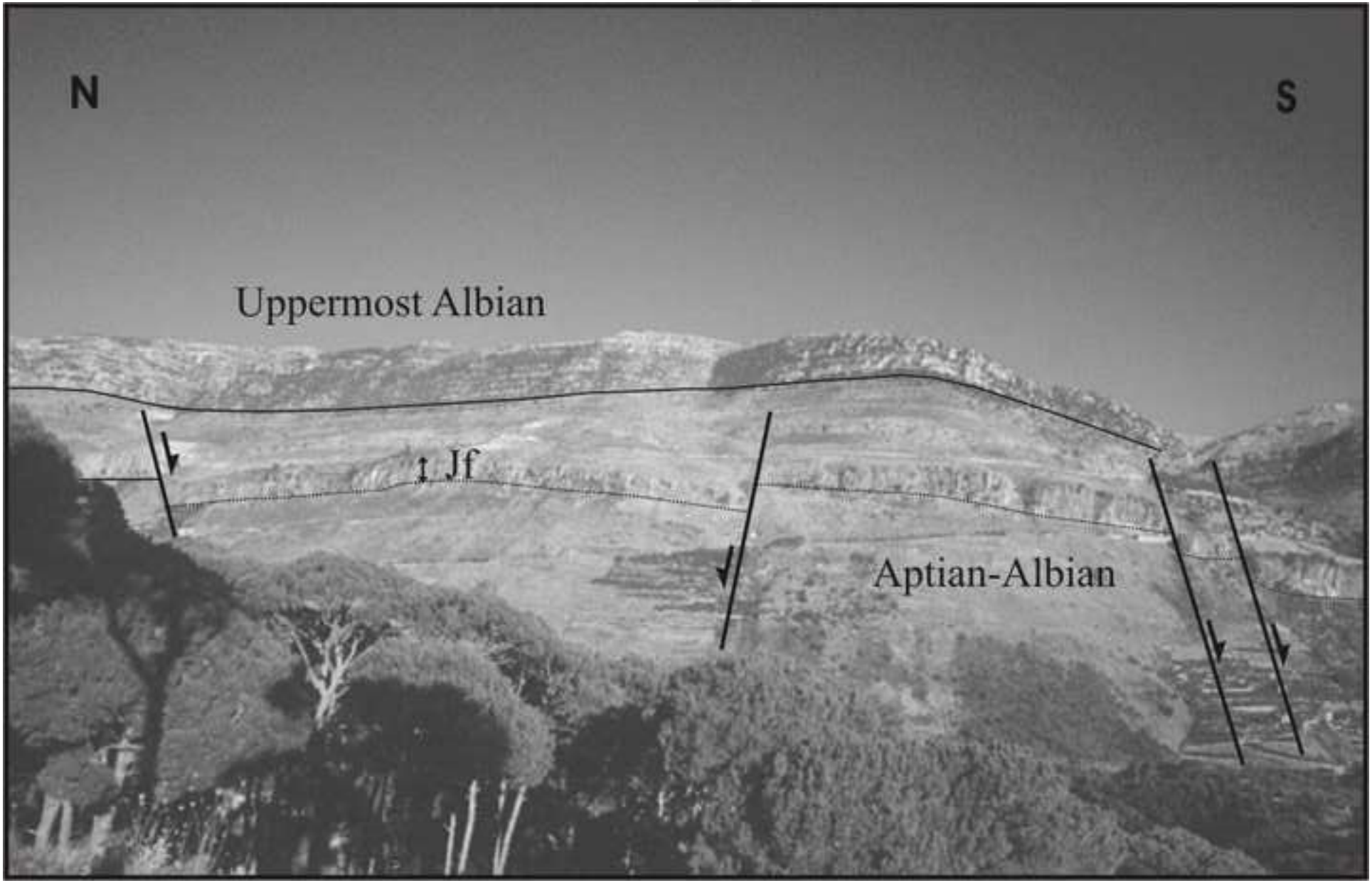


Figure3

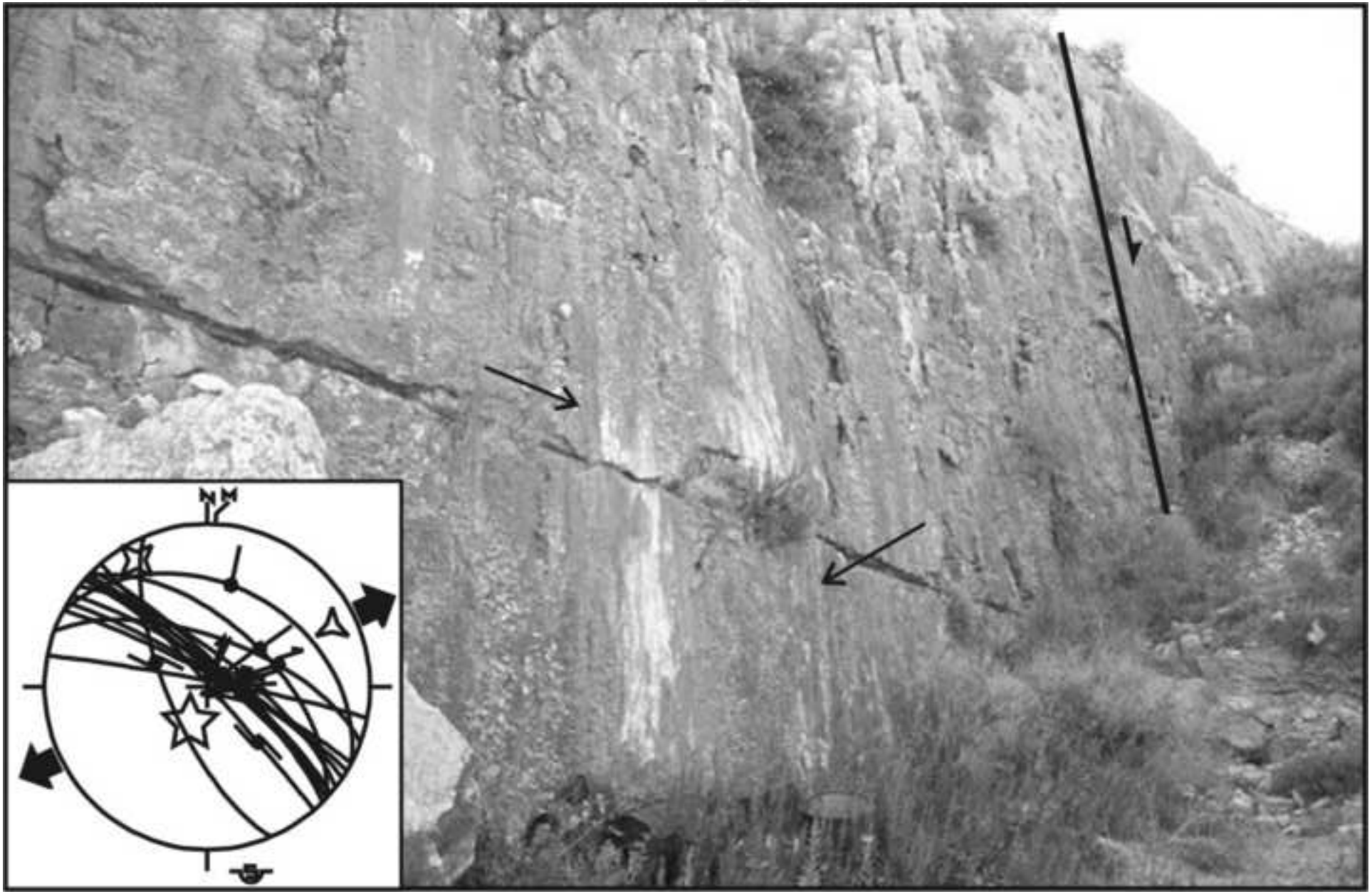
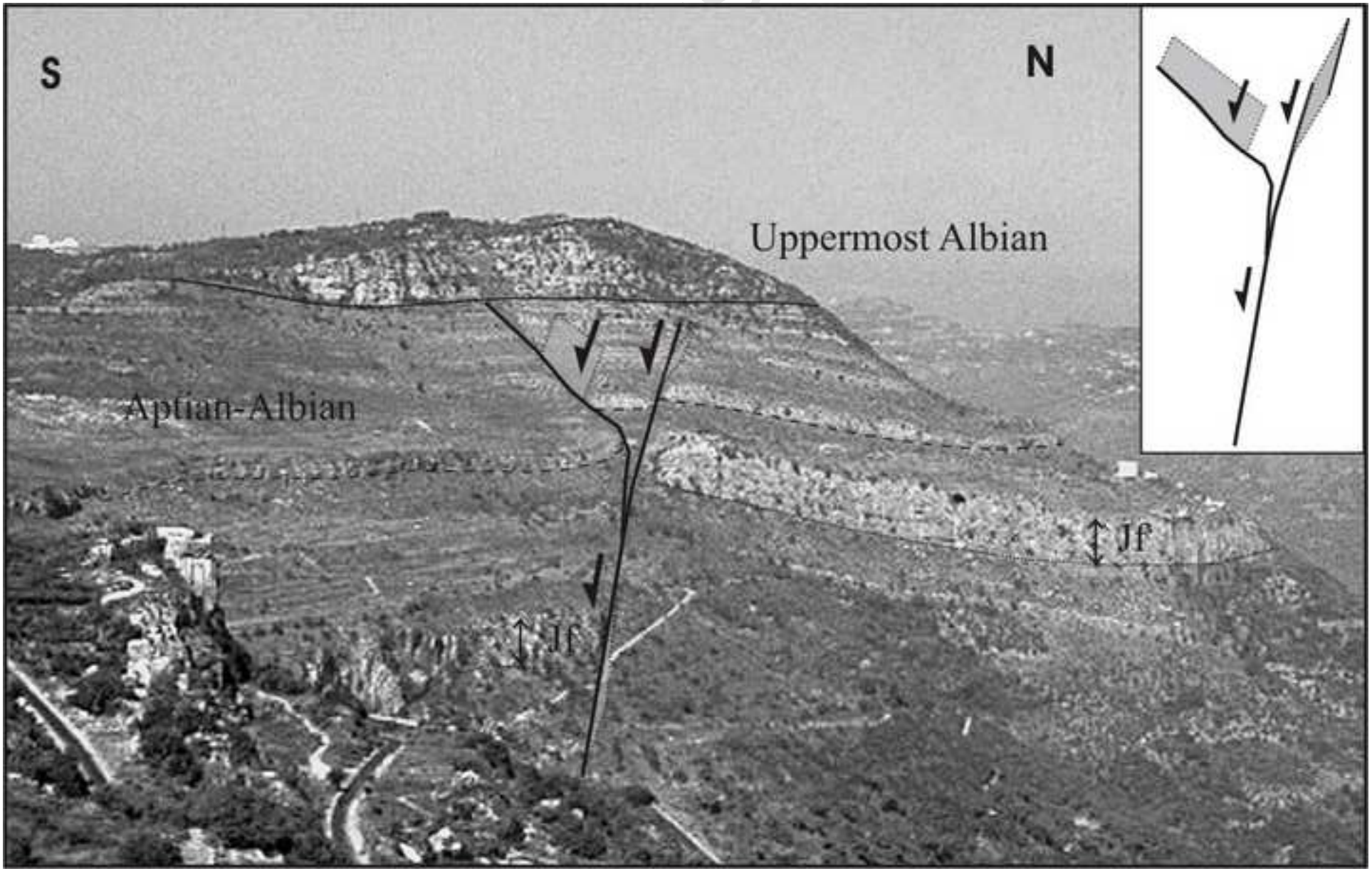


Figure4



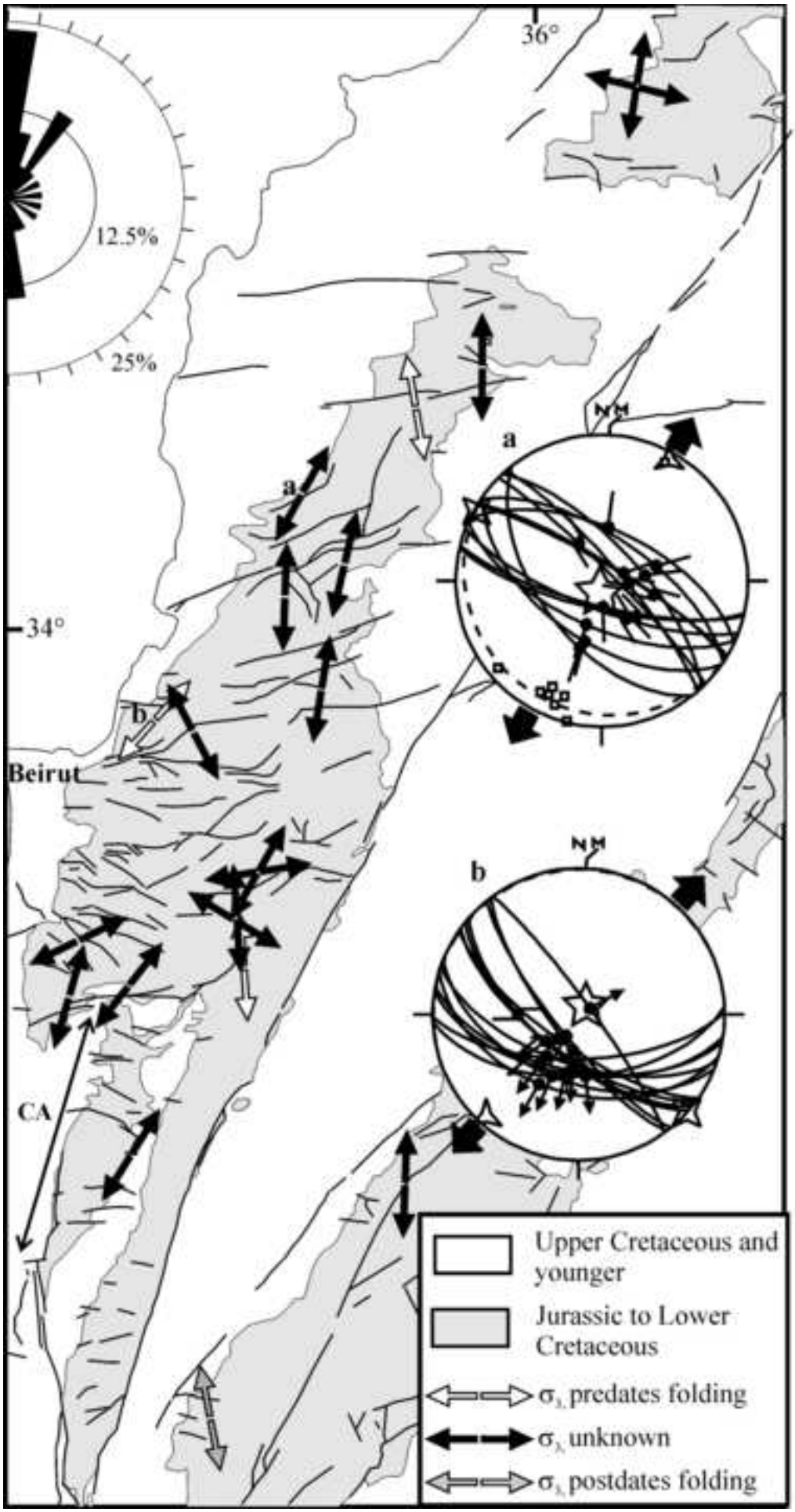
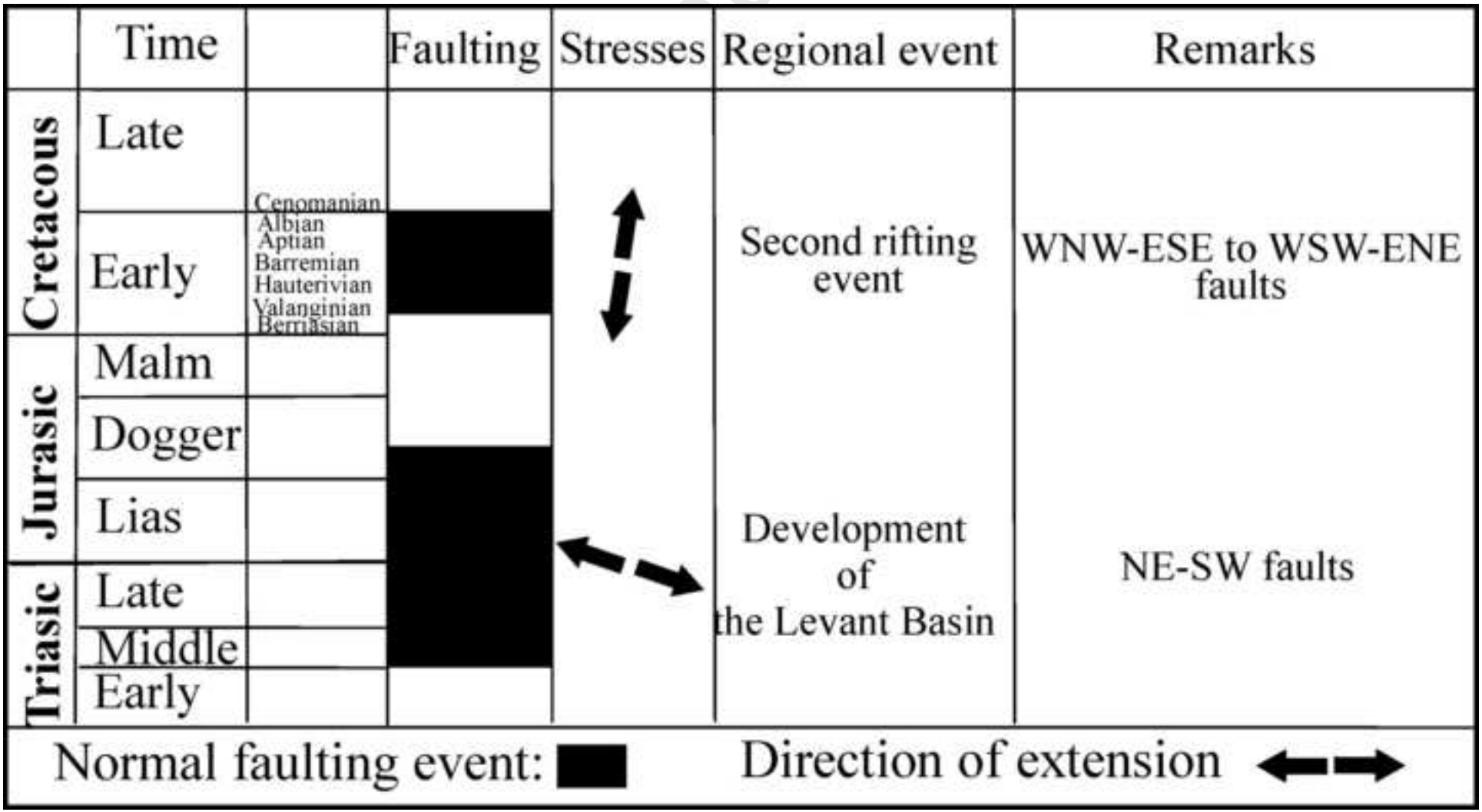


Figure6


Time
Faulting
Stresses
Regional event
Remarks
Cretacous
Late
Early
Cenomanian
Albian
Aptian
Barremian
Hauterivian
Valanginian
Berriasian
Second rifting event
WNW-ESE to WSW-ENE faults
Jurasic
Malm
Dogger
Lias
Development of the Levant Basin
NE-SW faults
Triasic
Late
Middle
Early
Normal faulting event:
Direction of extension