The Shear along the Dead Sea Rift [and Discussion]

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Phil. Trans. R. Soc. Lond. A 1970 **267**, 107-130
doi: 10.1098/rsta.1970.0027

Phil. Trans. Roy. Soc. Lond. A. **267**, 107–130 (1970) [107]
Printed in Great Britain

The shear along the Dead Sea rift

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Recent surface and subsurface geological investigations in Israel and Jordan provide new data for the re-examination of Dubertret's (1932) hypothesis of the left-hand shear along the Dead Sea rift. It is found that while none of the pre-Tertiary sedimentary or igneous rock units extend right across the rift, all of them resume a reasonable palaeographical configuration once the east side of the rift is placed 105 km south of its present position. It is therefore concluded that the 105 km post-Cretaceous, left-hand shear along the Dead Sea rift is well established.

The 40 to 45 km offset of Miocene rocks and smaller offsets of younger features indicate an average shear movement rate of 0.4 to 0.6 cm a^{-1} during the last 7 to 10 Ma. Unfortunately, the 60 km pre-Miocene movement cannot be dated yet.

Along the Arava and Gulf of Aqaba and in Lebanon the shear is divided over a wide fault zone within and outside the rift.

Historical review

The verse '...and the Mount of Olives shall cleave in the midst thereof towards the east and towards the west,...and half of the mountain shall remove towards the north, and half of it towards the south' (Zechariah, xiv. 4), can probably be regarded as a description of left-hand shear by an ingenious observer who lacked the professional terms. One century ago Lartet (1869) noticed that Arabia and Africa might have drifted apart in an oblique left-hand direction to open up the Red Sea.

About 60 years later Dubertret (1932), following Lartet's idea, advocated also by Bogolepov (1930) and von Seidlitz (1931), suggested that a 160 km left-hand shear along the Dead Sea rift, associated with a 6° rotation between Arabia and Africa, might explain several structural relations in the Levant. Wellings (in Willis 1938) realized that this hypothesis corresponds to the offset of the marine Cambrian and Jurassic beds across the rift south of the Dead Sea. Willis, however, rejected this hypothesis, and during the following 20 years it was completely neglected in papers about the geology of the Levant (e.g. Picard 1943; Dubertret 1947). It was not mentioned even in papers which discussed other strike slip faults in this region (Bentor & Vroman 1954; Renouard 1955; Vroman 1957).

Quennell (1958, 1959) revived Dubertret's hypothesis, though to his opinion the shear amounts to 107 km as indicated by the offsets across the rift of a Precambrian porphyry body, of Cambrian limestone, copper and manganese sandstone, of marine Triassic and Jurassic beds, of the southern extent of the marine Albian and the Upper Cretaceous transgressions, of Senonian bituminous chalk, and of three pairs of transverse faults. Quennell suggested that a Pleistocene movement of 45 km explains several geomorphic features, the most prominent of which is the shape of the deep depression of the Dead Sea. The remaining 62 km shear was in his opinion of Miocene age.

During the following decade the discussion developed according to two main general considerations: palaeographical and structural. Burdon (1959) reviewed Quennell's arguments, supplementing them by his observation of recent horizontal displacements of about 10 m in the rift, but he found difficulties in tracing either the continuation or the structural effects of the termination of the shear movement southwards and northwards. Consequently he preferred an alternative explanation of the facies offsets discussed by Quennell, namely that they reflect an original bend of the ancient coast lines along the place occupied now by the rift. Henson (1956) and Wetzel & Morton (1959) shared this opinion.

Bentor & Vroman (1960) carried this explanation one step further, suggesting that the bend of the coast was controlled by the east fault of the rift, which raised the east side higher than the west side already during the Jurassic, so that the transgression of the Jurassic sea from the northwest reached farther south on the west side than on the east side. In this way they explained the 600 m thick sequence of marine Jurassic in Massada-1 test well on the west margin of the Dead Sea, right opposite the complete absence of the Jurassic on the east side.

A detailed study of the Lower Turonian beds (Freund 1961) showed that various lithofacies and biofacies are offset across the rift by about 100 km left hand, in accordance with the offsets mentioned by Quennell. De Sitter (1962) accepted the Jurassic and Turonian data as evidence supporting the shear hypothesis.

Swartz & Arden (1960) discussed the rotational opening of the Red Sea and the Gulf of Aden (for which they used the term 'Pa'ar' proposed by Shalem 1954), but they did not refer to the shear movement along the Dead Sea rift. Vroman (1961) maintained, on the other hand, that the occurrence of Precambrian to Jurassic rocks in the Danakil Alps within the Red Sea depression, contradicts the opening of the Red Sea, and thereby also the shear along the Dead Sea rift. Later oceanographic studies (see other papers in this volume) provided, however, arguments in favour of the crustal separation in the Red Sea, making thus the southward continuation of the shear less of a problem.

As to the northward continuation of the shear, Freund (1965) suggested that it extends northwards along the rift, up to southern Turkey, and that the high structures of Lebanon are due to the excess of material formed by the northward shear movement along the N 30° E trending Yamuneh segment of the rift. This model seemed to forbid a shear movement exceeding 70–80 km, which was thought to be still compatible with the recorded offsets. To Dubertret (1967), however, the structures in Lebanon are far too gentle to accommodate this shortening. He was, therefore, reluctant to accept the shear hypothesis, maintaining that the shear movement could have continued northwards only along another fault (Roum Fault) which cuts northwards to the Mediterranean Sea near Beirut. Since Roum Fault disappears beneath Cenomanian beds, the shear movement could have been, according to Dubertret, only of pre-Cenomanian age.

Freund (1965) regarded the folding and the normal faulting of the Levant as secondary structures of the shear. Deducing from their age he concluded that the shear occurred in several phases since the Upper Cretaceous. The relation between the shear and the fold structures was criticized by Garfunkel (1966), but Vroman (1963, 1967) also considered the Levant folds as secondary to shear movements, admitting thereby a shear movement on a minor scale along the Dead Sea rift.

Bender (1965, 1968*a*) commented that detailed mapping in Jordan invalidated several of Quennell's arguments for the shear hypothesis. The 100 km offset of the Cambrian limestone, copper and manganese sandstone, and Precambrian porphyry across Wadi Arava should not be regarded as evidence in favour of the shear movement, because the same rocks occur in several intermediate locations, forming thus an almost continuous belt across the rift. Nevertheless, he accepted a 25–35 km shear movement according to the offset of a certain pegmatite hornblendite from a position opposite Timna on the east side to the vicinity of Elat on the west side.

Zak & Freund (1966) recorded horizontal displacements of about 150 m younger than the Lisan Marl (23 ka b.p.). Freund, Zak & Garfunkel (1968) showed that Miocene rock bodies are offset by 40 to 45 km across the rift, and suggested therefore that the average rate of the shear movement during the last 10 Ma is about 0.4 cm a^{-1}.

In conclusion, no general agreement about the shear movement along the Dead Sea rift has been reached yet, thus Neev & Emery (1967), discussing the geology of the Dead Sea, accepted it, whereas Picard (1966, 1968) did not.

METHOD

There is no intention to present any new hypothesis in this paper, but rather to examine whether Dubertret's and Wellings's shear hypothesis is, after some 40 years of extensive geological investigations, still conjectural or if it is well established. It should perhaps be recalled that hypotheses in natural sciences cannot be proven right or wrong beyond their correspondence to all known facts on one hand, and their success in predicitng new facts on the other. Quennell argued that the score of features that are offset by about 100 km across the rift establish the shear hypothesis; if this hypothesis is correct, then the prediction that all the other geological features are likewise offset should never fail. The results of the geological investigations along the Dead Sea rift during the last decade show that this prediction is indeed correct, though sometimes in a somewhat complex manner.

The description of the majority of the rock units along the Red Sea rift from Precambrian to Miocene is presented in a series of illustrations, each of them accompanied by a brief explanation of the main relevant features. It has been preferred to present the data in stratigraphic columnar sections rather than in isopach and lithofacies maps, because the interpretative nature of such maps might have cast some doubts about the validity of the data. Anyway, the results of the two methods of representation are equal, as the trend of the lithofacies lines is usually between ENE and NNE (see, for example, Aharoni 1964).

A second set of illustrations shows the same details of the various rock units from Precambrian to Upper Cretaceous on maps where the eastern side has been shifted 105 km southwards relative to the western side with a clockwise rotation of 6° of the east side, similar to the model proposed by Freund (1965).

Several rock units are not described because they lack significant facies which can be compared on the two sides of the rift (e.g. Upper Turonian, Maastricht-Paleocene). Others are not included because they occur only in very small isolated patches (Upper Eocene–Oligocene) or they have been insufficiently studied (Pliocene–Pleistocene).

THE DEAD SEA AND JORDAN RIVER

Along the median part of the Dead Sea rift shear movement is most probably confined within the rift, as there are no faults running parallel to the rift outside it. The entire stratigraphic column is known on the two sides of the Dead Sea; it is exposed on the east side, and is drilled through on the west side.

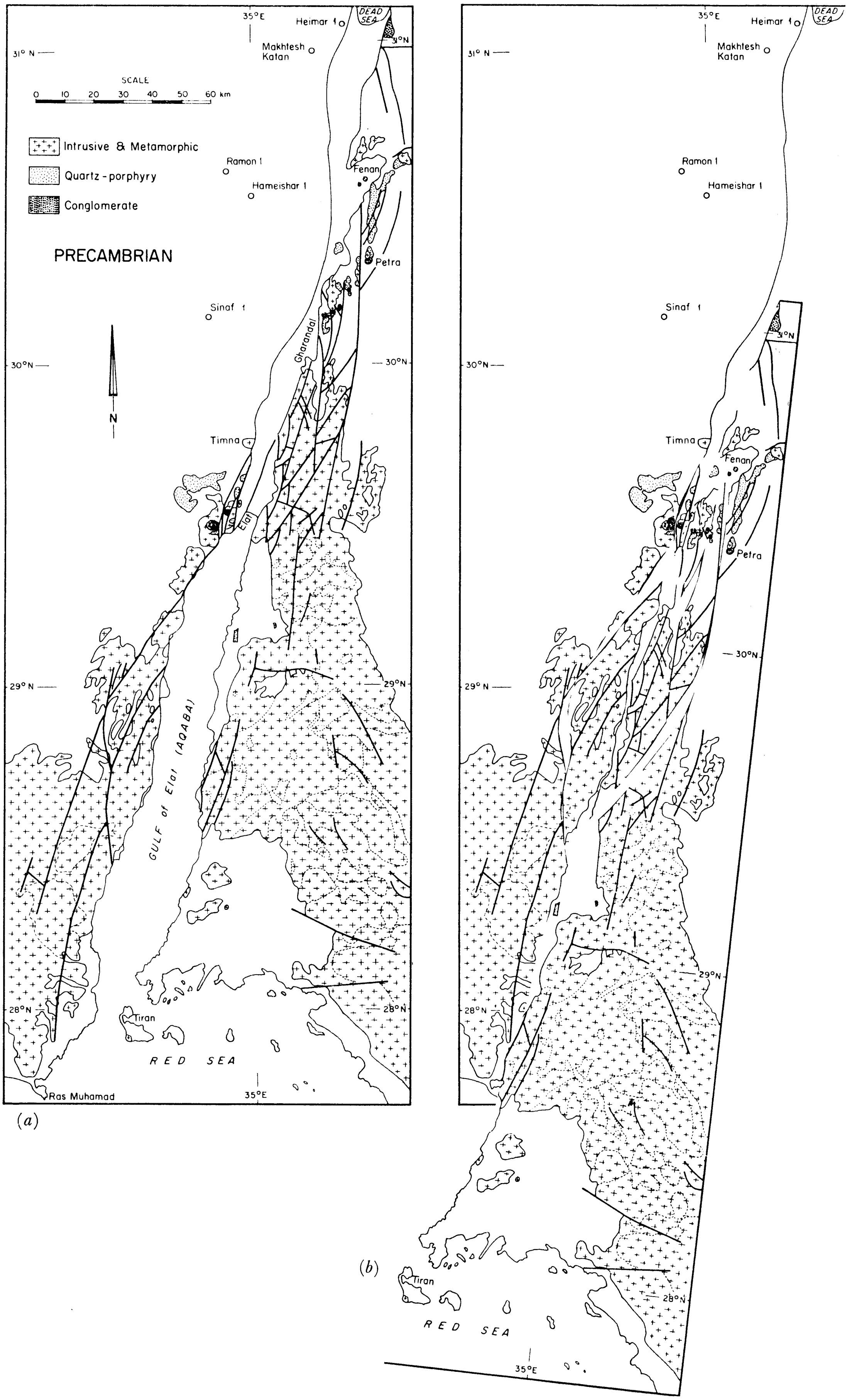

Figure 1. (*a*) Precambrian: quartz prophyry associated with conglomerates occurs in the vicinity of Elat in southern Israel, and from Gharandal to Fenan in Transjordan. A very thick sequence of arkose which underlies the Cambrian in Sinaf 1 and the Permo-Carboniferous in the other bore holes farther north is most probably of Precambrian or Infracambrian age. This arkose is identical to the arkosic cement of the Saramuj Conglomerate exposed on the southeast side of the Dead Sea beneath the Cambrian. Note the numerous anastomosing arcuate faults from Fenan to Aqaba on the east side and from Timna southwards on the west side. (References: Transjordan: Bender 1968*a*; Saudi Arabia: Bramkamp *et al.* 1963; Sinai: Geological Map of Egypt 1928; Southern Negev: Bentor & Vroman 1955; Z. Garfunkel (unpublished).)

(*b*) Schematic reconstruction of the shear. The two sides are shifted back 105 km, and the blocks between them are shifted and rotated by various amounts along the anastomosing faults. Thereby the quartz porphyry and conglomerate are brought in line.

Cambrian sediments are exposed on the east side of the Dead Sea in Wadi Hesi where their thickness exceeds 300 m, and in Zerka Main (figure 2*a*). On the west side of the Dead Sea the Cambrian is probably absent, and the Upper Palaeozoic sediments are overlying unconformably the Precambrian (or Infracambrian) arkose. Upper Palaeozoic (Upper Carboniferous–Permian) sedimentary and igneous sequence of 650 to 750 m has been encountered in all the deep test wells on the southwest side of the Dead Sea, from Zohar-8 and Lot-1 to Hameishar-1 (figure 3). Upper Palaeozoic rocks are absent on the east coast of the Dead Sea, and have recently been reported (Bender 1968*b*) from Safra-1 test well east of Amman.

Triassic section of 550 to 750 m occurs above Upper Palaeozoic sequence southwest of the Dead Sea, and is absent on the east side (figure 4*a*). The Triassic appears in Transjordan north of Wadi Mujib (Wetzel & Morton 1959; Bender 1968*b*). On both sides the section becomes thinner southwards both by attenuation of individual parts of the sequence, and by a truncation of the Triassic by the Jurassic and Lower Cretaceous unconformities. The gypsiferous facies of Mohila Formation (the uppermost one) extends on the west side from Ramon through Makhtesh Katan to Lot-1. This facies disappears both southeast and northwest from this belt. On the east side of the rift this gypsum occurs in Wadi Zerka.

The Jurassic sequence (figure 5*a*) on the west side of the rift is sandy from Ramon in the south to Lot-1 in the north. A few sand beds occur in Massada-1 and Halhul-1, but northwards the sandstone disappears. On the east side of the Dead Sea the Jurassic sequence is absent. Its southernmost occurrence is in Jordan Valley-1 well, and in Wadi Zerka the facies is still sandy. In Zohar wells, in Massada-1, Halhul-1 and Ramalla-1 occurs the Kidod Shale (Callovian-Oxfordian) at the bottom of which occur numerous small ammonites. This shale disappears northwards on the west side, but occurs on the east side of the rift on the southeastern slope of Mount Hermon.

The Lower Cretaceous Hathira formation (figure 6*a*) is completely sandy on the east side of the Dead Sea, measuring about 200 to 250 m, and the southernmost extent of thin beds of marine Albian limestones occur only as north as Wadi Zerka. In Massada-1 well the Hathira formation is about 400 m thick and half of it consists of marine limestone and shale. In Jerusalem (Motsa-1) and Wadi Malih the Lower Cretaceous sequence is about 700 m thick, more than two-thirds of which are marine limestones and shales. From Wadi Faria northwards on the west side the lower part of this section consists of volcanic rocks; whereas these volcanic rocks appear on the east side only on the southern slopes of Mount Hermon. The base conglomerate of the Lower Cretaceous occur only in Wadi Zerka east of the rift, and in and around Ramon on the west side.

The so-called Cenomanian part of Judea Limestone (figure 7*a*), the lower part of which is of Albian age, is about 650 m thick in Jerusalem, but only 300 m in Wadi Zerka and about 200 m in Zerka Main and Ed Dhira. In the southern Negev on the west side, it is 100 to 200 m thick, whereas in Naqb Ishtar it is less than 50 m thick.

The Lower Turonian sequence on the southeast side of the Dead Sea (figure 8*a*) consists of about 100 m of shale with limestone beds topped by gypsum beds, and it contains numerous ammonites, the most common of which are large *Choffaticeras*. Specimens of these ammonites collected by Professor L. Picard in Wadi Hesi are deposited at the Hebrew University. A similar sequence with abundant *Choffaticeras* occurs on the west side in the southern Negev, whereas on the southwest side of the Dead Sea the Lower Turonian consists of 20 m of limestone and marl where another ammonite, *Vascoceras pioti*, is abundant. This ammonite occurs on the east side

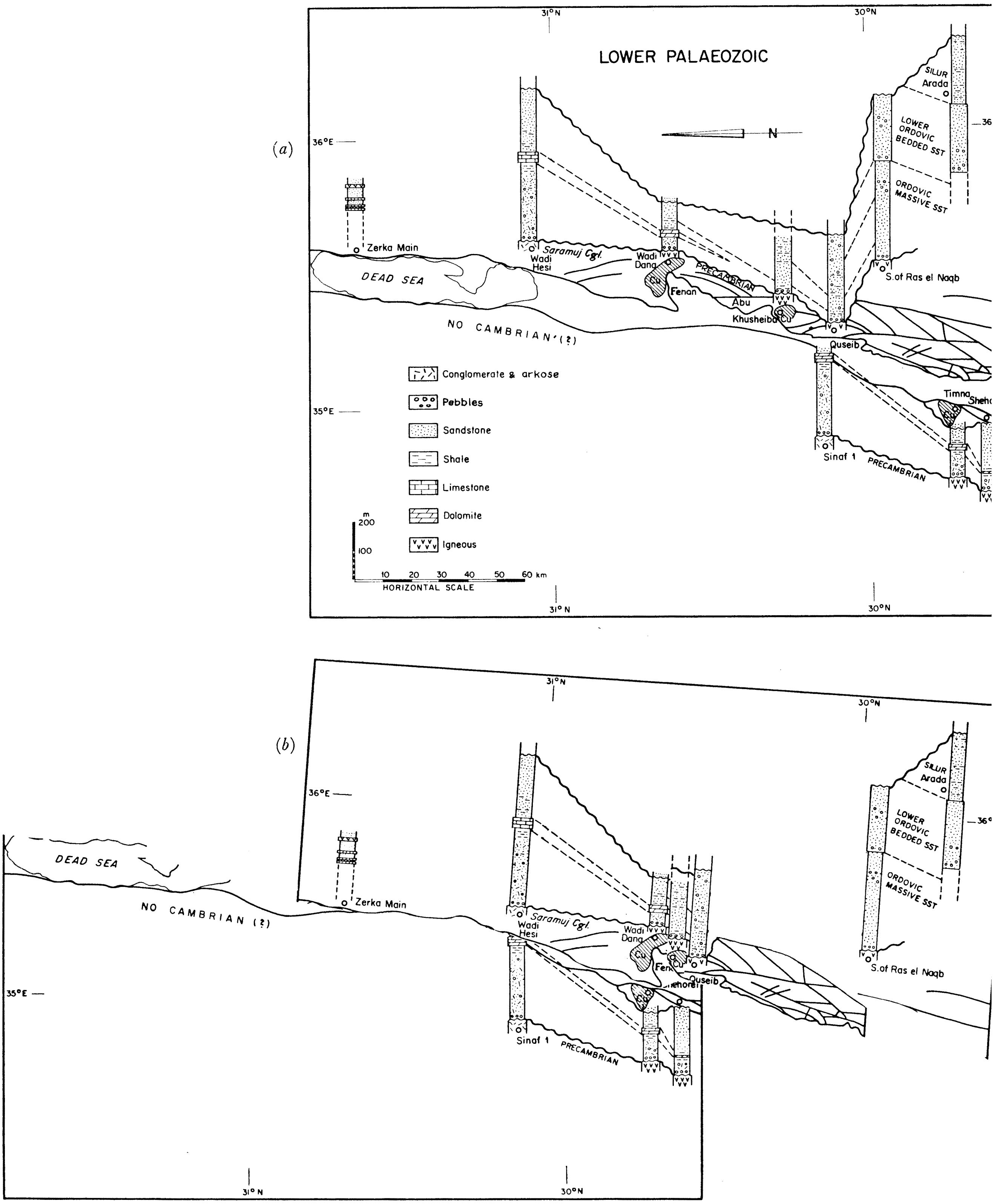

FIGURE 2. (*a*) Lower Palaeozoic: Marine Cambrian occurs in Transjordan from Zerka Main southwards to Wadi Abu Khusheiba. It is most probably absent on the west side of the Dead Sea and northern Negev, and extends from Sinaf 1 (*ca.* 300 m) through Timna to the vicinity of Elat. Copper and manganese sandstones occur between Fenan and Abu-Khusheiba in Transjordan, and in Timna in Israel. The Ordovic–Silurian sequence of southeast Transjordan is truncated towards the northwest by the Lower Cretaceous unconformity; it disappears already near Ras el Naqb, and it does not reach the Rift. (References: Transjordan: Wetzel & Morton 1959; Bender 1965. Israel: Weissbrod 1969*b*; Bartura 1966.)

(*b*) The reconstruction is similar to that of figure 1*b*. Note that the *ca.* 300 m Cambrian of Sinaf 1 is brought opposite Wadi Hesi, and that the sections of Wadi Dana (Fenan), Abu Khusheiba and Timna are brought together. It should, however, be admitted that the Cambrian of Zerka-Main, where the Permo-Carboniferous is absent, is inconveniently brought opposite the Permo-Carboniferous (and no Cambrian) of Ramon 1 and Hameishar 1 (cf. figure 3).

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near Es Salt. Specimens of *V. pioti* collected in Es Salt by Dr M. Blanckenhorn are deposited at the Hebrew University. On the west side of the Dead Sea the Lower Turonian is absent, and the Lower Turonian northwest of the Dead Sea does not contain *V. pioti* but other ammonites, similar to those found in the Beqa'a on the western slopes of Mount Hermon.

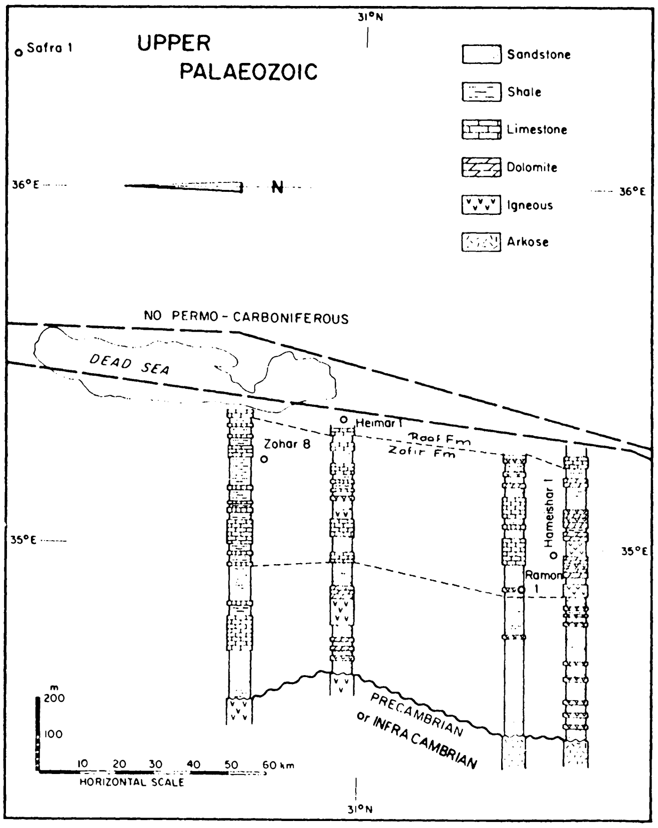

FIGURE 3. Upper Palaeozoic: the 750 m thick Permo-Carboniferous of Zohar-8 thins to the southeast to 650 m in Heimar 1, on the southwest margin of the Dead Sea, and the 750 m section of Ramon 1 thins to about 600 m (excluding the igneous material) in Hameishar 1. On the opposite east side of the Rift the Permo-Carboniferous is absent altogether. It is reported only from Safra 1 well. (References: Weissbrod 1969*a*; Bender 1968*b*.)

The *ca.* 200 m Senonian (Santonian–Campanian) sequence (figure 9*a*) on the southeast side of the Dead Sea contains flint and dolomite beds almost throughout, similar to the Senonian sequence in southern Israel, whereas on the west side of the Dead Sea the flint beds occur only in the upper half of the sequence and dolomite is absent. Section similar to the latter occurs in Transjordan farther north near Amman and Irbid, opposite which on the west side (Gilboa) the flint is very thin. The economic phosphorites of Israel occur on the southwest side of the Dead Sea; those of Transjordan beyond the northeast side.

In figures 4*b* to 9*b* the east side is shifted southwards 105 km relative to the west side with a 6° clockwise rotation. All the rock units without exception resume thereby a simple and reasonable configuration. The southward thinning out of the Triassic beds (figure 4*b*) as well as the gypsiferous belt of Mohila Formation come in line on the two sides. The southward thinning out of the Jurassic beds (figure 5*b*), the sandy facies of the Jurassic and the Kidod Shale come in line as well. The equivalent facies and thicknesses of the Lower Cretaceous (figure 6*b*) and the Cenomanian (figure 7*b*) come to juxtaposition. The various litho- and biofacies of the Lower Turonian (figure 8*b*) are placed exactly in their proper place, as do those of the Senonian along NNE trending isofacies lines (figure 9*b*).

The fact that all the dissimilarities across the rift disappear simultaneously by the 105 km shift is a strong evidence in favour of a 105 km left-hand shear along the Dead Sea rift in Post-Cretaceous times. The value of this evidence can be reduced only if an undisplaced rock unit will be encountered, or if another, simpler explanation can be proposed for the persistent changes of the rock units across the rift, or if this shear movement is shown to be impossible.

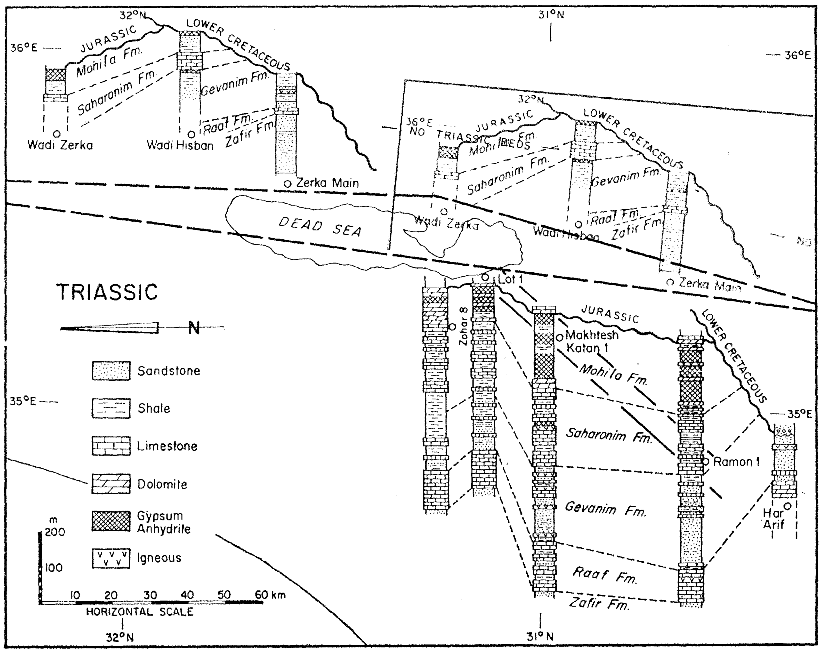

FIGURE 4. (*In black*) The Triassic section is 700 m thick in Ramon and 750 m in Makhtesh Katan 1. It thins to 550 m in Lot 1, and it is completely absent on the opposite side of the Rift. In Zerka-Main and Har Arif the Lower Triassic is truncated by the Lower Cretaceous unconformity. The gypsiferous facies of Mohila Fm extends on the west side from Ramon through Makhtesh Katan 1 to Lot 1, and disappears both to the southeast and to the northwest of this belt. It reappears in Wadi Zerka in Transjordan. (References: Transjordan: Wetzel & Morton 1959; Israel: I. Zak, I. Karcz & M. Goldberg (unpublished).)

(*In red*) The east side is displaced 105 km southwards together with the closing of the Rift. Zerka Main comes in line with Har Arif, and Wadi Zerka comes in line with Ramon to Lot-1 belt.

Another explanation (see, for example, Blake 1937 and Wetzel & Morton 1959) relates the above mentioned changes of the rock units across the rift to the original configuration of the Arabian Massive along the Dead Sea rift, reflected in the S bend of the Triassic and Jurassic coast lines. Bentor & Vroman (1960) noticed that the presumed ancient coast along the rift must have been particularly steep, and therefore suggested that the eastern fault of the rift was existing already in the Jurassic, with the Transjordan side rising relative to the west side at that time.

However, according to this explanation the *west* side must have been higher by 300 m in pre-Carboniferous times (with or without faulting) to account for the occurrence of the Cambrian beds on the eastern side only. Later, since the Upper Carboniferous and until the Cenomanian, the up and down movement was reversed and the *east* side was higher so that the 2000 excess sequence of the west side could be deposited. As the Upper Carboniferous to Ceno-

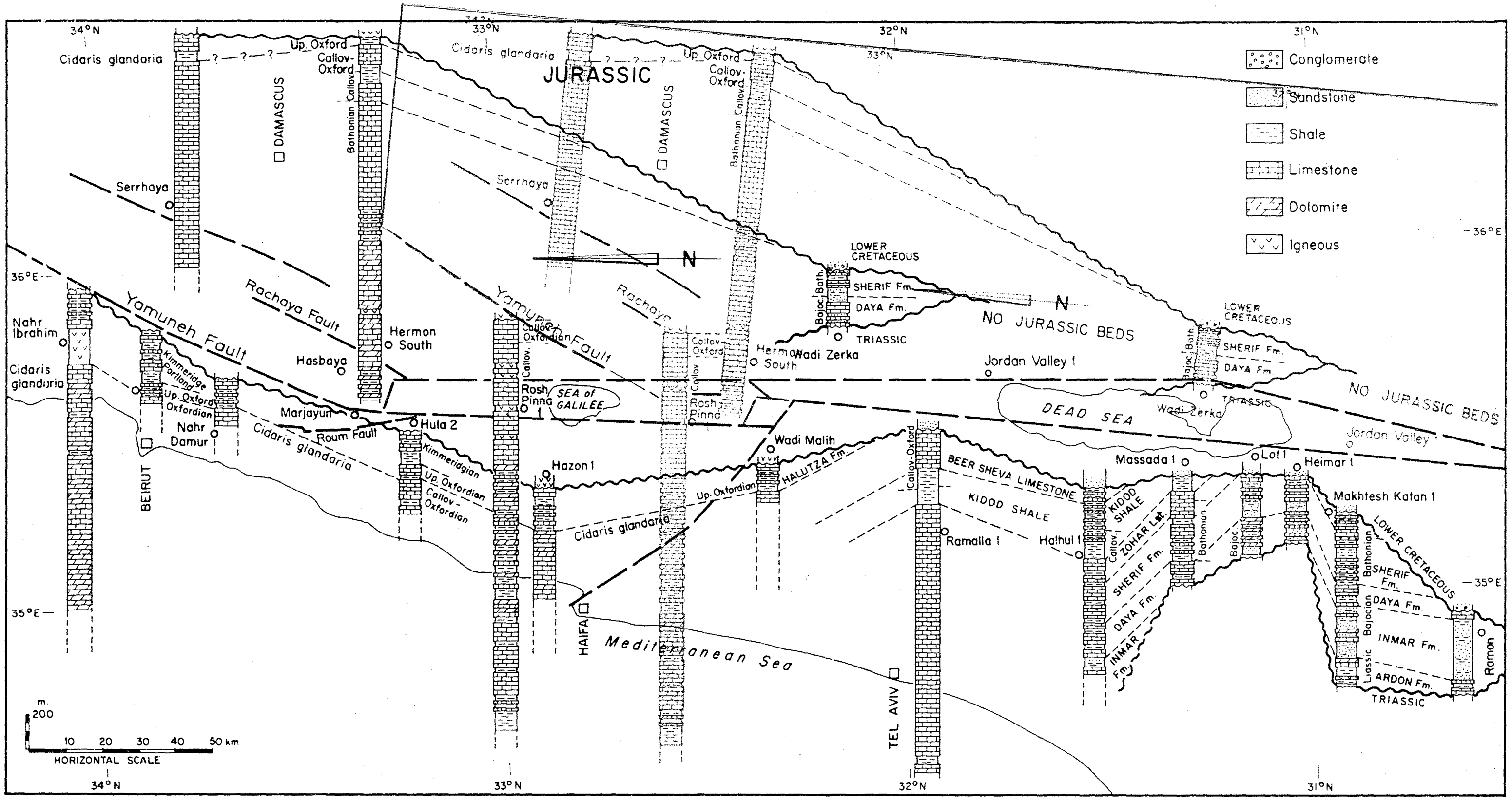

FIGURE 5. (*In black*) Jurassic: The sandy facies of the Jurassic extends in Israel from Ramon to Massada 1, opposite which in Transjordan the Jurassic is absent. It appears there in Jordan Valley 1, and in Wadi Zerka the facies is sandy. The Callovian–Oxfordian Kidod Shale occurs on the west side from the southwest side of the Dead Sea to Ramalla 1 bore hole; on the east side it occurs on the southeastern slope of Mount Hermon. Upper Oxfordian–Kimmeridgian section of 200 to 400 m occurs in the Galilee and Lebanon but is almost absent in southern Mount Hermon and Rosh Pinna 1 bore hole. It probably reappears in Anti-Lebanon from Serrhaya northwards. (References: Nahr Ibrahim: Renouard 1951; Beirut: Bishopp 1964; Nahr Damour: Heybroek 1942; Hula 2, Rosh-Pinna 1 and Hazon 1: B. Derin (unpublished); Serrhaya: Dubertret 1950; Hermon south: Dubertret 1951; M. Goldberg (unpublished); Wadi Malih: E. Aizenberg & B. Derin (unpublished); Wadi Zerka: Wetzel & Morton 1959; Northern Negev: M. Goldberg (unpublished).)

(*In red*) The east side is displaced 105 km southwards and Rosh Pinna 1 is displaced 60 km southwards. Wadi Zerka corresponds to Lot 1 and Hermon-south to Ramalla 1. A 55 km wide gap is opened along Yamuneh Fault; in this illustration the deformation of Lebanon is not restored.

manian section does not contain any conglomerate bed this upward movement of the east side must have been gradual, never forming a high relief. Afterwards, during the Turonian and the Senonian the movement was reversed again and the *west* side was rising to allow for the deposition of a thicker sequence on the east side. It is concluded that this explanation does not seem to be simpler than the shear hypothesis.

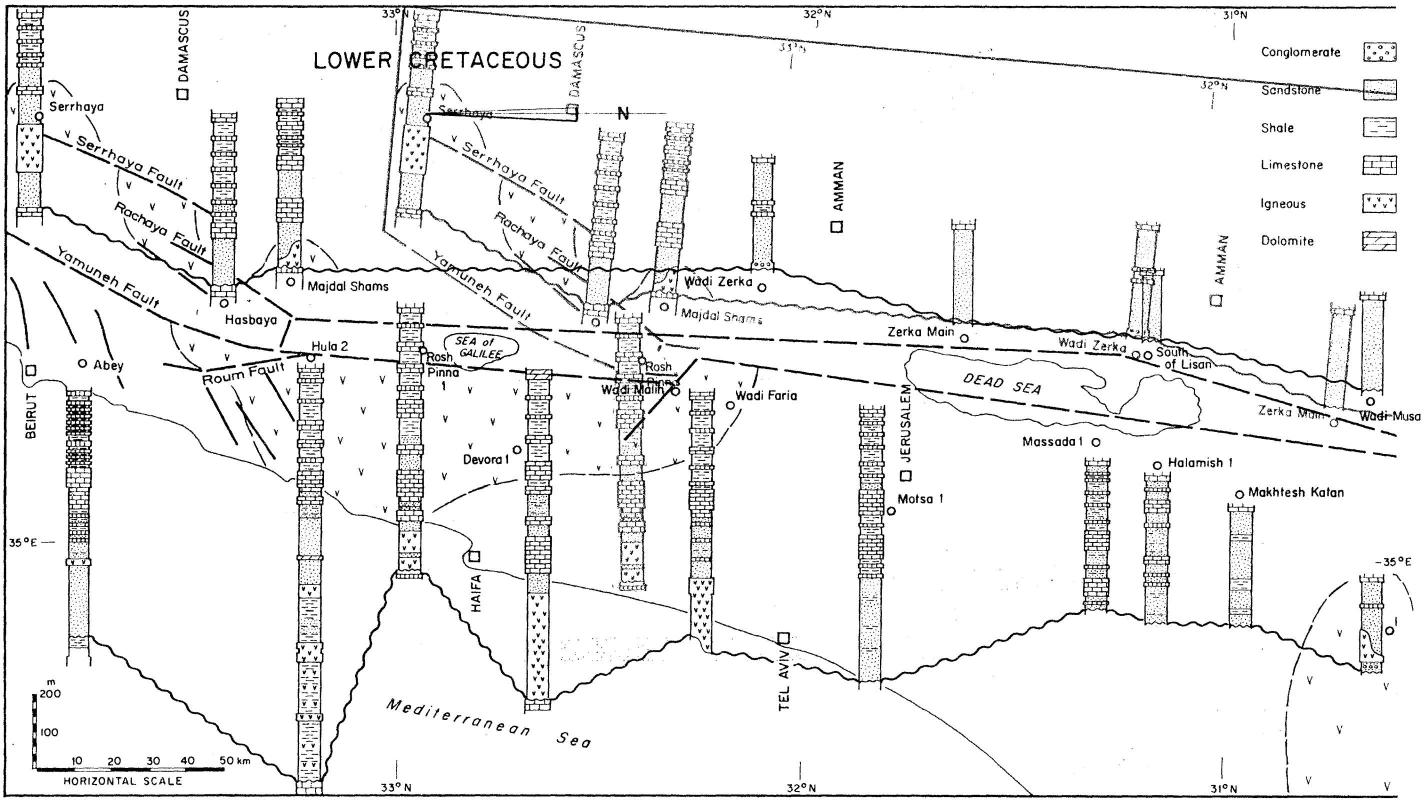

Figure 6. (*In black*) Lower Cretaceous: the marine Albian limestones extend in Israel as far south as Ramon, where the Lower Cretaceous starts with a base conglomerate, whereas in Transjordan the Albian limestone extends southwards only to Wadi Zerka, where the base conglomerate occurs again. Opposite Wadi Zerka, in Wadi Malih–Wadi Faria area the Lower Cretaceous section is 650 to 750 m thick, and more than two thirds of the sequence consist of marine limestones and shales. Volcanic rocks occur at the lower part of the Lower Cretaceous sequence from Wadi Faria to southern Lebanon (Marjayun), whereas on the east side they occur from Majdal Shams to Serrhaya. (References: Abey: Heybroek 1942; Serrhaya and Hasbaya: Dubertret 1950–51; Majdal Shams: U. Salzman (unpublished); Hula-2: Shiftan & Rosenthal 1963; B. Derin (unpublished); Rosh Pinna 1 and Debora 1: B. Derin (unpublished); Wadi Malih: J. Mimran & R. Freund (unpublished); Transjordan: Wetzel & Morton 1959; Bender 1968*b*; Negev and Motsa 1: Aharoni 1964; Arad 1964.)

(*In red*) The east side is displaced 105 km southwards and Rosh Pinna 1 is displaced 60 km southwards, but the displacements along Serrhaya-Rachaya faults and the Galilean and Lebanese faults are not restored, thus the gap of 55 km along Yamuneh Fault is maintained. Wadi Zerka corresponds to Ramon along north-east trending isofacies lines. Majdal Shams section corresponds to Wadi Malih section.

Wadi Arava and Gulf of Aqaba (Elat)

The offset of several Cambrian rock units, e.g. the copper and manganese deposits and of the southern extent of the Cambrian limestone from Fenan east of the Arava, to Timna which is about 100 km south of Fenan on the west side (figure 2*a*), was regarded by Quennell (1958,

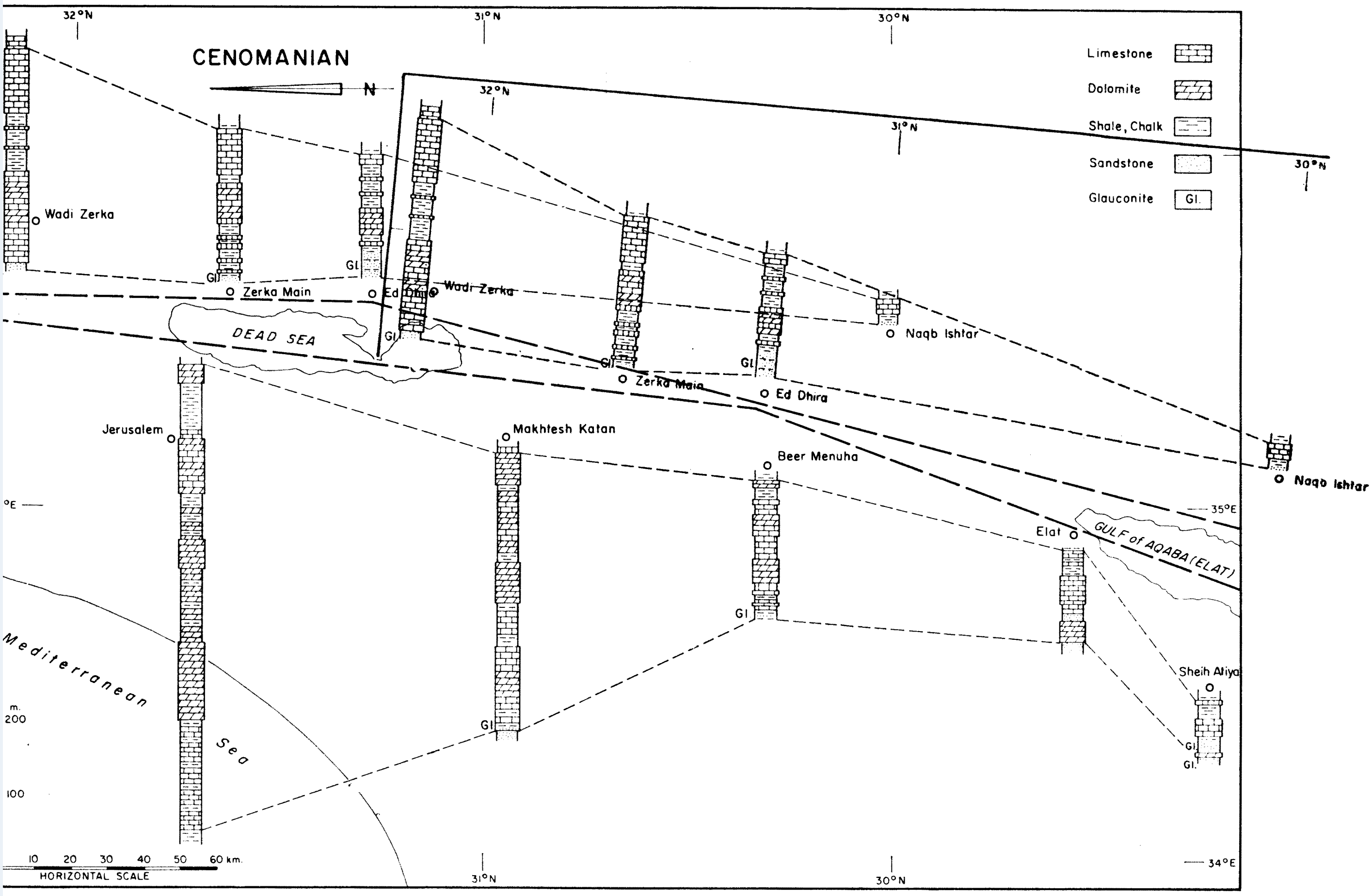

Figure 7. (*In black*) The Cenomanian section (including the upper part of Albian) of Jerusalem measures about 650 m, whereas that of Wadi Zerka only 280 m and those of Zerka Main and Ed Dhira about 200 m only, comparable to those of Beer Menuha (175 m). Opposite the latter the Cenomanian section of Naqb-Ishtar is less than 50 m thick. (References: Transjordan: Wetzel & Morton 1959; Jerusalem: Arkin *et al.* 1965; Makhtesh Katan: Arkin & Brown 1965; Beer Menuha: Sakal 1967; Elat and Sheih Atiya: Bartov *et al.* 1970.)

(*In red*) The east side is displaced 105 km southwards with the closing of the Rift. The thicknesses of the two sides match well along ENE trending isopach lines.

1959) as evidence for the shear movement along the rift. This was supplemented by the equal offset of an extensive body of Precambrian quartz porphyry from south of Timna on the west side to south of Fenan on the east side (figure 1*a*). Bender (1965, 1968*a*), however, argued that these data cannot be regarded as evidence for the shear movement because all these rocks occur as well in other places, such as Gharandal and Wadi Abu Khusheiba (figures 1*a* and 2*a*), forming thereby an almost continuous belt between Timna and Fenan. Bender accepted only a 25 to 35 km shear, according to the offset of a certain hornblendite-pegmatite from Elat on the west to a place opposite Timna in the east.†

Numerous parallel faults, which are anastomosing with the rift occur along this part of the rift. These faults extend in Transjordan northwards to Fenan, and perhaps to the southeast corner of the Dead Sea, and on the west side they extend from Timna southwards. These faults are nearly vertical and the upthrown and downthrown sides of these faults alternate sometimes

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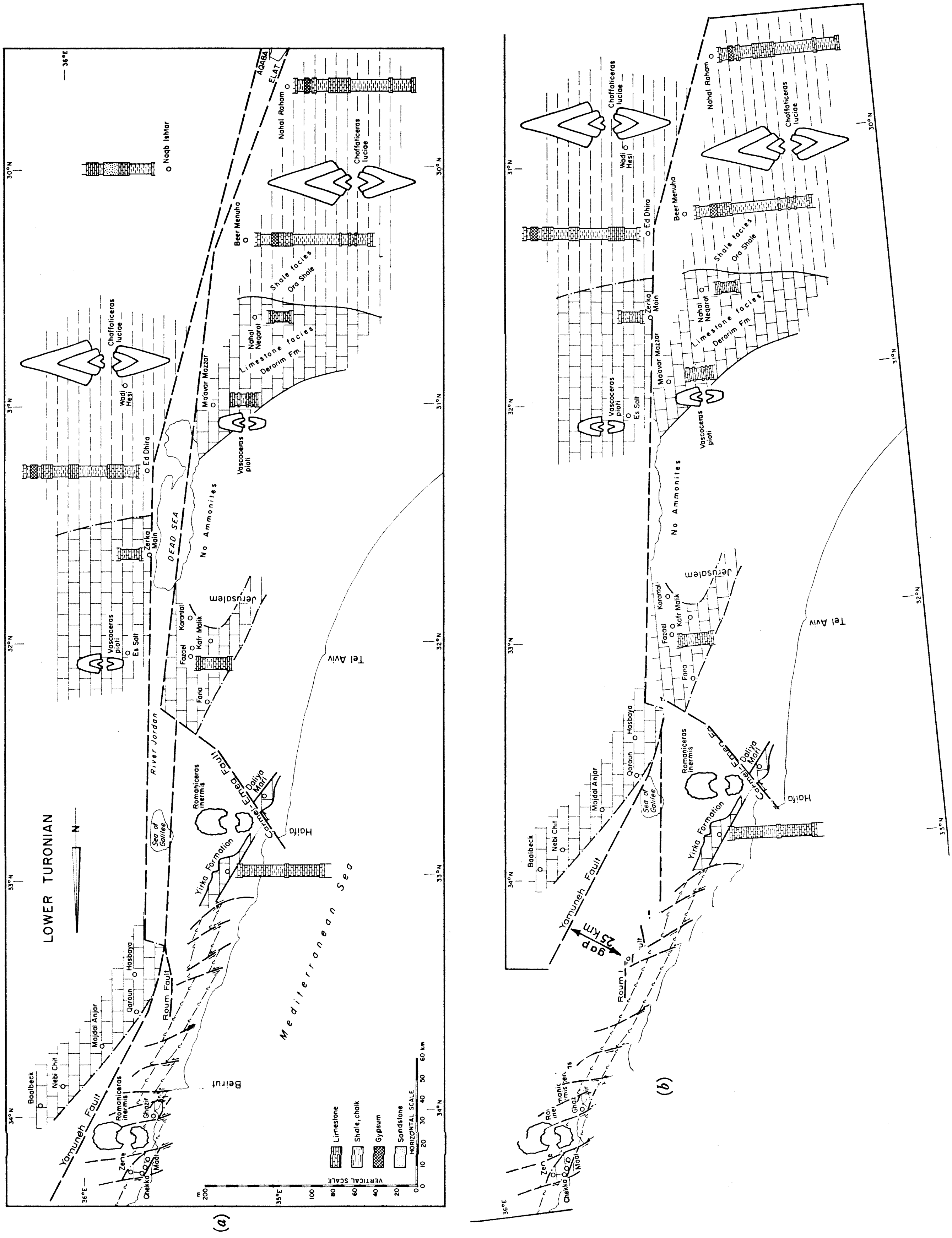
† Dr Bender amplifies this reasoning in his contribution to the discussion at the end of this paper (p. 127).


LOWER TURONIAN
N
Limestone
Shale, chalk
Gypsum
Sandstone
HORIZONTAL SCALE
0 10 20 30 40 50 60 km
VERTICAL SCALE
m 200 100 80 60 40 20 0
36° E
35° E
34° N
33° N
32° N
31° N
30° N
Yamuneh Fault
Roum Fault
River Jordan
Sea of Galilee
DEAD SEA
AQABA
ELAT
Mediterranean Sea
Beirut
Haifa
Tel Aviv
Jerusalem
Baalbeck
Nebi Chit
Majdal Anjar
Qaraoun
Hasbaya
Zene
Chekka
Ghazir
Mdei
Romaniceras inermis
Yirka Formation
Carmel–Emeq Fault
Daliya
Mari
Fana
Fazael
Kafr Malik
Karantal
Es Salt
Vascoceras pioli
Zerka Main
Ed Dhira
Ma'avar Mazzar
Nahal Neqarot
Limestone facies
Derorim Fm
Shale facies
Ora Shale
Beer Menuha
Wadi Hesi
Chofficeras luciae
Nahal Raham
Naqb Ishtar
No Ammonites
gap 25 km
(a)
(b)

from one side to the other along the faults. Numerous narrow fault depressions are located along these faults, where the rocks are intensively folded.

Horizontal slickensides occur on these faults in Israel and Sinai, and recent investigation has revealed that they are left-hand shears, varying in magnitude from several metres to a few kilometres. Although the faults on the Transjordanian side have not been equally studied, it seems justified to assume that they are left-hand shears as well. Moreover, an air photograph of some of these faults in Transjordan, published by Burdon (1959) shows clearly that dykes are displaced horizontally left-hand by these faults.

It seems therefore justified to propose that the shear movement is divided along this part of the rift among numerous anastomosing faults. Only a certain part of the shear is located within the rift depression, the rest occurs outside it. The reconstructions of the Precambrian (figure 1*b*) and Lower Palaeozoic (figure 2*b*) are carried out according to this proposal, by shifting back the two sides by 105 km, whereas the median blocks are shifted by various smaller amounts.

The Precambrian quartz-porphyry and conglomerates come thereby in line (figure 1*b*). Moreover, the Precambrian (or Infracambrian) arkose encountered in Sinaf-1, Hameishar-1 and Ramon-1 are removed away from their present position opposite the granite and quartz porphyry of Fenan and Gharandal, towards the Saramuj series of Wadi Hesi, which they closely resemble. The Cambrian carbonates, manganese and copper of Timna, Abu-Khusheiba and Fenan are clustered in one place, and the 300 m thick section of the Cambrian of Sinaf-1 is adequately placed opposite that of Wadi Hesi.

The reconstruction requires the rotation of some of the intermediate blocks throughout their changing positions. Frequently the various blocks do not fit properly into the new places. This is most probably the reason for intensive folding and faulting which is very common along these faults.

GALILEE–LEBANON–SYRIA

The difference between the east side and west side of the rift is as large in the Galilee and Lebanon as it is in the south, but the fault pattern of the region is more complex.

The Jurassic sequence (figure 5*a*) of the southeastern slope of Mount Hermon is truncated by Lower Cretaceous unconformity at the base of the *calcaire jaune inférieur* of Upper Oxfordian age, that of Hasbaya on the west side of Mount Hermon is truncated even lower in the section. In contrast with that, the Jurassic sections in the Galilee (except Rosh Pinna-1) and in Lebanon

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FIGURE 8. (*a*) The Lower Turonian section on the southeast side of the Dead Sea and in the southern Negev consists of 100 m of shales with beds of concretional limestone topped by gypsum beds, with abundant ammonites, the most common of which are several species of *Choffaticeras*. On the southwest side of the Dead Sea and near Es-Salt the section consists of about 20 m of yellow-red marl and limestone, where another ammonite, *Vascoceras pioti*, is most abundant. The boundary between the shale facies (Ora Shale) and the limestone facies (Derorim Fm) trends east–west across Ramon. On the west side of the Dead Sea the Lower Turonian ammonites are missing. The Lower Turonian northeast of Jerusalem and that on the east side of Yamuneh Fault contain almost only specimens of *Thomasites* and *Choffaticeras segne*, whereas that of Mount Carmel (Daliya Marl) of the western Galilee (Yirka Fm) and north of Beirut contain several ornamented ammonites, such as *Romaniceras* and *Mammites*. (References: in Freund 1961; Freund & Raab 1969; Beer Menuha: Sakal 1967.)

(*b*) An almost complete, though schematic reconstruction of the shear along the Dead Sea–Lebanon section. The east side is displaced southwards 105 km, the Galilee is displaced 10 km southeast along the Carmel–Emeq Fault, and several small right-hand shears are restored in Lebanon. The three pairs of the Lower Turonian facies correspond to each other across the Rift and the Daliya–Yirka–Ghazir–Maat occurrences are arranged in line. The gap along Yamuneh Fault is reduced to *ca*. 25 km only.

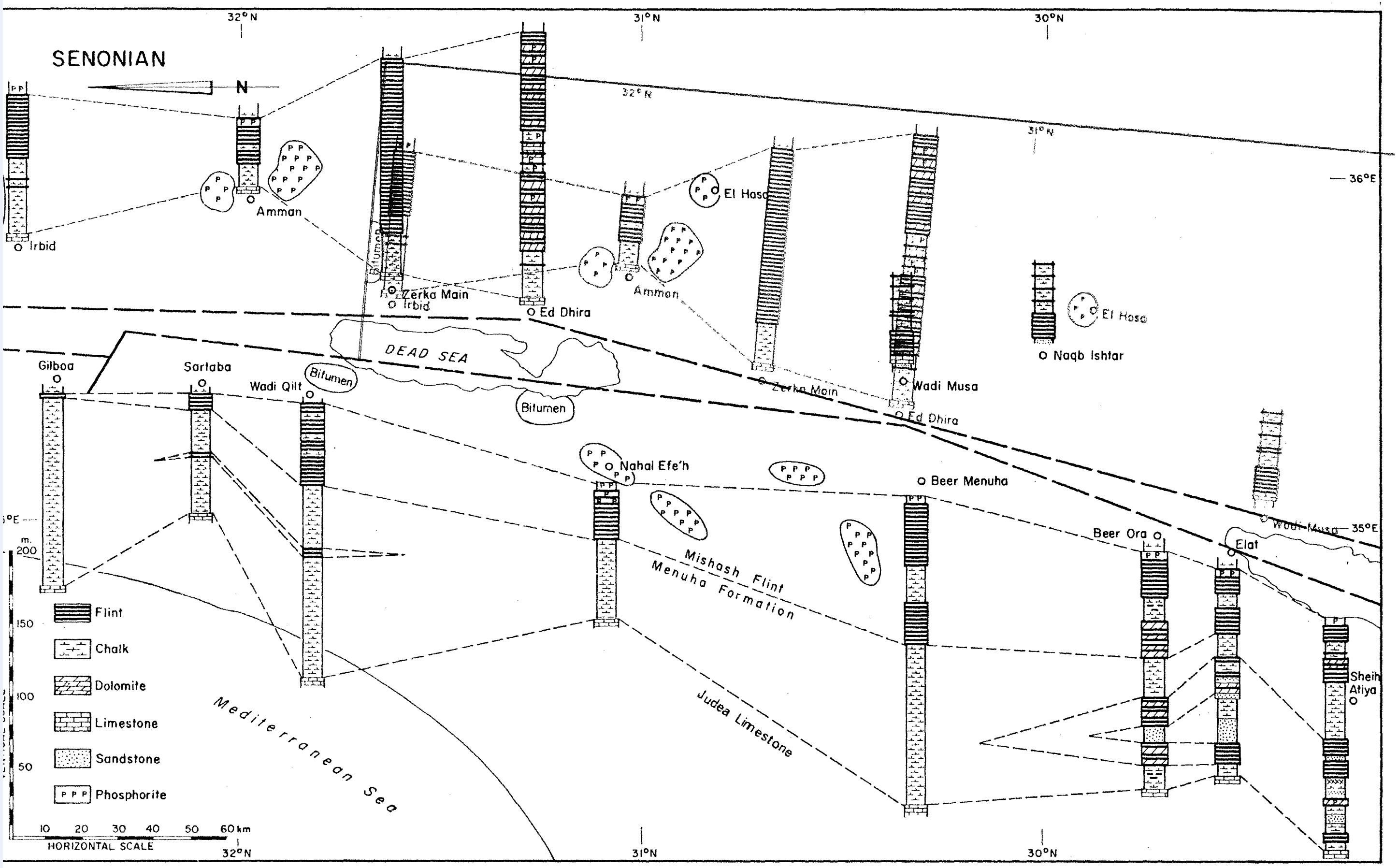

Figure 9. (*In black*) The *ca*. 200 m Senonian (Santonian–Campanian) sequence on the east side of the Dead Sea contains flint and dolomite almost throughout, as does the Senonian sequence in the southern Negev. However, the latter contains some sandstone beds which are not reported on the east side of the Dead Sea. On the west side of the Dead Sea and in the central Negev the flint beds occur only in the upper half of the section, similar to the section in north Transjordan. In northern Israel the flint beds are very thin or missing altogether. The economic phosphorites occur around Amman in Transjordan and in the northern Negev in Israel, but there is another occurrence in El Hasa in Transjordan. (References: Transjordan: Wetzel & Morton 1959; Bender 1968*b*; Gilboa: Flexer 1959; Sartaba: A. Flexer, Y. Weiler & R. Freund (unpublished); Wadi Qilt I. Rot (unpublished); Nahal Efeh: Kolodny 1967; Beer Menuha: Sakal 1967; Beer Ora, Elat and Sheih Atiya: Bartov *et al*. 1970.)

(*In red*) The 105 km southwards movement of the east side brings the corresponding facies on the two sides in line along NNE-trending facies lines.

terminate 200 to 400 m higher in the Upper Jurassic. In Rosh Pinna-1 well which is drilled through a block located within the rift, the Jurassic terminates within the Callovian–Oxfordian, as it does in Hasbaya.

The Lower Cretaceous section (figure 6*a*) of the southern slopes of Mount Hermon is about 400 m thick, whereas that of the Galilee and southern Lebanon, right across Yamuneh Fault, is about 1000 m thick. The volcanic lower part of the Lower Cretaceous occurs on the west side from Wadi Faria in the south, to Marjayun in the north. The volcanic sequence thins out northwards and is almost absent in Abey. On the east side of Yamuneh Fault it extends from Majdal Shams to Rachaya on Mount Hermon, and on the east side of Serrhaya Fault it extends farther north. Again the Lower Cretaceous of Rosh Pinna-1 does not correspond to that of the Galilee, but resembles those of Mount Hermon and Wadi Malih.

In figures 5*b* and 6*b*, the east side is shifted 105 km southwards, and the intermediate Rosh Pinna block is displaced southwards by about 60 km† to a location near Wadi Malih on the west side and Mount Hermon on the east side. In this way both the Jurassic and the Lower Cretaceous become reasonably similar on the two sides of the rift.

This reconstruction leads, however, to a structural problem. The southward movement of the east side leaves a 55 km wide gap along the N 30° E trending Yamuneh Fault (figure 5*b* and 6*b*). In other words, the left-hand shear movement along the diverted section of Yamuneh Fault should result in an overlap of 55 km (figure 10*a*, *b*). Such an overlap would certainly be excessively large even for the high structures of the Lebanon mountains. A closer examination of the fault pattern of the Galilee and Lebanon shows, however, that this problem can be accounted for.

It is proposed that the 55 km overlap can be reduced to about 20 to 25 km by the restoration of the deformation of the faults in this area, as demonstrated in a geometrical model (figure 10*c*):

(1) 10 km left-hand shear along the Carmel–Emeq Fault (de Sitter 1962);
(2) extensive east–west normal faults in the Galilee;
(3) small ENE trending right-hand shear faults in Lebanon (Renouard 1955);
(4) left-hand shear along Rachaya-Serrhaya fault zone.

This geometrical reconstruction is certainly schematic and, moreover, the writers of this paper are unable to examine the tectonic pattern in Lebanon. This model has therefore a qualitative value only. Still it is successful in explaining not only the dissimilar facies on the two sides of Yamuneh Fault and the fault pattern in Lebanon and the Galilee, but also the occurrence of the high Lebanon and Anti-Lebanon mountains exactly along the diverted section of Yamuneh Fault.

The western side from Haifa to Tripoli is stretched by about 30 km through the combined deformation of the above-mentioned faults, so that the amount of shear along the rift should decrease north of Lebanon to about 75 km. This result is in line with the 70 km left-hand offset of the southern boundary of the ophiolites (roches vertes) belt of Maastrichtian age (Dubertret 1955) across the rift in northern Syria (figure 11).

The palaeogeography of the Lower Turonian is reconstructed according to the above-mentioned model (figure 8*b*). The Lower Turonian north of Beirut, in which the ammonite assemblage corresponds to that of western Galilee and Mount Carmel (e.g. *Mammites* and *Romaniceras*), is brought in this way in line with the latter locations.

STRUCTURAL EVIDENCE OF THE SHEAR MOVEMENT

Apart from the horizontal offset of the rock-bodies across the rift there are numerous structural features indicating the strike slip or shear nature of many of the rift faults.

(1) Many faults of the rift system, as those in Lebanon (e.g. Dubertret 1947, 1967) and the anastomosing faults on the two sides of Wadi Arava (Bender 1968*a*, *b*) and the Gulf of Aqaba are nearly vertical, a characteristic feature of strike slip faults.

(2) Horizontal slickensides are observed on some of these faults in southern Israel and on Mount Hermon.

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† The *ca.* 60 km shear between Rosh Pinna-l and the Galilee occurs on the western fault of the Hula depression which is supposed to extend southwards on the west side of the Fuliyya and Hordos blocks beneath the Neogene sediments. This fault was apparently active only in pre-Neogene times, and the 40 to 45 km shear of post-Miocene time has apparently taken place on the fault east of Sea of Galilee and Hula depressions.

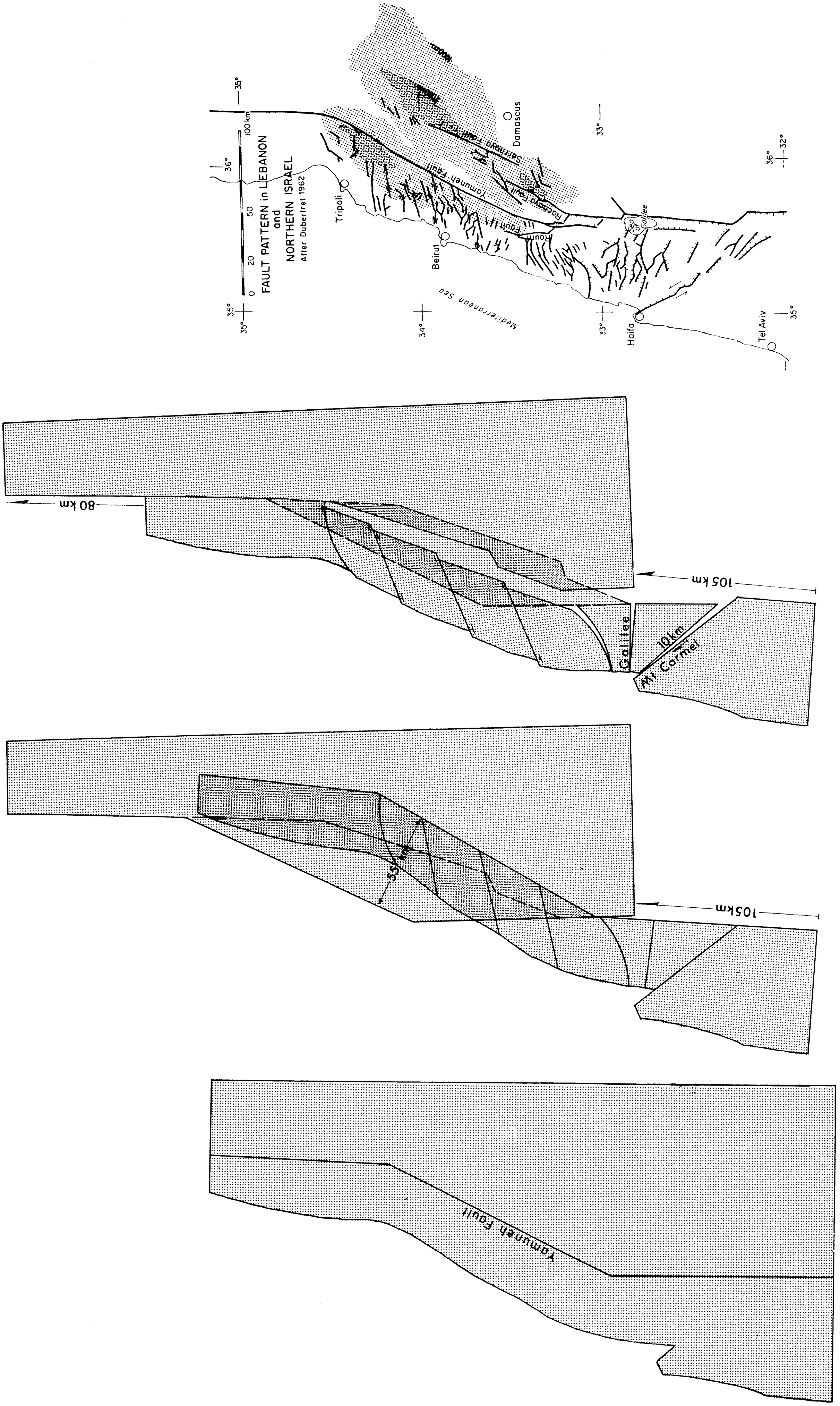

FIGURE 10. For legend see facing page.

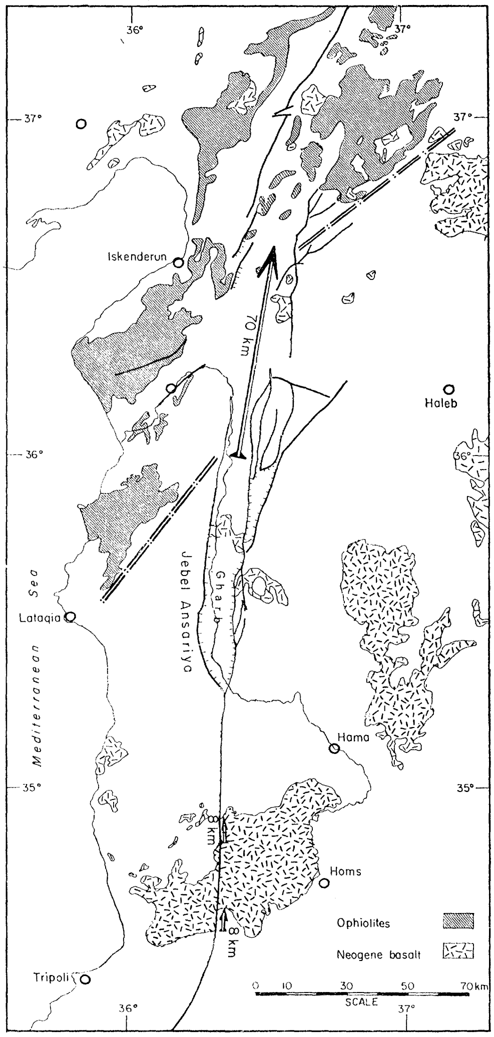

FIGURE 11. The southern boundary of the ophiolites (roches vertes) of northern Syria is offset left-hand by about 70 km across the Rift. The Pliocene (?) basalt west of Homs is offset by *ca.* 8 km. The *échelon* arrangement of the Rift faults on the two sides of the rhomb-shaped depression of Gharb, is typical of strike slip faults. (Reference: Dubertret 1962.)

FIGURE 10

FIGURE 10. A schematic geometrical model intended to show that the fault deformation in Lebanon and the Galilee can be explained by a large scale left-hand shear along the Dead Sea rift.

(*a*) Pre-shear; showing only the position of the rift faults, with the diverted section of the Yamuneh Fault.

(*b*) 105 km left-hand shear (with 6° anticlockwise rotation of the east side) results in an overlap of 55 km along the Yamuneh segment. The position of the faults in the Galilee, Lebanon and Hermon is marked.

(*c*) The following movements have taken place: 10 km left-hand shear along Carmel–Emeq fault, with normal faulting (small gaps) in the Galilee; small right-hand shears in Lebanon, and left-hand shear along Rachaya-Serrhaya fault zone. The 55 km overlap is reduced thereby to two narrow overlaps on the two sides of the Beqa'a each one being *ca.* 10 km wide. The amount of shear between the two blocks is reduced from 105 km south of Lebanon to 80 km north of Lebanon.

(*d*) Fault pattern of the Galilee and Lebanon according to Dubertret (1962). Right-hand shears in Lebanon according to Renouard (1955). Areas above topographical elevation of 1000 and 2000 m are marked. Compare the structure and topography of (*d*) with the schematic model (*c*).

(3) The up and down sides of the faults alternate frequently from one side to the other (see, for example, Dubertret 1967), a feature typical for strike slip faults.

(4) The two sides of several faults are at exactly the same elevation along certain stretches (see, for example, Dubertret 1967), yet the faults are clearly visible. This phenomenon is particularly evident along recent fault traces in the Arava and Jordan Valley. A fault without vertical throw must have a horizontal displacent.

(5) Rhomb-shaped 'grabens' such as the Hula depression in northern Israel and Gharb depression (figure 11) in Syria are conveniently explained by left-hand shear along an *échelon* offset of the fault line, as proposed by Quennell (1959) for the Dead Sea.

Other structural features, as the relation of the complex structure of Lebanon and the Galilee to the left-hand shear along the diverted Yamuneh Fault, and the anastomosing shears of Wadi Arava and Gulf of Aqaba, have already been discussed in this paper. The relation of the structure of the Dead Sea rift to the shear movement has been demonstrated by Freund (1965).

AGE AND RATE OF THE SHEAR MOVEMENT

The fact that all the rocks from the Precambrian to the Upper Cretaceous are displaced by the same amount indicates that the whole shear movement is post-Cretaceous and that no movement has taken place before it. It is, however, difficult to determine the exact age of the movements. It has recently (Freund *et al.* 1968) been reported that several rock bodies of Miocene, probably up to early Pliocene age, are offset left hand by 40 to 45 km across the rift. The 40 to 45 km movement has apparently taken place during the last 7 to 12 Ma thus the average rate of the movement is about 0.35 to 0.6 cm a^{-1}.

The younger Pliocene basalt is apparently displaced by about 10 km in the Galilee (Freund *et al.* 1968) and by about 8 km in north Lebanon (figure 11). The age of this movement has not yet been determined.

The Lissan Marl of the Jordan Valley which is older than 23 ka (Neev & Emery 1967) is displaced by about 150 m; the rate of movement is therefore 0.65 cm a^{-1} (Zak & Freund 1966).

If this rate (0.4 to 0.6 cm a^{-1}) is the average rate of the whole 105 km movement, then this movement has started some 20 to 30 Ma ago—during the Late Oligocene to Early Miocene. There are, however, indications that the last movement of 40 to 45 km was preceded by a quiet period of unknown duration.

It is most unfortunate that rocks of the age between Late Cretaceous to Miocene are rare along the Rift, except those of Paleocene and Eocene age, and even those are of little value in determining the amount of displacement: The Taqiya Shale of Paleocene age lacks distinct facies change, whereas the facies changes of the Eocene are very rapid and of local nature (figure 12).

Structural considerations (e.g. excessive large thickness of Senonian and Eocene sequences in the rift, contemporaneous compressional and tensional deformation at different places along the rift, etc.) have lead one of the present writers (Freund 1965) to advocate shear movements in several phases since Late Cretaceous. However, there is no conclusive evidence in this matter.

Several contributors have joined efforts in this paper to present as comprehensive a review of the rocks of the two sides as possible, and this paper includes results from their research projects which have not yet been published, such as that on the fault pattern on the west side of the Gulf of Elat (Aqaba) by Z. Garfunkel, on the Triassic by I. Zak, I. Karcz and M. Goldberg, on the Jurassic of southern Israel by M. Goldberg, on the Jurassic and Lower Cretaceous in northern Israel by B. Derin, on the Palaeozoic stratigraphy by T. Weissbrod and on the recent faulting of the rift by I. Zak, Z. Garfunkel and R. Freund.

Moreover, data from other unpublished works are included in this paper, and the writers wish to express their gratitude for these valuable contributions to Y. Bartov, B. Z. Begin, Y. Druckman, M. Eyal, A. Flexer, E. Gerry, Y. Mimran, I. Rot, E. Sakal, U. Salzman, G. Steinitz and Y. Weiler.

Data from deep test wells which have been recently drilled in the vicinity of the rift, the results of which have not yet been published, are presented here. The generous permission of Lapidoth Oil Co., Naphta Oil Co., Israel National Oil Co. and Israel Continental Oil Co. to publish the results of their deep test wells is gratefully acknowledged.

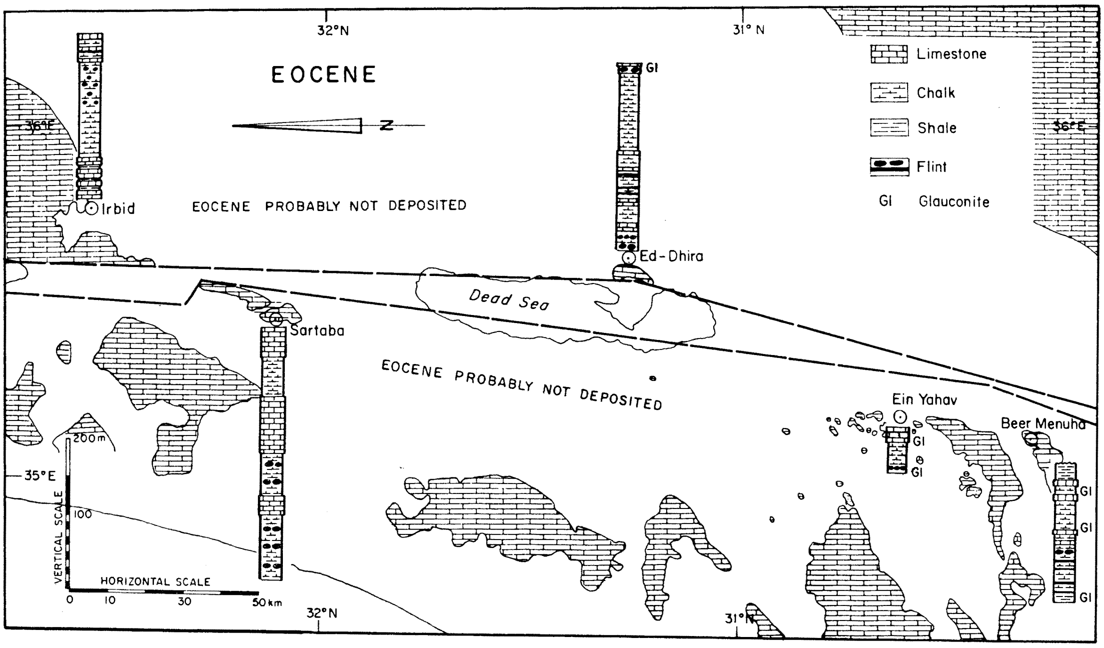

Figure 12. The Eocene sequences change rapidly in thickness and facies over a few kilometres, therefore they are of little value in measuring the amount and age of the shear. A reconstruction of 45 km left-hand shear would place Irbid opposite Sartaba, and Ed Dhira opposite the northeast extent of the Eocene near Ein Yahav. However, any larger offset up to a 105 km is not impossible. (References: Transjordan: Wetzel & Morton 1959; Sartaba: A. Flexer, Y. Weiler & R. Freund (unpublished); Ein Yahav: Bentor & Vroman 1957; Beer Menuha: Sakal 1967.)

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Discussion

F. Bender (*Bundesanstalt für Bodenforschung, Hannover, Germany*). Referring to Dr R. Freund's discussion on 'The shear along the Dead Sea rift' I should like to list below a number of observations made in Jordan. These observations, mainly mapping results, allow a simpler explanation of the anomalies in geological features across the rift than does the assumption of a post-Cretaceous 105 km left-hand shear. They also throw more light on the age of the Dead Sea geosuture. They have been described and interpreted in some more detail in a paper titled: 'Über das Alter und die Entstehungsgeschichte des Jordangrabens am Beispiel seines Südabschnittes (Wadi Araba, Jordanien)' by F. Bender (*Geol. Jb.* **86**, 177–196, Hannover 1968).

(1) At the west side of the southern Wadi Araba, the Precambrian 'Eilat-Gabbro' and the 'Timna-Gabbro' are exposed together with two small occurrences of a pegmatitic hornblendite (lateral facies of the Eilat–Gabbro complex; Bentor 1961). Meanwhile, also at the *east* side of the southern Wadi Araba, gabbro has been mapped with small occurrences of the very typical hornblendites. According to the locations of these rocks, a lateral displacement of about 25 to 35 km (sum of all lateral movements since the Precambrian) may be assumed. It is, however, just as reasonable to explain these observations with an approximate NNE–SSW-tending complex of gabbroide rocks within the basement, cut by a 'normal' 'graben' (here *ca.* 15 km wide).

(2) Quartzporphyries have been mapped along the central east side of the Wadi Araba, where they occur for about 70 km in a regional NNE–SSW striking direction (Geol. Map of Jordan, 1:250 000, sheet Aqaba-Ma'an, published by the Geol. Surv. of the Federal Republic of Germany, Hannover, 1968). They do not show evidence of a piece-by-piece cutting and movement to the north by shear forces. Their SSW-continuation points exactly to the quartzporphyries occurring at the west side of the southern Wadi Araba, and therefore does not imply a 105 km lateral displacement.

(3) The facies borders of Cambrian sediments have been determined quite accurately and continuously along the east side of the Wadi Araba, due to very favourable outcrop conditions. They run in a NNE–SSW direction. ESE of the Wadi Araba, only continental Cambrian sediments have been found. The SSW-continuation of the facies border between continental and marine Cambrian sediments points to the central portion of the southern Wadi Araba; therefore, the existence of near-shore marine Cambrian at the west side of the southern Wadi Araba can be explained without any lateral displacement.

(4) The copper ore mineralization of parts of the Cambrian sediments has also been followed continuously for about 70 km from Feinan to the south along the Wadi Araba east side. No

copper mineralization is observed in the continental Cambrian; the copper mineralization is concentrated in the shallow marine facies and consequently occurs along a NNE–SSW tending belt, clearly and without shift pointing to the copper ore mineralized Cambrian in Timna at the west side of the southern Wadi Araba.

(5) Shorelines, isopachs and facies borders of the Triassic and Jurassic run WNW to ENE to the west side of the central Wadi Araba; they leave the rift in the Dead Sea area in a NE to ENE direction. They may have been shifted; they may as well have been influenced by the palaeogeographic west border of an elevated 'Transjordan Block' (as it happened with the Cambrian facies borders). Because of the thick cover of younger sediments in the rift valley, this question remains yet unanswered. The sudden increase in thickness and the rapid facies changes of Triassic and Jurassic sediments as observed across the rift are in other parts of the world quite a common feature over tectonical hinge lines or zones of weakness.

(6) Marine sediments of Albian age have been determined near Jerusalem; they also exist opposite the rift at the east side of the Jordan valley.

(7) No detailed investigation on Lower Turonian ammonites has yet been made in south Jordan east of the rift. It can therefore not be decided whether or not there is a NE continuation of a certain ammonite zone which Freund (1961) found west of the Wadi Araba. Recent studies have shown that facies and thicknesses of the Upper Cretaceous are very much changing in south Jordan and are to a great extent controlled by the SE–NW striking El Jafr sedimentary basin.

(8) Bituminous limestones and marls are observed in the Maestrichtian through Eocene sequence, as far south as El Hasa in south Jordan. Those occurrences are definitely not restricted to Nebi Musa at the west side of the southern Jordan valley, and to the Yarmuk area at the east side of the northern Jordan valley (which would ask for a 107 km shift according to Quennell 1958).

(9) The Lisan peninsula in the Dead Sea is not formed by fluviatile deltaic sediments shifted for 45 km (Quennell 1956, 1959) but is formed by Upper Pleistocene lacustrine marls overlying thick evaporites.

(10) Along the entire east side of the rift there is an overwhelming evidence of dip-slip movements along hundreds of faults and fault zones with vertical throws up to 1000 m. Direct evidence of lateral displacements, however, (horizontal slickensides, etc.) is very rare (observed at three places) and in the order of centimetres up to a few metres. These minor lateral movements and some minor folding due to tangential compression are explained as secondary structural phenomena: taphrogenesis due to vertical movement demands a lengthening of the crust in a right angle to the direction of the graben (H. Cloos 1939).

As to the age of the Wadi Araba–Dead Sea rift, the existence of a meridional zone of weakness (or hinge linge, or geosuture) preceding the formation of the rift may be inferred from:

(i) The disposition of the Precambrian structural pattern, and of parts of the Precambrian joint and dyke system in Jordan.

(ii) The pronounced relief of the surface of the Precambrian basement complex covered by thick conglomerates of the Lower Cambrian along both sides of the Wadi Araba; the peneplanation of the Precambrian rock complex and absence of conglomerates east of the present rift in south Jordan.

(iii) The quartzporphyry-volcanism during uppermost Proterozoic to Lower Cambrian, occurring along the zone of weakness.

(iv) The Cambrian facies borders, running for more than 70 km almost parallel to the present rift, the rapid change of thicknesses and facies characteristics across the hinge line of Triassic, Jurassic and Cretaceous sediments.

(v) The taphrogenetic structural movements which initiated the formation of the graben followed this meriodional zone of weakness and occurred in the (?) Upper Eocene–Oligocene. In the Upper Oligocene, the block east of the southern part of the 'graben' had been already elevated structurally and was subject to continental erosion, and, locally, to continental deposition. In the 'graben' itself, marine sediments still occur in the Oligocene part of the section. During the Neogene and Pleistocene, several phases of major structural (taphrogenetic) movements are recorded in the stratigraphical column.

F. E. Wellings (*Iraq Petroleum Company*). Drs Dubertret and Freund have mentioned my modest contribution to the Dead Sea problem 35 years ago in the form of a southerly displacement of Cambrian and Jurassic shorelines on the west (Palestine–Sinai) side of the Jordan–Dead Sea–Akaba trough.

The originator, Lartet in 1869, did not base his 160 km slip along the eastern fault on geological evidence from the Dead Sea but from trying to make the two granite sides of the Red Sea fit together, like a jig-saw puzzle. He would be as gratified to see the new structural and stratigraphic data produced by Dr Abel-Gawad as I was to hear Dr Freund's exposition using new well logs and giving more detail than Quennell in 1956.

Geologists investigating Dead Sea tectonics have to decide between three theories of origin, namely: (1) the rift or graben faulting of Suess and Blanckenhorn, (2) Lartet's earlier longitudinal slip, (3) Bailey Willis's 1938 ramp or reverse faults observed along Mount Gilboa and Mount Carmel.

The then Government Geologist, G. S. Blake, said I was the first geologist he knew of to make a trek from Beersheba down to the south end of the Dead Sea and on down the Wadi Araba to Akaba in 1933. I was impressed with the huge NE–SW asymmetric and faulted anticlines exposing Jurassic in their cores as well as by the lack of rift faulting along the west side of the Wadi Araba until nearing Akaba.

I gave Dubertret my shoreline data because the year before (1932) he had revived Lartet's slip which he renounced today.

In 1934 I sent Bailey Willis a letter and map giving my field evidence of compressive folding oblique to the trough, the way boundary faults swing outwards at both ends of the Dead Sea as crescentic and reverse faults and die out along the flanks of plunging folds and the fact that for long distances along the Palestine side of the Jordan and Wadi Araba there are no border faults, only dip slopes.

Willis published this in 1938.

The present trough is probably due to rift faulting of Pleistocene age but the main folding in post-Eocene times that formed the trough in which the Neogene (Usdum) conglomerates, clastics and evaporites were deposited could well have had elements of ramp and thrust faulting.

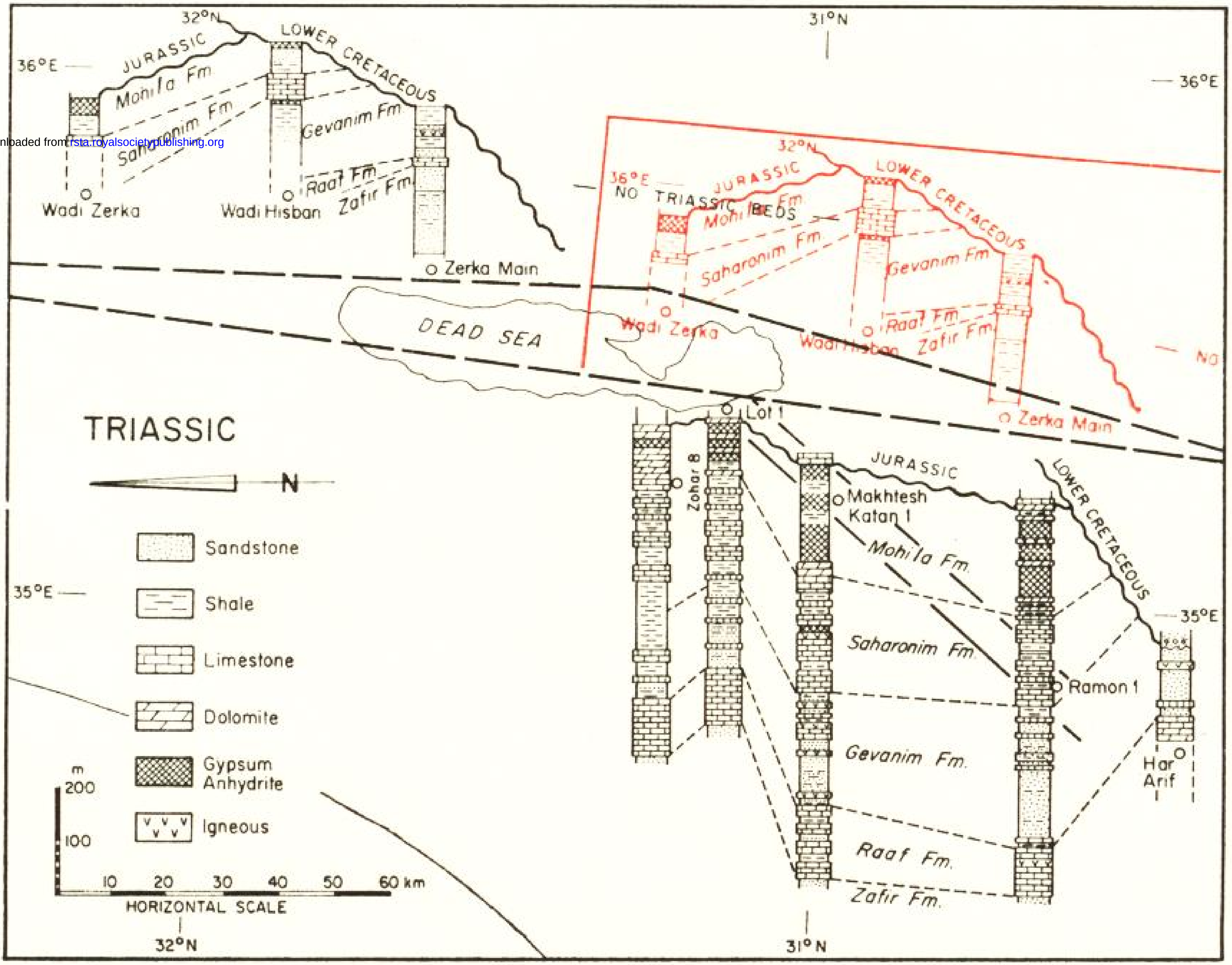
We need more field investigation of these alternative rift, ramp and wrench faulting at fault contacts.

R. Freud (written reply). Dr Bender's comments are somewhat misleading. For example, the marine Albian (comment 6) does indeed occur in Wadi Zerka, but it is very different from that of the Jerusalem area (see figure 6). On the other hand it resembles that of the Negev, about 100 km south of Wadi Zerka on the west side. Comment 9 concerning the Lisan Peninsula is most probably correct, but Dr Bender should direct it to Quennell, not to us. We made our opinion clear that the post-Lisan movement is 150 m, not 45 km. Dr Bender is selective about the occurrence of the pegmatitic hornblendite in Transjordan (comment 1); his 1968 geological map of Transjordan shows that the same rock occurs not only opposite Timna, but in several other places along a NNE direction. These are separated one from the other by the anastomosing faults east of the Arava, having been sheared into several pieces along a 100 km stretch of the shear zone. Dr Bender's other comments are fully dealt with in the text.

The major weakness in not accepting the shear hypothesis is the necessity to provide a separate *ad hoc* explanation for every single dissimilarity across the rift. Whereas the restoration of the 105 km shear (*a*) gives one single explanation to all the dissimilarities, (*b*) places all the equivalent features (more than twenty) in adjacent positions, and (*c*) does not create a single new dissimilarity across the rift. The fact that Dr Bender in his lengthy discussion could not point out a single failure to these quantitative tests speaks for itself.

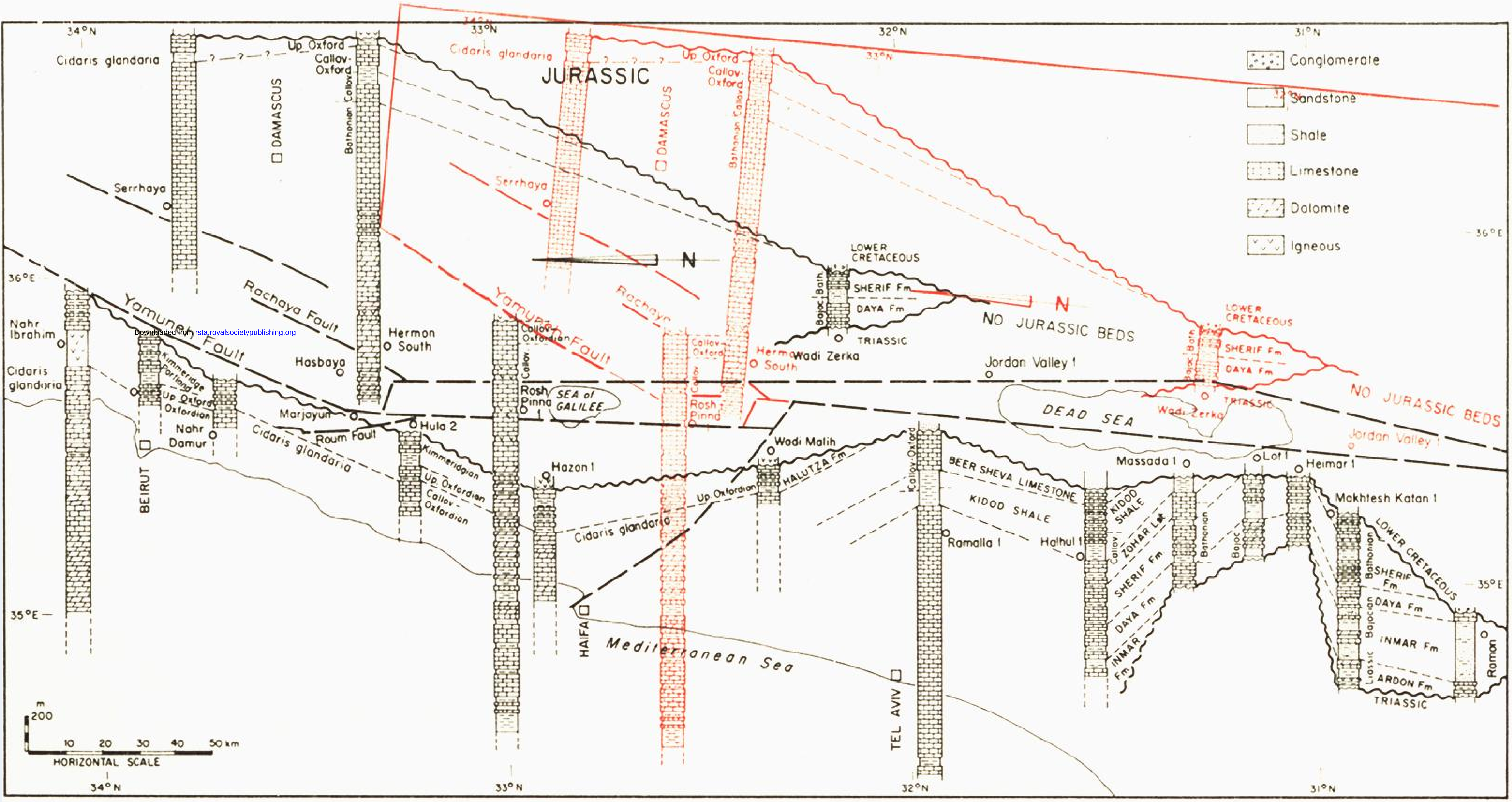
R. W. Girdler (written comments). Independent evidence for *recent* strike-slip motion along the Dead Sea rift comes from earthquake magnitude–frequency studies. Miyamura (1962, *Proc. Jap. Acad.* **38**, 27–30) suggested that the values of the constants in the relation lg $N = a - bM_b$ (N is the number of events of body wave magnitude M_b or greater) may be dependent on the tectonics of the region where the earthquakes occur. Francis (1968, *Earth & Plan. Sci. Lett.* **4**, 39–46) in a detailed study of the seismicity of mid-ocean rifts finds the value of b is significantly different for rift zones (regions of normal fault motion) from that of fracture zones (regions of strike-slip motion). Using 154 events from 1963 to May 1967 associated with the mid-Atlantic part of the world rift system Francis found $b = 1.72$ for 79 events in regions of rifting and $b = 0.99$ for 75 events associated with fracture zones.

In a review of the seismicity of Israel and adjacent areas Arieh (1967, *Bull. geol. Soc. Israel* **43**, 1–14) finds $b = 0.8$ for 25 events of magnitude $M_b \geqslant 4.5$ for the period 1919 to 1963. As nearly all these events are likely to be associated with the Jordan rift, Arieh concludes that the seismicity of the Jordan Valley–Baka'a region may be described to a first approximation by lg $N = 4.9 - 0.8M_b$. The low value of b would suggest that the events are associated with strike-slip motion and is consistent with the geological evidence given above.



IGURE 4. (*In black*) The Triassic section is 700 m thick in Ramon and 750 m in Makhtesh Katan 1. It thins to 550 m in Lot 1, and it is completely absent on the opposite side of the Rift. In Zerka-Main and Har Arif the Lower Triassic is truncated by the Lower Cretaceous unconformity. The gypsiferous facies of Mohila Fm extends on the west side from Ramon through Makhtesh Katan 1 to Lot 1, and disappears both to the southeast and to the northwest of this belt. It reappears in Wadi Zerka in Transjordan. (References: Transjordan: Wetzel & Morton 1959; Israel: I. Zak, I. Karcz & M. Goldberg (unpublished).)

(*In red*) The east side is displaced 105 km southwards together with the closing of the Rift. Zerka Main comes in line with Har Arif, and Wadi Zerka comes in line with Ramon to Lot-1 belt.



IGURE 5. (*In black*) Jurassic: The sandy facies of the Jurassic extends in Israel from Ramon to Massada 1, opposite which in Transjordan the Jurassic is absent. It appears there in Jordan Valley 1, and in Wadi Zerka the facies is sandy. The Callovian–Oxfordian Kidod Shale occurs on the west side from the southwest side of the Dead Sea to Ramalla 1 bore hole; on the east side it occurs on the southeastern slope of Mount Hermon. Upper Oxfordian–Kimmeridgian section of 200 to 400 m occurs in the Galilee and Lebanon but is almost absent in southern Mount Hermon and Rosh Pinna 1 bore hole. It probably reappears in Anti-Lebanon from Serrhaya northwards. (References: Nahr Ibrahim: Renouard 1951; Beirut: Bishopp 1964; Nahr Damour: Heybroek 1942; Hula 2, Rosh-Pinna 1 and Hazon 1: B. Derin (unpublished); Serrhaya: Dubertret 1950; Hermon south: Dubertret 1951; M. Goldberg (unpublished); Wadi Malih: E. Aizenberg & B. Derin (unpublished); Wadi Zerka: Wetzel & Morton 1959; Northern Negev: M. Goldberg (unpublished).)

(*In red*) The east side is displaced 105 km southwards and Rosh Pinna 1 is displaced 60 km southwards. Wadi Zerka corresponds to Lot 1 and Hermon-south to Ramalla 1. A 55 km wide gap is opened along Yamuneh Fault; in this illustration the deformation of Lebanon is not restored.

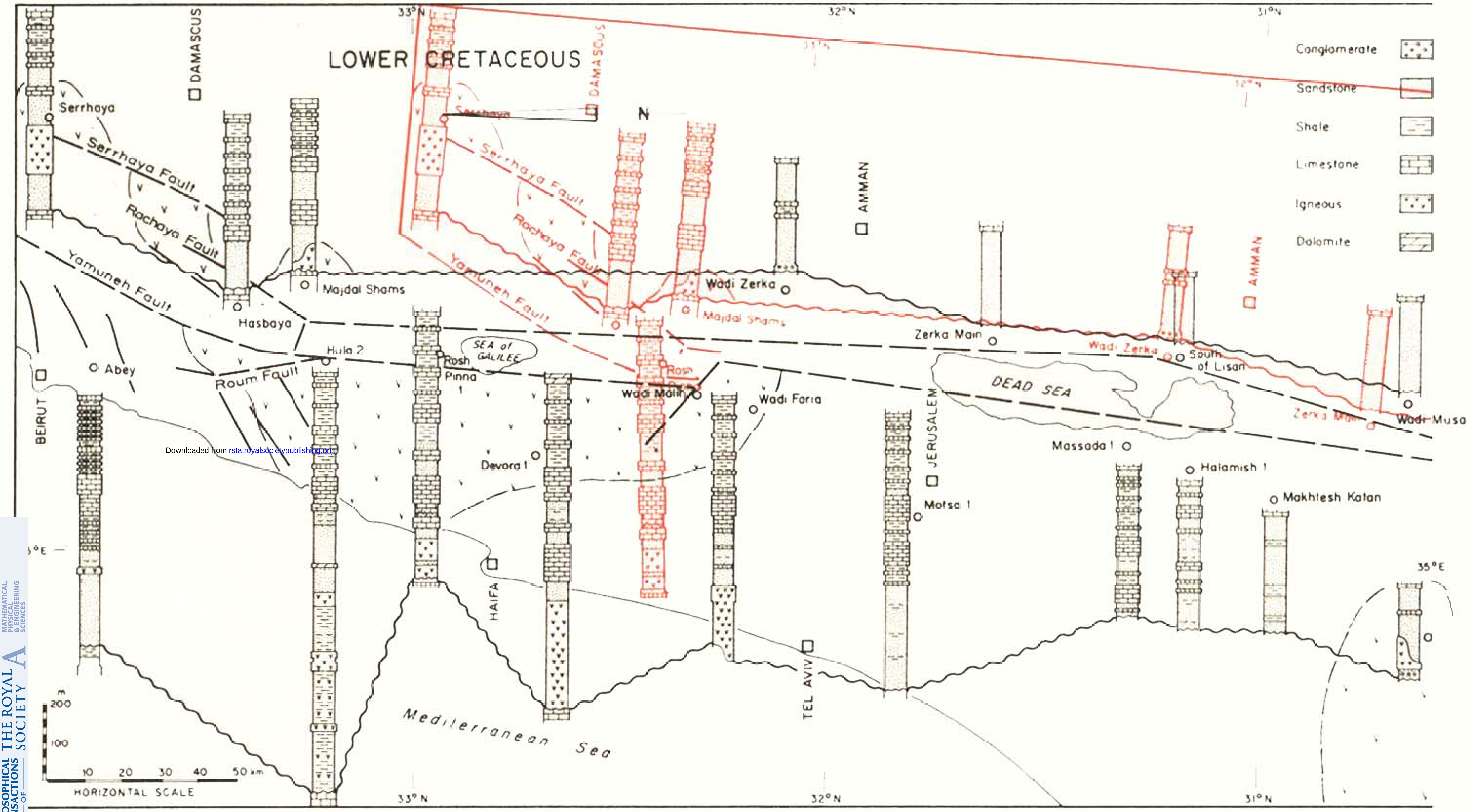


FIGURE 6. (*In black*) Lower Cretaceous: the marine Albian limestones extend in Israel as far south as Ramon, where the Lower Cretaceous starts with a base conglomerate, whereas in Transjordan the Albian limestone extends southwards only to Wadi Zerka, where the base conglomerate occurs again. Opposite Wadi Zerka, in Wadi Malih–Wadi Faria area the Lower Cretaceous section is 650 to 750 m thick, and more than two thirds of the sequence consist of marine limestones and shales. Volcanic rocks occur at the lower part of the Lower Cretaceous sequence from Wadi Faria to southern Lebanon (Marjayun), whereas on the east side they occur from Majdal Shams to Serrhaya. (References: Abey: Heybroek 1942; Serrhaya and Hasbaya: Dubertret 1950–51; Majdal Shams: U. Salzman (unpublished); Hula-2: Shiftan & Rosenthal 1963; B. Derin (unpublished); Rosh Pinna 1 and Debora 1: B. Derin (unpublished); Wadi Malih: J. Mimran & R. Freund (unpublished); Transjordan: Wetzel & Morton 1959; Bender 1968*b*; Negev and Motsa 1: Aharoni 1964; Arad 1964.)

(*In red*) The east side is displaced 105 km southwards and Rosh Pinna 1 is displaced 60 km southwards, but the displacements along Serrhaya-Rachaya faults and the Galilean and Lebanese faults are not restored, thus the gap of 55 km along Yamuneh Fault is maintained. Wadi Zerka corresponds to Ramon along north-east trending isofacies lines. Majdal Shams section corresponds to Wadi Malih section.

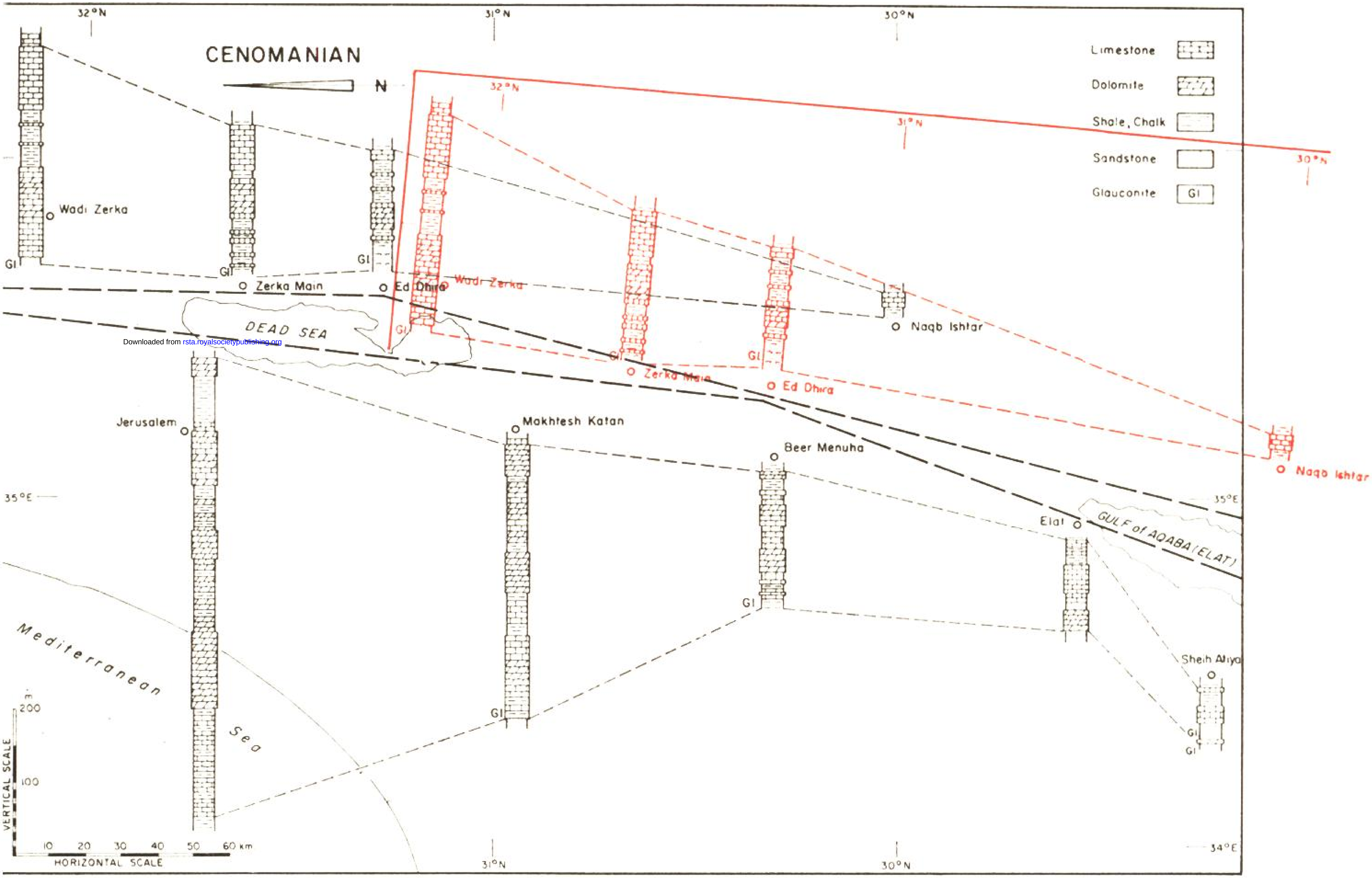


FIGURE 7. (*In black*) The Cenomanian section (including the upper part of Albian) of Jerusalem measures about 650 m, whereas that of Wadi Zerka only 280 m and those of Zerka Main and Ed Dhira about 200 m only, comparable to those of Beer Menuha (175 m). Opposite the latter the Cenomanian section of Naqb-Ishtar is less than 50 m thick. (References: Transjordan: Wetzel & Morton 1959; Jerusalem: Arkin *et al.* 1965; Makhtesh Katan: Arkin & Brown 1965; Beer Menuha: Sakal 1967; Elat and Sheih Atiya: Bartov *et al.* 1970.)

(*In red*) The east side is displaced 105 km southwards with the closing of the Rift. The thicknesses of the two sides match well along ENE trending isopach lines.

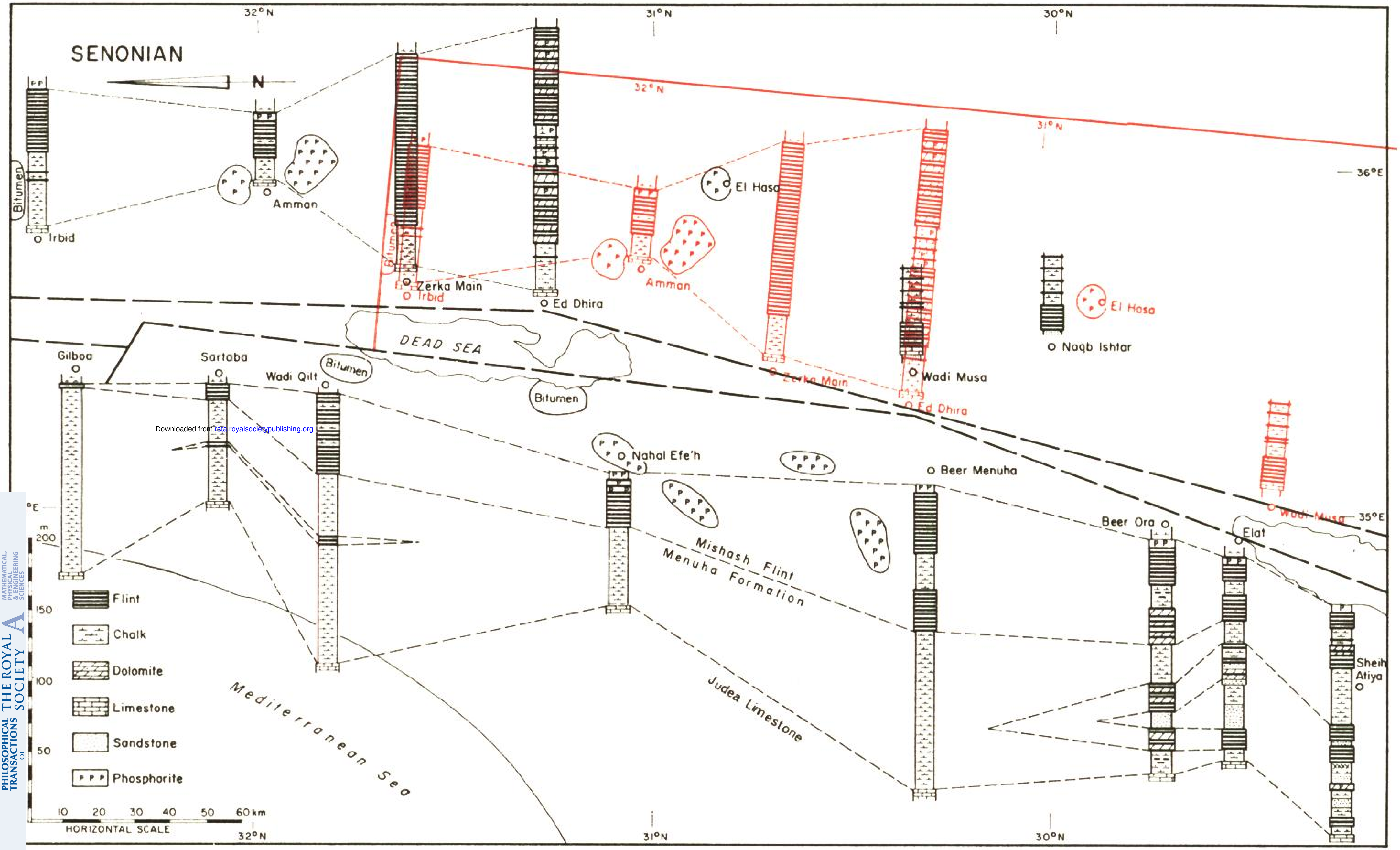


FIGURE 9. (*In black*) The *ca.* 200 m Senonian (Santonian–Campanian) sequence on the east side of the Dead Sea contains flint and dolomite almost throughout, as does the Senonian sequence in the southern Negev. However, the latter contains some sandstone beds which are not reported on the east side of the Dead Sea. On the west side of the Dead Sea and in the central Negev the flint beds occur only in the upper half of the section, similar to the section in north Transjordan. In northern Israel the flint beds are very thin or missing altogether. The economic phosphorites occur around Amman in Transjordan and in the northern Negev in Israel, but there is another occurrence in El Hasa in Transjordan. (References: Transjordan: Wetzel & Morton 1959; Bender 1968*b*; Gilboa: Flexer 1959; Sartaba: A. Flexer, Y. Weiler & R. Freund (unpublished); Wadi Qilt I. Rot (unpublished); Nahal Efeh: Kolodny 1967; Beer Menuha: Sakal 1967; Beer Ora, Elat and Sheih Atiya: Bartov *et al.* 1970.)

(*In red*) The 105 km southwards movement of the east side brings the corresponding facies on the two sides in line along NNE-trending facies lines.