PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Seismicity and Structure of the Zagros (Iran): The Main Recent Fault between 33 and 35 degrees N

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SEISMICITY AND STRUCTURE OF THE ZAGROS (IRAN): THE MAIN RECENT FAULT BETWEEN 33 AND 35° N

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[Plates 1–3]

CONTENTS

The most recent tectonic deformation of the Zagros, and in particular the late Quaternary right-lateral wrench movement along the Main Recent Fault, is summarized in the context of the general tectonic history of the range. The seismicity along the Main Recent Fault between latitudes 33 and 35° N is examined, and details are given for several destructive earthquakes, including the 1909 Selakhor earthquake which was associated with over 40 km of surface faulting along a segment of the Main Recent Fault and which is described here for the first time. The relation between the seismicity and the individual fault segments forming the Main Recent Fault is studied and interpreted in terms of a continuing right-lateral strike slip deformation. The implications of this contemporary deformation for the seismotectonics of the Zagros are considered, and in particular its bearing on the problem of the relative motion of the Arabian Plate with respect to Central Iran.

1. Introduction to Zagros tectonics

The Zagros mountain range which extends over a length of over 1500 km from eastern Turkey, through part of Irak and Iran, to the Gulf of Oman, is one of the key structural elements in the Alpine and Recent tectonics of the Middle East. Structurally, it appears to result from the collision of the continental plate of Arabia in the southwest with Central Iran in the northeast (figure 1). The range acquired its present-day structure through a series of compressive tectonic phases, the principal ones occurring at the end of the Triassic, at the end of the Jurassic, at the end of the Cretaceous, during the Oligocene and during the Pliocene. Extensional interludes probably also took place, in particular during the earlier phases. The intense present-day seismicity of the region indicates that tectonic deformations are still in progress.

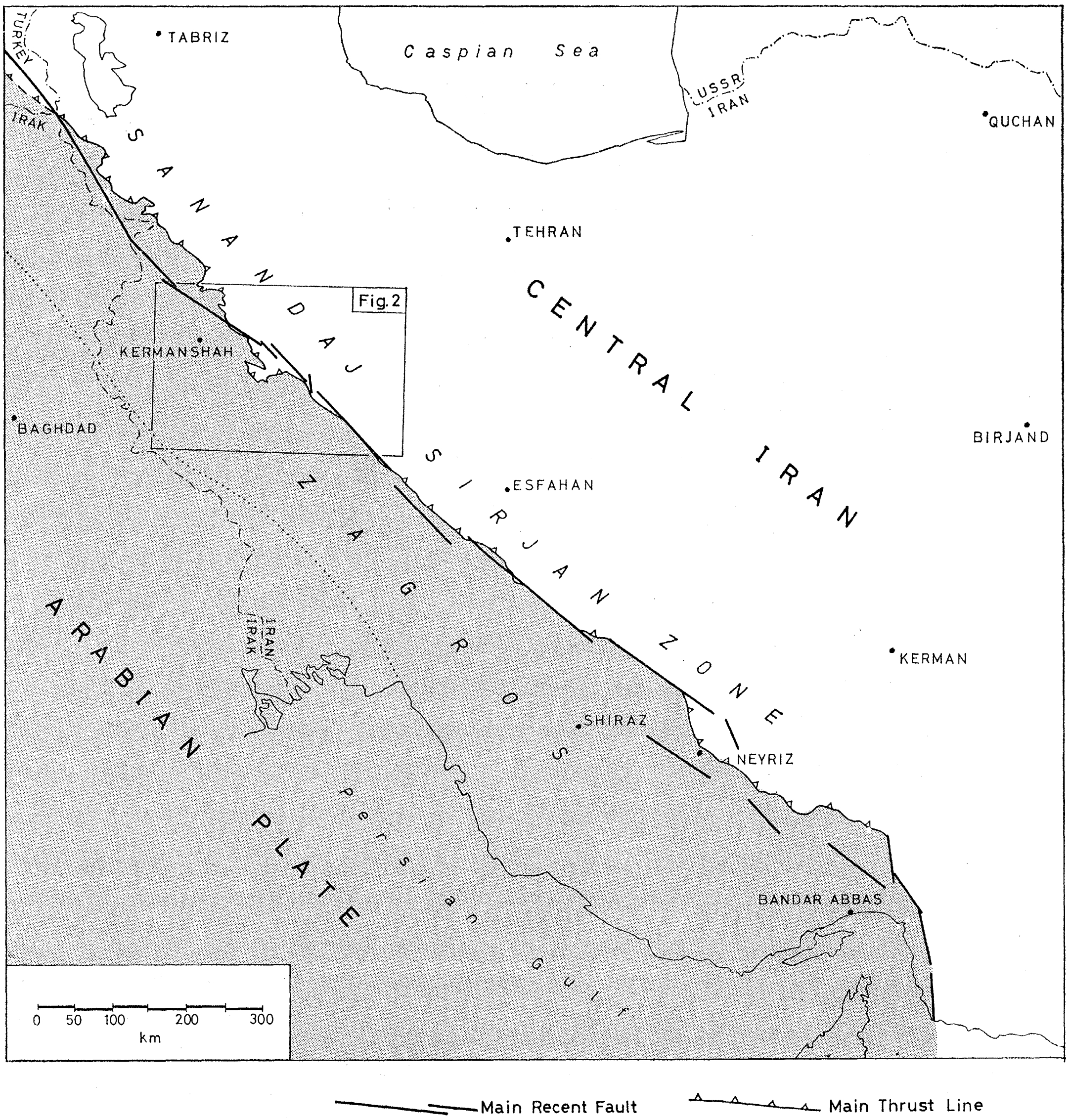

Figure 1. Situation of the Zagros in Middle Eastern tectonics. The Arabian Plate is shown shaded. The dotted line marks the southwestern limit of the Zagros folded range, the northeastern limit being the Main Thrust Line. The region studied here is the one covered by figure 2.

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Detailed analysis of the different tectonic phases observable in the Zagros is beyond the scope of the present study. In brief, the phases at the end of the Triassic and at the end of the Jurassic involved only the northeastern border of the ocean trough from which the range was eventually to emerge. The resulting zone is usually referred to as the metamorphic zone of the Zagros or the Sanandaj–Sirjan Zone (Stöcklin 1968). The late Cretaceous displacements were probably much more important, as they resulted in ejection and emplacement on the margins of the Arabian Plate of an oceanic series with ophiolites and radiolarites (Ricou 1971). After this phase, a physiography of longitudinal ridges and basins predominated, the most northeastern basin, probably located on the ophiolites, being rapidly filled with flysch deposits (Bizon, Bizon & Ricou 1972).

At the end of the Pliocene, a new compressive phase crushed this northeastern flysch basin and initiated folding of the formations covering the margin of the Arabian Plate, gradually building up the topography which can be seen today. The Pliocene deformations also generated along the northeastern side of the mountain range a major tectonic discontinuity termed by geologists the *Main Thrust Line* (or Zagros Thrust Line). The importance of this structure which is continuous over the whole length of the range was pointed out by several authors (Gansser 1955; Falcon 1967, 1969; Stöcklin 1968). It separates a Zagros domain in the southwest from a Central Iranian domain in the northeast. Thus, immediately southwest of the Main Thrust Line one finds a *Thrust Zone* (or Imbricated Belt) containing strongly tectonized series with radiolarites and ophiolites, as well as with some limestone units; further to the southwest starts the simply folded *Zagros s. str.* formed of practically continuous sedimentary series from the Cambrian to the Pliocene. To the northeast of the Main Thrust Line the series containing the metamorphic rocks were considered as characteristic of Central Iran.

Two regions of the Main Thrust Line and Thrust Zone, Kermanshah in the northwest and Neyriz in the southeast (figure 1), have been recently studied in detail and mapped on a 1:50000 scale (see references in Ricou 1973 and Braud 1974). These studies have shown that the Main Thrust Line is a complex zone of structures (rather than a single structure), and that several palaeogeographic domains can be recognized as tectonic units within the Thrust Zone: autochtonous, Cretaceous nappes with radiolarites, ophiolites, Bisitun limestone, Tertiary flysch basin. Each unit is thrust southwestwards over the preceding unit, and consequently several thrust faults of different ages, namely Senonian and Pliocene, are present within the Thrust Zone. It is usually possible, however, to define one of these thrusts in a manner which corresponds with the original Main Thrust Line concept of the early authors, i.e. the southwestern thrust front of the Central Iranian domain over the Zagros domain. In the present paper, the term Main Thrust Line (or its abbreviated form, Main Thrust) is used specifically to designate the southwestern limit of the domain which underwent an early tectonic phase (Triassic and end-Jurassic) and which contains Mesozoic series tectonized, metamorphized and granitized during Mesozoic and Tertiary orogenies (the Sanandaj–Sirjan Zone of Stöcklin (1968), or the Metamorphic Zagros of Braud (1974)). The thrust nature of this limit is particularly evident in the region studied here between Sahneh and Dorud where the metamorphic series lie horizontally over the Tertiary cover of the radiolaritic and ophiolitic series. The age of this thrust movement is post-Bakhtiary (? end-Pliocene).

Apart from clarifying the nature of the Main Thrust Line, mapping in the Kermanshah and Neyriz regions has brought to light the existence of another major structure broadly parallel to, but quite distinct from, the Main Thrust Line (Braud & Ricou 1971). It is also younger than the latter, which it transects in several places. It is termed here the *Main Recent Fault*. In the two regions where it has been studied in detail, it appears as a succession of vertical fault segments each of the order of 100 km or more in length. The disposition of these segments *en echelon*, as well as the presence of associated conjugate faults and minor fold and thrust structures, indicate that the Main Recent Fault is a right-lateral wrench fault. Between the two regions mentioned above, the fault trace as shown on figure 1 was drawn during a reconnaissance trip (Braud & Ricou 1972), and beyond these regions it was established provisionally on the basis of aerophotographs and existing geological documentation. The seismicity and structure of the Main Recent Fault are the principal concern of this paper.

The continuing tectonic deformation of the Zagros can be demonstrated with cases of folding in very recent and even contemporary formations, and with numerous cases of active faulting. The region is also, especially in the south, the most seismic of Iran and possibly of the entire Middle East. The great majority of earthquakes are located quite clearly within the boundaries of the range, with very few events occurring either in the Sanandaj–Sirjan Zone or in the interior of the Arabian Plate. Fault-plane solutions obtained by various workers generally yield thrust mechanisms in broad agreement with a SSW–NNE motion of the Arabian Plate deduced from observations in the surrounding oceans (McKenzie 1972).

The present study examines the relation between seismicity and most recent tectonic deformation along the Main Recent Fault. For this purpose the segment between 33 and 35° N was chosen because it combined the advantages of comparatively well-known geology and well-documented earthquakes. How far this segment is representative of the entire length of the fault is discussed in the concluding section.

2. Seismicity along the Main Recent Fault

(*a*) *Early earthquakes*

Three pre-twentieth-century earthquakes which occurred near the Main Recent Fault have been partially documented. The first two were located near Dinawar in the northwest, and the third near Lake Irene in the southeast (figure 2). The Dinawar earthquakes occurred in May 912 and in April 1008, causing serious destruction and casualties in the town of Dinawar, today an uninhabited site near Kargsar. For the first earthquake it is mentioned that a mountain split open at Dinawar and that streams of water gushed from it, submerging many villages. There is also some evidence that ground fractures, possibly of tectonic origin, occurred during the second earthquake. It will be seen in § 3 that the Dinawar region is indeed one of the localities where the trace of the Main Recent Fault is particularly clear through modern alluvial sediments. Details of these two earthquakes are given in Ambraseys (1974).

The Lake Irene earthquake, for which documentation is less precise, occurred some time before 1889. The small mountain lake located on the Main Recent Fault southeast of Dorud is often connected in the local legend with a destructive earthquake which happened a few generations ago. Sawyer, who explored the region in 1889 and named the lake after his daughter, found ruins of ancient Armenian stone villages deserted on account of frequent earthquakes which triggered off large rockfalls (Sawyer 1894). No further details have so far been found on this event.

Archaeological explorations in progress at Kangavar, Godin Tepe and at other localities in the region provide some indication of much earlier destructive earthquakes (Matheson 1972);

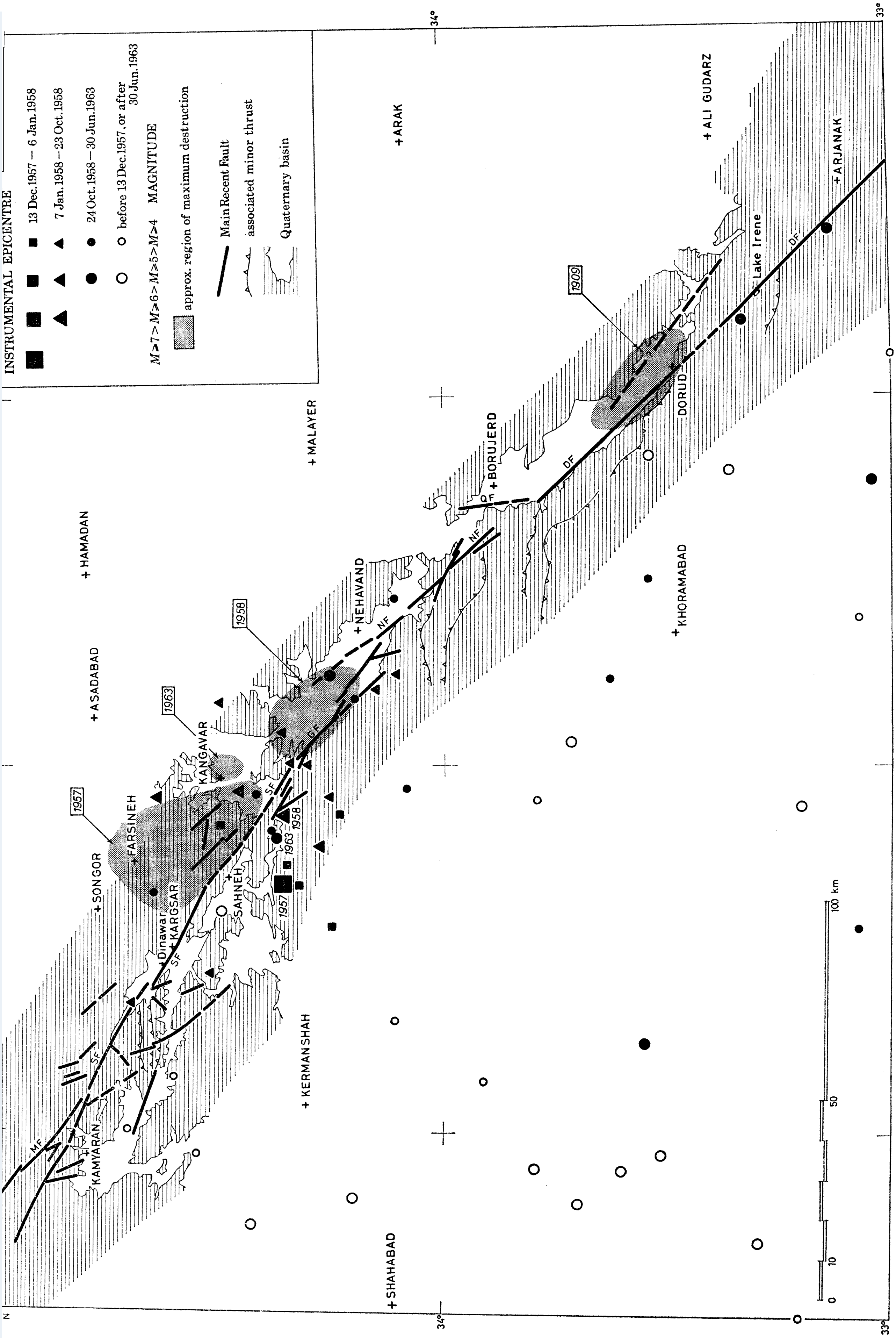

FIGURE 2. Seismicity and structure of the Main Recent Fault. Only the most recent and active structure (the Main Recent Fault) is shown, to the exclusion of the Main Thrust Line. DF, Dorud Fault; GF, Garun Fault; MF, Morvarid Fault; NF, Nehavand Fault; SF, Sahneh Fault (Southeastern, Central and Northwestern sections); QF, Qal'eh Hatam Fault. Interrupted line where fault trace is uncertain. Epicentres are for 1913–1972 (see Appendix). Dates refer to instrumental epicentres and approximate regions of maximum destruction of largest earthquakes. The 1957 region includes effects of main shock and principal aftershocks.

it seems likely that the Main Recent Fault has had a seismic history extending several hundred years in the past.

(*b*) 23 *January* 1909: *Selakhor earthquake*

The earthquake occurred at 02h 48m 18s GMT (6.18 a.m. local time) on 23 January 1909, and had a body-wave magnitude of 7.4 (Gutenberg & Richter 1954; Peronaci 1958). It caused between 5000 and 6000 deaths, and was associated with a fault-break over 40 km long. As very little has been published on this important earthquake, the bibliographical and field data collected by the authors is given here in some detail.

The region of maximum damage was located in the District of Selakhor, and a contemporary poet, Sa'mete Borujerdi, was the first to have referred to the event by the name of the district (Borujerdi 1909). Many European stations recorded the earthquake, and the daily and scientific press reported it briefly (*The Times*, 18 Feb. 1909; Dongier 1909; Lysakowski 1910). In Russia, several attempts were made to calculate the instrumental epicentre, resulting in locations all at quite some distance from the true epicentre. As these results are used in many modern earthquake catalogues, sometimes with a considerable amount of confusion (see, for example, Wilson 1930; Rezanov 1959), it seems worth while to explain how they were obtained at the time. The first epicentre was calculated at 36° N, 56° E on the basis of arrival times at the stations of Irkutsk, Pulkovo and Tibilisi (Golitsin 1909*a*). This was subsequently modified to 33.9° N, 48.8° E when the press reported destruction in southwestern Persia (Golitsin 1909*b*). Later, after the macroseismic effects had been investigated in the field, it was decided to place the epicentre at the mid-point between Borujerd and Isphahan, i.e. at 33.3° N, 50.2° E (Shtelling 1910). It will be seen that the macroseismic epicentre from the present study is approximately located at 33.5° N, 49.0° E.

On instructions from Golitsin, the Russian Consul in Kermanshah sent a team into the epicentral region to investigate the effects of the earthquake. A summary of this team's findings was reported by Shtelling to the Permanent Seismic Commission in St Petersburg (Shtelling 1910). Shtelling's report, together with the field mapping and interviews of some survivors carried out by the present authors in 1971, are the basis of the following description of the earthquake.

In Kermanshah and in the villages on the road from Kermanshah to Borujerd the earthquake was felt but caused no damage. In Borujerd, objects were thrown down from furniture, and the Russian investigation team deduced from descriptions of the waves created in ponds that the strongest shaking had been in the east–west direction. There was, however, no destruction in the town. Aftershocks were felt frequently by the team until it left Borujerd on 1 February 1909. Two of these shocks, the first on 31 January and the second on 1 February, were particularly violent, the latter throwing the Kossak guards 'out of their beds on to the floor'.

The northeastern limit of the zone of destruction is well defined as Shtelling specifies that Zargeran (Zargina) was the first village to have been damaged on the road from Borujerd to Dorud (figure 3). In Zargeran 10 out of 200 houses were destroyed, but there were no casualties. Farther to the southeast, a total of 58 villages were either completely destroyed or very severely damaged; out of these the Russian report mentions specifically Lavan (25 people killed), Mirabad, Gushepol, Baba Khuni, Chegha Abdar, Sangar and Dorud. Limited information for the region southeast of Dorud makes it more difficult to define precisely the southeastern extent of the zone of destruction. The Russian investigation team did not travel beyond Dorud (then known as Bahrein) because a cholera epidemic had declared itself in the devastated area.

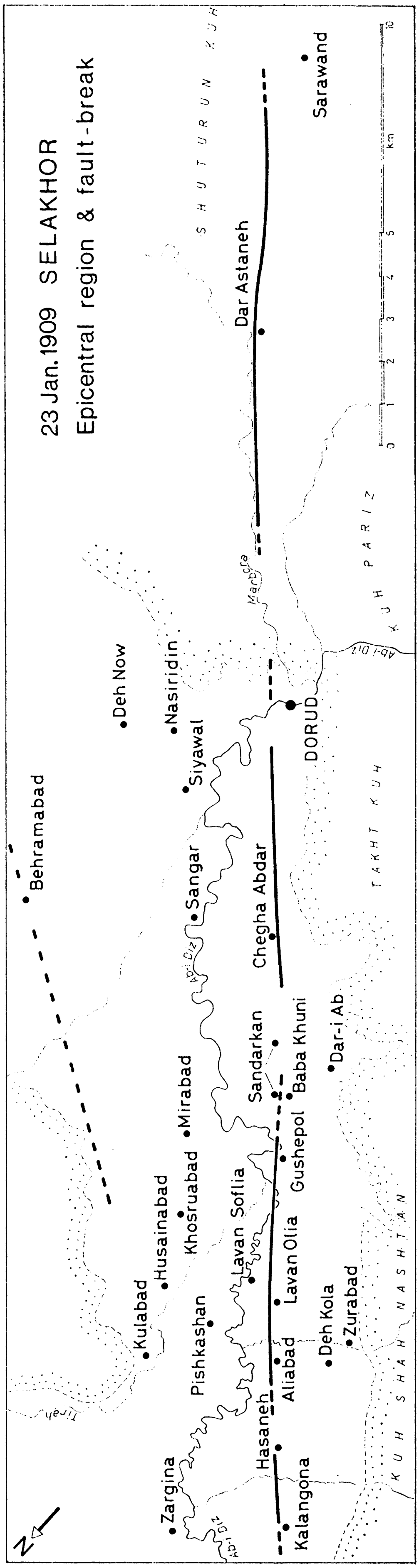

FIGURE 3. 1909 Selakhor earthquake. Villages in the epicentral region and identified segments of the earthquake fault-break (dashed where trace is uncertain). Sketch map based on field mapping and 1:50000 aerial photographs.

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Their report mentions that, on the basis of indirect information, damage was thought to extend into the adjoining district of Haft Lang, and that villages were affected all the way to Esfahan (about 260 km from Dorud). This information seems to us very doubtful, and it was not verified by any of our findings. From our investigations in 1971 and 1972 and interviews of a few survivors, it was deduced that Mianrudan, Dar Astaneh and Sarawand had been damaged and had suffered casualties, that Darband, Kal Qal'eh and Maqsudabad were only lightly damaged and without casualties, and that the shock was felt but did not cause any damage in Azna and Ali Gudarz (figures 2 and 7). Contemporary reports suggest that it was only very lightly felt south of the Karun River.

Altogether, the available macroseismic information indicates that damage was confined to the southeastern part of the narrow plain watered by the upper Ab-i Diz River and referred to today as the Borujerd (or Selakhor) Valley (figure 4, plate 1). The earthquake happened without warning, and continuous shaking was reported to have lasted about 4 min. The number of people killed was estimated by the Russian team to have been between 5000 and 6000.

Ground fissures, some a few kilometres in length, are mentioned by contemporary reports, and in 1971 some survivors remembered the large 'crack into which the river disappeared for two days'. The location generally indicated by the inhabitants corresponds with a marked topographic step, linear in plan, that can be followed on the ground and on aerial photographs over a length of more than 40 km, from Kalangona in the northwest to Dorud in the southeast (figure 3). This step is located in the flat part of the valley, in modern river alluvium except between Lavan and Kalangona, where it separates the plain from the alluvial fans originating in the mountains to the southwest. The northeastern side of this topographical step is always downthrown by up to 1 m (figure 5, plate 1). The trace cuts a meander of the Ab-i Diz River near Gushepol at the approximate location where the inhabitants had indicated that the river had disappeared into a crack. Southeast of Dorud the alluvial scarp is continued by a marked fault in the rock formations of the Shuturun Kuh, and was reactivated during the earthquake at Dar Astaneh and as far south as Sarawand (figure 7).

There seems little possible doubt that this topographical step is the eroded expression of the fault scarp associated with the 1909 earthquake. The displacement along the fault during the earthquake is not known from contemporary accounts. It is, however, highly probable that the vertical displacement in 1909 was as suggested by the present-day topography, i.e. that the northeastern block was downthrown. The amount of the displacement must have exceeded 1 m. No suitable markers have been found so far to establish whether any horizontal displacement also took place, and if so in which sense, but further field work is planned. The earthquake scarp corresponds very precisely with the Dorud Fault segment of the Main Recent Fault and will be examined in more detail in §3.

(*c*) 13 *December* 1957: *Farsineh earthquake*

After 1909, on the basis of the instrumental data used here (see Appendix), the Main Recent Fault between 33 and 35° N underwent a period of relative quiescence which lasted for nearly 50 years. A few epicentres were located during this period in the mountains southwest of the Main Recent Fault. The shock nearest to the Fault occurred on 4 December 1955 near Razan, causing rockfalls which destroyed the village and killed three people (figure 7).

The Farsineh earthquake occurred at 01h 45m 04s GMT on 13 December 1957. Its instrumental epicentre was located about 12 km south of Sahneh at 34.35° N, 47.67° E, and the

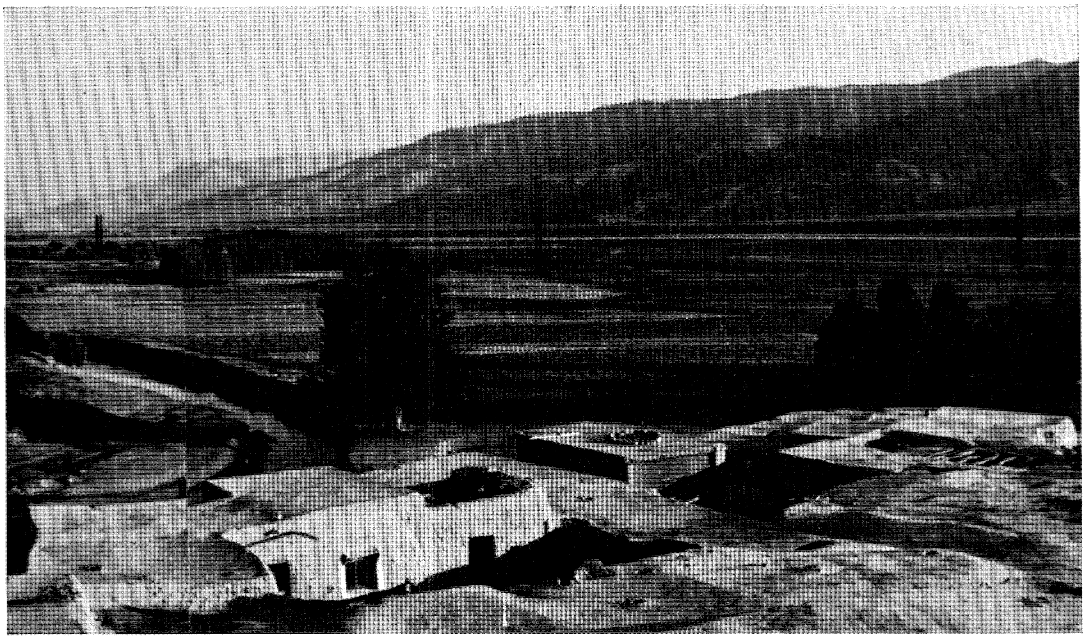

FIGURE 4. Epicentral region of the 1909 Selakhor earthquake. The southeastern part of the Selakhor Valley with the upper Ab-i Diz River. The 1909 fault scarp (indicated by arrows) was produced by reactivation of the Dorud Fault, a segment of the Main Recent Fault. The village of Lavan Soflia (foreground), today rebuilt in the same style and at the same location, was destroyed in 1909 and suffered 25 fatalities. Looking southeast.

FIGURE 5. 1909 Selakhor earthquake Fault. Eroded fault scarp in the Selakhor Valley between Lavan Olia and Aliabad. Typical scarp height is now 1 m but must have been greater before erosion. Looking northwest.

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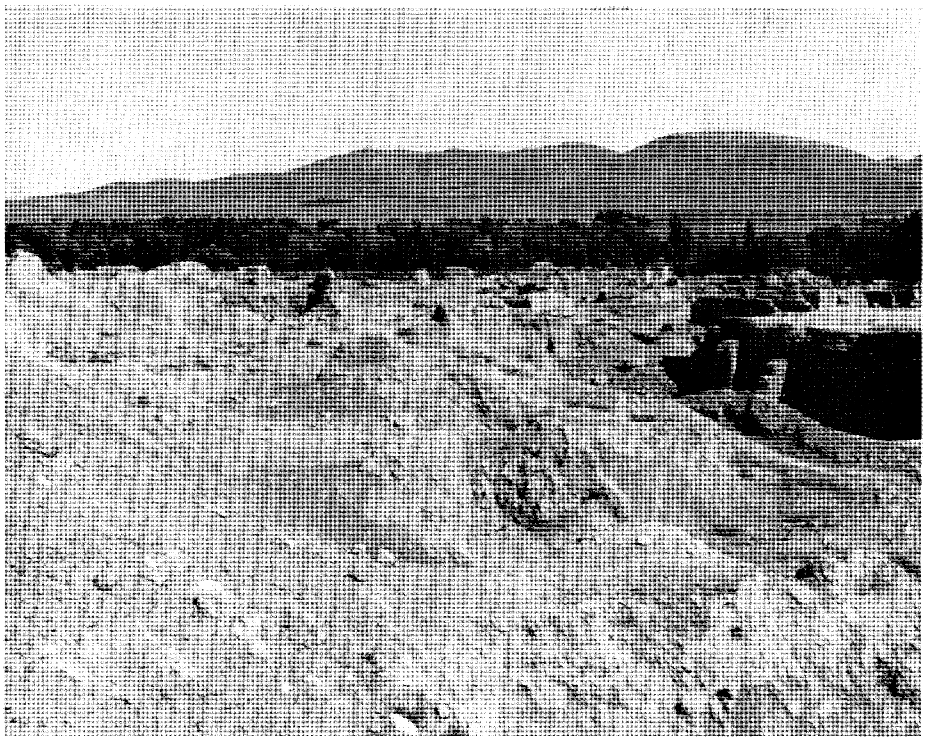

FIGURE 6. 1957 Farsineh earthquake. Ruins of the old village of Farsineh where 703 people, constituting about 50% of the population, were killed by the earthquake. Photographed in 1971.

FIGURE 9. Nehavand Fault. Active scarp near Fambyar. Northeastern side (left in photo) is downthrown by about 2 m. The fault continues in the southeast (arrow) towards Chaqawal, through the region damaged slightly by an earthquake in 1961 (no. 7 in figure 8).

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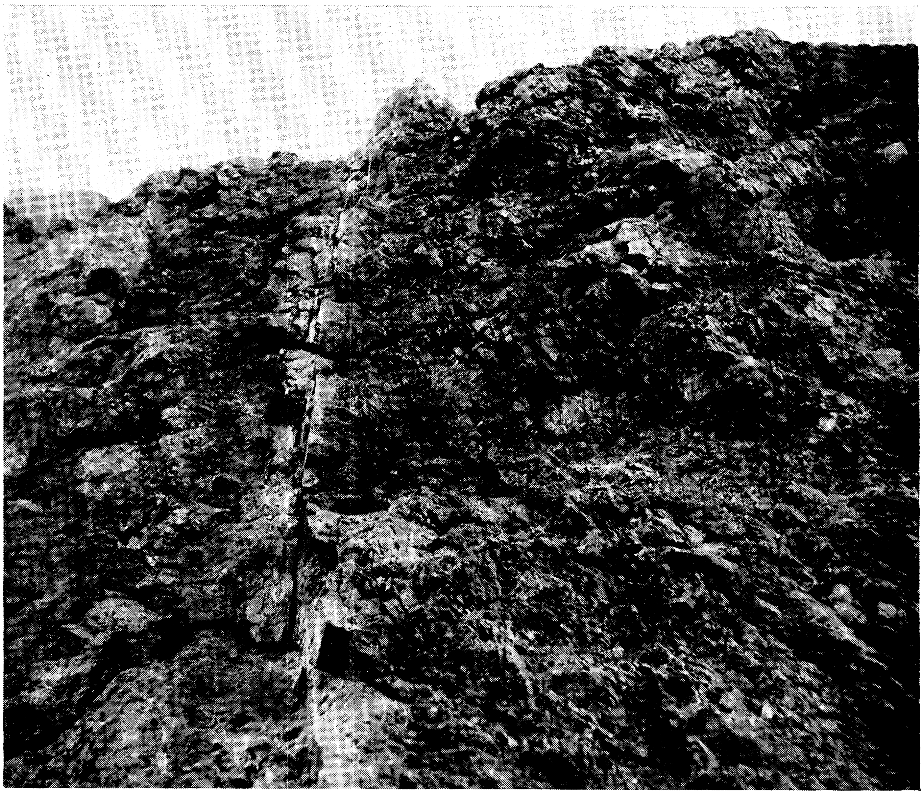

FIGURE 11. Sahneh Fault. Mylonite zone in Cretaceous limestone southeast of Sarab Bidsurkh, along the Central section of the Sahneh Fault.

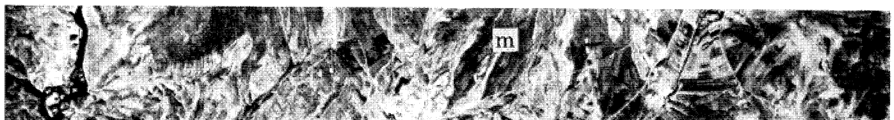

FIGURE 12. Sahneh Fault. Aerial view of the fault trace (between arrows) which separates the modern alluvium in the southwest (lower left of photograph) from the earlier Quaternary formations in the northeast (upper right). Kargsar is located just left of the symbol 'K', and the site of the ancient Dinawar just right of 'D'. The metamorphic rocks of the Sanadaj–Sirjan Zone are indicated by 'm'. North is at the top of the photograph.

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average body-wave magnitude from several stations was 7.0. Official figures for casualties and destruction were 1130 people killed and 211 villages destroyed or severely damaged. A great number of aftershocks in the first weeks after the earthquake increased the destruction caused by the main event.

The combined macroseismic effect of the main shock and immediate aftershocks were studied in the field soon after the earthquake (Peronaci 1958, 1971), and special points studied by the present authors in 1971. The villages most severely affected were the ones located at the periphery of the Kuh Nakuchal north of Sahneh (figure 10). Farsineh, at the northern foot of the mountain suffered the greatest percentage of casualties (figure 6, plate 2), and the maximum destruction was considered to be located between Farsineh and Kangavar (Peronaci 1971). In the south, destruction became unequal and decreased rapidly beyond the Kangavar–Bisitun road: for example, Sarab-Bidzurkh was severely damaged and had 53 fatalities, whereas Sahneh, Gakul and Bisitun suffered only relatively minor destruction.

Thirty-two aftershocks were felt locally during the first months after the main shock and caused further damage and casualties. Epicentres of shocks which were strong enough to be determined instrumentally showed a NE–SW trend approximately normal to the Main Recent Fault (figure 2). The smaller shocks, however, which caused damage in the days after the main event, were centred near Kangavar (13 and 18 December) and Firuzabad (28 December), indicating a NW–SE trend. The earthquake was associated with some fissuring in the alluvium northwest of Sahneh, and with rockfalls and an interruption of the Sarab Bidsurkh spring northwest of that village, in both cases in locations which correspond approximately to the Central section of the Sahneh Fault (see §3 (*c*)). The information on ground deformation is, however, insufficient to establish with certainty that fault movement occurred.

(*d*) 16 *August* 1958: '*Nehavand*' *earthquake*

After January 1958 the seismic activity initiated by the Farsineh earthquake decreased for a few months until August 1958, when there occurred a series of shocks along the Main Recent Fault to the southeast of the 1957 epicentral region. The largest was recorded at 19h 13m 43s GMT on 16 August 1958, and had a body-wave magnitude of 6.6. About 110 villages were destroyed or damaged, and 191 people were killed (Hagiwara & Naito 1959; Montandon 1961; *The Times*, 23 Aug. 1958). The instrumental epicentre was located about 17 km to the east of the Farsineh epicentre, at 34.36° N, 47.86° E (figure 2, and no. 3 in figure 8). The region of maximum destruction extended, however, from the destroyed villages of Gilabad and Muhinabad in the southeast to Firuzabad Bozorg in the northwest, i.e. it was centred approximately 30 km ESE of the instrumental epicentre. It is likely that the location of the region of destruction was influenced by two foreshocks of magnitude $4\frac{1}{2}$–5 which were strongly felt locally and which weakened many houses. The first, on 15 August at 04h 23m 14s, was located at 34.11° N, 48.24° E, and the second, on 16 August at 17h 09m 19s, 34.29° N, 47.86° E, locations on either side of the region damaged by the main shock (nos. 1 and 2 in figure 8). These two foreshocks and the main shock indicate a migration from the southeast to the northwest along a zone which will be shown in §3 (*b*) to correspond approximately with the Garun Fault segment of the Main Recent Fault.

A surface fault-break between 5 and 15 km in length accompanied the earthquake. It was situated along the left bank of the Gamasiab, near the village of Kirdian and Qilab (figure 8). Vertical displacements were between 1 and 2 m with the northeast side downthrown; horizontal movements could not be determined in 1971 from the eroded fault scarp, but the disposition of the fault trace *en echelon* is characteristic of a right-lateral component. The fault-break was caused by reactivation of the Garun Fault (see §3(*b*)). Farther to the east, on either side of Firuzabad, ground deformation along a line coinciding approximately with the 1500 m contour may also have been of tectonic origin.

As in the case of the Farsineh earthquake, the largest aftershocks in 1958 indicate both a NW–SE and a NE–SW trend, i.e. along and normal to the Main Recent Fault (figure 2).

(*e*) 24 *March* 1963: *Karkhaneh earthquake*

In the years following the 'Nehavand' earthquake, several small shocks caused localized damage in and around the epicentral regions of the 1957 and 1958 earthquakes; in particular, on 29 September 1958 in Kargsar, on 2 April 1960 near Asadabad, on 14 October 1961 in Aliabad Magh, on 24 March 1963 in Karkhaneh and 30 June 1963 in Tapeh (and Ali Gudarz?).† The largest of these shocks was the one which occurred on 24 March 1963 at 12h 44m 04s, with an average magnitude of 5.8. The instrumental epicentre was located between the Farsineh and 'Nehavand' epicentres, and damage was strongest around Kangavar, in particular at the villages of Karkhaneh and Aliabad (figure 8). The effect of this earthquake was thus to link the macroseismic regions of the 1957 and 1958 earthquakes. It was estimated at the time that a total of about 5000 houses were severely damaged and nearly 100 people injured.

After 1963, most earthquakes were concentrated in the mountains southwest of the Main Recent Fault. Occasionally, however, some shocks were still felt along the Fault, as on 15 February 1967 (34.5° N, 47.6° E, $M_b = 5$) felt in Sahneh and Asadabad, and on 28 January 1971 (35.0° N, 47.0° E, $M_b = 4.6$) felt in Kamyaran and Sanandaj. Shocks too small to be reported by the world network also occurred: two were felt by one of the authors (J.B.) in Kangavar on 12 September 1971 at 11 a.m. and at 20.30 p.m.

(*f*) *Migration of seismic activity*

The locations of the destructive earthquakes described so far suggest that they were all in some way related to the Main Recent Fault, a point which will be returned to in detail in §3. It is, however, already apparent at this stage that the Main Recent Fault was not simultaneously seismic over its whole length between 33 and 35° N, but that various sections were active at different periods. Latitude 34° N can be conveniently used to divide the Fault into a northern and a southern section. The 1909 earthquake and its aftershocks were related to the southern section, whereas the 1957–63 series of shocks were related to the northern section. The lengths of fault segment actually involved in each case can be approximately assessed by considering the extent of the respective epicentral regions (including the fault-break in 1909) as well as the locations of aftershocks. In 1909 the activated fault segment extended approximately from Dorud to Borujerd, and in 1957–63 from Nehavand to Kargsar, involving in each case a fault length of the order of 100 km (figure 2). It is not entirely clear whether these two segments can be considered to join near 34° N, or whether an intermediary section, quiescent since about 1900, exists between them.

The general conclusion which may be drawn from the seismicity data alone is that regional

† Damage in Qal'eh Hatam on 14 October 1961 (Rothé 1969) and in Maqsudabad in June 1961 was not found by the authors to be unambiguously attributable to earthquakes.

tectonic strain was released in two short episodes separated by an interval of about 50 years and along two consecutive fault segments each of the order of 100 km in length. The recurrence rate of activity along either segment cannot be precisely determined from the data at hand, but the remarkable absence of epicentres south of 34° N since the 1909 earthquake would suggest that large earthquakes on the Main Recent Fault are separated by periods of at least 75 years.

3. Relation between seismicity and structure

The location of destructive earthquakes seen in the previous section, and their migration during the twentieth century, suggested some relation between the regional seismicity and the Main Recent Fault. This relation will now be studied more carefully, and in particular the structure of the Main Recent Fault will be examined in more detail. The Main Recent Fault is not a single structure but a narrow zone formed by a succession of individual fault segments, often arranged in a right-lateral *en echelon* pattern. From southeast to northwest the main fault segments are (figure 2): the Dorud Fault, the Nehavand Fault, the Garun Fault, the Sahneh Fault and the Morvarid Fault. The Recent activity of each segment, and its relation with the earthquakes located nearest to it, is examined below.

(*a*) *The Dorud Fault*

The Dorud Fault segment enters the region near Arjanak, and can be traced in a straight line (N 315°) for about 100 km until the vicinity of Borujerd (figure 7). The small town of Dorud, situated approximately at mid-point of this trace, may be conveniently used to distinguish a southeastern section contained in the Shuturun Kuh mountains, from a northwestern section contained in the Selakhor Valley.

A number of streams follow the fault trace in the mountainous region of the southeastern section: Darreh Luku flowing SE into the Karun River, and the Gahr and Marbora flowing NW into the Ab-i Diz. Lake Irene on the Gahr was created when the river was blocked by a large landslide possibly triggered by an old earthquake (see § 2 (*a*)). Near the lake, the northeastern block is formed by Palaeozoic and Mesozoic series dipping NE, and the southwestern block by an E–W anticline of Cretaceous limestone. Near Dar Astaneh, the fault brings into contact Bakhtiary conglomerates (Pliocene) in the northeast with east-dipping Mesozoic rocks in the southwest. The fault scarp is best studied along the Marbora, between Dorud and Dar Astaneh, where it is marked by a mylonitized limestone with conspicuous vertical shear planes displaying horizontal (as well as other) striations. This locality represents the southernmost extent of ground fracturing due to fault reactivation in the 1909 earthquake.

Northwest of Dorud the fault follows approximately the southern border of the Selakhor Valley, where it is entirely located in the late Quaternary alluvium of the Ab-i Diz. The scarp formed by the 1909 earthquake has already been described (§ 2 (*b*)). Vertical displacements were then at least 1 m (NE side downthrown), but in places such as Kalangona the topographical step is several metres high, probably as a result of previous fault movement. A number of small springs mark the fault throughout the valley. The linearity of the fault trace along its entire length from the mountains in the southeast to the alluvial valley in the northwest indicates that the fault plane at depth is vertical.

A smaller topographical step (but with reversed displacement: SW side downthrown) borders the other side of the Selakhor Valley between Zargina and Suran (figure 7). The valley thus

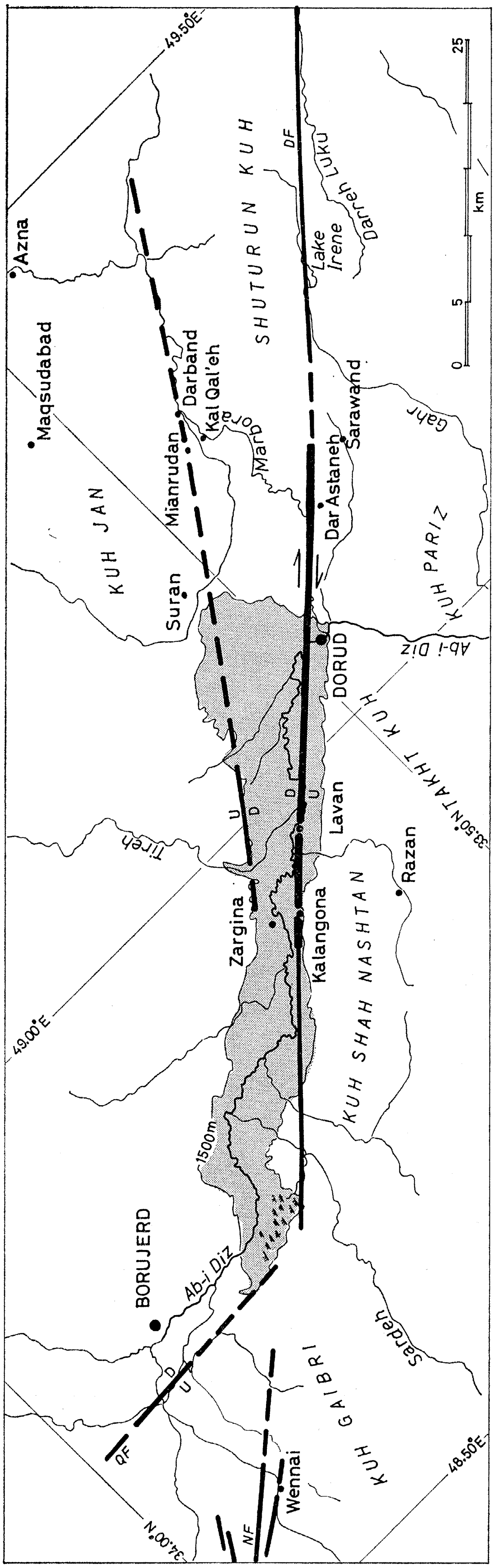

FIGURE 7. Dorud Fault. The 1909 earthquake fault scarp is shown by the thicker line. Shaded area is region below 1500 m. Fault movement U up, D down. DF, Dorud Fault; NF, Nehavand Fault; QF, Qal'eh Hatam Fault.

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appears as the result of the subsidence of a narrow zone between two subparallel Quaternary faults.

In the northwest the Dorud Fault terminates near Borujerd, where it meets a short nearly N–S fault (precisely N 350°), the Qal'eh Hatam Fault. This fault displaces very recent horizontal conglomerates and clays, with the eastern block downthrown by at least 10 m. Topographically, the Selakhor Valley may be considered as limited in the northwest by the Qal'eh Hatam Fault.

The drainage pattern in the vicinity of the Ab-i Diz is particularly revealing as to the most recent tectonic deformation (figure 7). The Ab-i Diz starts near Borujerd and first follows a N–S course parallel to the Qal'eh Hatam Fault. It then crosses the length of the Selakhor Valley until Dorud, with a course made up of segments oriented in two predominant directions, N–S and NW–SE. It is suggested here that the N–S direction, also evident in the small left-bank tributaries where these cross the valley floor, could result from buried normal faults similar to the Qal'eh Hatam Fault. The NW–SE direction on the other hand is mainly determined by the Dorud Fault scarp, which acts as a barrier to the river. In the mountains to the south and southeast of the Selakhor Valley the drainage pattern differs, and the larger streams such as the Sardeh and Gahr have long E–W stretches reflecting the local fold axis and minor thrust directions.

The drainage pattern described above is consistent with the subsidence of a narrow zone bordering the northeastern side of the Dorud Fault. The deformation mechanism at the origin of this subsidence is most probably a right-lateral strike slip movement along a N 315° direction, possibly of the 'divergent wrench' type described by Wilcox, Harding & Seely (1973). Such a deformation would produce N–S normal faults like the Qal'eh Hatam Fault and the buried faults under the valley, and E–W compression features like those observed in the mountains to the south and southeast.

After the 1909 Selakhor earthquake (and an earlier Lake Irene earthquake?) the documented activity of the Dorud Fault is confined to two earthquakes of magnitude over 5, in 1958 and in 1963, located on the Main Recent Fault to the southeast of Dorud (figure 2). The earthquake which damaged Razan in 1955 may also possibly be connected with the Dorud Fault (§2(*c*)).

(*b*) *The Nehavand and Garun Faults*

The Nehavand Fault starts in the southeast near Wennai (west of Borujerd) and extends in a N 320° direction to Gusheh (northwest of Nehavand), a total length of about 55 km (figure 8). Its direction is the same as that of the Dorud Fault, but its trace is displaced by about 3 km to the northeast. The Qal'eh Hatam Fault previously described separates the Nehavand from the Dorud Fault.

The Nehavand Fault is formed by several shorter segments which are referred to here by the name of the nearest village. The Wennai segment forms the northeastern limit of the Miocene flysch formations of the Kuh Garri. East of the village of Wennai, it is entirely contained in Bakhtiary conglomerates. Displacement is by downthrow of the northeastern block, with several fault planes displaying also horizontal striations. The Amirabad–Chaqawal segment is at a slight angle to the other fault segments. Along its western half it separates the Miocene formations from Quaternary alluvium and, in places, from the metamorphic 'Hamadan' rocks in the northeast. Along its eastern half, it determines a topographical ridge in Quaternary alluvial deposits. Recent movement is by subsidence of the northeast block; near

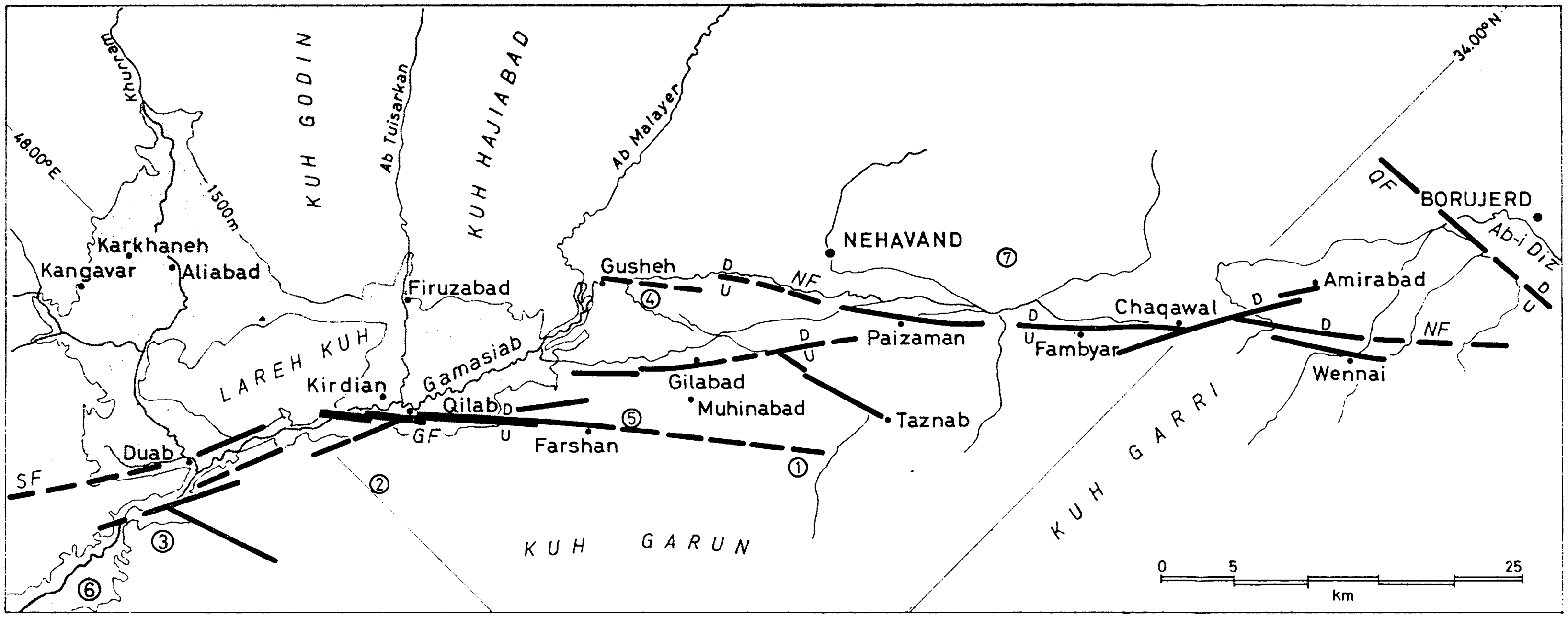

FIGURE 8. Nehavand and Garun Faults. Shaded area is region below 1500 m. Fault movement U up, D down. GF, Garun Fault; NF, Nehavand Fault; QF, Qal'eh Hatam Fault; SF, Sahneh Fault (Southeastern section). The 1958 earthquake fault scarp is shown by the thicker line. Circled numbers are epicentres for the following earthquakes: (1) Foreshock 15 August 1958, 04h 23m 14s GMT, $M_b = 4.4$; (2) Foreshock 16 August 1958, 17h 09m 19s GMT, $M_b = 4.75$; (3) Main shock 16 August 1958, 19h 13m 43s GMT, $M_b = 6.6$; (4) and (5) Consecutive shocks 2 April 1960, 22h 35m 59s and 23h 33m 13s GMT; (6) Karkhaneh earthquake 24 March 1963; (7) Southernmost shock on the Nehavand Fault, 14 October 1961.

Chaqawal however, marble outcrops on the northeastern side of the fault appear uplifted by several hundred metres with respect to the Miocene flysch, probably as a result of an earlier tectonic phase. The Fambyar, Paizaman and Gusheh segments are mainly contained in Quaternary and modern formations. In all cases, the northeastern block is downthrown, forming in places such as Fambyar a sharp topographical rise of several metres (figure 9, plate 2). Near Gusheh, the fault trace becomes less well defined: it seems to separate the modern Gamasiab deposits (NE) from a line of earlier Quaternary alluvial hills (SW). Beyond Gusheh, there are strong topographical arguments to continue the Nehavand Fault in the valley between the Kuh Godin and Lareh Kuh, in the general direction of Kangavar.

The Garun Fault is approximately parallel to the Nehavand Fault and located about 10 km farther southwest (figure 8). It can be followed for about 25 km, from the Taznab region in the southeast, until its intersection with the Gamasiab River and the Sahneh Fault in the northwest. Over most of its length it marks the southwestern limit of the Nehavand valley, separating the young alluvium from the metamorphic formations of the Kuh Garun. At its northwestern end, near Qilab and Kirdian, it departs from the mountain front and enters the alluvial valley where its trace is marked by a topographical step several metres high. This section was reactivated during the 1958 earthquake (see §2(*d*)).

The Gilabad segment, situated between the Nehavand and Garun Faults, is at an angle (N 305°) to these faults and seems to interconnect them (figure 8). It is entirely contained in Quaternary alluvium and shows again a downthrow of the northeastern block. A shorter branch passing near Taznab is in a more northerly orientation comparable to that of the Qal'eh Hatam Fault.

The Recent activity of the Nehavand and Garun Faults is shown by the displacement of Quaternary and modern alluvial formations, as well as by the occurrence of earthquake faulting. Epicentre locations, especially for the shocks associated with the 1958 'Nehavand' and 1963 Karkhaneh earthquakes are also evidence for this activity (figure 2). If we assume that the epicentre locations determined instrumentally are approximately correct, the sequence formed by the 1958 earthquake with its two immediate foreshocks is of particular interest as it indicates a migration of activity along the Garun Fault from the southeast to the northwest (nos. 1, 2 and 3 in figure 8). Also relevant are the two consecutive earthquakes on 2 April 1960 at about 1 h interval (M_b 5.1 and 4.5), centred at opposite locations on the Nehavand and Garun Faults, and suggesting a kinematic relation between them (nos. 4 and 5 in figure 8). Finally, the southernmost epicentre connected with the Main Recent Fault in this region is located near the Nehavand Fault about 12 km from the town (14 October 1961; no. 7 in figure 8); the villages damaged (lightly) by this shock were located in the Fambyar–Chaqawal region.

(*c*) *The Sahneh Fault*

The Sahneh Fault which connects the Garun Fault in the southeast to the Morvarid Fault in the northwest is about 100 km long and strikes between N 295° and N 300° (figure 10). Its direction is exceptional compared to the other segments of the Main Recent Fault, which are characteristically at about N 315°. The Sahneh Fault may be divided into three sections of approximately equal lengths referred to here as the Southeastern, Central and Northwestern sections.

The Southeastern section starts at the intersection with the Garun Fault and follows the Gamasiab Valley, separating the Kuh Khalineh mountains from the Kangavar Valley. At the

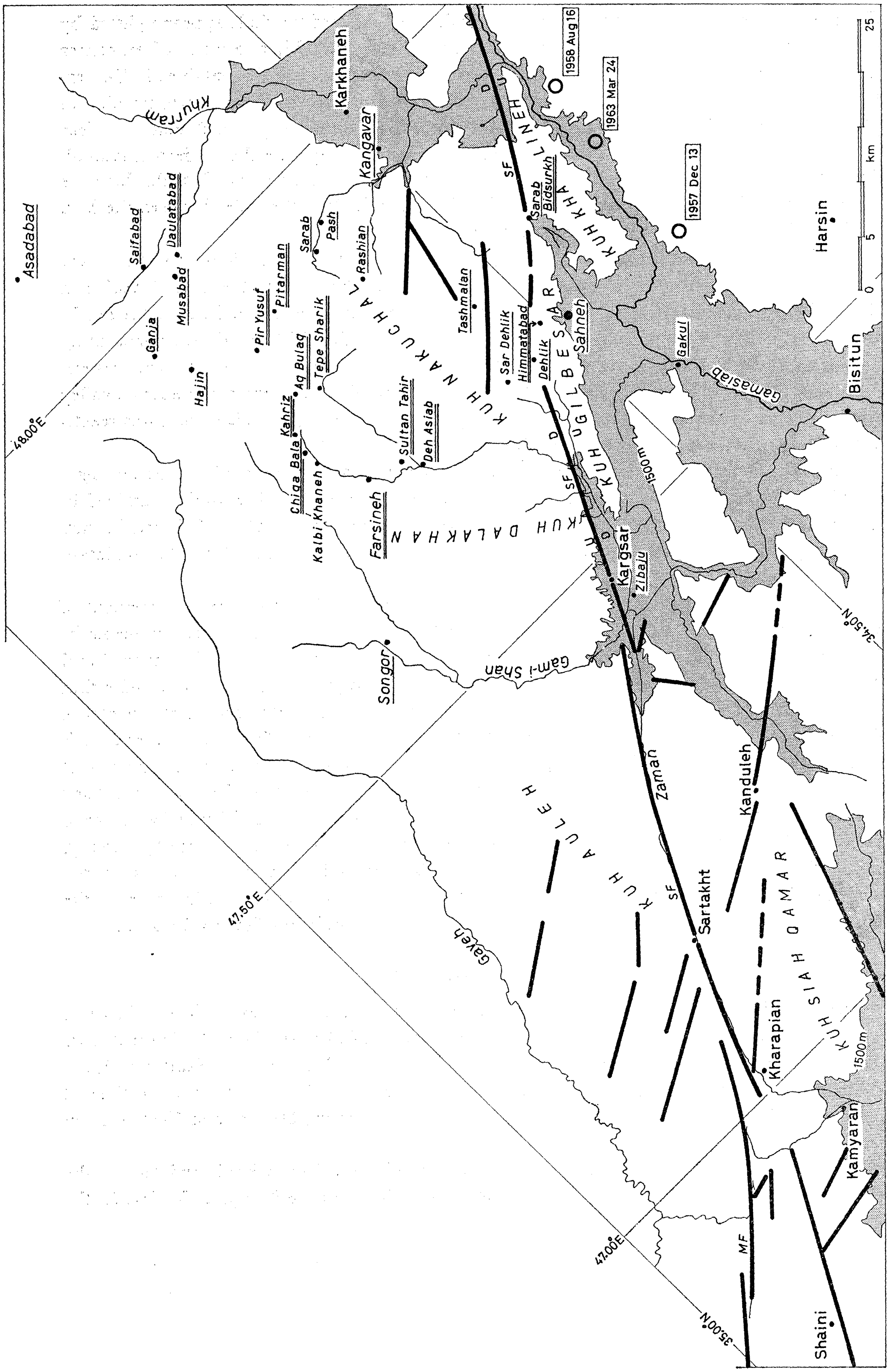

FIGURE 10. Sahneh Fault and villages destroyed by the 1957 earthquake. Shaded area is region below 1500 m. Fault movement, U up, D down. SF, Sahneh Fault (Southeastern, Central and Northwestern sections); MF, Morvarid Fault. Villages written in italics and underlined once were severely damaged by the 1957 Farsineh earthquake; those underlined twice were destroyed and had people killed. Instrumental epicentres shown are for the 1957 Farsineh, 1958 'Nehavand' and 1963 Karkhaneh earthquakes.

Bidsurkh pass it is marked by a substantial mylonite zone where it crosses the Cretaceous limestone and their metamorphic basement (figure 11, plate 3).

The Central section starts near the town of Sahneh, approximately in the continuation of (or possibly displaced by 1 or 2 km to the NE) the previous section. It separates a narrow rectilinear limestone ridge, the Kuh Gilbesar in the southwest, from the main mountain range (Kuh Dalakhan and Kuh Nakuchal) in the northeast. The fault trace is well marked in the hydrography by streams arriving from the northeast to the upfaulted Kuh Gilbesar and then being diverted along the fault until they find an exit into the Sahneh Plain. It is therefore likely that the southwestern block was elevated after installation of the stream pattern. Farther to the northwest, however, near Kargsar, vertical displacement is in the opposite sense (NE up): Recent alluvial formations of partly consolidated clays and gravels can be seen to be cut by the fault forming a southwest facing scarp about 20 m high and only very slightly rounded by erosion (figure 12, plate 3).

The Northwestern section, which coincides over much of its length with the Zaman Valley, is entirely contained in Mesozoic and Tertiary formations. The northeast side, formed of basic volcanic rocks, contains several short N 335° faults terminating on the Sahneh Fault. South of the fault, the same volcanic rocks are thrust over an E–W band of Tertiary flysch.

The relation between seismicity and structure is not as simple for the Sahneh Fault as for the previously seen Dorud and Garun Faults. Instrumental epicentres of the three largest shocks (1957 Farsineh, 1958 'Nehavand' and 1963 Karkhaneh) are located close to each other, on an apparent E–W alinement, a few kilometres south of the Sahneh Fault (figure 10). Macroseismic epicentral regions of the 1957 and 1963 events† are, however, centred northeast of the Fault at a distance of 30 and 20 km respectively from the instrumental epicentres. Furthermore, foreshock and aftershock trends were both in a NE–SW and NW–SE direction, i.e. normal to and parallel to the Main Recent Fault. Assuming tentatively that the instrumental epicentre coordinates are approximately correct, a seismotectonic model which would reconcile these apparently contradictory observations would be as follows:

The region in which most epicentres between 1957 and 1963 are located is contained between the Nehavand and Morvarid Faults (figure 2). Structurally these two faults can be considered as *en echelon* Riedels in a right-lateral wrench fault zone, and continued right-lateral deformation is known to accumulate strain in, and bring to failure, the material between the two Riedels (Tchalenko 1970). The seismic history of the Main Recent Fault suggests that both the Nehavand and Morvarid Faults are active, and it seems indeed likely that this resulted in a gradual strain accumulation in the region situated between them (figure 13*a*). The inferred situation of kinematic restraint during which strain accumulation is taking place is also favoured by the unusual direction of the Sahneh Fault segment at an angle to the other *en echelon* segments. Tectonic strain was released, and kinematic continuity re-established by the series of earthquakes starting in 1957.

The fault plane solution of the 1957 earthquake throws some light on the mechanism by which the tectonic strain was released. The solution retained here is the one given by McKenzie (1972) and is based on short period observations. The plane which is nearest to the direction of the Main Recent Fault strikes N 316° and dips 50° SW; the slip vector is approximately E–W and the mechanism is reverse faulting with a small left-lateral horizontal component.

† The macroseismic epicentre for the 1958 earthquake was seen to be influenced by the foreshock locations (§ 2 (*d*)).

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This solution is shown schematically in figure 13*b*. The solution given by Shirokova (1962) is similar with the corresponding plane striking N 305° and the slip vector oriented at N 70°. As the Farsineh earthquake fault did not break surface, it is not known whether it coincides with the Sahneh Fault, or whether the latter is the surface expression of some more complicated movement on buried faults of the Sahneh type. Whichever the case, some of the unusual aspects of the 1957–63 earthquakes may be explained, at least qualitatively, by the tectonic model based on the fault plane mechanism. Figure 13*b* shows how the location of instrumental epicentres south of the Sahneh Fault, and the displacement of the macroseismic regions to the northeast, are attributable to the SW dip of the earthquake fault. The apparent E–W alinement of the

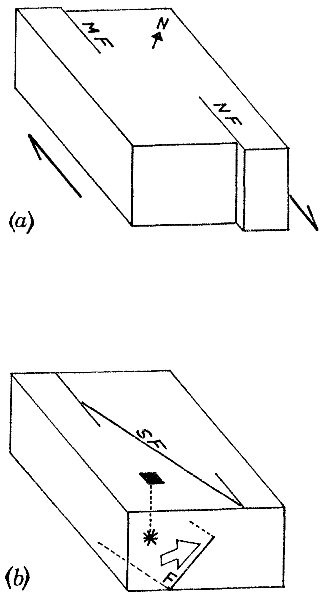

FIGURE 13. Seismotectonic model postulated for the Sahneh Fault region.

(*a*) Phase of strain accumulation between two active *en echelon* faults during regional pre-1957 right-lateral deformation; NF, Nehavand Fault; MF, Morvarid Fault;

(*b*) Phase of strain release starting with the 1957 earthquake. F, fault plane and slip vector from the fault plane solution; SF, Sahneh Fault; ■, epicentre; *, hypocentre of the Farsineh earthquake.

instrumental epicentres of the three largest shocks is consistent with a slip vector obtained from the fault plane solution. The NE–SW and the NW–SE epicentre trends indicate shocks occurring respectively along the dip and along the strike of the earthquake fault. Finally, the change in sense of vertical displacement along the Sahneh Fault from 'SW up' in the south to 'NE up' in the north are also as would be expected from the geometry of the fault plan mechanism.

Many further data are required to establish more precisely the structure and kinematics of the Main Recent Fault in the Sahneh region. The model described above is proposed as a working hypothesis based on available seismicity and tectonic information.

(*d*) *The Morvarid Fault*

The Sahneh Fault can be followed through Karapian and as far as Shaini (figure 10). At Karapian, however, it is crossed by the Morvarid Fault striking N 310–315° and extending north beyond the limits of the region considered here. Near Kamyaran, the Morvarid Fault forms the northeastern limit of an extensive outcrop of basic volcanic rocks displaying strong

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hydrothermal alteration along the fault trace. The freshness of striations on the fault plan indicates very recent fault movements.

Epicentres along the Morvarid Fault are found mainly north of 35° N (figure 15).

(*e*) *Summary of the seismicity–structure relation*

The earthquakes located on the Main Recent Fault were shown to be closely related to the individual constituent fault segments, and they were interpreted in terms of a contemporary right-lateral strike slip deformation entirely compatible with observed late Quaternary deformations. Thus in the southeast, the subsidence of the Selakhor Valley, probably a consequence of Quaternary right-lateral movements on the Dorud Fault and on a small subparallel fault,

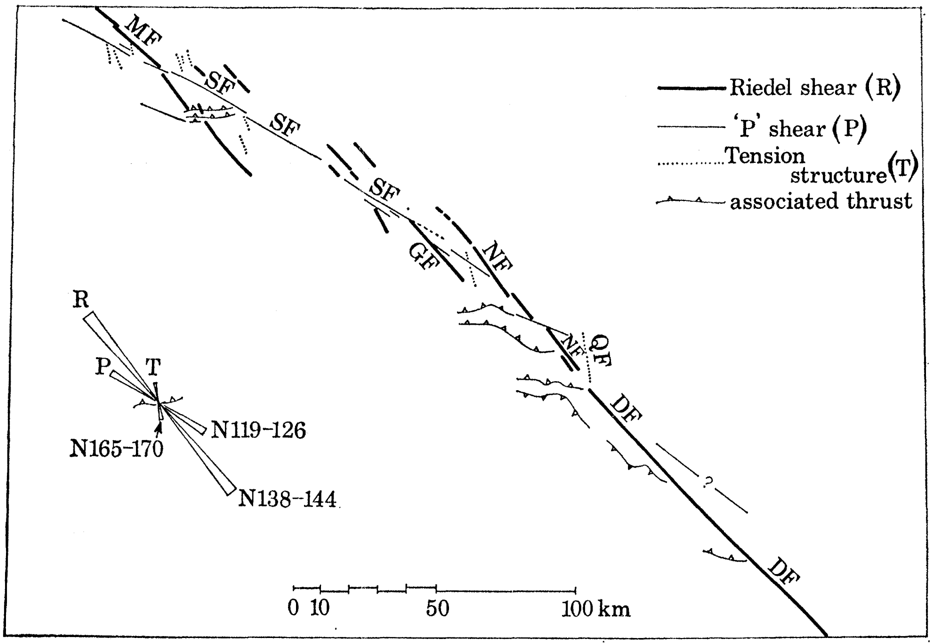


Figure 14. Structural analysis of the Main Recent Fault between 33 and 35° N. DF, Dorud Fault; GF, Garun Fault; MF, Morvarid Fault; NF, Nehavand Fault; SF, Sahneh Fault; QF, Qal'eh Hatam Fault.

was renewed during the 1909 earthquake. Near the centre of the region studied, the Nehavand Plain is similarly limited by two strike slip faults, the Nehavand and Garun Faults, both of which were reactivated, at least along their northern sections, between 1958 and 1963. In the northwest, the Sahneh Fault is characterized by its exceptional direction, which is at about 20° to the other faults studied here. Vertical displacement varies along its strike, and epicentres are not directly alined on it but contained in a region limited by the extensions of the Nehavand and Morvarid Faults. The fault plane solution of the Farsineh earthquake, and several other observations, suggest that the intense seismicity between 1957 and 1963 resulted from an overall right-lateral deformation which strained the region between the Nehavand and Morvarid Faults.

From a kinematic point of view, the deformation in the Sahneh Fault region represents the process by which the Morvarid Fault is being linked to the Nehavand Fault, thus creating a continuity in displacement along the Main Recent Fault in this part of the Zagros. This aspect becomes clear when the directions and pattern of the fault segments forming the Main Recent

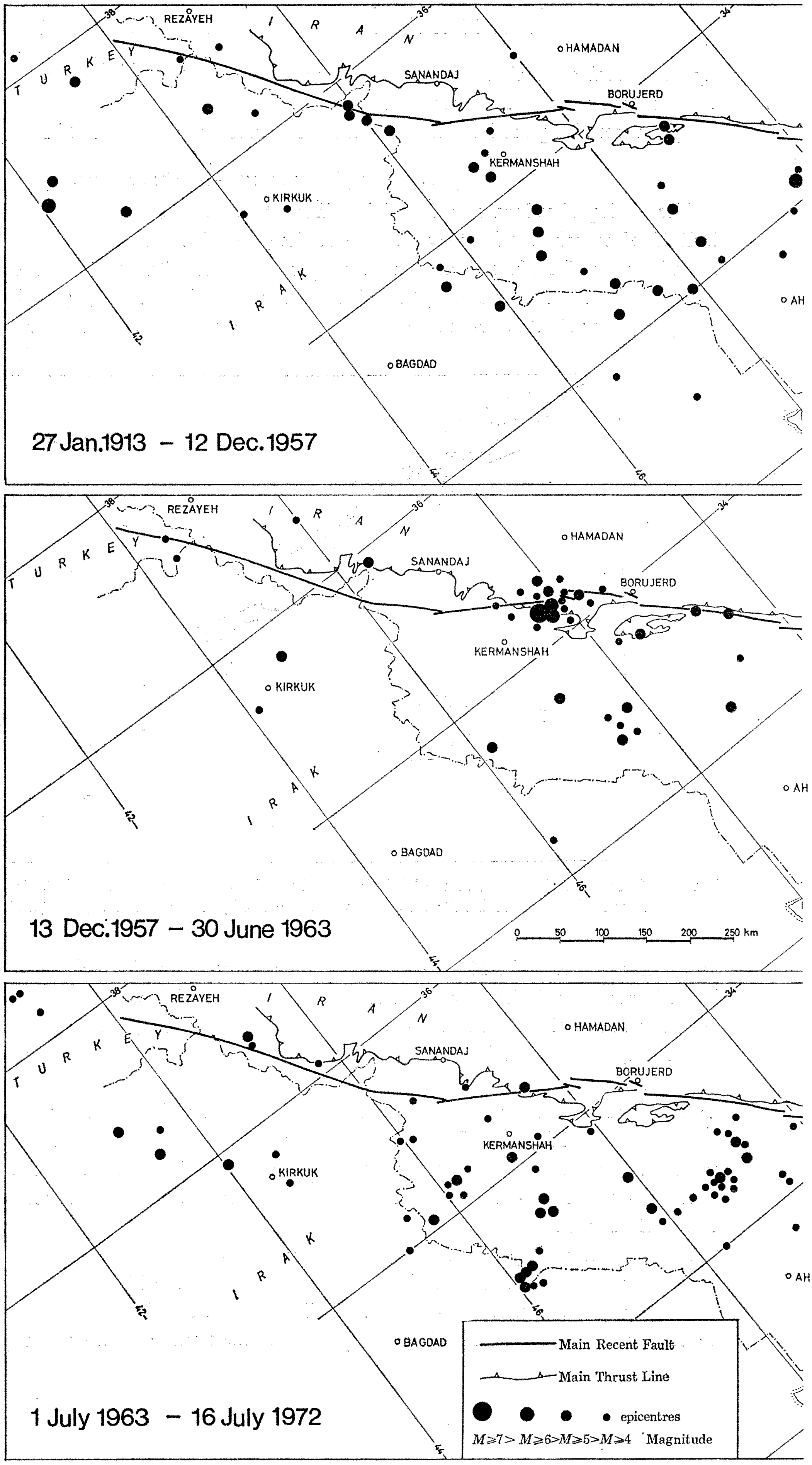
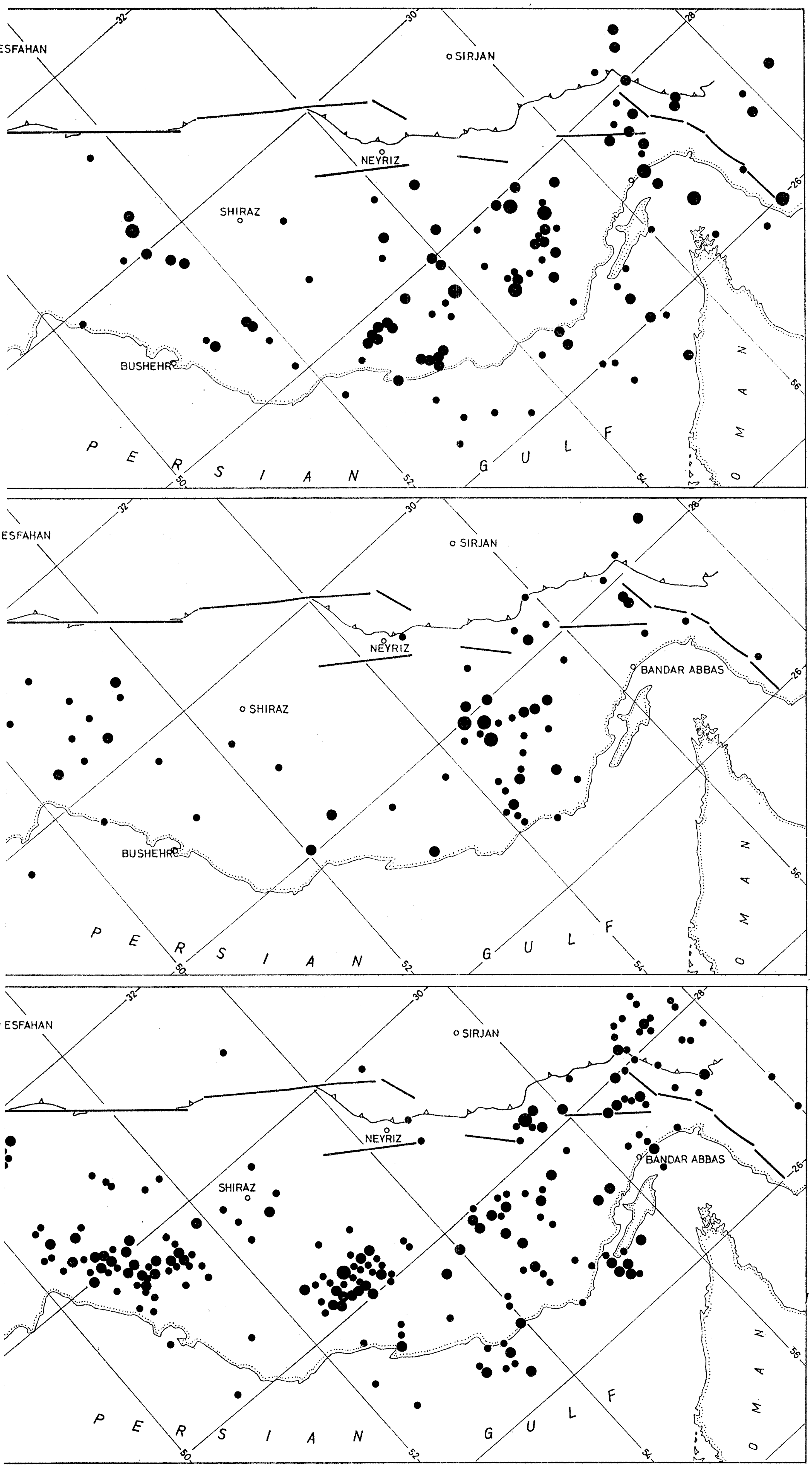


FIGURE 15. Epicentre map of the Zagros range. Instrumentally determined epicentres for the along the Main Recent Fault between 1957 and 1963.



period before (top), during (middle) and after (bottom) the intense phase of seismic activity
of epicentral parameters is explained in the Appendix.

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Fault between 33 and 35° N are analysed in terms of the structural evolution of a typical right-lateral strike slip shear zone (Tchalenko 1970). Figure 14 shows that practically all these segments fall into the three categories of Riedel shears, P shears and tension structures. The Riedels which were formed during the first stages of the deformation are represented by the two *en echelon* systems, the Dorud–Nehavand Faults and the Morvarid Fault, as well as by the shorter Garun Fault. The P shears, which were formed at a later stage in the structural evolution and resulted in an interconnexion of the *en echelon* Riedels, are represented mainly by the three sections of the Sahneh Fault. The tension structures, of which the Qal'eh Hatam Fault is the best example, are much shorter and less numerous, and seem to be located near the intersections of the Riedels and P shears. To these typical structures must be added the contemporary minor thrusts oriented approximately at right angles to the tension structures. The overall structure of the Main Recent Fault between 33 and 35° N thus appears as a perfect example of a right-lateral shear zone at a comparatively early stage of its structural evolution.

4. Implications for Zagros seismotectonics

The present study has shown that the Main Recent Fault is seismically active along its section between 33 and 35° N. Even though other sections have not yet been studied in similar detail, it may already be examined whether, with the information available to date, one would anticipate the entire length of the fault to be equally seismic. Figure 15 shows epicentre locations for the whole of the range from 1913 to 1972 as well as the trace of the Main Recent Fault. The seismicity is divided into three time periods in order to distinguish the phase of intense activity along the Main Recent Fault seen in this paper (1957–63) from the preceding (1913–57) and subsequent (1963–72) periods. It may be seen from this figure that earthquakes which occurred on or near the Main Recent Fault were all situated along the northern part of the structure, approximately north of latitude 32° N. This northern part includes the region studied here, as well as the regions farther north near Penjun where the fault passes through Irak, and along the Little Zab Valley near Rezayeh. South of 32° N, epicentres are located away from the Main Recent Fault in the fold belt bordering the Persian Gulf, except near 28° N where a seismic zone crosses the fault without apparently being influenced by it. Hence on the basis of the data collected so far, the seismicity of the 33–35° N section seems to be characteristic only of the northern part of the fault.

Figure 15 also shows that, even during the phase of intense activity, the earthquakes which occurred on or near the Main Recent Fault constitute only a small proportion of all the earthquakes which occurred in the Zagros. These earthquakes connected with the Main Recent Fault seem, however, to be of a special nature: they include the events with the largest magnitudes, and they nearly all occurred during short phases of intense activity. Thus the 1909 Selakhor and the 1957 Farsineh earthquakes are the only events of magnitude greater than 7 out of about 600 shocks known for the Zagros. On this basis alone it may be postulated that the mechanism of the Main Recent Fault earthquakes is different from that of the earthquakes in the rest of the range. Furthermore, the documented activity along the Main Recent Fault took place over two short periods of time, i.e. around 1909, and between 1957 and 1963. The intermediate periods of quiescence are of much longer duration, as can be deduced from the absence of earthquakes in the Sahneh region from 1913 (or even earlier) to 1957, and in the Selakhor region from about 1909 to the present day. As observed in other parts of Iran, short periods of a few years of intense activity and including strong earthquakes alternate with long periods of quiescence lasting probably more than 100 years (Tchalenko, 1974).

The presence of an active structure of the importance of the Main Recent Fault adds a new element to the seismotectonic problem of the Zagros first mentioned by Falcon in 1969. Recently, two slightly differing Plate Tectonic models have been suggested for the region. In the first model, the 'relative motion of the Arabian Plate with respect to the Persian Plate is, at least partially, accounted for by a wide subduction zone along the folded foothills of the Zagros' (Nowroozi 1972). In the second model, an active subduction is postulated for the southern Zagros with an east–west strike and a north dip, so that 'Iran is overthrusting the oceanic plate since continental crust cannot sink to produce a slab in the mantle' (McKenzie 1972). Neither model throws any light on the possible role of the Main Recent Fault. For the northern Zagros, however, McKenzie thinks that 'a component of right-handed strike slip is probably present across the Zagros active belt', and it may be inquired whether this strike slip is taking place preferentially along the Main Recent Fault. In the equivalent oceanic plate tectonic situation, Fitch (1972) has shown that many island arcs often have large transform faults behind them, a concept which would, in the case of the Zagros, explain the presence of both thrust and wrench structures. Clearly, much more data, especially geophysical, are needed to begin to unravel the active tectonic mechanism implied by the observations on the Main Recent Fault.

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Addendum, 29 *April* 1974

Since writing the paper, we received an advance copy of a field report describing stratigraphic marker-beds truncated and displaced along the Main Recent Fault in a right-lateral sense by at least 10, and possibly as much as 60 km (Gidon, Berthier, Billiault, Halbronn & Maurizot 1974. Sur les caractères et l'ampleur du coulissement de la 'Main Fault' dans la région de Borujerd-Dorud, Zagros oriental, Iran. *C.r. hebd. Séance. Acad. Sci. Paris* **278**, 701–704). The faults involved in this displacement are the ones referred to in our paper as the Nehavand and the Dorud Faults, and the magnitude of the displacement is compatible with the relatively early stage in the evolution of the wrench fault (§ 3*e*).

An earthquake of magnitude about $5\frac{1}{2}$ occurred on 11 November 1973 at 07.15 G.M.T. and destroyed about 1000 houses in Gheshlagh, Deh Bid and five surrounding villages; one person was killed and eight others severely injured (M. Berberian, personnal communication). The epicentral region was located on the Main Recent Fault at about 53.0 N 30.0 E, and the event suggests that the southern part of this fault is probably also active (see § 4).

Appendix: Choice of epicentral parameters

As the earthquakes for the whole of the instrumental period are not covered by any single set of determinations, the following determinations were used as providing the most reliable parameters:

1913–49 I.S.S., recalculated at I.G.S. Edinburgh (see Nabavi 1972)
1950–65 Nowroozi (1971)
1966–72 U.S.C.G.S. (subsequently N.O.A.A.)

Focal depths are not considered systematically in this paper because of the large uncertainty in their determination. The reader is referred to McKenzie (1972) for a discussion on focal depths of earthquakes in the Zagros: most earthquakes occur in the crust, and there do not seem to be any below 100 km.

References

Ambraseys, N. N. 1974 Historical seismicity of North-central Iran. In *Materials for the study of seismotectonics of Iran; North-central Iran. Rep. Geol. Surv. Iran*, no. 29. Tehran.
Bizon, G., Bizon, J. J. & Ricou, L. E. 1972 Etude stratigraphique et paléogéographique des formations tertiaires de la region de Neyriz (Fars interne, Zagros Iranien). *Rev. Inst. Fr. Petrole* **27**, 369–405.
Borujerdi, Sa'mete 1909 The Earthquake of Selakhor. In *Collected poems*, Said Esmaili Ketabchi.
Braud, J. 1974 Données nouvelles sur le domaine métamorphique du Zagros au niveau de Kermanshah-Hamadan. *Eclog. geol. Helv.* (forthcoming).
Braud, J. & Ricou, L.-E. 1971 L'accident due Zagros ou Main Thrust, un charriage et un coulissement. *C. r. hebd. Séanc. Acad. Sci., Paris* **272**, 203–206.
Braud, J. & Ricou, L.-E. 1972 Une reconnaissance le long de l'Accident du Zagros entre Kermanshah et Neyriz. *Internal Rep. Geol. Surv. Iran*, Tehran.
Dongier, R. 1909 Le tremblement de terre du 23 Janvier 1909. *Rev. Sci.* **47**, 310.
Falcon, N. L. 1967 The geology of the north-east margin of the Arabian basement shield. *Advmnt Sci.* **24** (119), 31–42.
Falcon, N. L. 1969 Problems of the relationship between surface structure and deep displacements illustrated by the Zagros Range. In *Time and place in orogeny* (ed. Kent, Satterthwaite and Spencer). *Spec. Publs Geol. Soc. Lond.* **3**, 9–22.
Fitch, T. J. 1972 Plate convergence, transcurrent faults, and internal deformation adjacent to Southeast Asia and the Western Pacific. *J. Geoph. Res.* **77** (23), 4432–4460.
Gansser, A. 1955 New aspects of the geology of Central Iran. *4th Petrol. Congr.* **1**, 279–300.
Golitsin, B. B. 1909*a* Kratkoe soobshenie o zemletriasenii 10/23vo ianvaria 1909 goda: *Izv. imp. Akad. Nauk* **3**, 159–160.
Golitsin, B. B. 1909*b* Dopolnitelnoe soobshenie o zemletriasenii 10/23vo ianvaria 1909 goda. *Izv. imp. Akad. Nauk* **4**, 243–244.
Gutenberg, B. & Richter, C. F. 1954 *Seismicity of the Earth and associated phenomena* (2nd ed.). Princeton University Press.
Hagiwara, T. & Naito, T. 1959 A report of the Japanese Mission sent to Iran for investigating the problem related to disastrous earthquakes in Iran. (Duplicated report.) January 1959.
Lysakowski, Ch. de 1910 Tremblements de terre de la Perse du 23 Janvier et de la Bulgarie du 15 Fevrier 1909. *Soc. Astr. Fr.* **24**, 45–50.
Matheson, S. A. 1972 *Persia: an archeological guide*. London: Faber and Faber.
McKenzie, D. 1972 Active tectonics of the Mediterranean region. *Geophys. J.* **30** (2), 109–185.
Montandon, F. 1961 Chronique des catastrophes. *Rev. Etud. Calam.* **36**, 71.
Nabavi, M. 1972 Seismicity of Iran. M.Ph. Thesis, University of London.
Nowroozi, A. A. 1971 Seismo-tectonics of the Persian plateau, eastern Turkey, Caucasus, and Hindu Kush regions. *Bull. Seism. Soc. Am.* **61**, 317–341.
Nowroozi, A. A. 1972 Focal mechanism of earthquakes in Persia, Turkey, West Pakistan, and Afghanistan and Plate tectonics of the Middle East. *Bull. Seism. Soc. Am.* **62** (3), 823–850.
Peronaci, E. 1958 Sismicita dell'Iran. *Annali Geofis.* **11**, 55–68.
Peronaci, E. 1971 Il terremoto di Farsineh del 13 Dicembre 1957 (duplicated report). *Inst. Naz. Geof., Rome.*
Rezanov, I. A. 1959 *Tectonics and seismicity of the Turkmeno-Khorassan Mountains*. Acad. Sci. U.S.S.R.: Inst. Phys. Earth. (In Russian.)

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Ricou, L.-E. 1971 Le croissant ophiolitique peri-arabe, une ceinture de nappes mises en places au Crétacé supérieur. *Rev. Geog. Phys. Geol. Dyn.* **8** (4), 327–350.
Ricou, L.-E. 1973 Relation entre phases tectoniques et stades paleogeographiques sur l'exemple des Zagrides. *Bull. Soc. Geol. Fr.* **15** (5), (in press).
Rothé, J.-P. 1969 *The seismicity of the Earth* 1953–1965. Paris: UNESCO.
Sawyer, H. A. 1894 The Bakhtiary mountains and Upper Elam. *Geogr. J.* **4**, 481–505.
Shirokova, E. I. 1962 Stresses effective in earthquake foci in the Caucasus and adjacent districts. *Izv. Akad. Nauk USSR*, Ser. Geophiz. **10**, 809–815. (Engl. transl.)
Shtelling, E. 1910 Svedenia o zemletriaseni v Persii 10:23 ianvaria 1909 goda. *C. r. Com. Sism. Perm.* **3** (III). Acad. Imp. Sci., St Petersb.
Stöcklin, J. 1968 Structural history and tectonics of Iran: a review. *Bull. Am. Assoc. Petrol. Geol.* **52** (7), 1229–1258.
Tchalenko, J. S. 1970 Similarities between shear zones of different magnitudes. *Bull. Geol. Soc. Am.* **81**, 1625–1640.
Tchalenko, J. S. 1974 Outline of seismotectonic provinces of North-central Iran. In *Materials for the study of seismotectonics of Iran: North-central Iran. Rep. Geol. Surv. Iran*, no. 29.
Wilcox, R. E., Harding, T. P. & Seely, D. R. 1973 Basic wrench tectonics. *Bull. Am. Ass. Petrol. Geol.* **57**, 74–96.
Wilson, A. T. 1930 Earthquakes in Persia. *Bull. Sch. Orient. Studies* **6** (1), 103–131.

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FIGURE 4. Epicentral region of the 1909 Selakhor earthquake. The southeastern part of the Selakhor Valley with the upper Ab-i Diz River. The 1909 fault scarp (indicated by arrows) was produced by reactivation of the Dorud Fault, a segment of the Main Recent Fault. The village of Lavan Soflia (foreground), today rebuilt in the same style and at the same location, was destroyed in 1909 and suffered 25 fatalities. Looking southeast.

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IGURE 5. 1909 Selakhor earthquake Fault. Eroded fault scarp in the Selakhor Valley between Lavan Olia and Aliabad. Typical scarp height is now 1 m but must have been greater before erosion. Looking northwest.

(*Facing p.* 8)

IGURE 6. 1957 Farsineh earthquake. Ruins of the old village of Farsineh where 703 people, constituting about 50% of the population, were killed by the earthquake. Photographed in 1971.

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IGURE 9. Nehavand Fault. Active scarp near Fambyar. Northeastern side (left in photo) is downthrown by about 2 m. The fault continues in the southeast (arrow) towards Chaqawal, through the region damaged slightly by an earthquake in 1961 (no. 7 in figure 8).

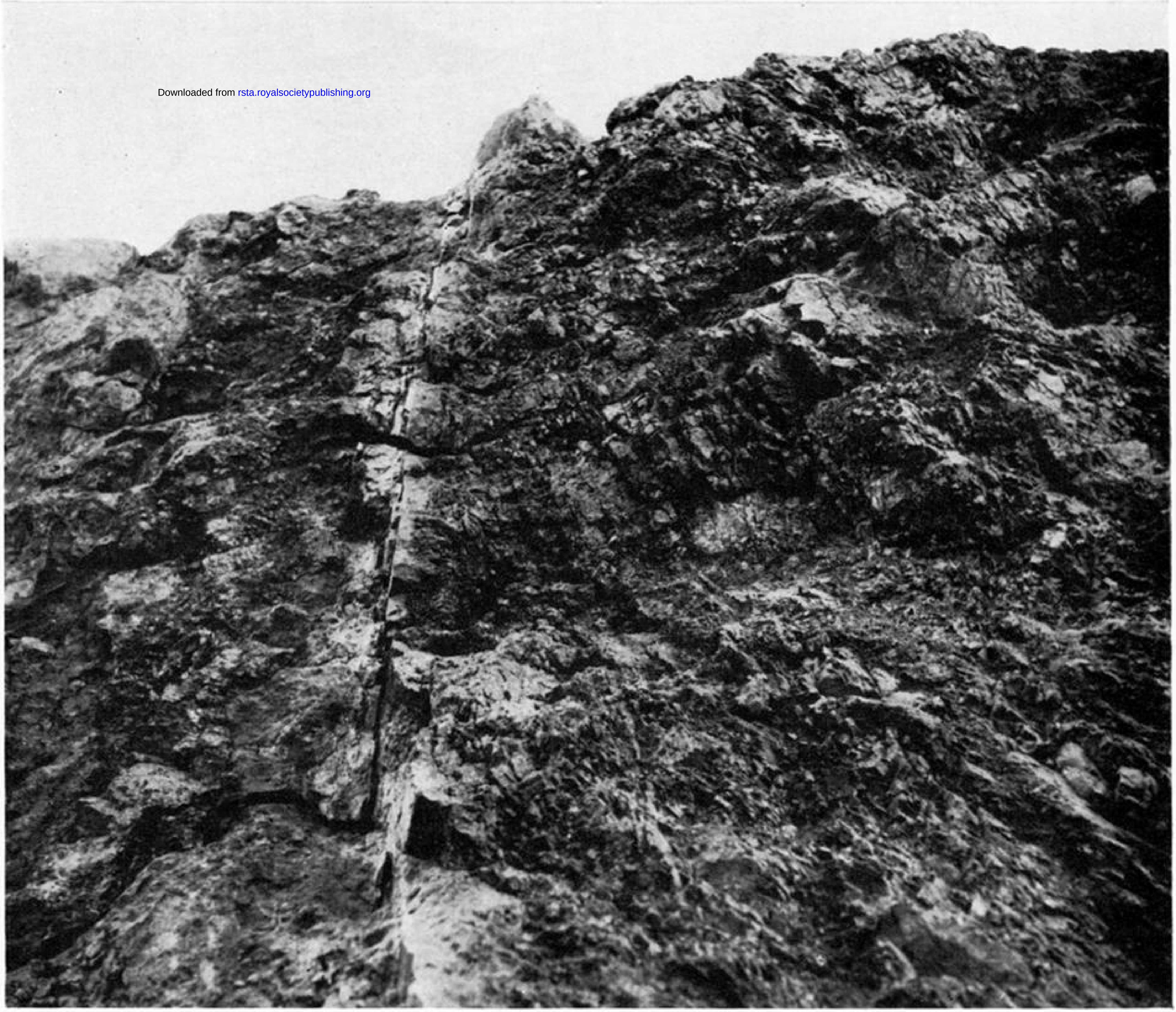

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FIGURE 11. Sahneh Fault. Mylonite zone in Cretaceous limestone southeast of Sarab Bidsurkh, along the Central section of the Sahneh Fault.

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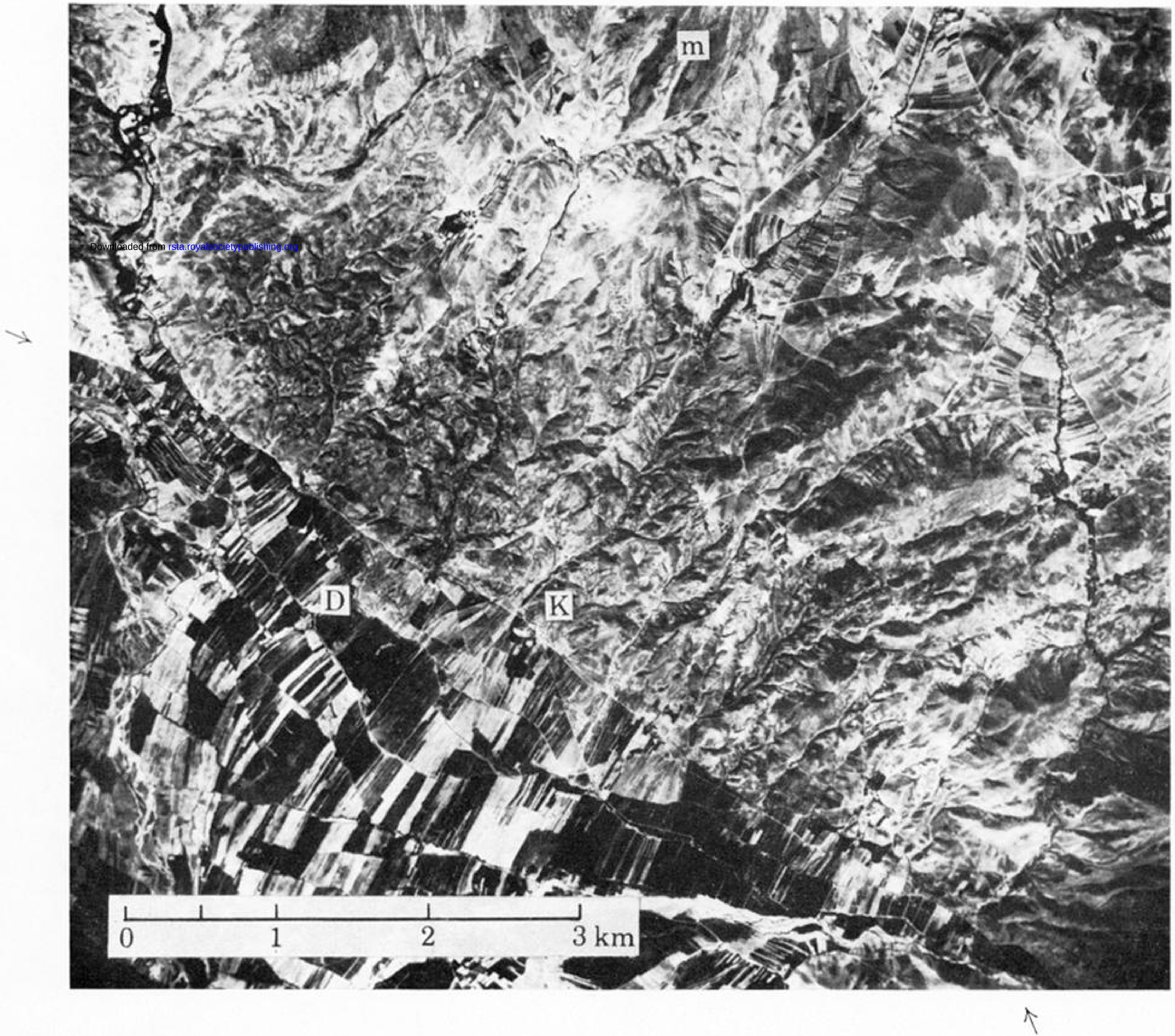

FIGURE 12. Sahneh Fault. Aerial view of the fault trace (between arrows) which separates the modern alluvium in the southwest (lower left of photograph) from the earlier Quaternary formations in the northeast (upper right). Kargsar is located just left of the symbol 'K', and the site of the ancient Dinawar just right of 'D'. The metamorphic rocks of the Sanadaj–Sirjan Zone are indicated by 'm'. North is at the top of the photograph.