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SEISMICITY AND STRUCTURE OF THE KOPET DAGH (IRAN, U.S.S.R.)

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[Plates 1–3]

CONTENTS

The region considered under the general term 'Kopet Dagh' is located east of the Caspian Sea, and includes Northeast Iran and southern Soviet Turkmenia. The regional tectonics are reviewed with special emphasis on the post-Alpine 'Diagonal Fault System'. The seismicity over the last 100 years is studied, and the four strongest earthquakes in Northeast Iran, i.e. 1871/2, 1893 and 1895 Quchan and 1929 Baghan–Germab, are described in detail for the first time on the basis of new bibliographical and field data. These four earthquakes were located on the NNW–SSE 'Bakharden–Quchan Zone', which forms part of the Diagonal Fault System. The 1929 earthquake in particular was accompanied by a surface fracture over 50 km long caused by re-activation of one of the faults of this Zone. Russian work on the seismotectonic aspects of the 1948 Ashkhabad earthquake which occurred in an adjoining zone, and migration of seismic activity in the Kopet Dagh since about 1870, are examined.

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The overall seismotectonics of the Kopet Dagh are interpreted in terms of an eastern 'NNW trend' which is separated by a longitudinal zone of relative quiescence near 56–57° E from a western 'NNE trend'. Active surface structures throughout the region are on average consistent with a tectonic model based on a NNE motion of Iran with respect to the Turan Plate. Many tectonic features are characteristic of the margins of converging continental plates.

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1. Introduction to Kopet Dagh tectonics

(a) *General outline*

The region considered in this study is contained partly in Iran and partly in the U.S.S.R. (Soviet Turkmenia). It is referred to as the 'Kopet Dagh' after its highest structure, the Kopet Dagh mountain range (figure 1). Structurally, it represents the margin of Central Iran at the edge of the Turan Plate. It constitutes the northeastern limit of the Alpine–Himalayan mountain belt, and, in this respect, it is a structure homologous to the Zagros which forms the corresponding southwestern limit (figure 1, inset).

The tectonic background to the sketch-map shown in figure 2 was compiled from E.R.T.S. 1 satellite photographs and from the studies of Huber (1968), Jaafari & Ghadimi (1971), Kalugin (1946), Rezanov (1959), Rastsvetaev (1966), Krymus & Lykov (1969) and Amursky (1971), with some details in the Quchan and Shirvan region added from my field notes. From NE to SW, the main structural units are (figure 2, inset): the Turan Plate, the Main Fault Zone, the Kopet Dagh range, the Atrek–Kashaf Lineament, the Allah Dagh–Binalud range and Central Iran.

The Kopet Dagh and Allah Dagh–Binalud mountain ranges together form a mountain belt about 600 km long and up to 200 km wide. They represent thicknesses of up to 10 km of Mesozoic and Tertiary sediments which, during the last phase of the Alpine orogeny, were folded into long linear folds concave in plan towards the south. Maximum heights are over 3000 m, contrasting sharply with the near uniform 100 m altitude of the Turan Plate. The Allah Dagh–Binalud range is the eastern continuation of the Alborz range of Northcentral Iran and dates from the Paleogene–Neogene, whereas the Kopet Dagh range was formed later during the Neogene–Quaternary (Stocklin 1968). The mountains are highest and narrowest in the centre and east, and relatively lower in the west, a morphological contrast which has led some Soviet authors to distinguish an 'uplifted' Central and Eastern Kopet Dagh from a 'subsided' Western Kopet Dagh (see, for example, Krymus & Lykov 1969).

In the northeast, the Kopet Dagh range is limited by the Main Fault Zone which truncates the folds in the west but is parallel to them in the east. This fault zone corresponds to a fundamental basement structure separating the Turan Plate from the Kopet Dagh. At the surface it is located between narrow box-like folds of a frontal range (the Peredovoy range) in the south, and a narrow longitudinal foothill basin (the 'Foredeep') in the north. The Main Fault Zone is formed by three partly overlapping fault segments parallel to the overall NW structure and each slightly offset with respect to the other (Rastsvetaev 1966; Krymus & Lykov 1969). The regions of overlap are characterized by short south-dipping folds and thrusts striking on average east–west. Each fault segment at its southeastern end bends into a NNW–SSE fault zone which extends into the mountain range. Thus the segment between Kazanjik and Kizyl Arvat bends into a fault zone passing near Bujnurd, the segment between Kizyl Arvat and

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Bakharden bends into a fault zone extending from Bakharden to Quchan, and the segment between Bakharden and Ashkhabad bends into a fault zone passing near Kapkan.

The narrow NW–SE basin separating the Kopet Dagh from the Allah Dagh–Binalud ranges, and referred to here as the Atrek–Kashaf Lineament after the name of the valleys which it follows, is approximately parallel to the Main Fault Zone, and is also generally thought to correspond to a basement structure.

The southern limit of the Allah Dagh–Binalud range is not defined by any single structure comparable to the Main Fault Zone. The geomorphological limit appears to be the

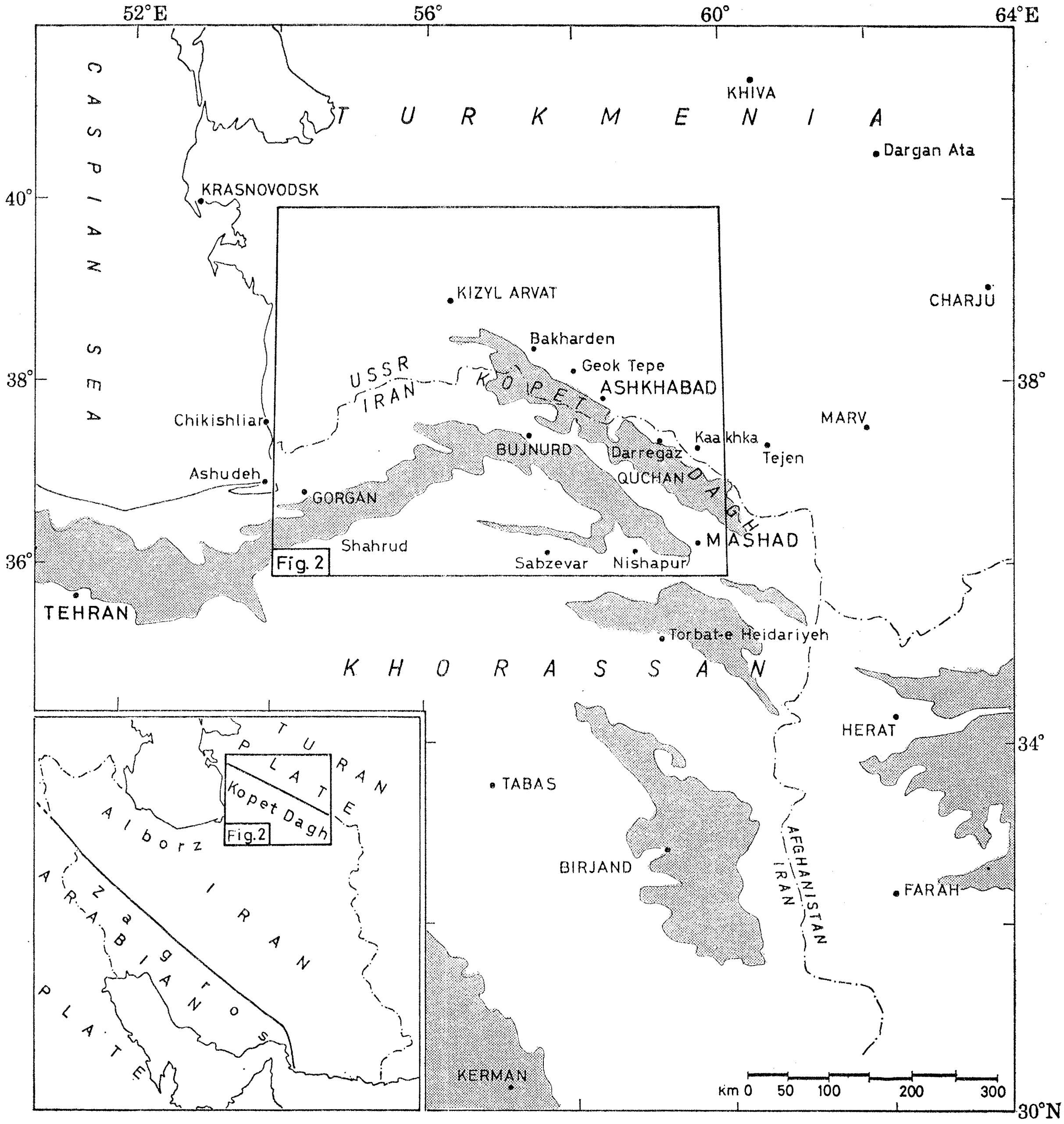

FIGURE 1. Location map of the Kopet Dagh. Box corresponding to fig. 2 is region studied for tectonics. Shaded region is above 1500 m. Inset shows situation with respect to Middle Eastern tectonics.

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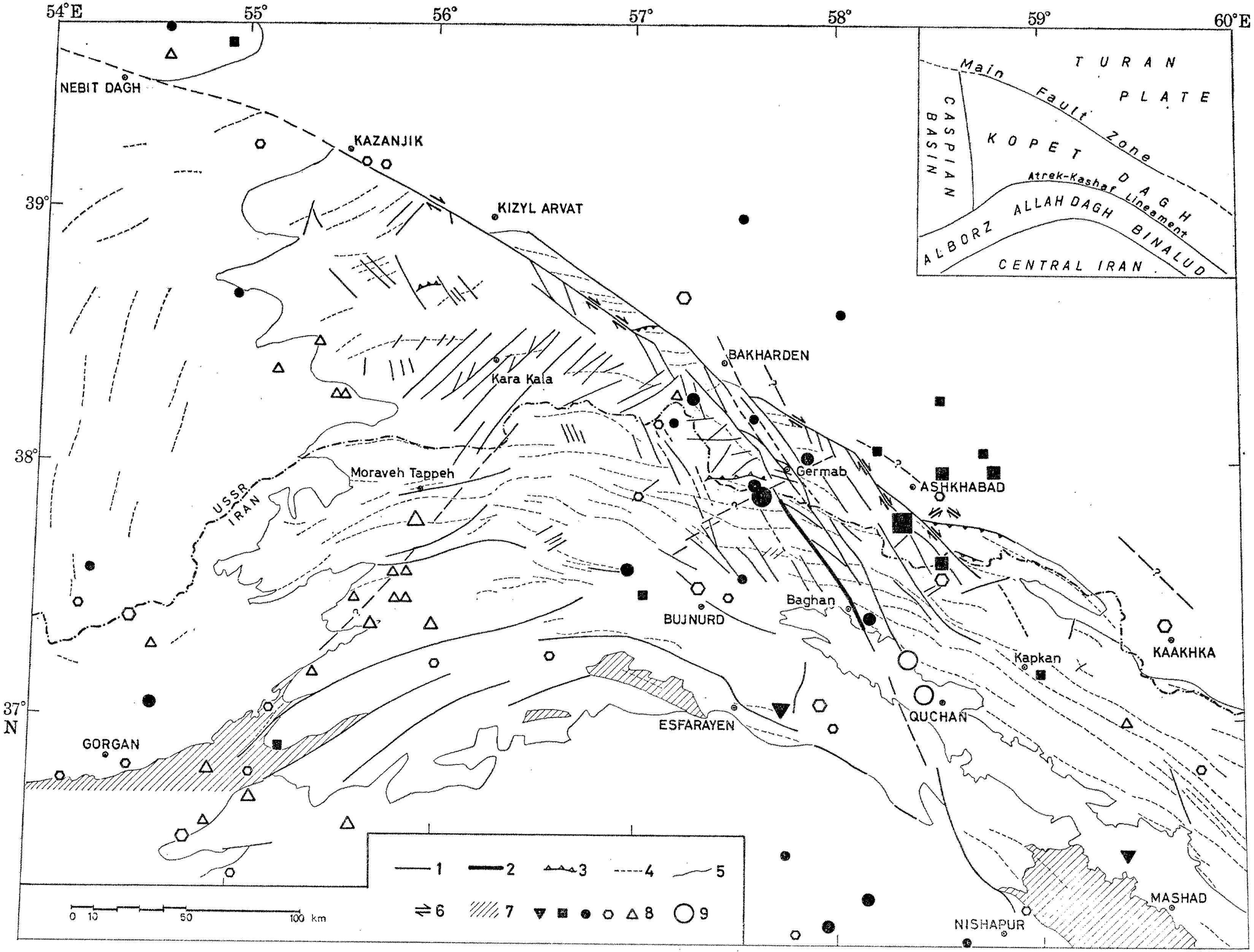

FIGURE 2. Seismotectonic sketch-map of the Kopet Dagh. 1, Late-Alpine fault; 2, Baghan–Germab 1929 earthquake fault; 3, minor thrust; 4, principal anticline; 5, limit of Neogene–Quaternary depression; 6, location where Recent fault displacement has been measured; 7, pre-Alpine massif; 8, instrumental epicentre (see legend of figure 11); 9, macroseismic epicentres of the Quchan earthquakes (1871/2, 1893, 1895). For sources consulted, see text. Inset shows main structural units.

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longitudinal basin extending from Nishapur in the east to Esfarayan and Shahrud in the west, south of which one finds the Coloured Melange and Eocene volcanics (N.I.O.C. 1959).

In the west the coastal lowlands adjoining the Caspian Sea limit the Kopet Dagh near 55° E. Subsidence has been proceeding here, probably along meridional basement step-faults, since the end of the Pliocene (Val'be, Smirnov, Ptushkin & Allanov 1970; Ushko, Syrnev & Palochkin 1971; Jaafari & Ghadimi 1971). Farther south, however, the Allah Dagh is continued by the Alborz which bends around the southern Caspian Sea. In the east, the limits of the region are taken here at longitude 60° E, beyond which there occurs a very sudden decrease in seismicity. The corresponding structure, not yet known in any detail, could be associated with a northern continuation of the East Iranian Rift described in the Lut region farther south, and with a north–south basement structure often postulated in the Turan Plate (Stocklin, Eftekhar-Nejad & Hushman-Zadeh 1972; De Lapparent 1972; Sokolov, Val'be, Denisevich & Ashirmamedov 1973; Kulakov 1970).

(*b*) *Basement structure*

The deep structure of the region is only known for Soviet Turkmenia. At its southern edge, the Turan Plate displays two structural highs or massifs, the first located east of the Caspian Sea, and the second north of Ashkhabad (Ishutin 1970). At the centres of these massifs, the granitic basement rises to about 1.5 km below ground surface, and at the edges near the Foredeep, to about 3.5 km. The Foredeep is a narrow trough, with basement depths varying between 9 and 18 km. The Main Fault Zone is thought to correspond to four parallel sutures, the two northernmost isolating the Foredeep, and the southernmost isolating a horst in which the basement rises to a depth of about 2 km and which at surface is expressed as the Peredovoy range (Amursky 1971). Under the Kopet Dagh mountains, the basement varies between 12 and 16 km, with localized depressions in the west as deep as 20 km (Bulin 1967; Amursky 1971). There is some indication of a basement structure corresponding to the Atrek–Kashaf Lineament and which is marked in the U.S.S.R. by an alinement of thermal springs (Kudel'skiy 1970).

(*c*) *Diagonal Fault System*

The Kopet Dagh and Allah Dagh–Binalud ranges are dissected by a post-Alpine fault system which, although not mapped and published at any detailed scale, can be deduced in its broad outlines from available studies. It is referred to here as the 'Diagonal Fault System', and consists mainly of NNW–SSE right-lateral and NE–SW left-lateral strike slip faults, as well as some minor sub-latitudinal thrusts. Even though the tectonic importance of these faults has been recognized for some time in the Soviet geological literature, the association with regional seismicity has generally escaped notice.

The NNW–SSE faults (average strike N 150°) are located predominantly in East Kopet Dagh and are found separately or in zones about 10 km wide and up to 150 km long. At their northwestern end they bend into the Main Fault Zone, and at their southeastern end into the Atrek–Kashaf Lineament, suggesting that they are structurally related to both these fundamental structures. The most important of the NNW–SSE faults (in length and in total displacement) are found in the Bakharden–Quchan Zone which, it will be seen further on, is also a key element in the regional seismicity. In Soviet Turkmenia, up to 4 km of right-lateral displacement has been measured on some faults of this zone, with vertical displacements of much smaller magnitude (Rastsvetaev 1970). In Iran, the total right-lateral displacement of

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fold axis by this fault zone is about 7 km (H. Huber, personal communication). Continuity of the Bakharden–Quchan Zone on either side of the political frontier is not yet completely established, mainly because the region is geologically unmapped territory. There seems, however, to be some indication that strike slip faults may be interrupted locally where they bend into NW–SE bedding-slip features. In the south, recent work suggests a probable continuation of the zone beyond the Atrek–Kashaf Lineament towards Nishapur (H. Huber, personal communication).

The NE–SW faults (average strike N 50°) are mainly located in the Kara Kala region of West Kopet Dagh. They are left-lateral and shorter than the previous faults. Maximum horizontal displacements along individual faults have been estimated at between 2.7 km (Kopp 1970) and 4 km (Rastsvetaev 1970). In Iran these faults are found mainly north of Moraveh Tappeh.

Initiation of movement along the faults of the Diagonal Fault System is generally thought to have started some time during the Pliocene (Krymus & Lykov 1969; Val'be *et al.* 1970), i.e. before the end of folding. Most of the faults are vertical or nearly vertical. Displacements are predominantly strike slip, systematic vertical displacements being found only in West Kopet Dagh where the 'Caspian' side of a fault is always downthrown (Kopp 1970). Elsewhere, geophysical data confirm that, at the crystalline basement level, movements are also predominantly horizontal (Amursky 1970). There are many examples of NNW–SSE and NE–SW faults in associated conjugate positions, sometimes accompanied by small E–W thrusts, suggesting a common and simultaneous origin for all these structures. Several workers have indeed pointed out that both right- and left-lateral faults may be explained by a near horizontal compression from the NNE (Kalugin 1946; Kalyayev 1946). Rastsvetaev (1970) reviewing previous studies and his own results, found that the average compression direction was N 20°, whereas Huber (1968) draws this direction at about N 15°. On the tectonic sketch-map of figure 2 the overall axis of symmetry for the Diagonal Fault System would be about N 10°. For the purposes of this study, the compression direction is referred to as being NNE, a more accurate assessment being deferred until the relevant geological maps become available.

The Main Fault Zone, of average direction N 120°, is not normal to this compression direction, but is at an angle of about 15° to it and in a clockwise sense, i.e. in the sense for which one would expect right-lateral fault displacement. The intimate fault structure does indeed suggest such a displacement, especially in the regions between the overlapping fault segments. Krymus & Lykov (1969) have interpreted the E–W Quaternary folds of the Peredovoy range between Kizyl Arvat and Bakharden as compression ridges characteristic of right-lateral wrench faulting. It should be noted that this does not establish that the structure is a fundamental wrench fault, merely that its late-Quaternary displacements included an important right-lateral strike slip component.

Detailed field studies of several faults of the Diagonal Fault System have shown that they were probably associated with earthquakes throughout the Quaternary and that many are presently active (Kopp, Rastsvetaev & Trifonov 1964). For the Main Fault Zone, measurements of sheared qanat tunnels have indicated an average right-lateral displacement rate of 3–8 mm/year (Trifonov 1971). Similar studies are only beginning in Iran, and quantitative data are not yet available for the Kopet Dagh. Nevertheless, the regional seismotectonic framework may be deduced from the analysis of earthquakes and active faults, in particular from the study of the structure which showed most activity during the last 100 years, i.e. the Bakharden–Quchan Zone.

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2. Seismicity

(a) *Earthquakes along the Bakharden–Quchan Zone*

Four out of the five strongest earthquakes which occurred in the Kopet Dagh since the last quarter of the nineteenth century were associated with the Bakharden–Quchan Zone. These were: 1871/2, 1893 and 1895, Quchan earthquakes; and 1929, Baghan–Germab earthquake. As these events have not been documented so far, they are described here in some detail. The fifth earthquake was the 1948 Ashkhabad (U.S.S.R.) earthquake which, although not directly related to the Bakharden–Quchan Zone, is nevertheless relevant to its seismic activity. A summary of the seismotectonics of this event is given, and other smaller destructive earthquakes are briefly discussed in a review of the overall seismicity of the Kopet Dagh.

(i) 23 *December* 1871 *and* 6 *January* 1872: *Quchan earthquakes*

There are several indications of an early seismic history of the Quchan region. For example, Tsimbalenko (1899) noted that the inhabitants of Quchan remembered destructive earthquakes occurring during the nineteenth century at intervals of about 20 years. Yate (1900) refers to an earthquake in 1852 (22 February?) which killed 200 people and destroyed the dome of the Sultan Ibrahim mosque (see also Wilson 1930). He also suggests that Khabushan, a ruined town and fort about 20 km to the NNE of the 1893 town of Quchan (the town was relocated in 1895), may have been abandoned after destruction by an earlier earthquake (Yate 1894). Khabushan is generally considered to be the first settlement of Quchan, and a legend about its destruction by an earthquake persists in the region today. The event referred to, if factual, must have occurred before 1822 when the town was described in its 1893 location (Fraser 1825).

Two violent earthquakes occurred near the town of Quchan, on 23 December 1871 and 6 January 1872 (Alison 1872; Anon. 1872*a*; Anon. 1872*b*; Anon. 1872*c*; Wilson 1930). Both shocks caused destruction, but it is not known which one was the stronger, i.e. if the succession was a foreshock–main shock or a main shock–aftershock sequence. From several descriptions it appears that about half the town was completely destroyed and the remainder severely damaged (Alison 1872; Baker 1876; Napier 1876; MacGregor 1879). Of the larger buildings, a well-built school of brick masonry collapsed, and the dome of the shrine of Sultan Ibrahim was damaged beyond repair. It is not clear whether there were any casualties: Alison (1872) mentions that 2000 inhabitants were killed by the first shock, and 4000 by the second, but Napier (1876) states that no lives were lost because the population had been warned by foreshocks.

The extent of the epicentral region of the 1871/2 earthquakes can be deduced from contemporary accounts. The region of severe damage (figure 3) extended in the NNW from an unnamed village northwest of Esnafinjir (or Isfijir: 80 houses destroyed) to Quchan in the SSE (Napier 1876). Eight villages, among which Jafurabad (70 inhabitants killed), were completely destroyed, as was the fort of Khabushan (MacGregor 1879). Damage did not extend much beyond Quchan, as a village (Filab?) located about 1.5 km east of the town, and Hai Hai, Chalata and Yusefkhan did not suffer at all (Napier 1876). In the northwest, despite the claims of many earthquake catalogues (Perrey 1875; Sieberg 1932; Rezanov 1959; Rustanovitch 1957), the town of Shirvan was undamaged, 'the earthquake having been scarcely felt here' (Napier 1876). The epicentral region thus defined measured about 35 km in length (NNW–SSE)

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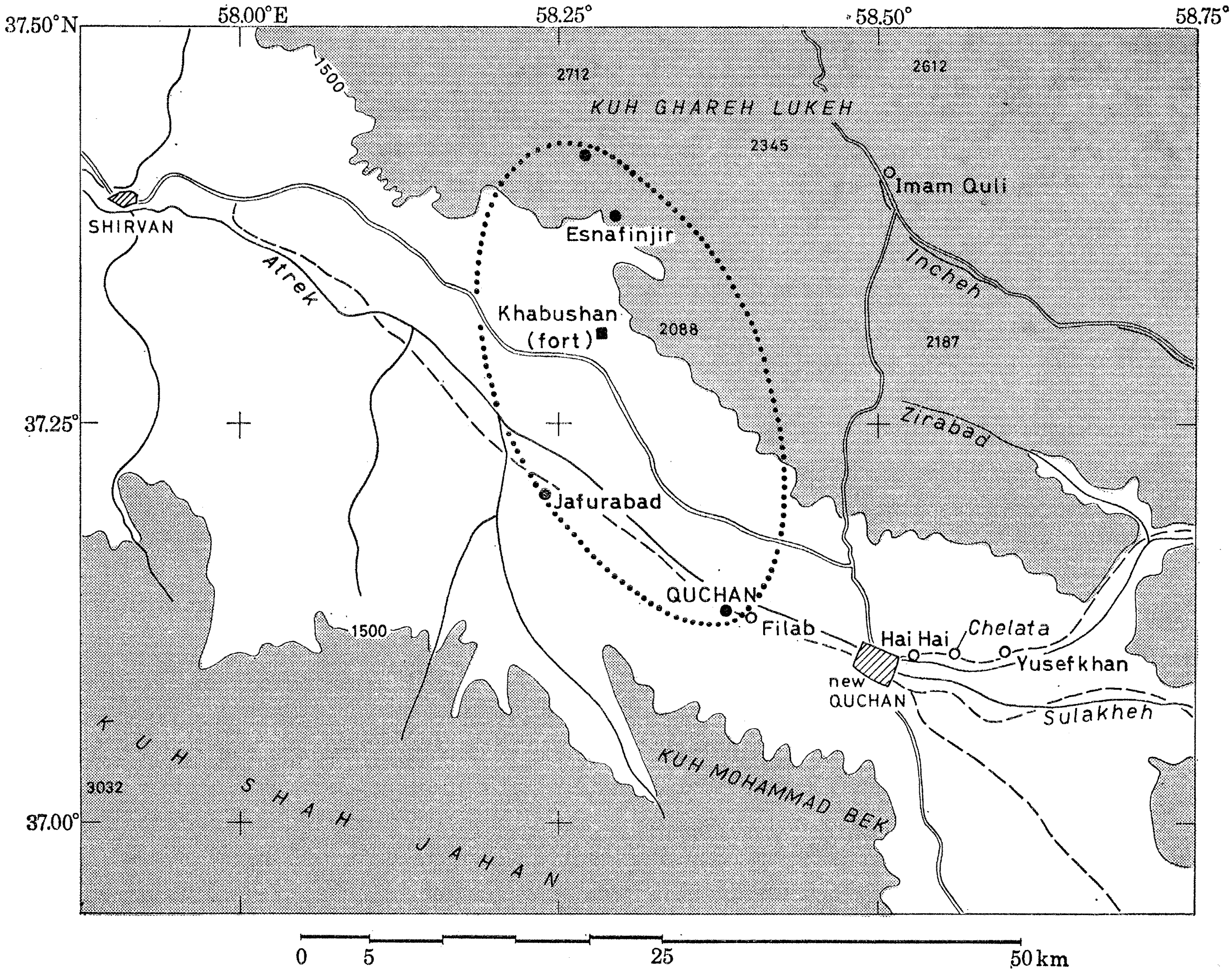

FIGURE 3. Quchan earthquakes of 23 December 1871 and 6 January 1872. ●, Destroyed village; ○, undamaged village. Only villages for which macroseismic information is available are shown. Those written in italics are shown in their 1871/2 location where this differs from the present. Dotted line inscribes the region of maximum destruction. Shaded area is region above 1500 m; altitude of highest points shown in metres. The 1971 road is shown by a double line, the old roads by a dashed line.

and 20 km in width (ENE–WSW) and contained the town of Quchan near its south-eastern limit.

(ii) 17 *November* 1893: *Quchan earthquake*

The information on this earthquake was compiled from the accounts of Europeans who visited the town soon after the event: Tsimbalenko (1893, 1899), Baumgarten (1896), Oranovsky (1896), Thomson (1894), Yate (1894, 1900). Further descriptions of the town and its surroundings were obtained from Coningham (1893) and Vlassov (1893, 1894).

About one month before the earthquake, a foreshock was felt locally in the town towards midnight on 20 October 1893. The main shock occurred without warning on 17 November 1893 at about 7.30 p.m. local time, and was recorded at 19h06 by the Ashkhabad seismoscope

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station.† The earthquake was felt over an area of about 150000 km², in particular in the towns of Bujnurd, Nishapur, Sabzavar and Mashad in Iran, and Ashkhabad, Kaakhka, Goek Tepe, Bakharden and Kizyl Arvat in Russian Turkmenia. In Ashkhabad, where the contemporary intensity estimate was 4–5 on the Rossi-Forrell scale, clocks stopped and some buildings were fissured.

A strong aftershock, also felt in Mashad, was recorded at Ashkhabad at 19h45. In Quchan, about 70 tremors were felt during the first 24 h after the main shock, decreasing to an average of about 30 per day 2 weeks later, and to one every 10 days about 6 months later. About 14 months after the earthquake, Quchan was once more destroyed by another major shock (see §2(*a*)(iii)).

The destruction of Quchan was almost total. The majority of the houses in the town were built of sun-dried bricks, with flat roofs made of timber beams covered with a mud-and-straw mixture: they were all completely destroyed. A few houses incorporating timber frameworks in their walls‡ resisted slightly better even though they were also very severely damaged. Generally the east–west walls suffered most. Only the few kiln-brick and mortar houses built with timber framework survived partly. The bazaar, which was nearly one mile long with over 1100 shops and roofed alleys built in the style of the sun-dried brick houses, was levelled to the ground. Of the three larger better-built constructions in the town, the school and the governor's palace collapsed, and only the Sultan Ibrahim shrine remained standing even though its two minarets had toppled over. The shrine's dome, built of kiln-brick and good mortar, had been previously destroyed by an earthquake in 1852, rebuilt and then damaged again during the 1871/2 earthquakes after which it had been dismantled and reconstructed (Yate 1900). It was to collapse again during the 1895 earthquake. Today (1972) a new shrine is nearing completion at the same location.

Estimates of the number of people killed in the town vary between a half and a third of the population. The most reliable source on the subject, Tsimbalenko, mentions that about 5000 people were killed in Quchan alone. Many survivors are known to have died after the earthquake from exposure due to the exceptionally severe winter. About 1500 head of cattle, mostly housed in adobe stables, were also killed.

Many villages located around the town of Quchan were also destroyed. Those for which specific damage and/or casualty information could be found are shown in figure 4. They include, in alphabetical order

Gujeh: severe damage, people killed;
Jafurabad: mostly destroyed;
Kalateh Turopkhaneh (or Kelata): 70 out of 100 houses destroyed, 25 people killed;
Kalukhi: severe damage;
Kelbalasi: severe damage, people killed;
Mirza Mohammed Reza: destroyed, 35 people killed;
Moheb Seraj: severe damage, people killed;
Nowruz: severe damage; people killed;
Oturabad: damage, no casualties;
Waliabad: mostly destroyed;

† Ashkhabad time was one half hour behind Iranian local time.
‡ A construction technique adopted after the 1871/2 earthquakes as a precaution against future earthquake (MacGregor 1879).

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Yazdinabad: destroyed, about 60 people killed;
Yusefabad: severe damage.

Other villages for which precise information is lacking were also destroyed or damaged. The most severe damage was noted as confined to the Atrek valley (Tsimbalenko 1899), and to extend from Waliabad in the NW (beyond which villages such as Kharkan were 'hardly damaged at all' (Yate 1894, 1900)) to Kalukhi in the SW (Baumgarten 1896). It may also be assumed that the village of Hai Hai situated near the present-day (post-1895) town of Quchan was outside the region of severe damage, as it had been considered after the earthquake as the best site for the new town. More distant villages, such as Imam Quli (about 30 km from Quchan), suffered practically no damage at all. The region of severe damage thus measured about 35 km in the NW–SE direction and 20 km across (NE–SW) and contained the town of Quchan approximately at its centre. The dimensions of the epicentral region were therefore quite similar in 1871/2 and in 1893.

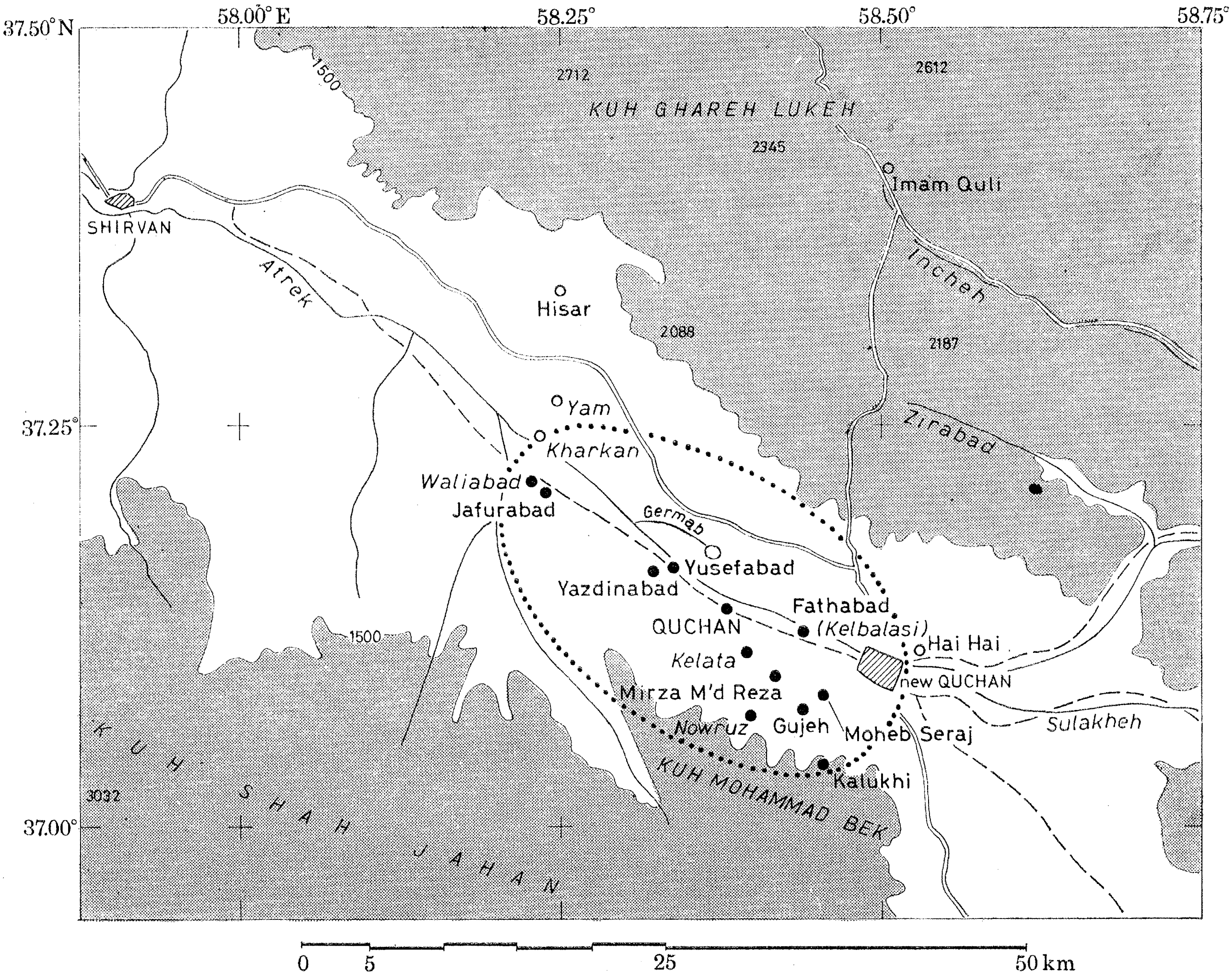

FIGURE 4. Quchan earthquake of 17 November 1893. ●, Destroyed village; ○, undamaged village. Only villages for which macroseismic information is available are shown. Those written in italics are shown in their 1893 location when this differs from present. Dotted line inscribes the region of maximum destruction. Shaded area is region above 1500 m; altitude of highest points is shown in metres. The 1971 road is shown by a double line, the old roads by dashed lines.

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FIGURE 5. Germab Valley (Iran). The probable location of the 1893 ground fractures is indicated by the arrow. The Germab Valley runs from the upper right (east) to the lower left (west) of the photograph. A sub-horizontal lacustrine limestone (mid-distance, left) is interrupted by Cretaceous limestone forming a ridge (fault?) across the valley.

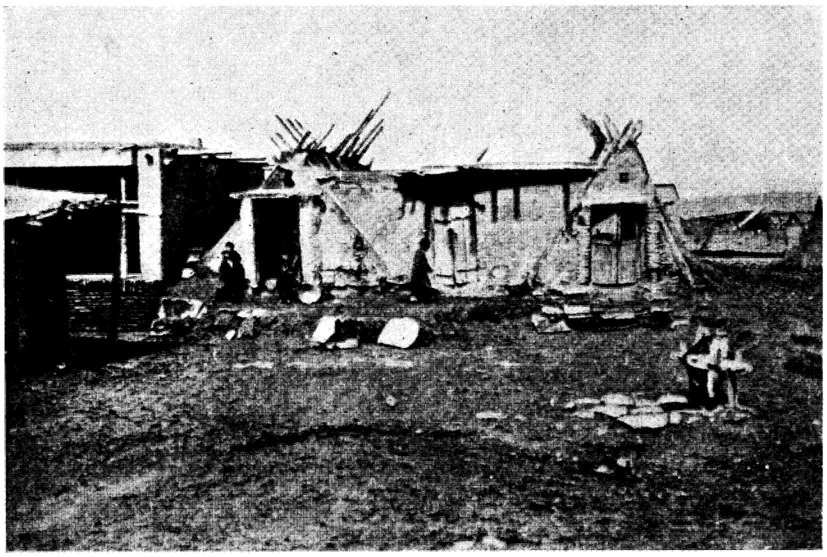

FIGURE 6. Quchan in 1903. After the 1895 earthquake, Quchan was relocated to its present site, but the old town shown in this photograph lingered on. Two 'A' frame shelters built in 1893 or 1895 from roof beams of destroyed houses are seen incorporated into a more permanent dwelling. From Pumpelly (1905, fig. 153).

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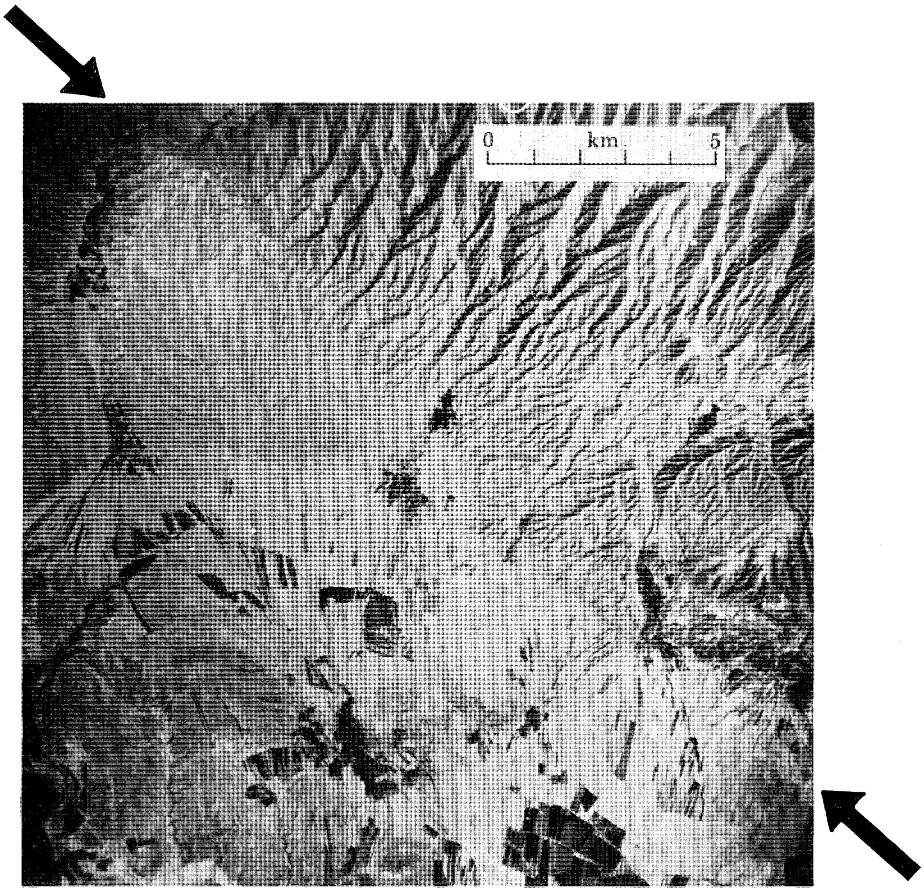

FIGURE 8. 1929 earthquake fault near Baghan. Aerial view showing the fault trace (between arrows). Baghan and its gardens are the two dark patches approximately at the centre of the photograph. The village on the fault in the lower right hand corner is Suqeh. North is top.

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FIGURE 9. 1929 earthquake fault near Kakeli. The fault trace follows the gully in the foreground down to the valley floor where evidence of obstruction of the river is still visible. It then climbs the mountain flank, from the point indicated by the arrow to the summit, marked first as a darker strip in the wheat fields, then by a small scarp. Looking SE.

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FIGURE 10. 1948 Ashkhabad earthquake. Ground fractures near Kuru Gaudan attributed to fault movement (see text). Photograph by G. Gorshkov.

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The earthquake caused many slides and slumps along the banks of the Atrek River, in particular at Germab, a small thermal spring flowing into the Atrek and located about 3 km to the NW of Quchan (figure 4). Large landslides blocked the Germab valley, and many ground fissures and possibly a fault scarp were observed (figure 5, plate 1). Most of the qanats in and around Quchan were damaged, reducing the supply of water to the town by about one half and causing extensive ground fissuring. Oil was also reported to have appeared on the water surface in canals.

(iii) 17 *January* 1895: *Quchan earthquake*

The information on this earthquake was compiled from observations by Maula Bakhsh (1895), Mayevsky (1899), Ferguson (1895), Yate (1900), Pumpelly (1905) and Thomson (1894).

Efforts to resite the town of Quchan after the 1893 earthquake near the village of Hai Hai were to fail for political reasons. By the end of 1894, Quchan was partly rebuilt at its former location, when it was once more destroyed by another major earthquake. The shock occurred on 17 January 1895 at about 11.30 a.m. local time and seems to have been preceded by a smaller shock a few seconds earlier. It was felt in Mashad as strongly as the 1893 earthquake, as well as in Shahrud, Birjand, Goek Tepe and Tejen (U.S.S.R.). In Quchan, aftershocks were felt every few seconds until about 8 p.m., then at a rate of one every 2–3 min, decreasing to one every few hours by the end of January, and to a few occasional tremors by mid-February. One aftershock on the night of the 22/23 January is known to have cracked walls in Jafarabad, about 25 km SE of Quchan.

Destruction in the town was, as in 1893, nearly total. All houses and official buildings were destroyed, but casualties were relatively light, mainly due to the extensive use of timber framework in the new buildings. The time of the day when the earthquake occurred, and the possible warning by a foreshock, may also have contributed to reducing the number of people killed. Furthermore, part of the population was still living in light temporary shelters of a type now familiar to Quchan after earthquakes, and which resisted with a minimum amount of damage (figure 6, plate 1). The bazaar, containing about 650 shops, was also built in the style of the shelters. It was estimated at the time that the percentage of occupants which died in the ruins was 5% for the houses and 10% for the shops where conditions were more crowded and escape more difficult. Casualties in the official buildings are known quite accurately and give an idea of the severity of the shock. In the Sultan Ibrahim shrine, previously damaged in 1893, 2 out of its 6 occupants at the time were killed, but there were no casualties in any of the other mosques of the town. In the Nammam-e Pachanar, a public bath for women, 43 people died, and in the other public baths, a total of 57 people were killed. In the Custom House buildings, 2 out of 30 people were killed, and in the Governor's house 6 out of 40.† None of the 13 employees of the Post Office were killed, and there were also no casualties in the Telegraph Office and in the Mayor's house. Altogether, out of a population of about 8000, the number killed was between 677 and 700. It is probable that the intense cold which prevailed during the night following the earthquake (–50 °C reported) caused further victims.

The earthquake destroyed completely 5 villages near Quchan, and damaged 18 others. The region of maximum destruction measured about 24 km in length (NW–SE) and 18 km across (NE–SW), and coincided with the narrowest part of the Atrek valley. It probably did

† Shuja-ud-Dowleh, the Governor of Quchan, was at the time under detention in Mashad.

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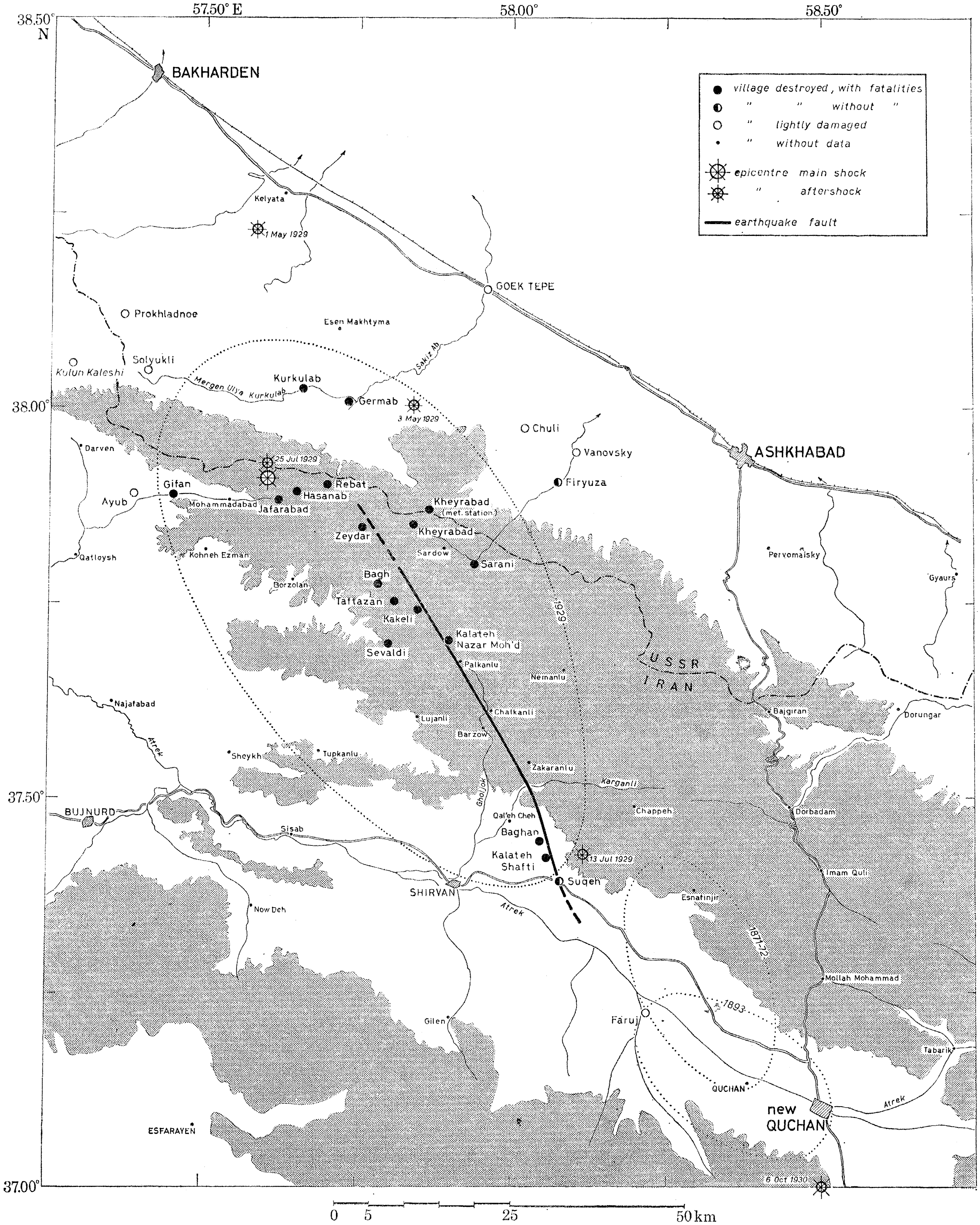

FIGURE 7. Baghan–Germab earthquake of 1 May 1929. Dotted line indicates approximate limit of severe destruction. Shaded area is region above 1500 m. Roads shown are as in 1971. The Quchan earthquakes are shown for reference; the sizes of their epicentral regions are not directly comparable to the 1929 region (see footnote, p. 17).

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not differ greatly from the epicentral region of the 1893 earthquake. Ground fissures were observed in many parts of the town, qanats collapsed and slumping occurred along the banks of the Atrek river.

(iv) 1 *May* 1929*: Baghan–Germab earthquake*

The first major destructive earthquake to occur in the Kopet Dagh after the Quchan events of 1893 and 1895 was the Baghan–Germab earthquake of 1 May 1929. This earthquake is of special seismotectonic importance as it was associated with a surface fault which, together with the Quchan epicentral regions, defines the active Bakharden–Quchan Zone over more than half of its length. Russian references often refer to the earthquake as 'the 1st Ashkhabad earthquake', but as this introduces an unnecessary geographical confusion, the name Baghan–Germab is used here instead.

The main shock occurred without any reported foreshock at 15h 37m 36s GMT (7.07 p.m. local Iranian time). The instrumentally determined epicentre was located in Iran just south of the Soviet border at 37.92° N, 57.60° E, and the average body wave magnitude from several station determinations was 7.0. The shock was felt up to 400 km from the epicentre in places such as Zeagli in the Kara Korum and Dargan Ata and Charuj on the Amu Daria River. In Ashkhabad, about 70 km from the epicentral region, many houses were cracked and one person died (Gorshkov 1947). In the northwestern part of the epicentral region the earthquake was described as starting with an underground rumbling sound, followed by strong vertical shocks and then by horizontal shaking which gave the impression of arriving from the southwest. Shaking lasted for about 15 s and was strong enough to throw people to the ground.

The zone of destruction was located for the greatest part in Iran, with comparatively less damage in Soviet Turkmenia. A fairly accurate assessment of the extent of damage may be obtained from the information provided by Russian investigators (Gabeman 1929; Nazarevsky 1930, 1932; Gorshkov 1941, 1947) and from contemporary press reports (*Etela'at*, *Bahar*, *The Near East*, *The Times*, *The Daily Telegraph*). I obtained some additional details in 1971 and 1972 by interviewing survivors of the earthquake. The region most severely destroyed was located just south of the Soviet border, near the instrumental epicentre (figure 7). The approximate number of casualties can be reconstructed for the most important villages: Gifan, 350; Jafarabad, 18; Hasanabad, 30; Zeydar, 300 (only one survivor); Rebat, 330; Kheyrabad, 320; Sarani (very many killed). West of Gifan, a small thermal spring greatly increased its flow, and has since become famous under the name of Ayub Pey Ghambar.

In the central part of the epicentral region, villages such as Bagh, Taftezan, Kakeli, Kalateh Nazar Mohammed and Sevaldi were destroyed. In Kakeli and Kalateh Nazar Mohammed, about 15 and 70 people were killed respectively. Farther south in the Shirvan region, Baghan was destroyed and about 25 of its inhabitants were killed. Suqeh was the last village in the south to have suffered. Beyond it, Faruj and the settlements near Quchan were only lightly damaged. Shirvan must also have been damaged to some extent as relocation of the town was considered after the earthquake. Altogether, official figures for Iran alone state that 88 villages were destroyed or damaged, 3257 people were killed and 1121 injured, and 6546 head of cattle perished.

In the northern part of the epicentral region, in Soviet Turkmenia, the effects of the earthquake are known in some detail from Gabeman's and Nazarevsky's reports. In Germab where

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14 inhabitants out of a population of 200 were killed, the destruction was complete and included the worker's club (ex-church), a stone masonry construction with good lime mortar, and the meteorological station. Nearby, Kurkulab was similarly destroyed. In the Kheyrabad Meteorological Station (U.S.S.R.), the main stone masonry building, the kiln-brick annexes and the sanatorium collapsed. In Firyuza, all houses were damaged, but the meteorological station was spared. In Telia (location ?), 18 houses were damaged, but there were no casualties. Also reported as affected were Solyukli, Prokhladnoe (further damaged by an aftershock on 13 May 1929), Chuli, Vanovsky, Upper Zinovevka and Lower Zinovevka.

Altogether, the zone of maximum destruction measured about 100 km NNW–SSE and 40 km ENE–WSW, and extended across the whole of the Kopet Dagh range, from the Atrek valley in the south to the north-facing mountain flank in the north.

A surface fault over 50 km long was associated with the earthquake. It extended from Suqeh in the SSE to the Iran–U.S.S.R. frontier in the NNW, following one of the faults of the Quchan–Bakharden Zone (figure 7). In Soviet Turkmenia, extensive ground fissuring but no clear fault scarp were observed in the Germab and Kurkulab regions. I mapped in the field two sections located near the ends of the earthquake fault, near Baghan and near Kakeli, and traced the intermediate section with the help of 1:50000 aerial photography, press reports and field interviews. Even though a more complete study is required, the Baghan and Kakeli sections described below serve to illustrate some characteristics of the earthquake faulting which took place in 1929.

In the field, the earthquake fault trace is marked by a saddle morphology and a slight discoloration of the top soil (figure 8). The 1929 scarp, still visible in places, appears as a rounded topographical step up to 2 m high with the NE side uplifted. Suitable markers for measuring horizontal movements were not found during the short period of our investigation. North of Baghan, two qanats which were supplying the village were damaged by fault movement.

In the southeast, the fault trace can be followed through the villages of Kalateh Shafti and Suqeh which were both destroyed, but not beyond Suqeh into the Atrek valley (figure 7 and figure 8, plate 2). Northwest of Baghan, the trace follows N 345° up to the Karganli stream bed, then takes its more general N 330° direction. Its linearity through the mountain range suggests a nearly vertical fault plane at depth. The fault passes near the villages of Zakaranlu, Barzow, Chalkanli, Palkanlu, Kalateh Nazar Mohammed and Kakeli. Between the latter two, it crosses a col in Lower Cretaceous limestone and its trace can be followed as a darker zone through the wheat fields (figure 9, plate 3). Evidence was found here of a quasi-instantaneous opening and closing of the earthquake fault fracture at surface. The transactions of the Kheyrabad Meteorological Station (quoted in Gorshkov 1941) mention that a fracture appeared along a path, and that 'the ground opened and then closed again in such a manner that in one place the ears of a donkey were found sticking out of the ground; the donkey was dug up, but the man leading it could not be found'. In July 1972, R. Aryan and I were able to clarify this story by talking to Hajji Mohammed Qulieh Rezai in Kakeli who had been involved in the same rescue attempt. The young man who had been killed was apparently walking at some distance from the donkey. He was struck by a falling rock, and it was the donkey alone which fell into the crack which then closed up on it. There is every reason to believe that the substance of this account is factual; if so, it may be added to the two other known cases of living beings fallen into, and crushed by, an earthquake ground fracture, i.e. at San Francisco in 1906, and at Fukui (Japan) in 1948 (Richter 1958).

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Beyond Kakeli the fault trace passes through Bagh and possibly Zeydar. It is unlikely that it extended in 1929 into Soviet territory as the Russians sources are very thorough on ground deformations and do not mention anything on the subject.

In Turkmenia the Bakharden–Quchan Zone crosses the Mergen Ulya stream near Germab and Kurkulab, and then bends into the Main Fault Zone. The ground fractures which occurred in these two villages seem to have been exclusively due to slumping and landslides. In Germab, fractures with vertical displacements of 20 cm were observed near the banks of the Mergen Ulya and Sakiz Ab streams, and the water-table rose by several metres with respect to the ground surface. Many streams temporarily increased their output. In Kurkulab, fissures were also observed along the Mergen Ulya and one of its smaller tributaries, the Tunchi. At one point where these fissures crossed a road, Nazarevsky (1930) noted: 'Here occurred a displacement of the road to the left.' He does not mention this again in his 1932 report, and it is not clear from the text whether these fissures were any different from the slump scarps which he describes at other localities. Fissures up to 15 m in length were also reported at the Kheyrabad meteorological station, and in the mountains many tracks were blocked by rockfalls and landslides.

A large number of aftershocks followed the main event. During the first 24 h a tremor could be felt in Germab (U.S.S.R.) every 10–20 min, and 10 days later an average of about 6 shocks per day were felt on the Iranian side. For the period up to 1 May 1930, the meteorological station at Germab recorded 101 shocks, and at Kheyrabad, 104 shocks. From the times given it appears that each station was recording different shocks, indicating small local events. The total number of shocks recorded by all the stations of the region including Ashkhabad was 302 (Gorshkov 1957). Epicentres of aftershocks with magnitudes greater than about $4\frac{3}{4}$ were determined by the international and by the Russian networks. They indicate activity in the region of the main shock as well as at the extremities and prolongations of the earthquake fault (figure 7). The shock of 13 July 1929 ($M_b = 5\frac{3}{4}$) is of particular interest as its epicentre was located about half-way between the southern end of the fault and Quchan. In Faruj, a small town which had been spared by the main shock, many houses were destroyed and 5 people out of a population of about 3000 were killed.† This aftershock links the Baghan–Germab epicentral region with that of the 1871/2 Quchan earthquakes, indicating that all these shocks are associated with the reactivation of the Bakharden–Quchan Zone. This point will be returned to in §3*a*.

(*b*) *Seismotectonic aspects of the Ashkhabad earthquake* (1948)

The Ashkhabad earthquake of 5 October 1948 was the first major earthquake in the Kopet Dagh after the 1929 Baghan–Germab earthquake. Its instrumental epicentre was located on Soviet territory about 10 km south of Ashkhabad, with a focal depth of around 25 km and a magnitude (M_b) of 7 (Soviet determination). The epicentral region was located to the north-east of the 1929 region, and the two zones of destruction were approximately contiguous and parallel to each other. The number of people killed in the U.S.S.R. probably exceeded 10000. In Iran, the villages of Chenar, Sheykhan, Nowkhandan and Tumur Khan were severely damaged (I. Asudeh, personal communication), and in Darregaz many buildings collapsed. Casualties in Iran were 352 people killed and 540 injured. For details of this earthquake, the reader is referred to the extensive Russian literature on the subject, most of which is listed in two papers recently translated into English – Rezanov (1958) and Rustanovitch & Shirokova (1964).

† Most of the population was out of doors when the earthquake occurred at 11 a.m. local time.

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Only the seismotectonic aspects will be reviewed here as they are directly relevant to the understanding of the active tectonics of the Kopet Dagh.

Of the large number of ground fractures associated with the earthquake, those at Kuru Gaudan were probably the most significant. About 0.5 km to the south of the village, a system of scarps was observed 'crossing a small transversal ravine and a watershed' (Kopp *et al.* 1964), 'entirely unrelated to the local topography' (Gorshkov & Yakushova 1967). The main body of fractures formed a zone about 200 m long and 40 m wide, with individual scarps striking between N–S and N 40° (figure 10, plate 3). The trace of the fractures was uneven and branched. Vertical displacements were up to 50 cm, and scarps often combined with counterscarps to form small grabens between them. Open fissures without vertical displacements and generally oriented N–S were also observed. The overall system formed by these fractures was a graben with stepped sides and a general N 30° orientation. For Kopp *et al.* (1964) the fractures were of primary origin and resulted from subhorizontal movement, their tensional aspect suggesting that they had been formed in a plane normal to the minor principal stress, i.e. by a compression oriented approximately NNE. Gorshkov (1957) also favoured a tectonic interpretation for these fractures. However, Medvedev (1955) and, to a certain extent, Rezanov (1958, 1959) consider that the fractures could have been of secondary origin, i.e. resulting from the responses of the sedimentary cover to seismic shaking and gravitational forces. Nevertheless, most authors agree that the Main Fault Zone was not reactivated, a point which was carefully checked in the field by Gorshkov.

Relevelling and retriangulation of the Trans-Caspian Railway carried out after the earthquake and compared to earlier results showed that both vertical and horizontal displacements had taken place (Butovskaya & Kovalenko 1955; Kolibaev 1962). The level of the town of Ashkhabad remained approximately unchanged, but a region to the northwest was uplifted (maximum 33 cm at Bezmein), and a region to the southeast lowered (maximum −22 cm at Gyaurs). Horizontal movements were even greater and attained a maximum of 178–190 cm NNE displacement at Ashkhabad. The direction of this displacement agrees well with the compression direction deduced from the ground fractures at Kuru Gaudan.

The strike of the nodal planes of the fault plane solution for the main shock was N 110°, with one plane nearly vertical and slip of the northern block upwards, and the other plane nearly horizontal and slip of the southern block towards the NNE (Rustanovitch & Shirokova 1964; McKenzie 1972). Medvedev (1955) originally adopted the first plane, but when the retriangulation results became available, the second plane was generally preferred (Rustanovitch & Shirokova 1964). This fault plane solution is consistent with the fracture analysis and retriangulation results seen above. It indicates thrust of the southern block towards the NNE along a fault striking N 110° and dipping by a few degrees to the south.

Two special aftershock studies with temporary networks carried out in June–October 1949 and in June–September 1953 are reported in Rustanovitch (1957). During both periods, the majority of shocks were located near the Palaeozoic basement at a depth of 10–12 km, and concentrated near the NW and SE ends of the zone of maximum destruction, at Kuru Gaudan and at Bezmein. Aftershocks greater than $M_b = 4$ determined by the international network are situated in a NW–SE zone extending into Iran and approximately parallel to the macroseismic epicentral zone. This aftershock zone adjoins the 1929 aftershock zone without overlap (figure 11).

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(*c*) *Seismicity of the Kopet Dagh*

Figure 11 is an epicentre map showing the locations of the principal earthquakes between 1913 and the present (1972), and including the regions of destruction† of the strongest earthquakes since about 1870. The sources of information used, and the category of earthquakes considered, are explained in appendix A, and the principal earthquakes and periods of seismicity are summarized below. It is immediately apparent from the map that most of the Kopet Dagh south of the margins of the Turan Plate is seismically active. The southern limit of this activity is not well defined and probably extends south of the region considered here. The eastern limit is clearly marked if one takes into account the fact that for several degrees east of 60° E there are no further epicentres of the category considered in this study. In contrast, the western limit is less defined and can only be approximately traced in the north at about 54° E.

The seismicity of the Kopet Dagh may also be divided into time periods which are shown in figure 11 by different epicentre symbols. These periods are

1871–1895: only the major destructive shocks are known, i.e. the three Quchan earthquakes of 1871/2, 1893 and 1895 (see § 2*a*) located at the southeastern end of the Bakharden–Quchan Zone, and the 1890 Tash earthquake in the west of the region (Ambraseys 1974).

1895–1929: all the destructive earthquakes, except 17 September 1923, were located at the periphery of the region considered. The relatively small number of shocks known is probably due to the small number of reliable epicentre determinations available. The stronger shocks are listed in appendix B.

1929–1948: the period started with the Baghan–Germab earthquake of 1 May 1929 (see § 2*a*). The aftershocks of this event, and the shocks which followed up to the 1948 Ashkhabad earthquake, occurred, with only a few exceptions, in a NNW–SSE zone, including and extending south of the 1929 epicentral region. In the Kopet Dagh mountains, this seismic zone is approximately restricted in the east by the eastern limits of the Bakharden–Quchan zone, and in the west by longitude 57° E. The principal exceptions mentioned above occurred in 1944 and 1946 and are summarized in appendix B.

1948–1954: after the Ashkhabad earthquake of 5 October 1948 and its aftershocks which occurred mainly in a zone adjacent in the east to the 1929–48 zone, smaller shocks continued in the same region with the majority located north of 37° N. The exception was the 1953 Torud earthquake (appendix B) which should be considered together with the seismicity of North-central Iran (Tchalenko 1974).

1954–1969: earthquakes during this period occurred in many regions of the Kopet Dagh, and in particular in the Alborz and Allah Dagh–Binalud mountains as well as near the Doruneh Fault and the southern margin of the Turan Plate. Two shocks of moderate magnitude caused destruction in the Esfarayan valley south of Baghan (appendix B). The second shock on 3 January 1969 had a fault plane solution indicating a thrust towards the NE along a NW striking plane (McKenzie 1972).

1969–1972: a marked change in the seismicity pattern took place in 1969. Since about 1870, the eastern margin of the Caspian Basin had remained relatively quiescent. A series of moderate-size earthquakes started in this region with the Sharluk earthquake of 1969, and continued with

† The areas of the different regions of destruction are not directly comparable. Those of the earliest earthquakes are generally too small when compared to the later ones because the early data usually include only complete or most severe destruction. The location and shapes of the regions are, however, more relevant.

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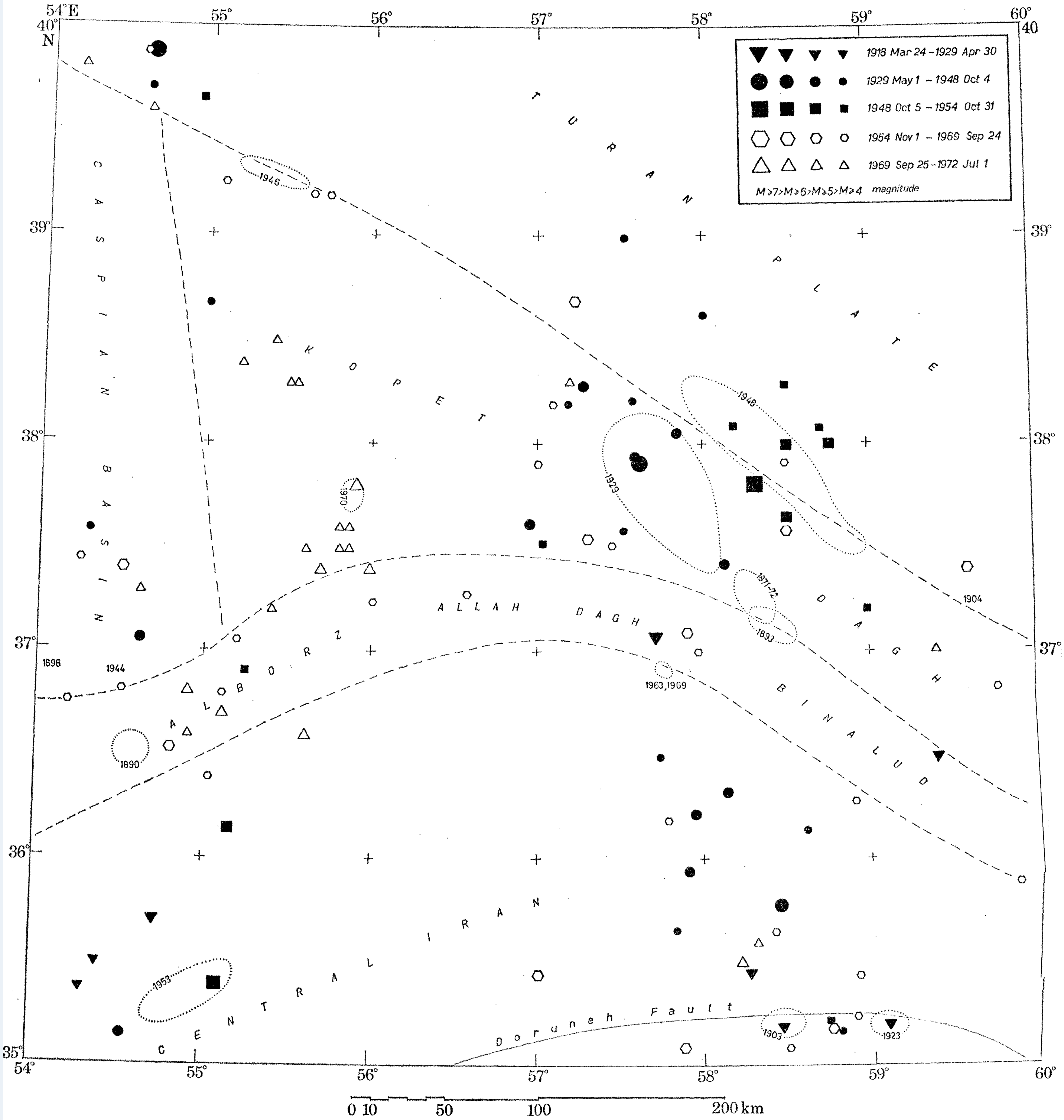

FIGURE 11. Epicentre map of the Kopet Dagh and Northeast Iran. Choice of instrumental parameters is explained in Appendix A. Dotted lines inscribe regions of maximum destruction of the largest earthquakes (see footnote, p. 17). Years shown alone indicate macroseismic epicentres.

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the Farseyan and Karnaveh earthquakes of February and July 1970 (appendix B). The shape of the Karnaveh epicentral region, and the trend obtained by the combined locations of the Farseyan shock with the Karnaveh main shock and immediate aftershocks, suggest a NNE alinement. The fault plane solution also indicates this direction (N 19° strike, 43° NW dip) and a normal faulting mechanism accompanied by a small left-lateral strike slip component (D. McKenzie, personal communication). Fault plane solutions obtained for small shocks farther north with local arrays are on average consistent with this mechanism (Bessonova *et al.* 1957; Petrushevsky, Rezanov & Rastvorova 1954).

Recently, an isolated shock on 26 May 1971 near Kashmar (appendix B) provided a fault plane solution similar to 3 January 1969: thrust on a SW dipping plane striking about N 140° (D. McKenzie, personal communication).

3. Relation between seismicity and structure

Some general characteristics of the relation between seismicity and structure in the Kopet Dagh emerge from the comparison of known tectonics (§1) and earthquake locations (§2). The two basic elements of this relation are also suggested by the change in seismicity pattern which took place around 1954. Before that date, earthquakes were mainly occurring in the east along a NNW zone containing the Bakharden–Quchan Zone, whereas after that date they were most frequent in the west, along a NNE zone at the margins of the Caspian Basin. The data on these two regions of activity are summarized below, with reference to figures 2 and 11.

(*a*) *The Bakharden–Quchan Zone and the NNW trend*

Direct evidence of the reactivation of one of the faults of the Bakharden–Quchan Zone was provided by the fault-break associated with the 1929 earthquake. The location of epicentres indicates that this zone is also active beyond the segment which moved in 1929. The epicentral regions of the Quchan earthquakes of 1871/2, 1893 and 1895 are alined along the zone, and the interconnexion of these events with the 1929 earthquake is provided by the continuity of the respective macroseismic regions, as well as by the locations of the 1929 aftershocks. The intersection of the Bakharden–Quchan Zone in the NW with the Main Fault Zone was marked during the last 10 years by a concentration of small damaging earthquakes located near Bakharden (Nepesov, Saval'eva & Golinskii 1967; Golinsky, Lagutochkina & Nepesov 1968; Golinsky, Kalluar, Lagutochkina & Nepesov 1970; Nepesov *et al.* 1971). In the SE, the intersection with the Atrek–Kashaf Lineament seems to have determined the locations of the three Quchan earthquakes.

An interesting feature of the epicentre locations is the relation between the regions affected by the 1929 Baghan–Germab and the 1948 Ashkhabad earthquakes. If the period between the two earthquakes (1 May 1929 to 4 October 1948) is compared to the period following the second earthquake (5 October 1948 to 1 November 1954), the two regions affected are seen to be parallel to each other and oriented NNW, and are contiguous without any appreciable overlap. This NWW trend is obvious for the 1929 earthquake. For the 1948 earthquake, it is suggested by the shape of the isoseismals (Medvedev 1955) and by the aftershock locations. It is significant that no direct connexion was found between the earthquake and the Main Fault Zone.

When the two regions of the 1929 and 1948 earthquakes are considered together, they

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constitute the northern part of a seismic zone oriented approximately NNW–SSE and extending in the south beyond the region studied. This zone includes most of the strongest earthquakes of Northeast Iran and southern Turkmenia and is referred to here as the 'NNW trend'. It intersects the Doruneh Fault in the south along the only section where this fault is known to be seismic, and may form a branch of an important N–S structure located approximately along the Afghan–Iranian frontier.

(*b*) *Eastern margin of the Caspian Basin and the NNE trend*

After 1954 the seismicity was characterized by epicentres scattered over many parts of the region and not showing any pronounced concentration in any particular area. After 1969, however, the number of earthquakes occurring in the east decreased very appreciably, and a large number of shocks occurred between 55° and 56° E in a zone which had been previously quiescent. This zone, corresponding approximately to the eastern margin of the Caspian Basin, was in particular marked by several destructive earthquakes in 1969 and 1970. On the basis of the limited amount of information available, it was suggested that these earthquakes were controlled by normal faulting on a NNE–SSW structure which is referred to here as the 'NNE trend'.

Both McKenzie (1972) and Nowroozi (1972) have postulated the existence of a NE–SW plate boundary starting on the Main Fault Zone in the vicinity of Ashkhabad and extending southwestwards along the Alborz range, and separating a Caspian from an Iranian Plate. There is no surface structure which could, even in the broadest terms, correspond to such a boundary, but there is indeed a marked change from the NNW Trend in the east to the NNE Trend in the west. This change occurs in the region of 56–57° E and corresponds to a longitudinal zone which has been nearly entirely devoid of earthquakes during the time period considered in this study. Other changes which characterize this zone are: the dominant direction of faulting (NNW in the east, NE in the west) and sense of strike slip (right-lateral in the east, left-lateral in the west), the mechanisms indicated by the available fault plane solutions (thrusting in the east, normal faulting in the west) and the time-sequence pattern of shocks (activity in the east when the west is quiescent, and vice versa). This difference between an eastern and a western region had been previously noted in seismicity studies of Soviet Turkmenia (Gorshkov 1957; Bessonova *et al.* 1957; Linden & Savarensky 1961; Golinsky, Nepesov & Rustanovitch 1964; Odekov, Muradov, Rakhimov & Annamuknamedov 1974). The significance of these observations made both in Iran and in the U.S.S.R. may become clearer with more geophysical information.

4. Model of active tectonics and seismotectonic implications

A number of structures in the Kopet Dagh were shown to be presently active, on the evidence of measured Quaternary fault movement, of faulting associated with earthquakes and of seismicity pattern: the faults forming the Diagonal Fault System (NNW right-lateral, NE left-lateral and associated E–W thrusts), the Main Fault Zone, the NW striking thrusts (from fault plane solutions) and the NNE normal faults. Activity on all these structures is, on average, consistent with a continuation of the NNE compression which initiated the Diagonal Fault System at the end of the Pliocene (§1*c*). Such a compression maintains the same sense of displacement on the faults of the Diagonal Fault System as throughout the Quaternary, causes

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right-lateral strike slip on the Main Fault Zone because of its non-orthogonality to the compression direction, and explains NNE tensional structures (the normal faults) by their parallelism to this direction. The different deformations which accompanied the Ashkabad earthquake, i.e. the NNE directed thrust on a N 110° plane indicated by the fault plane solution and retriangulations, the NNE tensional type of ground fracturing and the NNW zone of aftershock activity, illustrate the interconnexion between these different structures. The tectonic model based on this NNE compression implies a NNE motion of Iran relative to the Turan Plate (figure 12). In this respect, the Kopet Dagh has similarities with the Zagros where Quaternary structures are also presently active and indicate a NNE motion of the Arabian Plate relative to Iran (Tchalenko & Braud 1974).

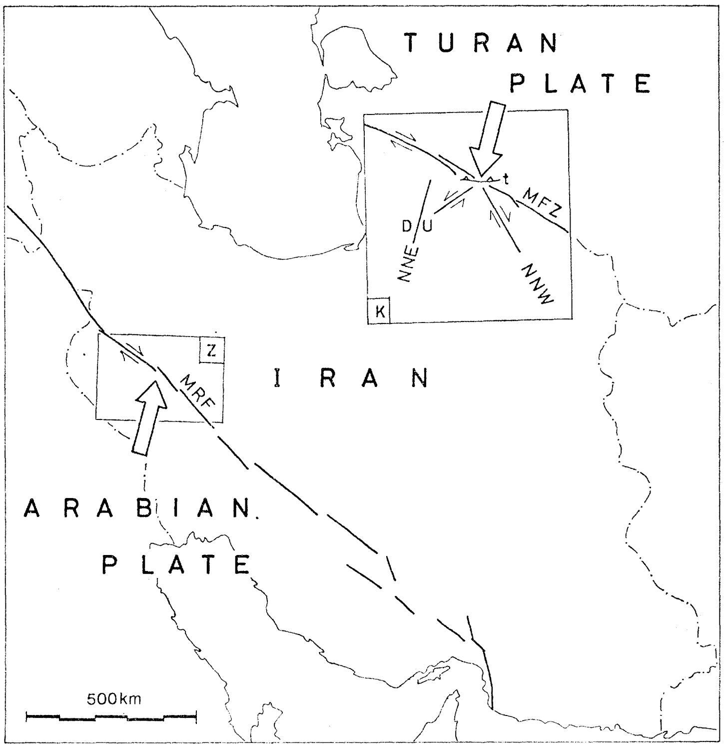

Figure 12. Model of active tectonics. Inset K: schematic representation of active structures in the Kopet Dagh and compression direction arising from the motion of the Turan Plate with respect to Iran. MFZ, Main Fault Zone; NNW, NNW trend; NNE, NNE trend; t, minor thrust; D/U, normal faulting. Inset Z: schematic representation of the Main Recent Fault (MRF) in the Zagros and compression direction arising from the motion of the Arabian Plate with respect to Iran (Tchalenko & Braud 1974).

If the mechanism of active tectonics can thus be interpreted in its broad outlines, the time factor involved in the deformation is still largely unknown. Seen as a whole, the Kopet Dagh appears as a large area reacting to a NNE compression by sudden fracture reactivation which causes the earthquakes. Microshock activity and fault creep movement, about which nothing is known in the Kopet Dagh, are undoubtedly also taking place. What governs the location of tectonic activity at any given time, and what explains the migration of this activity from one region to another? Taking as example the best documented structure, the Bakharden–Quchan Zone, its strongest earthquakes since the second half of the century took place in 1852, 1871/2, 1893, 1895 and 1929, i.e. at intervals of 19, 21, 2 and 34 years. This sequence seems to have

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released all the strain energy stored along the Zone, as very few shocks have occurred there during the 44 years since 1929. If the adjacent Ashkhabad zone and the 1948 earthquake are also taken into account, it would seem that by the mid-twentieth century most of the strain accumulated along the NNW trend, at least above 36° N, had been released, and the activity moved to the NNE trend. Together with the great width of the seismic zone and the complicated mechanism of active tectonics, such a simultaneous strain accumulation in one part of a region and seismic release in another is one of the marked features of the Kopet Dagh. It is a process probably characteristic of the interaction occurring at the margins of converging continental plates.

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Appendix A. Choice of epicentral parameters

The epicentre determinations used were the following: 1913–49, I.S.S. relocated epicentres as given in Nabavi (1972) based on I.G.S. redeterminations using original station readings and improved time tables; 1950–65, Nowroozi (1971); 1966–73, U.S.C.G.S. (N.O.A.A.). The lowest magnitude included in these determinations is about 4, but for the first period not all earthquakes of magnitude 4 or greater are necessarily tabulated. The instrumental determination was adhered to even in the rare cases where macroseismic data suggested that they could be in error.

There are several other determinations which can be used in such studies, and originally figures 2 and 11 had been plotted using all other networks (B.C.I.S., I.S.S., U.S.S.R., U.S.C.G.S. before 1966, etc.). This increased appreciably the number of earthquakes available for analysis, especially when the Soviet network (U.S.S.R.) was included, but the accuracy of epicentre locations by different networks was no longer homogeneous, and problems arose when several different locations were available for a same event. It was therefore considered preferable, after having verified that the overall seismicity pattern remained unchanged when these other determinations were also included, to restrict the data to the 'better located' events given by the sources mentioned above.

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Appendix B. Principal earthquakes of the Kopet Dagh

1871 December 23: Quchan (§2(*a*)(i)).

1872 January 6: Quchan (§2(*a*)(i)).

1890 July 11: Tash (Ambraseys 1974).

1893 November 17: Quchan (§2(*a*)(ii)).

1895 January 17: Quchan (§2(*a*)(iii)).

1895 July 9: Krasnovodsk. Centred just outside the region of this study at about 40° N 53° E, this event is included as it is generally considered to be associated with the Main Fault Zone. The earthquake was one of the strongest of Turkmenia and Northeast Iran, and probably had a focus of exceptional depth for the region, about 100 km (Gorshkov 1947; Savarensky, Linden & Masarsky 1953; Petrushevsky *et al.* 1954; Masarsky 1961; Linden & Savarensky 1961). Severe destruction and ground deformations extended from the Caspian Sea to SE of Kazanjik (Ivanovsky 1899).

1898 January 15: Chikishlar (about 37.6° N, 54.0° E). Caused damage in the towns of Chikishlar and Gorgan (Gorshkov 1947).

1903 September 25: Turshiz (about 35.2° N, 58.5° E). Destroyed part of the town of Turshiz (now Kashmar) and some surrounding villages, and killed 209 people (Almazov 1905; Tchalenko 1973). Probably associated with the Doruneh Fault (Tchalenko, Berberian and Behzadi 1973).

1904 November 9: Kaakha (about 37.4° N, 59.6° E). Five consecutive shocks caused some damage in Kaakha and were felt in Ashkhabad and Mashad (Anonymous 1906).

1923 February 4–5: Bujnurd? (about 37.5° N, 57.3° E?). Rezanov (1959) mentions an earthquake which destroyed 200 houses, but no other data have been found.

1923 May 25: Torbat-e Heidariyeh (about 35.3° N, 59.2° E). Destroyed completely 5 villages and killed 2219 people (Tchalenko 1973). Probably associated with the Doruneh Fault (Tchalenko, Berberian & Behzadi 1973).

1923 September 17: the instrumental epicentre for this earthquake of magnitude about 6–6½ is 37.1° N, 57.7° E. Nine villages were destroyed and 22 damaged, 157 people were killed and 156 injured (Anon. 1923). The region of destruction has not yet been established.

1928 August 21, 19 h 12 m GMT: insrumental epicentre 36.52° N, 59.43° E (probably in error). Apparently 10 people were killed in Nishapur, and Sabzevar and Shirvan were damaged (Anon. 1923).

1929 May 1: Baghan–Germab (§2(*a*)(iv)).

1929 July 13: Baghan–Germab aftershock (§2(*a*)(iv)).

1944 April 5: Gorgan. Instrumental epicentre 37.03° N, 54.62° E. Magnitude $M_b = 4\frac{1}{2}$–5. About 60% of the town of Gorgan was severely damaged and some surrounding villages were affected (Gorelikov 1960); 20 people were killed (Bozorgnia 1962).

1946 November 4: Kazanjik. Instrumental epicentre 39.84° N, 54.59° E, $M_b = 6\frac{1}{2}$–$7\frac{1}{2}$. Strongly felt over a considerable area between Krasnovodsk and Kizyl Arvat, causing severe damage in Kazanjik, Jebel and Nebit Dagh (Rezanov 1955). Like the 1895 Krasnovodsk earthquake, it is generally thought to be associated with the Main Fault Zone.

1953 February 12: Torud. Instrumental epicentre 35.40° N, 55.08° E, $M_b = 6\frac{1}{2}$. Torud and 7 other villages were destroyed, and 920 people were killed. Ground fractures, probably associated with an ENE fault, were observed (Abdalian 1953).

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1959 February 11: Bolshevik. $M_b = 4$ (Nepesov, Golinskii & Gargozov 1964).
1960 August 16: Porsi Kuyu. Nepesov *et al.* (1964).
1963 March 31: Dahaneh Ojaq. Instrumental epicentre 37.00° N, 57.97° E, $M_b = 4.6$. In Dahaneh Ojaq, 76 houses were destroyed and 4 inhabitants killed.
1963 September 18: Archman. $M_b = 4.4$ (Nepesov *et al.* 1967).
1963 September 20: Bami. $M_b = 4.2$ (Nepesov *et al.* 1967).
1964 January 11: Nokhur. $M_b = 3.8$ (Golinsky *et al.* 1968).
1964 February 12: Kizyl Arvat. $M_b = 4\frac{1}{4}$ (Golinsky *et al.* 1968).
1964 April 14: Izgant. $M_b = 3.5$ (Golinsky *et al.* 1968).
1964 April 18: Bakharden. $M_b = 3.5$ (Golinsky *et al.* 1968).
1964 May 13: Yablovonsky. $M_b = 3.5$ (Golinsky *et al.* 1968).
1966 June 29: Nebit Dagh. $M_b = 3.7$ (Golinsky *et al.* 1970).
1966 August 18: Bakharden. Golinsky *et al.* (1970).
1966 October 24: Kaakhka. Golinsky *et al.* (1970).
1966 November 26: Shamli. $M_b = 4.0$ (Golinsky *et al.* 1970).
1967 March 30: Tagarevo. Nepesov *et al.* (1971).
1968 July 14: Kazanjik. Nepesov *et al.* (1972).
1968 November 15: Ashkahabad. $M_b = 5.6$ (Nepesov *et al.* 1972).
1969 January 3: Dahaneh Ojaq. Instrumental epicentre 37.1° N, 57.9° E, $M_b = 5.6$. Destruction in Dahaneh Ojaq and Esfarayan; 50 people were killed, 300 injured, 2000 rendered homeless.
1969 March 26: Nebit Dagh. $M_b = 3.8$ (Nepesov, Golinskii, Lagutochkina & Kolesnikova 1973).
1969 November 23: Sharluk. $M_b = 5$ (Nepesov *et al.* 1973).
1970 February 24: Farseyan. Instrumental epicentre 37.4° N, 55.7° E, $M_b = 5.0$. Slight damage at Shahpasand, Dasht-e Shah, Hoseinabad-e Kalpus, Farseyan and Minudasht.
1970 July 30: Karnaveh. Instrumental epicentre 37.8° N, 55.9° E, $M_b = 6.3$–6.7. 40 villages were damaged and about 200 people killed (Ambraseys, Moinfar & Tchalenko 1971 *a*, *b*).
1971 May 26: Kashmar. Instrumental epicentre 35.5° N, 58.2° E, $M_b = 5.4$. Strongly felt in Kashmar.

This earthquake list is not exhaustive as regards the smaller shocks, but mainly mentions those of direct relevance to this study, or those which are little known. The reader is also referred to Ambraseys *et al.* (1971 *b*).

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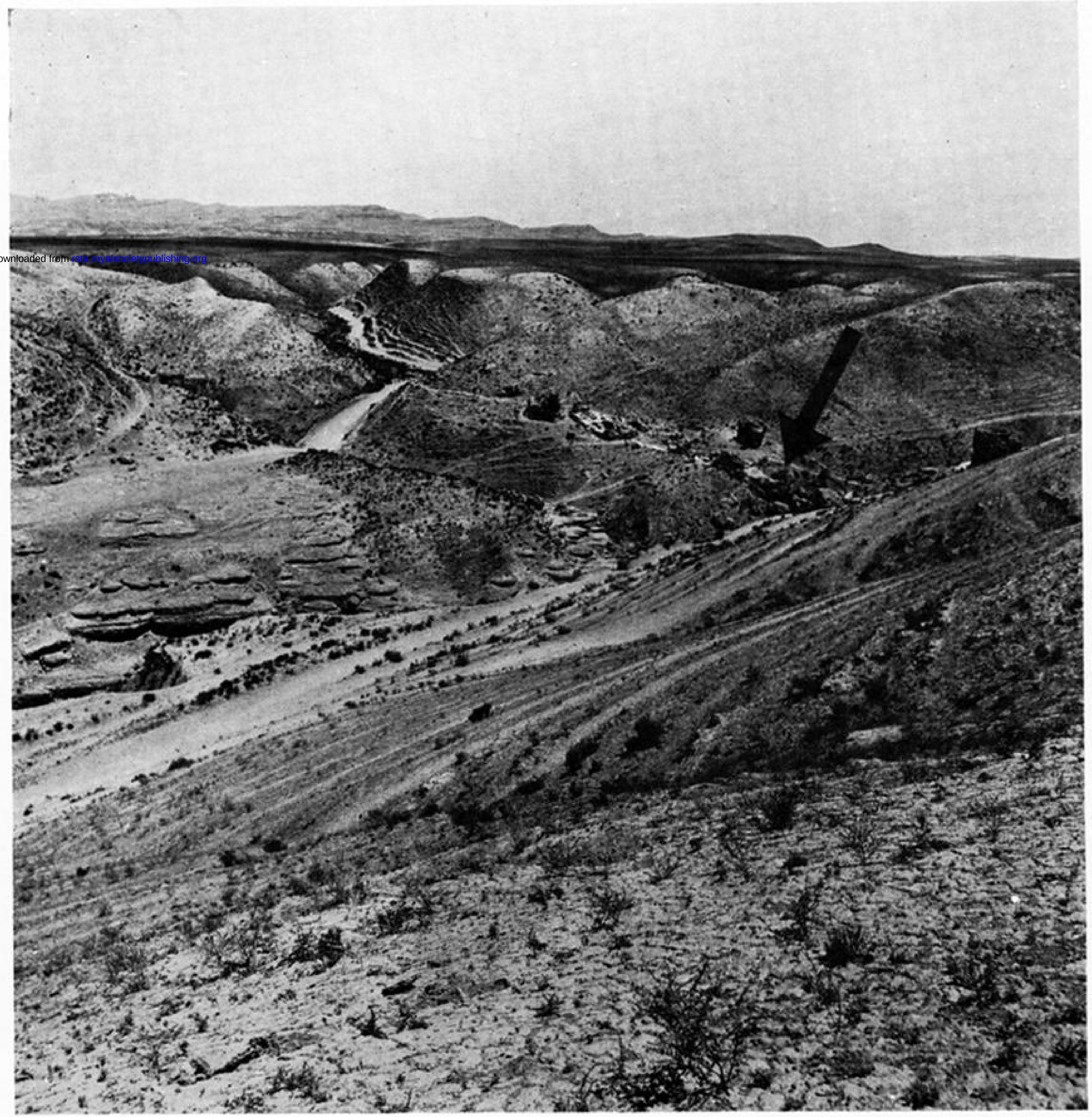

FIGURE 5. Germab Valley (Iran). The probable location of the 1893 ground fractures is indicated by the arrow. The Germab Valley runs from the upper right (east) to the lower left (west) of the photograph. A sub-horizontal lacustrine limestone (mid-distance, left) is interrupted by Cretaceous limestone forming a ridge (fault?) across the valley.

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[F]IGURE 6. Quchan in 1903. After the 1895 earthquake, Quchan was relocated to its present site, but the old town shown in this photograph lingered on. Two 'A' frame shelters built in 1893 or 1895 from roof beams of destroyed houses are seen incorporated into a more permanent dwelling. From Pumpelly (1905, fig. 153).

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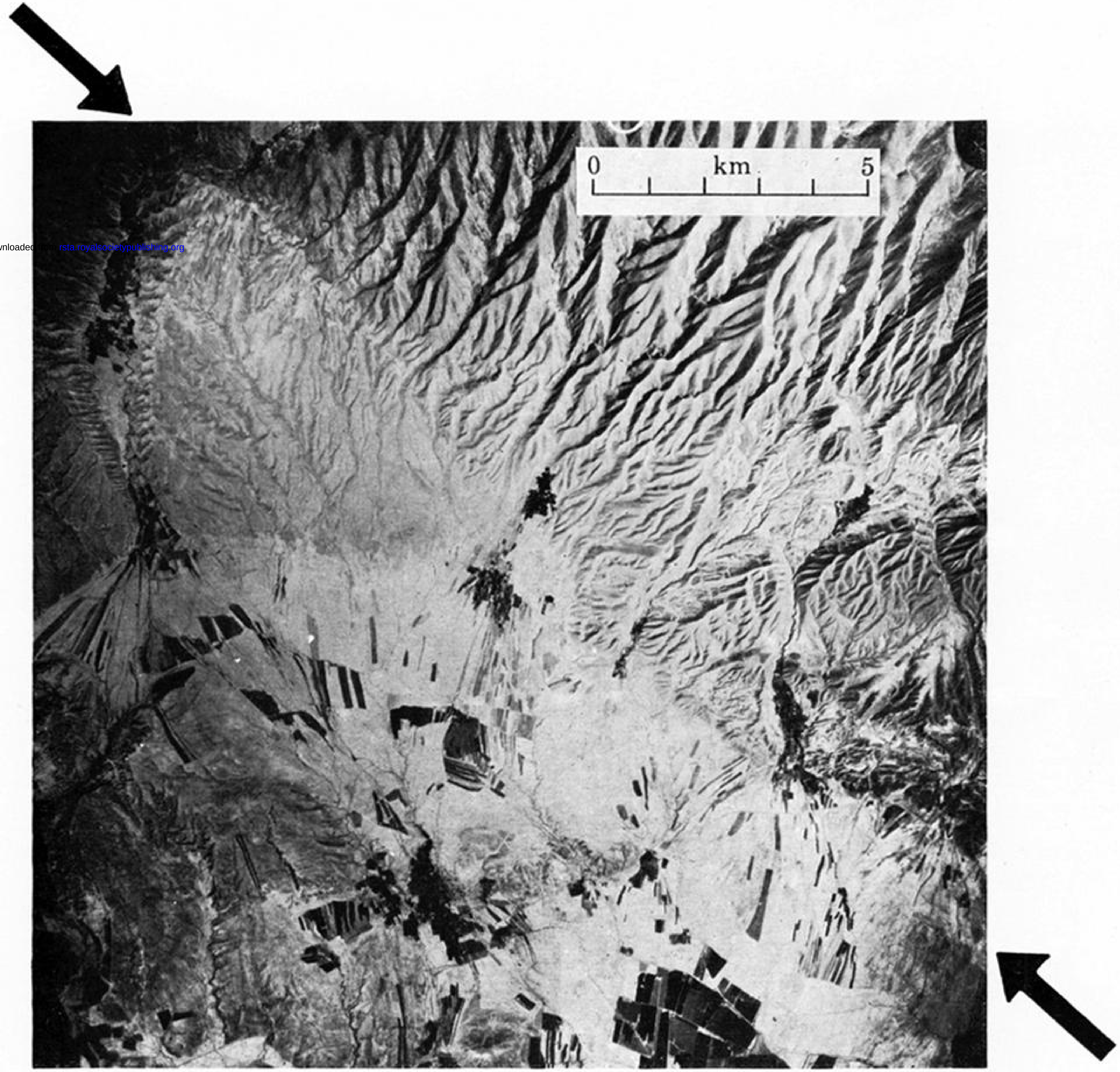

FIGURE 8. 1929 earthquake fault near Baghan. Aerial view showing the fault trace (between arrows). Baghan and its gardens are the two dark patches approximately at the centre of the photograph. The village on the fault in the lower right hand corner is Suqeh. North is top.

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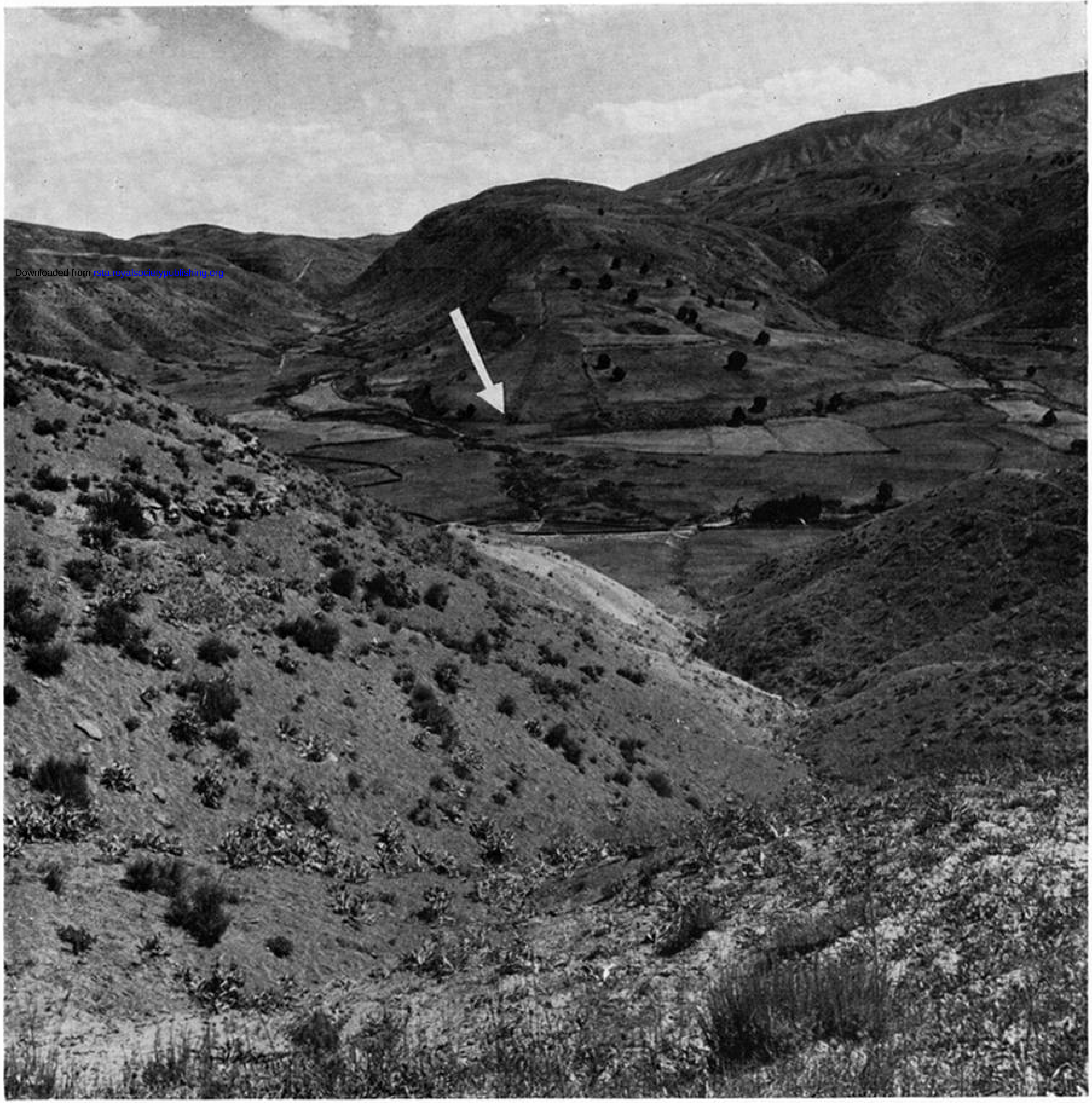

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IGURE 9. 1929 earthquake fault near Kakeli. The fault trace follows the gully in the foreground down to the valley floor where evidence of obstruction of the river is still visible. It then climbs the mountain flank, from the point indicated by the arrow to the summit, marked first as a darker strip in the wheat fields, then by a small scarp. Looking SE.

IGURE 10. 1948 Ashkhabad earthquake. Ground fractures near Kuru Gaudan attributed to fault movement (see text). Photograph by G. Gorshkov.

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