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Background and precursory seismicities along and surrounding the Kunlun fault before the M_s8.1, 2001, Kokoxili earthquake, China

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Abstract

The M_s8.1 Kokoxili, China, earthquake on 14 November, 2001, occurred on the western portion of the Kunlun fault. By analyzing data from geological surveys and records of historical and modern earthquakes, we know that at least 8 M_s6.9–8.1 earthquakes occurred along the Kunlun fault from 1879 AD to 2000 AD. The spatial arrangement of these ruptures indicates the existence of two rupture gaps, the Kokoxili and the Maqu, on the fault before 2001. The Kokoxili gap and surrounding area experienced a long-term seismicity quiescence of $M_s \geqslant 5$ earthquakes and developed the corresponding background seismic gap at least from 1966 to 2001. The 2001 Kokoxili earthquake occurred on the Kokoxili gap. The Maqu gap on the eastern portion of the Kunlun fault was found to be a site where the seismicity rate of smaller earthquakes increased anomalously about 3.4 years before the Kokoxili earthquake. We analyze this anomalous increase in seismicity rate and conclude that it was a significant precursor of the Kokoxili earthquake. The cases in this study suggest that rupture gaps on a great inland strike-slip fault zone could be sites of potentially major or great earthquakes, or sites of precursory seismicities, emerging prior to major or great earthquakes on the same fault zone.

Keywords: Kokoxili earthquake; Kunlun fault; Seismic gap; Precursory seismicity

1. Introduction

The Kokoxili earthquake of surface-wave magnitude (M_s) 8.1 occurred on 14 November, 2001, as the greatest earthquake on mainland China since 1951. It occurred on the lake Kusaihu segment of the Kunlun fault (also named the east Kunlun fault zone) and produced a 426-km-long rupture zone (Xu et al., 2002a,b). Our interest is on the backgrounds of seismic activities along and surrounding the Kunlun fault before the 2001 earthquake, including strong and major earthquakes along the fault in the past 100 years or more, as well as the anomalous seismicities of smaller earthquakes in the years and decades before the 2001 earthquake.

Investigation of anomalous seismicity has been an important aspect of earthquake forecast research. Some cases have shown that anomalous seismicity patterns exist, and even time-variations of anomalous seismicity rates, that are medium-short term precursors that emerge before many major earthquakes (e.g. Wiemer and Wyss, 1994; Wyss and Habermann, 1988; Wyss and Wiemer, 2000). There have been several reports about anomalous seismicity patterns of strong and major earthquakes in western China and its surroundings in the long-term and medium-long term stages before the 2001 earthquake, and about seismicity quiescence and increase patterns of $M_s \geqslant 5$ earthquakes for over 10 years before the 2001 earthquake (Sun and Cao, 2003; Liu et al., 2003; Dong, 2003). The latter suggest medium-long term and medium-term precursors. So far, however, there have been fewer reports about the time variation for anomalous seismicity of smaller earthquakes on and near the Kunlun fault that

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would be the medium to short-term precursor of the 2001 earthquake.

Unlike the above-mentioned studies on anomalous seismicity patterns in a great region before the 2001 earthquake, this study intends to pay more attention to seismicities closely related to the Kunlun fault. On the basis of combined data from historical earthquakes, geological investigations of recent earthquake ruptures, and modern recording of earthquakes, we try to determine the along-fault distribution of earthquake ruptures produced over the last over 100 years, and analyze the position of the 2001 rupture of the Kokoxili earthquake in the distribution. We then investigate the regional seismicity patterns of $M_s \geqslant 5$ earthquakes on and surrounding the Kunlun fault for the decades preceding the 2001 earthquake. We also investigate the time-variation of seismicity of smaller earthquakes on the fault during the period 1990–2003, and its implication as a precursor of the 2001 earthquake.

2. Earthquake ruptures and seismic gaps along Kunlun fault

The WNW to nearly EW-trending Kunlun fault is an active strike-slip fault that borders the active tectonic blocks in the Qinghai-Tibetan Plateau (Fig. 1). It has a total length of about 1800 km and mainly exhibited left-lateral motion during the late Quaternary (Meyer et al., 1998; Van-der-Woerd et al., 1998, 2000; Xu et al., 2002a,b; Zhang et al., 2003). The long-term slip rates of the fault have been estimated to be 11–12 mm/yr along the mid-western portion for the last ~40,000 years (Van-der-Woerd et al., 1998, 2000) and about 7 mm/yr along the eastern portion for the last ~13,000 years (Li et al., 2004).

The western portion of the Kunlun fault, west of the Kunlun Mt. Pass, extends through Kokoxili, the largest wasteland on the Qinghai-Tibetan Plateau. The mid-eastern portion of the fault extends through a slightly inhabited pasture area on the plateau between the Kunlun Mt. pass and the town of Maqu (Fig. 1). Along these two fault segments, strong and major earthquakes occurred during and after 1902 are able to have been recorded by instruments and documents (Department of Earthquake Disaster Prevention, China Earthquake Administration, 1995; Department of Earthquake Disaster Prevention, China Earthquake Administration, 1999; Institute of Geophysics, China Earthquake Administration, and Institute of Historic Geography, Fudan University, 1990). However, near the eastern end of the fault, the earliest records of destructive earthquakes date back to the 186 BC event with a magnitude 6–7 near Wudu, Gansu province, and the 638 AD event of magnitude $5\frac{3}{4}$ near Songpan, Sichuan province. An analysis of historical seismic data suggests that the area near the eastern end of the Kunlun fault has a complete record of $M_s \geqslant 6.5$ earthquakes for at least the last 300 years (Department of Earthquake Disaster Prevention, China Earthquake Administration, 1995; Institute of Geophysics, China Earthquake Administration, and Institute of Historic Geography, Fudan University, 1990).

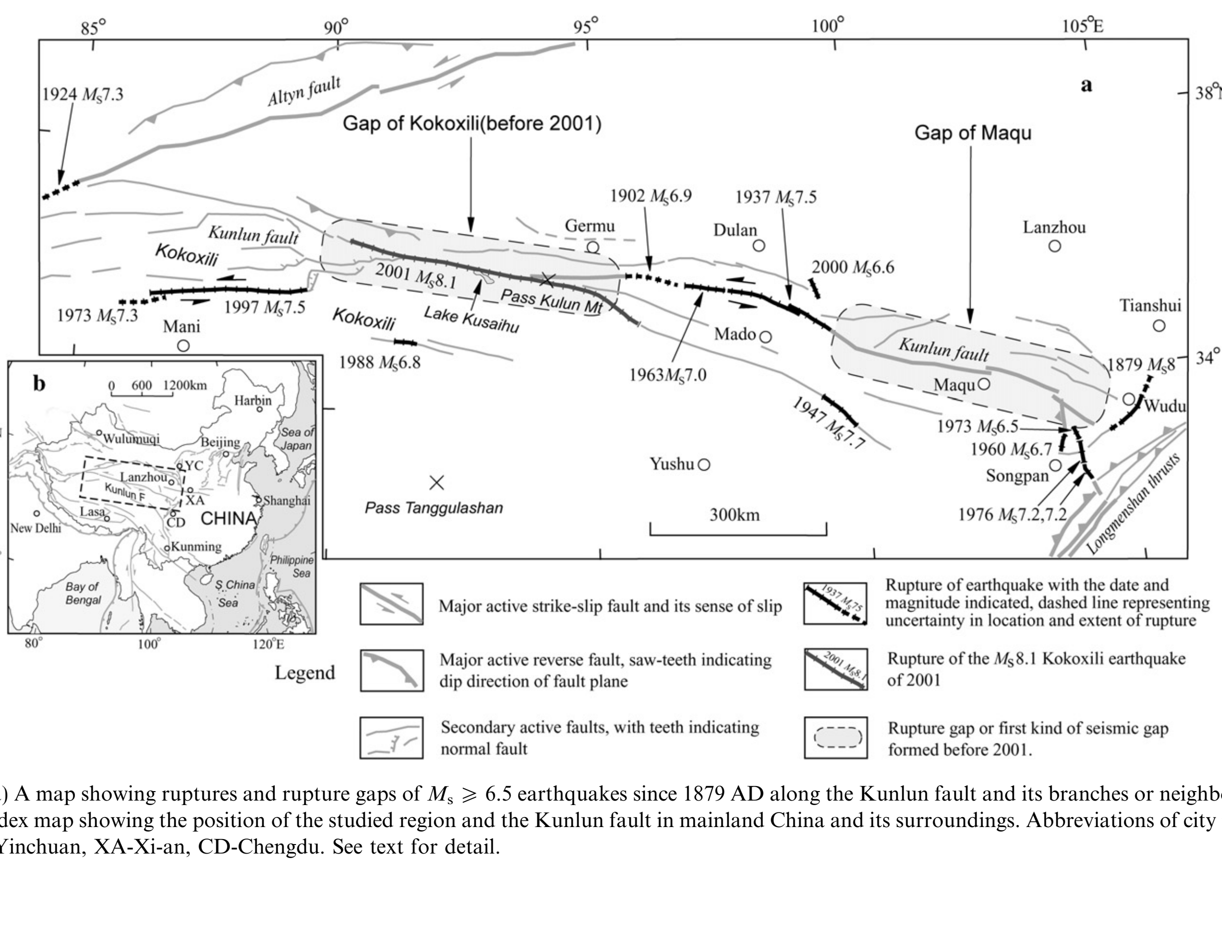

Fig. 1. (a) A map showing ruptures and rupture gaps of $M_s \geqslant 6.5$ earthquakes since 1879 AD along the Kunlun fault and its branches or neighbor faults. (b) An index map showing the position of the studied region and the Kunlun fault in mainland China and its surroundings. Abbreviations of city names in (b): YC-Yinchuan, XA-Xi-an, CD-Chengdu. See text for detail.

On the basis of data from literal records of earthquake destruction, instrument recordings of recent and modern earthquakes, and geological surveys for surface rupture of earthquakes, we have drawn a map showing the distribution of $M_s \geqslant 6.5$ earthquake ruptures on and near the Kunlun fault for the period since 1879 AD (Fig. 1a). Rupture events with $M_s < 7$ that occurred between 1879 and 1902 are probably incomplete, but may not affect our analysis that focuses on the $M_s \geqslant 7$ rupture distribution. In addition, earthquake magnitudes used in this study are from Chinese earthquake catalogs (i.e. Department of Earthquake Disaster Prevention, China Earthquake Administration, 1995, 1999; and the Earthquake Catalog of China Seismic Networks).

Three types of data are used to determine the positions and extent of the ruptures in Fig. 1a: (1) Geographic distributions of areas that were severely damaged during earthquakes are used for five ruptures: the 1879 (M_s8), 1924 (M_s7.2), 1960 (M_s6.7), 1963 (M_s7.0) and 1973 (M_s6.5) earthquakes. The data are available from publications by the Department of Earthquake Disaster Prevention, China Earthquake Administration (1995); Department of Earthquake Disaster Prevention, China Earthquake Administration (1999), and Institute of Geophysics, China Earthquake Administration, and Institute of Historic Geography, Fudan University (1990). The position of the central section of the 1879 rupture inferred from the corresponding extent of the damaged area has been confirmed by a recent geological survey by Hou et al. (2005). (2) Aftershock distributions are used for ruptures of the 1973 (M_s7.3), 1976 (two M_s7.2) and 2000 (M_s6.6) earthquakes. The aftershock data are mainly from the Earthquake Catalog of China Seismic Networks, and partly from Jones et al. (1984) for the 1976 (two M_s7.2) events. Among these ruptures, the 1973 (M_s7.3) event is inferred from the aftershock distribution that was not well located, and has uncertainties in its position and extent. (3) Information from geological surveys or investigations is used in locating the other ruptures. Among them, data for the 1937 M_s7.5 rupture and the 1947 M_s7.7 rupture are from two maps by Liu et al. (1996) and Zhang et al. (1996), respectively. Information on the 1988 M_s6.8 rupture is from a report by Wu et al. (1994). The 1997 M_s7.5 rupture and the 2001 M_s8.1 rupture are located from the InSAR analysis by Peltzer et al. (1999) and from the field investigations by Xu (2000) and Xu et al. (2002a,b). The earlier instrument records for the 1902 M_s6.9 event located it at latitude 36.0°N and longitude 96.0°E, west of the town of Dulan, Qinghai province, and several tens of kilometers away from the major Kunlun fault. However, in their field investigation, Liu et al. (1996) discovered a relatively old surficial rupture belt of unknown-age west of the 1937 (M_s7.5) and 1963 (M_s7.0) ruptures along the major fault, and inferred that it was produced during the 1902 earthquake. We therefore relocate the 1902 rupture on the major fault west of the 1937 and 1963 ruptures (Fig. 1a) with uncertainty in its extent.

It can be seen from Fig. 1a that at least eight $M_s \geqslant 7$ earthquakes successively ruptured the major Kunlun fault and some nearby branch faults in the period from 1879 to 2000. Four of them, the 1902 M_s6.9 (considered roughly as M_s7), 1937 M_s7.5, 1947 M_s7.7 and 1963 M_s7.0 earthquakes ruptured the mid-eastern portion of the fault between longitudes 95°E and 100°E. At least two events, the 1973 M_s7.3 and 1997 M_s7.5 earthquakes, ruptured the western portion of the fault along the southern branch known as the Margaichaka fault (Xu, 2000) between longitudes 85°E and 89°E. Moreover, near the eastern end of the fault around longitude 105°E, the 1879 earthquake of M_s8.0 ruptured a NE-trending left-lateral reverse fault (Hou et al., 2005) that could be a surficial trace of buried thrusts trending nearly perpendicular to the Kunlun fault (Duan, 2002). Two 1976 M_s7.2 earthquakes ruptured a left-lateral reverse fault, the NNW-trending Huya fault (Jones et al., 1984) that appears to be a branch-out of the Kunlun fault near its southeastern end (Fig. 1a).

As shown in Fig. 1a, the array of earthquake ruptures produced during the period from 1879 to 2000 suggests clearly that, before 2001, there were two seismic gaps along the Kunlun fault, the Kokoxili gap between longitudes 89°E and 95°E and the Maqu gap between longitudes 100°E and 105°E. The 2001 Kokoxili earthquake of magnitude 8.1 occurred only on the Kokoxili gap and produced a 426-km-long rupture zone (Xu et al., 2002a) that encompassed about five-sixths of the gap's extent (Fig. 1a).

There has been little information about the last major or great earthquakes in both the Kokoxili gap before the 2001 rupture and the Maqu gap due to the short historical record. However, in field investigations on the western portion of the Kunlun fault the third author (Xu X.) found the remains of an older surficial rupture belt that is recognizable at places along the 2001 rupture zone. This suggests that on the Kokoxili gap fault segment, the last rupture of a major or great earthquake before 2001 occurred in an unknown year not long before the beginning of the instrument record (about in 1902). In another field investigation in 2005, the first and third authors (Wen X. and Xu X.) and their colleagues found a surficial rupture belt of unknown-age on the western section of the Maqu gap. The rupture extends along the Kunlun fault roughly from the eastern end of the 1937 rupture to somewhere west of Maqu, with an observed maximum coseismic left-lateral slip of about 5 m. It must be the last earthquake rupture on the western section of the Maqu gap and may have formed during the last half of the 19th century because it is still clearly visible and because local Tibetan herdsmen describe a very strong shock in the area more than 100 years ago. The investigation in 2005, however, did not find any remains of surficial ruptures on the eastern section of the Maqu gap, east of Maqu, suggesting that the last major or great earthquake on the eastern section of the Maqu gap could have occurred earlier than that on the west section of the gap.

3. Background seismicity patterns in decades before the 2001 earthquake

The quiescence of seismicity is sometimes a precursor to major or great earthquakes (e.g. Wyss and Habermann, 1988; Wyss and Martirosyan, 1998; Wiemer and Wyss, 1994). Several investigations have reported patterns of regional seismicity quiescence for $M_s \geqslant 5$ earthquakes before the 2001 Kokoxili earthquake, and the corresponding background seismic gaps in various versions of developing periods and geographic distributions. Liu et al. (2003) found that a $M_s \geqslant 5$ seismic gap developed from 1986 to 2001 in the area east of the epicenter of the potential 2001 earthquake, resembling a nearly E–W-trending and about 750 km-long ellipse. Sun and Cao (2003) thought that a $M_s \geqslant 5$ seismic gap developed from 1989 to 2001 that centered about 250 km eastward from the epicenter of the potential 2001 earthquake. In the version given by Dong (2003), a $M_s \geqslant 5$ seismic gap is thought to have developed between 1994 and 2000 and had a geographic distribution similar to that of Sun and Cao (2003).

We are doubtful whether the $M_s \geqslant 5.0$ seismic gaps mentioned above are representative of the medium-term precursory quiescence pattern of seismicity prior to the 2001 Kokoxili earthquake. In this section, we intend to study further the possible seismicity quiescence and corresponding patterns in the region near and surrounding both the Kunlun fault and the potential source of the 2001 Kokoxili earthquake.

The 2001 Kokoxili earthquake occurred in the central to northern Qinghai-Tibetan Plateau, a region of poor seismic detectability. In this region, strong and major earthquakes in the period from 1902 to the middle 1950s have been cataloged mainly from instrumental records from several stations in China along with some contemporaneous international stations, and from relevant geological investigations and literal records. Records for strong earthquakes in the early stage of the period, however, might be somewhat incomplete (Department of Earthquake Disaster Prevention, China Earthquake Administration, 1995; Department of Earthquake Disaster Prevention, China Earthquake Administration, 1999). In the 1950s, 5 of the 12 seismic stations in mainland China were set up in the cities of Yinchuan, Lanzhou, Xi-an, Chengdu and Kunming, respectively, in western China. By 1965, another 10 stations were built in western China, and most of them were distributed in the northwest, north to northeast, and east to southeast of the studied region. Only one (Lasa) was located south of the studied region. By the middle 1960s, smaller earthquakes in the central to northern Qinghai-Tibetan Plateau could have been recorded. With the increase in number of seismic stations, seismic detectabilities have continuously improved in eastern and central China since the late 1960s. However, in the Qinghai-Tibetan Plateau, especially in the central and western parts, the seismic detectability was little improved until the end of the 1970s (Editor Committee of China Earthquake Yearbook, 1990).

We know that for the studied region, only strong and major earthquakes could have been recorded and cataloged during the period from the early 20th century to the middle 1960s. Fig. 2 shows the distribution of $M_s \geqslant 6.0$ earthquakes from 1920 to 1965 in the studied region, and suggests that the activity of strong and major earthquakes on and surrounding the Kunlun fault was intense during those 46 years: two major events of $M_s 7$ and 7.5 occurred on the middle portion of the fault and at least 6 strong events of $M_s = 6.0$–6.2 on and near the western portion (west of the pass Kunlun Mt) of the fault, with the last one in 1959.

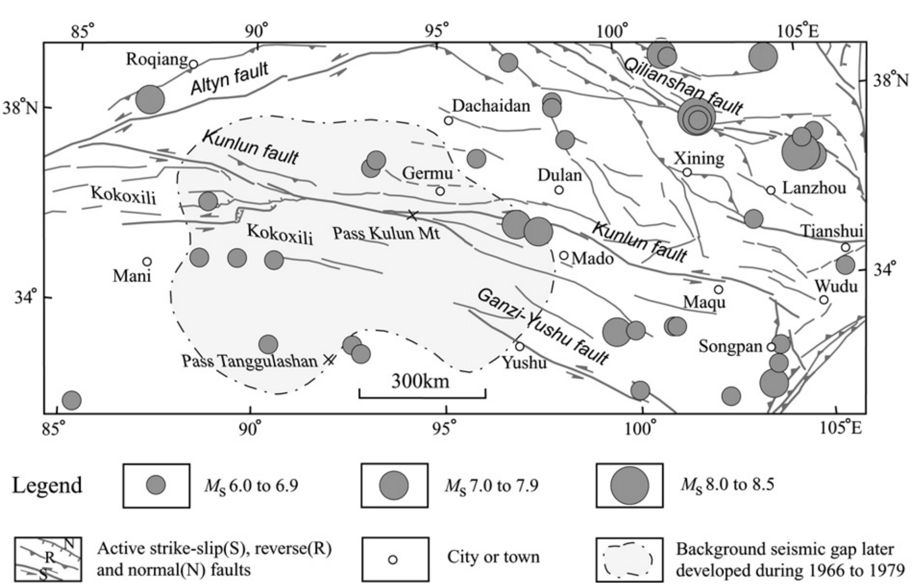

Fig. 2. Distribution of $M_s \geqslant 6.0$ earthquakes recorded in the period from 1920 to 1965 in the studied region. Data are from The Catalogue of Modern Earthquakes of China (Department of Earthquake Disaster Prevention, China Earthquake Administration, 1999).

We also know from the above information that seismic detectability in the studied region improved from 1965 to the end of 1970s, and has been further, but limitedly, improved since the end of 1970s, although it is still poor relative to other regions of China. In order to study the seismicity since the middle 1960s, it is necessary to determine the minimum magnitude of completeness for the area with the least number of seismic stations, between longitudes 85°E and 97°E, and between latitudes 31.7°N and 39.4°N, in the studied region for the period between 1966 and 1999. Using data of the Earthquake Catalog of China Seismic Networks, our analysis suggests that the minimum magnitude of completeness for the selected area and period is round about M_s4.7 (Fig. 3d). Therefore, for the entire studied region centered along the Kunlun fault, we can study seismicity patterns of $M_s \geqslant 5.0$ earthquakes at least for the last 36 years (1966–2001) before the M_s8.1 Kokoxili earthquake of 2001.

Figs. 3a–c display the distributions of $M_s \geqslant 5.0$ earthquakes and corresponding seismic gaps in three various stages of the about 36 years from 1966 to just before the 2001 Kokoxili earthquake. Fig. 3a suggests that no $M_s \geqslant 5.0$ earthquakes occurred on the middle to western portions of the Kunlun fault, and in the area north of the Pass of Tanggulashan in the period at least from 1966 to 1979. By 1979, a background seismic gap, A, formed preliminarily, which essentially should have been a second kind of seismic gap (Mogi, 1979), and had an area of about 43.5×10^4 km^2. Earthquakes that occurred around gap A were mainly between magnitudes 5.0 and 6.8, the largest one being the 1973 M_s7.3 event near Mani, Tibet Autonomous Region, just west of gap A. It is noteworthy, however, that in the 46 years before 1966, at least seven M_s6–6.5 and two M_s7–7.5 earthquakes occurred within the area that later became gap A (Fig. 2), suggesting that the gap formed in an area that had much stronger seismicity before, and was produced from a temporal decrease in seismicity. Therefore, gap A should be a seismic gap with the background of medium-long term precursory seismicity quiescence.

With an increase of $M_s \geqslant 5.0$ earthquakes from 1980 to 1990, gap A from the previous stage changed gradually into two smaller background seismic gaps, B and C. Both of the smaller gaps were adjacent to each other and had

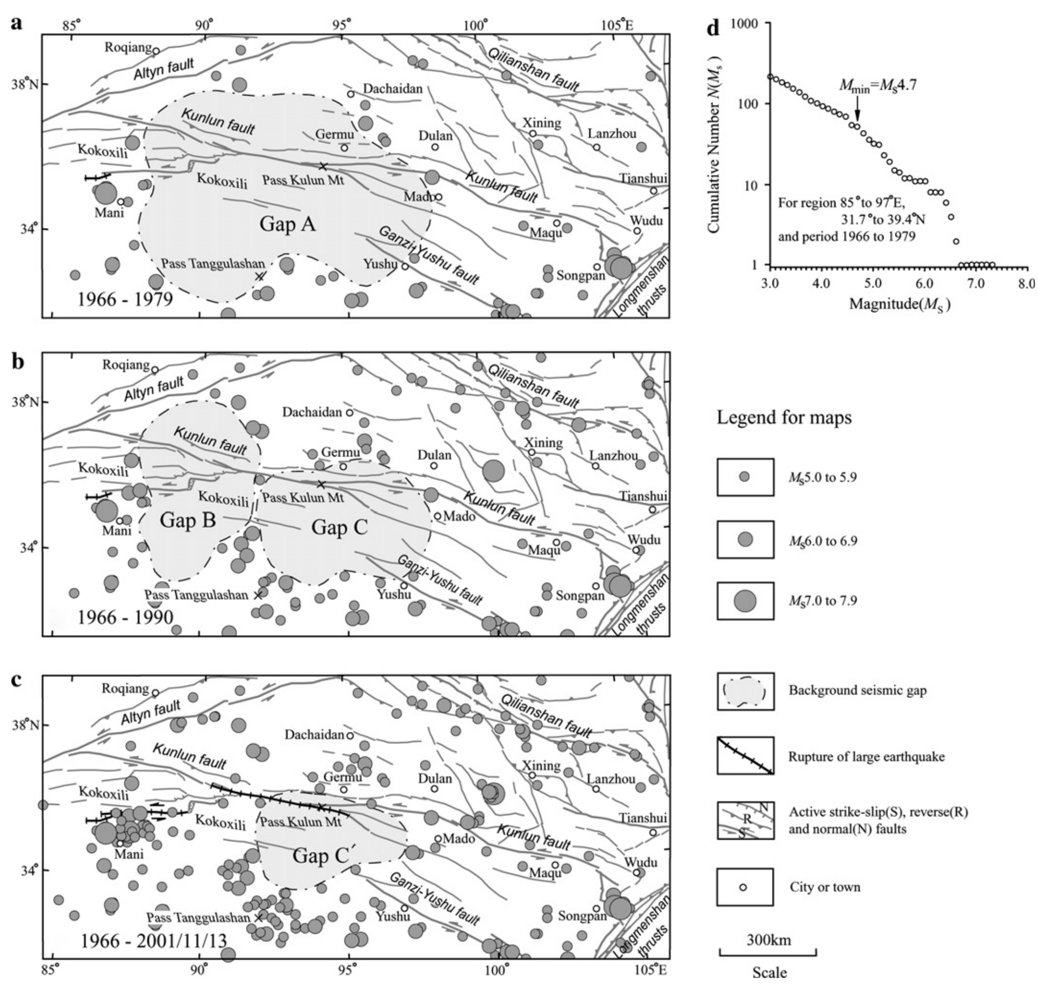

Fig. 3. (a)–(c) are maps of $M_s \geqslant 5.0$ earthquake epicenters in three various periods before the 2001 Kokoxili earthquake, and also show patterns of background seismic gaps in the three periods, 1966–1979, 1966–1990 and 1966 to 13 November, 2001. (d) A magnitude-cumulative frequency relation and the identified minimum completeness magnitude M_{min} in the region of the central and northern Qinghai-Tibetan Plateau for the period 1966 to 1979.

areas of $14.9 \times 10^4\ km^2$ and $16.3 \times 10^4\ km^2$, respectively (Fig. 3b). At this stage, there were also more M_s6.0–6.8 earthquakes surrounding gaps B and C than in the previous stage.

During the approximately 11 years from 1991 to 13 November, 2001, gap B disappeared gradually after an increase of local seismicity, including the occurrence of the M_s7.5 Mani, Tibet Autonomous Region, earthquake of 1997 (Fig. 3c). About half of the 1997 rupture occurred in gap B, and the other half extended to the west of gap B. In the meantime, gap C contracted gradually to an even smaller area of $10.6 \times 10^4\ km^2$, due to the increasing seismicity in the south and east of the previous gap C. We mark the contracted gap C as gap C′. During the 2001 Kokoxili earthquake, about two-thirds of the rupture occurred in gap C′ and the other one-third in the previous gap B west of the gap C′ (Fig. 3c).

We conclude that those $M_s \geqslant 5.0$ seismic gaps identified by previous studies (Liu et al., 2003; Sun and Cao, 2003; Dong, 2003), centered in the east of the potential epicenter of the 2001 earthquake 7 or 15 years before the earthquake, were equivalent to both gap C (in its later stage) and gap C′ identified in this research and shown in Figs. 3b and c.

Although the Kokoxili and the Maqu rupture gaps (or first-kind of seismic gaps) existed on the Kunlun fault before 2001(Fig. 1a), only the Kokoxili gap experienced the formation and evolution of a background seismic gap (or second-kind of seismic gap) for at least 36 years (Fig. 3). The 2001 earthquake of M_s8.1 occurred just on the Kokoxili gap.

Studies of the southern San Andreas fault and the 1992 Landers earthquake faults, California, suggest that aseismic regions surrounding major fault planes are possibly locked and may be sites of future major or great

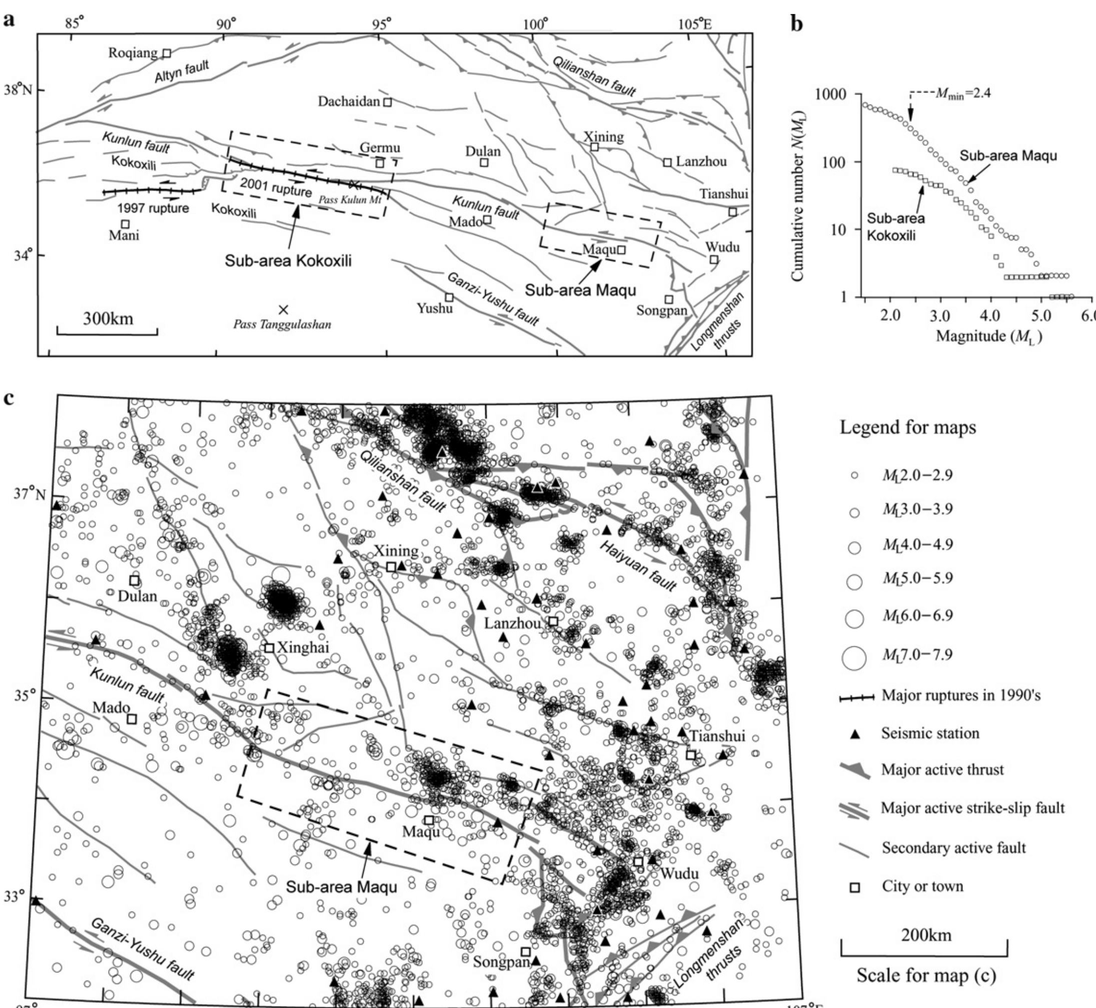

Fig. 4. (a) A map showing two rectangular sub-areas along the Kunlun fault for minimum completeness magnitude analyses of earthquakes recorded since 1990. Both sub-areas are designed to be on the rupture gap of Kokoxili before 14 November, 2001, and on the rupture gap of Maqu, respectively. (b) Magnitude-cumulative frequency relations and identified minimum completeness magnitudes for the two rectangular sub-areas shown as in (a) for seismic records from 1 January, 1990, to 13 November, 2001. (c) A map showing distributions of $M_L \geqslant 2.0$ earthquakes and seismic stations in the region of the eastern portion of the Kunlun fault and its surroundings for the period from 1990 to 2003. The rectangle shows the Maqu sub-area in which time-variations of seismicity are studied and shown as Fig. 5.

earthquakes (Hauksson and Jones, 2000). This might explain the seismicity patterns shown in Figs. 3a–c: the formation of the background seismic gap A and its evolution from A to C suggest that, in most of the 36 years from 1966 to 2001, the seismicity of $M_s \geqslant 5.0$ earthquakes in the region on and surrounding the fault segment of the potential 2001 rupture was low, implying that the fault segment was probably near-fully locked and therefore almost aseismic (without $M_s \geqslant 5.0$ events). However, in the last decade before the potential 2001 rupture, several smaller-scale slips or breaks (5-magnitude earthquakes) occurred in the area on and near the locked fault segment and resulted in gap C contracting into gap C′, implying greater stress buildup in this area close to the potential 2001 rupture.

4. Temporal variation of seismicity in the Maqu gap

To determine whether anomalous seismicities of smaller earthquakes, which possibly belong to precursors of the 2001 Kokoxili earthquake, existed along the Kunlun fault before the earthquake, we select two rectangular sub-areas on the fault for seismicity analysis (Fig. 4a). They are designed to be on the rupture gap of Kokoxili before 2001 and the rupture gap of Maqu (see Fig. 1), respectively. Basing on the Earthquake Catalog of China Seismic Networks, a completeness analysis of seismic data for the two sub-areas suggests that only a very small number of smaller earthquakes in the sub-area of Kokoxili could have been recorded from 1 January, 1990, to 13 November, 2001, due to poor detectability (Fig. 4b). However, the sub-area of Maqu and its surroundings have much better seismic detectability (although not good enough) (Fig. 4c), where almost one thousand earthquakes have been recorded in the period from 1990 to 2003, with a minimum completeness magnitude $M_{min} = M_L$ 2.4 (Fig. 4b). In this section we investigate the temporal variation of seismicity for the Maqu sub-area. The western border of the Maqu sub-area is about 470 km away from the eastern end of the 2001 rupture of the Kokoxili earthquake (Fig. 4a).

From the Earthquake Catalog of China Seismic Networks, we selected $M_L \geqslant 2.4$ earthquakes in the Maqu sub-area for the period from 1990 to 2003. Three $M_L = 2.4$–3.8 aftershocks were removed from the original data for two of the biggest mainshocks in the period, the M_L 5.6 earthquake (at 34°35′ N, 101°28′ E) of September 27, 1999, and the M_L 5.5 earthquake (at 34°31′ N, 99°52′ E) of November 26, 1999. We eliminate the aftershock data by Maeda's criteria (Maeda, 1996), on which, aftershocks

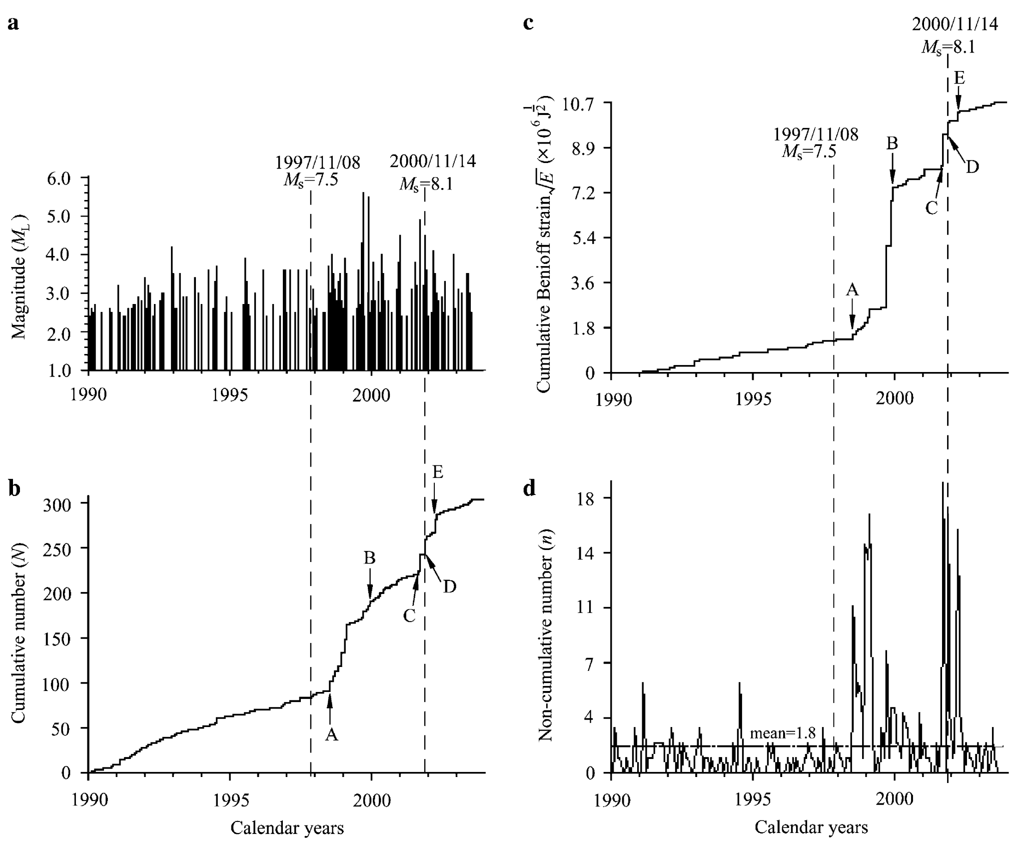

Fig. 5. Diagrams showing time-variations of seismicity from 1990 to 2003 in the Maqu sub-area on the eastern portion of the Kunlun fault. (a) An M–t chart. (b) A diagram of cumulative earthquake number versus time. (c) A diagram of cumulative Benioff strain release versus time. (d) A diagram of non-cumulative earthquake number versus time. Earthquake number and Benioff strain on (b), (c) and (d) are accounted for unit time (month). The vertical dashed-lines indicate dates of two major or great earthquakes on the Kunlun fault in 1997 and 2001. See text for detail.

that have the spatial and temporal relations, as follows, with a mainshock, will be to eliminated from the original data:

Epicentral distance L (in km) from a mainshock: $L < 10^{(0.5M_m - 1.8)}$,

Time t (in days) from occurrence of a mainshock: $t < 10^{(0.17+0.85(M_m-4.0))/1.3} - 0.3$,

Mainshock and aftershock magnitudes, M_m and M_a: $M_a < M_m - 1.0$ $M_a < M_m - 1.0$.

Thus, we have a seismic data set of over 300 $M_L \geqslant 2.4$ earthquakes, which permits analysis of seismicity rates and their temporal variations in the Maqu sub-area (Fig. 5).

As shown in Fig. 5, seismicity rates in the Maqu sub-area are mainly described with the monthly cumulative number, the non-cumulative number, and the cumulative Benioff strain of earthquakes. The Benioff strain (Benioff, 1951) is equivalent to the square root of the seismic energy E (in Joule) released, and have been calculated using the formula $\log E = 4.8 + 1.5M$ from magnitude M (Gutenberg and Richter, 1954). The corresponding average seismicity rates and their temporal variations during various periods or stages between 1990 and 2003 are summarized in Table 1. We know from Fig. 5 and Table 1 that in the period from 1990 to July 1998 (a period on left of point A in Fig. 5), the cumulative numbers and Benioff strain release grew at low and relatively invariable rates of 0.9 times/month and 0.13×10^5 Joules$^{1/2}$/month, respectively. Compared with those in the following stages, this period seems to have had normal seismicity rates, implying there was no anomalous seismicity at least in the Maqu sub-area before July, 1998, and before the 1997 M_s7.5 Mani, Tibet Autonomous Region, earthquake that occurred on the southern branch of the western portion of the Kunlun fault (Fig. 1a).

However, in the Maqu sub-area, a 3.4-year-long anomalous increase in the seismicity rate occurred between July, 1998, and December, 2001 (a period from points A to D in Fig. 5). This includes two sub-stages of rates increasing saliently, shown between points A and B, and C and D in Fig. 5, and one sub-stage of rates decreasing temporally, shown between points B and C in Fig. 5 (also see Table 1). The M_s8.1 Kokoxili earthquake on November 14, 2001, occurred at the end of this period. Following another short period of decreasing rates (between points D and E in Fig. 5), the seismicity rate returned to normal (right side of point E in Fig. 5). In the first stage of the 3.4-year-long period of anomalous seismicity rate increase, the most prominent anomalous events in the sub-area are two destructive earthquakes of M_L 5.6 and M_L 5.5 that occurred in September and November, 1999. All these suggest that the increase of seismicity rate in the Maqu sub-area during the period from July, 1998, to December, 2001 (between points A and D in Fig. 5) was closely related to the 2001 Kokoxili earthquake. Thus, about 3.4 years before the 2001 Kokoxili earthquake, an obvious seismicity precursor took place in the rupture gap of Maqu on the eastern portion of the Kunlun fault.

Table 1
Average seismicity rates and their variations during different periods or stages between 1990 and 2003 in the Maqu sub-area

Time periods or stages	Periods or stages marked on Fig. 5	Average seismicity rates (for $M_L \geqslant 2.4$)		Variation and anomaly of seismicity rates	
		Monthly earthquake numbers (times)	Monthly Benioff strain release ($\times 10^5$ J$^{1/2}$)		
January 1990 to July 1998	Left of A	0.90	0.13	Normal	
July 1998 to December 1999	Between A and B	6.3	3.8	Salient number increasing and strain-release accelerating	Anomalous increase in seismicity
December 1999 to September 2001	Between B and C	2.3	0.41	Number and strain-release decreasing temporarily	
September 2001 to November 2001	Between C and D	17.3	7.87	Quick number increasing and strain-release accelerating	
November 2001 to March 2002	Between D and E	4.77	0.92	Number decreasing and strain-release decelerating	
March 2002 to December 2003	Right of E	0.97	0.19	Normal	

Note: J = Joule.

5. Discussion

Anomalies on time-variation curves of seismicity rates have been regarded as indicators of changes in crustal stress (e.g. Kato and Wiemer, 1998; Kato and Hirasawa, 1999; Wyss and Wiemer, 2000; Bowman and King, 2001). In our case, the anomalous increase of seismicity rates in the period between points A and D in Fig. 5 can be inferred to be a response to stress loading. Our preliminary inference is that, as a rupture gap or seismic gap of the first kind, the Maqu sub-area on the eastern portion of the Kunlun fault should have already had a high stress build-up, so that the sub-area itself was/is sensitive to temporal stress-loading from the same fault zone. The anomalous increase in seismicity was in response to the stress-loading, especially around 3.4 years before the 2001 Kokoxili earthquake. Although the mechanism of such stress loading still remains unknown, a study by Kato and Hirasawa (1999) suggests that aseismic sliding along a fault segment may cause stress variation and may affect seismicities on other segments of the fault. We do not know exactly whether aseismic sliding occurred along the potential 2001 rupture segment of the Kunlun fault about 3.4 years prior to the rupture, but we notice that Yang et al. (2003) have distinguished pre-slipping or slow-slipping events on the potential 2001 rupture segment from waveform analysis of long-periodic waves recorded at several stations in Xinjiang, that started about 3.5 days before the rupture and lasted for about 48 h. So, it seems reasonable to deduce that slow-slipping or aseismic sliding along the potential 2001 rupture segment of the Kunlun fault, and perhaps neighboring fault-segments, is one of the probable causes that produced the anomalous increase of seismicity in the rupture gap of Maqu about 3.4 years before the 2001 Kokoxili earthquake.

6. Conclusions

Before the 2001 Kokoxili earthquake, two rupture gaps (or first kind of seismic gaps), the Kokoxili and the Maqu, existed on the Kunlun fault. The region on and surrounding the Kokoxili gap experienced a seismicity quiescence of $M_s \geqslant 5.0$ earthquakes and formation of a background seismic gap (or second kind of seismic gap) for at least 36 years from 1966 to 2001. The 2001 Kokoxili earthquake ruptured only the Kunlun fault segment of the Kokoxili gap.

About 3.4 years before the 2001 Kokoxili earthquake, an anomalous increase of seismicity rates took place in the other rupture gap, the Maqu, on the eastern portion of the Kunlun fault, and can be regarded as a significant seismicity precursor of the 2001 Kokoxili earthquake.

This study suggests that rupture gaps on an active strike-slip fault zone within an intraplate tectonic environment like mainland China could be sites of potentially major or great earthquakes, or sites of precursory seismicity prior to major or great earthquakes.

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