二、昆仑山 8.1 级地震破裂

昆仑山走滑断裂是青藏高原北部的重要活动断裂和地震构造带，构成昆仑活动地块与可可西里活动地块的边界。沿昆仑山活动断裂百余年来曾发生 1971 年 3 月 24 日托索湖 6.8 级地震、1963 年 4 月 19 日阿拉克湖东 7 级地震、1937 年 1 月 7 日花石峡 7.5 级地震和 1902 年 11 月 4 日阿拉克湖西 7 级地震。2001 年 11 月 14 日沿昆仑山走滑断裂西侧库赛湖活动断裂发生 8.1 级强烈地震，称为昆仑山 8.1 级地震或昆仑山口西 8.1 级地震，宏观震中位于库赛湖附近，仪器记录震中位于布喀达坂峰地区。昆仑山 8.1 级强烈地震在地表产生长达 350-426km 的地震破裂，穿切青藏公路、通讯光缆、青藏铁路施工便道等工程设施，导致昆仑山雪崩和西大滩房屋破坏（中国地震局，2003；吴珍汉等，2005），引起国内外地质学家的广泛关注。

昆仑山 8.1 级地震破裂主要由北西西向左旋走滑主地震破裂、北东东向张扭性分支地震破裂、地震鼓包、张扭性裂陷规律性组合而成（吴中海等，2004）。地震鼓包长 5-30m，宽 1-15m，高 0.2-2m。地震裂陷宽 30-50m、长 25-40m，深 0.5-6m。在青藏公路西侧，河流高河漫滩、河床、山麓斜坡上的小型冲沟被地震断裂左旋错动 2.6-4.8m，人工水坝被断层左旋错动 3.2m。在青藏公路东侧，光缆和铁路施工便道被地震断裂左旋错动 3.5m，河流阶地和河漫滩各左旋错动 4.3m 和 3m。地震破裂的空间产状、破坏方式、工程危害与地表地质状况、岩土结构组成、工程设施力学性质存在密切关系。

PART 2 SEISMIC FRACTURES OF THE Ms 8.1 KUNLUN EARTHQUAKE

The Kunlun strike-slip fault, a boundary between Kunlun and Hohxil blocks, is a major active fault and an important seismic zone, along which occurred Ms 6.8 Tuosuohu earthquake on March 24, 1971, Ms 7.0 eastern Alaghu earthquake on April 19, 1963, Ms 7.5 Huoshixua earthquake on January 7, 1937, Ms 7.0 western Alaghu earthquake on November 4, 1902, and Ms 8.1 Kunlun (Kusaihu) earthquake on November 14, 2001. The epicenter of Ms 8.1 Kunlun earthquake is located in Kusaihu according to seismological survey or near Bukedaban Peak according to seismograph records (China Seismological Bureau, 2003). The Ms 8.1 Kunluan earthquake formed seismic fracture zone as long as 350~426km, resulted in ~4m offset of highway, communication optical cable and railway line and avalanche of south Kunlun Mts., and destructed some buildings in Xidatan, however no one was killed by this very intense earthquake (China Seismological Bureau, 2003; Wu et al., 2005).

Seismic fracture zone of Ms 8.1 Kunlun earthquake is consisted of NWW-trending strike-slip major fractures, NEE-trending en-echelon branch fractures, pressure ridges, pull-apart basins and seismic depressions. Pressure ridges are 5~30m long, 1~15m wide and 0.2~2m high, and seismic depressions are 25~40m long, 30~50m wide and 0.5~6m deep in both sides of the Golmud-Lhasa Railway and Highway. In west side of the Highway, sinistral offset of dam is 3.2m and sinistral offset of stream ranges in 2.6-4.8m. In east side of the Highway, sinistral offset of optical cable and road is 3.5m and stream offset reaches to 3-4.3m. Seismic fracture pattern and intensity of destruction and hazard of the Ms 8.1 Kunlun earthquake are closely related to surface geological condition, rock type, soil structures and mechanical properties of engineering facilities.

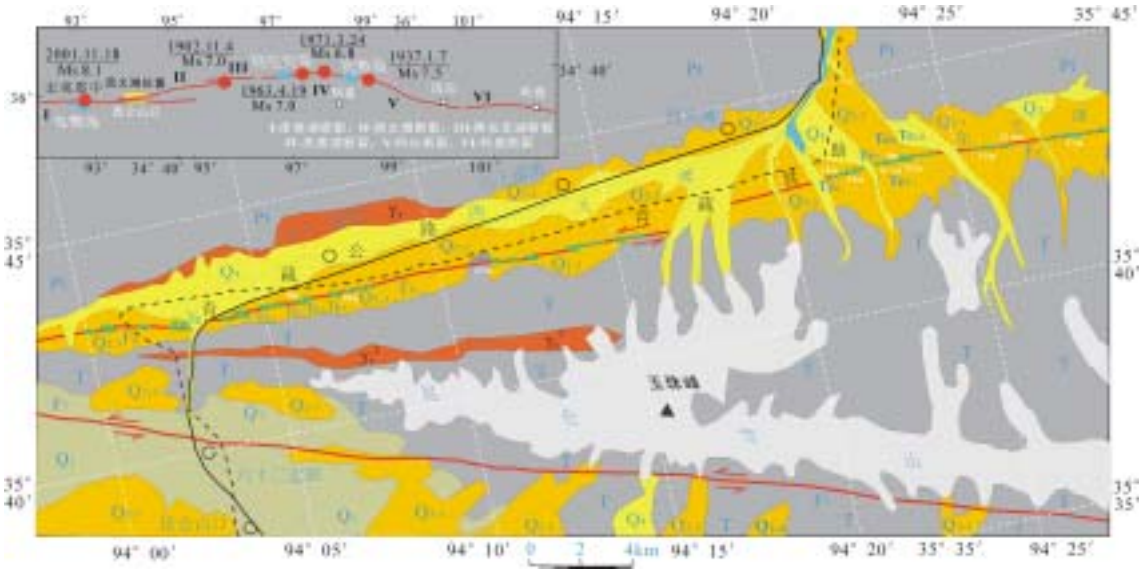


图 8 昆仑山南部活动断裂分布图

图中，F_6 为西大滩左旋走滑断裂，F_7 为昆仑山南缘（库赛湖）左旋走滑断裂，两者斜接复合构成昆仑山活动断裂（西段）。沿西大滩走滑断裂（F_6），全新世早期（5000-10000 年）曾发生 3-4 期 Ms≥7-8 强烈地震，形成串珠状斜列分布的多期地震鼓包和地震破裂。沿昆仑山南缘库赛湖走滑断裂（F_7），2001 年 11 月 14 日发生 8.1 级强烈地震，形成长达 350-420km 的地震破裂。TC_1~TC_{10} 表示横切地震鼓包和地震破裂的探槽位置，4m、9m、18m、27m 等表示水系、冲沟和阶地的左旋位移

Fig.8 Sketch map of active faults in south Kunlun Mts. Explanation: F_6-Xidatan sinistral strike-slip fault; F_7-marginal fault of south Kunlun Mts. i.e. Kusaihu sinistral strike-slip fault. Faults F_6 and F_7 are Juxtaposed to constitute west segment of East Kunluan fault. At least 3~4 earthquakes with Ms≥7~8 occurred along the Xidatan strike-slip fault (F_6) in Early Holocene (5~10kaB.P.), formed multiphase of pressure ridges and seismic fractures. Along Kusaihu strike-slip fault (F_7) in south margin of Kunlun Mts. occurred the Ms 8.1 Kunlun earthquake in November 14, 2001 and formed seismic fracture zone of 350~420km long. TC_1~TC_{10} show locations of trenches perpendicular to pressure ridges and seismic ruptures. And 4m, 9m, 18 and 27m etc. indicate sinistral offsets of stream, gully and terrace at different localities.

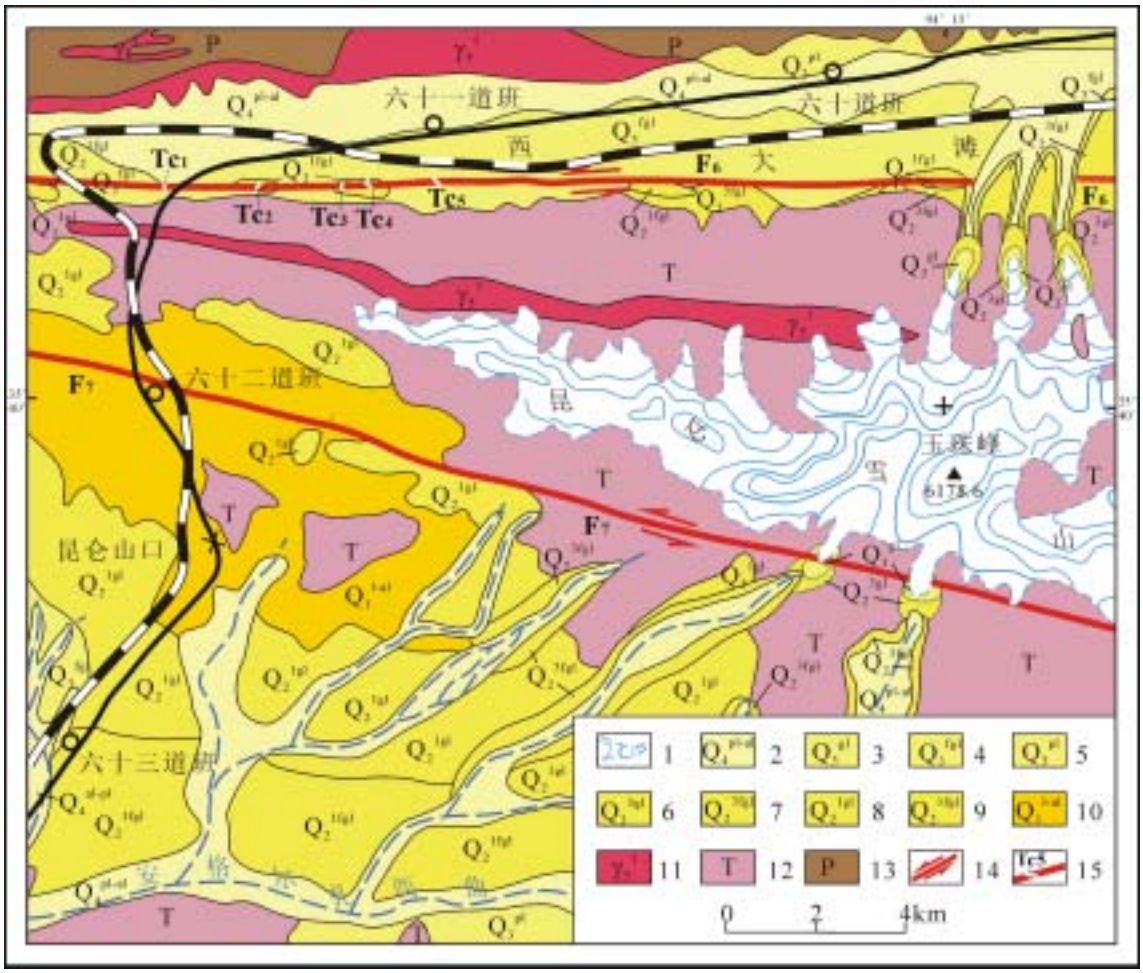


图 9 昆仑山口第四纪地质图

图例说明：1-现代冰川；2-全新世冲洪积物；3-晚更新世玉珠峰冰期冰碛；4-晚更新世玉珠峰冰期冰水沉积；5-晚更新世洪积物；6-中更新世晚期垭口冰期冰碛；7-中更新世晚期垭口冰期冰水沉积；8-中更新世早期唐古拉冰期冰碛；9-中更新世早期唐古拉冰期冰水沉积；10-早更新世羌塘组湖相-三角洲相沉积；11-三叠纪花岗岩；12-三叠系；13-元古界；14-左旋走滑断裂；15-沿断裂分布挤压脊、探槽位置及编号。

Fig.9 Quaternary geological map of Kunlun Pass and its adjacent areas. Explanation: 1-modern mountainous glacier; 2-Holocene alluvial and fluvial deposits; 3-Late Pleistocene moraine of Yuzhufeng glacial stage; 4-Late Pleistocene glacial-flood or glaciaquatic deposits of Yuzhufeng glacial stage; 5-Late Pleistocene fluvial deposits; 6-late Middle Pleistocene moraine of Yakou glacial stage; 7-late Middle Pleistocene glacial-flood or glaciaquatic deposits of Yakou glacial stage; 8-early Middle Pleistocene moraine of Tanggula glacial stage; 9-early Middle Pleistocene glacial-flood or glaciaquatic deposits of Tanggula glacial stag; 10-Early Pleistocene Qiangtang Formation of lake-delta deposits; 11-Triassic granite; 12-Triassic; 13-Proterozoic; 14-sinistral strike-slip fault; 15-location of pressure ridge and trench as well as trench number.



图 10 昆仑山 8.1 级地震地表破裂

摄于 2001 年 11 月 22 日，镜头向东；地震破裂走向 100°-105°，穿切河床与青藏公路。

Fig.10 View eastward on November 22, 2001 at major seismic rupture zone trending in 100°-105° and sinistral offsets of dam and highway of the Ms 8.1 Kunlun earthquake



图 11 青藏公路东侧昆仑山 8.1 级地震分支与主干破裂

摄于 2001 年 11 月 22 日，镜头向东；分支地震破裂走向 65°-70°，斜列分布，与主地震破裂呈 30°-35°交角。

Fig.11 View eastward on November 22, 2001 at seismic fracture zone trending in 100°-105° and en-echelon branch fractures trending in 65°-70° of the Ms 8.1 Kunlun earthquake in east of the Golmud-Lhasa Railway and Highway



图 12 青藏公路东侧昆仑山 8.1 级地震张扭性分支破裂

摄于 2001 年 11 月 22 日，镜头向东；地表分支破裂宽达 0.1-2.0m，深 0.5-6m，长达 5-50m，部分延长超过 200m。

Fig.12 View eastward on November 22, 2001 at shear-extensional branch fractures of 0.1-2.0m wide, 0.5-6.0m deep and 5-50m long of the Ms 8.1 Kunlun earthquake in east of the Golmud-Lhasa Railway



图 13 昆仑山 8.1 级地震断裂左旋错断青藏公路西侧水坝

摄于 2001 年 11 月 22 日，镜头向西；主地震破裂左旋错断水坝 3.2m。

Fig.13 View westward at 3.2m sinistral offset of dam along major seismic fracture in west of the Highway on November 22, 2001



图 14 青藏公路西侧昆仑山 8.1 级地震主破裂面近水平擦痕

摄于 2001 年 11 月 22 日，镜头向南；主地震破裂面同震擦痕，擦痕侧伏角为 3°-8°，指示昆仑山活动断裂的同震水平走滑运动。

Fig.14 View southward at gentle dipping strialtion on slickenside along a seismic fracture on November 22, 2001, indicating strike-slip faulting during Ms 8.1 Kunlun earthquake



图 15 昆仑山 8.1 级地震破裂左旋错断青藏公路东侧冲沟

摄于 2002 年 6 月，镜头向北。主地震破裂左旋切割、错断昆仑山南缘的河床及现代冲积物，造成 4.7m 的较大同震位移。

Fig.15 View northward at 4.7m sinistral offset of stream along major seismic fracture zone in east of the Railway in June of 2002



图 16 昆仑山 8.1 级地震破裂左旋错断山体与冲沟

摄于 2002 年 6 月，镜头向北。主地震破裂在铁路线附近左旋错断现代冲沟，造成 3-4m 的同震位移。

Fig.16 View northward at 3-4m sinistral offsets of gullies along seismic fracture zone near Golmud-Lhasa Railway line in June of 2006



图 17 昆仑山 8.1 级地震分支破裂切割青藏铁路施工便道

摄于 2001 年 11 月 22 日，镜头向南东。张扭性分支地震破裂左旋错断青藏铁路施工便道，形成宽达 50-120cm 的路面开裂。

Fig.17 View southeastward at sinistral offset of road near Golmud-Lhasa Railway along shear-extensional branch fractures of 50-120cm wide on November 22, 2001

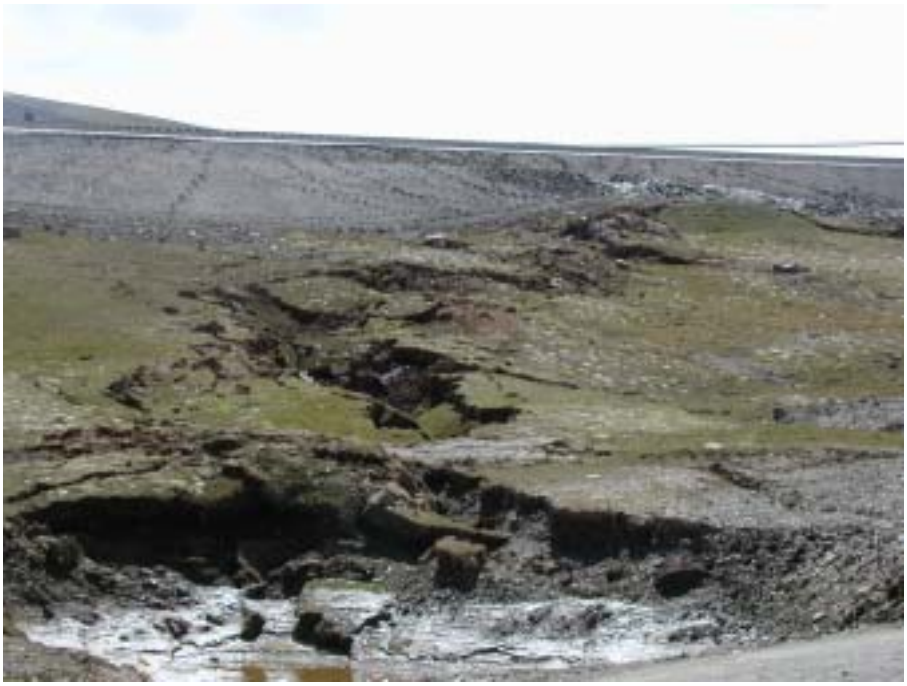


图 18 昆仑山 8.1 级地震鼓包与拉分断陷

摄于 2002 年 7 月，镜头向东；青藏铁路以路基通过地震破裂带。

Fig.18 View eastward at pressure ridge, seismic fractures and pull-apart pond in west of the Railway in July of 2002

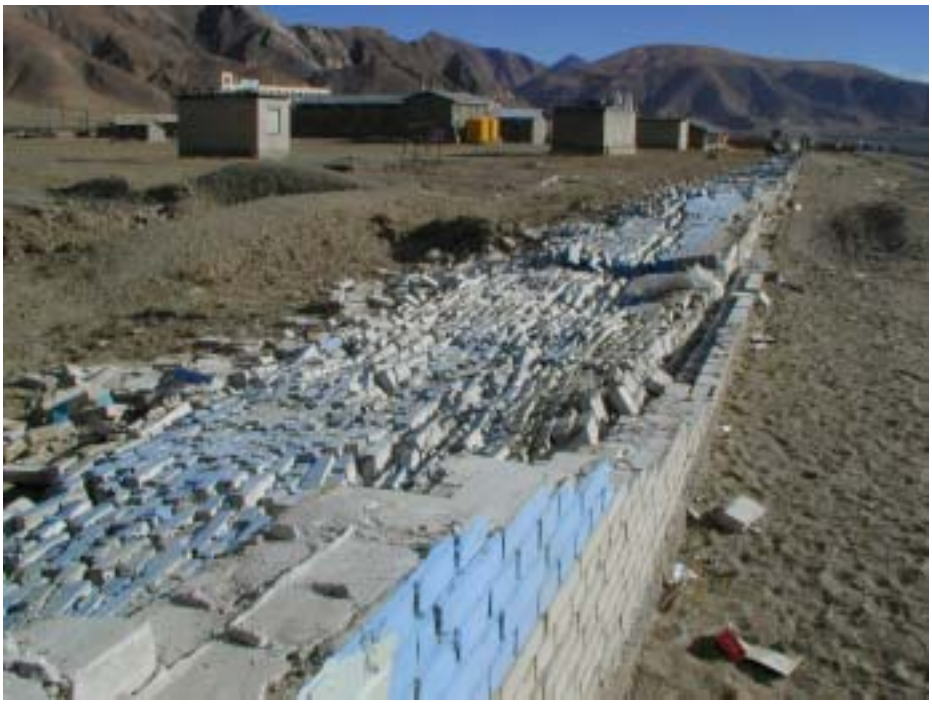


图 19 昆仑山 8.1 级地震震塌西大滩泵站围墙

摄于 2001 年 11 月 24 日，镜头向东；昆仑山 8.1 级地震造成西大滩部分围墙倒塌和房屋开裂。

Fig.19 View eastward at collapsed wall of Xidatan oil-reservoir in November 14, 2001, indicating destruction of building of Ms 8.1 Kunlun earthquake



图 20 昆仑山地震破坏昆仑山口青藏公路桥涵

摄于 2001 年 11 月 22 日，镜头向东。

Fig.20 View eastward on November 22, 2001 at broken bridge of the Golmud-Lhasa Highway destructed by Ms 8.1 Kunlun earthquake



图 21 昆仑山 8.1 级地震产生的雪崩

摄于 2001 年 11 月 24 日，镜头向南；地震诱发的雪崩发生在西大滩盆南玉珠峰西侧。

Fig.21 View southward on November 24, 2001 at avalanche in west of Yuzhu Peak of south Kunlun Mts. caused by Ms 8.1 Kunlun earthquake



图 22 昆仑山 8.1 级地震产生的雪崩近景

摄于 2001 年 11 月 24 日，镜头向南；地震诱发雪崩在沟口堆积的冰雪厚度≥1.0m。

Fig.22 Near view southward on November 24, 2001 at frontier of avalanche in south of Xidatan valley caused by Ms 8.1 Kunlun earthquake



图 23 昆仑山 8.1 级地震雪崩产生的冰块羽裂

摄于 2001 年 11 月 24 日，冰块羽裂构造揭示冰川内部的快速崩裂过程。

Fig.23 Near view on November 24, 2001 at feather structure of fractures of avalanched ice block formed during Ms 8.1 Kunlun earthquake