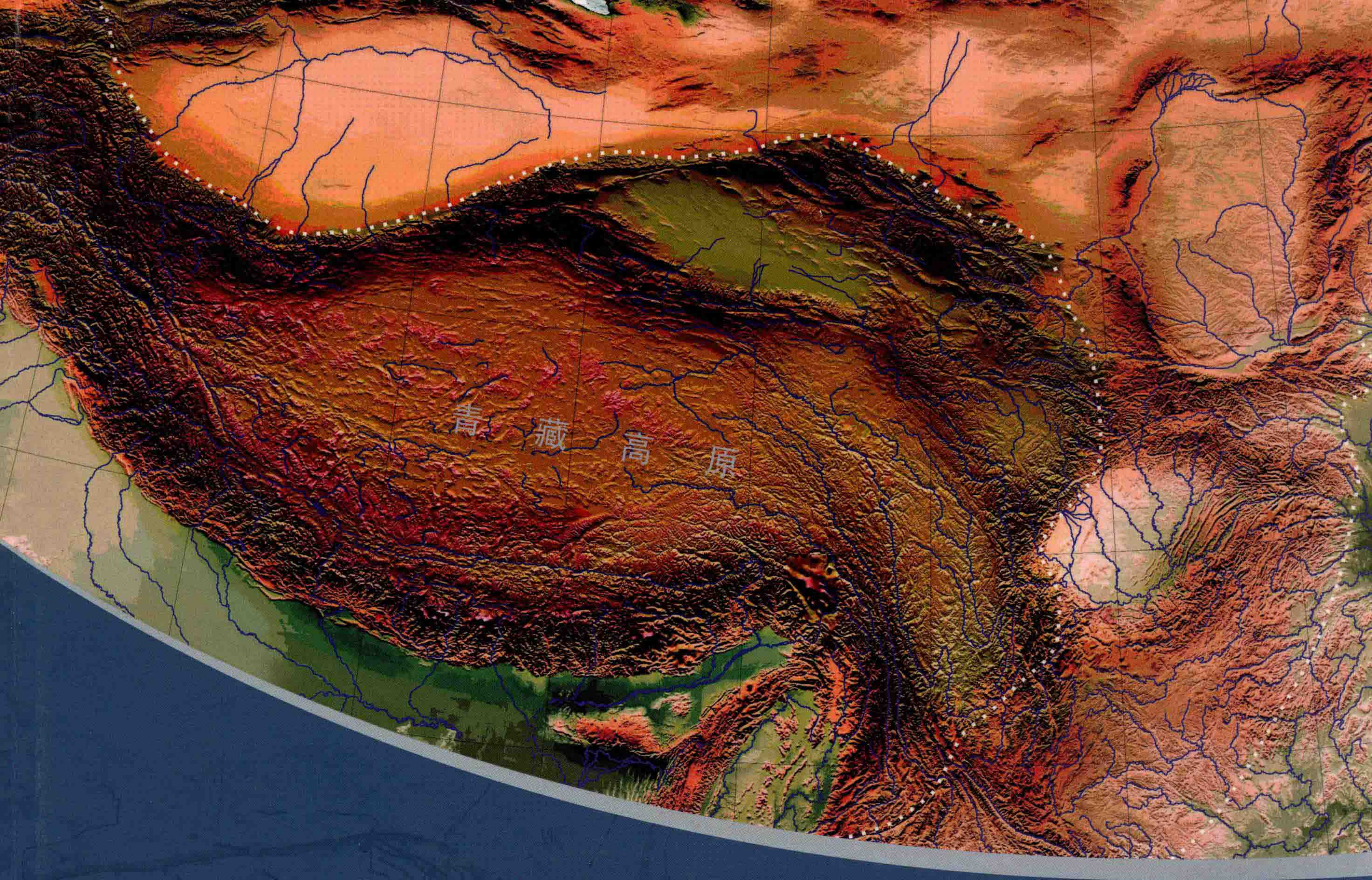

青藏高原东部

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张永双 姚 鑫 郭长宝 石菊松 等编著

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科 学 出 版 社

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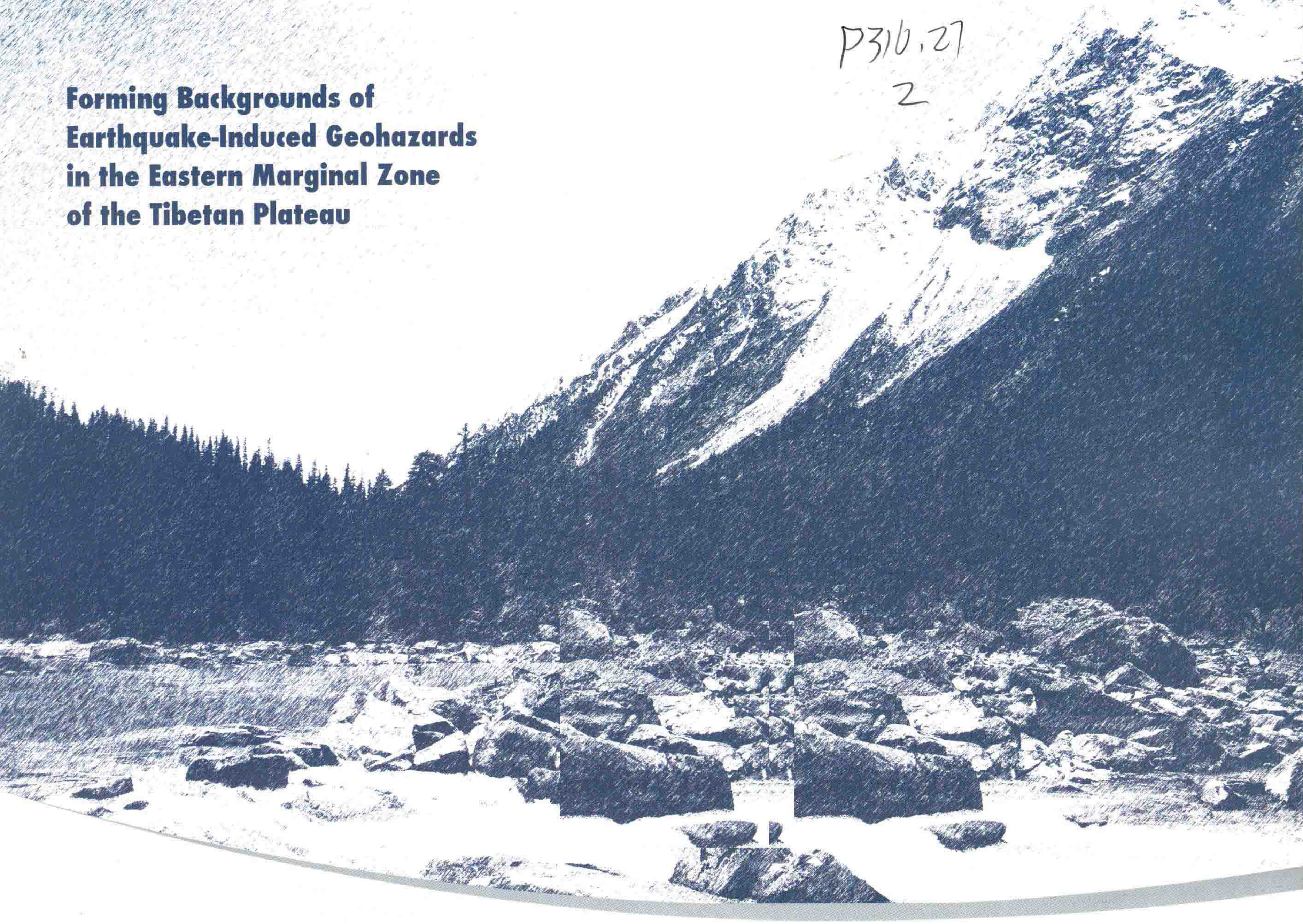

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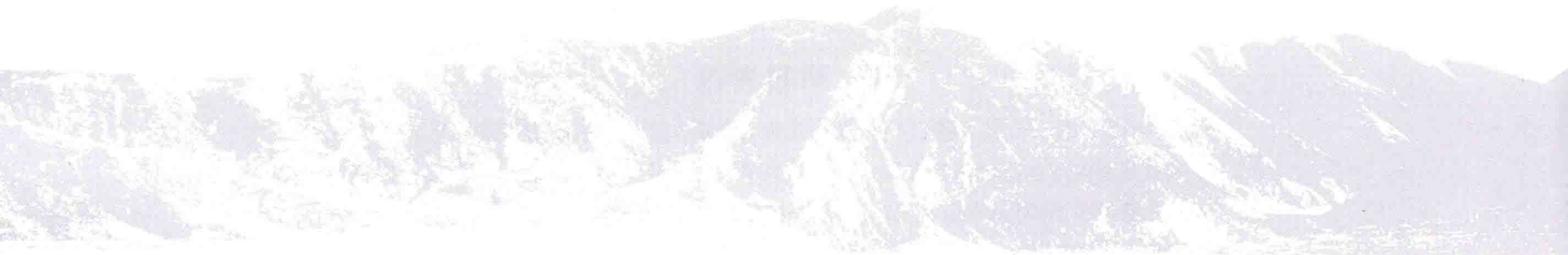

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Forming Backgrounds of Earthquake-Induced Geohazards in the Eastern Marginal Zone of the Tibet Plateau

Chief Editors: Zhang Yongshuang, Yao Xin, Guo Changbao, Shi Jusong

Editors: Ma Yinsheng, Wang Jun, Wang Tao, Wang Xianli, Lan Hengxing, Sun Ping, Liu Jian, Cheng Yuliang, Liu Yonghua, Su Shengrui, Wu Shuren, Yu Kai, Yang Weimin, Zhang Chunshan, Zhou Nengjuan, Zheng Wanmo, Hu Daogong, Ni Huayong, Lei Weizhi, Xiong Tanyu

English Editors: Zhang Yongshuang, Sun Ping

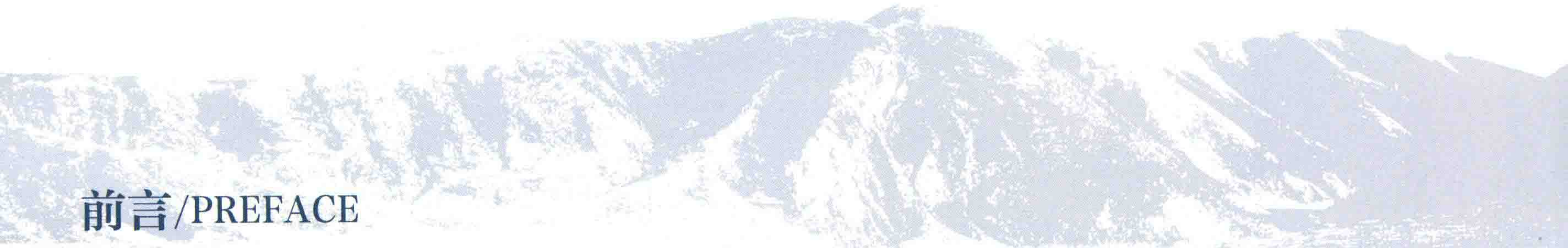
前言/PREFACE

青藏高原东部地形急变带是我国东西自然地理、地质环境的重要分界带，是典型的高山峡谷地区，崇山峻岭、峡谷纵横，地形起伏度在1000m/km^{2}以上。在地貌上，从海拔不到500m的成都平原，向西穿过龙门山，在不到100km的距离内上升到海拔4000m以上，形成一个巨大的地形陡变带。这些强烈起伏的地形表明，青藏高原东部地形急变带遭受快速的隆升和强烈的河流深切，成为内外动力地质作用都非常强烈的地区，在国际新构造运动与地质灾害研究领域具有很高的关注度。

中国是世界上陆内地震活动最强烈和地质灾害最严重的国家之一。2008年5月12日14时28分，中国四川汶川发生M_s8.0级地震，造成69227人死亡、17923人失踪、374643人受伤，是新中国建立以来，中国大陆发生的破坏性最为严重的一次灾难性地震。特别是，“5·12”汶川地震之后，在龙门山及邻近构造带又相继发生了多次强烈地震，其中2010年4月14日发生的“4·14”青海玉树M_s7.1级地震和2013年4月20日发生的“4·20”四川芦山M_s7.0级地震造成的地震地质灾害比较严重。它们与“5·12”汶川地震一样，都是发生在巴颜喀拉地块的边界断裂上，在成因方面具有一定的联系。在今后一段时期，地震地质灾害的防灾减灾工作仍将是国家重大战略需求，亟待进一步加强地震工程地质与地质灾害相关科学问题的研究。

地震地质灾害作为工程地质领域的重要研究内容，得到国内外学者的广泛关注。近年来，在国家科技基础性工作专项课题（2011FY110100-2）、国家“十二五”科技支撑课题（2011BAK12B09）和中国地质调查局地质调查项目（1212010914025）的资助下，编著者开展了大量野外地质调查工作，获得了青藏高原东部地形急变带地震地质灾害及其成灾背景方面的第一手资料，为地震地质灾害特征研究提供了重要依据。本图集试图以龙门山及邻近构造带主要活动断裂和地震地表破裂为对象，以地震诱发的典型地质灾害为切入点，展示青藏高原东部活动断裂地质灾害效应的主要表现形式，为探索内外动力地质作用耦合成灾机理以及活动构造带地质灾害早期识别提供参考资料。

本项工作得到国土资源部中国地质调查局、中国地质科学院相关领导的大力支持，中国地质环境监测院、成都地质调查中心、四川省地质调查院、成都理工大学、青海省地质环境监测总站、青海省环境地质勘查局、陕西省地质矿产勘查开发局、甘肃省地质环境监测院等单位的领导和技术人员在野外调查及资料共享方面给予了大力支持，并提供了不同形式的帮助。在本图集编撰过程中，始终得到国土资源部地质灾害防治技术指导中心殷跃平总工程师、中国地质科学院董树文副院长和吴珍汉副院长、地质力学研究所龙长兴所长、赵越副所长、侯春堂副所长的指导，中国地质调查局水环部文冬光主任、郝爱兵副主任、李铁锋处长等给予了多方面的指导和帮助。借此机会，特向对本项研究提供帮助、支持和指导的所有领导、专家和同行表示衷心的感谢!



前言/PREFACE

The eastern marginal region of the Tibetan Plateau is a very distinct landform-changing zone of China. Here are lofty mountains and high ridges as well as crisscross gorges and valleys, showing a relief degree more than 1000 m/km^2. From the Chengdu Plain with elevations of lower than 500 m to the west side of the Longmenshan Mountains with elevations of higher than 4000 m, for example, in this distance less than 100km, the elevation increases by more than 3500 m. Relief is so sharp!

This zone is also a strong earthquake zone famous in China. So it is not surprised that many large earthquakes have occurred there. The Wenchuan earthquake with M_s 8.0 on May 12, 2008 exactly occurred in this zone. Following it, the Yushu earthquake with M_s 7.1 did on April 14, 2010 and the Lushan earthquake with M_s 7.0 did on April 20, 2013. All of these earthquakes occurred on boundary faults of the Bayan Har block which is in this zone. On the one hand these earthquakes directly caused serious loss in people's life and property, on the other hand they induced, are inducing and will induce various geohazards, of which some might last for several years or even for a hundred years. Geohazards induced by the Wenchuan earthquake have still continued up to now, and they have been made realistic and potential threats to the post-earthquake reconstruction. Therefore, to study various conditions favorable for earthquake-induced or post-earthquake geohazards are very necessary.

The prediction or forecast of earthquakes is difficult, or even impossible, as some have held, but the effective prevention and reduction of their induced geohazards are possible and viable. In recent years, supported by the National Special Project of Scientific and Technological Basic Work (2011FY110100-2), the National Scientific and Technological Supporting Project of the Twelfth Five-year Plan (2011BAK12B09), and the Geological Survey Project of China Geological Survey (1212010914025), we have carried out a lot of field investigation on earthquake-induced or post-earthquake geohazards and their forming conditions and backgrounds in the eastern marginal zone of the Tibetan Plateau and obtained abundant and first-hand data. These data have provided an important basis for the prevention and reduction of coming earthquake-induced geohazards in this zone.

The book focuses on a line from the Longmenshan fault to the Anninghe fault and displays visions after earthquakes by a lot of our in-situ shot pictures. They include the complex relief features to strengthen earthquake hazards, active faults to initiate earthquakes, earthquake surface ruptures, and various post-earthquake geohazards. We wish that the book can enlighten and improve people' s consciousness of earthquake prevention and disaster reduction, stimulate researchers' interests, and rivet the related authorities' more attention upon this problem. The publishing of the book in 6 anniversaries of the Wenchuan earthquake is a memory for it and also a report to all the deceased in earthquakes since human initiated seismic research.

Finally, we would like to thank the following organizations and individuals for their guides and helps on different aspects: China Geological Survey, Chinese Academy of Geological Sciences, Chinese Institute of Geological Environment Monitoring, Chengdu Geological Survey Center, Geological Survey Institute of Sichuan Province, Chengdu University of Technology, Qinghai Province General Station of Geological Environment Monitoring, Qinghai Province Environmental Geology and Exploration Bureau, Shaanxi Province Geological Mineral Exploration and Development Bureau, and Geological Environment Monitoring Institute of Gansu Province as well as Profs. Yin Yueping, Dong Shuwen, Wu Zhenhan, Long Changxing, Zhao Yue, Hou Chuntang, Wen Dongguang, Hao Aibing, and Li Tiefeng.

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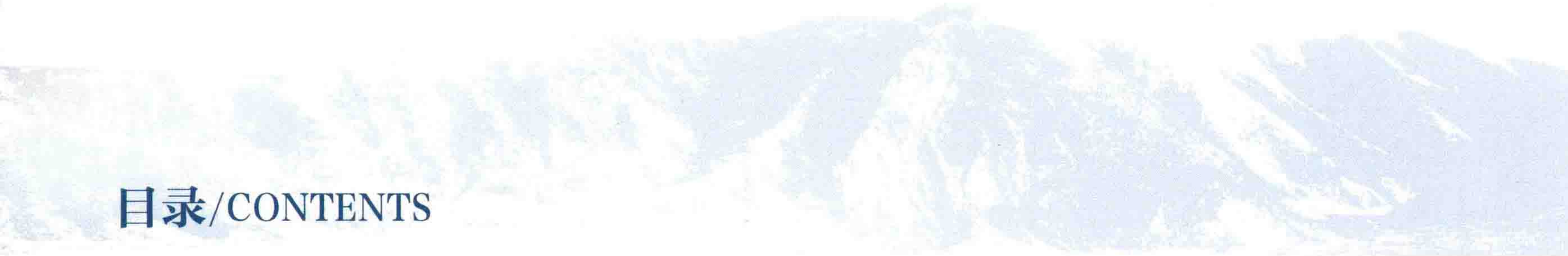

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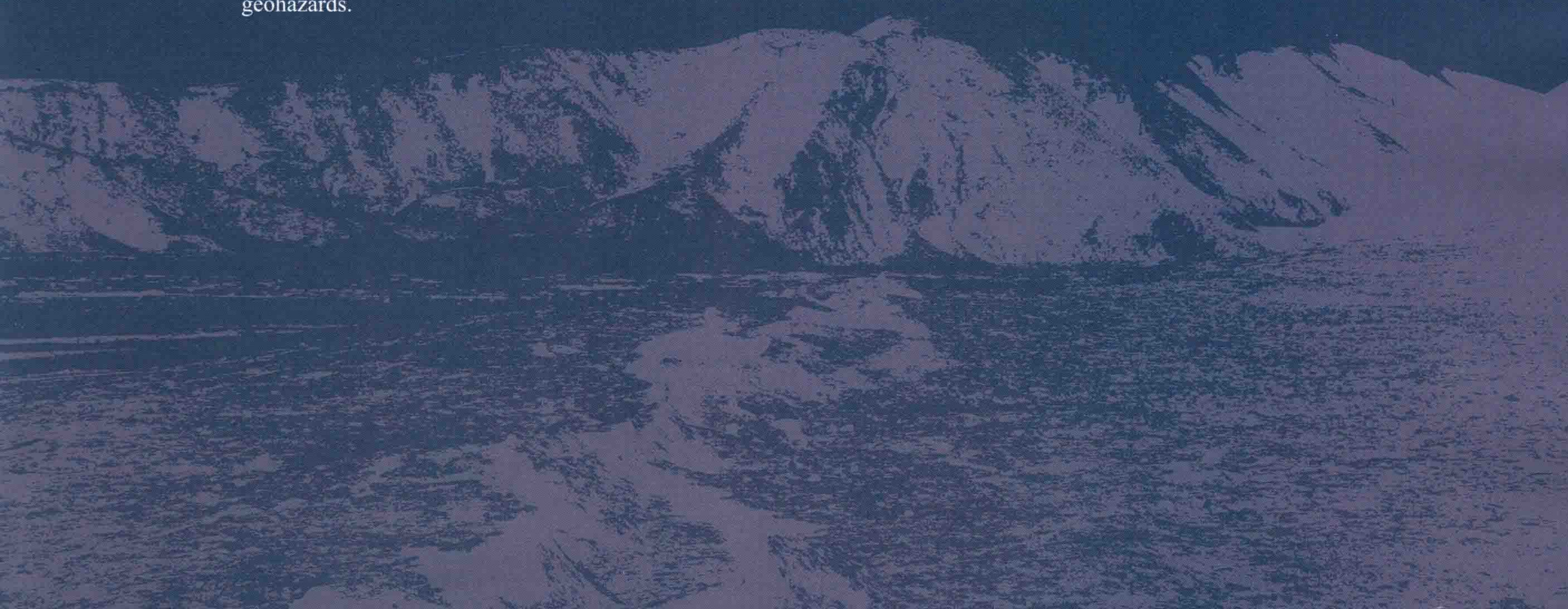
1

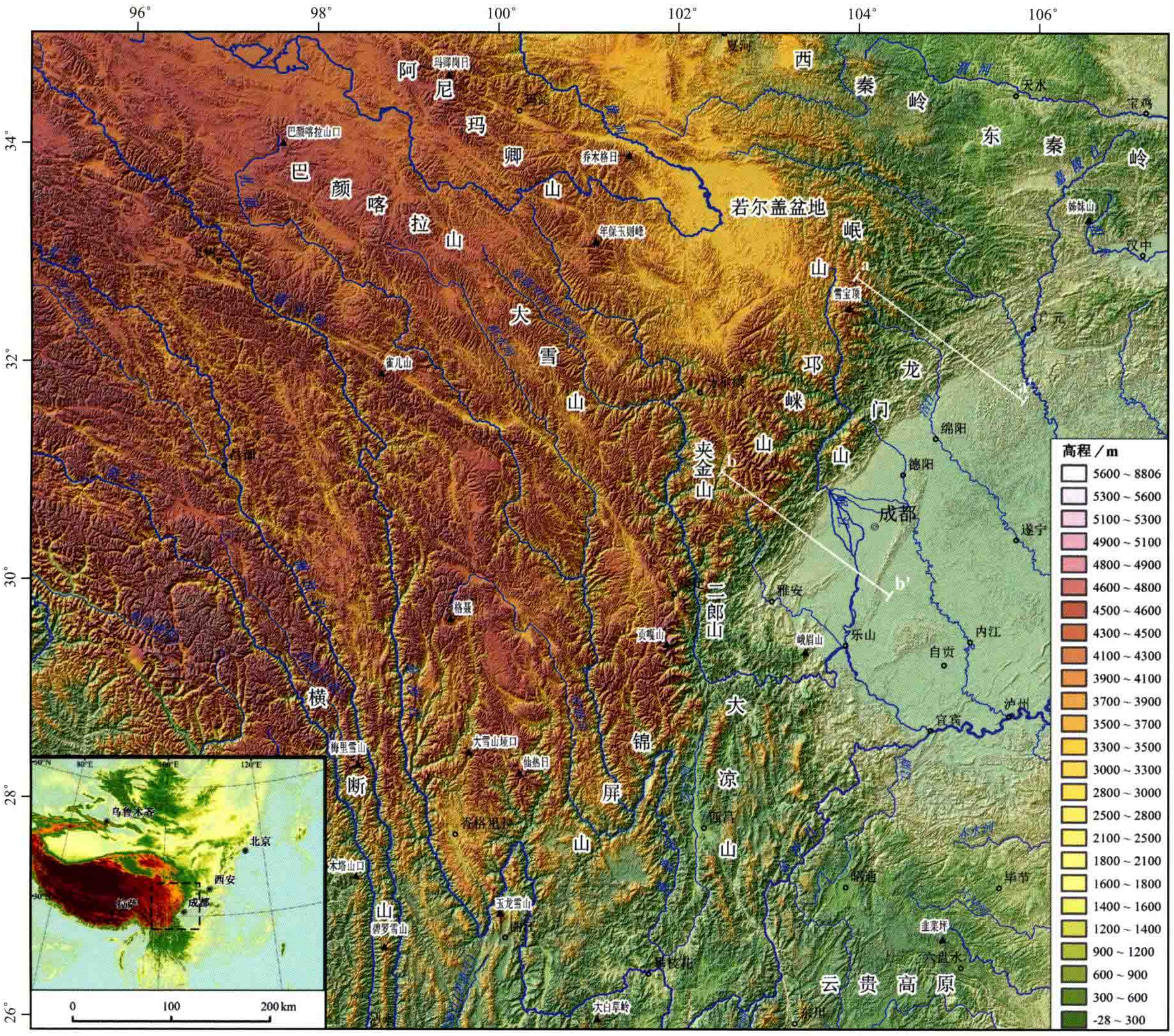
区域地震地质背景

Regional Seismogeological Backgrounds

青藏高原晚新生代以来的强烈隆升，对周边地区气候与环境产生了深刻影响。在青藏高原向东挤出过程中，在高原东部形成了显著的地貌、地质构造分异带，成为强烈构造活动区（曾融生、孙为国，1992；张培震等，2003；徐锡伟等，2007）。据不完全统计，1900年至2013年间，中国大陆共发生M_s7.0级以上大震64次，其中37次发生在青藏高原东部（南北地震带）。青藏高原东部复杂的地质演化历史和新构造活动，导致地层岩性和岩体结构完整性差、地形陡峻、河流深切，为地震地质灾害的发生创造了有利条件。

The strong uplift of the Tibetan Plateau in Late Cenozoic has had a profound climate and environment impact. During the eastward squeezing-out process of the Tibetan Plateau, a distinct landform and geotectonic differentiation zone formed on the eastern margin of the plateau, and thus has become an intense tectonic active zone (Zeng and Sun, 1992; Zhang *et al*., 2003; Xu *et al*., 2007). According to incomplete statistics, from 1900 to 2013, there were 64 earthquakes bigger than M_s7.0, among which 37 occurred in the eastern marginal region of the Tibetan Plateau (South-North Earthquake Belt). The complex geological evolution history and neotectonic activity have resulted in integrity of strata and rock mass structure, high and precipitous landform, and deeply incised rivers in the region, which have provided favorable conditions to the occurrence of earthquake geohazards.



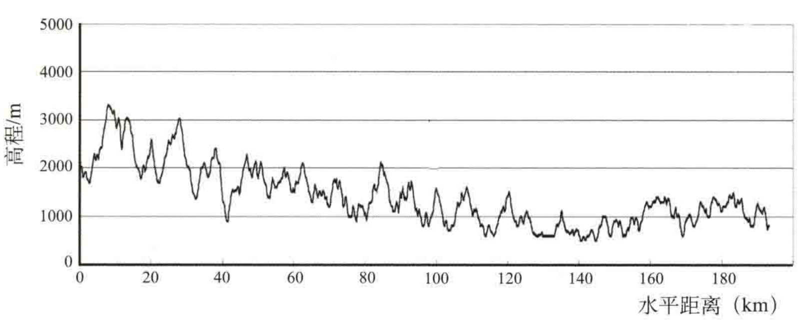


青藏高原东部地形地貌及主要水系分布图

Topographic map of the eastern marginal region of the Tibetan Plateau

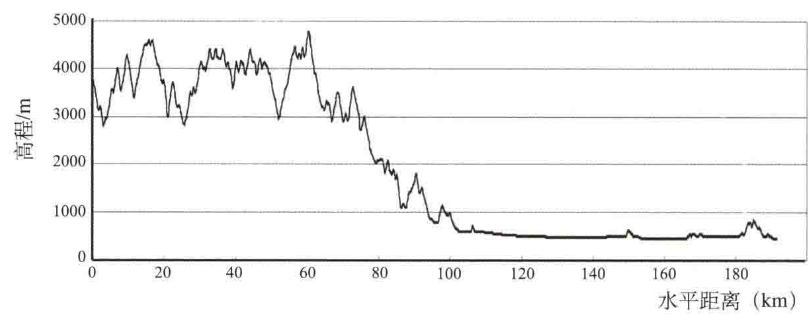
青藏高原东部在新构造运动和水系深切作用下，形成复杂的地形地貌格局。一般将四川盆地西缘的龙门山及其南延的锦屏山、玉龙雪山看作是中国东西部一级地貌边界带。以阿尼玛卿山、大雪山、贡嘎山、锦屏山、玉龙雪山一线为界，西部高原地势相对平坦，东部地区侵蚀地貌发育。青藏高原东部大江大河发育，以金沙江、怒江、澜沧江最为著名。

It is the neotectonic movement and the river-incision that would make the eastern margin of the Tibetan Plateau appear as a complex geomorphological framework. Generally, Mt. Longmenshan and its southern extension, i.e. Mt. Jinping and Mt. Yulong, are regarded as a first-level geomorphological boundary between the west and the east of China. This region can be further divided into two parts by taking Mt. Anyemaqen, Mt. Daxueshan, Mt. Gongga, Mt. Jinping and Mt. Yulong as the boundary: the western part is relatively even, the eastern part is occupied with high mountains and deep valleys. And there are such famous rivers as the Jinsha River, the Nu River, and the Lancang River to flow through here.



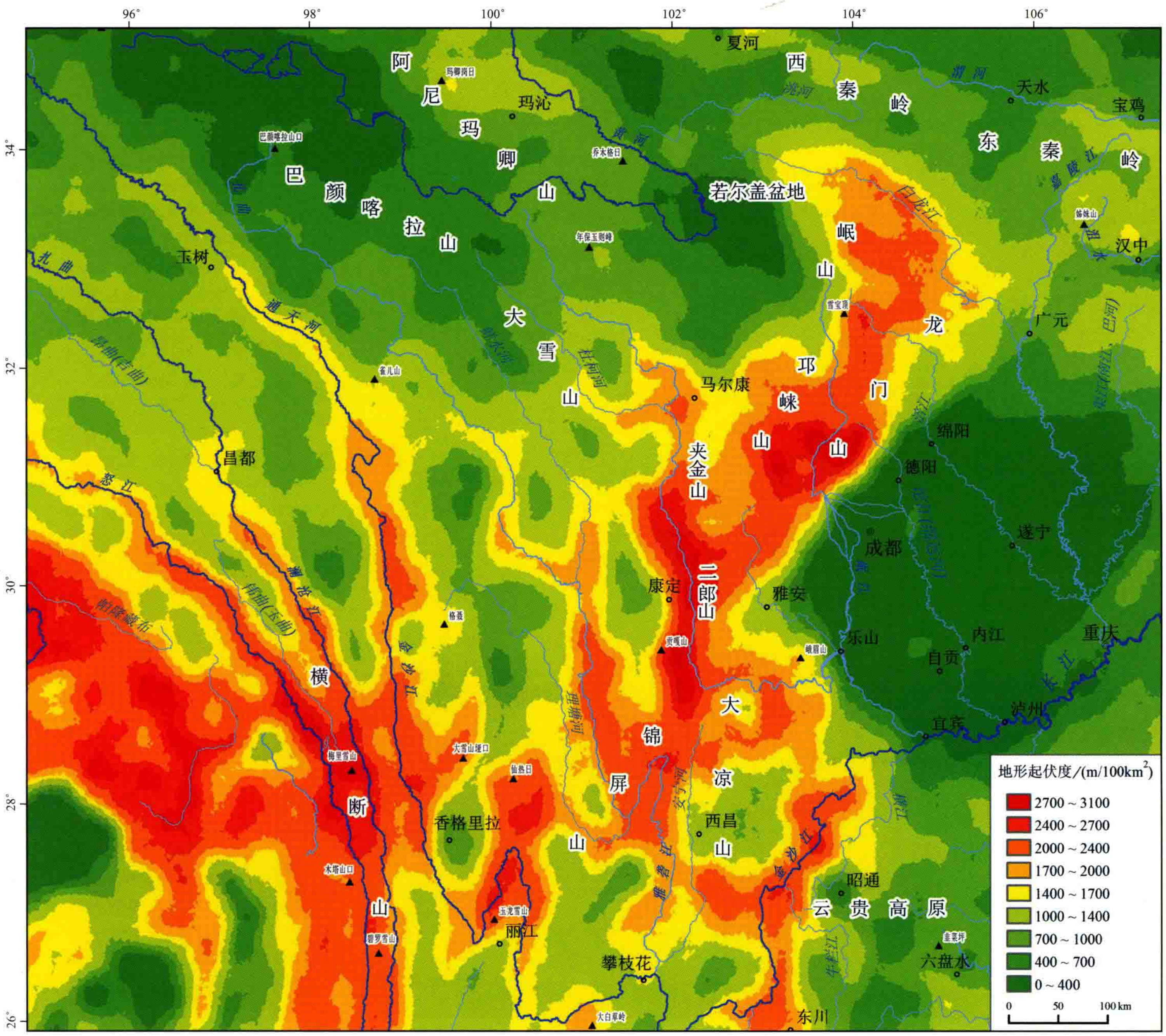
a–a′ **地形剖面**

Topographic section of *a-a′*



b–b′ **地形剖面**

Topographic section of *b-b′*

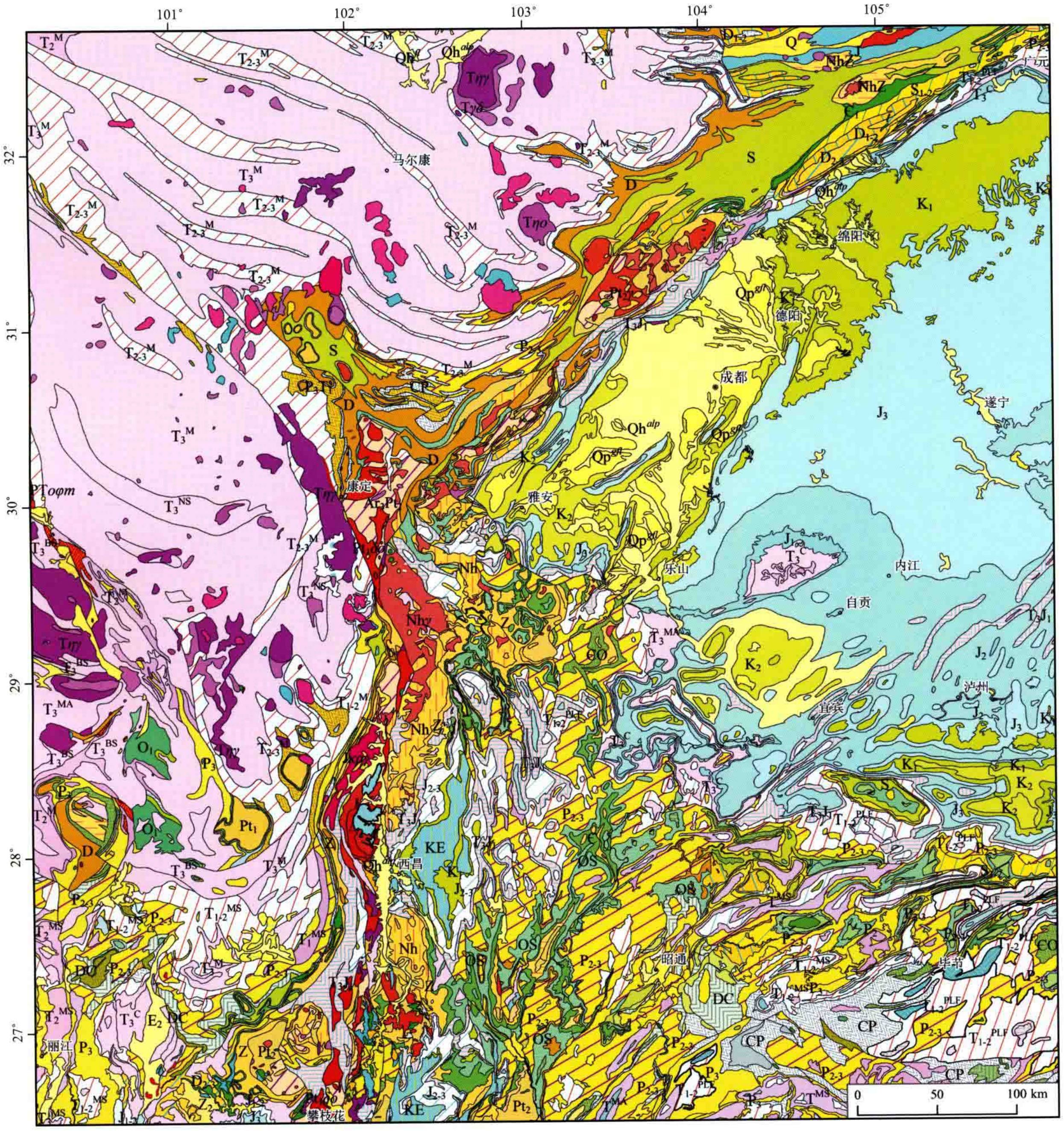


青藏高原东部地形起伏度图

Relief degree of the eastern marginal region of the Tibetan Plateau

青藏高原东部崇山峻岭、峡谷纵横，在地貌上从海拔不到500m的成都平原，向西上升到海拔4000m以上，形成一个巨大的地形陡变带。区内地形起伏度大多在1000m/km²以上，地形起伏最大的地区位于若尔盖盆地以东和以南的岷山、邛崃山、龙门山和大雪山，以及南部贡嘎山和锦屏山一带，最大地形起伏超过3000m/km²。

The eastern marginal region of the Tibetan Plateau is occupied with lofty mountains and high ridges, as well as crisscross gorges and valleys. A huge geomorphologic sharp-change zone occurs from the Chengdu Plain with elevations of lower than 500 m to the west side of Mt. Longmenshan with elevations of higher than 4000 m. The relief degree is commonly more than 1000 m/km². The areas covered by Mt. Minshan, Mt. Qionglai, Mt. Longmenshan, Mt. Daxueshan, Mt. Gongga, and Mt. Jinping, are the most distinct in relief degrees, more than 3000 m/km².



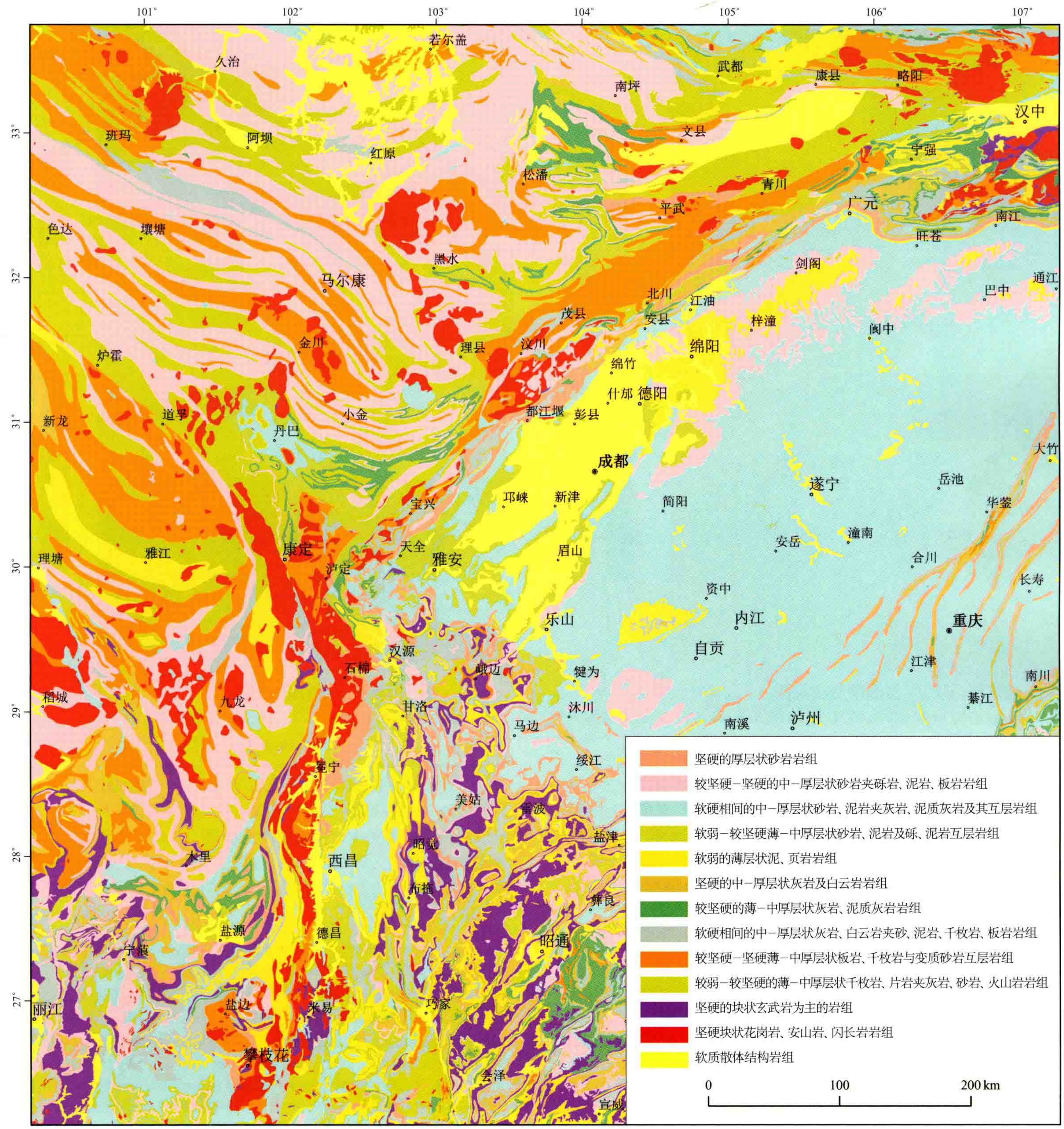
Qh^{alp}.全新统冲洪积; Q^{hfl}.全新统湖泽堆积; Qp^{gfl}.更新统冰水堆积; Q.第四系; N.新近系; E.古近系; E_2.始新统; KE.白垩系与古近系未分; K_2.上白垩统; K_1.下白垩统; J_3.上侏罗统; J_2.中侏罗统; J_{2-3}.中上侏罗统; J_{1-2}.下中侏罗统; J_1.下侏罗统; J.侏罗系; $J_{\chi o \gamma}$.侏罗纪碱长花岗岩; TJ.三叠系与白垩系未分; T^{MS}.三叠系浅海相飞仙关组须家河组; T_3J_1.上三叠统与下白垩统未分; T_3.上三叠统; T_3^{C}.上三叠统陆相; T_3^{BS}.上三叠统盆地相; T_3^{MS}.上三叠统浅海相; T_3^{MA}.上三叠统海陆过渡相; T_3^{NS}.上三叠统陆棚相; T_3^{M}.上三叠统海相; $T_{2-3}{}^{M}$.中上三叠统浅海相; T_2^{M}.中三叠统海相; T_2^{MS}.中三叠统浅海相; T_{1-2}^{PLF}.下中三叠统台地相; $T_{1-2}{}^{MA}$.下中三叠统海陆过渡相; $T_{1-2}{}^{MS}$.下中三叠统浅海相; $T_1{}^{MS}$.下三叠统浅海相; $T\eta\gamma$.三叠纪二长花岗岩; $T\gamma\delta$.三叠纪闪长岩; $T\eta o$.三叠纪石英正长岩; $PTo\varphi m$.二叠系与三叠系蛇绿混杂岩; P_3T_1.上二叠统与下三叠统未分; P_3.上二叠统; P_{2-3}.中上二叠统; P.二叠系; CP.石炭系与二叠系未分; DC.泥盆系与石炭系未分; D.泥盆系; D_{2-3}.中上泥盆统; D_{1-2}.下中泥盆统; S.志留系; OS.奥陶系与志留系未分; O_1.下奥陶统; ЄO.寒武系与奥陶系未分; Є.寒武系; $Є_1$.下寒武统; Pz_1.下古生界; Z.震旦系; Z_2.上震旦统; NhZ.南华系与震旦系未分; Nh.南华系; $Nh\gamma$.南华纪花岗岩; Pt.元古界; Pt_2.中元古界; $Pt_2\gamma$.中元古界花岗岩; $Pt_1\delta o$.下元古界石英闪长岩; Ar_3Pt_1.上太古界与下元古界未分。

青藏高原东部地层岩性分布略图

Stratigraphic map of the eastern marginal region of the Tibetan Plateau

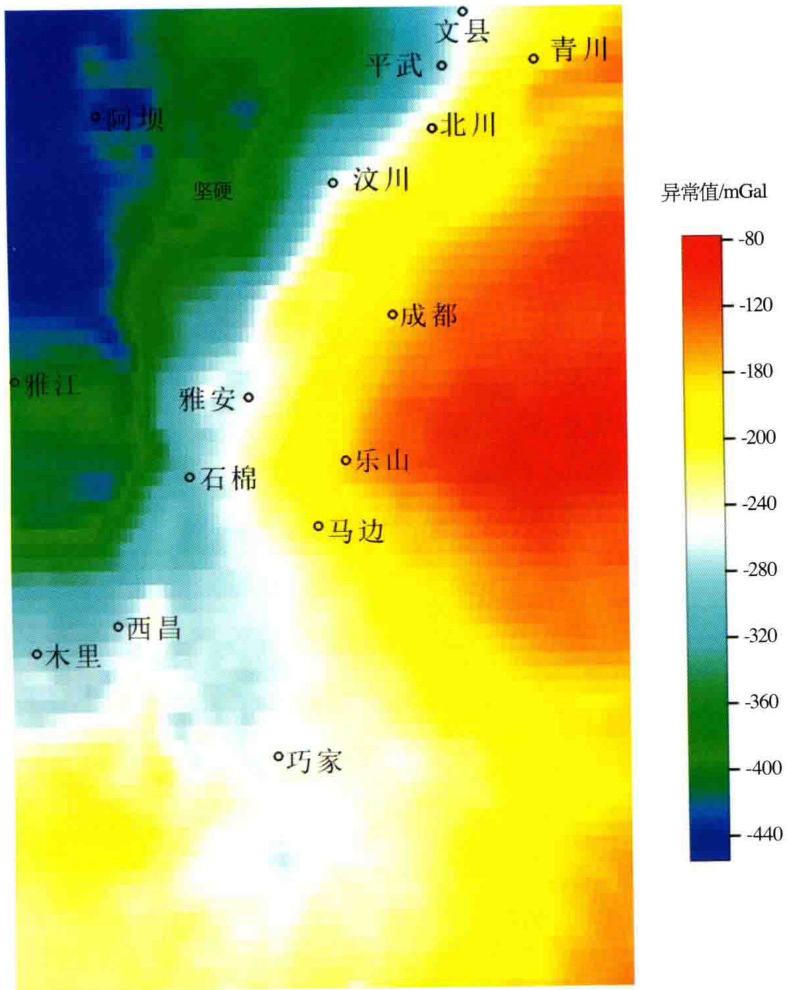
青藏高原东部涉及地域广，跨越多个地层单元。地层从上太古界到第四系均有出露，其中侏罗系、三叠系分布最广泛，占全区的30%以上。不同时代地层或岩浆岩的空间分布明显受到地质构造的控制。

The eastern marginal region of the Tibetan Plateau covers a wide area where there are multiple stratigraphic units from the Upper Archean to the Quaternary to be exposed. Among them, the strata of Jurassic and Triassic are most widely distributed, accounting for more than 30% of the total area. The spatial distribution of them and magmatic rocks is significantly controlled by geological structures.



青藏高原东部工程地质岩组分布略图

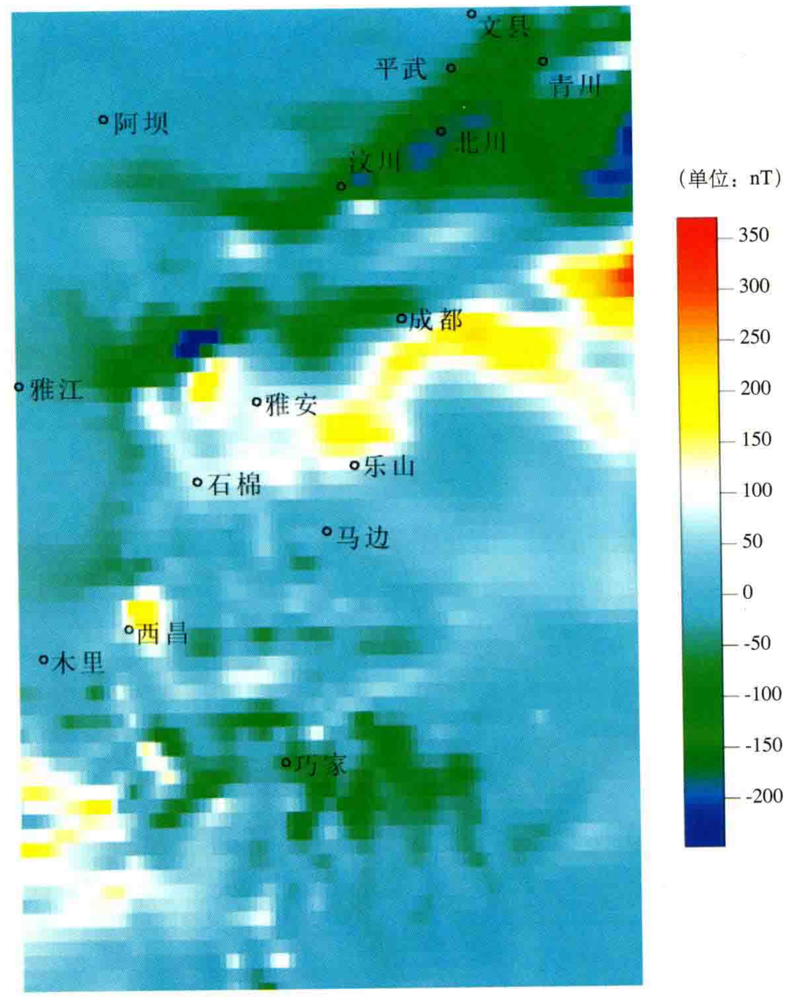
Engineering geological rock groups in the eastern marginal region of the Tibetan Plateau



龙门山及邻区布格重力异常图（据方慧等，2013）

Bouguer gravity anomaly in Mt. Longmenshan and its adjacent areas

(after Fang *et al*., 2013)



龙门山及邻区航磁异常图（据方慧等，2013）

Aeromagnetic anomaly in Mt. Longmenshan and its adjacent areas

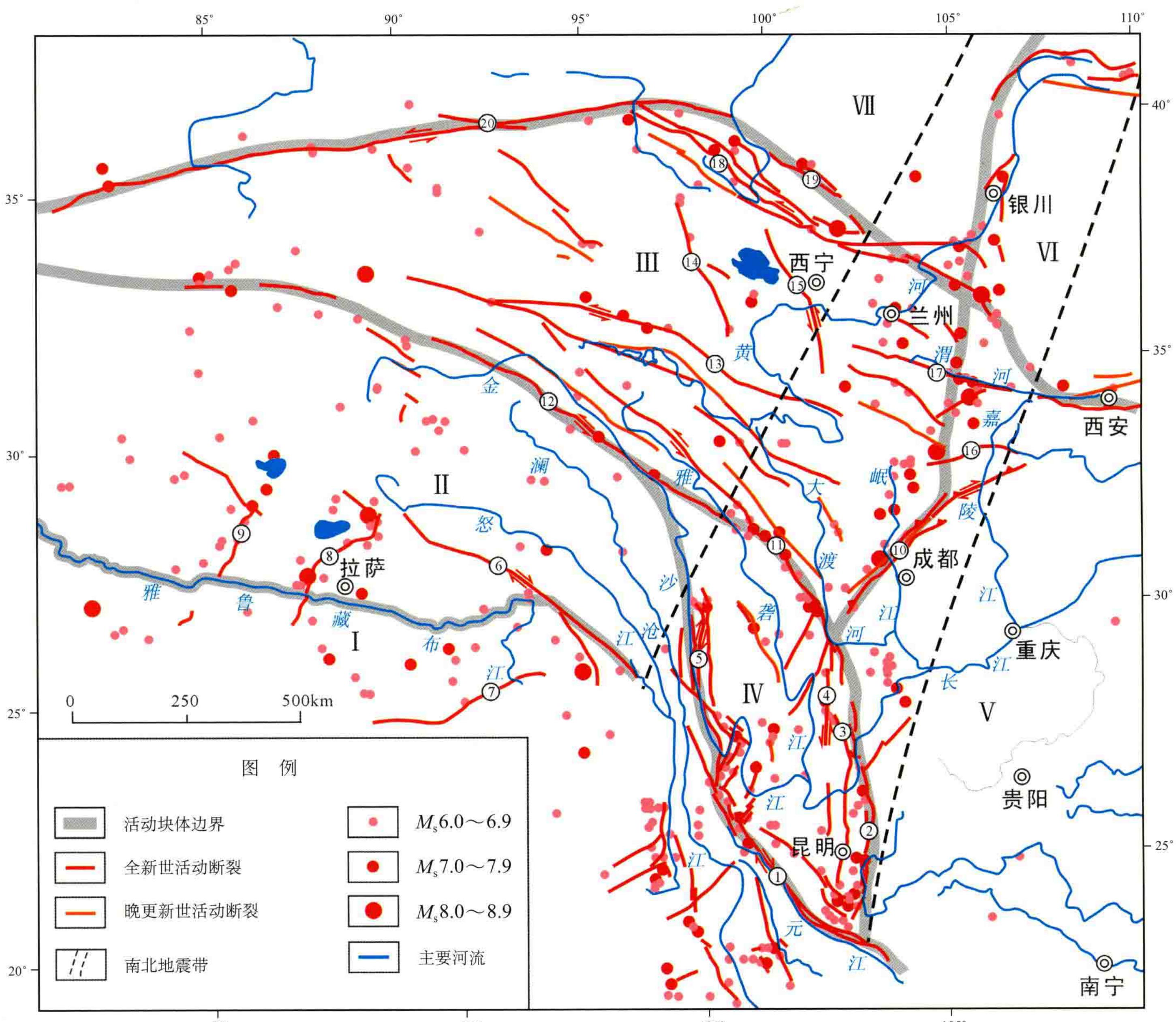
(after Fang *et al*., 2013)

龙门山及邻区布格重力异常值全部为负值，以龙门山–锦屏山为明显过渡带，由东南向西北逐渐降低。从东到西可划分为明显不同的三个区带：川中重力低负异常区带、九寨沟–石棉–攀西裂谷重力渐变带和松潘–甘孜重力高负异常区带。“两区夹一带”的布格重力异常特征及明显的南宽北窄异常带，显示该区深部构造格局形成于复杂的构造挤压作用背景。

Bouguer gravity anomalies in Mt. Longmenshan and its adjacent areas all are negative, and by Mt. Longmenshan and Mt. Jinping as an obvious transitive zone, gradually decrease from southeast to northwest. Thus three distinct zones can be divided into from east to west: the central Sichuan lower negative gravity anomaly zone, the Jiuzhaigou-Shimian-Panxi gravity anomaly transition zone, and the Songpan-Garzi higher negative gravity anomaly zone, suggesting that the deep tectonic framework here would form under complicated tectonic compression.

龙门山及邻区航磁异常强弱层次分明，可划分为以龙门山–锦屏山为界的华南地块磁异常区带和松潘甘孜地块磁异常区带。前者的磁场以高值正异常为主，展布方向主要是北东向和南北向，并偶有北西向和东西向；后者的磁场以低值负异常为主，局部有低值正异常，多呈北西向、南北向展布。上述特征反映了不同地质构造单元的区别。

Aeromagnetic anomalies in Mt. Longmenshan and its adjacent areas are distinct in gradient, and by Mt. Longmenshan and Mt. Jinping as a boundary, can be divided into the South China block aeromagnetic anomaly zone and the Songpan-Garzi aeromagnetic anomaly zone. The former is dominated by higher positive anomalies, mainly showing the NE and NS extending trends but locally the NW and EW trends, whereas the latter is dominated by lower negative anomalies, mainly showing the NW and SN extending trends. The above features indicate the difference between different tectonic units.

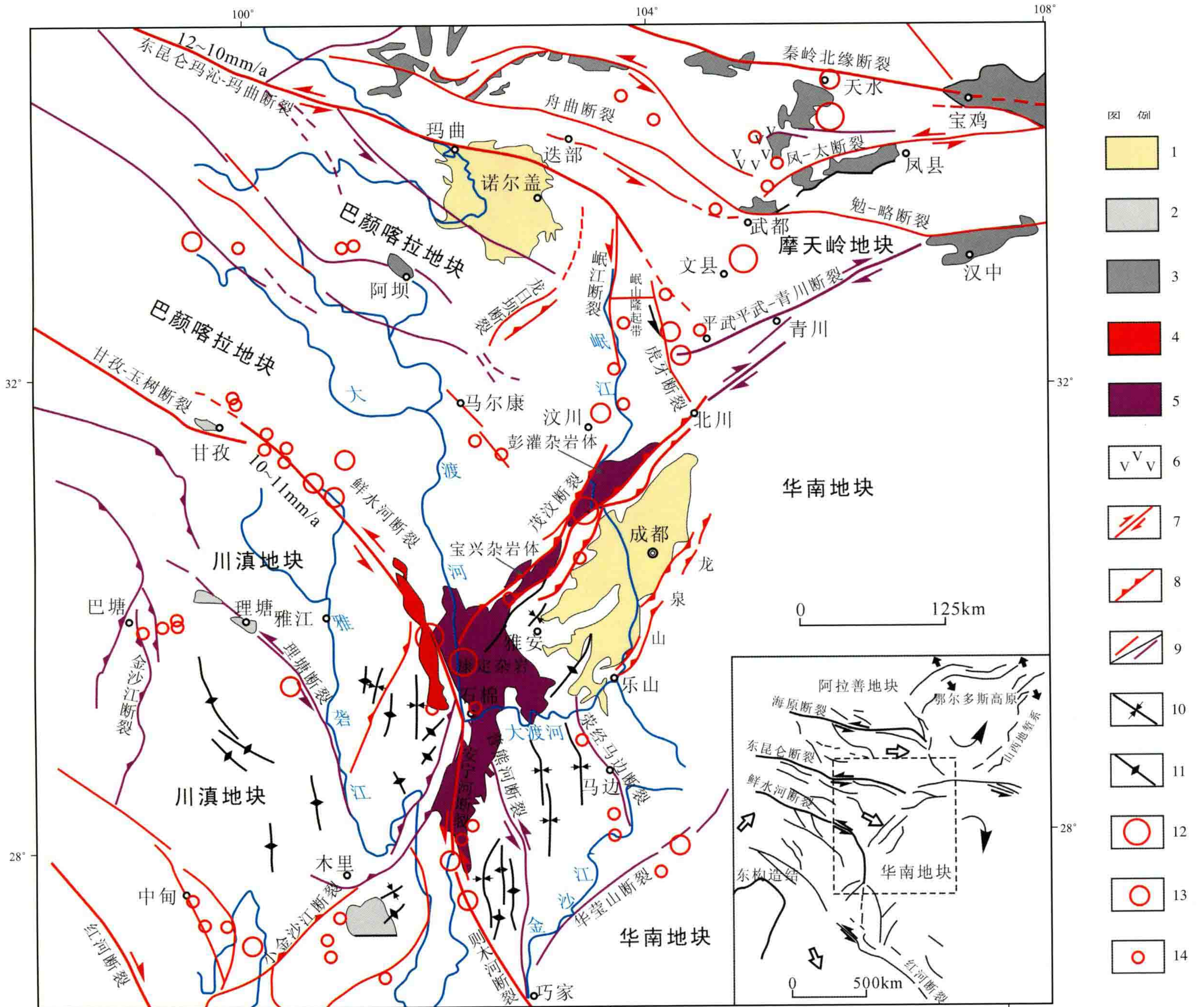


青藏高原东部活动构造分区及主要活动断裂分布图

Active tectonic zonation and main active faults in the eastern marginal region of the Tibetan Plateau

I. 喜马拉雅地块；II. 西藏地块；III. 甘青地块；IV. 川滇地块；V. 华南地块；VI. 鄂尔多斯地块；VII. 塔里木地块；1. 红河断裂；2. 小江断裂；3. 则木河断裂；4. 安宁河断裂；5. 金沙江断裂；6. 嘉黎断裂带；7. 喜马拉雅南麓主山断裂带；8. 亚东-谷露断裂；9. 甲岗-定结断裂带；10. 龙门山断裂带；11. 鲜水河断裂；12. 玉树断裂；13. 东昆仑断裂带；14. 鄂拉山断裂；15. 日月山断裂；16. 文县断裂；17. 西秦岭北缘断裂；18. 海原断裂带；19. 龙首山断裂；20. 阿尔金断裂带

I. Himalayan block; II. Tibet block; III. Gansu-Qinghai block; IV. Sichuan-Yunnan block; V. South China block; VI. Ordos block; VII. Tarim block; 1. Red River fault; 2. Xiaojiang fault; 3. Zemuhe fault; 4. Anninghe fault; 5. Jinsha River fault; 6. Jiali fault zone; 7. Himalayan south slope fault zone; 8. Yadong-Gulu fault; 9. Jiagang-Dingjie fault zone; 10. Longmenshan fault zone; 11. Xianshuihe fault; 12. Yushu fault; 13. East Kunlun fault ; 14. Elashan fault; 15. Riyueshan fault; 16. Wenxian fault; 17. Northern Xiqinling fault; 18. Haiyuan fault zone; 19. Longshoushan fault; 20. Altyn Tagh fault



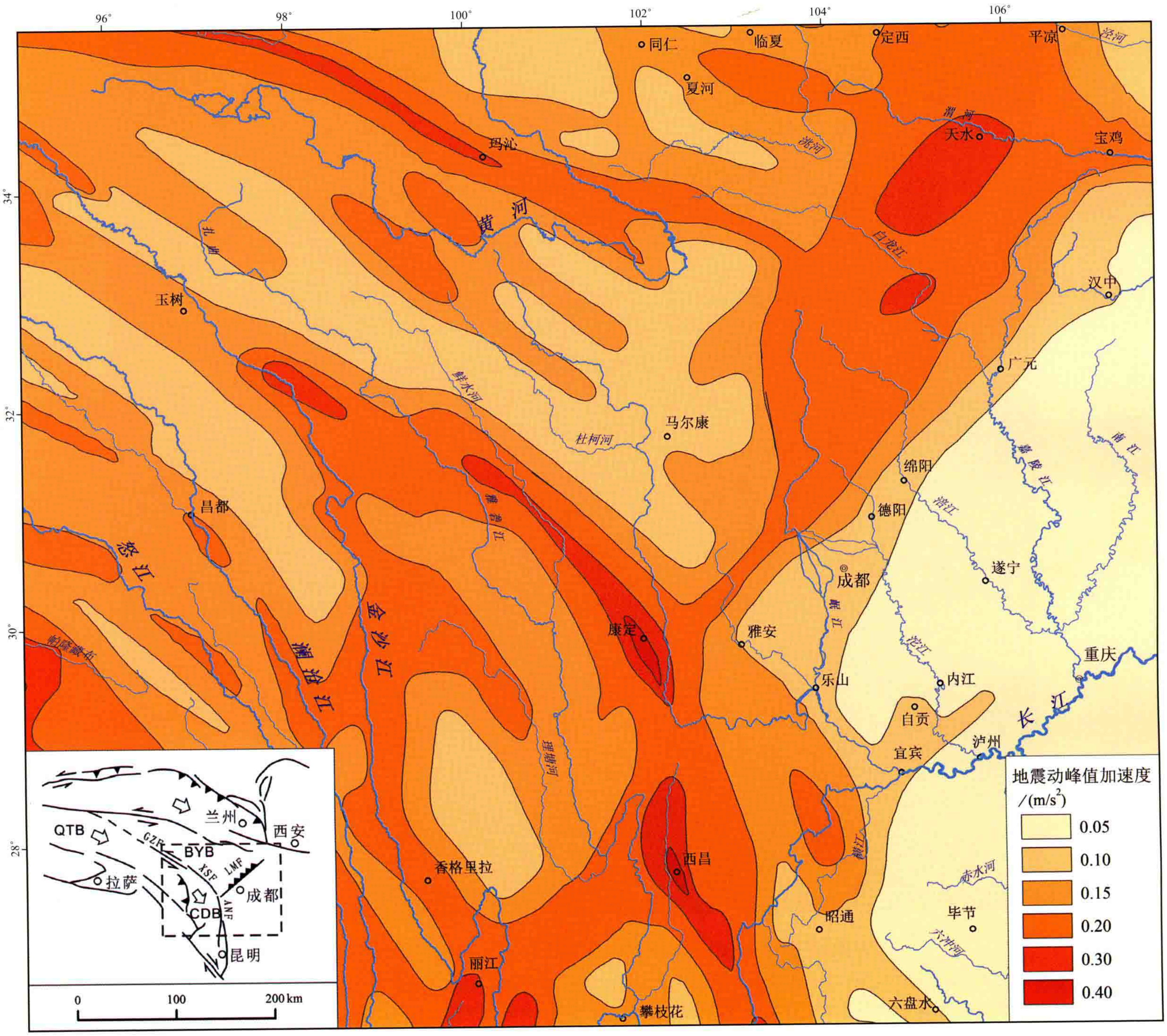
青藏高原东部主要活动构造特征图（据徐锡伟等，2005；张岳桥等，2008；张培震，2008，修编）

Major active structures in the eastern marginal region of the Tibetan Plateau

(modified after Xu *et al*., 2005; Zhang *et al*., 2008; Zhang, 2008)

1. 中-上更新统；2. 上新统－第四系；3. 新近系；4. 晚新生代侵入岩；5. 前寒武纪杂岩；6. 晚新生代火山岩；7. 走滑断裂；8. 逆冲断裂；9. 晚更新世以来活动断裂和早中更新世活动断裂；10. 向斜；11. 背斜；12. $M_s \geqslant 8.0$级地震；13. $8.0 > M_s \geqslant 7.0$级地震；14. $7.0 > M_s \geqslant 6.0$级地震

1. Middle-Upper Pleistocene; 2. Pliocene–Quaternary; 3. Neogene; 4. Late Cenozoic intrusion; 5. Precambrian complex ; 6. Late Cenozoic volcanic rock ; 7. strike-slip fault; 8. thrust fault; 9. Late Pleistocene active fault and Early-Mid Pleistocene active fault; 10. syncline ; 11. anticline ; 12. earthquake of $M_s \geqslant 8.0$; 13. earthquake of $8.0 > M_s \geqslant 7.0$; 14. earthquake of $7.0 > M_s \geqslant 6.0$

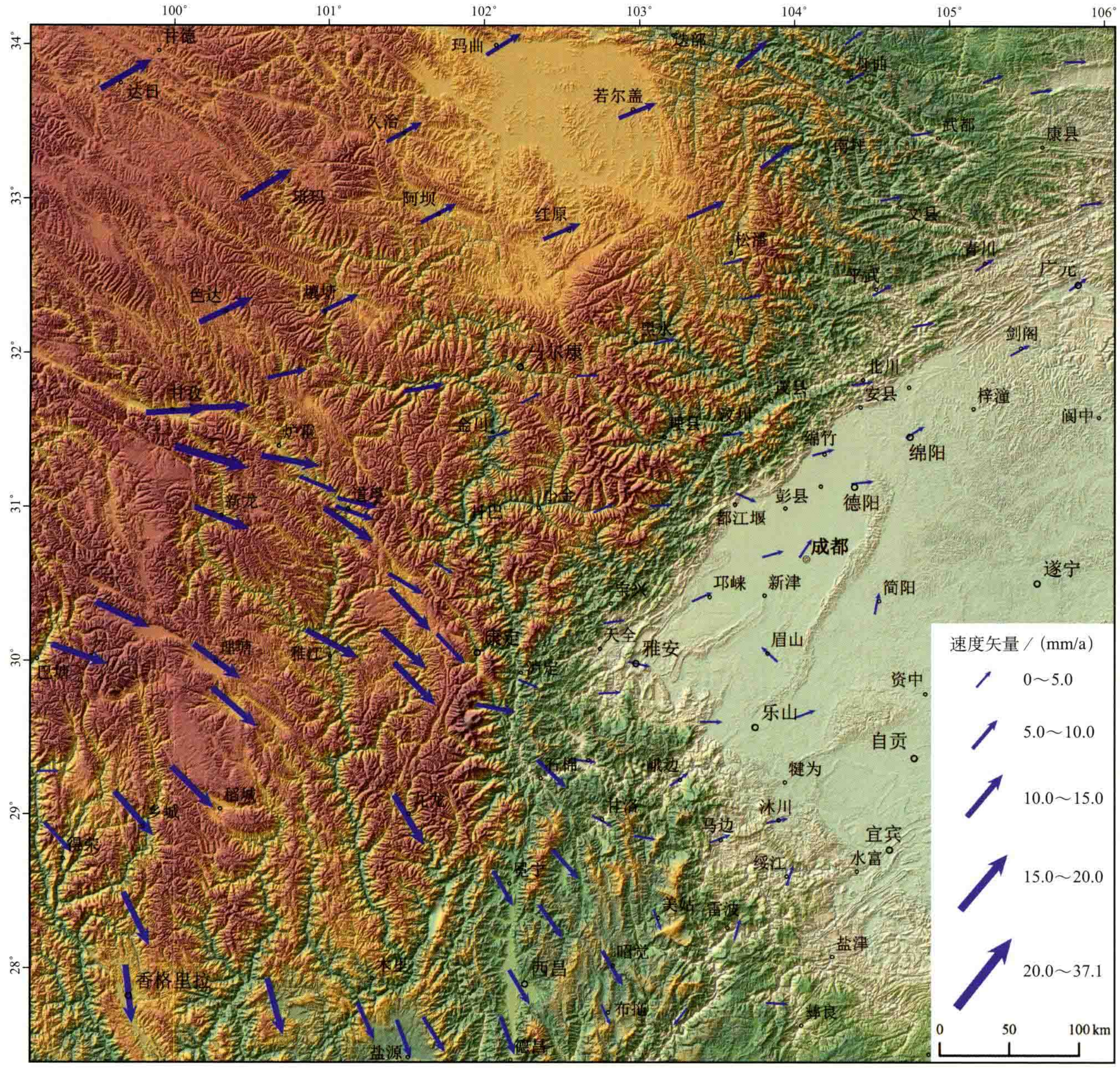


青藏高原东部地震动峰值加速度图

（据GB 18306－2001《中国地震动参数区划图》，第1号修改单，2008年6月11日批准）

Distribution of peak ground accelerations in the eastern marginal region of the Tibetan Plateau

(after Chinese Seismic Zoning Map, 2008)



汶川地震前（1999～2008年）青藏高原东部GPS运动速度矢量图

（据国家重大科学工程“中国地壳运动观测网络”项目组, 2008; 中国地震局监测预报司, 2009; 唐文清等, 2013。以华南地块为参照）

GPS-based velocity vectors in respect of the South China block in the eastern Tibetan Plateau before the Wenchuan earthquake

(after Project Group of National Major Scientific Engineering, 2008; Monitor and Forecast Department, CEA, 2009; Tang *et al.*, 2013)

在汶川地震之前，青藏高原东部位移场的总体特征为：① 以鲜水河-玉树-玛尼断裂带为界，南部地块表现为绕喜马拉雅东构造结的顺时针挤出式“流滑”，北部地块表现为左旋兼向南挤压；② 东缘边界构造带附近速度矢量和南北分量值较小；③ 速度矢量在各个地块内部的变化幅度较大。

Before the Wenchuan earthquake, the overall characteristics of the displacement field in the region are as follows: ① by the Xianshuihe fault-Yushu fault-Mani fault as a boundary, the south block shows a clockwise squeezing-out-style "flow-slip" in respect of the Himalayas East tectonic knob, and the north block shows a left-lateral strike-slip combined with southward compression; ② the velocity vector and its north and south components are smaller on the most eastern margin; and ③ the velocity vector is obviously varying within individual blocks.