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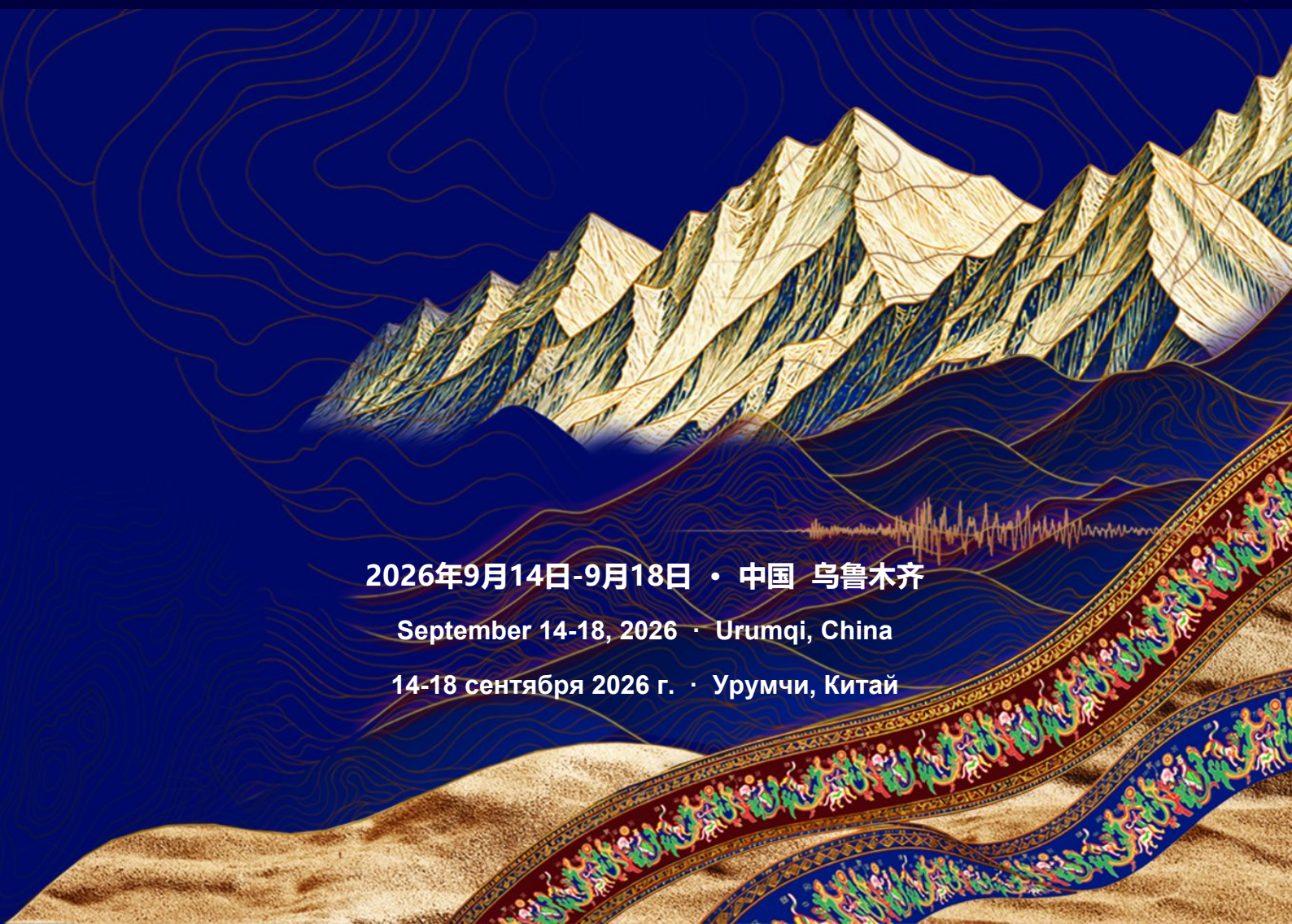
Abstract Volume

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СТРУКТУРНО-ГЕОФИЗИЧЕСКИЕ И СЕЙСМОТЕКТОНИЧЕСКИЕ МОДЕЛИ ЗЕМНОЙ КОРЫ ЮЖНОГО КАЗАХСТАНА КАК ОСНОВА ОЦЕНКИ СЕЙСМИЧЕСКОЙ ОПАСНОСТИ

A B Yerkinova, N P Stepanenko, O K Kurilova, T M Kaidash, T S Uteuliyev

(National Scientific Center for Seismological Observations and Research, Almaty, Kazakhstan)

АННОТАЦИЯ: Южный Казахстан входит в состав Приаральско-Каратауского сейсмоопасного региона, характеризующегося сложным геолого-тектоническим строением и проявлениями современной сейсмической активности. Несмотря на наличие значительного объема геологических и геофизических материалов, территория региона в сейсмологическом и сейсмотектоническом отношении остается изученной недостаточно. В то же время накопленные данные о глубинном строении, мощности земной коры и особенностях верхней мантии создают основу для комплексного изучения связи глубинного строения литосферы с современной геодинамикой и сейсмичностью.

На территории Южного Казахстана в разные периоды наблюдений были зарегистрированы сейсмические события с магнитудами $M=2,5-7,5$, что свидетельствует о наличии реальных и потенциальных сейсмогенерирующих зон, способных формировать сильные землетрясения. Такие зоны являются источниками интенсивных динамических воздействий на геологическую среду и, соответственно, на здания, сооружения и среду жизнедеятельности населения. Современная сейсмическая активность территории в значительной степени определяется предшествующей историей ее геологического развития, особенно процессами, происходившими на новейшем тектоническом этапе.

Цель исследования заключается в комплексном анализе структурно-геофизических и сейсмотектонических особенностей земной коры Южного Казахстана и построении моделей, которые могут быть использованы в качестве основы для оценки сейсмической опасности региона. Для решения поставленной задачи выполнено комплексирование имеющихся геолого-тектонических, геофизических и сейсмологических материалов. Структурно-геофизическая составляющая исследования характеризует особенности глубинного строения территории, включая неоднородности земной коры и верхней мантии. Сейсмотектоническая составляющая основана на анализе тектонических разломов, современной сейсмичности и пространственного положения реальных и потенциальных зон возникновения очагов землетрясений.

На основе комплексного анализа геофизических, геолого-тектонических и сейсмологических данных разработана региональная сейсмотектоническая модель Южного Казахстана, представленная картой сейсмогенерирующих зон. В пределах исследуемой территории выделены реальные и потенциальные зоны возникновения очагов землетрясений. Их положение рассматривается во взаимосвязи с основными тектоническими структурами и особенностями глубинного строения земной коры. Такой комплексный подход позволяет учитывать не только проявления современной сейсмичности, но и структурные факторы, определяющие геодинамическую активность территории.

Особое значение имеет карта тектонических разломов Южного Казахстана, систематизирующая информацию о разрывных структурах исследуемого региона. Она может использоваться при проведении сейсмотектонических и геодинамических построений, а также для решения прикладных задач, связанных с оценкой и прогнозированием опасных природных процессов, обусловленных деструкцией земной коры. Совместно с базой геолого-геофизических и сейсмологических данных карта формирует основу для дальнейшего накопления информации, ее тектонофизического анализа и развития тематических картографических проектов.

Разработанные структурно-геофизические и сейсмотектонические представления позволяют более обоснованно характеризовать потенциальные источники сейсмической опасности Южного Казахстана. Региональная сейсмотектоническая модель может служить основой для расчетов сейсмической интенсивности в вероятностной постановке и прогнозирования параметров сейсмических воздействий, в том числе пиковых ускорений грунта. Комплексное рассмотрение глубинного строения земной коры, тектонических разломов, сейсмогенерирующих зон и современной сейсмичности способствует более глубокому пониманию закономерностей сейсмотектонического и геодинамического развития Южного Казахстана и совершенствованию научной основы оценки сейсмической опасности региона.

STRUCTURAL-GEOPHYSICAL AND SEISMOTECTONIC MODELS OF EARTH'S CRUST OF SOUTHERN KAZAKHSTAN AS A BASIS FOR SEISMIC HAZARD ASSESSMENT

A B Yerkinova, N P Stepanenko, O K Kurilova, T M Kaidash, T S Uteuliyeu

(National Scientific Center for Seismological Observations and Research, Almaty, Kazakhstan)

Abstract: Southern Kazakhstan is part of the seismically hazardous Aral–Karatau region and is characterized by a complex crustal structure and significant seismic activity. Earthquakes with magnitudes of $M=2.5-7.5$ indicate the presence of actual and potential seismogenic zones. Based on integrated geological, geophysical, tectonic, and seismological data, structural-geophysical and seismotectonic models of Southern Kazakhstan were developed. The models characterize crustal and upper-mantle heterogeneities, tectonic faults, seismicity, and potential earthquake source zones. The developed seismotectonic model and fault map provide a basis for probabilistic seismic hazard assessment and estimation of seismic effects, including peak ground acceleration. The results contribute to a better understanding of the relationships between deep crustal structure, tectonics, and seismicity in Southern Kazakhstan.

STATISTICAL ANALYSIS OF SEISMIC DATA OF STRONG EARTHQUAKES IN ZHONGARIA

A. Danabayeva¹, Arman S. Kussainov², A. Katubayeva³, R. Gashimov⁴

(1. LLP "Institute of Seismic Safety" Almaty, Republic of Kazakhstan; 2. Physics and Technology Department, al-Farabi Kazakh National University, Almaty, Republic of Kazakhstan; 3. National Scientific Center for Seismological Observations and Research, Ministry of Emergency Situations of the Republic of Kazakhstan, Almaty, Republic of Kazakhstan; 4. LLP "Institute of Seismic Safety" Almaty, Republic of Kazakhstan)

Abstract: The paper presents an analysis of the seismic regime in the Zhongar-Borokhor border region, characterized by high seismic hazard and large potential earthquake source zones. Spatial analysis of strong events ($M \geq 6.1$) confirmed two linear seismic zones extending ~ 800 km and ~ 700 km along the mountain system. For data processing ($\sim 190,000$ events), a VBA macro in MS Excel was implemented, performing spatial polygon selection via a ray-casting algorithm, data sorting, and recurrence parameter calculation (trend slope $\gamma = 0.40-0.48$ for K_p). Particular emphasis is placed on constructing Benioff cumulative strain diagrams. In the software, deformation energy $\sum \sqrt{E_i}$ was computed with sign inversion for strong events ($K_p \geq 14$) to differentiate strain accumulation and release. The Benioff diagrams reveal a clear cyclicity in the seismic regime, where periods of strain accumulation alternate with strain release during strong earthquake clustering. The automated data processing tool and identified temporal patterns contribute to regional seismic hazard assessment.

СТАТИСТИЧЕСКИЙ АНАЛИЗ СЕЙСМИЧЕСКИХ ДАННЫХ СИЛЬНЫХ ЗЕМЛЕТРЯСЕНИЙ ЖОНГАРИИ

¹Данабаева А.Т. ²Кусайнов А.С. ³Катубаева А. М. ⁴Гашимов Р. А.

(1.ТОО «Институт сейсмической безопасности», г. Алматы, Республика Казахстан;
2.Физико-технический факультет, Казахский национальный университет имени аль-
Фараби, г. Алматы, Республика Казахстан; 3.Национальный научный центр
сейсмологических наблюдений и исследований МЧС РК, г. Алматы, Республика
Казахстан; 4.ТОО «Институт сейсмической безопасности», г. Алматы, Республика
Казахстан)

Аннотация: Жонгаро-Балхашский регион занимает особое место в оценке общей сейсмической обстановки юго-восточного Казахстана, поскольку по уровню сейсмического потенциала он занимает второе место после Северо-Тянь-Шаньского региона. В последние годы произошли некоторые изменения административных границ данного региона, в связи с чем наблюдается интенсивное освоение его территории. Это требует научно обоснованной оценки сейсмической опасности.

Информационную базу сейсмологических исследований составили каталоги сильных и слабых землетрясений юга и юго-востока Казахстана, а также унифицированный каталог землетрясений Тянь-Шаня, созданный в результате совместных исследований сейсмологов Казахстана, Кыргызстана и Сейсмологического бюро СУАР КНР. Уточнения каталога проводились в рамках международных проектов CASRI («Оценка сейсмического риска в Центральной Азии»), EMCA («Модель землетрясений в Центральной Азии») и международного сейсмологического каталога IRIS (Incorporated Research Institutions for Seismology).

Пространственный анализ показал, что эпицентры землетрясений с магнитудами $M \geq 4,8$ распределены по территории региона достаточно широко. При этом наиболее высокая концентрация сильных событий наблюдается в Южной Жонгарии и районе хребта Боро-Хоро. На территории Северной Жонгарии сильные землетрясения встречаются значительно реже. В западной части Жонгарии с конца 1970-х годов отмечается повышение сейсмической активности, связанное, в частности, с Баканасским землетрясением 1979 г. ($M = 5,8$), Текелийскими землетрясениями 1993 г. ($M = 5,8$) и 2009 г. ($M = 5,5$).

Особое значение имеют наиболее сильные исторические землетрясения региона. К числу наиболее разрушительных относятся события 1812 г. ($M \approx 7,5-8,0$), 1906 г. ($M \approx 7,5-8,0$) и 1944 г. ($M \approx 7,2$), эпицентры которых расположены преимущественно в районе хребта Боро-Хоро. Анализ событий с $M \geq 6,1$ показывает их выраженную пространственную организованность. Очаги сильных землетрясений формируют две протяженные линейные зоны севернее и южнее Жонгаро-Боро-Хоринской горной системы. Их протяженность составляет порядка 800 и 700 км соответственно. Большинство очагов имеет простирание с северо-запада на юго-восток.

Для количественной обработки репрезентативной базы данных (содержащей более 190 тыс. событий с древнейших времен до 2026 г.) был разработан программный VBA-макрос в среде Microsoft Excel. Программа осуществляет первичный анализ базы данных, сортировку событий по временным и энергетическим параметрам, а также пространственную выборку точек, попадающих в границы произвольного полигона, с использованием алгоритма пересечения луча (Ray-casting). На основе сформированных выборок выполнялось построение графиков повторяемости землетрясений. Применение методов линейной регрессии и наименьших квадратов позволило определить наклон линии тренда (угла наклона $\gamma \approx 0,40 \div 0,48$ для энергетических классов K_p) и оценить временные интервалы представительности данных для различных классов.

Основной акцент в работе сделан на исследовании процессов накопления и разрядки сейсмической энергии с использованием метода Беньюффа. В программном модуле был реализован алгоритм пересчета условной упругой деформации $\sum \sqrt{E_i}$ для каждого события выборки. Для дифференциации этапов накопления напряжений и их последующего сброса в алгоритме применен подход инверсии знака: слабым землетрясениям условно присваивается положительный вклад, а сильным событиям ($K_p \geq 14$) — отрицательный. Это дает возможность компактно представить многолетний временной ряд и сопоставлять фазы активизации и затишья.

Анализ построенных диаграмм Беньюффа для Жонгарского региона показывает четкое чередование периодов повышенной сейсмической активности и относительного спокойствия. Сильные землетрясения в большинстве случаев проявляются группами (кластерами), разделенными во времени интервалами пониженной активности.

Выводы: На территории Жонгаро-Боро-Хоринского региона подтверждено существование двух линейных зон возникновения разрушительных землетрясений. Использование автоматизированной системы обработки каталогов в Excel/VBA позволило повысить эффективность статистического анализа и построения диаграмм Беньюффа. Построенные графики упругой деформации демонстрируют циклический характер сейсмического режима региона, выражающийся в смене периодов накопления и разрядки упругих напряжений, что служит важной основой для долго- и среднесрочной оценки сейсмической опасности.

ACTIVE FAULTS ALONG THE CHINA-KYRGYZSTAN-UZBEKISTAN RAILWAY ROUTE

Abdrakhmatov_Kalysova

Abstract: The planned China-Kyrgyzstan-Uzbekistan railway line is a major transportation project being implemented in conditions of high seismic risk. The route runs through the Tianshan folded region, which is characterized by high tectonic activity. The key engineering challenge is to cross a number of active faults capable of generating strong earthquakes. The designers' task is not simply to lay a path, but to ensure the long-term stability of the roadbed, bridges, and tunnels under possible seismic impacts.

Along the route, specialists have identified several significant fault zones, each of which is characterized by a specific type of movement and seismic potential. Most of them are reverse faults—faults in which one crustal block is displaced upward relative to another. This kinematics leads to sharp vertical movements, which are particularly dangerous for linear structures. Among the most significant faults are the Torugart (segment length approximately 50 km, fault plane dip 30–55°, potential magnitude up to M_w 7.07) and the Aksay (Sredinny) fault, approximately 60 km long, northwest-oriented, and with a magnitude up to M_w 7.17. The Sredinno-Arpinsky fault, also classified as a reverse fault, has similar parameters.

The Dzhamantoo fault, which consists of two segments – the Southern and Northern – requires special attention. The southern segment is approximately 80 km long and has the highest seismic potential of the zone's segments—up to M_w 7.32. The northern segment is shorter (approximately 25 km) but is also classified as high-risk. Hazardous areas include the Baibichetoo and South Toguz-Torou faults (both reverse faults, approximately 70 km long). Traces of ancient earthquakes have been discovered in the South Toguz-Torou fault zone, including the Beshköl paleoearthquake, which manifested itself as a large seismic landslide. The presence of such evidence indicates the recurrence of strong seismic events and increases design requirements. From a seismic hazard perspective, the Talas–Fergana Fault is considered the most critical structure. Its central segment extends for approximately 160 km with a dip angle of 60–70°. Unlike most of the other faults along the route, it exhibits oblique-slip normal fault kinematics, combining both horizontal strike-slip and vertical normal displacement components. This makes deformation more difficult to predict and requires a more detailed assessment of potential fault displacements.

The fault is capable of generating earthquakes with a potential magnitude of up to M_w 7.63, while the estimated seismic intensity may exceed IX (9) on the MSK-64 scale. Peak Ground Acceleration in some sections reaches 0.6 g or higher, imposing stringent requirements on the strength and seismic performance of engineering structures.

The South Fergana Fault is also classified as a high-potential seismic source and must be carefully considered during route alignment and engineering design. Seismic hazard along the railway corridor is associated not only with the potential occurrence of strong earthquakes but also with a range of secondary earthquake-induced processes. The most significant of these is surface fault rupture, which may result in displacement of the railway track, damage to bridge piers, and deformation of tunnel portals. In mountainous terrain, seismic shaking can trigger landslides, rockfalls, and slope failures capable of blocking the railway alignment or damaging engineering structures. High Peak Ground Acceleration (PGA) values generate substantial dynamic loads on structures, while the heterogeneous ground conditions within fault zones—characterized by highly fractured and weakly cemented rocks—increase the risk of ground loosening and foundation settlement.

To minimize these risks, a comprehensive approach is adopted that integrates route optimization, engineering design, and monitoring measures. During the route selection stage, the alignment is adjusted to reduce the length of crossings over the most hazardous fault segments or, where feasible, to avoid them entirely. At locations where fault crossings are unavoidable, special structural provisions—such as expansion joints and flexible connections—are incorporated to accommodate potential fault displacements without causing structural failure. Major load-bearing structures, including bridges, tunnels, and retaining walls, are designed with enhanced seismic resilience, taking into account the design Peak Ground Acceleration values and site-specific ground response spectra.

Slope stabilization measures also play a critical role in risk mitigation. On potentially unstable slopes, engineering solutions such as retaining walls, rock anchors, drainage systems, and protective galleries are incorporated into the design to reduce the likelihood of landslides and rockfalls. To ensure continuous assessment of the railway corridor and early detection of deformation, monitoring systems are planned, including seismic sensors and geodetic benchmarks that enable real-time tracking of crustal movements and structural deformations.

The engineering design is based on a comprehensive set of geological and geotechnical data, including the results of geological and structural investigations, paleoseismological evidence, and instrumental measurements.

In summary, the China–Kyrgyzstan–Uzbekistan railway corridor crosses several active fault zones with high seismic potential, where earthquakes with intensities of IX (9) or greater on the MSK-64 scale may occur. The combined effects of active tectonic deformation, slope instability, and strong dynamic ground motions necessitate the implementation of multi-level engineering mitigation measures. The successful realization of the project depends on an interdisciplinary approach that integrates geological, seismological, and structural engineering expertise, together with continuous monitoring of infrastructure performance throughout the entire service life of the railway.

STRESS-STRAIN STATE OF THE NORTHERN TIAN SHAN AND THE METHOD FOR CALCULATING THE PHYSICAL AND MECHANICAL PARAMETERS OF STRONG EARTHQUAKE FOCI

Abdullaev A U, Amirov N B, Litovchenko I N, Lyutikova V S

(National Scientific Center for Seismological Observations and Research, Ministry of Emergency Situations
of the Republic of Kazakhstan)

Abstract: This paper describes the stress-strain state of the Northern Tianshan and describes a method for calculating the physical and mechanical parameters of strong earthquake foci. The geodynamic and physical-mechanical conditions of strong earthquake foci, the mechanisms of focal formation, and the stress-strain state of the environment are examined. Methods for calculating the physical and mechanical parameters, implementation algorithms, and numerical values for these parameters are presented. The conducted analysis allows us to evaluate the thermodynamic regime and rheological layering of the crust of the Northern Tianshan, and it also becomes possible to predict zones of partial melting and weakening of channels in the orogen crust. The stress-strain state of the Northern Tianshan is characterized by high instability, dynamism, and activity, driven by ongoing neotectonic movements and the collision of the Indian and Eurasian plates, which leads to frequent earthquakes, rockfalls, and the formation of the modern topography. This region exhibits complex stress fields (vertical and horizontal) that vary in time and space, creating conditions conducive to seismic activity. As a result of the conducted research, new scientific and practical results were obtained in the study of the stress-strain state of the environment where strong earthquakes originate, and a method for calculating physical and mechanical parameters was proposed. The crust of the Northern Tianshan is in a state of high modern tectonic activity within the Alpine folding, which causes frequent earthquakes and the formation of a high-mountain dissected relief with active scree, moraines, and alluvial fans caused by powerful compression and uplift of mountain ranges and basins, with sharp cliffs and steep slopes facing the plains, characteristic of the northern part. This entire zone is a potential environment for seismic landslide hazards and strong earthquakes. The geodynamic and physical-mechanical conditions for the formation of strong earthquake foci, the mechanisms of foci formation, and the stress-strain state of the environment were examined. Methods for calculating physical-mechanical parameters, implementation algorithms, and numerical values for these parameters were presented. Attention is paid to machine learning based on pattern recognition algorithms and the technology for their implementation. The increasing swarm activity in the Northern Tianshan region also confirms the active stress-strain state of the environment. The results of the conducted research can be used to construct maps of the spatiotemporal distributions of physical and mechanical parameters in the focal zones of strong earthquakes for further monitoring of their development. Overall, the conducted research is the final result of the research project “Stress-strain state of seismically active regions of the Northern Tianshan as an environment for the origin of strong earthquake foci and a method for calculating their physical and mechanical parameters.”

Author Biography:

Abdullaev Abdulaziz — Doctor of Geological and Mineralogical Sciences, Academician of MANEB MAIN, National Scientific Center for Seismological Observations and Research, Ministry of Emergency Situations of the Republic of Kazakhstan.

E-mail: u.abdullaev@mail.ru

Lyutikova Veronica — Master of Engineering and Technology, Leading Researcher, National Scientific Center for Seismological Observations and Research, Ministry of Emergency Situations of the Republic of Kazakhstan.

E-mail: nikki.vallo16@gmail.com

Litovchenko Irina — Leading Researcher, National Scientific Center for Seismological Observations and Research, Ministry of Emergency Situations of the Republic of Kazakhstan.

E-mail: litovira@rambler.ru

Amirov Nurkanat — Leading Researcher, National Scientific Center for Seismological Observations and Research, Ministry of Emergency Situations of the Republic of Kazakhstan.

E-mail: aminurbak@gmail.com

LATERAL FOLD GROWTH AND LINKAGE IN THRUST-FOLD BELT: INSIGHTS FROM NORTHERN TIANSHAN FOLD-AND-THRUST BELT

Chen Jiakun^{1,2,3}, Yao Yuan^{2,3}, Chen Jie^{2,3,4}, Di Ning^{2,4}

(1.University of Emergency Management, Langfang 065201,Hebei, China; 2.Xinjiang Pamir Intracontinental Subduction National Field Observation and Research Station, Urumqi 830011, Xinjiang, China;3.Urumqi Institute of Central Asia Earthquake, China Earthquake Administration, Urumqi 830011, Xinjiang, China;4.State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, Beijing 100029, China)

Abstract: "During their growth, folds evolve through shortening and uplift along the principal stress direction, as well as via lateral expansion perpendicular to it. This lateral expansion commonly induces structural interference between adjacent folds." Three-dimensional numerical simulation methods provide important insights into the linkage patterns of adjacent folds. However, linkage patterns derived from three-dimensional numerical simulations still require validation against modern landscape morphology. To investigate this issue, we selected the Halaand and Anjihai anticlines as study objects. The Halaand – Anjihai thrust-fold belt constitutes the third frontal row of the Northern Tianshan Fold-and-Thrust Belt (FTB); however, the linkage pattern between its constituent anticlines remains unresolved. We employed seismic profiles, detailed topographic surveys, UAV based aerial photography, and three-dimensional numerical modeling. Our results reveal that the Halaand anticline is a detachment fold, with the Cretaceous Tugulu Group acting as the detachment surface; meanwhile, the Anjihai anticline results from the interaction of deep and shallow structures, comprising a fault-propagation fold within the Cretaceous and a detachment fold in the Jurassic Xishanyao Formation. The Halaand and Anjihai anticlines extend laterally to the east and west, and ultimately converge. Based on prior research findings, the Halaand and Anjihai anticlines were expected to link up, ultimately forming a continuous anticlinal belt. However, when controlled by detachment surfaces at different depths, the lateral propagation directions of the two anticlines gradually diverge, thereby preventing their linkage. This finding indicates that the complexity of fold linkage patterns controlled by multiple detachment surfaces significantly far exceeds that predicted by simplified three-dimensional numerical simulations.

Keywords: Lateral fold growth; Fold linkage; Thrust-Fold belt; interaction of deep and shallow structure; Tian Shan

Author Biography: Chen Jiakun (2001—), Male, Master Degree Candidate, mainly engaged in research on active tectonic and structural geomorphology. E-mail:16651175870@163.com

LITHOSPHERIC DELAMINATION OF THE PAMIR DRIVEN BY THE UNDERTHRUSTING INDIAN PLATE AS INFERRED FROM SEISMIC OBSERVATIONS

Zhou Kecheng¹, Bao Xuewei¹, Zhang Bingfeng², Chen Hanlin¹, Pan Yang¹, Wu Yingkai¹

(1. School of Earth Sciences, Zhejiang University, Hangzhou 310027, Zhejiang, China; 2. Division of Mathematical Sciences, School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore 639798, Singapore)

Abstract: The tectonic evolution and deformation mechanisms of the Pamir remain controversial, partly because the crustal response to deep lithospheric geodynamic processes is insufficiently constrained. Two competing lithospheric tectonic models are under consideration: subduction of the Asian slab and delamination of Pamir lithosphere, each of which predicts distinct crustal anisotropic signatures. Here, we use shear-wave splitting of Moho P-to-S converted-phases from receiver functions recorded at 198 seismic stations to map crustal anisotropy across the Pamir and the surrounding regions, thereby providing direct constraints on crustal deformation styles. We further determine crustal thicknesses and V_p/V_s ratios using H - κ - c stacking. Crustal thickness correlates positively with surface elevation and negatively with Bouguer gravity anomalies, indicating that crustal thickening provides the dominant first-order support for the high topography. More importantly, Pms splitting measurements reveal strong crustal anisotropy, with a mean delay time of ~ 0.66 s, and a systematic rotation of fast-polarization orientations across the intermediate-depth seismicity belt. In the southern Pamir, convergence-parallel fast directions record N-S-oriented basal shear imposed by the indented Indian lithospheric mantle (ILM), which has likely promoted Quaternary extension of southern Pamir. Conversely, to the north of this belt, orogen-parallel fast directions signify pure-shear thickening of the Pamir lithosphere. Together with low crustal V_p/V_s ratios of 1.60–1.72 beneath the southern Pamir, which are consistent with a felsic bulk crust and removal of mafic lower crust, these observations favor Indian-lithosphere-induced delamination of the Pamir lithosphere rather than a model dominated by uniform southward subduction of Asian lithosphere.

Key words: Pamir Plateau; Crustal Deformation; Seismic Anisotropy; Crustal Thickness

SEISMIC REGIME OF THE WESTERN SEGMENT($\varphi=20-50^\circ$, $\lambda=68-80^\circ$) OF JUNCTION OF EURASIAN AND INDIAN LITHOSPHERIC PLATES

Omuralieva_Omuraliev

Abstract: The most seismically dangerous territory on Earth under study includes densely populated areas (from south to north) of India, Pakistan, Afghanistan, Tajikistan, Uzbekistan, China, Kyrgyzstan, Kazakhstan, and Russia. At the junction of the Eurasian and Indian lithospheric plates, mountain ranges (from south to north) form, including the Himalayas (at the foreland), Tibet, Pamir, Tianshan, Altai, and others, as a result of counter-mantle convection. The rate of subduction of the Indian Plate beneath the Eurasian Plate is currently 48 mm/year.

The results of the work of numerous researchers have noted the active right-lateral strike-slip faults: BOK Boluokenu, TFF Talas-Fergana, KRF Karakoram, JLF Jiali, RRF Red River, SGF Sagaing; left-lateral strike-slip faults: ATF Altyn-Tag, KKF Karakax, HYF Haiyuan, KLF Kunlun, XXF Xiangsu-Xiaojiang, KKF Karakax, CMF Chaman; thrust-reverse faults: MHT Main Himalayan, MKT Main Karakoram, LMSF Longmenshan, MPT Main Pamir, STSF Southern Tien Shan, as well as suture zones (from south to north): YTS Yarlung-Tsangpo, BNS Bangkok-Nujiang, JRS Jinshan, bounding terranes: Lasa, Kiantan, Songpan. In the central part of the Lasa terrane, a system of graben basins with Quaternary sediments develops. These basins suggest that they formed as a result of the upwelling of a mantle diapir in the Mount Everest region, spreading eastward and westward, followed by clockwise and counterclockwise rotation, respectively. A detailed seismic tomography study of the Kyrgyz Tien Shan revealed that the Kazakh Shield lithospheric plate is subducting beneath the Tianshan lithosphere in the north, while the Tarim lithospheric plate is subducting beneath the Tianshan lithosphere in the south. Beneath these zones, there are two low-velocity mantle anomalies that embed themselves in the Tianshan lithosphere.

The initial data for the seismic regime study were USGS earthquake catalogs for 1900–2026. Hierarchies of seismic cycles are marked on the distribution of magnitude and seismic moment in time and space. Each consists of phases of seismic activity, a peak of activity, a decline in seismic activity, and a seismic quiescence phase, each with its own specific magnitudes. The dependence of the average period of the seismic cycle (T) on the hierarchical order is expressed by the empirical formula:

$$T=952.95 n^{-3.534}, R^2=0.98$$

where T is the average period of the cycle (years), n is the hierarchical order (1, 2, 3, ...) of the seismic cycle, R^2 is the approximation reliability. Peaks of seismic activity were observed in 1900–1920 ($M \geq 8$), in 1940–1950 ($M=7.6-7.7$). After these peaks, a decline was observed. A sharp decline in seismic activity ($M < 7.4$) occurred after 1970–1974. In 1995, a seismic lull occurred ($M < 7.3$). From 2008–2010, there were bursts of seismic activity ($M < 7.7$), one of which was the Uchturfan earthquake of 2024 ($M=7.0$). Analysis of seismic regime trends shows that about 50 years from 1975 to 2026 are not comparable with the seismic activity levels for about 70 years from 1900 to 1970.

СЕЙСМИЧЕСКИЙ РЕЖИМ ЗАПАДНОГО СЕГМЕНТА ($\varphi=20-50^\circ$, $\lambda = 68-80^\circ$) СОЧЛЕНЕНИЯ ЕВРАЗИЙСКОЙ И ИНДИЙСКОЙ ЛИТОСФЕРНЫХ ПЛИТ

На исследуемой наиболее сейсмоопасной территории Земли находится густонаселенные районы (с юга на север) Индии, Пакистана, Афганистана, Таджикистана, Узбекистана, Китая, Кыргызстана, Казахстана, России.

На сочленении Евразийской и Индийской литосферных плит формируются горные системы (с юга на север) Гималая (в передовой части), Тибета, Памира, Тянь-Шаня, Алтая и др. в результате встречных мантийных конвекций. Скорость поддвигания Индийской плиты под Евразийскую плиту в настоящее время составляет 48 мм/год.

Результатами работ многочисленных исследователей отмечены активные разломы правосдвиговые: BOK Болуокенуйский, TFF Талас-Ферганский, KRF Каракорумский, JLF Цзялиский, RRF Красной реки, SGF Сагаинг; разломы левосдвиговые: ATF Алтын-Тагский, KKF Каракакский, NYF Хайюаньский, KLF Куньлуньский, XXF Сяньсуйхэ-Сяоцзянский, KKF Каракакский, CMF Чаманский; разломы взбросо-надвиговые: MHT Главный Гималайский, MKT Главный Каракорумский, LMSF Лонгменшаньский, MPT Главный Памирский, STSF Южный Тяньшань, а также шовные зоны (с юга на север): YTS Ярлунг-Цангпоский, BNS Бангкок-Нуцзянский, JRS Цзиньшаньский, ограничивающие террейны: Ласа, Киантан, Сонпан. В центральной части террейна Ласа развивается система грабеновых впадин с четвертичными отложениями. Эти впадины позволяют предположить, что они образовались вследствие подъема “мантийного диапира” в районе горы Эвереста, “растекающего” в восточном и западном направлениях и дальнейшего вращения течения по часовой и против часовой стрелки, соответственно. На основе изучения методом детальной сейсмической томографии Кыргызского Тянь-Шаня отмечено, что литосферная плита Казахского щита поддвигается под литосферу Тянь-Шаня на севере, а на юге литосферная плита Тарима поддвигается под литосферу Тянь-Шаня. Под этими зонами имеются два потока низкоскоростных аномалий в мантии, которые внедряются в литосферу Тянь-Шаня.

Исходными данными изучения сейсмического режима являлись каталоги землетрясений USGS за 1900-2026 гг. На распределении магнитуды и сейсмического момента во времени и пространстве отмечены иерархии сейсмических циклов. Каждая из них состоит из фаз сейсмической активизации, пика активизации, фазы спада сейсмической активизации, фазы сейсмического затишья со свойственными магнитудами. Зависимость среднего периода сейсмического цикла (Т) от иерархического порядка выражается эмпирической формулой:

$$T=952.95 \, n^{-3.534}, R^2=0.98$$

где T -средний период цикла (лет), n –иерархический порядок (1, 2, 3, ...) сейсмического цикла, R^2 - достоверность аппроксимации. Пики сейсмической активизации отмечались в 1900-1920 гг. ($M \geq 8$), в 1940-1950 гг. ($M=7.6-7.7$). После этих пиков проявился спад. Резкий спад сейсмической активизации ($M < 7.4$) произошел после 1970-1974 гг. В 1995 г. наступило сейсмическое затишье ($M < 7.3$). С 2008-2010 гг. произошли всплески сейсмической активизации ($M < 7.7$), одним из них является Учтурфанское землетрясение 2024 г. ($M=7.0$). Анализ тенденций сейсмического режима показывает, что в течение порядка 50 лет с 1975 г. по 2026 г. не сопоставимы с уровнями сейсмической активности за около 70 лет с 1900 г. по 1970 г.

SHORTENING RATE ACROSS TUGULU ANTICLINE IN NORTHERN TIANSHAN, DOCUMENTED BY GROWTH STRATA AND DEFORMED TERRACES

Liu Qi , Chen Jie, Li Tao, Qin Jintang, Yang Huili, Di Ning

(State Key Laboratory of Earthquake Dynamics and Forecasting, Institute of Geology, China
Earthquake Administration, Beijing 100029, China)

Abstract: Large-magnitude earthquakes that occur both along subduction zones and within fold-and-thrust belts have led to tens of thousands of deaths and billions of dollars of damage to infrastructure. However, deformation associated with thrust fault can be complicated, and even many active thrust faults are blind, such that surface deformation is characterized exclusively by folding. Recent studies have applied fault-related folding models to quantitatively relate surface folding strains to fault activity. The South Junggar Thrust Belt (SJT), developed at the northern foot of the Tianshan, was a natural laboratory for studying the geometry and kinematic mechanisms of the thrust-and-fold belts. SJT comprises 3-4 rows of nearly parallel eastern-western out-of-sequence active anticlines on the surface. A series of rivers cut through the anticlines, providing typical growth strata sections and multiple fluvial terraces to record the deformation history of the fold. In this study, we integrated records of surface deformation, subsurface structure, and geochronology to investigate active deformation history of Tugulu anticline, second row of the SJT, from ~300 ka to present.

Key words: South Junggar Thrust Belt (SJT); Growth strata; GNSS; Fold scarp

Author Biography: Liu Qi (1993–), Male, Associate Researcher, mainly engaged in active tectonics and quaternary geochronology. E-mail: liuqidzs@163.com

INTEGRATED THREE-DIMENSIONAL ANALYSIS OF ACTIVE FAULTS, EARTHQUAKE HYPOCENTERS AND TOPOGRAPHY IN THE NORTHERN TIAN SHAN USING GIS TECHNOLOGIES

Джанзаков Руслан Нурмашович¹, Балтабаева Бану Абдіманапқызы¹, Егинбекова
Назым Тазабековна¹

¹ТОО «Национальный научный центр сейсмологических наблюдений и
исследований» (ТОО «ННЦНИ»)

Аннотация

Северный Тянь-Шань является одной из наиболее сейсмоактивных областей Центральной Азии, где высокая плотность активных тектонических разломов обуславливает формирование многочисленных очагов землетрясений различной магнитуды. Исследование пространственного положения активных разломов, распределения гипоцентров землетрясений и особенностей рельефа представляет значительный интерес для оценки современных геодинамических процессов и совершенствования методов сейсмического районирования. Современные геоинформационные технологии позволяют объединить разнородные пространственные данные в единую трехмерную модель, существенно повышая наглядность анализа и достоверность интерпретации.

Целью настоящего исследования является создание трехмерной геоинформационной модели Северного Тянь-Шаня и проведение комплексного пространственного анализа взаимосвязи активных разломов, гипоцентров землетрясений и рельефа местности.

В качестве исходных данных использованы цифровая модель рельефа (DEM), цифровой слой активных тектонических разломов, а также каталог землетрясений Северного Тянь-Шаня за период **2005–2025 гг.** с координатами эпицентров, глубинами очагов и магнитудами. Пространственная обработка данных выполнена в программных комплексах **ArcGIS** и **Oasis Montaj**. На первом этапе все пространственные данные были приведены к единой системе координат и объединены в единую геобазу данных. Далее построена трехмерная модель территории исследования с использованием цифровой модели рельефа, на которую были наложены тектонические разломы и гипоцентры землетрясений. Для повышения информативности модели применены методы трехмерной визуализации, позволяющие отображать глубину расположения очагов землетрясений относительно поверхности рельефа.

Проведенный анализ показал, что распределение гипоцентров землетрясений носит выраженный пространственный характер и во многих случаях приурочено к зонам развития активных разломов. Наиболее высокая концентрация очагов наблюдается в пределах крупных тектонических структур Северного Тянь-Шаня, характеризующихся сложным строением рельефа и интенсивной современной тектонической активностью. Трехмерное отображение позволило более наглядно проследить взаимное положение разломов и гипоцентров, определить особенности их пространственного распределения и выявить участки повышенной концентрации сейсмических событий.

Созданная трехмерная геоинформационная модель демонстрирует высокую эффективность комплексного использования цифровых моделей рельефа, геологических и сейсмологических данных для исследования современных геодинамических процессов. Полученные результаты могут использоваться при уточнении схем активной тектоники, анализе пространственной структуры сейсмичности, подготовке тематических карт, а также при оценке потенциальной сейсмической опасности территории Северного Тянь-Шаня.

Научная новизна исследования заключается в создании единой трехмерной геоинформационной модели, объединяющей рельеф, активные разломы и гипоцентры землетрясений Северного Тянь-Шаня, что обеспечивает более полное представление о пространственных закономерностях современной сеймотектонической активности региона.

Ключевые слова: Северный Тянь-Шань, активные разломы, гипоцентры землетрясений, трехмерное моделирование, GIS, ArcGIS, Oasis Montaj, цифровая модель рельефа.

**INTEGRATED THREE-DIMENSIONAL ANALYSIS OF ACTIVE FAULTS,
EARTHQUAKE HYPOCENTERS AND TOPOGRAPHY IN THE NORTHERN TIAN
SHAN USING GIS TECHNOLOGIES**

Ruslan N. Dzhanzakov¹, Banu A. Baltabayeva¹, Nazym T. Yeginbekova¹, Arai B. Gaipova¹

¹LLP "National Scientific Center for Seismological Observations and Research" (NSCSOR),
Almaty, Kazakhstan

Abstract

The Northern Tien Shan is one of the most seismically active regions of Central Asia, where the high density of active tectonic faults contributes to the occurrence of numerous earthquakes of varying magnitudes. The study of the spatial distribution of active faults, earthquake hypocenters, and topographic features is of considerable importance for assessing modern geodynamic processes and improving seismic zonation methods. Modern geoinformation technologies make it possible to integrate heterogeneous spatial data into a unified three-dimensional model, significantly enhancing the visualization of spatial relationships and the reliability of interpretation.

The aim of this study is to develop a three-dimensional geoinformation model of the Northern Tien Shan and to conduct a comprehensive spatial analysis of the relationships between active faults, earthquake hypocenters, and terrain relief.

The input data included a digital elevation model (DEM), a digital layer of active tectonic faults, and an earthquake catalog for the Northern Tien Shan covering the period **2005–2025**, including epicenter coordinates, focal depths, and magnitudes. Spatial data processing was carried out using **ArcGIS** and **Oasis Montaj** software. At the first stage, all spatial datasets were transformed into a unified coordinate system and integrated into a single geodatabase. Subsequently, a three-dimensional model of the study area was created using the digital elevation model, with tectonic faults and earthquake hypocenters overlaid on the terrain surface. To improve the informativeness of the model, three-dimensional visualization techniques were applied to represent the focal depths of earthquakes relative to the Earth's surface.

The analysis showed that the distribution of earthquake hypocenters exhibits pronounced spatial patterns and, in many cases, is associated with zones of active fault development. The highest concentration of earthquake hypocenters is observed within major tectonic structures of the Northern Tien Shan, characterized by complex topography and intense modern tectonic activity. Three-dimensional visualization made it possible to more clearly examine the spatial relationships between faults and hypocenters, identify patterns in their spatial distribution, and delineate areas with an increased concentration of seismic events.

The developed three-dimensional geoinformation model demonstrates the high effectiveness of integrating digital elevation models, geological data, and seismological data for

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the investigation of modern geodynamic processes. The results obtained can be used to refine active tectonic schemes, analyze the spatial structure of seismicity, prepare thematic maps, and assess the potential seismic hazard of the Northern Tien Shan.

The scientific novelty of the study lies in the development of a unified three-dimensional geoinformation model integrating terrain relief, active faults, and earthquake hypocenters of the Northern Tien Shan, providing a more comprehensive understanding of the spatial patterns of modern seismotectonic activity in the region.

Keywords: Northern Tien Shan, active faults, earthquake hypocenters, three-dimensional modeling, GIS, ArcGIS, Oasis Montaj, digital elevation model.

SEISMIC-INDUCED HAZARDOUS GEOLOGICAL PHENOMENA AND THEIR DISTRIBUTION IN SOUTHEAST AND EASTERN KAZAKHSTAN AS A REFLECTION OF MODERN GEODYNAMIC PROCESSES

Abstract: The main factors determining engineering-geological conditions, patterns of development, and distribution of hazardous geological phenomena (HGP) in the territory of Eastern and South-Eastern Kazakhstan have been identified. The diversity of geological, hydrogeological, engineering-geological, and seismic conditions of the territory under consideration determines the development of various genetic types of hazardous geological phenomena, such as: earthquakes, seismic dislocations, seismic collapses, landslides, scree, avalanches, mountain lakes, mudflows, etc. At present, it is especially important to conduct monitoring studies of the occurrence of hazardous phenomena in order to study the assessment of the scale of manifestations and reduce the damage from them.

Аннотация: Выявлены основные факторы, определяющие инженерно-геологические условия, закономерности развития и распространения опасных геологических явлений (ОГЯ) на территории Восточного и Юго-Восточного Казахстана

Разнообразие геологических, гидрогеологических, инженерно-геологических, сейсмических условий рассматриваемой территории обуславливают здесь развитие различных генетических типов опасных геологических явлений, таких как: землетрясения, сейсмодислокации, сейсмообвалы, оползни, осыпи, лавины, горные озёра, селевые потоки и др.

В настоящее время особенно актуально проведение мониторинговых исследований ОГЯ с целью изучения оценки масштабов проявлений и уменьшение ущерба от них.

EARTHQUAKE-SOURCE DIRECTIONS RECORDED IN SEISMITES

EARTHQUAKE-SOURCE DIRECTIONS RECORDED IN SEISMITES

Shi Xuhua^{1,2,3,4*}, Yang Xiao^{1,2}, Yang Haibin^{1,2*}, Chen Hanlin^{1,2*}, Liu Xin^{1,2}, Lu Yin⁵,
Ge Jin⁶, Li Feng⁷, Yan Yixi¹, Bai Zhuona¹, Chen Jie^{3,8}, Yann Klinger⁹

(1. School of Earth Sciences, Zhejiang University, Hangzhou, China; 2. Research Center for Structures in Oil and Gas Bearing Basins, Ministry of Education, Hangzhou, China; 3. Xinjiang Pamir Intracontinental Subduction National Field Observation and Research Station, Urumqi, China; 4. Zhejiang Key Laboratory of Advanced Technology Research for Work Safety and Natural Disaster Emergency, Hangzhou, China; 5. State Key Laboratory of Marine Geology, Tongji University, Shanghai, China; 6. Jiangsu Earthquake Agency, Nanjing, China; 7. GFZ German Research Centre for Geosciences, Potsdam, Germany; 8. State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, Beijing, China; 9. Université Paris Cité, Institut de Physique du Globe de Paris, CNRS; Paris, France)

Abstract: Earthquake source direction is central to understanding rupture processes and seismic hazards, yet remains difficult to recover before the instrumental era. Seismites—sedimentary records of earthquake shaking preserved as soft-sediment deformation structures—are widely used to identify paleoearthquakes, but their capacity to retain directional information about seismic wavefields has remained unresolved. Here we show that well-preserved, non-collapse seismites record directional signatures of earthquake wavefields in three-dimensional deformation fabrics where slope-driven deformation is limited. Numerical simulations indicate that horizontally polarized shear waves generate the strongest asymmetric shear and folding on planes perpendicular to wave propagation. Applied to a confirmed three-dimensional seismite exposure in the northeastern Pamir, this framework reconstructs event-specific wave-propagation directions and identifies likely source regions. Seismites can therefore retain a physical memory of earthquake-wave propagation where instrumental and surface-rupture records are absent.

Key words: Earthquake Source Direction; Seismite; Deformation Fabrics; Pre-instrumental Earthquakes; Seismic Wavefields

Author Biography: Shi Xuhua, Male, Professor specialized in active tectonics, geomorphology and earthquake geology. E-mail: shixuhua@zju.edu.cn

GREAT EARTHQUAKE BEHAVIOUR UNLIKELY TO BE CONTROLLED BY SUBDUCTION INTERFACE ROUGHNESS

Yang Xiaodong^{1,2}, Rebecca E. Bell², Alexander C. Whittaker², Xu Haobo^{1,3}, Han Xinze^{1,3},
Angela R. Knowlson², Valerie Locher²

(1. State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, China ; 2. Department of Earth Science and Engineering, Imperial College London, London, UK; 3. University of Chinese Academy of Sciences, Beijing, China)

Abstract: Subduction zones host the largest seismogenic zones on earth and hence the largest earthquakes. However, although some subduction margins generate some of the most destructive earthquakes (e.g., Japan, Sumatra), others appear to slip less dramatically in slow slip events, by aseismic creep or in small-moderate earthquakes (e.g., north Hikurangi). Subduction interface topography ('roughness') has emerged as a leading parameter in controlling the seismicity at subduction zones, although there is strong debate as to whether rough patches are asperities or barriers to large rupture. This issue persists because observational studies are limited to individual margins, seafloor bathymetry used as proxy for plate interface topography is not direct measurement, and historical earthquake record is short, which together make the precise assessment of earthquake potential in a subduction margin challenging. Here we test whether geodetic interplate coupling is an indicator of earthquake potential in lieu of a longer historical records. We then use direct seismic reflection observations from 35 plate boundary faults to quantify three types of roughness at 1–10 km length scales. We find a strong and positive relationship between maximum magnitude and interplate coupling. Strikingly, no relationship is observed between any of the roughness parameters and maximum earthquake magnitudes/interplate coupling. This result challenges the long-standing paradigm that the plate interface roughness is a pivotal factor in governing seismogenic behaviour. We suggest that short-wavelength (≤ 10 km) roughness has different effects on earthquake nucleation depending on the prevailing stage of earthquake cycle. Our findings challenge the prevailing hypothesis that subduction interface roughness is a predominant control on its seismogenic behaviour, and imply that interface roughness measured over length scales up to 10 km should not be used to assess a margin's seismic hazard.

Author Biography: Yang Xiaodong. E-mail: xdyang@scsio.ac.cn

APPLICATIONS OF ROCK SURFACE LUMINESCENCE DATING TO GRAVEL DEPOSITS IN PALEOSEISMIC TRENCHES

Yuan, B.Q.¹Liu, J.F.¹Yuan, Z.D.¹Kook, M.²Cui, F.R.¹Tian, Y.Q.¹Huang M.C.¹Chen, J.¹Qin,
J.T.¹Yang, H.L.¹Li, S.H.¹

- (1. State Key Laboratory of Earthquake Dynamics and Forecasting, Institute of Geology, China Earthquake
Administration, Beijing 100029, China;
2. Department of Physics, Technical University of Denmark, Risø Campus, Roskilde, DK-4000, Denmark)

Abstract: Paleoseismic research provides a key approach to understanding the recurrence patterns and spatiotemporal distribution of large earthquakes. The precise establishment of a chronological sequence of paleoseismic events forms the foundation of such studies. Trench investigations represent one of the primary methods in paleoseismic research. By identifying deformation records in fault zones and adjacent sedimentary strata, chronological constraints on paleoseismic events can be determined by luminescence dating techniques, which are conventionally applied to sediment grains of silt (a few microns) and fine sand (about 100 microns) in size. This study explores the methodological aspects of dating using gravels larger than 4 mm, which are several orders of magnitude larger than silt and fine sand. Dating sediments with contrasting grain sizes can reveal distinct sedimentological characteristics, as different grain fractions exhibit different transport histories and degrees of sunlight exposure.

Rock surface luminescence dating was adopted in this study. Cobbles and pebbles were collected from different depositional positions in several paleoseismic trenches excavated on active faults in the Southern Tianshan thrust belt in western China, and a two-dimensional (2D) luminescence imaging system was employed to obtain the spatial distribution of luminescence signals and to analyze signal variations at different orientations within individual gravels. The bleaching variability among gravels from modern surfaces, paleo-surfaces, and colluvial wedges was compared within a trench. The influence of gravel orientation on dating results was evaluated, and the mechanisms and processes of luminescence signal bleaching were inferred. Based on 2D imaging measurements, appropriate gravel clasts were identified and selected for burial age determination. These results were further integrated with luminescence dating of sediment grains in silt and sand sizes to establish a chronological sequence that constrains the timing of paleoseismic events.

This study provides a methodological basis for constraining the chronology of gravel-dominated depositional systems in paleoseismic trenches and offers new technical support for understanding the recurrence characteristics of large earthquakes along active faults in western China.

Key words: Rock surface luminescence dating; Paleoseismic trenches; Southern Tianshan; 2D luminescence imaging system

SEISMIC ENERGY RELEASE DYNAMICS ACROSS ACTIVE DEEP FAULT ZONES OF EASTERN UZBEKISTAN

Yusupov V R, Boltaev F Sh

(Institute of Seismology, Academy of Sciences of the Republic of Uzbekistan, Tashkent)

Abstract: Earthquake forecasting remains one of the most pressing yet least resolved problems in modern seismology. At the Institute of Seismology of the Academy of Sciences of the Republic of Uzbekistan, comprehensive research into precursors of strong earthquakes is being carried out using geophysical, hydrogeoseismological and deformometric methods, supported by an expanding network of seismic stations established in accordance with Resolution No. PP-4794 of the President of the Republic of Uzbekistan, dated 30 July 2020, “On measures for the fundamental improvement of the system of seismic safety of the population and territories of the Republic of Uzbekistan”. Among the known approaches to earthquake forecasting — analysis of changes in seismic wave velocity, source mechanisms, construction of Benioff graphs, and the study of periodicity and migration of earthquake sources — a special place belongs to the study of regularities in the release of seismic energy in time and space within zones of active deep faults. Despite its practical importance, this aspect remains insufficiently studied.

The purpose of the present work was to investigate the temporal distribution of seismic energy in the zones of three major active faults of Eastern Uzbekistan — the Karzhantau, North Fergana and South Fergana faults. The Karzhantau fault, about 200 km long and 1-15 km wide in the northeast, widening to 25-30 km in the southwest, is the most active fault in the Tashkent region; it was formed in the Upper Paleozoic-Mesozoic and has a reverse-thrust morphology. The South Fergana and North Fergana faults, which reach the Paleozoic basement, bound the Fergana Valley on both sides and are recognized by many researchers as major tectonic structures of the region.

The composite earthquake catalogue of Central Asia for the period 1970-2020 was used as the initial data, covering the territory bounded by coordinates 36-42°N and 66-74°E. A total of 4735 earthquakes with magnitude $M \geq 3.5$ were analyzed. The energy of each event was calculated using the formula $\lg E = 1.8M + 4$, where M is the earthquake magnitude. The study areas of the faults were divided into elementary cells with a step of 0.1° in latitude and longitude; moving from west to east, the longitudinal coordinates of the cells changed while the latitudinal coordinates remained constant. The linear size of each cell was about 80 km, corresponding to the characteristic size of the precursory zone for earthquakes with $M \geq 3.5$ and providing the necessary statistics of annual seismic energy ($E \geq 10^{12}$ J). Time series of the cumulative annual energy $E\Sigma$ for each fault zone were constructed using Excel and ArcGIS software, following the algorithm for calculating the seismic regime parameter.

The results showed that in all three zones, the release of seismic energy occurs unevenly, alternating between active and quiet periods. In the Karzhantau fault zone, an active period was observed in 1971-1987, during which the Tavaksay (1977) and Nazarbek (1980) earthquakes occurred; relative calm was observed from 1988 to 2007, followed by renewed activation of seismicity from 2008 to 2019. The South Fergana fault is characterized by substantially higher seismic activity compared with Karzhantau: the amount of energy released during active periods (1974-1985 and 2008-2020) exceeds the level typical of the quiet period of 1988-2007 by 2-3 orders of magnitude. At the same time, the active and quiet periods in the Karzhantau and South Fergana fault zones coincide almost synchronously. In contrast, the North Fergana fault demonstrates a different rhythm of activation: anomalous energy releases were recorded in 1972-1978, 1983-1995 and 2014-2016, while relative quiescence occurred in 1979-1982 and 1996-2004, which does not coincide in time with the activation of the neighboring structures.

Thus, the results obtained indicate that each of the studied active deep faults has its own characteristic rhythm of seismic energy release, which in some cases is synchronized between neighboring structures and in others develops independently. Systematic monitoring of annual variations of the $E\Sigma$ parameter in zones of active deep faults may serve as a useful tool for medium- and long-term forecasting of seismic hazard in the territory of Uzbekistan.

Key words: Seismic energy release; Active deep faults; Karzhantau, Fergana Valle; Earthquake catalogue; Seismic hazard forecasting

Author Biography: Yusupov V R (Head of Lab, PhD), Boltaev F Sh (Leading engineer.) Institute of Seismology, Academy of Sciences of the Republic of Uzbekistan, Tashkent. E-mail: valijon.yusupov@mail.ru; boltayevfarhod373@gmail.com

**Абилаханова И.Т.^{1,2}, Досымбекова Ж.Б.², Исаева Л.Д.¹, Тогизов К.С.¹,
Балтабаева Б.А.^{1,2}, 2026**

¹Сатпаев Университет, ул. Сатпаева 22, Алматы, Казахстан

² Национальный Научный Центр Сейсмологических Наблюдений и Исследований
(ННЦСНИ), ул. Аль – Фараби 75 А, Алматы, Казахстан

ГИДРОГЕОЛОГИЧЕСКИЕ ПРИЗНАКИ АКТИВНОСТИ ТЕКТОНИЧЕСКИХ РАЗЛОМОВ АЛМАТИНСКОЙ АГЛОМЕРАЦИИ ПО ДАННЫМ РАДОНОВЫХ ИССЛЕДОВАНИЙ

**Абилаханова И.Т.^{1,2}, Досымбекова Ж.Б.², Исаева Л.Д.¹, Тогизов К.С.¹,
Балтабаева Б.А.^{1,2}, 2026**

(1. Сатпаев Университет, ул. Сатпаева 22, Алматы, Казахстан; 2 Национальный
Научный Центр Сейсмологических Наблюдений и Исследований (ННЦСНИ), ул. Аль –
Фараби 75 А, Алматы, Казахстан)

Абилаханова Индира – докторант кафедры Геофизики и сейсмологии, Satbayev University, Алматы,
Казахстан,

E-mail: Botashka_89@inbox.ru, <https://orcid.org/0000-0003-0704-1713>

Досымбекова Жансая - докторант кафедры Геофизики и сейсмологии, Satbayev University, Алматы,
Казахстан,

E-mail: z.dossymbekova@satbayev.university, <https://orcid.org/0009-0000-6683-4604>;

Исаева Людмила Джандуйсеновна – Доктор геолого-минералогических наук, ассоциированный профессор
кафедры Геофизики и сейсмологии, Satbayev University, Алматы, Казахстан,

E-mail: lissayeveva@satbayev.university

Тогизов Куаныш– PhD, Геофизика және сейсмология кафедрасының профессоры, Сатбаев университеті,
Алматы, Қазақстан,

E-mail: k.togizov@satbayev.university, <https://orcid.org/0000-0002-4830-405X>;

Балтабаева Бану – докторант, Satbayev University, Алматы, Казахстан,

E-mail: banuka89@mail.ru

Алматинская агломерация расположена в пределах Северного Тянь-Шаня и относится к регионам с высокой сейсмической активностью. В связи с активным освоением территории и развитием городской инфраструктуры особое значение приобретает изучение активных тектонических разломов, оказывающих влияние на современные геодинамические процессы. Одним из информативных подходов к их исследованию является анализ гидрогеологических и газогеохимических признаков, отражающих особенности строения и проницаемости разломных зон.

Среди газогеохимических показателей наиболее чувствительным индикатором тектонической активности считается радон. Его миграция к поверхности осуществляется преимущественно по системам трещин и разломов, которые служат естественными путями переноса газа. Повышенные концентрации радона в почвах и грунтах, как правило, приурочены к зонам повышенной трещиноватости и проницаемости, что позволяет использовать радоновые аномалии при выявлении активных тектонических нарушений.

Целью исследования являлось изучение гидрогеологических признаков активности тектонических разломов Алматинской агломерации по результатам определения концентрации радона в почвах и грунтах. Основное внимание уделялось оценке пространственного распределения радона в пределах известных разломных зон и выявлению участков с аномальными значениями.

Исследования проводились на трех профилях: Каскеленском, Котырбулакском и Бельбулакском. Выбор этих участков обусловлен их расположением в пределах активных тектонических нарушений, выделенных по данным геологических исследований. На каждом

профиле выполнялись измерения концентрации радона с поверхности почв и грунтов. Полученные результаты сопоставлялись с положением известных разломов и особенностями геологического строения исследуемых территорий.

Результаты исследований показали, что активные разломы Алматинской агломерации сопровождаются устойчивыми зонами повышенных концентраций радона. На всех исследованных профилях выявлены газогеохимические аномалии, пространственно совпадающие с ранее установленными тектоническими нарушениями. Это подтверждает, что радоновые аномалии являются надежным признаком современной активности разломных зон и отражают их повышенную проницаемость.

Наиболее интересные результаты получены на Каскеленском профиле. Помимо аномалий, соответствующих известным разломам, здесь выделен дополнительный участок с повышенной концентрацией радона. Его положение не совпадает с ранее картированными тектоническими нарушениями, что позволяет предположить существование маломощных разломов в районе притока реки Каскелен. Данная аномалия требует дальнейшего изучения с привлечением комплекса геолого-геофизических методов, однако уже на данном этапе она представляет интерес для уточнения тектонического строения рассматриваемой территории.

Полученные результаты свидетельствуют о высокой информативности радоновых исследований при изучении активных разломов. В отличие от многих других методов, радоновая съемка позволяет фиксировать зоны современной повышенной проницаемости, связанные с процессами тектонической активности. Это особенно важно на участках, где разломы перекрыты рыхлыми четвертичными отложениями и не имеют четкого выражения в рельефе.

Следует отметить, что интерпретация радоновых аномалий должна проводиться с учетом геологического строения территории, литологического состава пород, гидрогеологических условий и других природных факторов, способных оказывать влияние на миграцию радона. Поэтому наиболее достоверные результаты достигаются при комплексном использовании геологических, гидрогеологических, геофизических и газогеохимических методов исследования.

Таким образом, выполненные исследования подтвердили возможность использования радона как одного из наиболее чувствительных индикаторов активности тектонических разломов Алматинской агломерации. Выявленные аномальные зоны совпадают с положением известных разломов, а обнаруженный участок повышенной концентрации радона в районе притока реки Каскелен, вероятно, связан с ранее невыделенными маломощными тектоническими нарушениями. Полученные данные могут быть использованы при дальнейшем изучении современной геодинамики региона, уточнении схем активных разломов, а также при инженерно-геологических и сейсмотектонических исследованиях территории.

HYDROGEOLOGICAL INDICATORS OF ACTIVE TECTONIC FAULTS IN THE ALMATY AGGLOMERATION BASED ON RADON SURVEYS

Abstract: The Almaty agglomeration is located within the Northern Tianshan, a region of high seismic activity. This study evaluates active fault zones using soil radon concentrations as a hydrogeological and gas-geochemical indicator. Radon migrates to the surface mainly through fractures and faults; therefore, elevated concentrations indicate increased rock permeability and possible tectonic activity. Radon measurements were carried out along three profiles: Kaskelen, Kotyrbulak, and Belbulak. The results show stable radon anomalies that coincide with previously mapped active faults, confirming the reliability of radon as an indicator of fault activity. The most significant result was obtained on the Kaskelen profile, where an additional radon anomaly was detected outside known fault zones. This anomaly may indicate previously unmapped minor faults near a tributary of the Kaskelen River. The findings demonstrate that radon surveys are an effective tool for identifying active fault zones, especially where faults are covered by Quaternary deposits. These results can support further geological, engineering, and seismotectonic investigations in the Almaty region.

天山及塔里木盆地岩石圈有效弹性厚度特征研究

艾力夏提·玉山^{1,2}，刘代芹²，黄金水¹，侍文³

(1. 中国科学技术大学地球和空间科学学院, 安徽 合肥 230026; 2. 新疆维吾尔自治区地震局, 新疆 乌鲁木齐 830011; 3. 中国地震局地球物理研究所, 北京 100081)

摘要: 天山及塔里木盆地位于欧亚大陆内部的重要构造变形区, 是印度板块与欧亚板块持续碰撞远程效应的典型响应区域, 是研究大陆内部强震孕育机理和岩石圈力学性质的理想天然实验室。岩石圈有效弹性厚度 (T_e) 作为综合反映岩石圈热结构、流变强度和构造改造程度的关键参数, 对理解深部应力传递、应变积累及地震空间分布具有重要意义。然而, 该区域地形起伏剧烈、构造单元分异显著, 基于卫星数据的重力场模型存在系统误差, 此外由于缺乏地面观测数据的制约, 在天山及邻区重力模型精度较低, 制约了 T_e 反演的可靠性及深部结构分析的精细程度。

针对上述问题, 本文以天山及塔里木盆地为研究对象, 系统开展多源重力数据融合研究。首先, 基于 3 000 余个地面实测重力数据获取区域高精度布格重力异常。在此基础上, 提出一种多项式趋势面系统偏差校正与深度学习精细校正相结合的两阶段融合方法: 利用二阶多项式拟合 WGM2012 全球重力模型与地面实测数据间的区域趋势性偏差, 再构建多尺度残差神经网络, 以重力场值、梯度幅值、局部统计量和空间坐标等多维特征为输入, 学习并校正残差中的局部非线性信号, 最终获得兼具区域背景稳定性和局部异常细节的高精度布格重力场模型。随后, 利用联合导纳和相关函数反演方法, 结合 Crust1.0 地壳模型和 ETOPO1 地形数据, 在贝叶斯最优参数估计框架下反演研究区岩石圈有效弹性厚度 (T_e) 及初始载荷比 (F) 的空间分布。初步结果表明, 研究区 T_e 值总体介于 14~48 km, 不同构造单元之间分异显著, 反映了天山活动造山带与塔里木稳定克拉通之间的岩石圈强度差异, 且中低 T_e 区与历史强震密集带、盆山边界逆冲断裂带及重力梯度带具有较好的空间对应关系, 指示岩石圈力学弱化带对地震孕育和破裂起始具有重要控制作用。本研究不仅为天山及邻区提供了高精度区域重力场模型, 也为揭示大陆内部造山带与盆地过渡带的深部动力学过程及地震危险性评估提供了重要地球物理约束, 具有理论探索与应用实践的双重价值。

关键词: 天山; 塔里木盆地; 布格重力异常; 岩石圈有效弹性厚度

作者简介: 艾力夏提·玉山 (1984-), 男, 高级工程师, 主要从事重力与地震预测研究.E-mail: irxat@163.com

CHARACTERISTICS OF THE EFFECTIVE ELASTIC THICKNESS OF THE LITHOSPHERE BENEATH THE TIANSHAN OROGEN AND TARIM BASIN

Ailixiati Yushan^{1,2}, Liu Daiqin², Huang Jinshui¹, Shi Wen³

(1. School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China; 2. Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, China; 3. Institute of Geophysics, China Earthquake Administration, Beijing 100081, China)

Abstract: The Tianshan and Tarim Basin region serves as an ideal natural laboratory for investigating the seismogenic mechanisms of intracontinental large earthquakes and the mechanical properties of the continental lithosphere. The effective elastic thickness (T_e) of the lithosphere, as a key parameter that comprehensively reflects the thermal structure, rheological strength, and degree of tectonic reworking of the lithosphere, plays a critical role in understanding deep-seated stress transfer, strain accumulation, and the spatial distribution of earthquakes. However, this region is characterized by rugged topography and significant lateral variations in tectonic units. Gravity field models derived from satellite data suffer from systematic errors, and the scarcity of ground-based gravity observations further limits the accuracy of existing gravity models across the Tianshan and its adjacent areas, thereby hampering the reliability of T_e inversions and the resolution of detailed deep structural analyses. This study focuses on the Tianshan orogen and Tarim Basin and systematically carries out a multi-source gravity data fusion. First, we computed high-precision complete Bouguer gravity anomalies based on more than 3,000 ground-based gravity measurements. On this basis, we propose a two-stage fusion approach that combines polynomial trend-surface correction for systematic bias and deep-learning-based fine correction. Specifically, a second-order polynomial is employed to fit the regional trend of the systematic deviations between the WGM2012 global gravity model and the ground-measured data. Subsequently, a multi-scale residual neural network is constructed, taking multi-dimensional features—including gravity field values, gradient amplitudes, local statistical moments, and spatial coordinates—as inputs to learn and correct the residual local nonlinear signals. Through this procedure, we obtain a high-precision Bouguer gravity field model that preserves both the stability of the regional background field and the detailed local anomalous features. Then, using the joint inversion method of admittance and coherence functions, combined with the Crust1.0 crustal model and the ETOPO1 topographic data, we invert for the spatial distribution of the lithospheric effective elastic thickness (T_e) and the initial load ratio (F) under a Bayesian optimal parameter estimation framework. The results indicate that the T_e values in the study area range from 14 to 48 km overall, with pronounced spatial variations among different tectonic units, reflecting the lithospheric strength contrast between the active Tianshan orogenic belt and the stable Tarim craton. Furthermore, the moderate-to-low T_e zones show a good spatial correspondence with the clusters of historical large earthquakes, the foreland thrust fault systems along the basin–orogen boundaries, and the gravity gradient belts, suggesting that lithospheric mechanical weak zones exert significant control on earthquake preparation and rupture initiation. This study not only provides a high-precision regional gravity field model for the Tianshan and its neighboring regions but also offers important geophysical constraints for understanding the deep dynamic processes across the transitional zone between the intracontinental orogen and the basin, as well as for regional seismic hazard assessment, bearing both theoretical significance and practical application value.

Key words: Tianshan; Tarim Basin; Bouguer Gravity Anomaly; Effective Elastic Thickness of the Lithosphere

Author Biography: Ailixiati Yushan (1984-), Male, Senior Engineer, mainly engaged in research on gravity observations and earthquake prediction. E-mail: irxat@163.com

新疆乌恰县城市活动断层探测项目主要成果简介

常想德, 胡伟华, 吴国栋, 巴图孟克, 黄高风

(新疆维吾尔自治区地震局, 新疆 乌鲁木齐 830011)

摘要: 新疆乌恰县位于塔里木盆地、南天山褶皱山及西昆仑—帕米尔构造带三大构造单元交汇部位, 是中国大陆受板块动力作用最强烈、强震频发的地区之一。本项目以乌恰县主城区和规划区作为探测目标区, 采用遥感调查、地貌填图、槽探、钻孔探测、浅层地震勘探及深地震反射探测等方法, 对目标区内的活动断层及其深部地震构造环境进行了系统的探测, 对目标断层的危险性和危害性进行了评价, 项目成果为乌恰县城市发展规划、土地利用、重大工程选址以及防震减灾提供科学依据。

乌恰县目标区断裂为乌恰盆地南缘断裂, 断裂走向近 EW, 全长约 60 km, 南倾逆冲断层, 为全新世活动断裂。该断裂东以恰克玛克河为界, 向西经天门大峡谷北、康什维尔村、乌恰县城南部区域、黑孜苇乡、江结尔农场, 最终止于康苏河东岸。断层在中新世背斜中通常表现为 $60^{\circ} \sim 80^{\circ}$ 高倾角逆冲性质, 而在晚第四纪洪积扇砾石层却表现为 $15^{\circ} \sim 30^{\circ}$ 缓倾角逆掩性质。断层在目标区范围分为南北 2 支, 南支长度约 13 km, 主要沿乌恰南部山体前缘分布, 北支长度约 10 km, 以隐伏状为主通过县城南部, 局部出露地表。地貌测量分析表明, 乌恰盆地南缘断裂南支断层有 2 个垂直位移量峰值, 即约 0.3~0.5 m 和约 0.8~1.2 m, 可能分别代表了该断层在最近 1 次地震事件的垂直位移量和最近 2 次古地震事件的垂直位移总量。乌恰盆地南缘断裂北支断层陡坎最小垂直位移约为 0.25~0.30 m, 可能代表了该断层最近一次古地震事件的垂直位移量。探槽工作限定乌恰盆地南缘断裂全新世以来古地震事件主要有 3 次, 事件 E1 发生在 9.76~12.01 ka 之间; 事件 E2 发生在 9.31~9.76 ka 之间; 事件 E3 发生在 4.2~6.16 ka 之间, 综合认为古地震复发间隔为 2 900 年。目标断层全新世以来断裂整体垂直错位速率 0.076~0.13 mm/a。利用历史地震法和经验统计法, 综合判定乌恰盆地南缘断裂最大潜在地震震级为 7.5 级。通过宽频带地震动模拟方法计算得到在设定地震 M7.5 地震作用下, 乌恰镇遭受的地震动峰值加速度最大值约为 700 cm/s^2 , 黑孜苇乡遭受的地震动峰值加速度最大值为 892 cm/s^2 。目标区场地覆盖土层较厚, 对地震波有较强的放大作用。最大形变主要集中在黑孜苇乡东南部。

关键词: 活动断层探测; 乌恰; 城市; 地震危险性

作者简介: 常想德 (1982—), 男, 高级工程师, 主要从事工程地震与活动构造研究.E-mail: 252604735@qq.com

Brief Introduction to the Main Achievements of Urban Active Fault Surveying Project in Wuqia County, Xinjiang

Chang Xiangde, Hu Weihua, Wu Guodong, Batumengke, Huang Gaofeng

Earthquake Agency of Xinjiang Uygur Autonomous

Abstract: The Wuqia County of Xinjiang is situated at the junction of three major tectonic units: the Tarim Basin, the South Tianshan fold belt, and the West Kunlun–Pamir tectonic zone. It is one of the regions in the Chinese mainland that is most strongly affected by plate tectonic forces and has the highest frequency of strong earthquakes. This project takes the main urban area and planning area of Wuqia County as its study area. Using remote-sensing survey, geomorphic mapping, trench excavation, borehole exploration, shallow seismic prospecting and deep seismic reflection survey, it has carried out a systematic survey on active faults and their deep seismotectonic environment within the study area, and assessed the risk and hazard of the target faults. The project outcomes provide a scientific basis for urban development planning, land use, site selection of major projects, as well as earthquake prevention and disaster reduction in Wuqia County.

The fault in the study area of Wuqia County is the southern-margin fault of the Wuqia Basin. Striking nearly east-west (EW), the fault has a total length of about 60 km. It is a south-dipping thrust fault and a Holocene active fault. The eastern end of this fault is bounded by the Chakmak River; westward, it passes through the north of the Tianmen Grand Canyon, Kangshvier Village, the southern part of the Wuqia County seat, Heiziwei Township, and Jiangjie'er Farm, and finally terminates at the east bank of the Kangsu River. In Miocene anticlines, the fault typically exhibits a high-angle thrust character with dips of 60° – 80° , whereas in the Late Quaternary alluvial-fan gravel layers it shows a low-angle overthrust character with dips of 15° – 30° . Within the target area, the fault consists of two branches—the south branch and the north branch. The south branch is about 13 km long and is mainly distributed along the frontal margin of the mountains south of Wuqia; the north branch is about 10 km long and is largely buried, passing through the southern part of the county town, with local surface exposures.

Geomorphic measurement analyses indicate that the south branch of the southern-margin fault of the Wuqia Basin exhibits two peaks of vertical displacement: one of about 0.3–0.5 m and another of about 0.8–1.2 m. These probably represent the vertical displacement from the most recent earthquake event and the cumulative vertical displacement from the two most recent paleoearthquake events, respectively. The minimum vertical offset of fault scarps along the northern branch is about 0.25–0.30 m, which may correspond to the vertical displacement of its youngest paleoearthquake. Trenching investigations constrain three major paleoseismic events on the southern-margin fault of the Wuqia Basin since the Holocene. Event E1 occurred between 9.76 ka and 12.01 ka; Event E2 took place between 9.31 ka and 9.76 ka; Event E3 happened between 4.2 ka and 6.16 ka. Comprehensive analysis suggests that the paleoseismic recurrence interval is 2900 years. The overall vertical slip rate of the target fault since the Holocene is 0.076–0.13 mm/a.

Using both the historical earthquake method and empirical statistical methods, the maximum potential earthquake magnitude for the southern-margin fault of the Wuqia Basin is comprehensively determined to be M7.5. Broadband ground-motion simulation yields a peak ground acceleration (PGA) of up to 700 cm/s^2

for Wuqia Town and 892 cm/s^2 for Heiziwei Township under the scenario of the M 7.5 characteristic earthquake. The site conditions in the target area include thick overburden soils that significantly amplify seismic waves. The maximum co-seismic deformation is concentrated in the southeastern part of Heiziwei Township.

Keywords: Active fault survey; Wuqia; Urban area; Seismic hazard analysis

新疆图木舒克市城市活断层探测与地震危险性评价项目

主要成果简介

陈建波， 胡伟华， 李 帅， 葛 鸣， 黄高风， 侯新宇

（新疆维吾尔自治区地震局，新疆 乌鲁木齐 830011）

摘要：新疆兵团第三师图木舒克市位于新疆维吾尔自治区西南部塔里木盆地内部，构造上处于南天山柯坪推覆构造带与塔里木盆地交汇处的巴楚隆起东段。本项目以图木舒克市主城区和规划区作为探测目标区，对区内的活动断层及其深部发震构造进行了系统的探测，对区内活动断层的危险性和危害性进行了初步评价，为图木舒克市城市建设规划、土地利用规划、建筑工程抗震设防和防灾减灾规划制定提供科学依据。根据图木舒克市城市断层活动性鉴定结果，确定目标区内存在 2 条 NNW 向活动断层，由西向东分别为达坂塔格隐伏断裂和一间房隐伏断裂，图木舒克市夹持在这两条断层之间。其中，一间房隐伏断裂，走向为 NNW 向，断层上断点最浅埋深约 269 m，结合目标区第四纪标准孔，判定一间房断裂为早—中更新世断层；达坂塔格隐伏断裂，走向为 NW—NNW，依据浅层地震探测和钻孔联合剖面，断层深部表现为 $60^{\circ}\sim 75^{\circ}$ 高倾角逆冲性质断层，主城区附近断层上断点深度约 16m，断层最近一次活动时间在 $63.99\sim 39.39$ ka，在主城区西南达坂塔格山前洪积扇开挖探槽揭示，达坂塔格断层近地表断层倾角为 $22^{\circ}\sim 45^{\circ}$ ，为缓倾角逆掩性质，断层最新活动断错距今 (73.25 ± 4.38) ka $\sim (33.58\pm 2.47)$ ka，形成角砾石层，断层顶部被厚约 4 m 的角砾石层覆盖，古地震研究表明，达坂塔格断裂晚更新世以来有过 2~3 次古地震事件，事件 EP1 发生于距今 $(65.39\pm 3.40)\sim (52.55\pm 3.56)$ ka 之间，地震事件 EP2 发生于距今 $(50.97\pm 2.70)\sim (46.91\pm 2.57)$ ka 之间，地震事件 EP3 发生于距今 $(38.77\pm 2.92)\sim (33.58\pm 2.47)$ ka 之间，古地震复发周期平均约为 11.13 ka，断层平均同震位移约为 0.5m，其断层晚更新世以来垂直滑动速率减小为 0.07 mm/a、水平缩短速率减小为 0.14 mm/a。

深部地震探测揭示了探测区巴楚隆起内部地层特征及隐伏的造山褶皱发育特征，结合小震精定位，目标区内多数地震发生在低速向高速过渡的关键区域，构造断层以逆冲运动特征为主。通过区域地震构造环境分析，综合认为目标区存在发生 6~7 级地震的构造条件，但地震频度很低。通过经验公式估算和盆地内临近隐伏断裂构造类比，将达坂塔格断裂的潜在最大震级综合评定为 $M_s7.0$ ，一间房断裂潜在最大震级评定为 $M_s6.5$ 。目标区地震危害性研究表明，达坂塔格隐伏断裂在发生最大震级 $M_s7.0$ 地震时，在目标区范围内产生的影响为：水平向地震动峰值加速度值在 $200\sim 615$ cm/s² 之间，垂直向峰值加速度值在 $240\sim 500$ cm/s² 之间；水平向地震动峰值速度值在 $22\sim 61$ cm/s 之间，垂直向地震动峰值速度值在 $19\sim 59$ cm/s 之间；水平向地震动峰值位移值在 $13\sim 48$ cm 之间，垂直向地震动峰值位移值在 $12\sim 48$ cm 之间。

作者简介：陈建波（1976—），男，高级工程师，主要从事地震地质与活动构造研究.E-mail: 123827172@qq.com

BRIEF INTRODUCTION TO MAJOR ACHIEVEMENTS OF THE PROJECT FOR ACTIVE FAULT DETECTION AND SEISMIC HAZARD ASSESSMENT OF TUMUSHUKE CITY, XINJIANG

Chen Jianbo¹, Hu Weihua, Li Shuai, Ge Ming¹, Huang Gaofeng, Hou Xinyu

(Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, Xinjiang, China)

Abstract: Tumushuke City of the 3rd Division, Xinjiang Production and Construction Corps, is situated inside the Tarim Basin in the south-western part of the Xinjiang Uygur Autonomous Region. Tectonically, it lies in the eastern segment of the Bachu Uplift at the junction between the Kalpin Nappe Tectonic Belt of the South Tianshan Mountains and the Tarim Basin. Taking the main urban area and planned area of Tumushuke City as the survey target, this project has systematically investigated active faults and their deep-seated seismogenic structures within the area, and conducted a preliminary assessment of the hazard and harmfulness of local active faults. Tumushuke City is sandwiched between these two faults. The Yijianfang Buried Fault strikes NNW, and the shallowest depth of its upper breakpoint is approximately 269 m. Combined with data from Quaternary standard boreholes in the target area, the Yijianfang Fault is identified as an Early-Middle Pleistocene fault. The Dabantag Buried Fault strikes NW-NNW. According to shallow seismic exploration and combined borehole profiles, this fault is a high-angle thrust fault with a dip angle of 60°-75° at depth. Near the main urban area, the depth of its upper breakpoint is about 16 m, and its latest faulting episode occurred between 63.99 ka and 39.39 ka. Event EP1 took place between (65.39±3.40) ka and (52.55±3.56) ka; Event EP2 occurred between (50.97±2.70) ka and (46.91±2.57) ka; Event EP3 happened between (38.77±2.92) ka and (33.58±2.47) ka. The average recurrence interval of paleoearthquakes is about 11.13 ka, and the average co-seismic displacement of the fault is around 0.5 m. Since the Late Pleistocene, its vertical slip rate has decreased to 0.07 mm/a, and its horizontal shortening rate has decreased to 0.14 mm/a.

Deep seismic profiles reveal stratigraphic features and concealed orogenic fold characteristics within the Bachu Uplift in the survey area. Analysis of regional seismotectonic environment suggests that the target area possesses tectonic conditions for generating earthquakes of magnitude 6 – 7, albeit with very low seismic frequency. By empirical formula estimation and structural analogy with adjacent buried faults within the basin, the potential maximum magnitude of the Dabantag fault is comprehensively evaluated as *Ms* 7.0, and that of the Yijianfang fault as *Ms* 6.5. Seismic hazard analysis shows that when the Dabantag buried fault generates its maximum potential *Ms* 7.0 earthquake, the ground-motion effects within the target area are as follows: horizontal peak ground acceleration ranges from 200 cm/s² to 615 cm/s²; vertical peak ground acceleration ranges from 240 cm/s² to 500 cm/s²; horizontal peak ground velocity ranges from 22 cm/s to 61 cm/s; vertical peak ground velocity ranges from 19 cm/s to 59 cm/s; horizontal peak ground displacement ranges from 13 cm to 48 cm; vertical peak ground displacement ranges from 12 cm to 48 cm.

Key words: Active faults; Seismic hazard; Tumushuke; Tarim Basin

Author Biography: Chen Jianbo (1976–), Male, senior engineer, mainly engaged in seismogeology and active tectonics research. E-mail: 123827172@qq.com

东天山速度异常结构及动力学意义研究

崔冉¹, 周元泽², 孟令媛¹

(1.中国地震台网中心, 北京 100045; 2.中国科学院大学地球与行星科学学院, 北京 100049)

摘要: 天山是全球典型的陆内造山带之一, 其形成与演化经历了古亚洲洋闭合、陆块拼贴以及印度—欧亚板块碰撞远程效应影响下的新生代再活化过程。探究天山岩石圈及地幔过渡带速度异常结构及其形成机制, 对于理解陆内造山作用和深浅部物质循环具有重要意义。本研究通过二维谱元法模拟和 P 波三重震相波形拟合方法, 获得东天山岩石圈及地幔过渡带不同深度尺度下的速度异常特征。进一步结合地质构造背景及地球化学资料, 对岩石圈内异常结构的成因及其与深部地幔响应之间的关系进行了综合分析, 以探讨天山深部动力学演化过程。研究结果显示, 东天山 35~110 km 深度范围内存在低速异常体, 其速度降约为-6%, 主要分布于伊连哈比尔尕山附近下方。该低速异常体的形成可能与岩石圈拆沉, 以及软流圈热物质上涌有关, 上涌的热物质加热岩石圈, 促使部分熔融并形成低速异常体。同时, 东天山地幔过渡带附近存在高速异常体, 且高速异常体的速度值随深度逐渐增大, 在 660 km 间断面附近达到约 1%。此外, 660 km 间断面呈现由西向东逐渐加深的特征, 表明深部可能存在岩石圈俯冲, 或岩石圈拆沉物质运移到地幔过渡带并滞留的过程。该研究为认识天山陆内造山过程中的岩石圈变形及深浅部物质循环过程提供了新的地震学证据。综合分析表明, 东天山不同深度的速度异常结构反映了岩石圈拆沉、软流圈热物质上涌等过程, 以及岩石圈的拆沉物质向天山深部迁移导致地幔过渡带的局部速度结构的调整。

关键词: 天山造山带; 波形拟合; 速度异常结构; 岩石圈拆沉; 地幔过渡带

作者简介: 崔冉 (1995—), 女, 助理研究员, 主要从事地球内部结构及地震波传播方面的研究工作.E-mail: cuiran@seis.ac.cn

SEISMIC VELOCITY ANOMALY STRUCTURES BENEATH THE EASTERN TIANSHAN AND THEIR GEODYNAMIC IMPLICATIONS

Cui Ran¹, Zhou Yuanze², Meng Lingyuan

(1.China Earthquake Networks Center, Beijing 100045, China; 2.College of Earth and Planetary
Sciences, University of Chinese Academy of Sciences, Beijing 100049, China)

Abstract: Tianshan orogen represents one of the world's typical intracontinental orogenic belts. It records the closure of the Paleo-Asian Ocean, continental amalgamation, and Cenozoic tectonic reactivation driven by far-field effects of the India–Eurasia collision. Understanding its deep lithospheric evolution is essential for revealing intracontinental orogenic processes and deep material cycling. However, the mechanisms of lithospheric thickening and delamination, as well as their interactions with the mantle transition zone remain controversial due to limited seismic observations. In this study, we used two-dimensional spectral-element simulations and P-wave triplication waveform fitting to resolve the velocity anomalies at different depths in the upper mantle and mantle transition zone beneath the Eastern Tianshan. By combining geological and geochemical observations, we analyzed the origin of lithospheric anomalies and their dynamic relationship with mantle transition zone structures. We identified a prominent low-velocity anomaly (LVA) of 6% at depths of 35–110 km, which is beneath the Eastern Tianshan, proximal to the highest peak of the Yilianhabierga Mountains. This LVA is interpreted as a consequence of asthenospheric upwelling induced by lithospheric delamination, where thermal and hydrous materials promote partial melting. A high-velocity anomaly (HVA) is also detected within the mantle transition zone beneath the Eastern Tianshan, with velocity perturbations increasing progressively with depth to ~1% near the 660 km discontinuity. In addition, the 660 km discontinuity exhibits a gradual deepening trend from west to east, which indicates that subducted or delaminated lithospheric materials may have migrated to and stagnated in the mantle transition zone. Our findings yield important insights into lithospheric deformation, asthenospheric upwelling, mantle transition zone responses, and the tectonic evolution of the Tianshan orogen.

Key words: Tianshan Orogenic Belt; Seismic Waveform Fitting; Seismic Velocity Anomaly; Lithospheric Delamination; Mantle Transition Zone

Author Biography: Cui Ran (1995–), Female, Assistant Researcher, mainly engaged in research on Earth's internal structure and seismic wave propagation. E-mail: cuiiran@seis.ac.cn

基于 GNSS 的迈丹断裂现今分段形变与震间耦合特征研究

范文龙¹, 祝杰², 李桂荣¹

(1. 中国地震局乌鲁木齐中亚地震研究所, 新疆 乌鲁木齐 830011; 2. 中国地震台网中心, 北京 100045)

摘要: 为研究西南天山迈丹断裂现今分段形变特征, 应用研究区各类 GNSS 台站原始观测数据, 基于 PyGNSS Toolkit 平台解算地壳水平运动速度场, 依托 TDefnode 负位错反演程序获取断层三维闭锁系数与滑动亏损速率, 并划分 18 个 $1^{\circ} \times 1^{\circ}$ 格网分析 2011—2026 年面膨胀率和最大剪应变的时序变化特征。结果显示: (1) GNSS 速度场总体呈现由南西向北东逐渐减弱的空间分布特征, 高值区位于西南部帕米尔高原, 运动速率达 15~20 mm/a, 向南天山内部逐渐降低至 10~12 mm/a; 迈丹断裂两侧存在速度梯度, 断裂东段表现出走滑剪切变形特征。(2) 迈丹断裂具有明显的浅部强闭锁、深部弱耦合特征, 0~15 km 深度范围内闭锁系数普遍大于 0.8, 滑动亏损速率为 2.0~3.0 mm/a; 15~30 km 深度范围闭锁程度明显降低, 闭锁系数为 0.2~0.4; 30 km 以下断层逐渐趋于弱耦合状态。(3) 2011—2022 年研究区应变参数总体表现为缓慢积累, 其中最大剪应变持续增长, 2022 年底至 2023 年初, 多数格网应变参数出现同步阶段性变化, 面膨胀率快速降低, 最大剪应变增长趋势减弱, 反映区域构造应变状态发生调整。综合 GNSS 速度场、断层闭锁状态及应变演化特征, 迈丹断裂东段浅部强闭锁区与高应变集中区域具有较好的空间对应关系, 与 2024 年乌什 $M_s 7.1$ 地震震源区及后续地震活动区域相吻合, 表明该区域仍处于持续构造加载和应变积累状态。

关键词: 迈丹断裂; GNSS; 断层闭锁; 滑动亏损速率; 应变积累

作者简介: 范文龙 (1996—), 男, 助理工程师, 主要从事地壳形变与地震地质研究.E-mail: 75446135@qq.com

CONTEMPORARY SEGMENTED DEFORMATION AND INTERSEISMIC COUPLING CHARACTERISTICS OF THE MAIDAN FAULT BASED ON GNSS OBSERVATIONS

Fan Wenlong¹, Zhu Jie², Li Guirong¹

(1. Urumqi Institute of Central Asia Earthquake, China Earthquake Administration, Urumqi 830011, Xinjiang, China; 2. China Earthquake Networks Center, Beijing 100045, China)

Abstract: To investigate the present-day segmented deformation characteristics of the Maidan Fault in the southwestern Tianshan region, we utilized raw observations from various GNSS stations in the study area to derive the horizontal crustal velocity field using the PyGNSS Toolkit platform. The three-dimensional fault coupling coefficients and slip deficit rates were estimated using the TDefnode negative dislocation inversion model. In addition, the temporal variations in areal strain rate and maximum shear strain from 2011 to 2026 were analyzed by dividing the study region into eighteen $1^{\circ} \times 1^{\circ}$ grids. The results show that: (1) The GNSS-derived velocity field exhibits an overall spatial pattern characterized by a gradual decrease from the southwest to the northeast. The highest velocities occur in the southwestern Pamir Plateau, reaching 15–20 mm/a, and gradually decrease to 10–12 mm/a toward the interior of the Southern Tianshan region. A clear velocity gradient exists across the Maidan Fault, with the eastern segment exhibiting prominent strike-slip shear deformation characteristics. (2) The Maidan Fault demonstrates a typical pattern of strong shallow locking and weak deep coupling. At depths of 0–15 km, the coupling coefficient is generally greater than 0.8, with a slip deficit rate of 2.0–3.0 mm/a. The coupling strength decreases significantly at depths of 15–30 km, where the coupling coefficient ranges from 0.2 to 0.4. Below 30 km depth, the fault gradually transitions into a weakly coupled state. (3) From 2011 to 2022, strain parameters in the study area generally exhibited a gradual accumulation trend. The maximum shear strain continued to increase, whereas from late 2022 to early 2023, most grids experienced synchronous temporal variations, characterized by a rapid decrease in areal strain rate and a reduced growth rate of maximum shear strain, indicating an adjustment of the regional tectonic strain state. Integrating the GNSS velocity field, fault coupling characteristics, and strain evolution patterns, the shallow strongly locked zone and high-strain accumulation zone along the eastern segment of the Maidan Fault show a good spatial correlation with the 2024 Wushi $M_{\text{S}}7.1$ earthquake source region and subsequent seismic activity areas. These observations suggest that the region remains under continuous tectonic loading and strain accumulation.

Keywords: Maidan Fault; GNSS; fault locking; slip deficit rate; strain accumulation

Author Biography: Fan Wenlong (1996–), Male, Assistant Engineer. His research interests focus on crustal deformation and earthquake geology. E-mail: 75446135@qq.com

帕米尔东北缘肯别尔特断裂东段晚第四纪活动特征

黄高风¹, 吴国栋², 罗 炬², 孙亚飞¹, 姚 远¹

(1. 中国地震局乌鲁木齐中亚地震研究所, 新疆 乌鲁木齐 830011; 2. 新疆维吾尔自治区地震局, 新疆 乌鲁木齐 830011)

摘要: 晚新生代以来, 受印度—欧亚板块持续碰撞的影响, 帕米尔北缘弧形推覆构造带构造变形强烈, 地震活动频繁。在帕米尔东北缘, 该推覆构造带由主帕米尔逆断层 (MPT)、帕米尔前缘逆断层 (PFT) 及两者间的褶皱—逆断裂组成, 其构造演化模式至今仍存争议。前人研究多聚焦于活动性较强的 PFT, 而对 MPT 与 PFT 之间褶皱—逆断裂带的关注相对不足。肯别尔特断裂即位于该推覆构造带中部, 其晚第四纪活动特征对揭示帕米尔地区的构造演化模式具有重要的指示意义。本文通过遥感解译、野外地质调查、无人机微地貌测量、古地震探槽及光释光测年等方法, 分析了该断裂东段的几何展布、古地震特征与缩短速率。结果表明: 肯别尔特断裂东段整体呈近东西—北西向西向展布, 分为南北两支, 以逆冲为主。在其木干河西侧一处形成于约 87.5 ± 8.3 ka 的冲洪积扇上, 断裂上盘附近发育一系列反冲断层, 探槽揭露了至少 1~2 次古地震事件, 最新活动时代不晚于 28.63 ± 2.82 ka (晚更新世晚期)。综合主断裂与次级反冲断层的总缩短量 ($\geq 31.81 \pm 5.52$ m), 估算晚第四纪以来水平缩短速率不低于 0.36 ± 0.07 mm/a。该断裂晚更新世晚期仍具活动性, 初步暗示帕米尔东北缘推覆构造带内部应变分配较前人认识更为复杂, 其演化模式是否属于典型前展式尚需结合区域多条断裂活动特征的系统对比来进一步验证。本文结果为区域地震危险性评估提供了基础数据参考。

关键词: 帕米尔东北缘; 肯别尔特断裂东段; 晚第四纪; 缩短速率; 反冲断层

作者简介: 黄高风 (1996—), 男, 助理工程师, 主要从事活动构造与古地震研究. E-mail: hgfyys5410@163.com

LATE QUATERNARY ACTIVITY CHARACTERISTICS OF THE EASTERN SECTION OF THE KENENBIEERTE FAULT ON NORTHEASTERN MARGIN OF PAMIR

Huang Gaofeng¹, Wu Guodong², Luo Ju², Sun Yafei¹, Yao Yuan¹

(1.Urumqi Institute of Central Asia Earthquake, China Earthquake Administration, Urumqi 830011, Xinjiang, China; 2.Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, Xinjiang, China)

Abstract: Since the Late Cenozoic, the continuous collision between the Indian and Eurasian plates has resulted in intense tectonic deformation and frequent seismicity in the arcuate nappe structural belt along the northern margin of the Pamir. In the northeastern Pamir, this nappe structural belt consists of Main Pamir Thrust (MPT), Pamir Frontal Thrust (PFT), and the fold-and-thrust zones between them; its tectonic evolution model remains controversial to date. Previous studies have largely focused on the highly active PFT, whereas the fold-and-thrust zones between MPT and PFT have received relatively little attention. The Kenenbieerte fault is located in the central part of this nappe structural belt, and its Late Quaternary activity characteristics provide key insights into the tectonic evolution of the Pamir region. In this study, we employed remote sensing interpretation, field geological surveys, UAV-based micro-geomorphological mapping, paleoseismic trenching, and optically stimulated luminescence (OSL) dating to investigate the geometric distribution, paleoseismic history, and shortening rate of the eastern segment of the Kenenbieerte fault. The results show that the eastern segment of the Kenenbieerte fault strikes roughly E–W to NWW, consists of two branches (northern and southern), and is dominated by thrust motion. On an alluvial fan dated to ca. 87.5 ± 8.3 ka, located west of the Qimugan River, a series of back-thrust faults developed in the hanging wall of the fault. Trench exposures reveal at least one to two paleoseismic events, with the most recent activity occurring no later than 28.63 ± 2.82 ka (late Late Pleistocene). Integrating a total shortening of $\geq 31.81 \pm 5.52$ m across the main fault and secondary back-thrust faults, we estimate a Late Quaternary horizontal shortening rate of no less than 0.36 ± 0.07 mm/a. The fault remained active through the Late Pleistocene, suggesting that strain partitioning within the northeastern Pamir nappe structural belt is more complex than previously recognized. Whether its evolution follows a typical piggyback model requires further validation through systematic comparison with activity characteristics of multiple regional faults. These findings provide baseline data for regional seismic hazard assessment.

Keywords: Northeastern margin of the Pamir; Eastern section of the Kenenbieerte Fault; Late Quaternary; Shortening rate; Back-thrust fault

Author Biography: Huang Gaofeng (1996–), Male, Assistant Engineer, mainly engaged in research on active tectonics and paleoseismology. E-mail: hgfyys5410@163.com

库车坳陷博孜大北段盐上一盐下构造耦合变形机制研究

季文哲

（中国石油大学（北京）克拉玛依校区，新疆 克拉玛依 834000）

摘要：前陆褶皱冲断带是盆山耦合研究与油气勘探的重要载体。库车坳陷作为南天山山前叠合前陆盆地，超深层油气潜力巨大，滑脱层是圈闭发育的主控因素。现有研究多聚焦单一或双滑脱层，对多滑脱层耦合变形机制认识不清，难以解释构造差异，制约了超深层勘探发展。本研究以库车坳陷博孜大北段精细地震剖面解释为例，运用构造物理模拟与数值模拟方法，结合地质分析探究研究区盐岩层上下构造变形的耦合关系和控制因素。结果显示：当盐层厚度较厚时，对盐下地层的阻挡作用增强，盐下地层主要向上生长，盐上地层倾斜程度高，前端下倾；当盐层厚度较薄时，对盐下地层的阻挡作用减弱，盐下地层向前运动，滑脱的距离增大，盐上地层倾斜幅度减小。当古隆起的倾角高时，盐下部地层主要向上生长，各层楔冲构造前端位置相近，基底开始发育新断层，盐上部地层构造变形剧烈；当古隆起倾角低时，盐下部地层沿古隆起顶部楔冲，并向前运动，形成前展式构造，盐上部分地层前端呈斜向倾斜排列。研究结果表明库车坳陷大北段盐上盐下变形以盐岩层为纽带，呈现三期耦合演化：弱挤压期上下同步微弱变形；强挤压期盐下滑脱主导、盐上协同褶皱，盐下变形经盐层能量转换控制盐上强度与展布，盐上重力载荷反调深层滑脱；强烈推覆期分层解耦，盐下独立冲断定型、盐上掀斜错位，耦合差异受古隆起与盐厚共同控制。

关键词：库车坳陷；盐上一盐下耦合；盐层厚度；古隆起

作者简介：季文哲（1999—），男，硕士研究生，主要从事盆地构造解析研究.E-mail: 17767656644@163.com

STUDY ON COUPLING DEFORMATION MECHANISM OF SUPRASALT AND SUBSALT STRUCTURES IN BOZI-DABEI NORTHERN SEGMENT, KUQA DEPRESSION

Ji Wenzhe

(Karamay Campus, China University of Petroleum (Beijing), Karamay 834000, Xinjiang, China)

Abstract: Foreland fold-and-thrust belts are important carriers for basin–mountain coupling studies and hydrocarbon exploration. The Kuqa Depression, as a superimposed foreland basin in the southern Tianshan piedmont, has great ultra-deep hydrocarbon potential, and detachment layers are the main controlling factor for trap development. Existing studies mostly focus on single or double detachment layers; the coupled deformation mechanisms of multiple detachment layers remain poorly understood, making it difficult to explain structural variations and restricting the development of ultra-deep exploration. Taking the fine seismic profile interpretation of the Bozi–Dabei segment of the Kuqa Depression as an example, this study employs analogue modeling and numerical simulation combined with geological analysis to investigate the coupling relationship and controlling factors of structural deformation above and below the salt layer.

The results show that when the salt layer is thick, its buttressing effect on subsalt strata strengthens: subsalt strata mainly grow upward, suprasalt strata are strongly tilted, and their frontal parts dip downward. When the salt layer is thin, its buttressing effect on subsalt strata weakens: subsalt strata move forward, the detachment distance increases, and the tilting of suprasalt strata decreases. When the paleo-uplift has a high dip angle, subsalt strata mainly grow upward; the frontal positions of wedge-thrust structures in different layers are close to one another; new faults begin to develop in the basement; and suprasalt strata undergo intense structural deformation. When the paleo-uplift has a low dip angle, subsalt strata wedge-thrust along the top of the paleo-uplift and move forward, forming a foreland-propagating structure; the frontal parts of some suprasalt strata are arranged in an obliquely tilted pattern.

The results indicate that in the Bozi–Dabei segment of the Kuqa Depression, suprasalt and subsalt deformation are linked by the salt layer and show a three-stage coupled evolution. During the weak compression stage, the upper and lower units deformed synchronously and weakly. During the strong compression stage, subsalt detachment dominated and suprasalt strata folded in coordination; subsalt deformation controlled the intensity and distribution of suprasalt deformation through energy transfer within the salt layer, while suprasalt gravitational loading in turn modulated deep detachment. During the intense thrusting stage, vertical decoupling occurred, with independent subsalt thrusting finalized and suprasalt strata tilted and dislocated. The coupling differences were jointly controlled by the paleo-uplift and salt thickness.

Key words: Kuqa Depression; Suprasalt-infrasalt coupling; Salt thickness; Paleo-uplift

Author Biography: Ji Wenzhe (1999 -) , male, master's student, mainly engaged in research on basin structure analysis. E-mail: 17767656644@163.com

新疆“陆态网络”GNSS 垂向时间序列运动特征分析

李 瑞^{1,2}, 李桂荣^{1,2}, 李 杰^{1,2}, 苏力坦·玉散^{1,2}, 范文龙^{1,2}

(1.新疆维吾尔自治区地震局, 新疆 乌鲁木齐 830011;2.中国地震局乌鲁木齐中亚地震研究所, 新疆 乌鲁木齐 830011)

摘要: GNSS 连续观测是获取地壳运动监测最主要的手段之一, 尤其是亚毫米级的高精度水平运动速度场为构建区域参考框架、揭示板块运动, 量化地壳应变与地震危险性分析提供了无可替代的数据支撑。而垂向精度则受多种复杂误差源综合影响, 比如电离层延迟、对流层延迟、多路径效应等, 其精度通常比水平方向低 2~3 倍。因此从 GNSS 垂向时间序列中提取可靠的构造运动信息, 亟须有效分离周期性季节信号、环境负荷效应及时间相关噪声, 以准确估计长期趋势及其不确定度。本文基于新疆“陆态网络”32 个 GNSS 连续观测站长达十余年的日解数据, 采用 GAMIT/GLOBK 与全球 IGS 基准站联合解算, 通过参数转换获得欧亚大陆参考框架下的日解坐标时间序列。基于 Hector 软件实现最大似然估计, 构建包含线性速率、周年项和半周年项的函数模型, 随机部分采用广义高斯-马尔可夫噪声与白噪声的组合, 具体公式如下:

$$U_t = a + vt + A_1 \cos(2\pi t + \phi_1) + A_2 \cos(4\pi t + \phi_2) + \xi_{\text{GGM}} + \xi_{\text{White}}$$

剔除 3 个数据连续性不好的测站后, 所有测站均观测到不同幅度的周年变信号。在剩余 29 个测站中, 3 个测站在 $\pm 1\sigma$ 标准差内未表现出明显的抬升或沉降趋势, 其余 25 个测站观测到 0~3.12 mm/a 的垂向运动速率。此外还识别到 XJKL 站显著的非构造因素引起的垂向运动特征。计算还表明若不考虑周期项和有色噪声, 可能错误地将季节性波动或短期扰动解释为构造活动, 尤其当时间序列较短时, 较高的速率估计值与较大的周年振幅容易混淆, 不宜直接归因于地壳构造抬升。本文基于长时序观测数据获取的垂向速度及不确定度估计, 可为新疆地区现今地壳垂直形变研究提供关键的运动学约束。

关键词: 陆态网络; GNSS 时间序列; Hector; 垂向运动; 广义高斯-马尔可夫噪声

作者简介: 李瑞 (1991—), 男, 高级工程师, 主要从事地壳形变观测研究. Email: lirui646909820@163.com

VERTICAL MOTION CHARACTERISTICS DERIVED FROM GNSS TIME SERIES OF THE CRUSTAL MOVEMENT OBSERVATION NETWORK OF XINJIANG

Li Rui^{1,2}, Li Guirong^{1,2}, Li Jie^{1,2}, Sulitan Yusan^{1,2}, Fan Wenlong^{1,2}

(1. Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, Xinjiang, China; 2. Urumqi Institute of Central Asia Earthquake, CEA, Urumqi 830011, Xinjiang, China)

Abstract: GNSS continuous observation is one of the primary means for monitoring crustal movement. In particular, high-precision horizontal velocity fields with submillimeter-level accuracy provide indispensable constraints for establishing regional reference frames, characterizing plate motion, quantifying crustal strain, and assessing seismic hazards. However, vertical accuracy is comprehensively affected by various complex error sources, such as ionospheric delay, tropospheric delay, and multipath effects, resulting in precision typically 2 to 3 times lower than that in the horizontal direction. Therefore, extracting reliable tectonic information from GNSS vertical time series urgently requires the effective separation of periodic seasonal signals, environmental loading effects, and time-correlated noise to accurately estimate the long-term trend and its uncertainty. This paper is based on over decades of daily solution data from 32 GNSS continuous observation stations of the Crustal Movement Observation Network of China in Xinjiang. The data are processed jointly with global IGS stations using GAMIT/GLOBK, and the daily coordinate time series are transformed into the Eurasian reference frame through parameter conversion. Maximum likelihood estimation is implemented using the Hector software, with a functional model comprising a linear rate, annual and semi-annual terms. The stochastic part was modeled as a combination of Generalized Gauss-Markov (GGM) noise and white noise, as expressed by the following specific formula:

$$U_t = a + vt + A_1 \cos(2\pi t + \varphi_1) + A_2 \cos(4\pi t + \varphi_2) + \xi_{\text{GGM}} + \xi_{\text{White}}$$

After excluding three stations with poor data continuity, annual variation signals of different amplitudes were observed at all remaining stations. Among the 29 retained stations, three show no significant uplift or subsidence within $\pm 1\sigma$ standard deviation, while the other 25 display vertical rates ranging from 0 to 3.12 mm/yr. Additionally, significant non-tectonic vertical motion is identified at station XJKL. Calculations also indicate that neglecting periodic terms and colored noise may lead to misinterpretation of seasonal fluctuations or short-term disturbances as tectonic activity. This is especially true when the time series is short, where higher rate estimates can easily be confused with large annual amplitudes and should not be directly attributed to crustal tectonic uplift. The vertical velocities and their uncertainty estimates obtained in this paper based on long time-series observation data can provide key kinematic constraints for the study of present-day vertical crustal deformation in the Xinjiang region.

Key words: Crustal Movement Observation Network of China (CMONOC); GNSS time series; Hector; vertical motion; generalized Gauss-Markov noise¹

天山中段地壳密度结构与地震动力学环境研究

刘代芹

(新疆维吾尔自治区地震局, 新疆 乌鲁木齐 830011)

摘要: 天山中段是整个天山地震带中强震频发地区之一, 为揭示天山中段地壳密度结构与强震孕育关系, 利用该地区 957 个高精度地面实测重力数据及同址测点 GNSS 高程数据, 与重力场模型相融合, 获取研究区高精度布格重力异常, 并结合 2012 年以来在研究区内发生的 3 次 6 级以上地震, 开展天山中段地壳密度结构及孕震背景研究。首先, 对 EIGEN-6C4 重力场模型与实测地面重力观测数据进行融合, 获得天山及邻区高精度布格重力异常。将天山中段地壳、上地幔分成 6 个等效层, 分别计算各层剩余重力异常、水平梯度、垂直梯度和水平梯度垂向导数, 识别出天山中段不同地质体构造边界。其后, 基于贝叶斯重震联合反演算法, 获得天山中段地壳三维密度结构模型。最后, 根据天山中段南北向地壳密度剖面结果, 构建天山及两侧盆地之间的动力学耦合模型。

结果表明, 天山中段剩余重力异常分布与区域内大型断裂分布一致, 霍尔果斯—玛纳斯—吐谷鲁断裂、那拉提断裂、喀什河断裂、北轮台断裂两侧具有明显的重力异常差, 重力异常梯度走向与以上断裂走向较吻合。从剩余重力异常可以判断, 天山及塔里木盆地的边界处于北轮台断裂附近, 而天山及准噶尔盆地的边界处于霍尔果斯—玛纳斯—吐谷鲁断裂附近。天山中段密度结构具有纵向分层和横向分区特征, 在中上地壳, 天山中段地壳密度相对较高, 两侧盆地密度较低。在莫霍面附近, 天山和盆地的密度出现反向变化, 即天山为低密度区, 而南北两侧的塔里木盆地和准噶尔盆地为高密度区。通过分析穿过 3 次 6 级以上地震震源区的密度结构剖面发现, 震源区均显示出较为明显的密度横向变化剧烈的特征, 地震发生在南北双向滑脱的最大曲率处。穿越天山及两侧盆地的密度剖面显示, 塔里木盆地和准噶尔盆地以不同角度斜插到天山下方, 天山中段在南北两侧盆地的挤压插入作用下, 深部物质长期受到剥蚀, 导致天山不断隆升。

关键词: 天山中段; 重力; 地壳结构; 孕震环境

作者简介: 刘代芹 (1979—), 男, 正高级工程师, 主要从事时变重力与孕震机理研究.E-mail: xjdztldq@126.com

CRUSTAL DENSITY STRUCTURE AND SEISMODYNAMIC ENVIRONMENT IN THE CENTRAL TIANSHAN AREA

Daiqin Liu¹

(1. Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, Xinjiang, China)

Abstract: The central segment of the Tianshan is one of the regions with frequent moderate-to-strong earthquakes along the entire Tianshan seismic belt. To reveal the relationship between the crustal density structure and the seismogenesis of strong earthquakes in this area, this study integrates 957 high-precision ground gravity measurements and collocated GNSS elevation data with a global gravity field model to obtain a high-precision Bouguer gravity anomaly field over the study area. Combined with three earthquakes of magnitude ≥ 6.0 that have occurred since 2012, we investigate the crustal density structure and seismogenic background of the central Tianshan.

First, the EIGEN-6C4 gravity field model is fused with measured ground gravity data to derive high-resolution Bouguer gravity anomalies over the Tianshan and its adjacent regions. The crust and upper mantle beneath the central Tianshan are divided into six equivalent layers, and residual gravity anomalies are calculated for each layer; then, the structural boundaries of distinct geological bodies are reconstructed using horizontal gradient, vertical gradient, and vertical derivative of horizontal gradient analyses. Subsequently, a Bayesian joint inversion algorithm of gravity and seismic data is employed to obtain a three-dimensional crustal density structure model of the central Tianshan. Finally, based on the north–south crustal density profiles across the central Tianshan, a dynamic coupling model between the Tianshan orogen and the adjacent basins is constructed.

The results indicate that the residual gravity anomalies in the central Tianshan are broadly consistent with the distribution of major regional faults. Significant gravity anomaly contrasts are observed across the Huo'erguosi–Manasi–Tugulu fault, the Nalati fault, the Kashihe fault, and the Beiluntai fault, with the trends of gravity gradient zones coinciding well with the strikes of these faults. The residual gravity anomalies suggest that the boundary between the Tianshan and the Tarim Basin is located near the Beiluntai fault, whereas the boundary between the Tianshan and the Junggar Basin is situated near the Huo'erguosi–Manasi–Tugulu fault. The crustal density structure of the central Tianshan exhibits prominent vertical stratification and lateral segmentation. In the middle–upper crust, the central Tianshan is characterized by relatively high densities, whereas the flanking basins display lower densities. Near the Moho discontinuity, an inverse density contrast is observed: the Tianshan region shows low densities, while the Tarim Basin to the south and the Junggar Basin to the north are marked by high densities. Analysis of density profiles traversing the source regions of the three earthquakes reveals that all source zones are characterized by pronounced lateral density gradients, and the earthquakes occurred at locations of maximum curvature of the north–south bidirectional detachment structures. The density profiles across the Tianshan and the adjacent basins further demonstrate that the Tarim and Junggar Basins are underthrusting beneath the Tianshan at different dip angles. Under the combined compression and insertion from both the southern and northern basins, deep materials beneath the central Tianshan have been subjected to long-term denudation, leading to sustained uplift of the Tianshan range.

Key words: Central Tianshan Mountains; Gravity; Crustal Structure; Seismogenic Environment

Author Biography: Daiqin Liu (1979-), Male, Professor of Engineering, mainly engaged in research on time-varying gravity and seismogenic mechanisms. E-mail: xjdzjldq@126.com

西南天山—西昆仑地区三维速度结构与深部变形特征

刘建明¹, 孙业君², 李军辉³, 陈向军¹

(1.新疆维吾尔自治区地震局, 新疆 乌鲁木齐 830011; 2.江苏省地震局, 江苏 南京 210014; 3.安徽省地震局, 安徽 合肥 230031)

摘要: 西南天山—西昆仑地区位于印度—欧亚大陆碰撞远程效应与亚洲内陆块体构造变形相互作用的关键转换带, 但不同构造单元的深部接触关系、变形分段及其与地震活动的内在联系仍缺乏统一约束。本文利用新疆区域数字地震台网和国际地震中心的体波走时资料, 采用基于波速比一致性约束的双差层析成像方法, 联合反演研究区地壳和上地幔顶部三维 V_P 、 V_S 及 V_P/V_S 模型, 并获得 52 476 个地震的重定位结果。结果表明, 研究区深部结构具有显著的横向非均匀性、沿走向分段和垂向分层特征。以皮羌断裂为界, 柯坪前陆冲断带东西两段表现出明显不同的深部结构和地震活动特征。西段速度结构横向变化显著, 低速异常延伸较深且地震活动相对密集; 而东段速度结构横向变化相对平缓, 推测皮羌断裂可能是调节前陆冲断带差异性缩短和沿走向应变分配的重要构造转换边界。帕米尔东北缘—西昆仑不同剖面的浅部低速层形态、中下地壳速度及地震分布由西北向东南均表现出显著的沿走向变化, 支持多层次接触、垂向分层和沿走向分段的陆内汇聚变形模式。帕米尔东北缘及西南天山南缘 20~60 km 深度广泛发育相对低速异常, 与塔里木盆地中下地壳及上地幔顶部的相对高速结构形成鲜明对比。重定位地震的震源深度主要集中于 5~25 km, 多分布在主要断裂、构造单元边界及速度异常过渡带。研究结果表明, 地壳介质性质、沉积盖层—基底结构及深部构造边界差异共同影响区域深部变形分段和地震活动。研究结论为认识西南天山—西昆仑地区的介质非均匀性、深部变形分段及地震空间分布提供了新的地震学约束。

关键词: 西南天山—西昆仑; 波速比一致性约束的双差层析成像; 地震重定位; 速度结构; 变形分段

作者简介: 刘建明(1984—), 女, 高级工程师, 主要从事数字地震学研究.E-mail: inner369@163.com

THREE-DIMENSIONAL VELOCITY STRUCTURE AND DEEP DEFORMATION CHARACTERISTICS OF THE SOUTHWESTERN TIAN SHAN – WESTERN KUNLUN REGION

Liu Jianming¹, Sun Yejun², Li Junhui³, Chen Xiangjun¹

(1. Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, Xinjiang, China; 2. Jiangsu Earthquake Agency, Nanjing 210014, China; 3. Anhui Earthquake Agency, Hefei 230031, China)

Abstract: The southwestern Tianshan–western Kunlun region is a key tectonic transition zone where the far-field effects of the India–Eurasia collision interact with intracontinental deformation in Asia. However, the deep contacts among different tectonic units, the segmentation of crustal deformation, and their relationships with seismicity remain insufficiently constrained. In this study, we use body-wave travel-time data from the Xinjiang regional digital seismic network and the International Seismological Centre and apply double-difference seismic tomography with V_P/V_S -consistency constraints to jointly invert for three-dimensional V_P , V_S and V_P/V_S structures in the crust and uppermost mantle. A relocated catalog of 52,476 earthquakes is also obtained. The results reveal pronounced lateral heterogeneity, along-strike segmentation, and vertical stratification in the deep structure of the study region. Across the Piqiang Fault, the western and eastern segments of the Keping foreland thrust belt exhibit distinctly different velocity structures and seismicity patterns. The western segment is characterized by pronounced lateral variations in velocity structure, deeper-reaching low-velocity anomalies, and relatively dense seismicity, whereas the eastern segment shows comparatively smooth lateral variations. These differences suggest that the Piqiang Fault may act as an important tectonic transition boundary that regulates differential shortening and along-strike strain partitioning within the foreland thrust belt. Profiles across the northeastern Pamir–western Kunlun region show systematic northwest-to-southeast variations in the geometry of shallow low-velocity layers, middle-to-lower crustal velocity structures, and earthquake distributions. These observations support an intracontinental convergence model characterized by multilevel contacts, vertical stratification, and along-strike segmentation. Broad low-velocity anomalies are imaged at depths of 20–60 km beneath the northeastern Pamir and the southern margin of the southwestern Tianshan, in marked contrast to the relatively high-velocity middle-to-lower crust and uppermost mantle beneath the Tarim Basin. The relocated hypocenters are mainly concentrated at depths of 5–25 km and are preferentially distributed along major faults, tectonic-unit boundaries, and velocity-anomaly transition zones. These results indicate that variations in crustal properties, sedimentary cover–basement architecture, and deep tectonic boundaries jointly influence the segmentation of deep deformation and the spatial distribution of seismicity. This study provides new seismological constraints on structural heterogeneity, segmented deformation, and earthquake distribution in the southwestern Tianshan–western Kunlun region.

Key words: Southwestern Tianshan–western Kunlun; Double-difference seismic tomography with V_P/V_S -consistency constraints; Earthquake relocation; Velocity structure; Segmented deformation

Author Biography: Liu Jianming (1984–), Female, Senior Engineer, mainly engaged in research on digital seismology. E-mail: inner369@163.com

阿勒泰地区岩石圈有效弹性厚度及其构造意义研究

刘亚婧¹, 刘代芹^{2*}, 胡敏章^{1,3}

(1. 地震大地测量重点实验室, 中国地震局地震研究所, 湖北 武汉 430071; 2. 新疆维吾尔自治区地震局, 新疆 乌鲁木齐 830011; 3. 武汉引力与固体潮国家野外科学观测研究站, 湖北 武汉 430071)

摘要: 阿尔泰造山带记录了古亚洲洋俯冲、碰撞与后碰撞演化, 但其现今岩石圈力学强度如何分异, 以及这种分异如何影响盆山耦合与地震活动, 仍缺乏区域尺度的定量认识。本文基于岩石圈挠曲均衡理论, 采用三维有限差分方法, 使用 EIGEN-6C4 布格重力异常与 SIO topo.19.1 地形数据计算获得阿勒泰地区岩石圈有效弹性厚度 (T_e) 模型; 利用接收函数 Moho 深度和均衡重力异常检验模型可靠性, 并结合大地电磁、地震速度、大地热流及历史地震资料开展构造解释。结果表明, 研究区 T_e 为 2~130 km, 呈显著盆山分异: 准噶尔盆地 T_e 为 80~130 km, 表现为连续高值刚性块体; 额尔齐斯断裂带及阿尔泰山主脊线形成 2~30 km 的低 T_e 带, 盆山过渡区则表现为 40~80 km 的陡变梯度。多数 $M \geq 4$ 地震集中于 T_e 低于 50 km 的断裂及梯度带, 低 T_e 区同时与壳内高导、低速异常和较高热流空间吻合。综合分析认为, 准噶尔盆地长期冷却形成结构完整、壳幔耦合较强的高强度岩石圈; 阿尔泰造山带则受多期构造叠加、断裂复活及中下地壳热流变弱化共同影响, 形成“厚壳弱、薄壳强”的力学反差和易于应变集中的低强度带。该结果揭示了中亚内陆造山带“稳定盆地—弱化造山带”的力学分区及其深部热—构造控制, 为认识阿勒泰现今变形与地震活动提供了新的定量约束。

关键词: 阿勒泰地区; 岩石圈有效弹性厚度; 地震活动

作者简介: 刘亚婧 (2000—), 女, 在读研究生, 研究方向: 重力学. E-mail: liuyajing0110@163.com

LITHOSPHERIC EFFECTIVE ELASTIC THICKNESS AND ITS TECTONIC IMPLICATIONS IN ALTAY REGION

LIU Yajing¹, LIU Daiqin^{2*}, HU Minzhang^{1,3}

(1.Key Laboratory of Earthquake Geodesy, Institute of Seismology, CEA, Wuhan 430071, Hubei, China; 2.Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 831399, Xinjiang, China; 3.Wuhan Gravitation and Solid Earth Tide National Observation and Research Station, Wuhan 430071, Hubei, China)

Abstract: The present-day mechanical strength of the Altay lithosphere and its control on basin–mountain coupling and seismicity remain poorly quantified. We estimate the effective elastic thickness (T_e) using a three-dimensional finite-difference flexural model constrained by EIGEN-6C4 Bouguer gravity anomalies and SIO topo.19.1 topography. The model is tested against receiver-function Moho depths and isostatic gravity anomalies, and interpreted together with magnetotelluric, seismic-velocity, heat-flow, and earthquake data. T_e ranges from 2 to 130 km, reaching 80–130 km beneath the Junggar Basin, 2–30 km along the Ertix Fault Zone and the Altay ridge, and 40–80 km across the basin–mountain transition. Most $M \geq 4$ earthquakes occur where T_e is below 50 km, coinciding with crustal conductors, low-velocity anomalies, and elevated heat flow. These results reveal a cold, strong, and well-coupled lithosphere beneath the Junggar Basin, but a tectonically reactivated and thermally weakened lithosphere beneath the Altay Orogen, providing new quantitative constraints on intracontinental deformation and seismicity in the Central Asian Orogenic Belt.

Key words: Altay Region; Effective Elastic Thickness; Seismic Activity

Author Biography: Liu Yajing (2000-), female, is currently a graduate student. Her research focuses on gravimetry. E-mail: liuyajing0110@163.com

东准噶尔阿尔曼特断裂晚第四纪古地震复发特征

马云潇¹, 吴传勇^{1,2}, 张 丽¹, 白相东¹, 焦轩凯¹, 袁海洋¹, 王雪竹¹

(1.应急管理大学地震科学与技术学院, 河北 廊坊 065201; 2.新疆帕米尔陆内俯冲国家野外科学观测研究站, 新疆 乌鲁木齐 830000)

摘要: 晚新生代阿尔泰地区的地壳形变与强震活动主要由大型右旋走滑断裂系统调节。定量研究断裂的分段特征、滑动行为与古地震复发模式, 对于揭示低应变率陆内环境的地震复发机制、完善地震危险性评价具有重要意义。作为富蕴—纸房断裂的中段构造, 阿尔曼特断裂的晚第四纪破裂历史与复发行为仍缺乏明确约束, 1931 年 $M_s 8.0$ 富蕴地震造成的库仑应力加载所对应的潜在地震危险性也尚不明确。本研究整合高分辨率遥感解译、错断地貌标志野外调查、古地震探槽、光释光(OSL)测年及 OxCal 贝叶斯年代模拟等手段, 系统开展了阿尔曼特断裂晚第四纪活动性与古地震历史研究。结果显示, 自 T1 级阶地形成以来, 阿尔曼特断裂共识别出 2 次地表破裂型古地震事件, 模拟得到的事件年代分别为 13.23 ± 1.35 ka BP 与 9.68 ± 0.33 ka BP; 两次事件的复发间隔约 3.5 ka, 而最晚事件的离逝时间已超过 9.6 ka。上述特征表明, 阿尔曼特断裂的地震复发并非遵循简单的周期模式, 而可能呈现幕式丛集与长期平静交替的活动规律。若脱离年代学约束, 仅依据地貌面累积位错开展分析, 易对断裂的特征滑动行为形成过于简化的认识; 探槽获取的古地震证据进一步证实, 简单的特征滑动模型无法完整解释阿尔曼特断裂的活动模式。结合已有研究揭示的 1931 年 $M_s 8.0$ 富蕴地震对该断裂产生的正向库仑应力扰动, 在后续区域地震危险性评价工作中, 需重点关注阿尔曼特断裂的发震潜力。

关键词: 古地震; 地震危险性; 活动特征; 滑动习性

作者简介: 马云潇(2000—), 男, 硕士研究生, 主要从事活动构造与新生代构造等方面的研究.E-mail: mayx1206@163.com

LATE QUATERNARY PALEOEARTHQUAKE RECURRENCE OF THE ALMANT FAULT IN EASTERN JUNGGAR

Yunxiao Ma¹, Chuanyong Wu^{1,2}, Li Zhang¹, Xiangdong Bai¹, Xuankai Jiao¹, Haiyang Yuan¹, Xuezhu Wang¹

(1. School of Earthquake Science and Technology, University of Emergency Management, Langfang 065201, Hebei, China; 2. Xinjiang Pamir Intracontinental Subduction National Field Observation and Research Station, Urumqi 830000, Xinjiang, China)

Abstract: Late Cenozoic crustal deformation and strong earthquake activity in the Altai region are primarily accommodated by a system of large-scale right-lateral strike-slip faults. Quantitative characterization of fault segmentation, slip behavior, and paleoearthquake recurrence patterns is essential for understanding earthquake recurrence processes in low-strain-rate intracontinental settings and for improving seismic hazard assessments. As the central segment of the Fuyun–Zhifang Fault, the Late Quaternary rupture history and recurrence behavior of the Almant Fault remain poorly constrained, and the potential seismic hazard associated with Coulomb stress loading from the 1931 Ms 8.0 Fuyun earthquake remains uncertain. In this study, we investigate the Late Quaternary activity and paleoearthquake history of the AF by integrating high-resolution remote sensing interpretation, field investigations of displaced geomorphic markers, paleoseismic trenching, optically stimulated luminescence (OSL) dating, and OxCal Bayesian age modeling. Our results reveal that two surface-rupturing paleoearthquake events have been identified on the AF after the formation of the T1 terrace, with modeled ages of 13.23 ± 1.35 ka BP and 9.68 ± 0.33 ka BP. The recurrence interval between these two events is approximately 3.5 kyr, whereas the elapsed time since the latest event exceeds 9.6 kyr. These observations suggest that earthquake recurrence on the AF may involve episodic clustering and prolonged quiescence, rather than a simple periodic pattern. The cumulative offsets observed on geomorphic surfaces, when considered without chronological constraints, may lead to an oversimplified interpretation of characteristic slip behavior; however, trench-based paleoseismic evidence indicates that the AF cannot be fully explained by a simple characteristic-slip model. Considering the reported positive Coulomb stress perturbation associated with the 1931 Ms 8.0 Fuyun earthquake, the seismic potential of the AF deserves further attention in future regional seismic risk assessments.

Key words: Paleoearthquakes; Seismic Hazard; Activity Characteristics; Slip Behavior

Author Biography: Ma Yunxiao (2000–), Male, Master's Student, mainly engaged in research on active tectonics and Cenozoic tectonics. E-mail: mayx1206@163.com

帕米尔、天山及其邻区上地幔速度结构

潘 阳, 鲍学伟, 周克成, 蒋梦凡

(浙江大学地球科学学院, 浙江 杭州 31000)

摘要: 印度—亚洲碰撞带的西北部, 广泛发育强烈的构造变形, 例如造山带隆升和中下地壳剥露, 但这些浅部构造过程与深部地幔动力学之间的关系仍存在争议。本文利用 353 个地震台站记录的 3 321 个远震事件数据, 采用远震层析成像方法, 构建了帕米尔、天山及邻区上地幔 P 波速度结构模型。成像结果显示, 在南天山断裂系统下方, 中天山低速异常与塔里木岩石圈高速异常之间存在一条明显的近垂直速度边界, 表明塔里木岩石圈以近水平方式挤压中天山岩石圈。此外, 中天山上地幔中还发现一个小尺寸高速异常块体, 该异常可以解释为在塔里木岩石圈挤压作用下发生拆沉的天山岩石圈。在帕米尔—兴都库什地区, 兴都库什下方存在一条向下延伸至地幔过渡带的板片状高速异常, 结合帕米尔下方成像得到的近水平高速异常, 表明印度岩石圈在兴都库什下方发生陡倾俯冲, 而在帕米尔下方则近水平向北平板俯冲。此外, 帕米尔下方平板俯冲的印度岩石圈可能还迫使塔吉克岩石圈在西帕米尔下方发生拆沉, 表现为一个西南倾的高速异常。在帕米尔和喀喇昆仑下方地幔过渡带底部附近, 我们还成像出一处大尺度高速异常。该异常很可能代表约 20 百万年前, 印度板片发生断离后残留的在地幔过渡带的印度岩石圈。

关键词: 帕米尔; 天山; 远震层析成像; 印度岩石圈; 岩石圈拆沉

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作者简介: 潘阳 (1997—), 男, 博士研究生, 主要研究方向体波走时层析成像. E-mail: panyangziji@163.com

UPPER MANTLE STRUCTURE BENEATH PAMIR, TIANSHAN AND ADJACENT REGIONS

Yang Pan, Xuewei Bao, Kecheng Zhou, Mengfan Jiang

(School of Earth Sciences, Zhejiang University, Hangzhou 31000, Zhejiang, China)

Abstract: In the northwestern India–Asia collision zone, the relationship between tectonic deformation and deep mantle dynamics remains controversial. We construct a 3D P-wave upper-mantle velocity model beneath the Pamir, Tianshan, and adjacent regions using teleseismic tomography from 353 stations and 3,321 events. The model suggests that the Tarim lithosphere sub-horizontally compresses the central Tianshan and may have triggered lithospheric delamination. Beneath the Pamir–Hindu Kush, the Indian lithosphere steeply subducts beneath the Hindu Kush but underthrusts beneath the Pamir, possibly inducing Tajik lithospheric delamination. A high-velocity anomaly near the base of the mantle transition zone is interpreted as detached Indian lithosphere from slab breakoff at ~20 Ma. This work was supported by the National Natural Science Foundation of China (U22B6002 and 42374055) and the National Key Research and Development Program of China (Grant 2019YFA0708604).

Key words: Pamir; Tianshan; Teleseismic Tomography; Indian Lithosphere; Lithospheric Delamination

Author Biography: PanYang(1997–), Male, Ph.D. Candidate in Geophysics, mainly engaged in research on body-wave travel-time tomography, E-mail: panyangziji@163.com

利用接收函数分析西南天山盆山结合剖面地壳结构

唐明帅^{1,2,3}, 李越帅¹, 魏芸芸¹, 曹昌军¹, 郑雪刚¹

(1. 新疆维吾尔自治区地震局, 乌鲁木齐 830011; 2. 新疆帕米尔陆内俯冲国家野外科学观测研究站, 新疆 乌鲁木齐 830011; 3. 中国地震局乌鲁木齐中亚地震研究所, 新疆 乌鲁木齐 830011)

摘要: 西南天山与塔里木盆地的盆山结合地带是调节印度-欧亚板块碰撞远场应力的关键地带, 其新构造运动与变形十分强烈。为了认识西南天山与塔里木盆地的盆山结合部的地壳结构, 本文利用喀什以东跨越塔里木盆地北缘到西南天山的 10 个流动宽频带地震台和 3 个固定台记录的远震数据, 采用 P 波接收函数 $H-\kappa$ 叠加、贯续 $H-\kappa$ 叠加和 CCP 叠加方法揭示了该剖面下方的地壳间断面形态和介质泊松比特征。结果表明: 沿剖面从南到北地壳厚度从 45km 加深到 54km, 塔里木盆地北缘地壳厚度约为 45.3~47.2km (4 个台), 进入西南天山南麓的地壳厚度约为 51.7~54.3km (4 个台), 莫霍面深度在托特拱拜孜断裂处发生错断, 跨越断层南北台站的地壳厚度相差 5km, 迈丹断裂北面 2 个台的地壳厚度约为 51.7~52.9km (2 个台); 剖面下方存在清晰的壳内间断面, 位于塔里木盆地北缘的壳内间断面的深度约为 11~14km, 向北进入天山南麓逐渐加深到 20km 左右, 继续向北壳内间断面不明显, 可能暗示塔里木盆地基底向北俯冲, 俯冲距离可能到达迈丹断裂, 促进了西南天山南麓地壳的增厚; CCP 叠加显示出莫霍面和壳内间断面强烈的变形, 特征表现为一个 NW 倾向的一个“阶状”结构。沿剖面地壳介质泊松比变化复杂 (约从 0.235 到 0.311), 塔里木盆地北缘的地壳介质波速比在 1.86~1.91 (泊松比为 0.297-0.311), 西南天山南麓的地壳介质波速比在 1.70~1.80 (泊松比为 0.235-0.277); 从塔里木盆地北缘到西南天山, 地壳厚度和泊松比之间存在反相关关系 (相关系数约为 0.90), 意味地壳的增厚可能主要是通过以长英质岩石为主要组成成分的上地壳叠置而成, 与西南天山南麓的地壳介质波速比一致。地壳厚度与海拔具有很好的相关性 (相关系数为 0.88), 可能表明沿该剖面地壳整体上处于相对均衡的状态。研究揭示的地壳结构反映了陆内碰撞过程, 为认识西南天山与塔里木盆地的盆山结合地带在地质构造、深部结构与变形特征方面的显著分段性提供了动力学解释。获得的地壳间断面形态的波速比可以为造山过程中的地球内部响应提供直接证据, 也有助于深入理解该区域的构造演化。

关键词: 西南天山盆山结合部; 接收函数方法; 地壳厚度; 泊松比; 壳内间断面

作者简介: 唐明帅 (1976—), 女, 正高级工程师, 主要从事地震监测和地震学研究, E-mail: tmings@163.com

Crustal Structure Beneath the Basin – Mountain Junction Profile of the Southwestern Tianshan Using Receiver Function Analysis

TANG Ming-shuai^{1,2,3}, LI Yue-shuai¹, WEI Yun-yun¹, CAO Chang-jun¹,
ZHENG Xue-gang¹

(1. Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, Xinjiang, China;
2. Xinjiang Pamir Intracontinental Subduction National Field Observation and Research Station,
Urumqi 830011, Xinjiang, China; 3. Urumqi Institute of Central Asia Earthquake, China
Earthquake Administration, Urumqi 830011, Xinjiang, China)

Abstract: The basin-mountain junction between the Southwest Tianshan and the Tarim Basin is a key region accommodating the far-field stress from the India-Eurasia plate collision, characterized by intense neotectonic movement and deformation. To characterize the crustal structure of this junction zone, this study uses teleseismic data recorded by 10 portable broadband seismic stations and 3 permanent seismic stations along a profile east of Kashgar, spanning from the northern margin of the Tarim Basin to the Southwest Tianshan. We apply the P-wave receiver function H - κ stacking, sequential H - κ stacking, and common conversion point (CCP) stacking methods to reveal the geometry of crustal discontinuities and Poisson's ratio characteristics beneath the profile. The results show that crustal thickness increases from 45 km to 54 km from south to north along the profile: the crustal thickness at the northern margin of the Tarim Basin (four stations) ranges from 45.3 km to 47.2 km, while it reaches 51.7 km to 54.3 km in the southern piedmont of the Southwest Tianshan (four stations). The Moho discontinuity is offset across the Tuotegongbaizi Fault, with a 5 km crustal thickness difference between stations on the north and south sides of the fault. Two stations located north of the Maidan Fault show crustal thickness ranging from 51.7 km to 52.9 km. A clear intracrustal discontinuity is detected beneath the profile: it is located at 11 – 14 km depth beneath the northern margin of the Tarim Basin, and deepens gradually to approximately 20 km when extending northward into the southern piedmont of the Tianshan. The discontinuity becomes indistinct further north, which may indicate that the Tarim Basin basement subducts northward as far as the Maidan Fault, facilitating crustal thickening in the southern piedmont of the Southwest Tianshan. CCP stacking results show intense deformation of both the Moho and the intracrustal discontinuity, which is characterized by a northwest-dipping "stepped" structure. Poisson's ratio of crustal media varies complexly along the profile, ranging approximately from 0.235 to 0.311: the crustal V_p/V_s ratio at the northern margin of the Tarim Basin is 1.86 – 1.91 (corresponding to Poisson's ratio 0.297 – 0.311), while the V_p/V_s ratio in the southern piedmont of the Southwest Tianshan is 1.70 – 1.80 (corresponding to Poisson's ratio 0.235 – 0.277). There is an inverse correlation between crustal thickness and Poisson's ratio from the northern margin of the Tarim Basin to the Southwestern Tianshan (correlation coefficient ≈ 0.90), indicating that crustal thickening is likely dominated by stacking of upper crustal materials composed mainly of felsic rocks, which is consistent with the V_p/V_s ratio characteristics of crustal media in the southern

Crustal Structure Beneath the Basin–Mountain Junction Profile of the Southwestern Tianshan Using Receiver Function Analysis

piedmont of the Southwestern Tianshan. Crustal thickness also shows a strong positive correlation with surface elevation (correlation coefficient = 0.88), suggesting that the crust along the profile is generally in a state of approximate isostatic equilibrium. The crustal structure revealed in this study reflects the continental collision process and provides a geodynamic interpretation for the distinct segmentation of geological structures, deep structures and deformation characteristics in the basin–mountain junction zone between the Southwestern Tianshan and the Tarim Basin. The obtained morphology of crustal discontinuities and V_p/V_s ratios provide direct evidence for the geodynamic response during orogeny, and also contribute to an in-depth understanding of the tectonic evolution of this region.

Keywords: Southwestern Tianshan basin – mountain junction; Receiver Function Method; Crustal Thickness; Poisson's ratio; Intracrustal Discontinuity

Author Biography: Tang Mingshuai (1976—), female, professor-level senior engineer, mainly engaged in seismic monitoring and seismological research, E-mail: tmings@163.com

绝对重力观测揭示的青藏高原地区质量迁移机制

汪 健, 李亚豪, 胡敏章, 张新林

(中国地震局地震研究所, 湖北 武汉 430071)

摘要: 本文基于青藏高原地区 1999—2022 年绝对重力观测资料, 首先分析和去除各项地壳浅层重力效应, 提取了地壳深部质量迁移引起的重力变化特征; 然后采用 Parker-Oldenburg 迭代方法反演了近期 Moho 变形; 最后综合上述结果与地震学、大地测量学等研究成果, 探讨了青藏高原地区质量迁移过程及其地壳变形机制。结果表明: 青藏高原地壳深部物质迁移引起的重力变化具有显著横向差异, 整体呈重力正变化趋势 (均值 $0.67 \mu\text{Gal/a}$), 东缘重力场呈南正北负分布特征; 拉萨块体西部、东南缘北部及塔里木块体中部的重力正变化, 可能反映了板块俯冲与侧向挤出作用下的深部物质累积; 而天山块体、拉萨块体中部及高原东北缘的重力负变化, 则可能与岩石圈深部剥离、软流圈上涌或下地壳流活动相关。区域重力变化与下地壳密度异常间存在较强相关性, 其中高原西部及东北缘地区两者间比例因子 (K) 均值为 0.33, 凸显了周缘刚性克拉通对深部物质迁移的阻挡作用; 而高原东南缘北部及南部区域 K 均值为 -0.23, 反映了中下地壳软弱层对深部物质迁移的促进作用。高原西部—塔里木块体中部和东南缘北部近期 Moho 隆升速率分别为 $5.4 \pm 0.5 \text{ mm/a}$ 和 $2.6 \pm 0.6 \text{ mm/a}$, 而高原东北缘近期 Moho 下沉速率为 $1.7 \pm 0.6 \text{ mm/a}$; 高原西部及塔里木块体中部地壳变形与岩石圈构造变形具有一致性, 东北缘符合下地壳流模式, 而东南缘北部为连续变形模式。

关键词: 青藏高原; 绝对重力观测; 质量迁移; 密度异常; 地壳变形机制

作者简介: 汪健 (1986—), 男, 副研究员, 主要从事时变重力学应用研究.E-mail: kimyin447@163.com

MASS MIGRATION MECHANISMS IN TIBETAN PLATEAU REVEALED BY ABSOLUTE GRAVITY OBSERVATIONS

Wang Jian¹, Li Yahao¹, Hu Minzhang¹, Zhang Xinlin¹

(1. Institute of Seismology, China Earthquake Administration, Wuhan 430071, Hubei, China)

Abstract: Based on absolute gravity observation data in the Tibetan Plateau (TP) from 1999 to 2022, this study first analyzes and removes various shallow crustal gravity effects to extract the gravity change characteristics induced by deep crustal mass migration. Then, the Parker-Oldenburg iterative method is used to invert the recent Moho deformation. Finally, combining these results with seismological and geodetic research findings, the mass migration processes and crustal deformation mechanisms in the TP are discussed and analyzed. The results show that: (1) The gravity changes caused by deep crustal mass migration in the TP exhibit significant lateral heterogeneity, showing an overall positive gravity trend (mean value of $0.67 \mu\text{Gal/a}$). Along the eastern margin, a distinct south-positive and north-negative dipolar pattern is observed. The positive gravity changes in the western Lhasa block, the northern part of the southeastern margin, and the central Tarim block may reflect deep mass accumulation driven by plate subduction and lateral extrusion. In contrast, the negative gravity changes in the Tianshan block, the central Lhasa block, and the northeastern margin of the plateau may be related to deep lithospheric delamination, asthenospheric upwelling, or lower crustal flow activities. (2) There is a strong correlation between regional gravity changes and lower crustal density anomalies. The mean proportionality factor (K) between them is 0.33 in the western and northeastern plateau, highlighting the blocking effect of peripheral rigid cratons on deep mass migration. Meanwhile, the mean K value in the northern and southern parts of the southeastern margin is -0.23, reflecting the facilitating effect of the middle-lower crustal weak layer on deep mass migration. (3) The recent Moho uplift rates in the western plateau–central Tarim block and the northern part of the southeastern margin are $5.4 \pm 0.5 \text{ mm/a}$ and $2.6 \pm 0.6 \text{ mm/a}$, respectively, while the recent Moho subsidence rate in the northeastern plateau is $1.7 \pm 0.6 \text{ mm/a}$. The crustal deformation in the western plateau and the central Tarim block is consistent with the lithospheric tectonic deformation. The northeastern margin conforms to the lower crustal flow model, whereas the northern part of the southeastern margin follows the continuous deformation mode.

Key words: Tibetan Plateau; Absolute gravity observation; Mass transfer; Density anomaly; Crustal deformation mechanism

Author Biography: Wang Jian (1986–), Male, Associate Researcher, mainly engaged in time-varying gravity applied research. E-mail: kimyin447@163.com

唐山震区三维密度结构及其孕震背景研究

王嘉沛, 张明辉, 石文轩, 谈洪波, 吴桂桔, 杨光亮, 申重阳

(中国地震局地震研究所, 湖北 武汉 430061)

摘要: 为研究唐山地震震源区地下精细密度结构特征、地震孕育机理及深浅部构造的动力学关系, 本文基于地表实测高分辨率的布格重力异常数据, 利用小波多尺度信号分离技术提取了震区不同深度的小波细节信号, 并结合地震活动性分布特征进行了综合分析。同时, 利用一种包括深度加权、异常体形状和重力物理方程等多重物理约束的深度学习反演方法, 在经过数据集建立、网络模型搭建、多类型模型训练和多指标验证后, 应用于唐山震区的实测重力数据中。反演获得了唐山震区三维密度结构, 并与传统方法结果进行对比分析。结果表明: 唐山地震处于华北克拉通破坏背景下的唐山菱形断块复杂构造带内, 地震活动性分布在空间上表现出显著的趋向性, 紧邻菱形断块边界及重力异常的梯度带分布。唐山震区地下密度结构随着深度的增加, 从浅部的复杂离散逐渐转变为中深部的连续有序分布, 存在地幔高密度物质沿着断层线上涌过程, 以及深部物质密度不均匀的形态。在深部能量聚合与浅部构造约束的共同作用下, 诱发了唐山地震的快速错动释放。研究结论揭示了唐山震区三维密度结构特征和重力异常从深部聚合中心向浅部分散破裂带转换的地球物理过程, 可为华北克拉通破坏区强震孕震环境识别以及地震危险性评估提供了重要的技术支撑。

关键词: 唐山地震; 布格重力异常; 重力反演; 密度结构

作者简介: 王嘉沛 (1989—), 男, 副研究员, 主要从事重力变化观测及其机理研究.E-mail: wang_jia_pei@163.com

Three-Dimensional Density Structure and Seismogenic Background of the Tangshan Seismic Region

Wang Jiapei¹, Zhang Minghui¹, Shi Wenxuan¹, Tan Hongbo¹, Wu Guiju¹, Yang
Guangliang¹, Shen Chongyang¹

(1. Institute of Seismology, China Earthquake Administration, Wuhan 430061, Hubei, China)

Abstract: To investigate the fine-scale subsurface density structure, seismogenic mechanisms, and the dynamic relationships between deep and shallow structures in the source region of the Tangshan earthquake, this study employs high-resolution surface-measured Bouguer gravity anomaly data. Wavelet multi-scale signal separation techniques are used to extract wavelet detail signals at different depths in the seismic region, and a comprehensive analysis is conducted by integrating the seismicity distribution characteristics. Meanwhile, a deep learning inversion method incorporating multiple physical constraints — including depth weighting, anomalous body geometry, and the gravity physical equations — is developed. After dataset construction, network model establishment, multi-type model training, and multi-metric validation, this method is applied to the measured gravity data of the Tangshan seismic region. The inversion yields the three-dimensional (3-D) density structure of the region, which is subsequently compared with results from conventional inversion methods. The results indicate that the Tangshan earthquake occurred within the complex tectonic belt of the Tangshan rhombic block, under the background of North China Craton (NCC) destruction. The spatial distribution of seismicity exhibits a pronounced tendency, clustering adjacent to the boundaries of the rhombic block and the gradient zones of gravity anomalies. With increasing depth, the subsurface density structure of the Tangshan seismic region gradually transitions from complex, dispersed patterns in the shallow crust to continuous, ordered distributions at middle-to-deep depths. Evidence suggests the upwelling of high-density mantle material along fault lines, along with density inhomogeneities in deep-seated materials. Under the combined effect of deep energy accumulation and shallow structural constraints, the rapid dislocation release of the Tangshan earthquake was triggered. The findings reveal the 3-D density structure characteristics of the Tangshan seismic region and the geophysical process whereby gravity anomalies transition from a deep convergence center to shallow dispersed fracture zones. This study provides important technical support for identifying strong-earthquake seismogenic environments and assessing seismic hazards in the NCC destruction region.

Key words: Tangshan earthquake; Bouguer gravity anomaly; Gravity inversion; Density structure

Author Biography: Wang Jiapei (1989–), Male, Associate Researcher, mainly engaged in gravity variation observation and its mechanism research. E-mail: wang_jia_pei@163.com

应用地震学方法探查活动断层深部结构

王世广¹, 王未来¹, 房立华²

(1. 中国地震局地球物理研究所, 北京 100081; 2. 中国地震局地震预测研究所, 北京 100036)

摘要: 野外地质调查、遥感影像解译和无人机高精度 DEM 测量等方法, 可有效约束活动断层的地表展布、几何形态及地貌位错特征。然而, 活动断层深部几何结构和运动性质的探测仍面临较大挑战。探槽、钻孔和地震反射剖面等方法通常只能揭示局部区域内断层的二维结构, 且实施成本较高, 难以系统获取断层完整的三维深部形态。近年来, 随着密集地震台阵观测和人工智能技术的发展, 基于连续波形资料开展 AI 地震检测、精定位和震源机制解反演, 已成为探查活动断层深部结构和隐伏活动断裂的重要技术途径。通过地震丛集空间展布可建立断层三维几何模型, 结合震源机制解、InSAR 形变观测和野外地质调查结果, 可进一步约束断层的运动性质和现今活动性。在发震断层结构研究方面, 研究团队利用地震精定位和震源机制解, 揭示了 2023 年山东平原 M_w 5.5 地震和甘肃积石山 M_s 6.2 地震均与盆地内隐伏活动断层有关; 2024 年新疆乌什 M_w 7.0 地震则表现为主断裂发震、多条分支断裂共同参与同震变形的复杂破裂过程。在隐伏活动断裂探测方面, 基于华北密集台阵资料构建的 AI 地震检测与精定位目录, 识别出至少 5 条发震断层。由华北至青藏高原东缘依次为商都—张北断裂、巴丹吉林断裂、民勤断裂、腾格里断裂和哈南—武都断裂。结合震源机制解和 InSAR 形变监测, 我们进一步获得了这些活动断裂的运动性质和现今滑动速率。其中, 哈南—武都断裂滑动速率约为 3.4 mm/a, 是区域内活动性最强的断裂带之一, 其地震危险性值得关注。其余 4 条断裂带的发现, 分别在大地构造上拓展了张家口—渤海断裂带和阿尔金断裂带的空间连续性, 使这两条大型构造带的长度分别达到约 1 000 km 和 2 500 km。上述研究表明, 基于密集台阵连续波形资料的 AI 地震检测与精定位方法, 可有效用于活动断层深部结构成像和隐伏活动断裂识别, 为区域地震危险性评估和构造变形模式研究提供新的地震学约束。

关键词: 活动断层, 地震目录, 震源机制解, 人工智能, 隐伏活动断裂

作者简介: 王世广 (1992—), 男, 副研究员, 主要从事地震地质研究.E-mail: shigwang@foxmail.com

INVESTIGATING DEEP STRUCTURE OF ACTIVE FAULTS USING APPLIED SEISMOLOGICAL METHODS

Wang Shiguang¹, Wang Weilai¹, Fang Lihua²

(1. Institute of Geophysics, China Earthquake Administration, Beijing 100081, China; 2. Institute of Earthquake Forecasting, China Earthquake Administration, Beijing 100036, China)

Abstract: Field geological investigations, remote-sensing image interpretation, and high-resolution UAV-based DEM measurements can effectively constrain the surface traces, geometric characteristics, and geomorphic offsets of active faults. However, probing the deep geometry and kinematics of active faults remains challenging. Trenching, drilling, and seismic reflection profiling generally provide only local 2D constraints on fault structures, and their high cost limits their applicability for systematically imaging complete three-dimensional fault geometries at depth. In recent years, with the rapid development of dense seismic array observations and artificial intelligence techniques, AI-based earthquake detection, precise earthquake relocation, and focal mechanism determination using continuous waveform data have become powerful approaches for investigating the deep structures of active faults and identifying buried active faults. The spatial distribution of earthquake clusters can be used to construct 3D fault geometries, while focal mechanisms, InSAR deformation observations, and field geological evidence can further constrain fault kinematics and present-day activity.

For seismogenic fault investigations, our team used precise earthquake relocation and focal mechanism solutions to reveal that both the 2023 Mw 5.5 Pingyuan earthquake in Shandong and the 2023 Ms 6.2 Jishishan earthquake in Gansu were associated with buried active faults within basins. The 2024 Mw 7.0 Wushi earthquake in Xinjiang, by contrast, involved a complex rupture process in which a major seismogenic fault and multiple subsidiary faults jointly contributed to coseismic deformation. For buried active fault detection, an AI-based earthquake detection and relocation catalog constructed from dense seismic array data in North China revealed at least five seismogenic faults. From North China to the eastern Tibetan Plateau, these faults are the Shangdu-Zhangbei fault, Badain Jaran fault, Minqin fault, Tengger fault, and Hanan-Wudu fault. By integrating focal mechanism solutions with InSAR deformation observations, we further constrained the kinematics and present-day slip rates of these active faults. Among them, the Hanan-Wudu fault has a slip rate of approximately 3.4 mm/yr, making it one of the most active fault zones in the region and highlighting its potential seismic hazard. The discovery of the other four fault zones also extends, in a tectonic sense, the spatial continuity of the Zhangjiakou-Bohai fault zone and the Altyn Tagh fault zone, increasing their inferred lengths to ~1000 km and ~2500 km, respectively.

These applications demonstrate that AI-based earthquake detection and precise relocation using continuous waveform data from dense seismic arrays provide an effective approach for imaging the deep structures of active faults and identifying buried active faults. This methodology offers new seismological constraints for regional seismic hazard assessment and for re-evaluating regional tectonic deformation patterns.

Key words: Active Fault; Earthquake Catalog; Focal Mechanism Solution; Artificial Intelligence; Buried Active Fault

Author Biography: Wang Shiguang (1992–), Male, Associate Researcher, mainly engaged in research on seismogenic geology. E-mail: shigwang@foxmail.com

地貌对比厘定吉尔吉斯斯坦纳伦地区晚第四纪 活动断层滑动速率

吴国栋、黄帅堂、胡伟华、阿里木江·亚力昆、常想德、马建、赵江涛

(新疆维吾尔自治区地震局, 乌鲁木齐 830011)

摘要: 吉尔吉斯共和国纳伦地区位于天山西部, 地震活动强烈、活动断层发育。通过开展中国——吉尔吉斯斯坦——乌兹别克斯坦铁路沿线地质调查, 我们对纳伦地区活动构造开展详细的填图工作。调查中发现, 纳伦地区河流阶地和冲积扇地貌发育特征在整个中亚地区都具有代表性, 地貌面是由全球发生过的重大气候事件塑造的, 尤其是晚第四纪以来重大气候事件形成的地貌面保存完好。统计分析表明, 不同地区同一期次的地貌面几乎都是同时形成的。通过地貌对比, 我们初步判定其形成年龄, 通过测量地貌面断层陡坎垂直位移量和探槽开挖揭露断层剖面, 可以初步厘定断层地质滑动速率(时间尺度为 10^4 yr)。对比已有的横跨这些活动断层大地测量速率(时间尺度为 10 yr), 具有很好的一致性。格陵兰冰芯、北大西洋深海沉积物和中国黄土记录自晚更新世后期(MIS 4~60 ka)以来, 一些极端寒冷气候事件, 例如新仙女木冰阶(YD)、末次盛冰期(LGM)和海因里希冰阶事件(H), 几乎在北半球同步发生, 没有其他千年变化的证据(Hemming, 2004)。这些寒冷、干燥的极端气候事件(冰期/冰阶)在中亚地区普遍造成雪线下降、冰川推进和粗粒黄土(风沙)沉积。随之而来的温暖、潮湿的气候事件(间冰期/间冰阶), 又会造成雪线上升、冰川退缩和细粒黄土(古土壤)沉积, 形成振荡交替的气候条件。统计已有年龄数据表明, 吉尔吉斯纳伦地区晚第四纪河流阶地和洪积扇受控于这些重要气候事件, QIII(2)阶地和洪积扇形成于海因里希冰阶 I 期结束时, 大致时间为 16.25 ± 1.00 ka, QIII(3)阶地和洪积扇形成于新仙女木冰阶结束时, 大致时间为 11.31 ± 1.32 ka。最后在一些典型的地貌面上采集光释光年代样品进行测试, 验证了我们的初步判定。

Landscape comparison to determine late Quaternary slip rates of active faults in the Naryn region, Kyrgyzstan

Wu Guodong, Huang Shuitang, Hu Weihua, Alimujiang Yaliquun, Chang Xiangde, Ma Jian,
Zhao Jiangtao

(Xinjiang Uygur Autonomous Region Earthquake Bureau, Urumqi 830011)

Abstract: The Naryn region of the Kyrgyz Republic, located in the western Tianshan Mountains, is characterized by intense seismic activity and well-developed active faults. Through geological surveys along the China–Kyrgyzstan–Uzbekistan railway corridor, we conducted detailed mapping of active tectonics in the Naryn area. Our investigation revealed that the fluvial terraces and alluvial fan landforms in this region are representative of those throughout Central Asia. These land surfaces were shaped by major climatic events on a global scale, particularly well-preserved features formed during significant late Quaternary climate episodes. Statistical analysis indicates that land surfaces of the same age across different regions were nearly contemporaneous in formation. By comparing landform characteristics, we have preliminarily determined their ages. Measuring vertical displacement of fault scarps on these surfaces and excavating trench profiles to expose fault sections allows us to estimate the geological slip rates of faults (on a 10^4 -year timescale). These estimates show good consistency with existing geodetic measurements across these active faults (on a 10-year timescale). Ice cores from Greenland, deep-sea sediments from the North Atlantic, and Chinese loess records indicate that several extreme cold climate events—such as the Younger Dryas (YD), Last Glacial Maximum (LGM), and Heinrich stadials (H)—occurred almost synchronously across the Northern Hemisphere since the late Pleistocene (MIS 4, ~60 ka), with no evidence of other millennial-scale climate variations (Hemming, 2004). These cold, dry climatic episodes (glacial/stadial periods) generally led to lowered snowlines, glacier advances, and deposition of coarse-grained loess (aeolian silt) across Central Asia. Subsequent warm, humid interstadial periods caused snowline retreat, glacial recession, and accumulation of fine-grained loess (paleosols), resulting in oscillating climatic conditions. Statistical analysis of available age data shows that late Quaternary river terraces and alluvial fans in the Naryn region of Kyrgyzstan were controlled by these key climatic events: the QIII(2) terrace and alluvial fan formed at the end of Heinrich Stadial I, approximately 16.25 ± 1.00 ka; the QIII(3) terrace and alluvial fan formed at the end of the Younger Dryas, around 11.31 ± 1.32 ka. Finally, optically stimulated luminescence (OSL) samples dating collected from typical land surfaces confirmed our preliminary age determinations.

天山和塔里木地幔过渡带结构及动力学过程

吴颖凯¹, 鲍学伟²

(1. 空间环境与行星科学国际研究中心, 杭州市北京航空航天大学国际创新研究院, 浙江 杭州 311115; 2. 浙江大学地球科学学院, 浙江 杭州 310058)

摘要: 系统研究天山造山带、塔里木克拉通及周边区域深部地幔结构对于理解大陆碰撞、陆内造山等构造变形动力学过程十分重要。本研究利用超过 66 000 条高质量远震 P 波接收函数对研究区下方地幔过渡带 (MTZ) 结构进行成像, 为了获得更准确的结果, 我们利用地壳和地幔三维精细速度模型进行走时校正。结果显示, 在哈萨克下方 410-km 不连续面 (d410) 下降了 15~20 km, 与层析成像模型中低速异常体位置一致, 指示了该区域存在来自于 MTZ 的地幔上涌。此外, 西天山 d410 下降了约 8 km, 支持了塔里木岩石圈与西天山的碰撞, 导致岩石圈增厚拆沉, 西天山 660-km 不连续面 (d660) 的下降则指示了拆沉的岩石圈现今可能滞留在 d660 附近。由于新增的塔里木盆地内部宽频带地震数据, 能够对塔里木盆地下方 MTZ 精细结构进行成像。新结果显示, 由于 d410 显著下降 (15~20 km) 以及 d660 略微抬升, 塔里木中部地幔过渡带显著减薄。而塔里木西部和东部则由于 d660 的显著下降呈现出增厚的 MTZ。因此, 塔里木下方 d410 的大范围下降以及塔里木中部 MTZ 显著减薄, 表明塔里木下方可能存在深部地幔上涌, 与区域及全球地震层析成像结果一致。塔里木东部 d660 显著下降可能是岩石圈拆沉并滞留在 d660 附近造成的。然而, 塔里木地幔上涌和岩石圈拆沉的成因及其动力学机制仍需结合热动力学数值模拟等多种方法进一步研究。

关键词: 天山造山带; 地幔过渡带; 塔里木克拉通; 接收函数

作者简介: 吴颖凯 (1997—), 男, 博士后, 主要从事地球深部结构研究, 如地幔过渡带、地壳和岩石圈结构。E-mail: ykwu@zju.edu.cn

MANTLE TRANSITION ZONE STRUCTURE BENEATH TIANSHAN AND TARIM CRATON AND DEEP- SEATED DYNAMICS

Wu Yingkai¹, Bao Xuewei²

(1. GEOLAB, Hangzhou International Innovation Institute, Beihang University, Hangzhou
311115, Zhejiang, China; 2. School of Earth Sciences, Zhejiang University, Hangzhou
310058, Zhejiang, China)

Abstract: Systematical investigation of deep mantle structure beneath the Tian Shan, Tarim Craton and their surroundings is of great significance to understand dynamics of continental collision, intracontinental orogenesis and deformation in response to the India-Eurasia collision. In this research, we imaged the mantle transition zone (MTZ) structure beneath these regions using more than 66,000 high-quality P-wave receiver functions obtained from ~500 seismic stations. To obtain the accurate true depths of the 410-km discontinuity (d410) and 660-km discontinuity (d660), we conduct crustal and mantle correction using several high-resolution 3-D crustal and mantle velocity models during time-to-depth migration. Our results reveal significant 15-20 km depression of the d410 mainly beneath the southern Kazakh Shield, which is consistent with the low-velocity anomaly in tomographic models and thus attributed to the mantle upwelling from the MTZ. Considering that the d410 is slightly depressed by ~8 km beneath the western Tianshan, deep subduction of the Tarim lithosphere is likely excluded and its subhorizontal indentation into the Tianshan is preferred. As a result, segments of thickened Tianshan lithosphere delaminated and accumulated near the d660, which induced small-scale upwelling across the d410 there. With the incorporation of data from newly deployed seismic stations within the Tarim basin, our new results show a thinned MTZ beneath the central Tarim Craton, caused by the significantly depressed d410 and normal-to-slightly uplifted d660. In the meantime, a thickened MTZ beneath the eastern Tarim Craton is imaged, resulting from the slightly depressed d410 and significantly depressed d660. Accordingly, the depressed d410 beneath the whole Tarim Basin and thinned MTZ beneath central Tarim may indicate deep mantle upwelling beneath the Tarim Craton, consistent with the regional- and global-scale tomographic models. The lithospheric delamination near d660 beneath the eastern Tarim Craton is supported. But the origins and dynamics of the mantle upwelling and delamination should be further investigated using various methods such as thermo-mechanical numerical modeling.

Key words: Tianshan Orogenic Belt; Mantle Transition Zone; Tarim Craton; Receiver Function

Author Biography: Wu Yingkai (1997–), Male, Postdoctoral researcher, mainly engaged in research on deep-seated structures such as mantle transition zone, crustal and lithospheric structure using seismic methods. E-mail: ykwu@zju.edu.cn

霍尔果斯泥火山三相地球化学特征及其 对北天山断裂活动的指示意义

闫 玮, 朱文振, 贾永斌, 汪成国

(新疆维吾尔自治区地震局, 新疆 乌鲁木齐 830011)

摘要: 霍尔果斯泥火山位于新疆准噶尔盆地南缘与北天山的盆山过渡带, 构造上处于霍尔果斯背斜轴部, 是北天山泥火山群的重要组成部分。本文基于霍尔果斯泥火山多年、多期喷出物的连续观测资料, 开展了液相、气相及固相的三相地球化学特征分析, 探讨了其对区域断裂活动及地震危险性的指示意义。水化学分析结果表明, 霍尔果斯泥火山泉水呈弱碱性至碱性 (pH 8.02~8.52), 矿化度高 (TDS 11 681.45~14 301.44 mg/L), 阳离子以 Na^+ 为主导 (4 498.65~5 654.84 mg/L), 阴离子以 Cl^- 为主导 (6 987.10~8 405.90 mg/L), 水化学类型稳定为 Na-Cl 型。吉布斯图投影显示, 其水化学特征受深部盐岩溶解与地表强烈蒸发浓缩双重因素控制, 属于深循环卤水与蒸发作用叠加的演化模式。气体组分分析显示, 喷出气体以 CH_4 (59.09%~87.58%) 为主, CO_2 含量为 2.08%~6.14%, 碳同位素 $\delta^{13}\text{C}_{\text{CH}_4}$ 为 -36.77‰~-37.95‰, 属热成因气; 氦同位素 R/Ra 值为 0.45, 显示壳源特征为主, 兼具少量幔源组分贡献。固相矿物组成以石英 (45%)、长石 (15%)、方解石 (15%) 和伊利石 (10%) 为主。结合区域地震活动资料, 霍尔果斯泥火山的喷发活动与北天山地区中强地震存在时间上的关联性, 其流体地球化学异常波动可作为区域构造应力变化的指示参数。本研究为北天山泥火山形成机理及断裂活动监测提供了基础地球化学数据支撑。

关键词: 霍尔果斯泥火山; 地球化学特征; 碳同位素; 氦同位素; 断裂活动

作者简介: 闫玮 (1985—), 男, 高级工程师, 主要从事地震地下流体监测、预报研究.E-mail: yanwei.nan@163.com

THREE-PHASE GEOCHEMICAL CHARACTERISTICS OF HORGOS MUD VOLCANO AND THEIR IMPLICATIONS FOR FAULT ACTIVITY IN NORTHERN TIANSHAN MOUNTAINS

Yan Wei, Zhu Wenzhen, Jia Yongbin, Wang Chengguo

(Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, Xinjiang, China)

Abstract: The Horgos mud volcano is located in the transitional zone between the southern margin of the Junggar Basin and the North Tianshan Mountains, Xinjiang, and is structurally situated along the axis of the Horgos anticline. It forms an important component of the North Tianshan mud-volcano cluster. Based on multi-year, multi-phase continuous observation data of ejecta from the Horgos mud volcano, this study systematically analyzes the three-phase (liquid, gas, solid) geochemical characteristics and discusses their implications for regional fault activity and seismic hazard assessment. Hydrochemical analyses show that waters discharged by the mud volcano are weakly alkaline to alkaline (pH 8.02–8.52), with extremely high total dissolved solids (TDS: 11 681.45–14 301.44 mg/L). Cations are dominated by Na^+ (4 498.65–5 654.84 mg/L), whereas anions are dominated by Cl^- (6 987.10–8 405.90 mg/L), yielding a stable Na-Cl hydrochemical type. Gibbs diagram projections indicate that the hydrochemical signatures are jointly controlled by deep-seated salt dissolution and intense surface evaporation-concentration, pointing to an evolutionary model for deep-circulating brine modified by evaporation. Gas-composition analyses reveal that the discharged gases are dominated by CH_4 (59.09%–87.58%), with CO_2 contents of 2.08%–6.14%. Carbon isotope $\delta^{13}\text{C}_{\text{CH}_4}$ values range from -36.77‰ to -37.95‰, indicating a thermogenic origin. The helium-isotope R/Ra ratio is 0.45, suggesting a predominantly crustal source with a minor mantle-derived contribution. Solid-phase mineral assemblages are dominated by quartz (45%), feldspar (15%), calcite (15%), and illite (10%). Combined with regional seismic-activity records, eruptive activity of the Horgos mud volcano exhibits temporal correlation with moderate-to-strong earthquakes in the North Tianshan region; its fluid geochemical anomalies can act as indicators of regional tectonic-stress variations. This study provides fundamental geochemical data for understanding the formation mechanism of North Tianshan mud volcanoes and for fault-activity monitoring.

Key words: Horgos mud volcano; geochemical characteristics; hydrochemistry; emitted gases; carbon isotope; helium isotope; fault activity; North Tianshan

Author Biography: Yan Wei (1985-), male, senior engineer, engaged in seismic underground fluid monitoring and forecasting. E-mail: yanwei.nan@163.com.

天山地区阿拉湖断裂晚第四纪右旋走滑速率及其指示的区域构造含义

易文星¹, 李 安¹, 胡宗凯¹, 徐良鑫², 李小龙¹, 汪世轩¹, 王 越¹

(1.中国地震局地质研究所, 地震动力学与强震预测全国重点实验室, 北京 100029; 2.陕西省地震局, 陕西 西安 710068)

摘要: 受印度—欧亚大陆碰撞的远程效应影响, 天山在新生代时期发生复活造山并具有强烈的构造活动性。天山地区在新生代的构造变形主要表现为 N-S 向挤压, 而这种 N-S 向挤压在天山主要表现为逆冲断层吸收地壳缩短和走滑断层调节地壳汇聚变形。天山的地球动力学机制表明, 走滑断层是由东西向地壳缩短差异造成的产物, 在对天山应变分配的调节中起到了重要作用。因此, 天山地区发育的走滑断层在近年间逐渐成为研究热点, 更以活动强烈且特征明显的 NW 向右旋走滑断裂为重要研究对象。阿拉湖断裂是一条位于北天山地区的 NW 向右旋走滑断裂, 区域附近断裂活动性强烈但历史地震记录较少, 所以选择阿拉湖断裂为研究对象对于理解区域构造活动和未来强震风险具有重要意义。通过卫星影像遥感解译、高精度无人机航拍数据和野外地质调查, 阿拉湖断裂可以分为南北两支断裂。基于无人机航拍数据提取的高分辨率 DEM 和光释光年代学结果, 我们得到断裂南支的晚第四纪滑动速率为 1.33 ± 0.11 mm/a, 断裂北支的晚第四纪滑动速率为 1.27 ± 0.14 mm/a, 断裂总的滑动速率为 2.6 ± 0.25 mm/a。通过区域应变分配讨论, 我们认为阿拉湖断裂明显调节了天山地区的地壳汇聚变形, 阿拉湖断裂、博阿断裂和钦吉兹断裂组成的大型右旋走滑断裂的构造活动性沿 NW 走向从天山到哈萨克斯坦地台逐渐递减。最后, 基于断裂滑动速率、地质体百万年尺度的累计位移和锆石 U-Pb 定年结果等数据, 我们推断阿拉湖断裂的右旋走滑起始活动时间为晚中新世, 发生于天山新生代快速隆升的时期中。

关键词: 阿拉湖断裂; 天山; 右旋走滑; 晚第四纪滑动速率; 应变分配

作者简介: 易文星 (2000—), 男, 博士研究生, 主要从事活动构造于地震地质研究.E-mail: yiwenzxing7788@163.com

LATE QUATERNARY DEXTRAL STRIKE-SLIP RATE OF THE ALAKOL LAKE FAULT IN THE TIAN SHAN AND ITS REGIONAL TECTONIC IMPLICATIONS

Yi Wenxing¹, Li An¹, Hu Zongkai¹, Xu Liangxin², Li Xiaolong¹, Wang Shixuan¹, Wang Yue¹

(1. State Key Laboratory of Earthquake Dynamics and Forecasting, Institute of Geology, China
Earthquake Administration, Beijing 100029, China; 2. Academy of Seismic Engineering Surveys,
Earthquake Agency of Shaanxi Province, Xi'an 710068, China)

Abstract: The tectonic deformation of the Tian Shan region during the Cenozoic is mainly characterized by north-south (N-S) compression, and this N-S compression is primarily manifested as thrust faults accommodating crustal shortening and strike-slip faults accommodating crustal convergence deformation. Active NW-trending dextral strike-slip faults with prominent kinematic characteristics play a vital role in accommodating strain partitioning across the Tian Shan. Accordingly, this study focuses on the Alakol Lake fault (ALF), a NW-trending dextral strike-slip fault, developed in the northern Tian Shan region. Based on remote sensing interpretation of satellite images and field geological surveys, the ALF can be divided into south and north sections. Using interpreted offsets from high-precision DEM derived from UAV aerial surveys and OSL dating, we estimated a late Quaternary slip rate of 1.33 ± 0.11 mm/yr along the south section and 1.27 ± 0.14 mm/yr along the north section of the ALF. We believe that the ALF significantly accommodates convergence deformation in the Tian Shan region, and that the intensity of regional tectonic activity decreases northwestward from the north of the Tian Shan toward the Kazakhstan Platform. Finally, we infer that the initial activity time of the ALF was the late Miocene.

Key words: Alakol Lake Fault; Tian Shan; Dextral Strike-slip; Late Quaternary Slip Rate; Strain Partitioning

Author Biography: Yi Wenxing(2000—), PhD candidate, mainly engaged in active tectonics and seismogeology. E-mail: yiw Wenxing7788@163.com

东天山木垒断裂晚第四纪活动特征与强震危险性

袁海洋^{1,2}, 吴传勇^{2,3,4}, 于晓辉^{2,3}, 王雪竹², 臧柯智², 高 瞻², 马云潇^{2,3}

(1.中国地震局地质研究所, 北京 100029; 2.应急管理大学, 河北 三河 065201; 3.河北省地震动力学重点实验室, 河北 三河 065201; 4.中国新疆帕米尔陆内俯冲国家野外科学观测研究站, 北京 100029)

摘要: 天山造山带在晚新生代期间受印度—欧亚板块碰撞的远程效应影响再次发生陆内造山运动, 形成现今的构造格局与地貌形态, 地区南北向的地壳缩短主要被南北两侧的前陆冲断带所调节和吸收。博格达山脉是东天山活动性最强的造山带, 其北临准噶尔盆地、南接吐鲁番盆地。早期研究认为, 博格达山东部区域活动性变形与地壳缩短主要集中于山脉南缘, 是山体晚新生代隆升的主导因素。而最新的地质调查发现, 博格达山北缘同样存在着一条晚第四纪以来有过最新活动的断裂, 即木垒断裂, 该断裂作为博格达山与准噶尔盆地的构造边界, 其晚第四纪活动特征和滑动速率仍不清楚。

本文基于高分辨率遥感影像解译、精细野外填图与实地查证, 对断裂的几何学与运动学特征进行了系统分析, 通过无人机测量获取被错断的地貌面数据, 并结合光释光测年技术对晚第四纪沉积物进行定年来测定阶地面形成时代, 结果显示: 木垒断裂的南北向地壳缩短速率由西段的 $0.92 \pm 0.10 \text{ mm/a}$, 向东段递减至 $0.52 \pm 0.05 \text{ mm/a}$ 。这一变化规律与天山整体由西向东地壳缩短逐渐减弱的总体变形趋势一致。

探槽开挖与野外调查显示, 木垒断裂晚第四纪以来发生过 2 次古地震事件, 最新一次古地震事件的逝去时间已超过 9 ka, 该断裂具有较高的地震危险性, 未来具有发生大约 7.6 级地震的能力。研究表明, 博格达山东段南北两麓前缘的逆冲构造在深部几何形态上存在显著差异, 这种差异可能源于区域构造应力场的分区性与基底结构的不均一性。南麓的吐鲁番前陆逆冲断裂系作为薄皮构造, 其变形主要沿上地壳软弱层滑脱扩展, 而木垒断裂可能受准噶尔盆地的影响, 呈现出不同的几何学特征, 博格达山脉东部由北麓高角度厚皮逆冲构造与南麓薄皮逆冲构造共同调节了区域活动变形, 这正是博格达山隆升的动力学机制。

关键词: 博格达山; 木垒断裂; 地壳缩短速率; 晚第四纪; 变形模式

GEOMETRY, KINEMATICS AND LATE QUATERNARY CRUSTAL SHORTENING RATE OF MULEI FAULT IN EASTERN TIANSHAN, NW CHINA

Yuan Haiyang^{1,2}, Wu Chuanyong^{2,3,4}, Yu Xiaohui^{2,3}, Wang Xuezhu², Zang Kezhi², Gao Zhan², Ma Yunxiao^{2,3}

(1. Institute of Geology, China Earthquake Administration, Beijing 100029, China; 2. University of Emergency Management, Langfang 065201, Hebei, China; 3. Hebei Key Laboratory of Earthquake Dynamics, Langfang 065201, Hebei, China; 4. Xinjiang Pamir Intracontinental Subduction National Observation and Research Station, Beijing 100029, China.)

Abstract: The geometry and crustal shortening rate of the bounding fault of the Tian Shan orogenic belt are key parameters in the exploration of regional deformation patterns and seismic hazard levels. The Mulei Fault acts as the structural boundary of the Bogda Range and Junggar Basin, and its late Quaternary activities have yet to be well documented. In this study, we evaluated the geometry and kinematics of the fault using interpretations of detailed high-resolution remote sensing images and field investigations. Based on a survey of displaced geomorphic surfaces with an unmanned drone and the dating of late Quaternary sediments via OSL, we determined that the N-S crustal shortening of the MF decreased from 0.92 ± 0.10 mm/yr in the west to 0.52 ± 0.05 mm/yr in the east. This pattern aligned with the overall deformation trend of decreasing degrees of crustal shortening from west to east across the mountain range. Trench excavation and field investigations indicated that the elapsed time of the last paleoearthquake exceeded 10.89 ka and the MF had an earthquake with magnitude of approximately 7.6. Our results suggest that the high-angle, thick-skinned thrust faulting along the northern flank and the thin-skinned thrust faulting along the southern flank of the Bogda Range accommodated the active deformation and accounted for the mountain uplift.

Key words: Bogda Range; Mulei fault, crustal shortening rate; late Quaternary; deformation pattern

Author Biography: Yuan Haiyang (2000–), Female, Doctoral candidate, mainly engaged in research on active tectonics and Cenozoic tectonics. E-mail: yhy737420@126.com

新疆柯坪冲断带断层活动性及地震危险性分析

张庆云¹, 占伟¹, 朱爽¹

(1.中国地震局第一监测中心, 天津 300180)

摘要: 为研究柯坪冲断带现今运动特征, 及其内部主要断裂带有怎样的运动差异性, 未来该区域有怎样的地震危险性, 收集整理了覆盖研究区的 Sentinel-1 数据, 基于 GPU 加速的时序 InSAR 形变处理。利用时序 InSAR 技术获取的覆盖柯坪区域的升轨和降轨 InSAR 形变场结果, 从结果可以看出, InSAR 数据在该区域的相干性相对较好, 形变场结果较为完整地覆盖了柯坪冲断带区域。整个研究区整体形变量相对较小, 基本都在 ± 5 mm/a 之间。其中柯坪冲断带区域形变基本在 ± 3 mm/a, 以皮羌断裂为界, 皮羌断裂带左侧和右侧的柯坪冲断带形变速率存在一定的微小差异, 说明皮羌断裂带的存在在一定程度上对柯坪冲断带滑动速率产生了影响, 从而导致柯坪冲断带存在区域滑动分段特征。通过 D-InSAR 方法获取伽师地震同震形变场, 形变结果显示伽师地震造成的形变呈现南北向上不对称椭圆状分布。从升轨同震形变场结果可以看出, 抬升区域 LOS 向最大形变量约 50 mm, 主要分布于柯坪推覆构造的柯坪断裂和奥兹格尔他乌断裂之间, LOS 向最大沉降量约 40 mm, 主要分布于奥兹格尔他乌断裂上方, 最大形变量主要集中在发震断层近场区域; 从降轨形变结果可以看出, LOS 向最大抬升形变量相较于升轨, 形变量约为 40 mm, LOS 向最大沉降量为 50 mm。最后利用 GNSS 与 InSAR 数据融合结果, 通过最新两期主应变率, 面应变等应变场信息的对比, 分析了 2020 年伽师 $M_s 6.4$ 地震前后西北天山地区三维地壳形变时空演化特征; 利用 bolcks 模型计算了柯坪冲断带主要断层的运动状态及闭锁程度, 厘清了柯坪冲断带主要断层的运动状态及闭锁程度; 结合西南天山地区应变结果与 1976—2023 年 GCMT 地震目录, 进行地震发生概率预测, 通过概率预测计算认为西南天山仍是强震发生的危险区域, 为柯坪冲断带主要断层的地震危险性提供了支持, 为该区域的地震趋势判定提供了支持。

关键词: 柯坪冲断带; 地壳形变; InSAR; 地震危险性; 断层活动

作者简介: 张庆云 (1988—), 女, 高级工程师, 主要从事 InSAR 数据处理及地壳形变研究.E-mail: zhangqingyun1107@163.com

ACTIVITY AND SEISMIC HAZARD OF FAULTS IN KELPIN THRUST BELT

Zhang Qingyun, Zhan Wei, Zhu Shuang

(The First Monitoring and Application Center, China Earthquake Administration, Tianjin 300180, China)

Abstract: To investigate the present-day kinematic characteristics of the Kelpin thrust belt, the kinematic differences among its major fault zones, and the associated seismic hazard, this study collected Sentinel-1 data covering the study area and applied GPU-accelerated time-series InSAR processing. The ascending and descending InSAR deformation fields over the Kelpin region were obtained, revealing relatively good coherence and comprehensive coverage of the thrust belt. The overall deformation rate across the study area is relatively small, generally within ± 5 mm/a, with deformation in the Kelpin thrust belt mainly at ± 3 mm/a. Bounded by the Piqiang fault, slight differences in deformation rates are observed between its left and right sides, indicating that the Piqiang fault influences the slip rate of the Kelpin thrust belt to some extent, leading to segmented slip characteristics. The coseismic deformation field of the Jiashi earthquake was derived using D-InSAR, showing an asymmetric elliptic distribution along the north-south direction. The ascending results indicate a maximum LOS uplift of ~ 50 mm between the Kelpin fault and the Ozgelitao fault, and a maximum LOS subsidence of ~ 40 mm above the Ozgelitao fault, with the largest deformation concentrated near the epicentral area. The descending results show a maximum LOS uplift of ~ 40 mm and subsidence of ~ 50 mm. Furthermore, by integrating GNSS and InSAR data, the spatiotemporal evolution of three-dimensional crustal deformation in the northwestern Tianshan region before and after the 2020 Jiashi $M_s 6.4$ earthquake was analyzed using the latest principal strain rates and areal strain fields. The block model was used to estimate the kinematic state and locking degree of the major faults in the Kelpin thrust belt. Combined with strain results in the southwestern Tianshan and the GCMT catalog from 1976 to 2023, probabilistic seismic hazard analysis suggests that the southwestern Tianshan remains a high-risk area for strong earthquakes. These findings provide support for seismic hazard assessment of the major faults in the Kelpin thrust belt and for regional earthquake tendency determination.

Key words: Kelpin thrust belt; Crustal Deformation; InSAR; Seismic Hazard; Fault activity

Author Biography: Zhang Qingyun (1988–), Female, Senior Engineer, mainly engaged in InSAR data processing and crustal deformation research. E-mail: zhangqingyun1107@163.com

基于背景噪声成像的海原地震孕震环境研究

张文越¹, 刘少林^{1*}

(应急管理部国家自然灾害防治研究院, 北京 100085)

摘要: 青藏高原东北缘是青藏高原向东北扩展的前缘, 青藏高原与阿拉善块体、鄂尔多斯块体在此区域相互作用致使构造活动强烈, 强烈的构造活动表现为该区域发育有众多活动断裂, 海原断裂作为该区大型走滑断裂曾在 1920 年发生了海原 $M_s8.5$ 地震。研究海原地震震中及邻区的地壳 S 波速度结构, 对于认识海原断裂的深部构造特征和强震孕育环境具有重要意义。本文收集研究区 225 个宽频带地震台站记录的连续波形资料, 人工挑选了 18 323 条瑞利波频散曲线, 采用背景噪声成像方法获得海原断裂及邻区地壳 S 波速度结构。成像结果显示: (1) 研究区地壳 S 波速度具有明显的横向和垂向非均一性。浅部速度异常与地表构造单元和主要断裂的空间分布具有一定对应关系, 海原断裂两侧表现出不同的速度结构特征。(2) 震中附近中地壳以相对高速异常为主要特征, 震源位于高速异常内部或其边缘, 西南侧同深度介质速度相对较低, 表明震源位置与中地壳横向速度变化具有较好的空间对应关系。(3) 震中下方中下地壳的 S 波速度相对于上方中地壳明显降低, 而下地壳速度再次升高, 整体呈现中地壳相对高速、中下地壳相对低速、下地壳相对高速的垂向分层结构。综合上述结果, 海原地震震中附近地壳具有明显的横向速度差异和垂向速度分层: 海原断裂东段位于上地壳浅部高、低速异常的过渡部位, 震源邻近中地壳相对高速异常, 其下方为中下地壳相对低速异常。海原断裂、震源位置与不同深度速度异常之间的空间对应关系, 为认识海原断裂深部结构及海原地震的孕震环境提供了新的地震学约束。

关键词: 海原地震; 海原断裂; 背景噪声成像; S 波速度结构; 孕震环境

作者简介: 张文越 (2001—), 女, 硕士研究生, 主要从事背景噪声成像、地壳速度结构与强震孕震环境研究. E-mail: zhangwenyue24@mailsucas.ac.cn

现今地壳形变揭示帕米尔—西南天山深浅部构造耦合差异性

朱 爽，郭南男，占 伟

（中国地震局第一监测中心，天津 300180）

摘要：帕米尔—西南天山地区记录了印度—欧亚大陆碰撞产生的强烈远场效应，但该区域浅部形变与深部构造过程之间的耦合关系仍缺乏充分约束。本文融合 GNSS、InSAR 与震源机制解数据，得到了高分辨率三维形变场、应变率场与应力场，分析了区域应变分配、断层运动学特征以及深浅部形变耦合关系。主要认识如下：多尺度应变率场表现出显著的空间非均质性，形成以帕米尔弧前缘逆冲-剪切集中、东缘走滑挤出、前陆区差异化形变的形变格局。三维形变场揭示断层具有明显分段性与滑动分解特征。公格尔断裂系北部为右旋走滑（速率约 3 mm/a），向南转变为拉张活动（速率约 6.9 mm/a）。结合浅部应变场与深部应力场，识别出一种新的深浅耦合模式。帕米尔弧顶与柯坪逆冲带构成两个截然不同的耦合区，二者受不同形变机制控制：帕米尔弧顶以转换挤压应变累积为主；柯坪逆冲带表现为前陆逆冲系统内部局部地壳缩短与应力传递。这种空间差异耦合模式可以解释区域应变分配与断层运动学的差异，揭示陆内碰撞带深部岩石圈过程对地表形变的调控作用。上述研究成果为大陆碰撞过程中的形变分配与断层相互作用提供了新约束。

关键词：帕米尔—西南天山；多源数据融合；应变场；应力场；深浅部耦合

作者简介：朱爽（1987—），女，高级工程师，主要从事地壳形变与地震预测研究。E-mail: shzhu1026@163.com

PRESENT-DAY CRUSTAL DEFORMATION REVEALS DISTINCT DEEP SHALLOW COUPLING IN PAMIR SOUTHWESTERN TIANSHAN

Zhu Shuang, Guo Nannan, Zhan Wei

(The First Monitoring and Application Center, China Earthquake Administration, Tianjin 300180,
China)

Abstract: The Pamir–southwestern Tianshan region records strong far–field effects of the India–Eurasia collision, but the coupling between shallow deformation and deep tectonic processes remains poorly constrained. Here, we integrate GNSS, InSAR, and focal mechanism data to derive high–resolution three–dimensional deformation, strain–rate, and stress fields, and investigate regional strain partitioning, fault kinematics, and shallow–deep deformation coupling. The main findings are as follows. Multi–scale strain–rate fields reveal strong spatial heterogeneity, defining a deformation pattern characterized by concentrated thrust–shear along the Pamir arc front, strike–slip escape on the eastern flank, and differentiated foreland deformation. The three–dimensional deformation field reveals pronounced fault segmentation and slip partitioning. The Kongur system transitions from right–lateral strike–slip in the north (3 mm/yr) to extension in the south (6.9 mm/yr), whereas foreland faults accommodate shortening with variable strike–slip components and along–strike segmentation. Integrating shallow strain with deep stress fields reveals a previously unrecognized zonal framework of shallow–deep deformation coupling. The Pamir arc apex and the Keping thrust belt constitute two distinct coupling domains governed by different deformation mechanisms: deformation in the former is dominated by transpressional strain accumulation, whereas the latter reflects localized crustal shortening and stress transfer within the foreland thrust system. This spatially variable coupling framework explains the first–order differences in strain partitioning and fault kinematics and highlights how deep lithospheric processes regulate surface deformation in intracontinental collision zones. These findings provide new constraints on deformation partitioning and fault interaction during continental collision.

Key words: Pamir–southwest Tianshan; Multi–source data integration; Strainfield; Stress field; Shallow–deep coupling

Author Biography: Zhu shuang (1987–), Female, Senior Engineer, mainly engaged in research on crustal deformation and prediction, E-mail: shzhu1026@163.com

SEISMICITY AND THE REGION OF THE SEISMIC GAP BEFORE THE STRONG 2024 EARTHQUAKE WITH MAGNITUDE $M_w=6.4$ IN THE UCHTURFAN AREA OF THE SOUTHERN TIAN SHAN

A.M. Muraliev, M.B. Maldybaeva, B.S. Abdyraeva

(Institute of Seismology of the National Academy of Sciences of the Kyrgyz Republic, Bishkek

abmuraliev@mail.ru)

Abstract: The article presents a study of the seismicity of the territory of Kyrgyzstan and adjacent seismically active zones, aimed at understanding the mechanism of occurrence and forecasting strong earthquakes in the region. The main attention is paid to the spatiotemporal features of the occurrence of historically strong earthquakes. The study of the seismic activity of the Southern Tianshan zone is aimed at identifying areas of seismic gaps as potential sites of an expected strong earthquake. As an example, a retrospective analysis is shown of the occurrence of the strong earthquake of January 22, 2024, with magnitude $M_w=6.4$, whose epicenter was located in the area of the settlement of Uchturfán in the territory of China.

The Tianshan mountain system in the territory of Kyrgyzstan and adjacent areas can be conventionally divided into four seismically active zones: Northern Tianshan, Southwestern, Central, and Southern Tianshan, each of which has its own seismological and geological-geophysical features (Dzhanuzakov, Ilyasov, et al., 1977). Macroseismic data on strong earthquakes that have occurred in Kyrgyzstan have been collected over the past 255 years (1770-2025); the most reliable information from felt and strong earthquakes in Kyrgyzstan was obtained beginning in 1770 as a result of a macroseismic survey of the consequences of the strong Belovodsk earthquake in Kyrgyzstan [Dzhanuzakov, 1964].

Based on the seismological studies conducted in the territory of Kyrgyzstan and adjacent seismically active zones, the following conclusions can be drawn:

1. The Southern Tianshan is characterized as one of the highly seismic zones in the region. Of all the earthquakes that have occurred in the territory under consideration, 70% have epicenters that fall within this zone. The earthquake sources in this zone are located within the Earth's crust down to 30-40 km, i.e., we are dealing with continental crustal earthquakes. The epicentral fields of weak, felt, and strong earthquakes coincide. That is, where weak earthquakes occur, strong ones can also be expected there.

The migration of crustal earthquake sources has a nearly latitudinal direction, from southwest to northeast and back. Before strong earthquakes with magnitude $M_w \geq 5.0$, mainly first-kind seismic gaps are observed.

2. Before the strong ($M_w=6.4$) earthquake of 2024, which occurred in the Uchturfán area of the highly seismic Southern Tianshan zone, an ellipsoidal region of a first-kind seismic gap was identified. The epicenter of the strong 2024 earthquake was located in the center of the seismic gap region. The epicenters of the aftershocks filled this region within 3 months and continue to do so to this day.

Thus, the seismological method of identifying the region of a seismic gap can be used to predict the location of expected strong earthquakes in the Tianshan. Further development of seismological studies of the Tianshan requires the development of international exchange of primary seismic monitoring data and the creation of a unified earthquake catalog for the Central Asian region.

CONCEPTUAL MODELS OF THE OCCURRENCE OF FLUID ANOMALIES IN THE SYSTEM FOR PREDICTING STRONG EARTHQUAKES IN KAZAKHSTAN

Abdullaev A.U

Abstract: A new concept in Earth sciences — “dynamic hydrogeochemistry” — is presented, based on a phenomenological model of the functioning of locally equilibrium open hydrogeochemical systems under the continuous fluid regime in the Earth's crust of seismically active regions. This scientific concept makes it possible to establish a real physicochemical mechanism for forecasting the formation of precursor anomalies through temporal changes in fluid parameters and serves as a theoretical basis for forecasting seismic events at prediction sites.

Аннотация: Представлена новая концепция в науках о Земле — «динамическая гидрогеохимия», которая базируется на феноменологической модели функционирования локально-равновесных открытых гидрогеохимических систем в непрерывном ходе флюидного режима в земной коре сейсмоактивных областей. Такая научная концепция позволяет создать реальный физико-химический механизм прогнозирования в ходе во времени флюидных параметров формирования предвестниковых аномалий, служит теоретической основой прогнозирования сейсмических событий на прогностических полигонах.

Author Biography: Abdullaev A.U, Academician of the International Academy of Sciences and the Managing Directorate of Ecological and Biological Sciences, Doctor of Geological and Mineral Sciences, State Scientific Service, LLP of the Institute of Seismology of the Ministry of Emergency Situations of the Republic of Kazakhstan.

**Раздел 2. Теоретические основы, методология и передовые технологии
прогнозирования землетрясений**

**2.3. Процессы формирования очагов сильных землетрясений и механизмы
предвестниковых аномалий**

**СРАВНИТЕЛЬНЫЙ АНАЛИЗ ГАЗОГЕОХИМИЧЕСКИХ ПАРАМЕТРОВ
ПОДЗЕМНЫХ ВОД КАЗАХСТАНА И СУАР (КНР) ДЛЯ МОНИТОРИНГА
ГЕОДИНАМИЧЕСКИХ ПРОЦЕССОВ ТЯНЬ-ШАНЯ**

Б. А. Зулпухарова

*ТОО «Национальный научный центр сейсмологических наблюдений и исследований»
МЧС РК, г.Алматы, Казахстан, seismology@seismology.kz*

Тянь-Шань представляет собой одну из наиболее активных внутриконтинентальных орогенных систем Евразии, характеризующуюся высокой современной тектонической активностью и значительной сейсмичностью. Пространственная протяженность активных разломов и единая геодинамическая природа региона обуславливают необходимость проведения комплексных трансграничных исследований, основанных на совместном использовании данных геофизического и гидрогеохимического мониторинга.

Одним из наиболее перспективных направлений исследований предвестников землетрясений является газогеохимический мониторинг подземных вод. Изменение напряженно-деформированного состояния земной коры сопровождается активизацией миграции глубинных флюидов по разломным зонам, что может проявляться в вариациях концентраций радона (Rn), гелия (He), водорода (H₂), углекислого газа (CO₂), метана (CH₄) и других газовых компонентов. В условиях активной тектоники газогеохимические параметры подземных вод рассматриваются как чувствительные индикаторы изменения проницаемости разломов и перераспределения глубинных флюидных потоков. Аналогичные подходы используются и в системе гидрогеохимического мониторинга Алматинского прогностического полигона, где выполняются ежедневные наблюдения за газовым составом подземных вод. В основу исследования положены результаты ежедневного газогеохимического мониторинга, выполняемого на гидрогеохимических станциях Республики Казахстан, а также данные, получаемые в рамках международного обмена наблюдениями с сетью станций Синьцзян-Уйгурского автономного района Китая.

Основной целью является проведение сравнительного анализа газогеохимических параметров подземных вод Казахстана и СУАР, выявление общих закономерностей изменения газового состава в пределах

единой Тянь-Шаньской тектонической системы и оценка возможностей использования трансграничного обмена данными для мониторинга геодинамических процессов.

Предполагается выполнить сопоставление временных рядов газогеохимических параметров, определить наиболее информативные показатели, характеризующие изменение флюидного режима активных разломов, а также оценить степень согласованности вариаций, регистрируемых различными сетями наблюдений. Полученные результаты могут стать основой для развития единой системы трансграничного газогеохимического мониторинга Тянь-Шаня, направленной на совершенствование исследований процессов подготовки землетрясений и повышение эффективности комплексного геодинамического мониторинга региона.

COMPARATIVE ANALYSIS OF GROUNDWATER GAS-GEOCHEMICAL PARAMETERS IN KAZAKHSTAN AND XINJIANG , CHINA FOR MONITORING GEODYNAMIC PROCESSES IN THE TIANSHAN

B.A. Zulpukharova

(National Scientific Center for Seismological Observations and Research, Ministry of Emergency
Situations of the Republic of Kazakhstan, Almaty, Kazakhstan)

Abstract: The Tian Shan is one of the most active intracontinental orogenic systems in Eurasia, characterized by intense contemporary tectonic activity and high seismicity. The extensive distribution of active faults and the unified geodynamic framework of the region necessitate comprehensive transboundary investigations based on the integrated use of geophysical and hydrogeochemical monitoring data.

Gas-geochemical monitoring of groundwater is considered one of the most promising approaches for studying earthquake precursors. Variations in the stress-strain state of the Earth's crust promote the migration of deep-seated fluids along active fault zones, which may be reflected in changes in the concentrations of radon (Rn), helium (He), hydrogen (H₂), carbon dioxide (CO₂), methane (CH₄), and other gaseous components. In tectonically active regions, groundwater gas-geochemical parameters are regarded as sensitive indicators of fault permeability variations and deep fluid migration. Similar approaches are implemented within the hydrogeochemical monitoring system of the Almaty Prognostic Test Site, where daily observations of the gas composition of groundwater are carried out. The present study is based on the results of daily gas-geochemical monitoring conducted at hydrogeochemical stations in the Republic of Kazakhstan, as well as on data obtained through the international exchange of observations with the monitoring network of the Xinjiang Uygur Autonomous Region (China).

The main objective of this study is to perform a comparative analysis of groundwater gas-geochemical parameters in Kazakhstan and the Xinjiang Uygur Autonomous Region, to identify common patterns in gas composition variations within the unified tectonic framework of the Tian Shan, and to evaluate the potential of transboundary data exchange for monitoring ongoing geodynamic processes.

The study will compare time series of gas-geochemical parameters, identify the most informative indicators reflecting changes in the fluid regime of active fault zones, and assess the consistency of variations recorded by different monitoring networks. The expected results will provide a scientific basis for the development of an integrated transboundary gas-geochemical monitoring system for the Tian Shan, contributing to a better understanding of earthquake preparation processes and enhancing the efficiency of comprehensive geodynamic monitoring across the region.

RESEARCH ON ANOMALIES ASSOCIATED WITH UZBEKISTAN BOYSUN $M_w5.3$ EARTHQUAKE ON MAY 12 2022

Liu Jing¹, Valijon Yusupov², Liang Peng¹, Kakharbay Abdullabekov², Ouyang Xinyan¹,
Vakhitkhan Ismailov², Jing Feng¹, Zhang Xuemin¹, Xu Yueren¹, Alisher Rasulov²

(1. Institute of Earthquake Forecasting, China Earthquake Administration, Beijing100036,
China; 2. Institute of Seismology, the Academy of Sciences of the Republic of Uzbekistan, Tashkent
100128, Uzbekistan,)

Abstract:The preparation process of earthquakes triggers anomalous variations in multiple physical and chemical parameters across the crust, atmosphere, ionosphere and other geospheres. With the continuous development of observational technologies, ground-based and space-based observations become two core technical systems for capturing pre-earthquake anomalous signals. Focusing on the Uzbekistan Boysun $M_w5.3$ earthquake occurred on 12 May 2022, multi-source measured data were analyzed to detect the anomalies from differ layers. In terms of hydrochemical responses, water pH exhibited a decreasing anomaly starting about 20 days before the earthquake and persisted for nearly one month after the event, while post-earthquake disturbances of CO_2 and HCO_3^- were also observed, demonstrating sustained gas release along fault fractures during the seismogenic process. Continuous disturbances of magnetic field were captured by ground-based stations in 3-6 May, followed by magnetic field and electron density anomalies detected by Swarm satellite on 9 May. The discontinuous ionospheric anomalies of electron density observed by ZH-1 satellite were verified by different source data and different analysis method. Such inconsistent anomalous responses are mainly attributed to the inherent temporal-spatial sampling differences between continuous ground-based observations and globally covered discrete satellite measurements, as well as the internal characteristics of the lithosphere-atmosphere-ionosphere coupling (LAIC) process. Multi-parameter comparison further indicates that the chemical/DC electric field pathway and acoustic-gravity wave propagation dominate the energy transmission and multi-layer coupling process of Boysun earthquake. This study contributes to a better understanding of earthquake preparation process and complex physical mechanism of LAIC.

Key words: Uzbekistan Boysun earthquake; Hydrochemical observation; Space-based observations; Multi-parameter comparison; Seismogenic activity

Author Biography: LIU Jing (1979–), Female, Boffin, mainly engaged in Research on ionospheric disturbances caused by earthquakes.E-mail:16651175870@163.com

ON RELATIONSHIP BETWEEN DYNAMICS OF PARAMETERS OF MODERN GPS POINT MOTIONS AND EARTHQUAKES

K.K. Kolumbetova

(I.National Scientific Center for Seismological Observations and Research, Almaty, Kazakhstan)

Abstract : This article presents the results of a study on the relationship between the “migration” of GPS points forming a permanent network with continuous 24-hour observation programs and earthquakes occurring within the Tien Shan orogen, which occupies the northwestern part of the Central Asian mountain system. The research methodology is based on calculating correlation coefficients between the components of GPS point movements and seismicity parameters (N – number of earthquakes, E – seismic energy). The analysis makes it possible to assess the relationship between contemporary crustal movements recorded by GPS observations and variations in regional seismic activity. Particular attention is paid to identifying spatial and temporal patterns in the behavior of GPS points associated with changes in seismicity. Based on the obtained results, conclusions are drawn regarding the applicability of continuous GPS monitoring for studying geodynamic processes, and recommendations for solving relevant problems of space geodesy are proposed.

Author Biography: K.K. Kolumbetova.E-mail: kolumbetova@gmail.com

INFORMATION PARAMETERS OF BUDGERIGAR BEHAVIOR DURING EARTHQUAKE PREPARATION

Myrkasimova A.S.

Chief Research Scientist, LLP “National Scientific Center for Seismological Observations and Research”,
Ministry of Emergency Situations of the Republic of Kazakhstan. Almaty, Kazakhstan
e-mail: donka_af@mail.ru

Abstract: The paper presents the results of studies on the motor activity of budgerigars for 2025 and the 1st quarter of 2026, as well as for April and May 2026. Background and anomalous activity variations were identified. An analysis was performed of the dependence of anomalous motor activity of birds on atmospheric, geomagnetic factors, and seismic events. The scientific and methodological foundations of seismic biomonitoring were developed for the first time in the world, in the CIS, and in Kazakhstan by the biologist Serazetdinova B.Z. [1]. In the 1990s a bio-testing ground was established, housing animals with receptor systems sensitive to geophysical environmental factors, including seismic ones.

Keywords: Seismic biomonitoring, Budgerigar behavior, Motor activity, Anomalous variations, Birds, Budgerigar.

Раздел 2. Теоретические основы, методология и передовые технологии прогнозирования землетрясений

2.3. Процессы формирования очагов сильных землетрясений и механизмы предвестниковых аномалий

**ВАРИАЦИИ ЕСТЕСТВЕННОГО ЭЛЕКТРИЧЕСКОГО ПОЛЯ НА СЕВЕРНОМ
ТЯНЬ-ШАНЕ И ГЕОЭЛЕКТРИЧЕСКИЕ ПРЕДВЕСТНИКИ
ЗЕМЛЕТРЯСЕНИЙ**

П.У. Киланбекова, О.М. Белослюдцев, Е.Т. Мырзабек

*ТОО «Национальный научный центр сейсмологических наблюдений и исследований»
МЧС РК, г.Алматы, Казахстан, seismology@seismology.kz*

Территория юго-востока Казахстана является одной из самых сейсмоопасных в континентальной Азии, на которой за исторически короткое время произошел ряд разрушительных землетрясений. В последнее время в регионе наблюдается увеличение сейсмической активности, зарегистрирован ряд землетрясений с $M > 5$, что делает актуальным развитие методов краткосрочного прогноза. Сейсмологический мониторинг Северного Тянь-Шаня включает многолетние режимные геоэлектрические наземные скважинные наблюдения на сети комплексных станций, в результате анализа которых исследована структура вариаций естественного электрического поля и выделен ряд аномалий. Длительность возмущений ЭТП колеблется в широком диапазоне (от минут до года), а амплитуда аномалий достигает первых десятков мВ на линиях длиной 100-500 м. Накануне землетрясений с достаточно большими энергетическими показателями аномалии наблюдались на расстояниях до 100 километров и более от эпицентра землетрясения, проявляются в виде изменений среднего уровня поля (бухты, ступени), в также в неявном виде, выявляемые математическими методами.

Рассмотрены механизмы генерации аномальных измерений электрического поля в условиях земной коры Северного Тянь-Шаня с учетом физических свойств горных пород при воздействии однонаправленных тектонических напряжений в геосреде, в соответствии с законом Гельмгольца-Смолуховского, определяющим связь между током в капиллярах и градиентом давления, а уравнение – с законом Дарси, определяющим величину скорости течения жидкости в зависимости от приложенного давления. Преподложена физическую модель возникновения бухтообразных аномалий естественного электрического поля в период подготовки землетрясений, в стадии ускоренного изменения тектонических напряжений, которая объясняет, почему аномалии возникают не на всех измерительных линиях, чувствительными каналами

являются те, в которых приемные электроды находятся в зонах с различной скоростью капиллярных потенциалов течения.

В результате проведенных исследований реализована методика геоэлектрических наблюдений, разработаны алгоритмы обработки и анализа данных, что позволяет осуществлять выделение аномальных вариаций поля и проводить поиск краткосрочных аномалий с идентификацией их с краткосрочными предвестниками землетрясений.

Section 2. Theoretical Foundations, Methodology, and Advanced Technologies for Earthquake Forecasting

2.3. Processes of Strong Earthquake Source Formation and Mechanisms of Precursor Anomalies

VARIATIONS OF NATURAL ELECTRIC FIELD IN THE NORTHERN TIANSHAN AND GEOELECTRIC PRECURSORS OF EARTHQUAKES

P.U. Kilanbekova, O.M. Beloslyudtsev, Y.T. Myrzabek

(National Scientific Center for Seismological Observations and Research, Ministry of Emergency
Situations of the Republic of Kazakhstan, Almaty, Kazakhstan)

Abstract: The southeastern part of Kazakhstan is one of the most seismically hazardous regions in continental Asia, where a number of destructive earthquakes have occurred over a historically short period. Recently, an increase in seismic activity has been observed in the region, with a number of earthquakes with $M > 5$ recorded, highlighting the relevance of developing short-term earthquake forecasting methods. Seismic monitoring of the Northern Tien Shan includes long-term routine geoelectric surface and borehole observations conducted at a network of integrated monitoring stations. Analysis of these observations has revealed the structure of variations in the natural electric field and identified a number of anomalous variations. The duration of electric telluric field (ETF) disturbances varies widely, from several minutes to one year, while the amplitude of anomalies reaches several tens of mV on measurement lines 100–500 m long. Prior to earthquakes with sufficiently high energy parameters, anomalies have been observed at distances of up to 100 km or more from the earthquake epicenter. They manifest themselves as changes in the mean field level (bay-like variations and step-like changes), as well as in an implicit form, detectable using mathematical methods. The mechanisms responsible for the generation of anomalous electric-field measurements in the crust of the Northern Tien Shan were considered, taking into account the physical properties of rocks under the influence of unidirectional tectonic stresses in the geological medium. In accordance with the Helmholtz–Smoluchowski equation, which describes the relationship between electric current in capillaries and the pressure gradient, and Darcy’s law, which determines the fluid-flow velocity as a function of the applied pressure, a physical model of the formation of bay-shaped anomalies in the natural electric field during earthquake preparation was proposed. The model considers the stage of accelerated changes in tectonic stresses and explains why anomalies do not occur on all measurement lines. The most sensitive channels are those in which the receiving electrodes are located in zones characterized by different rates of capillary-flow potential variations. As a result of the studies, a methodology for geoelectric monitoring was implemented, and algorithms for data processing and analysis were developed. These approaches make it possible to identify anomalous field variations and detect short-term anomalies, with their subsequent identification as potential short-term precursors of earthquakes.

HYDROGEODEFORMATION FIELD MANIFESTATION FEATURES IN THEOROGENIC REGIONS OF UZBEKISTAN

Rasulov A V

(Institute of Seismology, Academy of Sciences of the Republic of Uzbekistan, Tashkent)

Abstract: Earthquake forecasting remains one of the most challenging and least resolved problems in modern seismology. At the Institute of Seismology of the Academy of Sciences of the Republic of Uzbekistan, comprehensive studies of earthquake precursors are conducted using hydrogeoseismological observations of groundwater parameters. Among the existing approaches to earthquake forecasting, particular importance is attached to the study of changes in groundwater physical, dynamic and hydrogeochemical parameters reflecting variations in the stress-strain state of the geological environment. The purpose of the present work was to investigate the features of manifestation of the hydrogeodeformation field in the orogenic regions of Uzbekistan using long-term observations from the hydrogeoseismological wells “Chartak No. 2” and “Chimion NP-1”. The study was based on monitoring data obtained during 2000–2025. The analysis focused on identifying the most informative groundwater parameters and determining the temporal characteristics of their anomalous variations preceding earthquakes. The results indicate that hydrogeochemical parameters are highly sensitive to changes in the stress-strain state of the geological environment. The observed anomalies may be associated with changes in deep-fluid migration, rock permeability, water-rock interaction and redistribution of tectonic stresses. The differences in the sets of informative parameters observed at the two wells also indicate the influence of local geological, hydrogeological and tectonic conditions on the manifestation of hydrogeoseismological precursors. Thus, the results obtained demonstrate that the hydrogeodeformation field in the orogenic regions of Uzbekistan is manifested through coordinated changes in groundwater physical, dynamic and hydrogeochemical parameters. Systematic monitoring of these parameters at hydrogeoseismological wells can serve as a useful tool for studying earthquake precursors and assessing the preparation processes of strong earthquakes in seismically active regions of Uzbekistan.

Key words: hydrogeodeformation field, hydrogeoseismology, groundwater, hydrogeochemical anomalies, earthquake precursors, orogenic regions, Chartak, Chimion

Author Biography: Rasulov A V (Senior Researcher) Institute of Seismology, Academy of Sciences of the Republic of Uzbekistan, Tashkent. E-mail: alisher.rasulov196208@gmail.com

IMPLEMENTATION OF MEDIUM-TERM FORECAST FOR MAJOR EARTHQUAKES IN ALMATY SEISMIC REGION

Sailaubayeva Zauresh Aimukhanovna

Abstract: A representative multi-parameter monitoring network dedicated to medium-term earthquake prediction has been successfully established within the seismically active Almaty region in Southeastern Kazakhstan. The observational infrastructure comprises 100 seismic stations integrated with extensive geophysical and environmental monitoring networks, including modular (17 sites) and component-based (6 sites) geomagnetic observation points, electromagnetic radiation (EMR) recording units (11 sites), natural electric field stations (6 sites), hydrogeodynamic and hydrogeochemical monitoring stations (15 sites), as well as ground deformation measuring points and 4 permanent GPS satellite observation sites.

This study examines the three-stage forecasting framework implemented in Kazakhstan, which categorizes seismic hazard assessment into long-term (6-10 years), medium-term (1-2 years), and short-term (1-2 months) horizons. A core theoretical foundation of this approach is a conceptual model of seismic regime evolution during the preparation phase of major earthquakes in the Dzungar-Northern Tien Shan region, developed at the Institute of Seismology (now the National Scientific Centre for Seismology and Research). The model details a distinct stage sequence: initial relative quiescence following a large seismic event due to partial stress release, localized seismic activation 3-5 years prior to a subsequent major mainshock ($R < 100-150$ km), a pre-shock calm phase 1-2 years before the event, and expanding circular rings of elevated seismicity reaching radii of 300-350 km for events with $M > 6.5$.

To systematically assess medium-term seismic probability, multiple analytical and quantitative methods are integrated:

1. The Seismic Cycle Method, based on spatial-temporal clustering and quasi-cyclical patterns of seismicity;
2. The Conditional Deformation Method, evaluating cumulative deformation dynamics across major seismically active fault zones;
3. Formalized Multi-Parameter Analysis, utilizing Principal Component Analysis (PCA) on multi-dimensional time series (including fractal dimension λ , event count N , Lode-Nadai coefficient μ , V_p/V_s wave velocity ratio, anomalous velocity counts N_a , and focal strain indicators) to separate background stress accumulation from medium-term precursor signals;
4. The Ksr Fracture-Density Parameter, measuring the ratio between average distance and length of seismogenic fractures as a physical stress-threshold indicator;
5. The Activation-Quiescence Method and the RTL Algorithm, tracking spatial-temporal- energy precursor anomalies along spatial peripheries;
6. Normalized Activation and Load-Unload Response Ratio (LURR), measuring crustal responsiveness during lunar-solar tidal phases.

The practical application of this multi-methodology is illustrated through annual medium-term forecast maps for 2017, 2021, 2023, and 2024. These maps successfully delineated localized sub-regions with an increased probability of moderate earthquakes ($M=4.5-5.0$) while correctly projecting the absence of catastrophic events ($M \geq 5.5$) within the target zones during the analyzed years.

The long-term performance of this integrated methodology from 2009 to 2025 demonstrates a forecast reliability rate of 0.7-0.8 for moderate seismic events. The findings underscore the critical importance of continuous, comprehensive multi-parameter monitoring for active seismic hazard mitigation and regional risk management in Central Asia.

Аннотация. В сейсмоактивном Алматинском регионе Юго-Восточного Казахстана успешно создана представительная многопараметрическая сеть мониторинга, предназначенная для среднесрочного прогнозирования землетрясений. Наблюдательная инфраструктура включает 100 сейсмических станций, интегрированных с обширными геофизическими и экологическими сетями мониторинга, в том числе модульные (17 пунктов) и компонентные (6 пунктов) пункты геомагнитных наблюдений, пункты регистрации электромагнитного излучения (ЭМИ) (11 пунктов), станции наблюдения естественного электрического поля (6 пунктов), гидрогеодинамические и гидрогеохимические пункты мониторинга (15 пунктов), а также пункты измерения деформаций земной поверхности и 4 постоянных пункта спутниковых GPS-наблюдений.

В работе рассматривается трехэтапная система прогнозирования, реализованная в Казахстане, которая подразделяет оценку сейсмической опасности на долгосрочный (6–10 лет), среднесрочный (1–2 года) и краткосрочный (1–2 месяца) периоды. Основу данного подхода составляет концептуальная модель эволюции сейсмического режима в период подготовки сильных землетрясений в Джунгаро-Северо-Тянь-Шаньском регионе, разработанная в Институте сейсмологии (ныне Национальный научный центр сейсмологии и исследований). Модель предусматривает определенную последовательность стадий: начальное относительное затишье после крупного сейсмического события вследствие частичного снятия напряжений, локальную активизацию сейсмичности за 3–5 лет до последующего сильного главного события ($R < 100\text{--}150\text{ км}$), фазу предсейсмического затишья за 1–2 года до события и расширение кольцевых зон повышенной сейсмичности до радиусов 300–350 км для событий с $M > 6,5$.

Для систематической оценки среднесрочной вероятности возникновения землетрясений применяется комплекс аналитических и количественных методов:

1. Метод сейсмического цикла, основанный на пространственно-временной кластеризации и квазипериодических закономерностях сейсмичности;
2. Метод условной деформации, позволяющий оценивать динамику накопленной деформации в пределах основных сейсмоактивных разломных зон;
3. Формализованный многопараметрический анализ, использующий метод главных компонент (PCA) для анализа многомерных временных рядов, включающих фрактальную размерность λ , количество событий N , коэффициент Луде–Надаи μ , отношение скоростей сейсмических волн V_p/V_s , количество аномальных скоростей N_a и показатели очаговой деформации, с целью отделения фонового накопления напряжений от среднесрочных предвестниковых сигналов;
4. Параметр плотности трещин K_{sr} , характеризующий отношение между средним расстоянием и длиной сейсмогенных разрывов как физический показатель порога напряжений;
5. Метод активации–затишья и алгоритм RTL, отслеживающие пространственно-временные и энергетические предвестниковые аномалии вдоль пространственных периферий;
6. Нормированный показатель активации и отношение отклика при нагрузке–разгрузке (LURR), характеризующие реакцию земной коры во время лунно-солнечных приливных фаз.

Практическое применение данного комплекса методов иллюстрируется годовыми картами среднесрочного прогноза за 2017, 2021, 2023 и 2024 годы. Эти карты позволили успешно выделить локальные участки с повышенной вероятностью возникновения умеренных землетрясений ($M = 4,5\text{--}5,0$), одновременно правильно прогнозируя отсутствие катастрофических событий ($M \geq 5,5$) в пределах целевых зон в течение анализируемых лет.

Долгосрочная эффективность данной интегрированной методологии за период 2009–2025 гг. демонстрирует надежность прогноза умеренных сейсмических событий на уровне 0,7–0,8. Полученные результаты подчеркивают критическую важность непрерывного и комплексного многопараметрического мониторинга для снижения сейсмической опасности и управления региональным риском в Центральной Азии.

MEDIUM AND SHORT-TERM ANOMALIES AND FORECAST OF 2026 HAIXI M_s 6.3 EARTHQUAKE IN QINGHAI

Zhang Zhiwei^{1,2}, Feng Lili¹, Guo Yingxia¹, Zhao Yuhong¹, Li Qilei¹, Li Xia¹

(1. Qinghai Earthquake Agency, Xining 810003, Qinghai, China; 2. Sichuan Earthquake Agency, Chengdu 610040, Sichuan, China)

Abstract: Before the Haixi M_s 6.3 earthquake in Qinghai Province on June 16, 2026, there were obvious medium- and short-term anomalies, such as seismic activity and geophysical field in the Qinghai region, and a good short-term prediction was realized based on these anomalies. We analyzed the anomalies before the earthquake retrospectively and summarized the forecasting basis for the time, location, and intensity of the earthquake, which provides a reference for the short-term forecasting of strong earthquakes in the future. The results show that: (1) Prior to the Haixi earthquake, there had been a long quiescence of $M \geq 6.0$ earthquakes in the Qinghai region, and the area was under a critical stress state where strong earthquakes might occur at any time. (2) Against the background of persistent high stress, seismic activity intensified near the epicenter after the break of $M \geq 3.0$ earthquake quiescence in the Haixi area. (3) About nine months before the earthquake, the number of anomalies in fixed-station geophysical field observations increased significantly, with an obvious expansion of anomaly coverage. (4) Three months prior to the earthquake, fixed-station geophysical anomalies migrated and contracted toward the epicenter, dominated by short-term fluid-related anomalies.

Key words: Haixi M_s 6.3 earthquake; Medium and short term anomaly; earthquake monitoring and tracking; forecast review

GEOMAGNETIC DAILY RATIO ANOMALY AND EARTHQUAKE PREDICTION

Aisa Yisimayili¹, Zhang Anhe¹, Song Chunyan¹, Ni Xiaoyin²

(1. Earthquake Agency of Xinjiang Uygur Autonomous Region ,Urumqi 830011, Xinjiang, China; 2. Fujian Earthquake Agency, Fujian Fuzhou 530003, China)

Abstract: The **daily** ratio method of the vertical component of the geomagnetic field is used to study the relationship between the ratio method of the geomagnetic field and the earthquake with M_s 5 or above in Xinjiang from January 1, 2015, to December 31, 2025. The results indicate a strong correlation between the daily ratio method of the geomagnetic field and earthquakes with a magnitude of M_s 5 or above. Within months after the daily ratio method of the geomagnetic field shows an abnormal threshold line, the probability of an earthquake with M_s 5 or above occurring in the corresponding area is high. and draws the following conclusions.

Based on the minute-sampled data of geomagnetic vertical component provided by the National Geomagnetic Network Center, this study analyzes 43 earthquakes of $M_s \geq 5.0$ in Xinjiang, China from January 1, 2015, to December 31, 2025. A total of 32 groups of geomagnetic daily ratio anomalies are counted, and 19 groups are followed by earthquakes. The anomaly correspondence rate is 59.4%, the false alarm rate is 40.6%, the earthquake missing rate is 44.1%, 21 earthquakes are successfully predicted, and the earthquake prediction accuracy is 48.8%. The dominant corresponding period is 2 months. Among them, only one geomagnetic daily ratio anomaly appeared before 7 earthquakes, while two or more anomalies occurred before 13 earthquakes. Multiple anomalies are common before earthquakes, and the false alarm rate of grouped anomalies is much lower than that of single anomalies. Due to the uniqueness of geotectonic and active tectonic conditions in Xinjiang, the geomagnetic daily ratio anomalies before strong earthquakes also show regional characteristics. From January 1, 2015, to December 31, 2025, there were 25 days with geomagnetic storms characterized by the daily mean Dst index > -70 nT in the global geomagnetic environment, and consecutive storm days were counted as one event. Among them, six storms triggered over-threshold geomagnetic daily ratio anomalies.

This paper also studies three strong earthquakes above M_s 6.0: the M_s 6.1 Shaya earthquake on January 30, 2023, the M_s 7.1 Wushi earthquake on January 23, 2024, and the Akqi M_s 6.0 earthquake on December 4, 2025. It is found that the frequency and spatiotemporal evolution of geomagnetic daily ratio anomalies before these three earthquakes show certain similarity and repeatability. Before the mainshocks, geomagnetic daily ratio anomalies migrated from distant areas to the epicenter, with anomaly areas shrinking from large to small or moving toward the locked seismogenic zone. Epicenters are mainly located at the intersections, concentrated zones, and high-curvature sections of anomaly threshold lines, which is helpful for predicting the location of future earthquakes before shocks.

By superimposing multiple daily geomagnetic ratio anomalies threshold lines on the same base map, an abnormal intersection area or a concentration area can be formed. Earthquakes frequently occur in these areas where daily geomagnetic ratio threshold lines are concentrated or intersect. Combined with the distribution of active tectonic faults, historical earthquake activity, the multi-parameter abnormal coupling and coordination of electromagnetic disciplines, and the long-term and short-term prediction of the potential dangerous area of strong earthquake and annual earthquake dangerous area in Xinjiang, further judgment of the seismic area can effectively reduce the "space-time strong" error range of the daily geomagnetic ratio prediction, provide the basis for the determination of the location and time of the subsequent strong earthquake.

Key words: Geomagnetic ; Vertical component; Geomagnetic daily ratio; Earthquake prediction; Abnormal overlap area

利用小波变换研究 2025 年 12 月 4 日阿合奇 $M_s6.0$ 地震前重力异常特征

陈 丽, 艾力夏提·玉山, 刘代芹, 方 伟, 赵 磊, 丁 宇, 温燕琳, 韩 锴

(新疆维吾尔自治区地震局, 新疆 乌鲁木齐 830011)

摘要: 根据中国地震台网测定, 2025 年 12 月 4 日新疆阿合奇县(北纬 41.13° , 东经 78.40°) 发生 $M_s6.0$ 地震, 震源深度 10 km。地震孕育与地壳内部及壳幔物质变动密切相关, 震前数年地壳能量汇集或释放会引起区域性物质运移, 多数 6 级以上地震前后地表可观测到与孕育过程相关的重力变化。重力场动态变化的深入分析有助于捕获强震前兆信息。利用小波变换方法对南天山地区 2024—2025 年重力场变化进行多尺度分离, 并结合径向对数功率谱分析估算近似场源深度, 以提取阿合奇地震前的重力异常信息。流动重力观测结果显示: 一年尺度重力场变化以正值为主, 量值整体偏小, 震中位于零等值线附近; 两年尺度变化仍以正值为主, 震中同样处于零等值线附近; 三年尺度变化图像显示喀什—乌恰交汇区量值增大形成高值集中区, 震中仍在零等值线附近。总体而言, 不同时间尺度的重力场变化均表现为南天山地区以正变化为背景, 而阿合奇地震始终位于重力变化梯度带的零等值线附近。2024—2025 年重力场动态变化的小波变换分解表明, 随着细节阶次增加, 异常分布趋于集中, 异常圈闭范围逐渐扩大, 反映了地下物质由浅至深的密度变化特征。4 阶小波细节显示, 南天山地区整体以正值变化为主, 震中仍位于零等值线附近。对各阶小波细节进行功率谱分析, 估算 1~4 阶细节对应的场源平均深度分别为 2 km、4 km、9 km 和 16 km。表明浅部(1~3 阶)重力变化较小, 而 4 阶(约 16 km 深度)及逼近项对应的深部重力变化显著增大, 暗示震源深度附近存在明显的物质调整或密度变化。

研究表明, 小波变换分解能有效分离不同深度的重力异常, 消除部分噪声, 提取与地震孕育相关的可靠异常信息。2024—2025 年南天山地区累积重力场异常变化具有明确的深部物理意义, 4 阶细节的显著变化可能与震源区深部构造活动有关。该研究为南天山地区地壳动力学提供了重力场依据。

关键词: 小波变换; 流动重力; 阿合奇 $M_s6.0$; 重力异常特征

作者简介: 陈丽(1984—), 女, 高级工程师, 主要从事地壳形变与地震预测研究.E-mail: dragon127653@sohu.com

STUDY OF GRAVITY ANOMALY CHARACTERISTICS USING WAVELET TRANSFORM BEFORE THE AHEQI $M_s6.0$ EARTHQUAKE ON DECEMBER 4, 2025

Chen Li, Ailixiati Yushan, Liu Daiqin, Fang Wei, Zhao Lei, Ding Yu, Wen Yanlin, Han Kai
(Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011)

Abstract: According to the China Earthquake Networks Center (CENC), an $M_s6.0$ earthquake occurred on December 4, 2025 in Aheqi County, Xinjiang (41.13°N , 78.40°E), with a focal depth of 10 km. Earthquake preparation is closely related to material changes in the crust and crust-mantle. The accumulation or release of crustal energy in the years before the earthquake will cause regional material migration. Gravity changes related to the preparation process can be observed on the surface before and after most earthquakes with $M \geq 6$. The in-depth analysis of the dynamic changes of the gravity field is helpful to capture the precursory information of strong earthquakes. The wavelet transform method is used to perform multi-scale separation of the gravity field changes in the southern Tianshan area from 2024 to 2025, and the approximate field source depth is estimated by combining the radial logarithmic power spectrum analysis to extract the gravity anomaly information before the Aheqi earthquake.

The results of mobile gravity observation show that the change of gravity field in one year scale is mainly positive, the magnitude is small as a whole, and the epicenter is located near the zero isoline. The two-year scale change is still dominated by positive values, and the epicenter is also near the zero contour. The three-year scale change image shows that the magnitude of the Kashi-Wuqia intersection area increases to form a high-value concentration area, and the epicenter is still near the zero contour. In general, the gravity field changes at different time scales are all characterized by positive changes in the southern Tianshan Mountains, while the Aheqi earthquake is always located near the zero isoline of the gravity gradient zone.

The wavelet transform decomposition of the dynamic change of gravity field from 2024 to 2025 shows that with the increase of detail order, the anomaly distribution tends to be concentrated, and the anomaly trap range gradually expands, reflecting the density change characteristics of underground materials from shallow to deep. The fourth-order wavelet details show that the southern Tianshan area is dominated by positive changes, and the epicenter is still near the zero contour. The power spectrum analysis of each order wavelet detail is carried out, and the average depth of the field source corresponding to the 1~4 order details is estimated to be 2 km, 4 km, 9 km, and 16 km, respectively. It is shown that the shallow gravity change (1~3 orders) is small, while the deep gravity change corresponding to the 4th order (about 16 km depth) and the approximation term increases significantly, suggesting that there is obvious material adjustment or density change near the focal depth.

Studies have shown that wavelet transform decomposition can effectively separate gravity anomalies at different depths, eliminate some noise, and extract reliable anomaly information related to earthquake preparation. The change of cumulative gravity field anomaly in South Tianshan area from 2024 to 2025 has clear deep physical significance, and the significant change of fourth-order details may be related to the deep tectonic activity in the source area. This study provides a gravity field basis for crustal dynamics in the South Tianshan area.

Key words: Wavelet Transform; Mobile Gravity; Aheqi $M_s6.0$; Gravity Anomaly Characteristic

Author Biography: Chen Li (1984–), Female, Senior Engineer, mainly engaged in research on crustal deformation and prediction. E-mail: dragon127653@sohu.com

北天山跨断层场地垂直形变异常与映震分析

丁 宇, 温燕林, 阿尔达克·卡德尔别克, 赵 磊

(新疆维吾尔自治区地震局, 新疆 乌鲁木齐 830011)

摘要: 通过对北天山地区布设的 12 条跨断层场地 2012—2025 年每年两 2 期观测资料进行分析, 各测线高差变化时序曲线显示, 西山测线自 2022 年 12 月出现持续拉张, 2025 年 9 月较 4 月变化量达 1.7mm。计算出 2012—2025 年各断层的趋势累积率 D_c , 卡子湾测线趋势累积率达+0.97, 表明霍尔果斯断裂长趋势小幅持续拉张; 伊宁县测线趋势累积率达-0.72, 表明喀什河断裂小幅持续挤压。形变速率累加曲线显示, 红山嘴测线 2025 年 9 月出现小幅阶跃上升异常变化(2026 年 4 月观测结果显示为回落至 2025 年 4 月水平), 伊宁县测线自 2024 年 9 月开始出现连续阶跃上升异常变化。西山测线、红山嘴测线和卡子湾测线形变异常对应了 2026 年 3 月 5 日呼图壁 M_s 4.6 地震和 2026 年 3 月 7 日呼图壁 M_s 4.8 地震; 伊宁县测线形变异常对应了 2026 年 6 月 5 日霍尔果斯 M_s 4.8 地震。震例类比表明, 2016 年 12 月 8 日呼图壁 M_s 6.2 地震前红山嘴测线形变速率累加出现阶跃变化, 幅度约为 2026 年呼图壁两次地震的 3 倍; 2016 年 2 月 11 日新源 M_s 5.0 地震、2017 年 8 月 9 日精河 M_s 6.6 地震和 2018 年 10 月 16 日精河 M_s 5.4 地震前伊宁县测线形变速率累积都出现阶跃变化。分析结果检验了跨断层水准场地观测在北天山地区的映震效能, 可为今后北天山地区地震趋势研判提供有效数据支撑。

关键词: 北天山; 跨断层水准; 趋势累积率; 形变速率累加

作者简介: 丁宇(1991—), 男, 工程师, 主要从事流动观测及地壳形变与地震预测研究.E-mail: mynameisdingyu@163.com

VERTICAL DEFORMATION ANOMALIES AND SEISMIC RESPONSE ANALYSIS OF THE CROSS-FAULT SITE IN NORTHERN TIANSHAN

Ding Yu, Wen Yanlin, Aldark Kadeerbek, Zhao Lei

(Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, Xinjiang, China)

Abstract: Based on the biannual observation data from 12 cross-fault sites deployed in the northern Tianshan region during 2012 to 2025, this paper carries out a comprehensive analysis. The time-series curves of elevation difference variations for each survey line reveal that the Xishan Line has undergone continuous tensile deformation since December 2022, with a variation of 1.7 mm between April and September 2025. The cumulative trend rate D_c of each fault from 2012 to 2025 was calculated: the Kazanwan Line attained a cumulative trend rate of +0.97, indicating sustained slight long-term tension along the Huoerguos Fault; the Yining County Line showed a cumulative trend rate of -0.72, representing mild continuous compression of the Kashi River Fault. The cumulative deformation rate curves demonstrate that the Hongshanzui Line exhibited a small step-up anomalous change in September 2025 (the April 2026 observation showed the deformation had declined back to the level recorded in April 2025), while the Yining County Line has presented successive step-up anomalies starting from September 2024. Deformation anomalies on the Xishan, Hongshanzui and Kazanwan Lines corresponded to the Hutubi M_s 4.6 earthquake on March 5, 2026 and the Hutubi M_s 4.8 earthquake on March 7, 2026; anomalies on the Yining County Line were associated with the Huoerguos M_s 4.8 earthquake on June 5, 2026. Analogies with historical earthquake cases indicate that stepwise variations in the cumulative deformation rate of the Hongshanzui Line occurred prior to the Hutubi M_s 6.2 earthquake on December 8, 2016, with an amplitude approximately three times that observed before the two 2026 Hutubi earthquakes. Pre-earthquake step anomalies were also detected on the Yining County Line before the Xinyuan M_s 5.0 earthquake on February 11, 2011, the Jinghe M_s 6.6 earthquake on August 9, 2017, and the Jinghe M_s 5.4 earthquake on October 16, 2018. The analytical results verify the earthquake-reflecting capability of cross-fault leveling observations in the northern Tianshan area, which can provide effective data support for future seismic tendency assessment in this region.

Key words: Northern Tianshan Mountains; Fault-crossing Leveling; Trend Accumulation Rate; Accumulation of Deformation Rate

Author Biography: Ding Yu (1991–), male, engineer, mainly engaged in mobile observation, crustal deformation, and earthquake prediction research. E-mail: mynameisdingyu@163.com

甘肃肃北 $M_{s5.5}$ 震群形变异常与应力演化

高曙德^{1,2}, 闫 勋², 陈玉鑫¹, 武善艺¹, 陈双贵²

(1.甘肃省地震局(中国地震局兰州地震研究所), 甘肃, 兰州 730000; 2.甘肃兰州地球物理国家野外科学观测研究站, 甘肃, 兰州 730000)

摘要: 本研究旨在探讨 2023 年 10 月 24 日及 12 月 1 日甘肃省肃北县 $M_{s5.5}$ 和 $M_{s5.0}$ 地震前后区域构造变形特征, 并揭示震前形变异常与区域运动场变化之间的内在关联。利用玫瑰图、地图投影等空间分析方法, 综合震源机制解、地表同震位移及区域 GNSS 速度场数据, 对肃北震群周边构造的变形特征进行系统分析; 同时, 重点对比了安西站与嘉峪关西沟站 SSY 洞体应变记录的震前趋势性异常与同震阶跃响应, 并将同震应变阶的拉张/压缩特征与地震水平位移场模式进行对比, 进一步结合 GNSS 速度场时间序列切片, 检验震前异常出现时间与区域水平运动方向偏转时刻的同步性。结果表明: 洞体应变清晰记录了震前应力累积(趋势性异常)与同震应力阶跃释放(阶变)的相反变化过程; 同震应变阶的拉张/压缩变化与地震水平位移场的变化模式高度一致; 震前应变异常的出现时间, 与 GNSS 速度场时间序列切片中区域水平运动方向显著偏转的时间点同步, 形变观测站点的异常响应与 GNSS 揭示的区域构造运动特征存在显著相关性。研究结论可为强震孕育过程中的应力—应变状态演化提供实例支撑, 并为后续融合多源形变观测资料、构建精细区域构造运动模型、动态反演震前构造应力场演化, 以及潜在震中位置的预判提供思路和参考。

关键词: SSY 洞体应变异常; 同震应变阶; GNSS 水平速度分布; 区域构造运动

作者简介: 高曙德(1970—), 男, 正高级工程师, 主要从事地震监测预测和科学研究.E-mail: gsd_gsd@126.com.

DEFORMATION ANOMALIES AND STRESS EVOLUTION OF $M_s5.5$ EARTHQUAKE SWARM IN SUBEI, GANSU PROVINCE

Gao Shude^{1,2}, Yan Xun², Chen Yuxin¹, Wu Shanyi¹, Chen Shuanggui¹

(1.Gansu Earthquake Agency & Lanzhou Institute of Earthquake Research, CEA, Lanzhou
730000, Gansu, China; 2.Lanzhou Geophysics National Observatory and Research Station, Lanzhou
730000, Gansu, China)

Abstract: This study aims to investigate the regional tectonic deformation characteristics before and after the M_s 5.5 and M_s 5.0 earthquakes that occurred on October 24 and December 1, 2023, in Subei County, Gansu Province, and to reveal the intrinsic relationship between pre-earthquake deformation anomalies and changes in the regional motion field. Using spatial analysis methods such as rose diagrams and map projections, and integrating focal mechanism solutions, surface co-seismic displacement data, and regional GNSS velocity field data, this study conducts a systematic analysis of the deformation characteristics of the tectonic structures surrounding the Subei earthquake swarm. At the same time, the study focused on comparing the pre-earthquake trend-based anomalies and co-seismic step responses recorded in the SSY tunnel at the Anxi Station and the Xiaoxigou Station in Jiayuguan. It also compared the tensile/compressive characteristics of the co-seismic strain steps with the patterns of the seismic horizontal displacement field, and further combined this with time-series slices of the GNSS velocity field to verify the synchrony between the onset of pre-earthquake anomalies and the timing of deviations in the direction of regional horizontal motion. The results indicate that the strain records in the boreholes clearly document the opposing processes of pre-seismic stress accumulation (trend-based anomalies) and intraseismic stress release (step changes); the tensile/compressive changes in the in-seismic strain step show a high degree of consistency with the variation patterns of the seismic horizontal displacement field; the onset time of pre-seismic strain anomalies is synchronized with the time points of significant deviations in the direction of regional horizontal motion observed in GNSS velocity field time-series slices, and there is a significant correlation between the anomalous responses at deformation observation stations and the regional tectonic motion characteristics revealed by GNSS. The findings of this study provide empirical support for the evolution of stress-strain states during the development of major earthquakes and offer insights and guidance for subsequent efforts to integrate multi-source deformation data, construct high-resolution regional tectonic motion models, dynamically invert the evolution of pre-seismic tectonic stress fields, and predict the location of potential epicenters.

Key words: SSY Tunnel Body Strain Anomaly; Coseismic Strain Step; GNSS Horizontal Velocity Distribution; Regional Tectonic Movement

Author Biography: Gao Shude (1970–), Male, Professor-level Senior Engineer, mainly engaged in earthquake monitoring, prediction, and scientific research. E-mail: gsd_gsd@126.com

一种检测强震前地震活动变化的方法

姜祥华¹, 孟令媛¹, 韩颜颜¹

(1.中国地震台网中心, 北京 100045)

摘要: 为了研究强震前地震活动的显著增强或显著减弱变化, 我们发展了一种定量检测方法, 名为地震发生率指数(seismicity rate index, SRI)。本方法以稳态泊松过程为参考模型, 根据一定时间内发生地震的次数, 计算得到处于 0 和 1 之间的累积概率分布值作为指数, 对地震活动水平进行统计度量。指数接近 0 或 1 意味着对稳态泊松模型的偏离, 接近 0 表明地震活动减弱, 接近 1 表明地震活动增强。通过空间上的网格剖分和时间上的切片处理, 实施扫描计算, 实现对局部地震活动异常的定量探测。以 2021 年 5 月 21 日云南漾濞 6.4 级地震为典型示例, 考察了震前地震发生率指数分布的演化特征。在地震前约 105 天, 震中附近出现地震活动增强异常网格。此后异常网格区域扩大且异常强度不断增加, 直至主震发生。进一步考察了其中一个典型异常网格的累积地震频度演化, 发现地震频度自 2021 年 1 月 3 日(主震前 138 天)开始迅速增加。最后, 检验了地震发生率指数对川滇地区强震的预测效能。检验时段为 2014 年 1 月 1 日至 2025 年 12 月 31 日, 期间共发生 11 次 6 级以上地震。 R 值评分结果显示, 地震发生率指数对川滇地区的强震具有较好的短期预测能力。上述研究结果表明, 地震发生率指数能在地震短期预测中发挥一定作用。

关键词: 地震发生率指数; 地震增强; 地震平静; 地震预测

作者简介: 姜祥华(1987—), 男, 高级工程师, 主要从事地震活动性与地震预测研究. E-mail: jiangxh@seis.ac.cn

A METHOD FOR DETECTING SEISMICITY RATE CHANGE PRIOR TO STRONG EARTHQUAKE

Jiang Xianghua, Meng Lingyuan, Han Yanyan

(China Earthquake Networks Center, Beijing 100045, China)

Abstract: We developed a quantitative method to study changes in seismicity rate before strong earthquakes. We call it the Seismicity Rate Index (SRI). This method uses the stationary Poisson model as a reference. It calculates a cumulative probability value between 0 and 1 according to the number of events in a time window. This value serves as an index to measure the level of earthquake activity. The index close to 0 indicates decreasing of seismicity rate, while close to 1 indicates increasing—both represent departures from the Poisson assumption. By applying the method over spatial grids and moving time windows, we can quantitatively identify local anomalies. We tested this method on the 2021 M6.4 Yangbi earthquake in Yunnan. About 105 days before the mainshock, anomalous grid cells with increased rate appeared around the epicenter. The anomalous area then expanded, and the anomaly grew stronger until the mainshock occurred. In one representative cell, the cumulative earthquake number started rising sharply on January 3, 2021—138 days before the mainshock. We also evaluated the predictive performance of SRI for strong earthquakes in the Sichuan–Yunnan region over the period from January 1, 2014, to December 31, 2025. During that time, 11 earthquakes of magnitude 6 or larger took place. R-score results show that the SRI has good short-term prediction capability for this region. Overall, our findings suggest that the SRI can contribute to short-term earthquake prediction in practice.

Key words: Seismicity rate index; Seismic activation; Seismic quiescence; Earthquake prediction

Author Biography: Jiang Xianghua (1987–), Male, Senior Engineer, mainly engaged in research on seismicity and earthquake prediction. E-mail: jiangxh@seis.ac.cn

天山构造带地下流体水化学特征及其地震前兆指示

李娜¹, 汪成国¹, 麻荣¹, 闫玮¹, 朱文振¹, 贾永斌¹, 韩时雨¹,
赛买尔那吉·喀依木¹, 赵影^{1,2}

(1.新疆维吾尔自治区地震局, 新疆 乌鲁木齐 830011; 2.江西省地震局, 江西 南昌 330026)

摘要: 天山构造带是新疆强震高发区域, 地下流体是地震前兆监测的核心载体, 系统厘清监测网水文地球化学特征与灵敏点位, 对区域震情跟踪与异常核实具有重要支撑作用。本文以天山地震重点监视区 26 个地下流体监测井/泉为研究对象, 通过水化学与氢氧同位素测试, 综合运用 Piper 三线图、离子比值、Gaillardet 端元图解及 Na-K-Mg 三角图等方法, 解析不同构造单元地下水演化规律, 结合连续观测序列开展映震效能检验与优势指示组分识别。研究表明, 区域地下水阳离子以 Na^+ 占主导, 阴离子以 HCO_3^- 、 SO_4^{2-} 、 Cl^- 为主, 水化学类型与构造分区高度对应: 北天山以浅循环 $\text{HCO}_3\text{-SO}_4\text{-Na}$ 型水为主, 天山中段与乌鲁木齐受断裂带深浅流体混合作用发育过渡型 $\text{SO}_4\text{-Na}$ 型水, 南天山以高矿化 $\text{Cl}\text{-SO}_4\text{-Na}$ 型水为特征。氢氧同位素证实地下水补给以大气降水为主, δD 值自南向北递减, 呈现显著纬度效应; 溶质物源整体以硅酸盐风化为基底, 叠加蒸发岩溶解与阳离子交换; 水体以部分平衡水和未成熟水为主, 水岩反应未达完全平衡, 具备天然构造响应潜力。基于多维度地球化学标识筛选出 10Q、21Q、25Q、60Q 共 4 个灵敏点位, 可划分为断裂带深浅混合型与深循环稳定型两类。2024—2026 年连续观测验证显示, 四站对不同方位地震表现出敏感响应: 10Q 对达坂城—托克逊、21Q 对呼图壁—玛纳斯、25Q 对精河—博州、60Q 对塔什库尔干—阿克陶方向的地震响应最为灵敏, 其中 10Q 以 HCO_3^- 骤降与 Cl^- 高值为特征, 21Q 以 K^+ 低值—震后反弹为典型模式, 25Q 以 SO_4^{2-} 高值与 K^+ 高低值转换为优势组合, 60Q 以 K^+ “高值—震前回落”过程最为清晰; 异常多集中于震前 5~35 天, 呈现多离子同步突变的单峰型演化规律, 对 $M_s \geq 4.0$ 地震的有效响应率达 80% 以上, 跨站点协同异常可有效提升前兆信号可信度。上述结果表明, Na^+ 、 Cl^- 、 SO_4^{2-} 为响应构造活动的优势指示组分, 各灵敏点兼具短临响应灵敏度与方位识别能力, 研究结果可为新疆地震流体监测网优化布局与前兆异常识别提供科学依据。

关键词: 地震; 地下流体; 氢氧同位素; 地球化学

作者简介: 李娜 (1986—), 女, 高级工程师, 主要从事地震地下流体监测预报与分析研究. E-mail: lina_vivid@163.com

HYDROCHEMICAL CHARACTERISTICS OF UNDERGROUND FLUIDS IN THE TIANSHAN TECTONIC BELT AND THEIR EARTHQUAKE PRECURSOR INDICATIONS

LI Na¹, WANG Chengguo¹, MA Rong¹, YAN Wei¹, ZHU Wenzhen¹, JIA Yongbin¹,
HAN Shiyu¹, SAIMAINAJI Keyimu¹, ZHAO Ying^{1,2}

(1. Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, China; 2. Jiangxi
Earthquake Agency, Nanchang 330026, China)

Abstract: Tianshan tectonic belt is a region of high earthquake frequency in Xinjiang, where underground fluids serve as a critical carrier for earthquake precursory monitoring. This study examines 26 monitoring wells/springs in the key earthquake surveillance area. Through hydrochemical and isotopic analyses combined with Piper diagrams and Na-K-Mg ternary plots, we investigated groundwater evolution and evaluated earthquake-reflecting effectiveness across different tectonic units. The results show that Na^+ is the dominant cation, while HCO_3^- , SO_4^{2-} and Cl^- are the major anions. Hydrochemical types correspond closely to tectonic subdivisions: the Northern Tianshan is characterized by $\text{HCO}_3 - \text{SO}_4 - \text{Na}$ type water; the central Tianshan exhibits transitional $\text{SO}_4 - \text{Na}$ type water; and the southern Tianshan is dominated by $\text{Cl} - \text{SO}_4 - \text{Na}$ type water. Isotopes indicate meteoric recharge, with solute sources mainly controlled by silicate weathering. The waters are predominantly in a state of partial equilibrium, indicating natural sensitivity to tectonic stress. Four sensitive sites (10Q, 21Q, 25Q, and 60Q) were identified and classified into two types: fault-zone mixing and deep-circulation stable types. Continuous observations from 2024 to 2026 demonstrate that 10Q responds with HCO_3^- drops and Cl^- peaks, 21Q shows K^+ low-to-rebound patterns, 25Q exhibits SO_4^{2-} and K^+ anomalies, and 60Q displays distinct K^+ pre-seismic rise-to-fall sequences. Anomalies predominantly occur within 5–35 days before earthquakes, with multi-ion synchronous spikes. The effective response rate for $M_s \geq 4.0$ events exceeds 80%, and cross-station coincident anomalies significantly enhance precursor reliability. This study provides a scientific basis for optimizing the Xinjiang underground fluid monitoring network and improving precursory anomaly identification.

Key words: Earthquake; Groundwater; Hydrogen-oxygen isotopes; Hydrogeochemistry

Author Biography: LI Na (1986–), Female, Senior Engineer, mainly engaged in underground fluid monitoring, earthquake prediction, and analysis. E-mail: lina_vivid@163.com.

新疆流体监测井泉氢氧同位素背景值特征

麻 荣, 韩时雨, 朱文振, 李思妍

(新疆维吾尔自治区地震局, 新疆 乌鲁木齐 830011)

摘要: 为准确识别地震流体前兆异常、建立适应本地监测需求的新疆井泉氢氧同位素背景基线, 弥补区域背景值调查尚不系统的不足, 本文利用天山及周边地区地震监测井(泉)样品, 对北疆 24 个、南疆 15 个泉/井水样的 $\delta^2\text{H}$ 、 $\delta^{18}\text{O}$ 组成进行系统测定与分析: 水样采用液态水同位素分析仪 (Picarro L2130-i) 测定, 以 VSMOW 为标准, $\delta^2\text{H}$ 分析精度优于 $\pm 1\%$ 、 $\delta^{18}\text{O}$ 优于 $\pm 0.1\%$, 每批次插入标准样进行质量控制; 在此基础上拟合局地大气降水线 (LMWL)、计算氘盈余, 并对南北疆同位素特征进行对比, 建立区域背景基线。结果表明: 全疆 $\delta^{18}\text{O}$ 介于 -16.88% ~ -7.43% , $\delta^2\text{H}$ 介于 -123.32% ~ -42.96% , 二者高度相关 ($R^2=0.927\ 5$), LMWL 为 $\delta^2\text{H}=7.78\ \delta^{18}\text{O}+10.24$; 南北疆差异显著, 北疆 $\delta^{18}\text{O}$ 、 $\delta^2\text{H}$ 均值分别为 -12.07% 、 -84.13% , 其 LMWL ($\delta^2\text{H}=7.87\ \delta^{18}\text{O}+10.89$, $R^2=0.927\ 4$) 接近全球大气降水线, 指示以高海拔冰雪融水补给为主、蒸发作用较弱, 而南疆均值分别为 -10.55% 、 -71.03% , LMWL 斜率与截距明显偏低 ($\delta^2\text{H}=7.31\ \delta^{18}\text{O}+6.08$, $R^2=0.899\ 6$), 呈干旱区蒸发线特征, 具有帕米尔贫化端元与盆地蒸发端元并存的“双端元”结构。研究结论可为新疆地震流体监测台网的异常判识、补给源解析及地震前兆信息提取提供定量依据。

关键词: 氢氧同位素; 局地大气降水线; 背景值; 地震流体监测

作者简介: 麻荣 (1985—), 男, 工程师, 主要从事地震地下流体监测.E-mail: mrxjeq@126.com

BACKGROUND VALUES OF HYDROGEN AND OXYGEN ISOTOPES IN FLUID-MONITORING WELLS AND SPRINGS, XINJIANG

Ma Rong, Han Shiyu, Zhu Wenzhen, Li Siyan.

(Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, Xinjiang,
China)

Abstract: To accurately identify seismic fluid precursory anomalies and establish a hydrogen and oxygen isotope background baseline for Xinjiang wells and springs that meets local monitoring requirements, thereby compensating for the lack of systematic regional background surveys, this study systematically measured and analyzed the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ compositions of 24 water samples from northern Xinjiang and 15 from southern Xinjiang, collected from seismically monitored wells and springs in and around the Tianshan Mountains. All water samples were measured with a liquid water isotope analyzer (Picarro L2130-i), with the results reported relative to Vienna Standard Mean Ocean Water (VSMOW); the analytical precision is better than $\pm 1\text{‰}$ for $\delta^2\text{H}$ and $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$, and standards were inserted into every batch for quality control. Local meteoric water lines (LMWLs) were then fitted, deuterium-excess values were calculated, and the isotopic compositions of northern and southern Xinjiang were compared, thereby establishing a regional background baseline. The results show that across the whole of Xinjiang, $\delta^{18}\text{O}$ ranges from -16.88‰ to -7.43‰ and $\delta^2\text{H}$ from -123.32‰ to -42.96‰ , with the two values highly correlated ($R^2 = 0.9275$); the LMWL is defined as $\delta^2\text{H} = 7.78\delta^{18}\text{O} + 10.24$. Marked differences exist between northern and southern Xinjiang. In the north, the mean $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values are -12.07‰ and -84.13‰ , respectively, and its LMWL ($\delta^2\text{H} = 7.87\delta^{18}\text{O} + 10.89$, $R^2 = 0.9274$) approaches the global meteoric water line, indicating that recharge is dominated by high-altitude snow and ice meltwater with weak evaporation. In the south, by contrast, the mean values are -10.55‰ and -71.03‰ , and the LMWL exhibits a markedly lower slope and intercept ($\delta^2\text{H} = 7.31\delta^{18}\text{O} + 6.08$, $R^2 = 0.8996$), displaying the evaporation-line signature typical of arid regions and a dual end-member structure consisting of a depleted Pamir end-member and an evaporative basin end-member. These findings provide a quantitative basis for anomaly identification, recharge-source discrimination, and seismic precursor extraction within the subsurface fluid monitoring network of Xinjiang.

Key words: Hydrogen and oxygen isotopes; Local meteoric water line (LMWL); Background value; Seismic fluid monitoring

Author Biography: Ma Rong (1985–), Male, Engineer, mainly engaged in research on the observation and monitoring of subsurface fluids related to earthquake precursors. E-mail: mrxjeq@126.com

阿合奇 $M_{6.0}$ 地震前重力场变化与异常特征分析

聂嘉旺, 赵 磊, 艾力夏提·玉山, 刘代芹, 阿卜杜塔伊尔·亚森, 丁 宇,

阿尔达克·卡德尔别克

(新疆维吾尔自治区地震局, 新疆 乌鲁木齐 830011)

摘要: 南天山西段地处塔里木盆地与南天山造山带的交汇部位, 构造活动强烈、强震频发, 地壳应力积累与深部物质运移过程会引发地表重力场的动态响应, 基于流动重力观测的震前异常识别已成为区域地震危险性研判的重要技术手段。本文利用 2020 年 4 月至 2025 年 3 月南天山地区多期流动重力观测数据, 通过重力场差分计算、累积变化量提取及典型测点时间序列分析等方法, 从年尺度与长时间序列双重维度, 系统研究了 2025 年阿合奇 $M_{6.0}$ 地震震区及周边区域的重力场时空动态演化特征, 深入探讨重力异常与强震孕育过程的内在关联。研究结果表明: 1) 空间分布上, 阿合奇地震震中南侧的柯坪块体以及喀什—乌恰构造交汇区重力变化量值集中且梯度特征显著, 重力等值线展布基本与区域主干断裂构造呈正交分布, 反映出重力场变化受区域构造运动的直接控制, 与地壳深部物质迁移及应力调整过程高度对应; 2) 时间演化上, 震前 2~4 年震中周边区域重力场变化幅度持续增大, 呈现出与应力加速积累相匹配的动态演化特征, 而震前 1 年重力场变化相对平缓, 整体进入相对稳定的临震调整阶段; 3) 构造关联上, 乌什—阿合奇一带的重力场正负交替过渡带及零等值线与发震构造空间匹配关系密切, 该类重力异常梯度带与正负交替区域往往对应地壳应力集中与能量积累的关键部位, 更易成为强震发生的有利区域。

区域重力异常的分区演化特征, 综合反映了 2020 年伽师 $M_{6.4}$ 地震、2024 年乌什 $M_{7.1}$ 地震的震后构造调整效应, 以及本次阿合奇 $M_{6.0}$ 地震的长期孕震过程, 进一步印证了重力场正负交替带与高梯度带多分布于地震危险性较强的活动构造区域的规律。本研究成果深化了南天山西段强震孕震过程的重力场响应认识, 对有效识别强震前的重力异常信息具有重要实践价值。

关键词: 阿合奇 $M_{6.0}$ 地震; 重力场变化; 流动重力; 南天山

作者简介: 聂嘉旺 (1999—), 男, 助理工程师, 主要从事地震流动重力测量工作及时空重力场变化研究。
E-mail: 18193589777@163.com

STUDY ON CHARACTERISTICS OF GRAVITY FIELD CHANGES BEFORE AHEQI $M_s6.0$ EARTHQUAKE¹

Nie Jiawang, Zhao Lei, Ailixiatiti Yushan, Liu Daiqin, Abudutayier Yasen, Ding Yu, Aerdake Kadeerbieke

(Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, Xinjiang, China)

Abstract: The western segment of the South Tianshan Mountains, situated at the junction between the Tarim Basin and the South Tianshan orogenic belt, is characterised by intense tectonic activity and frequent strong earthquakes. The accumulation of crustal stress and the migration of deep-seated materials trigger dynamic responses in the surface gravity field. Accordingly, identifying pre-earthquake anomalies through mobile gravity observations has become an important technical tool for regional seismic hazard assessment. Using multi-epoch mobile gravity data acquired in the South Tianshan region from April 2020 to March 2025, this study systematically investigates the spatiotemporal evolution of the gravity field in and around the source region of the 2025 Aheqi M_s 6.0 earthquake. The analysis employs gravity field differencing, cumulative change extraction, and time-series analysis of representative survey points, covering both annual and long-term timescales, with the aim of elucidating the intrinsic link between gravity anomalies and the seismogenic process of strong earthquakes. The main findings are as follows:

Spatial distribution – The Kalpin block south of the Aheqi epicentre and the Kashi – Wuqia tectonic junction exhibit concentrated gravity changes with pronounced gradients. The gravity contours are oriented approximately orthogonal to the regional master faults, indicating that gravity variations are directly controlled by regional tectonics and closely correspond to deep material transfer and stress adjustment.

Temporal evolution – During the 2 – 4 years preceding the earthquake, the amplitude of gravity changes around the epicentre increased continuously, matching the pattern of accelerating stress accumulation. In contrast, the gravity field remained relatively stable in the final year before the event, entering a quiet pre-seismic adjustment phase.

Tectonic association – The alternating positive-negative transition zones and the zero-contour lines of the gravity field in the Wushi – Aheqi area show a close spatial correspondence with the seismogenic structure. Such gradient belts and alternation zones typically mark the critical loci of crustal stress concentration and energy buildup, which are more prone to strong earthquake occurrence.

The partitioned evolution of regional gravity anomalies comprehensively reflects the post-seismic adjustments from the 2020 Jiashi $M_s6.4$ and 2024 Wushi M_s 7.1 earthquakes, as well as the long-term preparatory process of the 2025 Aheqi M_s 6.0 event. It further corroborates that positive-negative alternating belts and high-gradient zones are predominantly distributed in active tectonic regions with elevated seismic hazard. This study enhances our understanding of gravity-field responses during the seismogenic processes of strong earthquakes in the western South Tianshan, offers practical value for effectively identifying pre-earthquake gravity anomalies, and provides a solid scientific basis and technical support for seismic risk assessment and medium-to long-term earthquake forecasting in the region.

Key words: Aheqi $M_s6.0$ earthquake; Gravity field change; Mobile gravity; Southern Tianshan

Author's brief introduction: Nie Jiawang (1999–), male, Assistant Engineer, mainly engaged in seismic mobile gravity measurement and spatiotemporal gravity field variation research. E-mail: 18193589777@163.com

强震前短期形变变化与地震活动相关性研究

牛安福, 王海涛

(中国地震台网中心, 北京, 100045)

摘要: 强震前形变异常特征及其在有序迁移背景下的时空分布规律, 是识别可靠地震前兆和揭示地震孕育机制的关键。为建立不同时间尺度形变异常变化与地震之间定量关系, 本文首先从更大的空间尺度分析了强震活动的规律。青藏高原自 1995 年开始新一轮强震活跃期, 活跃期内 8 级地震、7 级地震和 6 级地震在时间—空间上呈现一定的规律性分布。如 2008 年以来玉树地震、芦山地震、九寨沟地震和玛多地震在空间上集中于巴颜喀拉块体东边界, 共圆(或共椭圆)分布, 且呈逆时针迁移特征。本文系统研究了这些强地震震前短期内形变异常的时空分布特征。结果表明, 在强震有序迁移的背景下, 震前短期形变异常通常与发震断层斜交, 并与地震在不同时间尺度上保持相对稳定的定量关系。结合地震波技术揭示的中上地壳 Q 值结构及区域地壳运动变形特征, 进一步分析表明, 震前短期形变异常和强震沿块体边界带的有序迁移可能均受深部地壳流体活动共同控制。最后, 提出了深部地壳物质流、地震活动和地表形变异常之间耦合关系的概念模型, 旨在深化对地壳形变观测意义的理解, 并探索短期定量地震预测的可能性。

关键词: 青藏高原; 强震迁移; 短期形变变化; 相关性判别; 深部物质流动

作者简介: 牛安福(1964—), 男, 二级研究员, 主要从事地壳形变与地震动力学研究. E-mail: niuanfu01@sina.com

SHORT-TERM DEFORMATION VARIATIONS BEFORE STRONG EARTHQUAKES AND THEIR CORRELATION WITH SEISMICITY

Niu Anfu, Wang Haitao

(China Earthquake Networks Center, Beijing 100045, China)

Abstract: The characteristics of deformation anomalies before strong earthquakes and their spatiotemporal distribution patterns against the background of orderly migration are key to identifying reliable earthquake precursors and revealing earthquake preparation mechanisms. To establish quantitative correlations between deformation anomaly variations and earthquakes at different time scales, this report analyzes the patterns of strong earthquake activity from a larger spatial perspective. Since 1995, the Tibetan Plateau has entered a new round of strong earthquake active period, during which M8, M7, and M6 earthquakes exhibit certain regular spatiotemporal distribution patterns. For example, since 2008, the Ms7.1 Yushu, Ms7.0 Lushan, Ms7.0 Jiuzhaigou, and Ms7.4 Maduo earthquakes have been spatially concentrated along the eastern boundary of the Bayan Har block, showing co-circular (or co-elliptical) distribution and counterclockwise migration characteristics. This report systematically investigates the spatiotemporal distribution characteristics of short-term deformation anomalies before these strong earthquakes. The results show that, against the background of orderly strong earthquake migration, short-term pre-seismic deformation anomalies are typically oblique to the seismogenic faults and maintain relatively stable quantitative relationships with the earthquakes at different time scales. Combined with the mid-to-upper crustal Q-value structure revealed by seismic wave techniques and regional crustal movement characteristics, further analysis indicates that both the short-term pre-seismic deformation anomalies and the orderly migration of strong earthquakes along block boundary zones may be jointly controlled by deep crustal fluid activity. Finally, a conceptual model of the coupling relationship among deep crustal material flow, seismicity, and surface deformation anomalies is proposed, aiming to deepen the understanding of the significance of crustal deformation observations and to explore the possibility of short-term quantitative earthquake prediction.

Key words: Tibetan Plateau; Strong Earthquake Migration; Short-term Deformation Variations; Correlation Discrimination; Deep Material Flow

Author Biography: Niu Anfu(1964–), Male, Research Fellow, Second Class, mainly engaged in research on crustal deformation and seismic dynamics. E-mail: niuanfu01@sina.com

2025 年缅甸 M_w 7.7 地震的库仑应力影响与未来地震危险性：对实皆断裂带和掸邦高原的启示

沈拓¹，吴伟伟^{1*}，孟国杰¹，刘泰¹，张鲁鹏¹，唐金²，徐锡伟³

(1. 中国地震局地震预测研究所，北京，100036; 2. 中国石油勘探开发研究院，北京，100083;

3. 中国地质大学（北京）地球科学与资源学院，北京，100083)

摘要：2025 年 3 月 28 日，缅甸实皆断裂带发生了一次 M_w 7.7 右旋走滑型大地震，造成了重大人员伤亡和基础设施破坏。自 1897 年以来，实皆断裂带的长期应力演化受此次地震所引起的同震和震后库仑破裂应力变化 (ΔCFS) 扰动的显著影响。本研究利用 PSGRN/PSCMP 软件的多层黏弹性模型，对这些应力变化进行了计算与评估。结果表明，此次地震显著加载了其破裂带的南、北两端以及多个邻近断层（如 Kyaukse 断裂、Loi Kwi 断裂、澜沧断裂和南汀河断裂南段），部分区域的 ΔCFS 增量超过了常用的 10 kPa 地震触发阈值。震后黏弹性松弛预计将在未来几十年内进一步增强这些区域的应力积累。本次地震异常长的同震破裂长度（约 500 km）明显超出经验震级-尺度关系的预测范围，凸显了构造上成熟断裂带易发生狭长型破裂的独特倾向。对多个同震滑动模型的对比表明，震级较大的模型在远场 GNSS 观测数据拟合方面表现出系统性更优的效果，而震级较小的模型则难以重现观测到的形变场。此外，对历史地震序列的分析显示，实皆断层北段长期存在持续的库仑应力积累，表明该区域未来仍具发生 M_w 7.3~7.7 强震的潜在可能性。本研究为理解应力触发机制提供了重要认识，并进一步完善了缅甸中部地区的地震危险性评估。

关键词：2025 年缅甸地震；实皆断裂带；库仑应力演化；同震库仑应力；同震位移场

作者简介：沈拓（1988—），男，助理研究员，主要从事地球动力学与地壳形变学研究. E-mail: 283473562@qq.com

COULOMB STRESS TRANSFER AND FUTURE EARTHQUAKE HAZARD FROM 2025 M_w 7.7 MYANMAR EARTHQUAKE: IMPLICATIONS FOR THE SAGAING FAULT AND SHAN PLATEAU

Shen Tuo¹, Wu Weiwei^{1*}, Meng Guojie¹, Liu Tai¹, Zhang Lupeng¹, Tang Jin², Xu Xiwei³

(¹ Institute of Earthquake Forecasting, China Earthquake Administration, Beijing 100036, China; ² Petro China Research Institute of Petroleum Exploration & Development, Beijing 100083, China; ³ School of Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China)

Abstract: On 28 March 2025, a major M_w 7.7 right-lateral strike-slip earthquake ruptured the Sagaing Fault in Myanmar, causing significant casualties and infrastructure damage. The long-term stress evolution of the Sagaing Fault since 1897 has been strongly influenced by coseismic and postseismic Coulomb failure stress change (ΔCFS) perturbations associated with this event. These stress changes are evaluated using the PSGRN/PSCMP software combined with a multi-layered viscoelastic model. Our results indicate that the earthquake significantly loaded the northern and southern tips of its rupture and several adjacent faults (e.g., the Kyaukme, Loi Kwi, Lancang and southern Nantinghe faults), with ΔCFS increases exceeding the commonly used 10 kPa earthquake-triggering threshold in some areas. Postseismic viscoelastic relaxation is projected to further enhance stress accumulation in these regions over the coming decades. The exceptionally long coseismic rupture (~500 km) observed in this event significantly exceeds predictions from empirical magnitude-scaling relationships, highlighting the unique propensity for long, narrow ruptures on structurally mature fault zones. Comparisons among multiple coseismic slip models further show that models with larger magnitudes provide systematically better fits to far-field GNSS observations, whereas smaller-magnitude models fail to reproduce the observed deformation field. Furthermore, analysis of the historical earthquake sequence reveals persistent Coulomb stress accumulation on the northern segment of the Sagaing Fault, indicating a potential for future large earthquakes (M_w 7.3~7.7). This research provides critical insights into stress triggering mechanisms and refines the seismic hazard assessment for central Myanmar.

Key words: 2025 Myanmar earthquake; Sagaing Fault; Coulomb stress evolution; Coseismic Coulomb stress; Coseismic displacement field

Author Biography: Shen Tuo (1988–), Male, Assistant Researcher, mainly engaged in research on geodynamics and crustal deformation. E-mail: 283473562@qq.com

地震波对新 30 井含水层渗透性与稳定性的影响分析

汪成国¹, 麻 荣¹, 闫 玮¹, 贾永斌¹, 朱文振¹, 韩时雨¹, 李 娜¹, 赵 影^{1,2}

(1.新疆维吾尔自治区地震局, 新疆 乌鲁木齐 830011; 2.江西省地震局, 江西 南昌 330026)

摘要: 本文基于新疆新 30 井 2008—2025 年期间井水位数据, 系统分析了多次远场强震引起的同震响应特征, 并利用 M_2 波潮汐因子与相位连续观测数据, 探讨了地震波对井—含水层系统渗透性及结构稳定性的长期影响。结果表明: 同震响应呈现阶升与阶降两种形态, 阶升型仅出现在震中距小于 500 km 的近场, 阶降型主要分布于 500~2 500 km 的中远场, 响应幅度与震级呈正相关趋势, 可能存在 6.3~6.7 级“震级阈值”; 2008 年汶川 8.0 级地震后, M_2 潮汐因子由 0.139 mm/ μ Gal 持续降至 0.124 mm/ μ Gal, 且震后长期未恢复, 而潮汐相位未发生明显变化, 指示远场低频面波提高了含水层渗透性并导致井—含水层结构发生不可逆或半可逆改变; 此后多次强震尽管产生了显著的瞬时水位阶变, 却未引起持续的潮汐因子异常, 表明汶川地震起到了“冲击致稳”作用, 消除了敏感裂隙或堵塞物, 使系统进入更稳定状态。本研究为揭示地震波与地下流体耦合作用及含水层长期动力学演化提供了新观测证据。

关键词: 井水位同震响应; 潮汐因子; 冲击致稳; 渗透性变化; 汶川地震

作者简介: 汪成国(1970—), 男, 高级工程师, 主要从事地震地下流体监测预报等.E-mail: 15709918384@163.com

INFLUENCE OF SEISMIC WAVES ON PERMEABILITY AND STABILITY OF THE AQUIFER IN NEW WELL 30

Wang Chengguo¹, Ma Rong¹, Yan Wei¹, Jia Yongbin¹, Zhu Wenzhen¹, Han Shiyu¹, Li Na¹,
Zhao Ying^{1,2}

(1. Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, China; 2. Jiangxi
Earthquake Agency, Nanchang 330026, China)

Abstract: This study is based on well water level data from New Well 30 in Xinjiang, covering the period from 2008 to 2025. It systematically analyzes the co-seismic response characteristics triggered by multiple distant strong earthquakes. Additionally, it explores the long-term effects of seismic waves on the permeability and structural stability of well-aquifer systems using M_2 tidal factors and phase continuous observation data. The results indicate that the co-seismic responses exhibit two patterns: stepwise increases and decreases. The stepwise increase occurs only within a distance of ≤ 500 km from the epicenter, while the stepwise decrease is primarily found in the intermediate to far field (500–2500 km). The amplitude of these responses shows a positive correlation with earthquake magnitude, suggesting the presence of a "magnitude threshold" between 6.3 and 6.7. Following the 8.0-magnitude Wenchuan earthquake in 2008, the M_2 tidal factor decreased from 0.139 mm/ μ Gal to 0.124 mm/ μ Gal and has not recovered significantly since then, despite no noticeable changes in tidal phase. This suggests that low-frequency surface waves from distant earthquakes have increased aquifer permeability and led to irreversible or semi-reversible changes in the well-aquifer structure. Although several subsequent strong earthquakes caused significant instantaneous water level changes, they did not result in sustained anomalies in tidal factors. This indicates that the Wenchuan earthquake acted as a "shock stabilization" event, clearing sensitive fractures or blockages and allowing the system to enter a more stable state. This research provides new observational evidence for understanding the coupling effects of seismic waves with subsurface fluids and the long-term dynamic evolution of aquifers.

Key words: Xin30 well; Coseismic response; Tidal factor; Shock-stabilization; Permeability change; Wenchuan earthquake

Author Biography: Wang Chengguo (1970-), Male, Senior Engineer, mainly engaged in seismic underground fluid monitoring and prediction. E-mail: 15709918384@163.com

2026 年 6 月 16 日青海海西 $M_{\text{s}}6.3$ 地震前重力场变化

隗寿春

(中国地震局第二监测中心, 陕西 西安 710054)

摘要: 2026 年 6 月 16 日青海省海西州发生 $M_{\text{s}}6.3$ 地震, 据中国地震台网测定, 震中位于青藏高原东北缘的祁连山地震带南缘 (37.80°N , 95.56°E), 属于祁连地块与柴达木地块的挤压逆冲边界带上, 初步判定其性质为逆冲型地震, 发震构造为大柴旦—宗务隆山断裂带。近年来, 宗务隆山断裂带附近中强地震频发, 包括 2003 年德令哈 $M_{\text{s}}6.6$ 、2004 年宗务隆山 $M_{\text{s}}6.2$ 、2008 年 $M_{\text{s}}6.3$ (李智敏等, 2010) 以及 2009 年 8 月两次 $M_{\text{s}}6.4$ 和 $M_{\text{s}}6.2$ 地震, 这些事件皆位于大柴旦断裂和宗务隆山断裂的交汇区域。该序列地震反映出柴达木盆地北缘—宗务隆山断裂带现今构造活动较为活跃, 中强地震具有明显的丛集性和重复性特点。

本文基于区域流动重力观测资料, 系统梳理了本次地震孕育阶段重力场时空演化规律, 发现区域重力场演化对海西 6.3 级地震有很好的反映。此次地震前重力场演化表现为“区域性重力异常—四象限分布特征性异常—反向变化发震”的系统演化过程。2022 年 9 月至 2024 年 9 月的重力变化显示以德令哈为中心存在显著的重力变化四象限分布特征; 2022 年 9 月至 2025 年 9 月, 重力变化差异有所减弱, 但正重力变化区域显著增强, 且四象限中心向大柴旦迁移, 海西 6.3 级地震就发生在该四象限的中心附近; 2025 年 9 月至 2026 年 6 月, 重力变化发生反向, 由原来的西北负—东南正的重力变化趋势变为西北正—东南负的重力变化趋势, 重力变化反向以后于 2026 年 6 月 16 日发生此次海西 $M_{\text{s}}6.3$ 地震。震前重力变化规律对此次地震有较好的反映, 震中也落在重力年度会商划定的异常危险区内。表明区域重力场变化对未来强震震中位置的判定具有独到优势。通过对该区域流动重力资料的精细处理和深入分析, 进而研究海西 $M_{\text{s}}6.3$ 地震前后的重力场时空演化特征, 对于认识大地震的发生规律、捕捉地震前兆信息等具有重要的实际意义。

关键词: 海西 $M_{\text{s}}6.3$ 地震; 流动重力; 重力场变化; 宗务隆山断裂

作者简介: 隗寿春 (1986—), 男, 高级工程师, 主要从事流动重力数据处理与地震预测研究.E-mail: scwei1986@126.com

GRAVITY FIELD CHANGES PRIOR TO THE HAIXI M_s 6.3 EARTHQUAKE IN QINGHAI ON JUNE 16, 2026

Wei Shouchun

(The Second Monitoring and Application Center, China Earthquake Administration, Xi'an 710054,
Shaanxi China)

Abstract: On June 16, 2026, an M_s 6.3 earthquake struck Haixi Prefecture, Qinghai Province. According to the China Earthquake Networks Center, the epicenter was located at 37.80° N, 95.56° E, on the southern margin of the Qilian Mountains seismic belt in the northeastern Tibetan Plateau. This region represents the compressive thrust boundary between the Qilian Block and the Qaidam Block. The earthquake was preliminarily identified as a thrust-type event, with the Da Qaidam-Zongwulongshan fault zone as its seismogenic structure. In recent years, moderate-to-strong earthquakes have frequently occurred near the Zongwulongshan fault zone, including the 2003 Delingha M_s 6.6 earthquake, the 2004 M_s 6.2 earthquake on the Zongwulongshan Fault, the 2008 M_s 6.3 earthquake (Li et al., 2010), and the M_s 6.4 and M_s 6.2 earthquakes in August 2009. All these events occurred near the junction of the Da Qaidam Fault-Zongwulongshan Fault. Such seismic sequences reveal that the northern Qaidam Basin-Zongwulongshan fault zone is currently tectonically active, where moderate-to-strong earthquakes show obvious clustering characteristics and periodic recurrence.

Based on regional mobile gravity observations, this study systematically analyzes the spatiotemporal evolution of the gravity field during the seismogenic process of the 2026 earthquake. The results indicate that gravity field variations well reflected the precursory information of this M_s 6.3 earthquake. The pre-seismic gravity evolution underwent a complete evolutionary process: starting from regional gravity anomalies, developing into a prominent four-quadrant pattern, and finally experiencing sign reversal prior to fault rupture. Significant four-quadrant distribution of gravity variations formed centered on Delingha during September 2022 – September 2024. From September 2022 to September 2025, the amplitude of gravity differences decreased slightly, while the positive gravity variation area expanded and intensified; meanwhile, the center of the four-quadrant pattern migrated toward Da Qaidam, consistent with the location of the eventual epicenter. During the final stage from September 2025 to June 2026, the gravity variation pattern reversed: the previous northwest-negative and southeast-positive distribution transformed into northwest-positive and southeast-negative. Shortly after this reversal, the Haixi M_s 6.3 earthquake occurred on June 16, 2026. The pre-seismic gravity variations exhibit good correlation with the earthquake, and the epicenter lies within the anomalous risk zone delineated by annual gravity seismic hazard assessment. This verifies that regional gravity field variations have unique advantages in predicting the epicenter locations of future strong earthquakes. By elaborate data processing and in-depth analysis of mobile gravity data, investigating the spatiotemporal evolution characteristics of gravity fields before and after the Haixi M_s 6.3 earthquake bears important practical significance for revealing the seismogenic mechanisms of strong earthquakes and capturing earthquake precursory signals.

Key words: Haixi M_s 6.3 earthquake; mobile gravity; gravity field changes; Zongwulongshan fault

Author Biography: Wei Shouchun (1986–), Male, Senior Engineer, mainly engaged in research on mobile gravity data processing and earthquake prediction. E-mail: scwei1986@126.com

新疆地区重力扰动与热带气旋的时空相关性研究

杨璐嘉, 张 政, 欧雪慧

(新疆维吾尔自治区地震局, 新疆 乌鲁木齐 830011)

摘要: 为准确剥离连续重力环境干扰并提取地震前兆信息, 利用连续两年的西太平洋热带气旋历史档案、新疆连续重力台站的高精度高频观测数据, 并与气象学相结合, 开展了重力扰动与热带气旋的时空相关性及物理动力学机制研究。首先提取并整编了影响时段内所有气旋的具体发生与截止参数, 推导了传统大气负载效应的空域积分数学模型, 由此论证了由热带气旋诱发中亚气旋后, 所产生的大气动力中介效应与水文负载突增现象。在此基础上, 基于流体力学与弹性动力学理论, 建立了双频微震向内陆重力场映射的物理控制方程。结果表明, 新疆地区连续重力观测中的高频重力扰动在时间上与数千千米外西太平洋超强台风的极盛期高度重合。扰动波形在时域上表现为振幅高频快速跃变、振幅包络线呈显著喇叭状非对称放大的动态响应特征, 在频域上则表现为宽频带高频毛刺状突变分布, 变化幅值达到数微伽量级。热带气旋不仅通过非线性海浪干涉激发微震面波直接造成高频重力毛刺扰动, 还通过激发准静止波动远程调制中纬度阻塞系统并诱发深厚的中亚气旋, 进而对内陆台站施加显著的局地气压和水文负载扰动, 导致重力基线发生低频长期漂移。研究结论可为复杂背景噪声下辨识真实孕震信息提供清晰的降噪准则与定量化工具支撑。

关键词: 连续重力观测; 高频扰动; 热带气旋; 双频微震; 大气负载

作者简介: 杨璐嘉 (1998—), 男, 助理工程师, 主要从事地震数据干扰与地震 AI 研究.E-mail: yanglujia@dzkyzs.wecom.work

STUDY ON SPATIOTEMPORAL CORRELATION BETWEEN GRAVITY DISTURBANCES AND TROPICAL CYCLONES IN XINJIANG

Yang Lujia, Zhang Zheng, Ou Xuehui

(Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, Xinjiang, China)

Abstract: To isolate environmental disturbances in continuous gravity data and extract precursors, this paper investigates the spatiotemporal correlation between gravity disturbances and tropical cyclones in Xinjiang by combining cyclone archives and continuous gravity data with meteorology. We compiled cyclone parameters, derived atmospheric loading models, and analyzed the intermediary effect of Central Asian cyclones. Based on fluid and elastic dynamics, mapping equations for microseisms were established. Results show that high-frequency gravity disturbances in Xinjiang highly coincide with the peak of intense cyclones. The disturbances exhibit high-frequency amplitude jumps, asymmetric trumpet-shaped envelope amplification, and wide-band spike-like patterns in the frequency domain. Cyclones generate microseisms and remote atmospheric and hydrological loading, causing baseline drift. The conclusions provide criteria for precursor identification.

Key words: Continuous Gravity Observation; High-frequency Disturbance; Tropical Cyclone; Microseisms; Atmospheric Loading

Author Biography: YANG Lujia (1998–), Male, Assistant Engineer, mainly engaged in research on seismic data interference and seismic AI. E-mail: yanglujia@dzkzyz.wecom.work

气相色谱仪更新的测值一致性与资料衔接

张 伟，赵 影，李新勇，张鹏程，汪成国

（新疆维吾尔自治区地震局，新疆 乌鲁木齐 830011）

摘要：为解决地震地下流体观测中气相色谱仪更新可能造成的资料序列断点和异常误判问题，量化 SP-3400 与 Agilent 8890 在乌鲁木齐 04 泉和 10 泉不同气体组分上的测值差异，判断新旧资料能否建立可解释、可验证的衔接关系。选取 2024 年 12 月 1 日至 2025 年 2 月 28 日共 90 d 并行观测原始记录，对 4 份数据逐日核验，按预先确定的规则处理多组分同步异常、精确零值、孤立异常和整段重复记录；H₂ 因 10 泉两仪器全期均为 0 且 04 泉零值比例较高，不进入定量一致性分析。采用 Bland-Altman 平均偏差（Bias）与一致性界限（LoA）、经验分位数 LoA、浓度相关偏差检验和 7 d 循环分块 Bootstrap 评价偏差及不确定性，并以 2024 年 12 月至 2025 年 1 月资料估计候选衔接参数，以 2025 年 2 月资料进行时间顺序独立验证。结果：04 泉 CH₄、04 泉 CO₂ 和 10 泉 CO₂ 的 Bias 分别为+1.814、-2.295 和+1.268 个百分点，相对 Bias 分别为+20.3%、-17.4%和+17.5%。04 泉 CH₄ 采用比例关系 $k=1.197$ ，04 泉 CO₂ 和 10 泉 CO₂ 采用平移关系 $b=-2.610$ 和+1.230 个百分点；独立验证期 MAE 下降 47.0%~62.0%，但衔接后 RMSE 仍为 0.906~1.837 个百分点。He 和 Ar 存在显著浓度相关偏差、时间漂移或检出限不确定性，不适合采用固定规则强制拼接。仪器更新后的资料衔接不能套用统一换算公式，应按泉点、组分、仪器配置和适用浓度范围分别评价，并依次完成原始记录核验、一致性评价、时间稳定性检验和后续时段验证。候选衔接值可用于减弱长期背景序列的基值台阶，但不宜替代原始日值用于小幅短临异常判定。

关键词：地震流体；气相色谱仪；仪器更新；一致性评价；Bland-Altman 分析；资料衔接

作者简介：张伟（1995—），男，助理工程师，主要从事地下流体监测和仪器对比分析工作.E-mail: 799629874@qq.com

MEASUREMENT AGREEMENT AND DATA CONTINUITY AFTER GAS CHROMATOGRAPH REPLACEMENT

Zhang Wei, Zhao Ying, Li Xinyong, Zhang Pengcheng, Wang Chengguo

(Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, Xinjiang, China)

Abstract: Objective: To quantify measurement discontinuities caused by gas chromatograph replacement in seismic-fluid monitoring and to determine whether data from the SP-3400 and Agilent 8890 can be connected using an interpretable and independently validated relationship. Methods: Ninety days of parallel observations from Urumqi Springs 04 and 10, covering 1 December 2024 to 28 February 2025, were checked record by record before modeling. Predefined quality-control rules were applied to multicomponent synchronous anomalies, exact zero values, isolated outliers, and a duplicated data segment. H₂ was excluded from quantitative agreement analysis because both instruments reported zero throughout the Spring 10 series and zero values dominated the Spring 04 series. Agreement was assessed using Bland-Altman bias and limits of agreement (LoA), empirical-quantile LoA, tests for concentration-dependent bias, and 7-day circular block-bootstrap confidence intervals. Candidate continuity parameters were estimated from December 2024-January 2025 data and independently validated using February 2025 data. Results: Biases for CH₄ at Spring 04, CO₂ at Spring 04, and CO₂ at Spring 10 were +1.814, -2.295, and +1.268 percentage points, respectively, corresponding to relative biases of +20.3%, -17.4%, and +17.5%. A ratio relationship with $k = 1.197$ was selected for CH₄ at Spring 04, whereas shift relationships with $b = -2.610$ and $+1.230$ percentage points were selected for CO₂ at Springs 04 and 10. Validation MAE decreased by 47.0%-62.0%, while post-adjustment RMSE remained 0.906-1.837 percentage points. He and Ar showed concentration-dependent bias, temporal drift, or detection-limit uncertainty and were unsuitable for fixed-rule splicing. Conclusion: Continuity parameters after instrument replacement should be established separately by site, component, instrument configuration, and applicable concentration range, and should be used only after raw-record checking, agreement assessment, temporal-stability testing, and validation on subsequent observations. Adjusted values are suitable mainly for reducing baseline steps in long-term records and should not replace original daily values for detecting small short-term anomalies.

Key words: Seismic fluid; Gas chromatograph; Instrument replacement; Agreement assessment; Bland-Altman analysis; Data continuity

Author Biography: Zhang Wei(1995-),male, Assistant Engineer, primarily engaged in underground fluid monitoring and instrument comparison analysis. E-mail: 799629874@qq.com

2025 年 12 月 4 日阿合奇 $M_s6.0$ 地震陆态网络资料特征研究

张 政¹, 杨璐嘉¹, 丁 宇¹, 李桂荣^{1,2}, 庞鑫柏¹

(1.新疆维吾尔自治区地震局, 新疆 乌鲁木齐 830011; 2.中国地震局乌鲁木齐中亚地震研究所, 新疆 乌鲁木齐 830011)

摘要: 南天山地区受印度—欧亚板块远程碰撞效应影响, 中强震频繁。2025 年 12 月 4 日新疆阿合奇 $M_s6.0$ 地震发生在乌什 $M_s7.1$ 地震破裂区附近, 是南天山盆山结合带推覆构造环境下的又一显著事件。研究该地震前的地壳形变与重力场异常特征, 对认识区域强震孕育过程、提升多手段前兆识别能力具有重要科学意义。利用陆态网络 GNSS 位移时间序列与乌什台连续重力观测资料, 系统分析震前地壳运动、基线变化和重力 M2 潮汐因子的时空演化特征 (GNSS 数据采用 GAMIT/GLOBK 10.7 解算, 参考框架为 ITRF2014; 重力潮汐因子通过标准调和分析提取)。结果表明: WUSH-XJBC 基线长期缩短速率约为 -1.558 mm/a , 与区域南北向挤压构造背景高度一致; 2023—2025 年基线加速缩短, 累计超过 24 mm , 远超前期背景波动, 指示震前存在显著的构造应变加速加载。2024 年 WUSH 与 XJBC 站同步出现位移异常, 东西向分量最大偏移达 30 mm , 南北向约 20 mm , 反映区域应力场协同扰动; 2025 年 9 月前后, 基线高频波动及形变异常进一步加剧, 预示区域应力状态由稳态积累向非稳态孕震调整转换。重力 M2 潮汐因子峰值异常与 2008 年以来新疆地区 $M_s\geq 5.0$ 地震具有良好时间对应, 且本次震前亦出现明显正异常, 与 GNSS 形变加速时段基本同步。上述多手段异常在时间上的协同响应表明, GNSS 形变与重力潮汐因子在震前出现了一致性异常; 多手段联合分析可有效约束单一参量异常的多解性, 提升前兆识别的可靠性。为南天山地区强震危险性研判提供了大地测量与重力联合约束, 也为区域多手段综合监测与异常判识提供了参考依据。

关键词: 阿合奇 $M_s6.0$ 地震; 陆态网络; GNSS; 乌什重力; 前兆异常

作者简介: 张政 (1998—), 男, 助理工程师, 主要从事大地测量数据处理工作. E-mail: 1002852901@qq.com

CHARACTERISTICS OF CMONOC DATA BEFORE DECEMBER 4, 2025 AHEQI $M_s6.0$ EARTHQUAKE

Zhang Zheng¹, Yang LuJia¹, Ding Yu¹, Li Guirong^{1,2}, Pang XinBai¹

- (1. Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, Xinjiang, China;
2. Urumqi Institute of Central Asia Earthquake, China Earthquake Administration, Urumqi 830011,
Xinjiang, China)

Abstract: The South Tianshan region, influenced by the far-field effect of the India–Eurasia collision, experiences frequent moderate–strong earthquakes. The December 4, 2025 Aheqi $M_s6.0$ earthquake occurred near the rupture zone of the 2024 Wushi $M_s7.1$ event, representing another significant shock in the nappe tectonic setting of the South Tianshan basin–mountain junction. Investigating crustal deformation and gravity field anomalies prior to this earthquake is crucial for understanding regional strong earthquake nucleation and improving multi-parameter precursor identification. Using GNSS displacement time series from the Crustal Movement Observation Network of China (CMONOC) and continuous gravity records from Wushi station, we systematically analyzed the spatiotemporal evolution of crustal motion, baseline length changes, and the gravity M2 tidal factor. GNSS data were processed with GAMIT/GLOBK 10.7 referenced to ITRF2014, and the tidal factor was derived by standard harmonic analysis. Results show that the WUSH–XJBC baseline exhibits a long-term shortening rate of -1.558 mm/a, consistent with the regional north–south compressional setting. From 2023 to 2025, the baseline shortened by more than 24 mm cumulatively, far exceeding the background level before 2022, indicating accelerated tectonic strain loading prior to the earthquake. In 2024, synchronous displacement anomalies at WUSH and XJBC stations (up to ~ 30 mm in the E-W component and ~ 20 mm in the N-S component) reflect a coherent regional stress perturbation. Around September 2025, intensified high-frequency baseline fluctuations and deformation anomalies suggest a transition from steady-state accumulation to unsteady pre-seismic adjustment. The peak anomaly of the M2 tidal factor shows a good temporal correspondence with $M_s \geq 5.0$ earthquakes in Xinjiang since 2008; a pronounced positive anomaly also appeared before the 2025 event, roughly synchronous with the GNSS-detected deformation acceleration. The temporal synergy of these multi-parameter anomalies indicates relatively consistent pre-seismic responses in GNSS deformation and the gravity tidal factor. Joint analysis can effectively reduce the ambiguity of single-parameter anomalies and improve the reliability of precursor identification. This study provides joint geodetic and gravity constraints for strong earthquake hazard assessment in the South Tianshan, and offers a reference for regional multi-parameter integrated monitoring and anomaly diagnosis.

Key words: Aheqi $M_s6.0$ earthquake; CMONOC; GNSS; Wushi gravity; Precursor anomaly

Author Biography: ZHANG Zheng (1998–), male, assistant engineer, mainly engaged in geodetic data processing. E-mail: 1002852901@qq.com

北天山前兆识别与预测：基于斜率差法的新途径

赵磊，艾力夏提·玉山，阿尔达克·卡德尔别克，阿卜杜塔伊尔·亚森，
聂嘉旺，丁宇

（新疆维吾尔自治区地震局，新疆 乌鲁木齐 830011）

摘要：新疆北天山地区构造运动强烈，是中亚典型陆内强震区。从海量地球物理观测数据中高保真识别地震前兆异常，是提升预测能力的关键挑战。传统方法处理日均值数据时，常在压制噪声的同时损失对中短期预测至关重要的高频异常信息。为此，本研究引入并优化了“斜率差信息法”。该方法通过动态计算背景窗长 L 与当前窗长 M 的局部斜率差值，构建数学期望为零的时序曲线，无需预设模型，既能有效抑制年变等长周期干扰，又能灵敏反映突变、转折等短期异常，且便于自动化识别。研究系统处理了北天山地区跨断层水准、GNSS 和连续重力等多源日均值数据，通过回溯试验对参数（ L 、 M 、警戒阈值 m ）进行本地化优化，形成适用于不同观测手段的最优参数方案。应用该方法，成功提取了 2016 年呼图壁 6.2 级、2017 年精河 6.6 级等地震前数月至一年的形变与重力异常。异常在时空上与主要活动断裂带密切相关，并呈现“重力中期异常—GNSS、形变中短期异常”的演化特征。 R 值评分统计检验显示，所有数据源均通过检验，其中 GNSS 南北分量预测效能尤为突出，与区域近南北向主压应力背景一致。研究表明，斜率差信息法在复杂构造区具有有效性和可靠性，通过参数优化与多源信息融合，可为地震中短期预测提供定量化支撑，对提升区域震情跟踪能力具有重要意义。

关键词：斜率差信息；北天山；前兆异常；多源数据； R 值评分

作者简介：赵磊（1991—），男，工程师，主要从事重力测量及地壳形变监测研究工作. E-mail: zhaolei202503@163.com。

PRECURSOR IDENTIFICATION AND PREDICTION IN NORTHERN TIANSHAN: A NEW APPROACH BASED ON SLOPE DIFFERENCE METHOD

Zhao Lei, Ailixiati Yushan, Ardake Kaderbieke, Abudutayier Yasen,
Nie Jiawang, Ding Yu

(Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, Xinjiang, China)

Abstract: Extracting high-fidelity seismic precursor anomalies from massive geophysical observation data is a key challenge in improving earthquake prediction capabilities. This study introduces the "slope difference information method" and conducts systematic retrospective tests to locally adapt and optimize its key parameters (background window, current window, dynamic threshold), forming an optimal parameter scheme applicable to multi-source observation data in the northern Tianshan region of Xinjiang. By dynamically calculating the difference in local slopes between the background window length and the current window length, a time-series curve with a mathematical expectation of zero is constructed. This method requires no preset model, effectively suppresses long-period interferences such as annual variations, and sensitively reflects short-term anomalies including abrupt changes and turning points, facilitating automated identification. The study systematically processes multi-source daily mean data and optimizes parameters through retrospective tests, establishing optimal parameter schemes for different observation techniques. Applying this method, deformation and gravity anomalies were successfully extracted from several months to one year before moderate-to-strong earthquakes, including the 2016 Hutubi $M_s6.2$ and 2017 Jinghe $M_s6.6$ earthquakes. The anomalies are spatiotemporally closely related to major active fault zones and exhibit an evolutionary pattern of "medium-term gravity anomalies $\rightarrow$ medium- to short-term GNSS and deformation anomalies." Statistical tests using the R -value score show that all data sources pass the significance test, with the north-south component of GNSS demonstrating particularly outstanding predictive performance. This study indicates that the slope difference information method is effective and reliable in complex tectonic regions. Through parameter optimization and multi-source information fusion, it can provide quantitative support for medium- to short-term earthquake prediction.

Keywords: Slope Difference Information Method; Northern Tianshan; Precursor Anomaly; Multi-source Data; R -value Score

Author Biography: ZHAO Lei (1991-), male, engineer. His research primarily focuses on gravity measurement and crustal deformation monitoring. E-mail: zhaolei202503@163.com

乌什 $M_s7.1$ 地震重力变化与深部密度时空演化特征研究

赵磊^{1,2,3}, 阿卜杜塔伊尔·亚森^{1,2,3}, 刘代芹^{1,2,3,4}, 艾力夏提·玉山^{1,2,3,4},
陈丽^{1,2,3}, 李杰^{1,2,3}, 韩锴^{1,2,3,5}, 孔祥魁⁶

(1.新疆维吾尔自治区地震局, 新疆 乌鲁木齐 830011; 2.新疆帕米尔陆内俯冲国家野外科学观测研究站, 新疆 乌鲁木齐 830011; 3.中国地震局乌鲁木齐中亚地震研究所, 新疆 乌鲁木齐 830011; 4.中国科学技术大学地球和空间科学学院, 安徽 合肥 230026; 5.新疆大学土木工程与建筑学院, 新疆 乌鲁木齐 830047; 6.中国地质大学(北京), 北京 100083)

摘要: 2024 年 1 月 23 日新疆阿克苏地区乌什县发生 $M_s7.1$ 地震, 发震构造为北东东走向的左旋压扭性迈丹断裂。为深入揭示此次地震的孕育机制与前兆特征, 本研究基于“场源互馈”理论框架, 利用 2020 年 3 月至 2024 年 1 月南疆地区高精度流动重力观测数据, 系统分析了震源区重力场的时空演化规律、地壳视密度变化及点位时序响应。研究表明: (1) 重力场时空演化与地震触发机制具有显著关联。乌什地震孕育阶段, 区域重力场呈现典型的四象限分布格局, 震中位于四象限中心及高梯度带附近; 临震前震源区重力场发生由负转正的反向变化, 反映深部物质运移导致的剪应力集中, 符合库仑破裂准则。(2) 多时间尺度视密度反演揭示了构造活动的深部响应。等效源反演结果显示, 震源区地壳视密度变化范围为 $-1\sim 3\text{ kg/m}^3$, 与地表重力异常强度 ($\pm 80\text{ }\mu\text{Gal}$) 显著相关, 证实等效源方法能有效从复杂背景场中提取构造相关的微弱信号, 明确了地壳物质迁移与应力积累是驱动地震的重要物理机制。(3) 点值时间序列揭示了重力前兆的演化规律。震中附近 5 个测点的时序分析显示, 震前重力呈缓升趋势, 临震阶段转为加速上升, 最大变化量达 $103\text{ }\mu\text{Gal}$, 表明深部高压流体等物质的定向迁移引起震源区密度急剧增加, 最终触发断裂失稳。本研究通过多维度重力分析, 系统揭示了乌什地震孕育过程中重力场、密度场与应力场的耦合演化特征, 深化了对强震发震机理的认识, 并验证了时变重力场在地震前兆识别和危险区判定中的重要价值。

关键词: 乌什地震; 时变重力场; 视密度反演; 重力异常; 地震前兆

作者简介: 赵磊(1991-), 男, 工程师, 主要从事重力测量及地壳形变监测研究工作。E-mail: zhaolei202503@163.com

GRAVITY CHANGES AND DEEP DENSITY SPATIOTEMPORAL EVOLUTION IN WUSHI $M_s7.1$ EARTHQUAKE

Zhao Lei^{1,2,3}, Abdutair Yassen^{1,2,3}, Liu Dai-Qin^{1,2,3,4,*}, Ailixiati YuShan^{1,2,3,4},
Chen Li^{1,2,3}, Li Jie^{1,2,3}, Han Kai⁵, Kong Xiang-Kui⁶

(1. Xinjiang Pamir Intracontinental Subduction National Field Observation and Research Station, Urumqi 830011, Xinjiang, China; 2. Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, China; 3. Urumqi Institute of Central Asia Earthquake, China Earthquake Administration, Urumqi 830011, China; 4. School of Earth and Space Science, University of Science and Technology of China, Hefei 230026, China; 5. College of Civil Engineering and Architecture, Xinjiang University, Urumqi 830047, China; 6. China University of Geosciences (Beijing), Beijing 100083, China)

Abstract: On January 23, 2024, an $M_s 7.1$ earthquake struck Wushi County, Xinjiang, with the NE-striking sinistral compressional Maidan Fault identified as the seismogenic structure. Based on the "field-source interaction" framework and high-precision mobile gravity data from Southern Xinjiang (March 2020 – January 2024), this study investigates the spatiotemporal evolution of the gravity field, crustal apparent density changes, and time-series responses near the epicenter. Results show that the gravity field evolution closely relates to the triggering mechanism. During the seismogenic phase, the regional gravity field exhibited a four-quadrant pattern, with the epicenter near the center and the high-gradient zone. Prior to the event, the gravity field reversed from negative to positive, reflecting shear stress concentration due to deep material migration, consistent with the Coulomb failure criterion. Multi-temporal apparent density inversion reveals that equivalent source-derived density changes in the epicentral crust ranged from -1 to $+3$ kg/m^3 , correlating significantly with surface gravity anomalies (± 80 μGal), confirming the effectiveness of the equivalent source method in extracting tectonic signals and highlighting mass migration and stress accumulation as key physical drivers. Time-series analysis at five near-epicenter points shows a gradual gravity increase, accelerating in the immediate pre-seismic period, with a maximum change of 103 μGal , suggesting that directional migration of deep high-pressure fluids caused a sharp density increase, ultimately triggering fault instability. This multi-dimensional gravity analysis systematically reveals the coupled evolution of gravity, density, and stress fields during the Wushi earthquake preparation, enhancing understanding of strong earthquake mechanisms and validating the value of time-varying gravity fields for identifying precursors and delineating hazard zones.

Key words: Wushi Earthquake; Time-Varying Gravitational Field; Apparent Density Inversion; Gravity Anomaly; Earthquake Precursor

Author Biography: Zhao Lei (1991–), male, engineer. His research primarily focuses on gravity measurement and crustal deformation monitoring. E-mail: zhaolei202503@163.com.

南天山伽师 $M_s6.4$ 地震区域重力场演化分析

朱治国

(新疆维吾尔自治区地震局, 新疆 乌鲁木齐 830011)

摘要: 为深入研究南天山巴楚—伽师区域强震活动的孕震机理与地球物理场演化特征, 本文利用 2015—2021 年新疆喀什—伽师流动重力观测网重力资料及“中国大陆构造环境监测网络”GNSS 连续观测成果, 系统分析了 2020 年 1 月 19 日伽师 $M_s6.4$ 地震前区域重力场与地壳形变场的时空变化特征, 探讨了重力场变化与 GNSS 应变场的关联性及其对地震活动的指示意义。重力数据处理采用 LGADJ 软件进行经典平差, 以塔什库尔干、乌什、库车 3 个绝对观测点为约束, 经固体潮、气压、仪器高及零漂改正后获取测点重力值, 观测精度优于 $10.4 \times 10^{-8} \text{ m} \cdot \text{s}^{-2}$ 。结果表明: (1) 一年尺度重力场动态变化清晰记录了地震前后“局部重力异常→重力变化'0'等值线拐弯与异常翻转→高梯度带及弱四象限特征→异常正向恢复”的系统演化过程, 反映了区域地壳物质迁移与能量积累—释放的阶段性特征。2015—2018 年, 柯坪断裂以北南天山山区重力正向累积增强, 塔里木盆地负向变化, 差异最大达 $170 \times 10^{-8} \text{ m} \cdot \text{s}^{-2}$, 能量持续积累; 2018—2020 年, 以柯坪断裂为界重力场发生翻转, 山区转为负变化、盆地转为正变化, 震中区域出现“0”等值线弯折与高梯度带, 并于 2020 年 1 月在重力持续反向变化过程中发生 $M_s6.4$ 地震; 震后 2020—2021 年, 正负差异缩小至 $70 \times 10^{-8} \text{ m} \cdot \text{s}^{-2}$ 左右, 区域趋于稳定。(2) 累积重力变化显示, 重力异常翻转过程受柯坪断裂控制, 该断裂作为塔里木盆地与南天山的构造分界, 其附近重力变化等值线走向与断裂走向高度一致, 地震均发生在“0”等值线拐弯与梯度陡变部位。联合区域 GNSS 观测结果分析表明, 重力正异常增强区域与面压缩极值区重叠, 反映了印度—欧亚板块碰撞远程效应下塔里木块体向北推挤导致地壳剪应力持续积累, 深部物质上涌引起密度变化, 当应力达到岩石破裂临界值时沿柯坪断裂发生错动, 地震后应力释放、重力场逐步恢复。本研究结果可为南天山地震带中长期地震危险性研判提供科学参考。

关键词: 天山造山带; 伽师 $M_s6.4$ 地震; 重力场变化; 柯坪断裂

作者简介: 朱治国 (1978—), 男, 高级工程师, 主要从事地壳形变与地震预测研究. E-mail: 9487132@qq.com

ANALYSIS OF REGIONAL GRAVITY FIELD EVOLUTION PRIOR TO THE JIASHI MS6.4 EARTHQUAKE IN THE SOUTHERN TIANSHAN

Zhu Zhiguo

(Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, Xinjiang, China)

Abstract: To investigate the seismogenic mechanism and geophysical field evolution in the Bachu-Jiashi region of the southern Tianshan, this study utilizes gravity data from the Kashi-Jiashi mobile gravity observation network (2015 – 2021) and continuous GNSS observations from the "Crustal Movement Observation Network of China." It systematically analyzes the spatiotemporal variations of the regional gravity and crustal deformation fields prior to the Ms6.4 Jiashi earthquake on January 19, 2020, and explores the correlation between gravity changes and GNSS strain fields and their implications for seismic activity. Gravity data were processed using LGADJ software for classical adjustment, constrained by three absolute stations (Tashkurgan, Wushi, Kuqa), with corrections for solid tides, atmospheric pressure, instrument height, and zero drift, achieving an accuracy better than $10.4 \times 10^{-8} \text{ m} \cdot \text{s}^{-2}$. The results show that: (1) The one-year-scale gravity changes clearly recorded a systematic evolution process before and after the earthquake: "local gravity anomaly $\rightarrow$ inflection of the 'zero' contour and anomaly reversal $\rightarrow$ high-gradient zones and weak four-quadrant pattern $\rightarrow$ positive recovery," reflecting phased crustal material migration and energy accumulation-release. From 2015 to 2018, the southern Tianshan mountainous area north of the Kalpin Fault showed positive cumulative gravity changes while the Tarim Basin showed negative changes, with a maximum difference of $170 \times 10^{-8} \text{ m} \cdot \text{s}^{-2}$, indicating continuous energy accumulation. From 2018 to 2020, the gravity field reversed across the Kalpin Fault: the mountain area transitioned to negative changes and the basin to positive changes. The epicentral region exhibited "zero" contour bending and high-gradient zones, and the Ms6.4 earthquake occurred in January 2020 during persistent reverse gravity changes. After the earthquake (2020 – 2021), the positive-negative difference narrowed to approximately $70 \times 10^{-8} \text{ m} \cdot \text{s}^{-2}$, suggesting regional stabilization. (2) Cumulative gravity changes indicate that the gravity anomaly reversal was controlled by the Kalpin Fault, the tectonic boundary between the Tarim Basin and the southern Tianshan. The gravity contours near the fault are highly consistent with the fault strike, and earthquakes all occurred at "zero" contour inflections and steep gradient zones. Combined with GNSS observations, the area of enhanced positive gravity anomalies overlaps with the extreme compression zone, reflecting that under the remote effect of the India-Eurasia collision, northward compression of the Tarim Block led to continuous crustal shear stress accumulation, with deep material upwelling causing density changes. When stress reached the critical value, slip occurred along the Kalpin Fault, followed by stress release and gradual gravity recovery. These findings provide a scientific reference for medium- to long-term seismic hazard assessment in the southern Tianshan seismic zone.

Keywords: Tianshan Orogenic Belt; Jiashi Ms6.4 Earthquake; Gravity Field Variation; Kalpin Fault

Author Biography: Zhu Zhiguo (1978 –), Male, Senior Engineer, mainly engaged in research on crustal deformation and earthquake prediction. E-mail: 9487132@qq.com

Determination of crustal surface wave parameters in the Tian Shan from the Wushi earthquake on 22.01.2024 using GNSS data

Sergey Kuzikov

(Research Station of the Russian Academy of Sciences in Bishkek city, Head of Laboratory 720049,
Bishkek-49, Research Station RAS, Kyrgyzstan. ksi-63@yandex.ru)

Abstract:

On January 22, 2024, at 18:09:04 UTC, a strong ($M7$) earthquake occurred in Wushi County, China, located 25 km from the border with Kyrgyzstan. The mainshock epicenter was situated at a depth of 13 km and localized at the junction zone between the southern margin of the Tian Shan mountains and the Tarim Basin.

While studies of modern crustal movements typically utilize daily GNSS coordinates, it is now feasible to determine crustal displacements at one-second intervals during earthquakes and other rapid geophysical events. The Wushi earthquake induced surface co-seismic displacements that were recorded in 1 Hz three-dimensional GNSS coordinate time series. The Bernese GNSS Software and PRIDE were employed to compute station positions every second over a 25-minute period. It is important to note that different software packages rely on distinct coordinate calculation algorithms, which may yield varying positions or even generate spurious displacements. Consequently, specialized processing techniques for coordinate time series are necessary to reliably detect co-seismic surface motions.

Analysis of the 1 Hz coordinate time series from GNSS stations located 90–800 km from the epicenter revealed surface displacements with variations reaching up to 8 cm. The arrival times of low-frequency surface waves were successfully determined, and these waves are more clearly manifested in the horizontal coordinate variations. The amplitude (14–82 mm) and propagation velocity (2.0–3.2 km/s) of the surface waves were found to depend on both the epicentral distance and the wave propagation direction across different sectors of the Tian Shan. Therefore, constructing distribution maps of surface wave amplitudes and velocities will enable the identification of hazardous zones characterized by elevated values of these parameters.

Furthermore, an investigation into the effect of GNSS data sampling frequency demonstrated that intervals of up to 10 seconds still permit the recording of surface motions from strong earthquakes at distances up to 800 km. Nevertheless, rigorous analysis of co-seismic surface displacements requires GNSS measurements with a sampling rate of ≥ 1 Hz.

Keywords: TianShan, 2024 Wushi earthquake, 1 Hz GNSS coordinates, co-seismic crustal displacements, surface waves, amplitude and velocity.

APPLYING PHASENET TO SEISMIC SIGNALS: A PHASE-PICKING FEASIBILITY STUDY

Abzal Kudaibergen^{1,2}, Auyeshzhanov Adilet¹, Temirlan Saparbay¹, Soldatenko Mikhail¹,
Kuttygozha Symbat^{1,3}, Zhumakhan Assel^{1,3}

(1. National Scientific Center for Seismological Observations and Research, Almaty 050060, Kazakhstan; 2. Almaty University of Power Engineering and Telecommunications, Almaty 050013, Kazakhstan; 3. Kazakh National Research Technical University, Almaty 050013)

Abstract: PhaseNet and related deep-learning pickers are trained almost exclusively on global archives, and their applicability to the legacy Central Asian archives remains unknown. We test this by training PhaseNet from scratch on KAZbench-Alatau, a three-component dataset from the Almaty region (Northern Tien Shan, Kazakhstan; 96 stations, 2005–2025), using event-based splits (730,205 training traces; no leakage) and 100 s windows, and by benchmarking a pretrained global model on the same test set. An in-domain PhaseNet trained from scratch recovers ~85% of P arrivals within 1 s (MAE 0.3 s), versus ~11% for a pretrained global model — a strong (~8×) domain shift; S-phase picking is left to future work. This shows deep phase pickers are viable for legacy Central Asian data when trained in-domain, enabling automatic P-picking for legacy archives.

Keywords: PhaseNet; Deep Learning; Phase Picking; Domain Shift

Author Biography:

1. Kudaibergen A. (1999–), Male, PhD student, Senior Researcher at NSCSOR, mainly engaged in research on machine learning for seismic waveform data, E-mail: abzal.k0011@gmail.com
2. Auyeshzhanov A. (2005–), Male, Junior Researcher at NSCSOR, mainly engaged in seismological research, E-mail: aueszanovadilet681@gmail.com
3. Saparbay T. (2005–), Male, Junior Researcher at NSCSOR, mainly engaged in seismological research, E-mail: t3265636@gmail.com
4. Soldatenko M. N. (2003–), Male, PhD student, Head of the Station Maintenance Department at NSCSOR, mainly engaged in seismic station operation and monitoring, E-mail: mikha_soldatenko@mail.ru
5. Kuttygozha S. (2004–), Female, Master’s student at KazNRTU and Researcher at NSCSOR, mainly engaged in seismic instrumentation engineering, E-mail: sttyozha@gmail.com
6. Zhumakhan A. (2003–), Female, Master’s student at KazNRTU and Researcher at NSCSOR, mainly engaged in seismic instrumentation engineering, E-mail: asel.zhumaxan@mail.ru

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Abzal Kudaibergen^{1,2}, Auyeshzhanov Adilet¹, Soldatenko Mikhail¹, Kuttygozha
Symbat^{1,3}, Zhumakhan Assel^{1,3}

(1. National Scientific Center for Seismological Observations and Research, Almaty 050060, Kazakhstan; 2. Almaty University of Power Engineering and Telecommunications, Almaty 050013, Kazakhstan; 3. Kazakh National Research Technical University, Almaty 050013)

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1. Kudaibergen A. (1999–), Male, PhD student, Senior Researcher at NNCSNI, mainly engaged in research on machine learning for seismic waveform data. E-mail: abzal.k0011@gmail.com
2. Auyeshzhanov A. (2005–), Male, Junior Researcher at NNCSNI, mainly engaged in seismological research. E-mail: aueshzanovadilet681@gmail.com
3. Soldatenko M. N. (2003–), Male, PhD student, Head of the Station Maintenance Department at NNCSNI, mainly engaged in seismic station operation and monitoring. E-mail: mikha_soldatenko@mail.ru
4. Kuttygozha S. (2004–), Female, Master's student at KazNRTU and Researcher at NNCSNI, mainly engaged in seismic instrumentation engineering. E-mail: sttyozha@gmail.com
5. Zhumakhan A. (2003–), Female, Master's student at KazNRTU and Researcher at NNCSNI, mainly engaged in seismic instrumentation engineering. E-mail: asel.zhumaxan@mail.ru

KAZBENCH-ALATAU: A CENTRAL ASIAN BENCHMARK SEISMIC WAVEFORM DATASET FOR AI/MACHINE LEARNING

Abzal Kudaibergen^{1,2}, Alibi Zhora^{1,3}, Yerik Alipuly¹, Muhammad Ilyas³, Gulzhan Rakhimbayeva¹,
Baikhanova Arailym¹, Rustam Yergaliyev^{1,2}

(1. National Scientific Center for Seismological Observations and Research, Almaty 050060, Kazakhstan;
2. Almaty University of Power Engineering and Telecommunications, Almaty 050013, Kazakhstan; 3.
Kazakh-British Technical University, Almaty 050000, Kazakhstan)

Abstract: Deep-learning phase pickers have transformed seismic monitoring, yet they are trained almost exclusively on global archives (STEAD, INSTANCE, DiTing) and degrade sharply on the legacy data that dominate Central Asian networks, leaving the region without an AI-ready labeled corpus. We introduce KAZbench-Alatau, the first benchmark seismic waveform dataset for the Almaty region (Northern Tien Shan, Kazakhstan). It comprises 1,042,518 three-component records from 96 stations over 2005–2025, with 1,037,003 manually reviewed P and ~1,006,000 S arrivals (magnitude 0.0–3.45) and leakage-free event-based splits. In baseline tests a model trained on these data recovers ~95% of P arrivals, whereas a picker pretrained on global data reaches only ~1%, revealing the severity of domain shift. KAZbench-Alatau offers a reproducible foundation for regional and legacy-archive seismic machine learning.

Keywords: Seismic Waveform Dataset; Machine Learning; Phase Picking; Central Asia; Benchmark

Author Biography:

1. Kudaibergen A., Male, PhD student, Senior Researcher at NSCSOR, mainly engaged in research on machine learning for seismic waveform data, E-mail: abzal.k0011@gmail.com
2. Zhora A., Male, Master's student at KBTU and Researcher at NSCSOR, mainly engaged in seismological research, E-mail: a.zhora@kbtu.kz
3. Alipuly E. (1981–), Male, PhD, First Deputy Director – Head of NSCSOR, mainly engaged in seismic station operation and monitoring, E-mail: alipulyerik@gmail.com
4. Muhammad Ilyas, Male, PhD, Professor at the Department of Robotics and Mechatronics (RaM), School of Information Technology and Engineering (SiTE), Kazakh-British Technical University (KBTU), Almaty, Kazakhstan, mainly engaged in research on robotics and artificial intelligence, E-mail: m.ilyas@kbtu.kz
5. Rakhimbayeva G., Female, Deputy Director, E-mail: gulzhanbaibol79@gmail.com
6. Yergaliyev R., Male, Scientific Secretary, E-mail: r.k.yergaliyev@gmail.com

AUTOMATED QUALITY CONTROL AND PROCESSING OF STRONG-MOTION RECORDS FOR SEISMIC ANALYSIS

Aiya Kudabayeva, Lyazzat Kaliyeva*

(National Scientific Center for Seismological Observations and Research, Almaty,
Kazakhstan)

Abstract: This work presents a Python-based approach for automated quality control and processing of strong-motion records. The workflow includes reading digital accelerograms, checking metadata and channel consistency, verifying component orientation, harmonizing record lengths, and preparing waveforms for further parameter calculation. The procedure reduces the risk of inconsistencies that may occur during manual preparation of multi-component records and provides a reproducible basis for calculating peak ground-motion parameters and significant shaking duration using the Husid method. The proposed workflow improves the reliability and uniformity of strong-motion datasets and supports their subsequent use in seismic hazard assessment, site-response studies, and engineering seismology applications.

Author Biography: Aiya Kudabayeva. E-mail: uapa89@mail.ru; Lyazzat Kaliyeva. E-mail: lks_77@mail.ru

IDENTIFICATION OF INDUSTRIAL EXPLOSIONS AND MINING-INDUCED COLLAPSES FOR SHORT-TERM ANALYSIS OF SEISMIC ACTIVITY AT ORE DEPOSITS IN KAZAKHSTAN

Gashimov R.A.¹, Istekova S.A.², Shulakov D.Yu.³, Zhanabayev D. B.⁴

(1.LLP "Institute of Seismic Safety", Almaty, Kazakhstan; 2.Satbayev University, Almaty, Kazakhstan;
3.Perm Federal Research Center UB RAS, Perm, Russia; 4.Satbayev University, Almaty, Kazakhstan)

Abstract: This study presents a methodology for identifying industrial explosions and mining-induced collapses in seismic event catalogues of Kazakhstan, based on statistical analysis of the temporal distribution and energy class of anthropogenic events. Using data from the International Seismological Centre (ISC) and the Incorporated Research Institutions for Seismology (IRIS) for 2025, we found that ~80% of industrial explosions occur on working days between 08:00–18:00, with energy class mostly $K=5-7$ (97% of registered explosions); their share of the overall seismic event catalogue was about 14%. A four-step filtering algorithm (time of day, day of week, energy class $K \geq 8$, spatial verification against known quarries) was validated on Zhezkazgan deposit data: 62% of $K \geq 8$ events were classified as induced collapses, 87.5% confirmed by geomechanical monitoring. The approach complements, rather than replaces, spectral discrimination methods and is comparable to international practice in explosion–earthquake discrimination.

ИДЕНТИФИКАЦИЯ ПРОМЫШЛЕННЫХ ВЗРЫВОВ И ТЕХНОГЕННЫХ ОБРУШЕНИЙ ДЛЯ КРАТКОСРОЧНОГО АНАЛИЗА СЕЙСМИЧЕСКОЙ ОБСТАНОВКИ НА РУДНЫХ МЕСТОРОЖДЕНИЯХ КАЗАХСТАНА

Гашимов Р.А.¹, Истекова С.А.², Шулаков Д.Ю.³, Жанабаев Д. Б.⁴

(1.ТОО «Институт сейсмической безопасности», г. Алматы, Казахстан; 2.КазННТУ
им. К.И. Сатпаева, г. Алматы, Казахстан; 3.ПФИЦ УрО РАН, г. Пермь, Россия;
4.КазННТУ им. К.И. Сатпаева)

Выводы : На месторождениях полезных ископаемых Республики Казахстан (РК) с длительным сроком эксплуатации, таких как Жезказганское медное месторождение, массовое разрушение междукамерных (МКЦ) и барьерных (БЦ) целиков приводит к формированию техногенных землетрясений.

Одной из ключевых проблем при анализе техногенных обрушений остаётся отделение полезного сигнала от технологических взрывов, которые составляют значительную долю в каталогах сейсмических событий. Согласно данным из Международного сейсмологического центра (ISC) и системы IRIS (Incorporated Research Institutions for Seismology), в 2025 году было зарегистрировано 2757 промышленных взрывов, что составляет около 14% всех сейсмических событий.

Для повышения достоверности выделения природной сейсмичности при решении задач краткосрочного анализа сейсмической обстановки на месторождениях полезных ископаемых предложена методика идентификации промышленных взрывов и техногенных обрушений в каталогах сейсмических событий, основанная на анализе статистических закономерностей пространственно-временного распределения техногенных событий и их энергетических характеристик.

Задача разделения промышленных взрывов и тектонических/техногенных землетрясений по данным региональных сетей мониторинга в мировой сейсмологии решается преимущественно методами спектральной дискриминации (отношения амплитуд разных типов волн – P, S, Pg, Lg, спектральная модуляция, сопоставление фактического очагового спектра с расчетным, знак первых вступлений по сети станций). В работе представлен взаимодополняющий, вычислительно простой подход, основанный на статистических закономерностях времени возникновения и энергетического класса события. Он может применяться как самостоятельно на начальном этапе фильтрации каталога, так и в сочетании со спектральными методами.

Установлено, что в каталоге промышленных взрывов преобладают события низких и средних энергетических классов: в 2025 году на классы $K = 5-7$ пришлось 97% всех зарегистрированных взрывов, тогда как события класса $K \geq 9$ составили лишь около 0,8% каталога взрывов, что подчёркивает статистическую редкость высокоэнергетических промышленных взрывов и обосновывает информативность выбранного порогового значения $K \geq 8$. Наибольшее число взрывов зарегистрировано в Абайской и Жамбылской областях (карьеры на месторождениях Жанатас, Успенровка, Аглатас); анализ распределения событий по часам суток показал повышенную плотность взрывов около 3, 8 и 14 часов по местному времени с характерным интервалом порядка 6 часов, а анализ по дням недели зафиксировал резкое снижение числа взрывов в выходные дни.

На основе выявленных закономерностей разработан четырёхшаговый алгоритм фильтрации сейсмических событий: (1) проверка времени суток (ночной интервал 22:00–06:00 повышает вероятность техногенного обрушения); (2) проверка дня недели (событие в выходной день классифицируется как вероятное обрушение); (3) проверка энергетического класса ($K \geq 8$ при несоответствии критериям взрыва по времени или дню классифицируется как вероятное обрушение); (4) пространственная верификация — сопоставление координат событий с известными карьерами и рудниками для событий с $K \geq 8$, произошедших в рабочее время.

Апробация методики на данных Жезказганского месторождения показала, что из 52 сейсмических событий с $K \geq 8$, зарегистрированных в 2025 году, 32 события (62%) были классифицированы как техногенные обрушения, из которых 28 (87,5%) подтверждены геомеханическими данными маркшейдерской службы о частичном или полном разрушении целиков. Показательно также, что наиболее энергетически значимые сейсмические события 2025 года, имеющие выраженную тектоническую природу, пространственно удалены от разрабатываемых месторождений, что подтверждает необходимость обязательной пространственной верификации как заключительного шага алгоритма.

Предложенный подход сопоставим с мировым опытом идентификации техногенных сейсмических источников: методиками спектральной дискриминации взрывов и землетрясений, сейсмической томографией повреждений массива при взрывных работах и анализом магнитуды техногенных землетрясений, апробированным в том числе на материалах Жезказганского и Жаман-Айбатского месторождений Казахстана, а также натурными экспериментами по регистрации взрывов в водонасыщенных грунтах и результатами изучения сейсмостектонической обстановки Тянь-Шаня и сопредельных территорий.

ИДЕНТИФИКАЦИЯ ПРОМЫШЛЕННЫХ ВЗРЫВОВ И ТЕХНОГЕННЫХ ОБРУШЕНИЙ ДЛЯ КРАТКОСРОЧНОГО АНАЛИЗА СЕЙСМИЧЕСКОЙ ОБСТАНОВКИ НА РУДНЫХ МЕСТОРОЖДЕНИЯХ КАЗАХСТАНА

Основным преимуществом предложенной методики является простота и возможность её автоматизации без привлечения сложных математических моделей, что позволяет реализовать её в рамках действующих систем сейсмологического мониторинга Казахстана, включая программное обеспечение GeoDAS, DIMAS и SeisComp. Ограничения методики связаны с возможными ложными срабатываниями при нештатных взрывах, а также в случаях относительно небольших обрушений, происходящих в типичное для взрывных работ время. В связи с этим представляется целесообразным, и даже необходимым, её комплексирование с геомеханическими и спектральными методами.

Направлениями дальнейших исследований являются формальная статистическая оценка точности классификации (доли ложноположительных и ложноотрицательных результатов) на расширенной выборке месторождений и лет наблюдений, а также комплексирование предложенных временных и энергетических критериев со спектральными методами дискриминации источника.

Анализ землетрясений магнитудой M7 и M5, произошедших в Тянь-Шане в январе и марте 2024 года, на основе космических данных с учетом тектонических условий.

Gulbanu Daurbayeva¹, Zhapsarbay Sultanbekov¹, Kuanysh Togisov², Dimitar Ouzounov^{3,4},
Galina Khachikyan¹

(1. National Scientific Center for Seismological Observations and Research, Almaty, Kazakhstan; 2. Satbayev University, Geophysics and Seismology, Almaty, Kazakhstan; 3. Potomac Falls, USA; 4. Institute of Physics of the Earth's Interior and Geohazards, HMUC, Chania, Greece)

Абстракт: 22 января 2024 года землетрясение магнитудой M7.0 произошло в Среднем Тянь-Шане в пограничном регионе Китая и Кыргызстана, вызвав трясение в Алматы с интенсивностью $I=5$ по шкале MSK-64. 4 марта 2024 года землетрясение M5 произошло в Северном Тянь-Шане на границе Кыргызстана и Казахстана, которое также вызвало трясение в Алматы с интенсивностью $I=5$.

Событие M7.0 было проанализировано с использованием ионосферных и метеорологических данных из спутникового аппарата Swarm и климатического реанализа MERRA-2 соответственно. Выделены сигнатуры (образы-предвестники) над очагом M7.0 землетрясения, произошедшего 22 января 2024 г. на центральном Тянь-Шане на приграничной территории Китая и Кыргызстана, которое проявилось в г. Алматы с интенсивностью сотрясений $I=5$ баллов по шкале MSK-64 по данным геофизических спутников Swarm и метеорологических спутников Suomi, к предвестникам отнесены:

- увеличение электронной концентрации над эпицентром примерно за сутки и в день землетрясения по сравнению с предыдущими днями;
- появление в ионосфере мелкомасштабной неоднородности, которая начала развиваться над эпицентром за сутки до землетрясения и достигла максимума в день основного сейсмического толчка;
- увеличение в атмосфере за сутки и в день землетрясения количества аэрозольных частиц, которое проходило одновременно с интенсивной конденсацией водяного пара и увеличением скрытой теплоты.

Учитывая результаты, которые показывают, что крупные ($M \geq 7$) землетрясения предпочитают происходить после геомагнитных бурь в продольных областях, которые находились в полярном каспа на момент начала магнитных бурь, мы изучили состояние солнечной и геомагнитной активности до и во время рассматриваемых землетрясений в Тянь-Шане. Результаты показали, что геомагнитные бури происходили со временным интервалом до 78 дней до сейсмических событий, что соответствовало заданным критериям для таких землетрясения. А именно, во время начала этих геомагнитных бурь магнитные локальные магнитные времена в районах будущих эпицентров были в интервале $Mlt=08-16$ h, в котором расположен полярный пик.

Анализ территории, затронутой землетрясениями, с использованием результатов моделирования скорости литосферы вдоль субширотного геотраверса Тянь-Шань на долготе $77^\circ E$ (Шапилов и др., 2005), показал, что в интервале долготы, где происходили сейсмические события M7.0 и M5.0, земная кора находится под слоем высокотемпературной мантии. Другими словами, в этих областях горячий мантийный поток (мантийная жидкость) приближается к коре. Этот результат подтверждает нашу прежнюю гипотезу о том, что геомагнитные бури могут влиять на активность восходящих потоков жидкости, которые впоследствии способствуют развитию землетрясений.

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Ключевые слова: Тянь-Шань, землетрясения, ионосферные предвестники, геомагнитные бури.

SATELLITE-BASED ANALYSIS OF THE M7 AND M5 EARTHQUAKES IN THE TIAN SHAN DURING JANUARY AND MARCH 2024, CONSIDERING REGIONAL TECTONIC CONDITIONS

Gulbanu Daurbayeva¹, Zhapsarbay Sultanbekov¹, Kuanysh Togisov², Dimitar Ouzounov^{3,4}
Galina Khachikyan¹

(1. National Scientific Center for Seismological Observations and Research, Almaty, Kazakhstan;
2. Satbayev University, Geophysics and Seismology, Almaty, Kazakhstan; 3. Potomac Falls, USA; 4.
Institute of Physics of the Earth's Interior and Geohazards, HMUC, Chania, Greece)

Abstract: On 22 January 2024, an M7.0 earthquake struck the Central Tianshan along the China–Kyrgyzstan border, causing seismic shaking in Almaty (Kazakhstan) with an intensity of $I = 5$ on the MSK-64 scale. A second event (M5.0) occurred on 4 March 2024 in the Northern Tianshan along the Kyrgyzstan–Kazakhstan border and produced a similar shaking intensity in Almaty. These earthquakes provide an opportunity to investigate possible lithosphere–atmosphere–ionosphere coupling (LAIC) processes in an intracontinental tectonic setting. For the M7.0 earthquake, ionospheric observations from the Swarm satellite constellation and meteorological data from the MERRA-2 reanalysis revealed several short-term anomalies preceding the main shock. Characteristic signatures (earthquake precursor patterns) were identified above the source region of the M7.0 earthquake that occurred on 22 January 2024 in the Central Tian Shan along the China–Kyrgyzstan border. The earthquake produced seismic shaking in Almaty with an intensity of $I = 5$ on the MSK-64 scale. The analysis was based on observations from the Swarm geophysical satellite constellation and Suomi meteorological satellite data. The following potential earthquake precursors were identified:

An increase in electron density above the epicentral region approximately one day before the earthquake, with elevated values persisting on the day of the main shock compared with the preceding days. The development of small-scale ionospheric irregularities, which emerged over the epicentral area about one day before the earthquake and reached their maximum intensity on the day of the main seismic event. An increase in atmospheric aerosol concentration during the day preceding the earthquake and on the day of the event, occurring simultaneously with enhanced water vapor condensation and increased latent heat flux. To investigate the possible role of space weather, we analyzed solar and geomagnetic conditions preceding both earthquakes. Following the concept proposed by Ouzounov and Khachikyan, we found that geomagnetic storms occurred within 78 days before both seismic events. At the onset of these storms, the future epicentral regions were located within the magnetic local time sector $MLT = 08–16h$, corresponding to the polar-center sector previously identified as favorable for the occurrence of large earthquakes. The tectonic framework was further examined using lithospheric velocity models along the sublatitudinal Tianshan geotraverse at $77^\circ E$. Both earthquakes occurred above a high-temperature upper mantle zone, suggesting the presence of ascending mantle fluids beneath the seismogenic crust. The coincidence of lithospheric conditions, ionospheric and atmospheric anomalies, and favorable geomagnetic forcing supports the hypothesis that geomagnetic disturbances may modulate mantle fluid migration and contribute to earthquake preparation processes. Although the proposed mechanism requires further validation using a larger statistical dataset, the results demonstrate the potential of integrating satellite observations, space-weather parameters, and tectonic information for studies of earthquake preparation in the Tianshan region.

Key words: Tianshan, earthquakes, ionospheric precursors, geomagnetic storms.

Development of an AI-Assisted Regional Seismic Dataset for Central Asia: Framework and Initial Results

Imashev Sanzhar

Abstract:

The increasing use of artificial intelligence in seismology has created a growing demand for large, high-quality regional datasets suitable for training and evaluating machine learning models. While several benchmark seismic datasets have been developed worldwide, Central Asia remains underrepresented despite its high seismic activity and complex tectonic environment.

This study presents the framework and initial results of an AI-assisted regional seismic dataset being developed for Central Asia. The project integrates earthquake catalogs, waveform archives from regional seismic networks, theoretical travel-time calculations, and deep-learning-based seismic analysis tools into a unified processing workflow. For each earthquake-station pair, standardized three-component waveform segments are extracted and supplemented with comprehensive metadata describing event parameters, station characteristics, source-receiver geometry, and theoretical P- and S-wave arrival times.

Artificial intelligence plays a key role in dataset generation and quality control. The SeisDetNet model is used for automatic event detection, identification of problematic waveform segments, and validation of both earthquake and noise records. The RSNet phase-picking model provides automatic P- and S-wave arrival estimates, which are further evaluated against theoretical travel-time predictions and compared with results from widely used models such as PhaseNet and EQTransformer. The resulting workflow enables automated assessment of waveform quality and phase-picking consistency while reducing the need for extensive manual inspection.

Initial results obtained from the pilot dataset demonstrate the feasibility of the proposed approach and highlight the potential of AI-assisted data curation for regional seismic monitoring. The developed framework provides a foundation for future machine-learning applications, including earthquake detection, phase picking, event relocation, magnitude estimation, and seismic hazard studies across Central Asia.

ASSESSMENT OF IMPACT OF OIL PRODUCTION ON FORMATION OF INDUCED SEISMICITY IN WESTERN KAZAKHSTAN

Ishpekbaeva A.K., Maulitova S.E.

(National Scientific Center for Seismological Observations and Research, Almaty, Kazakhstan)

Abstract: Western Kazakhstan is the country's largest oil and gas producing region, hosting major hydrocarbon fields such as Tengiz, Kashagan, Karachaganak, and Zhanazhol. Although the region is characterized by low natural seismicity, intensive hydrocarbon exploitation has significantly altered the geodynamic state of the subsurface, increasing interest in the study of induced seismicity. Induced seismicity is associated with long-term oil and gas production, which leads to reservoir pressure depletion, stress redistribution within rock formations, and compaction of productive reservoirs. An additional factor is water injection for pressure maintenance, which changes pore pressure and may reactivate pre-existing faults. As a result, even minor changes in the stress field can trigger local seismic events.

International experience confirms the relationship between hydrocarbon production and induced seismicity. Well-known examples include the Groningen gas field in the Netherlands and the oil-producing regions of Oklahoma, USA, where reservoir pressure changes were accompanied by a significant increase in the number of recorded earthquakes. These cases demonstrate the importance of continuous geodynamic monitoring in areas of intensive hydrocarbon development. In Kazakhstan, induced seismicity remains insufficiently studied. However, the occurrence of several seismic events in the oil-producing regions of Western Kazakhstan highlights the need for comprehensive investigations. Particular attention should be paid to the spatial relationship between earthquakes, major oil and gas fields, active faults, production volumes, and operational conditions.

A comprehensive assessment of the geodynamic environment requires the integration of regional seismic network data, microseismic monitoring, GNSS observations, remote sensing techniques, and geological and structural analysis. The combined interpretation of these datasets makes it possible to identify active deformation zones, evaluate stress-state changes within the Earth's crust, and improve geodynamic monitoring systems. Therefore, investigating the influence of oil production on induced seismicity represents an important research area in modern seismology and geodynamics. The results can contribute to geodynamic risk assessment, improved industrial safety of oil and gas infrastructure, and the development of more effective monitoring systems for hydrocarbon fields in Western Kazakhstan.

Key words: Induced seismicity; Oil production; Western Kazakhstan; Oil and gas fields; Geodynamic monitoring; Induced earthquakes

COMPIEX SHALLOW UNILATERAL RUPTURE OF THE 2025 M_w 7.0 HUBBARD GLACIER EARTHQUAKE TERMINATED BY A RESTRAINING BEND ON CONNECTOR FAULT

Mohammadreza Jamalreyhani¹, Niu Fenglin¹, Simone Cesca², Eric Bergman³

(1. State Key Laboratory of Precision Geodesy, School of Earth and Space Sciences, University of Science and Technology of China, Hefei, China; 2. German Research Centre for Geosciences, Potsdam, Germany; 3. Global Seismological Services, Golden, CO, USA)

Abstract: Despite decades of study, the detailed geometry of the Connector fault at the Alaska–Canada border remains poorly constrained. We investigate the rupture complexity and directivity of the 6 December 2025, M_w 7.0 Hubbard Glacier earthquake using hypocenter relocations, moment tensor inversions of the mainshock and aftershocks, and finite-fault modeling. We model seismological data using bootstrap and Bayesian-based probabilistic inversion. Observations indicate that the mainshock rupture was complex, nucleated with a right-lateral strike-slip mechanism and propagating northwestward, ultimately terminating in a restraining bend. Source inversion of the mainshock reveals shallow right-lateral oblique-slip on a fault striking 303° and dipping 63° NE. Relocated aftershocks delineate an ~ 60 km-long seismic zone characterized by strike-slip mechanisms along the ruptured area and reverse/thrust at the left stepover of the fault. Our results provide a detailed mechanism for a buried Connector structure and highlight the role of fault bends in controlling rupture evolution.

DO INTRAPLATE EARTHQUAKE FAMILIES CHARACTERIZE THEIR OWN SEISMIC CYCLE? AN INSAR–PALEOGEODETIC TEST

Nicolò Parrino, Salvatore Stramondo

(Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy)

Abstract: Intraplate deformation spans a broad tectonic spectrum, from active orogens such as the Tianshan, which accommodate tens of mm/yr of distributed shortening, to reactivated cratonic rifts and stable cratons at the geodetic noise floor. Most frequently, they share unresolved hazard problems, such as the interseismic signal being near-zero, recurrence intervals reaching 10^3 – 10^5 years, and due to their structural complexity, the seismic cycle itself being almost never observed. Geodesy resolves the coseismic rupture in minutes; the geological archive integrates deformation over millions of years. The cycle falls in the gap between them. We ask one question. Can the deformation field of a single large intraplate earthquake serve as a spatial unit of long-term fault activity? If it can, the long-term geomorphic record of surface deformation, accumulated over many cycles, is a direct multiple of the coseismic field, and the recurrence structure of the fault becomes quantitatively accessible.

Intraplate settings answer this question cleanly because of a chain of physical conditions. The near-zero interseismic signal leaves the coseismic event as the dominant observable at most timescales and persists where erosion rates are low enough to preserve geomorphic markers over numerous cycles. Tectonic relief standing above the erosional baseline is itself evidence that cumulative slip has concentrated in space: the landscape we observe could not exist unless successive ruptures stacked coherently, so spatial coherence is a physical requirement, not a starting assumption. Deep-source contributions to surface deformation, such as asthenospheric flow and glacial isostatic adjustment, act at wavelengths well above 100 km, spectrally separated from the coseismic near-field signal at $\lambda \sim 20$ –80 km, which is set by fault depth. The preserved geomorphic markers, therefore, can encode the coseismic cumulative faithfully, free of the postseismic viscoelastic relaxation that contaminates equivalent markers at subduction zones and transform boundaries, where it acts at the rupture wavelength. Thus, it is possible to separate coseismic from deep-source deformation in the physical domain.

We formalize this as a testable proposition, the characteristic earthquake family: a set of events sharing fault geometry and kinematics such that their cumulative deformation field stays spatially coherent across geological time. To test this hypothesis, we jointly invert the coseismic deformation field with long-term paleo-geodetic markers in a Bayesian framework. The markers are paleo-shoreline indicators, marine terrace inner edges, fossil tidal notches, lacustrine paleo-shorelines, and strath fluvial terraces, which record coseismic base-level perturbations propagated upstream as knickpoints. point migration and extend the approach to continental settings with no coast. The diagnostic is k , the number of characteristic cycles recorded by each marker level. A k that is spatially stable across marker levels of different age means the cumulative pattern has not changed shape, only scaled, and confirms the family; a k that diverges maps where and how the pattern varies, constraining the admissible envelope of recurrence scenarios for multi-source hazard assessment.

We test the framework on the Kachchh intraplate fault system, where we jointly invert the coseismic InSAR deformation field with a flight of paleo-shoreline angle levels and are now analysing whether k holds stable across them. The ideal test case for the characteristic family hypothesis demands a well-imaged intraplate rupture, datable geomorphic markers, and near-zero interseismic noise. The Tianshan meets each criterion: the Maidan Fault provides a well-imaged coseismic rupture and dated river terrace sequences offset by the same fault constrain its late Quaternary slip history. We propose it as the natural next laboratory for the characteristic family hypothesis, and we invite the Tianshan community to join the test.

Key words: Characteristic earthquake family; Paleo-geodetic markers; Joint Bayesian inversion

QUALITY-AWARE MULTI-COMPONENT ERROR FRAMEWORK FOR INSAR SEISMOGENIC SOURCE MODELING

Salvatore Stramondo, Nicolò Parrino

(Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy)

Abstract: Intracontinental seismicity encompasses a broad spectrum of tectonic settings from active orogens such as the Tianshan, accommodating tens of millimetres per year of crustal shortening across High-Complexity-of-Connectivity fault networks, to post-orogenic extensional provinces such as the central Apennines, reactivated craton rifts, and stable cratons operating at the geodetic noise floor. Across this diversity, seismogenic sources are frequently elusive: landscape evolution integrates the competing action of tectonic uplift and climatic erosion, while moment budgets are distributed across structurally complex fault networks, hampering the parametrization of individual seismogenic structures. Synthetic Aperture Radar Interferometry has become the most accessible and globally consistent tool for mapping crustal deformation in these settings, providing a critical pathway toward characterizing seismogenic sources even where their surface expression is limited, ambiguous or elusive. Crucially, this diversity of settings also implies archetype-specific error regimes, from topographic phase bias and unmodelled atmospheric gradients in active thrust belts, to thermal decorrelation and unwrapping failures where tectonic signals approach the instrumental noise floor, yet standard InSAR products deliver a single uncertainty scalar that treats them equivalently.

Those errors represent a critical gap that persists along the processing chain that connects satellite acquisitions to geophysical source modelling, which we term the *downstream gap*. Standard InSAR processing chains deliver displacement maps accompanied by a single uncertainty scalar derived from interferometric coherence via the Cramér-Rao Lower Bound. This scalar captures thermal decorrelation but ignores systematic error contributions that dominate at longer spatial wavelengths: unmodelled atmospheric signals, geometric residuals from DEM uncertainty and baseline geometry, and high-frequency phase unwrapping artifacts. Existing correction approaches that rely on external atmospheric reanalysis products introduce additional uncertainty that is not propagated downstream, compounding the problem rather than resolving it.

We present a Proof-of-Concept framework that aims at addressing this gap by modeling per-pixel InSAR uncertainty through four physically independent and internally estimated components, combined in quadrature: interferometric phase noise, an Unmodelled correlated residual, a geometric error term proportional to the perpendicular baseline (σ_{DEM}), and a local spatial texture term that identifies unwrapping instabilities. A key point lies in the estimation of σ_{UNM} without recourse to external models: a radially averaged Power Spectral Density is computed from high-coherence pixels, a power-law curve is fit in log-log space, and spectral breakpoints are detected where the slope changes significantly. Because atmospheric turbulence and tectonic deformation occupy distinct spatial wavelength ranges, this supervised spectral analysis allows an empirical noise floor to be defined and σ_{UNM} to be estimated directly from the data.

The multi-component uncertainty map enables a fitness-for-purpose classification: a pixel is serviceable for downstream inversion only if its total uncertainty σ_{TOTAL} falls below a tolerance threshold T scaled to the interferometric phase sensitivity of the sensor. The framework further exports the covariance structure of the error budget, separating spatially correlated (σ_{UNM} , σ_{DEM}) from uncorrelated (σ_{CRLB} , σ_{LOCAL}) components. This information allows downstream codes to construct a realistic data covariance matrix, preventing the pseudo replication that occurs when multiple spatially correlated observations are incorrectly treated as multiple independent constraints, and reducing the effective dimensionality of the inversion to its true information content.

The framework aims at demonstrating that quality-aware processing can recover honest displacement fields from data previously considered marginal. The output requires only four additional data columns plus a scalar correlation length, is fully compatible with existing inversion codes without modification, and is designed to be portable across intracontinental settings wherever archive SAR data precede modern quality standards.

Key words: InSAR uncertainty; Downstream gap (processing-to-inversion); quality-aware processing

INGV GEOSAR LABORATORY FOR THE STUDY OF NATURAL AND ANTHROPOGENIC PHENOMENA USING SAR REMOTE SENSING: INSIGHTS FROM THE 2025 DINGRI AND MYANMAR EARTHQUAKES

Silvia Puliero¹, INGV GeoSAR Laboratory¹, Valerio Ruocco^{1,2,3}, Michele Saroli^{1,2,3},
Pasquale Striano⁴, Fernando Monterroso⁴, Manuela Bonano⁴, Claudio De Luca⁴, Francesco
Casu⁴, Riccardo Lanari⁴

(1. Istituto Nazionale di Geofisica e Vulcanologia, via di Vigna Murata 605 00143, Rome, Italy; 2.
DICEM-Università degli Studi di Cassino e del Lazio meridionale, via di Biasio 43, 03043 Cassino, Italy;
3. European University of Technology, EUt+, European Union, 03043 Cassino, Italy; 4. Istituto per il
Rilevamento Elettromagnetico dell'Ambiente, Consiglio Nazionale delle Ricerche (IREA- CNR), via
Diocleziano 328, 80124 Naples, Italy)

Abstract: The INGV GeoSAR laboratory, situated in Rome (Italy), is a research infrastructure dedicated to the processing, analysis, and interpretation of Synthetic Aperture Radar (SAR) data for geological and geotechnical applications. The laboratory specializes in the interpretation of ground deformation measurements derived from Interferometric SAR (InSAR) techniques, integrating remote sensing observations with geological and geotechnical knowledge to investigate deformation processes across different spatial and temporal scales. In addition to deformation monitoring, the GeoSAR laboratory also exploits SAR imagery for change detection analyses aimed at identifying and monitoring both natural and human-induced environmental changes. These activities include developing methodologies for detecting marine plastic litter, such as floating plastic islands, within the framework of the Space It Up project, for environmental monitoring.

Recently, the GeoSAR Laboratory applied SAR data to investigate two significant earthquakes that affected the Asian area: on January 7, 2025, a M_w 7.1 earthquake struck Dingri County (Southern Tibetan Plateau), while on March 28, a M_w 7.7 seismic event hit central Myanmar. Following such strong earthquakes, rapid and accurate assessment of coseismic deformation and characterization of fault systems are crucial for understanding regional seismicity and supporting emergency response efforts. In this study, the GeoSAR Laboratory employed Synthetic Aperture Radar (SAR) techniques and inverse modeling to investigate fault parameters—including strike, dip, depth, and slip distribution—for both events. To achieve a comprehensive understanding of the Dingri earthquake, the GeoSAR Laboratory used SAR data from multiple sensors, including Sentinel-1 (European Space Agency) and ALOS-2 (Japan Aerospace Exploration Agency). For the Myanmar earthquake, the GeoSAR Laboratory utilized Sentinel-1 acquisitions. The GeoSAR Laboratory applied a combination of SAR-based techniques—Pixel Offset Tracking (POT), Multiple Aperture Interferometry (MAI), and conventional Interferometric SAR (InSAR)—to enhance sensitivity to different displacement components and ensure robust fault model inversion.

The results reveal a complex seismic source in the Southern Tibetan Plateau, involving the quasi-simultaneous activation of four distinct fault segments with normal faulting on a north-south structure, consistent with regional tectonic extension. For the Myanmar earthquake, the analysis indicates widespread crustal deformation, with rupture propagation extending approximately 500 km along the strike-slip Sagaing Fault and a maximum coseismic slip of about 5 meters. These findings contribute valuable insights into the earthquake rupture processes, which can provide useful data for seismic hazard assessment in these tectonically active regions.

Key words: INGV GeoSAR Laboratory; natural and anthropogenic phenomena; the 2025 M_w 7.1 Dingri earthquake; the 2025 M_w 7.7 Myanmar earthquake

AUTOMATIC SEISMIC PHASE PICKING BENCHMARK ON A LOCAL NETWORK IN CENTRAL ASIA: DEEP- LEARNING MODELS VERSUS A TUNED STA/LTA

Suratbek Khalbayev^{1,2}, Javokhir Kodirov^{1,2}, Ming Zhao^{3,4}, Shi Chen^{3,4}, Timur
Mamarozikov^{1,2}, Bakhodir Alimov¹, Timur Kurbanov¹

(1. Institute of Seismology, Academy of Sciences of the Republic of Uzbekistan, Tashkent
100128, Uzbekistan; 2. Gubkin Russian State University of Oil and Gas, Tashkent Branch,
Tashkent 100125, Uzbekistan; 3. Institute of Geophysics, China Earthquake Administration,
Beijing 100081, China; 4. Beijing Baijiatuan Earth Sciences National Observation and Research
Station, Beijing 100095, China)

Abstract: To constrain how deep-learning phase pickers behave under adverse, out-of-distribution conditions, we assembled a benchmark of 846 manually reviewed events from a compact local network in Central Asia, dominated by low-magnitude seismicity recorded at noisy stations over local to regional distances. Four detectors were evaluated under a single protocol: the DiTing seismic foundation model (DT-SFM), PhaseNet, EQTransformer, and a tuned STA/LTA baseline, all scored against the same manual reference picks. Ranked by P-phase F1, DiTing (0.307) leads, followed by the tuned STA/LTA (0.161), PhaseNet (0.127), and EQTransformer (0.077): only the foundation model surpasses the classical detector. Recall declines sharply with epicentral distance; the missed arrivals of PhaseNet are largely recoverable by lowering its probability threshold, whereas those of EQTransformer are not. Timing accuracy is comparable across methods, so detection rather than timing is the discriminating factor.

Key words: Seismic phase picking; Earthquake detection; Deep learning; STA/LTA; Central Asia

Author Biography: Suratbek Khalbayev (2005–), male, engineer at the Institute of Seismology, Academy of Sciences of Uzbekistan, mainly engaged in research on machine-learning applications in seismic data analysis. E-mail: surathalbayev@gmail.com

ADVANCES IN SEISMOLOGICAL MONITORING: NETWORKS, INSTRUMENTS, AND MULTI-DISCIPLINARY TECHNIQUES INTEGRATION OF MAGNETOMETRIC MEASUREMENTS INTO SEISMOLOGICAL MONITORING FOR EARTHQUAKE PRECURSOR ANALYSIS

Yersayin Dostay

(National Scientific Center for Seismological Observations and Research, Almaty 050060, Kazakhstan)

Abstract: The nature and mechanisms of earthquake occurrence have been studied for a long time; however, the problem of their detailed prediction remains unresolved to this day. For the regions of Central Asia - China, characterized by high seismic activity, significant population density, and developed infrastructure, the development of integrated monitoring systems aimed at identifying possible precursors of seismic events is of particular importance.

Under conditions of limited informativeness of direct methods, increasing attention is being paid to the study of indirect indicators of seismic activity. One such indicator may be variations in the Earth's magnetic field caused by deep tectonic processes and changes in the stress-strain state of the geological environment.

This study considers the application of SmartMag magnetovariational stations for recording the Earth's magnetic field at stationary observation points of the National Scientific Center for Seismological Observations and Research of the Republic of Kazakhstan in order to assess the relationship between magnetic field variations and seismic events. A significant stage in the development of the observation network has been its modernization carried out since 2023: at 10 observation points, outdated magnetometers were replaced with new SmartMag systems, while the measurement cycle was changed from 1 minute to 1 second. This made it possible to significantly improve the temporal resolution of observations, sensitivity to short-period variations, and the overall informativeness of magnetometric data.

Modern SmartMag hardware and software systems provide magnetometric observations both in real-time mode and in autonomous mode with high sampling rates (up to 10 Hz) and sensitivity (0.02 nT), creating conditions for analyzing magnetic field variations across different period ranges. The presence of an integrated high-precision GNSS receiver additionally allows for obtaining data on ground surface movements and using them in combination with magnetometric observations.

The conducted research is aimed at the accumulation and analysis of data for the development of integrated methodologies for identifying possible earthquake precursors and improving the efficiency of geophysical monitoring. The practical significance of the work is determined by the possibility of using the obtained results not only in collaboration with scientific centers but also in cooperation with industrial companies engaged in integrated geophysical studies and geological exploration within the territory of the Republic of Kazakhstan.

Key words: Earthquake precursors; Seismological monitoring; Integrated monitoring; Geomagnetic field variations; Magnetometric observations; Magnetovariational stations

ДОСТИЖЕНИЯ В ОБЛАСТИ СЕЙСМОЛОГИЧЕСКОГО МОНИТОРИНГА: СЕТИ, ПРИБОРЫ И МЕЖДИСЦИПЛИНАРНЫЕ МЕТОДЫ

Интеграция магнитометрических измерений в сейсмологический мониторинг
для анализа предвестников землетрясений

Ерсайын Достай

Национальный научный центр сейсмологических наблюдений и исследований

Аль-Фараби, 75а, 050000, Алматы, Казахстан

LLP GEODEVICE KAZAKHSTAN

Улица Сакена Жунисова, дом 134/82, 050000, Алматы, Казахстан

ersdos55@gmail.com; od@geodevice.kz;

Абстрактный

Природа и механизмы возникновения землетрясений изучались давно, однако проблема их детального прогнозирования остается нерешенной и по сей день. Для регионов Центральной Азии - Китай характеризующихся высокой сейсмической активностью, значительной плотностью населения и развитой инфраструктурой, разработка интегрированных систем мониторинга, направленных на выявление возможных предвестников сейсмических событий, имеет особое значение.

В условиях ограниченной информативности прямых методов все большее внимание уделяется изучению косвенных показателей сейсмической активности. Одним из таких показателей могут быть колебания магнитного поля Земли, вызванные глубинными тектоническими процессами и изменениями напряженно-деформированного состояния геологической среды.

В данном исследовании рассматривается применение магнитовариационных станций SmartMag для регистрации магнитного поля Земли на стационарных наблюдательных пунктах Национального научного центра сейсмологических наблюдений и исследований Республики Казахстан с целью оценки взаимосвязи между вариациями магнитного поля и сейсмическими событиями. Важным этапом в развитии наблюдательной сети стала ее модернизация, проводимая с 2023 года: в 10 пунктах наблюдения устаревшие магнитометры были заменены на новые системы SmartMag, а цикл измерений был изменен с 1 минуты на 1 секунду. Это позволило значительно улучшить временное разрешение наблюдений, чувствительность к короткопериодическим вариациям и общую информативность магнитометрических данных.

Современные программно-аппаратные комплексы SmartMag обеспечивают магнитометрические наблюдения как в режиме реального времени, так и в автономном режиме с высокой частотой дискретизации (до 10 Гц) и чувствительностью (0,02 нТл), создавая условия для анализа изменений магнитного поля в различных периодических диапазонах. Наличие встроенного высокоточного ГНСС-приемника дополнительно позволяет получать данные о перемещениях земной поверхности и использовать их в сочетании с магнитометрическими наблюдениями.

Проводимые исследования направлены на накопление и анализ данных для разработки комплексных методик выявления возможных предвестников землетрясений и повышения эффективности геофизического мониторинга. Практическая значимость работы определяется возможностью использования полученных результатов не только в сотрудничестве с научными центрами, но и в сотрудничестве с промышленными компаниями, занимающимися комплексными

геофизическими исследованиями и геолого-разведочными работами на территории Республики Казахстан.

Ключевые слова: предвестники землетрясений, сейсмологический мониторинг, комплексный мониторинг, вариации геомагнитного поля, магнитометрические наблюдения, магнитовариационные станции.

TECHNOGENIC SEISMICITY DURING UNDERGROUND MINING OF SOLID MINERAL RESOURCES: A CONCEPT FOR INTEGRATED MONITORING AND RISK MANAGEMENT FOR INDUSTRIAL FACILITIES (CASE STUDY OF KAZAKHMYN MINES, REPUBLIC OF KAZAKHSTAN)

Zhengis Taukebayev, Bekbolat Tashev, Bolat Sultanbayev, Dariga Suleimenova

(National Scientific Center of Seismological Observations and Research, Almaty 050060

E-mail: taukebayev.zh@seismology.kz)

Abstract: Technogenic seismicity associated with underground mining poses a significant threat to industrial facilities and infrastructure in mining regions. The mines of the Kazakhmys Corporation (Zhezkazgan, Kazakhstan) operate under conditions involving more than 200 million m³ of mined-out space; however, comprehensive geomechanical monitoring using modern methods has not yet been implemented at these sites. This study substantiates the concept of the first integrated monitoring system in Kazakhstan that combines microseismic observations, satellite radar interferometry (InSAR/SBAS), and numerical geomechanical modeling. The proposed approach is adapted to the room-and-pillar mining system and is based on verified international experience in managing mining-induced seismic risks, enabling a significant reduction in risks to personnel and industrial infrastructure.

Keywords: technogenic seismicity, rockbursts, microseismic monitoring, InSAR, SBAS, geomechanical modeling, room-and-pillar mining system, mine-induced seismicity, Kazakhmys, geomechanical risk management.

RAI-g 量子重力仪观测结果及性能分析

阿卜杜塔伊尔·亚森^{1,2}, 李忠亚^{3,4}, 邓小兵⁵, 艾力夏提·玉山^{1,2}, 刘代芹^{1,2}
 聂嘉旺^{1,2}, 丁宇^{1,2}

(1.新疆维吾尔自治区地震局, 新疆 乌鲁木齐 830011; 2.中国地震局乌鲁木齐中亚地震研究所, 新疆 乌鲁木齐 830011; 3.中国地震局地震研究所, 湖北 武汉 430071; 4.武汉引力与固体潮国家野外科学观测研究站, 湖北 武汉 430071; 5.国家精密重力测量科学中心, 华中科技大学, 湖北 武汉 430074)

摘要: 为研究冷原子绝对重力仪(下文统称量子重力仪)在地壳形变监测与地球动力学研究中的应用效果, 验证国产量子重力仪的观测可靠性, 本文利用我国自主研发的 RAI-g 量子重力仪开展台站连续重力观测, 仪器以 6s 为周期完成一次绝对重力数据采集。国产 RAI-g 量子重力仪基于冷原子物质波干涉机理完成重力加速度的绝对测量工作, 拥有长时间不间断平稳观测的性能优势。依靠高探测灵敏度、不存在长期零点漂移、支持仪器自主标定等多项优势特性, 该设备可输出高精度、连续性良好的重力观测时序数据, 搭配配套的数据校正算法, 能够充分滤除外界环境变化、天体运行带来的各项观测扰动。原始重力观测数据叠加了固体潮、海洋潮汐、大气压力、地极移动等多种干扰信号, 研究过程中依次采用 WDD 模型、FES2014b 海潮模型、 $0.3 \mu\text{Gal}/\text{mBar}$ 的气压响应系数以及国际地球自转服务(IERS)发布的极移参数, 对观测数据实施多层级改正处理。将校正完毕后的实测数据和布设在同一观测点位的 FG5X 经典落体式绝对重力仪监测数据做对比校验。

研究显示, RAI-g 量子重力仪在阿勒泰重力站开展连续观测, 原始观测数据经潮汐、气压变化、极移等效应改正并扣除常数后, 观测值主要分布在 $-150 \sim 100 \mu\text{Gal}$ 区间, 整体数据密集程度较高; RAI-g 量子重力仪观测结果中含有的系统误差是决定仪器性能的重要因素。本文中采用 FG5X 绝对重力仪观测结果作为参考值, 将量子重力仪观测结果与其比较得到准确度来衡量量子重力仪系统误差大小。为评估阿勒泰 RAI-g 量子重力仪观测值与该站参考重力值之间的差异, 使用同址 FG5X 型传统落体式绝对重力仪观测结果开展比对分析, 得到的 RAI-g 量子重力仪的准确度为 $1.93 \mu\text{Gal}$, 结果表明 RAI-g 量子重力仪准确度优于 $10 \mu\text{Gal}$ 。通过计算该站 RAI-g 量子重力仪进行比对的观测精度为 $0.0196 \mu\text{Gal}$; 为分析 RAI-g 量子重力仪观测过程中的稳定性, 计算了该站观测数据的阿伦偏差。阿伦偏差结果拟合了 RAI-g 量子重力仪在阿勒泰站观测结果的灵敏度为 $44 \mu\text{Gal}/\text{Hz}^{1/2}$, 即该仪器观测精度要达到 $1 \mu\text{Gal}$ 所需要的观测时间为 0.46 h ; RAI-g 量子重力仪的观测精度优于 $1 \mu\text{Gal}$, 准确度为 $1.93 \mu\text{Gal}$, 验证了 RAI-g 型仪器在连续重力观测中的可靠性与稳定性, 本研究为大地测量、地球物理观测与地震预测预报工作积累实测实证依据, 同时为我国高精度时变重力场相关研究提供全新技术支撑。

关键词: 量子重力仪; 绝对重力; 数据改正; 阿伦偏差; 观测精度

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作者简介: 阿卜杜塔伊尔·亚森(1985—), 男, 高级工程师, 主要从事重力场及其变化、地震监测预报。E-mail: tigerjan163@163.com

OBSERVATION RESULTS AND PERFORMANCE ANALYSIS OF RAI-g QUANTUM GRAVIMETER

Abudutayier Yasen^{1, 2}, Li Zhongya^{3, 4}, Deng Xiaobing⁵, Ailixati Yushan^{1, 2}, Liu
Daiqin^{1, 2}, Nie Jiawang^{1, 2}, Ding Yu^{1, 2}

(1. Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, Xinjiang, China; 2. Urumqi Institute of Central Asia Earthquake, China Earthquake Administration, Urumqi 830011, Xinjiang, China; 3. Institute of Seismology, China Earthquake Administration, Wuhan 430071, Hubei, China; 4. Wuhan Gravitation and Solid Earth Tide, National Observation and Research Station, Wuhan 430071, Hubei, China; 5. National Gravitation Laboratory, Huazhong University of Science and Technology, Wuhan 430074, Hubei, China)

Abstract: To investigate the practical performance of cold atom absolute gravimeters (here in after referred to as quantum gravimeters) in crustal deformation monitoring and geodynamic research, and verify the observational reliability of domestic quantum gravimeters, continuous station gravity observations are carried out using the self-developed RAI-g quantum gravimeter in this study. The instrument completes one acquisition of absolute gravity data at a sampling interval of 6 seconds. The domestic RAI-g quantum gravimeter realizes the absolute measurement of gravitational acceleration based on the interference mechanism of cold atom matter waves and possesses the capability of long-term uninterrupted stable observation. Benefiting from prominent merits including high detection sensitivity, the absence of long-term zero drift, and support for autonomous instrument calibration, this equipment is capable of outputting high-precision and well-continuous gravity observation time series. Combined with matched data correction algorithms, various observational disturbances induced by environmental variations and celestial movements can be effectively eliminated. Raw gravity observations are contaminated by multiple interfering signals such as solid earth tides, ocean tides, atmospheric pressure and polar motion. In this research, multi-layer corrections are implemented on observation datasets by adopting the WDD model, the FES2014b ocean tide model, a barometric admittance coefficient of $0.3 \mu\text{Gal}/\text{mBar}$, as well as polar motion parameters released by the International Earth Rotation and Reference Systems Service (IERS). The corrected measured data are compared and validated against monitoring records from the classic free-fall FG5X absolute gravimeter deployed at the identical observation site. The relevant conclusions are presented as follows: The raw continuous observations acquired by the RAI-g quantum gravimeter at the Altay Gravity Station, as well as the corrected values after corrections for tidal effects, Atmospheric pressure variations, polar motion and other disturbances (a constant offset has been deducted from all datasets) are illustrated in Figure 1. As demonstrated in Figure 1, the observational data measured by the quantum gravimeter are mainly distributed within the range of $-150 \mu\text{Gal}$ to $100 \mu\text{Gal}$, exhibiting a highly concentrated data distribution.

Key words: Quantum Gravimeter; Absolute Gravity; Gravity Data Correction; Allan Deviation; Observational Precision

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Author Biography: Abudutayier Yasen (1985–), Male, Senior Engineer, mainly engaged in gravity field and its variation, seismic monitoring and prediction, E-mail: tigerjan163@163.com

基于形变及地震监测的呼图壁储气库地表形变研究

阿卜杜塔伊尔·亚森^{1,2}, 苏金波^{1,2}, 艾力夏提·玉山^{1,2}, 李杰^{1,2}, 刘代芹^{1,2},
李桂荣^{1,2}, 黄旺², 李欣潞³

(1.新疆维吾尔自治区地震局, 新疆 乌鲁木齐 830011; 2.中国地震局乌鲁木齐中亚地震研究所, 新疆 乌鲁木齐 830011; 3.中国石油新疆油田储气库有限公司, 新疆 克拉玛依 834099)

摘要: 为厘清新疆呼图壁储气库地表形变时空分布特征, 明确储气库注采作业与地表形变、地下介质变化的定量关联, 保障储气库安全稳定运维, 本文以我国最大的西气东输核心基础设施——新疆呼图壁地下储气库为研究对象, 结合储气库春夏注气、冬季采气的季节性调峰作业模式, 综合采用精密水准测量、时序 InSAR 技术、GNSS 观测、气枪震源监测等高精度观测手段, 开展库区盖层地表周期性不规则变形监测, 获取注采压力变化下库区地表三维运动学时空图像, 探究形变力学关联及地下断层活动特征。结果表明:

水准监测结果表明, 储气库地表形变由注采压力变化主导, 而非区域构造运动。2024 年两期监测数据显示, 注气期储气库中部、西区地表小幅抬升, 东区出现轻微下沉; 近十年断层监测数据证实, 呼图壁断层垂直活动量稳定在 1–2 mm, 个别点位异常变化为局部扰动导致, 无构造活动迹象。时序 InSAR 监测清晰印证形变与注采周期高度同步。2015—2024 年储气库中心年均隆升速率约 14 mm, 部分测点累积抬升量达 133.4 mm, 整体呈现注气抬升、采气沉降的季节性规律。同时储气库表现出非对称形变特征, 东区周期性沉降、西区持续隆升, 主要受断层形态与岩层非均质特性控制。GNSS 监测明确了注采作业对断层的力学影响。注气阶段储气库内部测点出现北向加速运动与垂向抬升, 最大抬升量达 20 mm, 跨断层监测显示注气期间断层产生约 12 mm 拉张应变, 证明储层与围限断层存在显著力学耦合效应。气枪震源监测显示, 储气库边界 6 km 范围内地下介质横波速度存在 0.1%–0.3% 的季节性周期变化, 注气阶段波速降低、采气阶段逐步恢复。该变化与储层孔隙压力密切相关, 是浅层孔隙压力变动所致, 也明确了储气库作业对地下介质的影响范围。

针对我国最大的新疆呼图壁地下储气库随注采压力变化, 在注气、采气及平衡期阶段引发的地壳变形与地震活动, 依托高精度空间地震大地测量观测技术, 开展储气库盖层地表的“周期性不规则”变形监测, 获取注采过程中随压力变化下储气库区地表的三维运动学时空图像, 并结合气井压力变化开展形变力学关系研究, 厘定地下断层滑动速率在储气库安全运行过程中的活动特征和稳定作用。研究结论可为呼图壁储气库安全运维、灾害风险评估及稳定运行保障提供科学依据。

关键词: 储气库; 地壳形变; GNSS; 时序 InSAR; 地震监测

作者简介: 阿卜杜塔伊尔·亚森 (1985—), 男, 高级工程师, 主要从事重力场及其变化、地震监测预报。
E-mail: tigerjan163@163.com

STUDY ON SURFACE DEFORMATION OF HUTUBI UNDERGROUND GAS STORAGE BASED ON DEFORMATION AND SEISMIC MONITORING

Abudutayier Yasen^{1,2}, Su Jinbo^{1,2}, Ailixati Yushan^{1,2}, Li Jie^{1,2}, Liu Daiqin^{1,2},
Li Guirong^{1,2}, Huang Wang^{1,2}, Li Xinlu³

(1. Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, Xinjiang, China; 2. Urumqi Institute of Central Asia Earthquake, China Earthquake Administration, Urumqi 830011, Xinjiang, China; 3. Xinjiang Oilfield Gas Storage Co.,Ltd. ,PetroChina,Karamay 834099, Xinjiang, China)

Abstract: To clarify the spatiotemporal distribution characteristics of surface deformation in the Xinjiang Hutubi gas storage and quantitatively determine the correlations between gas injection-production operations, surface deformation and subsurface medium variations, and to ensure the safe and stable operation of the gas storage, this study takes the Xinjiang Hutubi underground gas storage, the largest core infrastructure of the West-to-East Gas Transmission Project in China, as the research object. Combined with its seasonal peak regulation mode of gas injection in spring and summer and gas production in winter, high-precision observation methods including precise leveling measurement, time-series InSAR technology, GNSS observation and airgun source monitoring are comprehensively adopted to monitor the periodic and irregular surface deformation of the cap rock in the reservoir area. The three-dimensional kinematic spatiotemporal images of surface deformation under variable injection-production pressures are obtained, and the mechanical correlation of deformation as well as the activity characteristics of underground faults are explored. The results show that: The surface deformation of the Hutubi gas storage is dominated by injection-production pressure changes rather than regional tectonic movement. The two-phase monitoring data in 2024 show that slight surface uplift occurs in the central and western parts of the gas storage during the gas injection period, while minor subsidence appears in the eastern part. The ten-year fault monitoring data confirm that the vertical activity of the Hutubi Fault is stable at 1–2 mm. The abnormal variations at individual monitoring points are caused by local disturbances, with no signs of tectonic activity. Time-series InSAR monitoring results clearly verify that surface deformation is highly synchronized with the injection-production cycle. From 2015 to 2024, the average annual uplift rate at the center of the gas storage is approximately 14 mm, and the cumulative maximum uplift of some measuring points reaches 133.4 mm, presenting an overall seasonal pattern of uplift during gas injection and subsidence during gas production. Meanwhile, the gas storage exhibits asymmetric deformation characteristics, with periodic subsidence in the eastern zone and continuous uplift in the western zone, which is mainly controlled by fault morphology and formation heterogeneity. GNSS monitoring clarifies the mechanical influence of injection-production operations on faults. During the gas injection stage, the internal measuring points of the gas storage show accelerated northward movement and vertical uplift, with a maximum uplift of 20 mm. Cross-fault monitoring reveals an extensional strain of approximately 12 mm in faults during gas injection, which proves that there is a significant mechanical coupling effect between the reservoir and the surrounding faults. Air gun source monitoring indicates that the shear wave velocity of subsurface media within 6 km of the gas storage boundary presents seasonal periodic variations of 0.1%–0.3%, decreasing during the gas injection stage and gradually recovering during the gas production stage. Such variations are closely related to reservoir pore pressure changes caused by shallow pore pressure fluctuations, which also define the influence scope of gas storage operation on subsurface media. Aiming at the crustal deformation and seismic activities induced by pressure changes during the gas injection, production, and balance periods of China's largest Hutubi underground gas storage, this study carries out monitoring on the

periodic irregular surface deformation of the gas storage cap rock based on high-precision space geodetic and seismic observation technologies. The three-dimensional kinematic spatiotemporal characteristics of surface deformation in the gas storage area under pressure changes during injection and production processes are obtained. Combined with the variation of gas well pressure, the deformation mechanical relationship is analyzed, and the activity characteristics and stabilizing effect of underground fault slip rate during the safe operation of the gas storage are clarified. The research conclusions can provide a scientific basis for the safe operation and maintenance, disaster risk assessment, and stable operation guarantee of the Hutubi gas storage.

Key words: Gas Storage; Crustal Deformation; GNSS; Time-series InSAR; Seismic Monitoring

Author Biography: Abudutayier Yasen (1985–), Male, Senior Engineer, mainly engaged in gravity field and its variation, seismic monitoring, and prediction. E-mail:tigerjan163@163.com

南天山—帕米尔 GNSS 发展现状与思考

李桂荣^{1,2}, 李杰^{1,2}, 李瑞^{1,2}, 苏力坦·玉散^{1,2}

(1.新疆帕米尔陆内俯冲国家野外科学观测研究站, 新疆 乌鲁木齐 830011; 2.中国地震局乌鲁木齐中亚地震研究所, 新疆 乌鲁木齐 830011)

摘要: 本文系统梳理了南天山—帕米尔地区 GNSS 观测连续站点的分布情况, 基于陆态网络、新疆 CORS、巨灾防范工程、“一带一路”及本项目站点升级改造站, 结合区域地质构造背景、地震分布情况, 系统分析了该区域 GNSS 观测现状及存在的问题。南天山至帕米尔地区位于印度—欧亚碰撞带西构造结, 地处 5 条巨型山脉交汇处, 是我国大陆现今构造变形最强烈的地区, 发育了全球最活跃的陆内中源地震带, 1800 年以来发生 7 级以上浅源地震 25 次, 复发间隔约为 $11 \pm 1a$, GNSS 速度场显示地壳运动速率较快, 处于高剪应变率集中区。诸多学者研究成果表明该区域研究价值高、成果丰富, 但仍存在诸多问题: 研究区内虽已有部分 GNSS 水平向地壳运动速度场, 但尚缺垂向速度场; 重点危险区和主要断裂上 GNSS 站点仍非常稀疏, 甚至存在观测空缺; 境外站点观测资料有限, 对区域地壳形变监测结果约束力较弱; 观测资料的变化在物理过程和动力学机制方面的解释略显欠缺; 巨灾防范工程、项目流动站点改造为连续站点的数量较多, 但积累时间较短, 尚不足以解释区域地壳运动变化特征, 更难以精细解析断层运动与地震的耦合关系; 部分站点仍为单站观测、定期取数, 动态监测的时效性仍然不足; 站点增加、数据量增大, 实行批处理计算, 精细化程度略有下降。针对上述问题, 本文探讨: 如何融合多源观测数据构建南天山—帕米尔地区高精度三维地壳形变场, 揭示主要断裂闭锁状态与应变积累规律, 进而定量评估区域地震危险性? 为此, 提出采用 GNSS 与 InSAR 数据融合方法构建三维形变场, 利用断层面有限单元反演模型 (DEFNODE) 厘定断裂闭锁深度与滑动亏损速率, 结合三维粘弹性有限元模型分析区域应变分配与深浅构造耦合关系, 并引入库仑 (Coulomb) 应力变化模型评估同震及震后应力转移对周边断裂的影响。预期成果包括: 建成南天山—帕米尔地区首套高精度三维地壳形变速度场, 厘定主要活动断裂的闭锁深度、滑动亏损速率与地震矩累积速率, 给出区域应变能分布与地震危险性定量评估结果。研究成果将为天山造山带现今构造变形机理研究提供新约束, 为新疆防震减灾和经济社会安全提供科技支撑, 并为中亚地区跨境地震危险性合作研究提供示范框架。

关键词: 南天山—帕米尔; GNSS; 三维地壳形变; 断裂闭锁; 地震危险性

作者简介: 李桂荣 (1980—), 女, 高级工程师, 主要从事地壳形变与 GNSS 观测研究.E-mail: 258565765@qq.com

DEVELOPMENT STATUS AND REFLECTIONS ON GNSS OBSERVATIONS IN THE SOUTH TIANSHAN-PAMIR REGION

Li Guirong^{1,2}, Li Jie^{1,2}, Li Rui^{1,2}, Sultan Yusan^{1,2}

(1.Xinjiang Pamir Intracontinental Subduction National Field Observation and Research Station,
Urumqi 830011, Xinjiang, China; 2. Urumqi Institute of Central Asia Earthquake, China Earthquake
Administration, Urumqi 830011, Xinjiang, China)

Abstract: This paper systematically reviews the distribution of continuous GNSS stations in the South Tianshan-Pamir region. Based on multi-phase networks including CMONOC, Xinjiang CORS, the National Catastrophe Prevention Project, Belt and Road stations, and upgraded project stations, combined with regional tectonic settings and seismicity, it analyzes the current status and existing problems of GNSS observations. The region, located at the western syntaxis of the India-Eurasia collision zone at the junction of five major mountain ranges, exhibits the most intense tectonic deformation in continental China and hosts the world's most active intra-continental intermediate-depth seismic belt, with 25 $M \geq 7$ shallow earthquakes since 1800 at $\sim 11 \pm 1$ year intervals. GNSS velocity fields show rapid crustal motion and high shear strain concentration. Despite rich research outputs, problems persist: vertical velocity fields are lacking; GNSS stations in key hazard zones and along major faults remain sparse or absent; overseas observation data are limited, weakening constraints on regional deformation monitoring; interpretations of physical processes and dynamic mechanisms remain insufficient; stations converted from mobile to continuous mode under the Catastrophe Prevention Project and other programs are numerous but have short observation records, inadequate for characterizing regional crustal motion or refining the coupling between faults movement and earthquakes; some stations still operate as single-site observation with periodic data collection, limiting monitoring timeliness; and batch processing of growing data volumes reduces precision. This paper explores: how can multi-source data fusion construct a high-precision 3D crustal deformation field for the region, revealing fault locking states and strain accumulation patterns for quantitative seismic hazard assessment? Methods include GNSS-InSAR fusion for 3D deformation fields, DEFNODE fault-plane inversion for locking depth and slip deficit rates, 3D viscoelastic finite element modeling for strain partitioning and deep-shallow structural coupling, and Coulomb stress change models for evaluating co-seismic and post-seismic stress transfer. Expected outcomes include: the first high-precision 3D crustal deformation velocity field for the region; locking depth, slip deficit rates, and seismic moment accumulation rates of major active faults; and quantitative assessment of regional strain energy distribution and seismic hazard. The findings provide new constraints for studies of present-day tectonic deformation of the Tianshan orogenic belt, scientific support for seismic hazard mitigation and socioeconomic security in Xinjiang, and a demonstration framework for cross-border seismic hazard cooperation research in Central Asia.

Key words: South Tianshan-Pamir; GNSS; 3D Crustal Deformation; Fault Locking; Seismic Hazard

Author Biography: Li Guirong, Female, Senior Engineer, mainly engaged in research on crustal deformation and GNSS observations. E-mail: 258565765@qq.com

中国地震科学台阵探测计划及初步成果

李 丽， 丁志峰， 袁松湧

（中国地震局地球物理研究所，北京 100086）

摘要：中国地震科学台阵探测计划（ChinArray）自 2010 年启动以来，已完成 4 期大规模流动地震台阵观测，累计布设 2 720 个宽频带地震台站，每台站连续观测 2 年，获取了高质量连续波形数据。全部数据经严格质控和标准化处理后，通过国际地震科学数据中心向全球开放共享，为研究中国大陆及周边地区地壳精细结构、地震活动性和深部动力学过程提供了宝贵基础资料，使该计划成为国际最具影响力的陆域地震观测项目之一。目前正在推进的深地计划拟于 2027 年前在中国西部完成 2 350 个台站的布设，力争 2029 年前实现西部地壳结构全覆盖探查。同时，计划积极推动与中亚、蒙古、尼泊尔、印度、巴基斯坦等邻国的联合观测，旨在深化对天山和喜马拉雅活动构造的认识，提升区域防震减灾能力。初步成果已揭示青藏高原隆升、华北克拉通破坏等关键构造问题，并为汶川、九寨沟等强震机理研究提供了重要数据支撑。

CHINA SEISMIC ARRAY PROJECT AND PRELIMINARY RESULTS

Li Li , Ding Zhifeng, Yuan Songyong

(Institute of Geophysics, China Earthquake Administration, Beijing 100086)

Abstract: Since its inception in 2010, the China Seismic Array (ChinArray) project has completed four phases of large-scale mobile seismic array observations, deploying a total of 2,720 broadband seismic stations, each operating continuously for two years and acquiring high-quality continuous waveform data. All data have undergone rigorous quality control and standardized processing, and are openly shared with the global community through the International Seismological Data Center. These data provide valuable fundamental information for studying the fine crustal structure, seismicity, and deep geodynamic processes of the Chinese mainland and its surrounding areas, making the project one of the most influential land-based seismic observation programs worldwide. Currently, the ongoing Deep Earth Project plans to deploy an additional 2,350 stations in western China by 2027, with the goal of achieving comprehensive structural exploration of the western crust by 2029. In parallel, the project actively promotes joint observations with neighboring countries including Central Asian nations, Mongolia, Nepal, India, and Pakistan, aiming to deepen understanding of active tectonics in the Tianshan and Himalayan regions and to enhance regional earthquake disaster prevention and mitigation. Preliminary results have already revealed key tectonic issues such as the uplift of the Tibetan Plateau and the destruction of the North China Craton, and have provided important data support for understanding the mechanisms of strong earthquakes like the Wenchuan and Jiuzhaigou events.

基于高频 GNSS 的 2023 年土耳其双强震动态破裂过程研究

李雪川, 占 伟, 陈长云

(中国地震局第一监测中心, 天津 300180)

摘要: 2023 年 2 月 6 日土耳其东南部先后发生 $M_w7.8$ 和 $M_w7.6$ 双强震, 造成重大人员伤亡与经济损失。全球导航卫星系统 (GNSS) 因其采样率高、无漂移特性, 已成为地震同震位移与破裂过程快速反演的重要工具。本文利用精密单点定位 (PPP) 技术处理了震中附近 59 个高频 GNSS 测站的 1 Hz 观测数据, 系统分析了两次地震的同震位移特征、预警震级估算能力及动态破裂过程。结果表明: (1) 两次强震均引发显著的永久性水平同震位移, $M_w7.8$ 地震的最大位移达 45 cm, $M_w7.6$ 地震的最大位移为 30 cm。断层两侧测站位移方向相反, 且沿破裂方向测站的位移量级明显大于垂直于破裂方向的测站, 这与左旋走滑断层的运动学特征完全吻合。(2) 基于同震位移序列提取的峰值地面位移 (PGD), 利用现有 PGD—矩震级 (M_w) 统计回归公式计算预警震级。结果显示, 各公式估算的 M_w 均比实际震级偏大约 0.2 个单位, 表明经验回归公式受区域地质条件、台站分布及震源机制差异的影响显著, 缺乏物理基础, 直接用于不同地震时需谨慎评估其适用性。(3) 采用滑动窗口滤波方法提取同震位移时间序列, 并反演两次地震的破裂分布。 $M_w7.8$ 地震形成四个显著破裂区, 破裂持续时间约 112 s, 最终矩震级稳定于 7.8; $M_w7.6$ 地震形成三个显著破裂区, 破裂持续时间约 106 s, 矩震级稳定于 7.5。两次地震均产生明显的地表破裂, 最大同震位移约 10 m。研究表明, 高频 GNSS 能够有效捕获大地震的近场同震位移场, 为震源机制判定和快速震级估算提供可靠数据; 但现有 PGD— M_w 经验公式的区域局限性不容忽视, 未来应发展更具物理意义的实时震级估算模型。同时, 基于滑动窗口的动态破裂反演方法可准确揭示破裂时空演化过程, 对地震应急响应与灾害评估具有重要参考价值。

关键词: 土耳其双强震; 高频 GNSS; 同震位移; 峰值地面位移

作者简介: 李雪川 (1986—), 男, 高级工程师, 主要从事 GNSS 高精度数据处理及地壳形变相关研究.E-mail: leexc0124@163.com

DYNAMIC RUPTURE KINEMATICS OF 2023 KAHRAMANMARAŞ EARTHQUAKE SEQUENCE CONSTRAINED BY HIGH-RATE GNSS

Li Xuechuan, Zhan Wei, Chen Changyun

(The First Monitoring and Application Center, CEA, Tianjin, China 300180)

Abstract: On February 6, 2023, two devastating earthquakes of $M_w7.8$ and $M_w7.6$ struck southeastern Türkiye in succession, causing massive casualties and economic losses. The Global Navigation Satellite System (GNSS), with its high sampling rate and absence of drift, has become an important tool for rapid inversion of coseismic displacement and rupture processes. In this study, we processed 1 Hz observations from 59 high-rate GNSS stations near the epicenters using the Precise Point Positioning (PPP) technique, and systematically analyzed the coseismic displacement characteristics, early warning magnitude estimation capability, and dynamic rupture processes of the two events. The results indicate that: (1) Both earthquakes induced significant permanent horizontal coseismic displacements, with a maximum displacement of 45 cm for the $M_w7.8$ event and 30 cm for the $M_w7.6$ event. Stations on opposite sides of the fault exhibited opposite displacement directions, and stations located along the rupture direction showed considerably larger displacements than those perpendicular to it, consistent with the kinematic characteristics of left-lateral strike-slip faulting. (2) Using the peak ground displacement (PGD) extracted from the coseismic displacement time series, the earthquake early warning magnitudes were estimated based on existing empirical PGD–moment magnitude (M_w) regression relationships. The results show that all tested formulas overestimated M_w by approximately 0.2 units relative to the actual magnitudes, indicating that these empirical regressions are significantly influenced by regional geological conditions, station distribution, and focal mechanism variations, and lack a physical basis. Caution is therefore required when applying them directly to different earthquakes. (3) By employing a sliding window filtering method to extract coseismic displacement time series, the rupture distributions of the two earthquakes were inverted. The $M_w7.8$ earthquake produced four distinct rupture patches with a rupture duration of approximately 112 s, and the final moment magnitude stabilized at 7.8; the $M_w7.6$ earthquake formed three distinct rupture patches with a rupture duration of about 106 s, and the moment magnitude stabilized at 7.5. Both earthquakes generated significant surface ruptures, with a maximum coseismic displacement of approximately 10 m. This study demonstrates that high-rate GNSS can effectively capture the near-field coseismic displacement field of large earthquakes, providing reliable data for source mechanism determination and rapid magnitude estimation. However, the regional limitations of existing PGD– M_w empirical formulas should not be overlooked, and future efforts should focus on developing physically based real-time magnitude estimation models. Furthermore, the sliding-window-based dynamic rupture inversion approach can accurately reveal the spatiotemporal evolution of rupture, offering valuable insights for earthquake emergency response and disaster assessment.

Key words: Kahramanmaraş Earthquake; High-rate GNSS; Coseismic offset; Moment magnitude

Author Biography: Li Xuechuan (1986—), Male, Senior Engineer, mainly engaged in research on GNSS data processing and crustal deformation simulation and analysis.

漾濞地震序列震源机制结果初步分析

林向东¹, 赵亮², 袁怀玉^{2,3}, 赵桂儒¹, 孙海霞¹, 叶泵⁴, 吴朋⁵, 杨选⁶, 武敏¹

(1.北京市地震局, 北京 100080; 2.中国科学院地质与地球物理研究所岩石圈演化国家重点实验室, 北京 100029; 3.Geological Survey of Western Australia, East Perth, Western Australia Australia 6004; 4.云南省地震局, 云南 昆明 650224; 5.四川省地震局, 四川 成都 610041; 6.广东省地震局, 广东 广州 510070)

摘要: 维西—乔后断裂附近继 2017 年漾濞 $M_s5.1$ 地震之后, 2021 年又发生了漾濞 $M_s6.4$ 地震序列。漾濞及邻区地震台站密度高, 观测资料丰富, 该地震序列为典型的前震-主震-余震序列, 震后受到了广泛的关注, 开展该地震序列的震源区的震源机制研究, 对深入了解该区域的应力情况具有重要意义。选取 2017 年 4 月至 2021 年 9 月 ($N25.0^\circ \sim 26.5^\circ$, $E99.4^\circ \sim 100.8^\circ$) $M_L2.5$ 以上地震事件, 共计 437 个事件进行震源机制研究。根据震级和震源机制方法的特点, 对 $2.5 \leq M_L \leq 4.2$ 的地震采用 FOCMEC 方法计算震源机制, $M_L \geq 4.3$ 的采用 TDMT 方法反演矩张量 (初动清晰的也同时采用 FOCMEC 方法计算)。结果表明: 漾濞震源区震源类型复杂, 主要为走滑型和正断型, 并伴随有少量的其他类型 (无法判断型、逆断型、逆走滑型、正走滑型等)。在漾濞地震序列发生之前的很长一段时间之内, 均为如此特征。在 2021 年漾濞地震序列发生时, 前期的震源类型主要为走滑型。在主震 $M_s6.4$ 发生之前, 震源类型主要为走滑型和正断型, 并伴随少量逆断型、正走滑型。自 2021 年 6 月底, 地震序列的活动性稍微减弱之后, 震源类型主要为正断型和走滑型。2021 年 5 月 21 日 21 时 21 分 24.8 秒漾濞 $M_L5.9$ 地震以及 2021 年 5 月 22 日 20 时 14 分 36.2 秒漾濞 $M_L4.8$ 地震两个较大地震事件纯偏差矩张量和全矩张量反演表明, 两种方式反演 VR 几乎无变化, ISO 成分改变也不显著。说明漾濞的这两个特殊事件含有显较大的 CLVD 成分, ISO 成分几乎可以忽略。高 CLVD 成分可能与破裂的复杂性或者地下流体运移有关。

作者简介: 林向东 (1981—), 男, 正高级工程师, 主要从事地震观测技术、震源机制与构造应力场研究. E-mail: lxdongd@hotmail.com

基于地震噪声等级的新疆重力站背景噪声对比与地震响应分析

欧雪慧¹, 温燕林², 杨璐嘉¹, 张政¹, 陈丽¹

(1. 新疆维吾尔自治区地震局, 新疆 乌鲁木齐 830011; 2. 上海市地震局, 上海 200062)

摘要: 为定量对比新疆地区超导重力仪与 gPhone 重力仪的观测数据质量, 以及背景噪声对地震事件的响应, 本文利用地震噪声等级 (SNM) 评估方法, 选取 2025 年下半年温泉、乌鲁木齐、乌恰站 3 台超导重力仪及库尔勒、若羌、乌什、于田站 4 台 gPhone 重力仪连续重力观测资料, 通过选取各台站最平静 5 天数据计算 SNM 值, 系统对比了两类仪器在地震频段 (200~600 s) 的背景噪声水平, 并分析了 2025 年 12 月 4 日阿合奇 $M_s6.0$ 地震前后各台站 SNM 的响应特征。研究结果表明, 超导重力仪背景噪声水平显著低于 gPhone 重力仪, 2025 年下半年超导重力仪 SNM 值为 $-0.26 \sim 0.98$, 优于全球新低噪声模型 (NLNM) 参考水平, 而 gPhone 重力仪 SNM 值为 $2.85 \sim 4.55$, 整体高于超导重力仪。阿合奇 $M_s6.0$ 地震发生后, 所有台站 SNM 均出现显著增大, 表现出强烈的同震响应, gPhone 重力仪 SNM 绝对增量为 $2.58 \sim 7.27$, SNM 增量与震中距呈明显负相关, 距离震中越近, 背景噪声增强越显著, 超导重力仪增量为 $0.38 \sim 1.59$, 较 gPhone 重力仪增量相对较小, 发震后超导重力仪 SNM 值 ($1.33 \sim 1.75$) 仍显著低于 gPhone 重力仪 ($5.68 \sim 10.12$), 体现了超导重力仪更低的背景噪声与相对稳定性。由此可见, 不同仪器对地震噪声的响应特征存在差异, gPhone 重力仪对高频地震信号响应更为敏感, 超导重力仪则表现出更低的自噪声和更高的稳定性, 适合作为区域背景噪声长期监测的基准。该研究为利用 SNM 指标进行地震前兆异常识别、台站观测效能评估及多仪器联合观测方案优化提供了参考。

关键字: 超导重力仪; 地震噪声等级; 背景噪声; 阿合奇 $M_s6.0$ 地震

作者简介: 欧雪慧 (1988—), 女, 工程师, 主要从事重力数据分析处理.E-mail:409976581@qq.com

COMPARISON OF BACKGROUND NOISE AND SEISMIC RESPONSE OF XINJIANG GRAVIMETER STATIONS BASED ON SEISMIC NOISE MAGNITUDE

Ou Xuehui¹, Wen Yanlin², Yang Lujia¹, Zhang Zheng¹, Chen Li¹

(1. Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, Xinjiang, China;
2. Earthquake Agency of Shanghai Municipality, Shanghai 200062, China)

Abstract: In order to quantitatively compare the observation data quality between superconducting gravimeters and gPhone gravimeters in Xinjiang, as well as the response of background noise to seismic events, this study employs the Seismic Noise Magnitude (SNM) evaluation method. Using continuous gravity observation data from the second half of 2025 collected by three superconducting gravimeters at Wenquan, Urumqi, and Wujia stations and four gPhone gravimeters at Kuerle, Ruoqiang, Wushi, and Yutian stations, the SNM values were calculated using data from the quietest five-day periods for each station to systematically compare the background noise levels of the two instrument types in the seismic frequency band (200~600 s), and to analyze the SNM response characteristics before and after the M_s 6.0 Aheqi earthquake on December 4, 2025.

The results indicate that the background noise level of superconducting gravimeters is significantly lower than that of gPhone gravimeters. In the second half of 2025, the SNM values for superconducting gravimeters range from -0.26 to 0.98 , which is superior to the global New Low Noise Model (NLNM) reference level, whereas the SNM values for gPhone gravimeters range from 2.85 to 4.55 , substantially higher than those of superconducting gravimeters. Following the M_s 6.0 Aheqi earthquake, all stations exhibited significant SNM increases, showing strong coseismic responses. The absolute SNM increments for gPhone gravimeters range from 2.58 to 7.27 , and the SNM increment shows a significant negative correlation with epicentral distance; the closer to the epicenter, the more significant the background noise enhancement. The increments for superconducting gravimeters range from 0.38 to 1.59 , relatively smaller than those of gPhone gravimeters. After the earthquake, the SNM values of superconducting gravimeters ($1.33\sim 1.75$) remain significantly lower than those of gPhone gravimeters ($5.68\sim 10.12$), reflecting the lower background noise and relative stability of superconducting gravimeters.

It can be seen that different instruments exhibit distinct response characteristics to seismic noise. gPhone gravimeters are more sensitive to high-frequency seismic signals, while superconducting gravimeters demonstrate lower self-noise and higher stability, making them suitable as benchmarks for long-term regional background noise monitoring. This study provides a reference for utilizing SNM indicators in seismic precursory anomaly recognition, station observation performance evaluation, and optimization of multi-instrument joint observation schemes.

Key words: Superconducting gravimeter; Seismic noise magnitude; Background noise; Aheqi M_s 6.0 earthquake

Author Biography: OU Xuehui (1988–), female, engineer, mainly engaged in gravity data analysis and processing.
E-mail: 409976581@qq.com

基于密集台阵的深层致密气藏开发区地应力场 动态监测与演化分析

王 斌¹, 张辉^{2,3}, 左可桢¹, 王志民^{2,3}, 王 鑫^{2,3}, 王 洵¹

(1.中国地震局地震预测研究所, 北京 100026; 2.中国石油天然气股份有限公司塔里木油田公司, 新疆 库尔勒 841000; 3.中国石油天然气集团有限公司超深层复杂油气藏勘探开发技术研发中心, 新疆, 库尔勒, 841000)

摘要: 拜城凹陷位于塔里木盆地北部山前挤压构造带, 深层为高压裂缝型致密砂岩气藏, 区域构造应力本就处于临界平衡状态, 油气规模化开采及后期气藏水侵等工业活动, 持续扰动原始地应力场。本文依托多期地震观测数据、震源机制解及地震波速参数, 结合天然地震应力反演方法, 系统研究油气开发全过程中深层地应力场动态演化规律。结果表明: 研究区地震活动、纵波速度、横波速度和纵横波速度比等地层物性参数随开采进程呈现规律性变化, 地震活动整体自东向西迁移; 结合储层特征与开发过程分析机理: 研究区储层以含气为主, 天然气会显著降低纵波传播速度, 对横波影响微弱, 因此原始气藏区形成高 V_p/V_s 异常。开发中后期气藏水侵加剧, 地层水逐步置换孔隙内天然气, 同时在地应力作用下储层裂隙不断压实固结, 横波速度抬升幅度大于纵波, 造成井区纵横波速度比持续下降。侵入的地层水沿断裂向工区外围扩散, 周边地层含水饱和度升高, 纵波增速更为明显, 最终导致外围区域纵横波速度比不断增大。油气开发可划分为原始构造应力平衡、纯气开采应力调整、气藏水侵应力重构 3 个阶段, 开采压降与气水流体置换驱动地应力逐步向西迁移, 并在 KS8 井区形成局部应力集中; 地应力演变与岩体压实、裂隙开合、流体运移存在强耦合关系, 共同构成“人工开发—流体演变—岩体压实—应力重分布”的响应机制。研究成果可为该区深层致密气藏高效开发与储层动态评价提供理论依据与技术支撑。

关键词: 拜城凹陷; 油气开发; 震源机制; 地应力场; 动态演化

作者简介: 王斌 (1985—), 男, 副研究员, 主要从事诱发地震及非常规油气藏地质力学研究.E-mail: wangbin@ief.ac.cn

DYNAMIC MONITORING AND EVOLUTION ANALYSIS OF IN-SITU STRESS FIELD IN DEEP TIGHT GAS RESERVOIR DEVELOPMENT ZONES VIA DENSE SEISMIC ARRAY OBSERVATIONS

Wang Bin¹, Zhang Hui^{2,3}, Zuo Kezhen¹, Wang Zhimin^{2,3}, Wang Xin^{2,3}, Wang Xun¹

(1. Institute of Earthquake Forecasting, China Earthquake Administration, Beijing 100036, China ;
2. Petro China Tarim Oilfield Company, CNPC, Korla 841000, Xinjiang, China ; 3. R&D Center for Ultra
Deep Complex Reservoir Exploration and Development, CNPC, Korla 841000, Xinjiang, China)

Abstract: The Baicheng Sag is located in the piedmont compressional structural belt in the northern Tarim Basin. Its deep formations host high-pressure fractured tight sandstone gas reservoirs, where the regional tectonic stress is inherently maintained in a critical equilibrium state. Industrial activities including large-scale hydrocarbon production and subsequent aquifer water influx continuously perturb the virgin in-situ stress field. In this paper, multi-period seismic observation datasets, focal mechanism solutions and seismic wave velocity parameters are integrated with natural seismic stress inversion methods to systematically investigate the dynamic evolution of deep in-situ stress fields throughout the entire hydrocarbon production cycle. The results reveal that seismic activity and formation physical properties including P-wave velocity, S-wave velocity and V_p/V_s ratio vary regularly as production proceeds, and seismic activity generally migrates from east to west. Mechanisms are analyzed in combination with reservoir characteristics and production history: the reservoir is predominantly gas-bearing. Natural gas significantly reduces P-wave velocity while exerting negligible influence on S-wave velocity, which leads to high V_p/V_s anomalies within the original gas-bearing zone. During the mid-to-late production stage, water influx intensifies, and formation water gradually displaces pore natural gas. Meanwhile, reservoir fractures undergo compaction and consolidation under in-situ stress. The increase in S-wave velocity outpaces that of P-wave velocity, resulting in a persistent decline of the V_p/V_s ratio within well blocks. Invading formation water diffuses outward along faults, raising water saturation in surrounding strata. The P-wave velocity rises more prominently in peripheral areas, which ultimately gives rise to an increasing V_p/V_s ratio in these regions. Hydrocarbon production can be divided into three stages: the original tectonic stress equilibrium stage, the stress adjustment stage during dry gas production, and the stress reconstruction stage dominated by reservoir water influx. Production-induced pressure drawdown and gas-water fluid displacement drive the gradual westward migration of in-situ stress, and local stress concentration emerges in the KS8 well block. The evolution of in-situ stress exhibits strong coupling with rock compaction, fracture opening/closing and fluid migration, jointly forming a response mechanism of “human-induced production – fluid evolution – rock matrix compaction – stress redistribution”. The findings provide theoretical basis and technical support for efficient development and dynamic reservoir evaluation of deep tight gas reservoirs in this area.

Key words: Baicheng Depression; Hydrocarbon Development; Focal Mechanism Solution; In-situ stress field; Dynamic evolution

Author Biography: Wang Bin(1985–), Male, Associate Research Fellow, focusing on induced seismicity and geomechanics of unconventional hydrocarbon reservoirs. E-mail: wangbin@ief.ac.cn

乳山震群 PhaseNet 微调模型的震相拾取可解释性分析

王 鹏¹, 戴宗辉², 王庆林², 徐长朋², 郑建常², 孔 雪¹

(1. 山东石油化工学院, 山东 东营 257061; 2. 山东省地震局, 山东 济南 250102)

摘要: 为探讨区域微调后 PhaseNet 震相拾取精度提高的原因, 本文利用山东乳山震群人工震相报告和连续三分量波形, 比较 SeisBench 中初始 PhaseNet 模型与乳山区域微调模型的拾取结果及其所利用的波形信息。微调时随机改变 P 波在 30 s 事件窗中的位置, 并设置 P 波固定于 5 s 的微调模型作为对照, 以检验截窗方式对模型结果的影响。采用积分梯度法计算不同时段波形对 P、S 概率峰的贡献, 分别统计人工到时和模型预测峰附近的贡献比例。结果表明, 在随机位置测试中, 区域微调模型 P、S 平均绝对偏差分别由原始模型的 0.664 s 和 0.488 s 降至 0.248 s 和 0.243 s; 人工到时附近的波形贡献更加集中, P、S 分别提高 0.103 和 0.182。经过多次独立训练、不同随机事件窗以及剔除与训练资料存在时间重叠的记录后, 主要结果仍然保持一致。将模型认为重要的波段替换后, 预测峰下降幅度明显大于替换低贡献值、随机或能量相近的波段, 说明所得结果能够反映模型拾取时实际利用的局部波形。在部分大偏差记录中, 模型预测峰对应相邻事件或其他震相, 表明密集震群中的事件重叠和震相竞争是影响拾取的重要因素。初步结果表明, 乳山区域微调不仅改善了 P、S 到时匹配, 也使 PhaseNet 更多利用目标震相附近的有效波形信息, 积分梯度分析可为密集震群自动拾取结果的解释、人工复核和模型改进提供依据。

关键词: 乳山震群; PhaseNet; 震相拾取; 积分梯度; 区域微调

作者简介: 王鹏 (1983—), 男, 副教授, 主要从事微震检测与定位研究. E-mail: pengwang@sdipct.edu.cn

EXPLAINABILITY ANALYSIS OF PHASE PICKING BY A FINE- TUNED PHASENET MODEL FOR RUSHAN EARTHQUAKE SWARM

Wang Peng¹, Dai Zonghui², Wang Qinglin², Xu Changpeng², Zheng Jianchang², Kong Xu¹

(1. Shandong Institute of Petroleum and Chemical Technology, Dongying 257061, Shandong, China;
2. Shandong Earthquake Agency, Jinan 250102, Shandong, China)

Abstract: To investigate why regional fine-tuning improves PhaseNet phase picking in the Rushan earthquake swarm, we compared the original SeisBench model with a locally fine-tuned model using reviewed phase reports and continuous three-component waveforms. P-wave positions were randomized in 30-s event windows, and integrated gradients identified waveform segments contributing to the predicted P- and S-phase peaks. In randomized-position tests, mean absolute deviations decreased from 0.664 to 0.248 s for P and from 0.488 to 0.243 s for S. The proportion of attribution concentrated near the manual arrivals increased by 0.103 for P and 0.182 for S. Repeated tests and waveform replacement experiments gave consistent results. Some large deviations were linked to neighbouring events or competing phases in the same window. Regional fine-tuning therefore improves both pick accuracy and the use of waveform information near the target phases, supporting the interpretation and review of automatic picks in dense earthquake swarms.

Key words: Rushan earthquake swarm; PhaseNet; Phase picking; Integrated gradients; Regional fine-tuning

Author Biography: Wang Peng (1983–), male, Associate Professor, mainly engaged in research on microseismic event detection and location. E-mail: pengwang@sdipct.edu.cn

阿合奇盆地侧向挤出控制 2024 年 $M_w7.0$ 乌什地震斜向破裂

王晓航^{1,3}, 许才军^{1*}, 江国焰^{2*}, 温扬茂¹, Mahdi Motagh³, 赵雄⁴, 杨九元⁵

贺克锋¹

(1. 武汉大学测绘学院, 湖北 武汉 430074; 2. 武汉大学地球与空间科学技术学院, 湖北 武汉 430074; 3. 德国地球科学研究中心, 波茨坦 14473; 4. 俄克拉荷马大学地球科学学院, 诺曼 73019; 5. 华北水利水电大学测绘与地理信息学院, 河南 郑州 450046)

摘要: 2024 年 $M_w 7.0$ 乌什地震是柯坪塔格褶皱冲断带 (KP.FTB) 有仪器记录以来规模最大的地震事件, 但其发震机制及区域构造控制因素仍有待进一步厘清。本研究基于 Sentinel-1 InSAR 数据和 GNSS 速度场资料, 综合震间、同震和震后形变约束, 解析震源区多阶段运动学特征及其构造意义。研究结果表明, 阿合奇前陆盆地 (AFB) 并非仅表现为局部沉降或边界断裂活动, 而是具有相对完整的构造单元属性, 其震间变形以侧向逃逸与构造沉降的耦合为主要特征。基于这一发现, 我们提出两点新的认识。首先, 乌什地震的斜向破裂受控于阿合奇前陆盆地长期的俯冲式挤出过程, 该过程可能促进了区域应变在盆地边界及邻近断裂系统上的集中。其次, 柯坪塔格褶皱冲断带的沿走向分段不能仅用沉积层厚度变化来解释。其东段构造活动性较弱并非异常现象, 而是反映了区域应变在一定程度上被阿合奇前陆盆地的俯冲式挤出过程所吸收和重新分配。这一认识在一定程度上拓展了以往主要从沉积层厚度变化解释柯坪塔格褶皱冲断带沿走向分段的传统观点, 并为理解南天山前陆地区的构造变形与强震孕育机制提供了新的约束。

关键词: 天山造山带; 乌什地震; 地震危险性; InSAR; GNSS

作者简介: 王晓航 (1992—), 男, 博士后, 主要从事地壳形变与地震预测研究. E-mail: xh_wang@whu.edu.cn

LATERAL EXTRUSION OF THE AHEQI BASIN CONTROLS OBLIQUE RUPTURE OF THE 2024 M_w 7.0 WUSHI EARTHQUAKE

Wang Xiaohang^{1,3}, Xu Caijun¹, Jiang Guoyan², Wen Yangmao¹, Mahdi Motagh³, Zhao Xiong⁴, Yang Jiuyuan⁵, He Kefeng¹

(1. School of Geodesy and Geomatics, Wuhan University, Wuhan 430074, Hubei, China; 2. School of Earth and Space Science and Technology, Wuhan University, Wuhan 430074, Hubei, China; 3. GFZ Helmholtz Centre for Geosciences, Potsdam 14473, Germany; 4. School of Geosciences, University of Oklahoma, Norman 73019, USA; 5. College of Surveying and Geo-Informatics, North China University of Water Resources and Electric Power, Zhengzhou 450046, Henan, China)

Abstract: The 2024 M_w 7.0 Wushi earthquake was the largest instrumentally recorded event within the Kepingtage fold-and-thrust belt (KP.FTB), yet its seismogenic mechanism and regional tectonic controls remain unclear. Based on Sentinel-1 InSAR observations and GNSS velocity fields, this study integrates interseismic, coseismic, and postseismic deformation constraints to investigate the multi-stage kinematics and tectonic implications of the source region. Our results show that the Aheqi Foreland Basin (AFB) does not merely exhibit localized subsidence or boundary fault activity, but behaves as a relatively coherent tectonic unit. Its interseismic deformation is characterized by coupled lateral extrusion and tectonic subsidence. Based on this finding, two new insights are proposed. First, the oblique rupture of the Wushi earthquake was controlled by the long-term plunging extrusion of the AFB, which may have promoted strain concentration along the basin margins and adjacent fault systems. Second, the along-strike segmentation of the KP.FTB cannot be explained solely by variations in sediment thickness. The relatively low tectonic activity of its eastern segment is not anomalous, but instead reflects regional strain being partly absorbed and redistributed by the plunging extrusion of the AFB. This interpretation extends the traditional view that mainly attributes the along-strike segmentation of the KP.FTB to sediment-thickness variations, and provides new constraints for understanding tectonic deformation and strong-earthquake generation in the foreland region of the Southern Tianshan.

Key words: Tianshan Orogenic Belt; Wushi Earthquake; Seismic Hazard; InSAR; GNSS

基于多种资料联合反演微小地震震源机制解 及其可靠性评估

杨 选¹, 林向东², 袁怀玉^{3,4}, 赵 亮⁴, 孙海霞², 姜喜姣¹, 谭争光¹

(1.广东省地震局, 广东 广州 510070; 2.北京市地震局, 北京 100080; 3.Geological Survey of Western Australia, East Perth, Western Australia Australia 6004; 4.中国科学院地质与地球物理研究所岩石圈演化国家重点实验室, 北京 100029)

摘要: 随着预警项目的建设, 中国地震台网原有和大量新建的测震台(基准站, 速度记录)、强震台(基本站, 加速度记录)和放于地面简易烈度计站(一般站, 加速度记录), 以及高频采样的大地测量观测站(GNSS等, 位移记录)记录了大量的数据, 密集的观测站网能记录大量较小地震资料, 如何利用这些观测资料约束求解获得可靠的微小地震震源机制解并对其可靠性进行评估, 是极有意义且具挑战的科学问题。计算微小地震震源机制解较为可行的方法主要有利用初动、振幅比、或者初动结合振幅比的方法, 这些方法受到台站方位分布, 数据信噪比, 震源位置、速度模型等因素的影响。在充分考虑这些影响因素的前提下, 结合方法的优势, 充分联合利用观测得到的多种资料, 利用 FOCMEC 方法开展震源机制计算, 并基于站网布局、最小空间旋转角、P 波清晰程度分布和初动矛盾比等指标提出了震源机制解可靠性评估的新方法。通过实际算例研究, 结果表明: 强震台记录的初动和振幅可以用于震源机制计算补充资料, 放于地面的简易烈度计的台记录的资料由于信噪比的原因对于震级较大地震 ($M \geq 4.5$) 30 km 内相对可用, 高频采样的大地测量资料也具有应用的前景; 在资料不是很充分的情况下, 利用初动结合振幅比相对比单独用初动或振幅计算震源机制的约束性高; 与波形反演得到的震源机制结果对比显示, 最小空间旋转角或 P 波清晰程度分布校验概率均能描述节面的不确定性, 可用于评估震源机制解的精度, 利用本文的方案优选出的最优解具有较高的合理性和可靠性。

作者简介: 林向东 (1981—), 男, 正高级工程师, 主要从事地震观测技术、震源机制与构造应力场研究。
E-mail: lxdongd@hotmail.com

强震记录低通截止频率的谱形自动识别方法

袁阳涛^{1,2}, 谢志南^{1,2}

(1. 中国地震局工程力学研究所地震工程与工程振动重点实验室, 黑龙江 哈尔滨 150080; 2. 地震灾害防治应急管理部重点实验室, 黑龙江 哈尔滨 150080)

摘要: 强震记录低通截止频率 (LPCF) 控制高频可用谱带, 是强震数据处理、傅里叶幅值谱 (FAS) 数据库建设和有效幅值谱 (EAS) 地震动模型构建中的关键参数。现有 LPCF 通常采用信噪比阈值或 FAS 谱形目视判别确定。信噪比方法流程清晰, 便于批量处理, 但依赖足够长且具有代表性的事前噪声窗, 并受信号窗划分和噪声非平稳性的影响, 难以稳定处理触发较晚或事前段缺失的丢头记录。FAS 谱形判别可直接检查高频谱尾是否由合理衰减转入噪声平台, 更贴近 FAS/EAS 数据产品的质量控制目标, 但人工判别效率低、主观性强、可重复性不足。本文提出一种自动 FAS-LPCF 识别方法, 通过 Konno-Ohmachi 平滑、对数谱斜率计算、主下降段及显著下降段识别, 自动确定噪声平台出现前的高频可用上限。对于缺少事前段的记录, 传统 SNR 阈值难以给出稳定判别, 而谱形斜率仍可利用主震动后的高频衰减信息形成约束。因此, 该方法既保留了人工谱形判别的物理含义, 又降低了批量处理中的人工成本。基于 3 746 条汶川强震单分量记录的验证表明, 当平滑因子 $b=5$ 时, 自动结果与 PEER 参考 LPCF 最一致, 3 482 条记录 (93.0%) 位于二倍误差带内; 完整记录和丢头记录的带内比例分别为 93.9% 和 92.4%, 说明该方法对不同触发条件具有较好的适用性。进一步对比显示, 不同 LPCF 方法对 PGA、PGV、PGD、Arias 强度、CAV 和显著持时等常规标量参数影响较小, 但会明显改变高频 FAS/EAS 谱尾。本文方法不依赖事前噪声窗, 能够提高 LPCF 判别的一致性和可复现性, 可为强震 FAS/EAS 数据库建设及 Fourier-domain 地震动模型提供高频谱形质量控制工具。

关键词: 低通截止频率; 傅里叶幅值谱; 有效幅值谱; 自动识别; 强震记录

作者简介: 袁阳涛 (1998—), 男, 博士研究生, 主要从事地震动模拟与预测研究. E-mail: yyt_get@qq.com

SPECTRAL-SHAPE-BASED AUTOMATIC IDENTIFICATION OF LOW-PASS CORNER FREQUENCY IN STRONG-MOTION RECORDS

Yuan Yangtao^{1,2}, Xie Zhinan^{1,2}

(1. Key Laboratory of Earthquake Engineering and Engineering Vibration, Institute of Engineering Mechanics, China Earthquake Administration, Harbin 150080, China; 2. Key Laboratory of Earthquake Disaster Mitigation, Ministry of Emergency Management, Harbin 150080, China)

Abstract: The low-pass corner frequency (LPCF) defines the usable high-frequency band of strong-motion records and is important for FAS/EAS databases. LPCFs are often selected by SNR thresholds or visual inspection of Fourier amplitude spectrum (FAS) shape. SNR is easy to automate but requires representative pre-event noise, whereas FAS inspection identifies the transition from physical decay to a noise plateau but is subjective. We propose an automatic FAS-LPCF method using Konno-Ohmachi smoothing, logarithmic spectral slope, and main/significant decay segments. Tests on 3746 Wenchuan single-component records show that $b=5$ best agrees with PEER reference LPCFs; 3482 records (93.0%) fall within a factor-of-two range. The method works for complete and pre-event-missing records. Different LPCFs weakly affect conventional scalar measures but clearly affect high-frequency FAS/EAS tails. It provides a reproducible quality-control tool for Fourier-domain ground-motion data products.

Key words: Low-pass corner frequency; Fourier amplitude spectrum; Effective amplitude spectrum; Automatic identification; Strong-motion records

花莲 M_w 7.4 地震事件对区域重力信号频段特性的影响

张晓彤¹, 王乐行², 江 颖¹

(1.中国地震局地震研究所, 湖北 武汉 430071; 2.中国科学院精密测量科学与技术创新研究院, 湖北 武汉 430071)

摘要: gPhone 重力仪是一种高精度弹簧重力仪, 具有较高的时间分辨率和良好的连续观测能力, 已在多次中强震事件中记录到显著的地震相关重力信号, 现有研究主要关注同震重力信号的时域特征或个别频段响应, 而针对不同频率范围内重力信号特性的系统对比分析仍相对较少, 尤其是在区域尺度台网条件下, 不同台站之间重力信号频段特征的空间差异尚缺乏充分讨论。为明确 2024 年花莲 M_w 7.4 地震前后重力信号的频段特性, 本文利用福建省境内 6 台 gPhone 重力仪观测数据, 选取地震发生前 48h 和震后 24h 的重力观测数据, 并结合 20 天背景数据作为背景参考, 通过固体潮改正、大气效应校正及带通滤波等预处理手段, 并采用 Welch 方法计算功率谱密度和振幅谱密度, 在 1~100 mHz 频段内对地震前后重力信号进行对比分析, 并进一步将研究频段划分为 1~3 mHz、3~30 mHz 和 30~100 mHz 3 个子频段, 分别统计同震与背景时段的频段能量变化特征。结果表明, 花莲 M_w 7.4 地震在区域连续重力观测中引起了可识别的频谱能量增强现象, 不同频段内的能量增强幅度及其空间一致性存在明显差异, 其中低频段能量增强幅度较大但台站间离散性较强, 高频段能量增强幅度相对较小但一致性较好。频段能量变化与震中距之间未呈现稳定的单调关系, 台站背景噪声水平及观测环境差异对结果具有重要影响。

关键词: 花莲地震; 连续重力; 重力信号; 频谱分析

作者简介: 张晓彤 (1990—), 女, 助理研究员, 主要从事连续重力数据处理.E-mail: 386741838@qq.com

INFLUENCE OF HUALIEN M_w 7.4 EARTHQUAKE EVENT ON THE FREQUENCY-BAND CHARACTERISTICS OF REGIONAL GRAVITY SIGNALS

Zhang Xiaotong¹, Wang Lexing², Jiang Ying¹

(1. Institute of Seismology, China Earthquake Administration, Wuhan 430071, Hubei, China; 2. Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences, Wuhan 430071, Hubei, China)

Abstract: The gPhone gravimeter is a high-precision spring gravimeter characterized by high temporal resolution and good continuous observation capability. It has recorded significant earthquake-related gravity signals during multiple moderate-to-strong seismic events. Existing studies have mainly focused on the time-domain characteristics of coseismic gravity signals or responses within individual frequency bands. However, systematic comparative analyses of gravity signal characteristics across different frequency ranges remain relatively scarce. In particular, under regional-scale network conditions, the spatial differences in frequency-band characteristics of gravity signals among different stations have not been sufficiently discussed. To clarify the frequency-band characteristics of gravity signals before and after the 2024 Hualien M_w 7.4 earthquake, this study utilizes observation data from six gPhone gravimeters in Fujian Province, China. Gravity data from 48 hours before and 24 hours after the earthquake are selected, together with 20 days of background data as a reference. After preprocessing steps including solid-tide correction, atmospheric effect correction, and band-pass filtering, the Welch method is employed to compute power spectral density and amplitude spectral density. The gravity signals before and after the earthquake are comparatively analyzed within the 1 – 100 mHz frequency band. The study frequency band is further divided into three sub-bands: 1 – 3 mHz, 3 – 30 mHz, and 30 – 100 mHz, and the energy variation characteristics of the co-seismic and background periods are statistically analyzed for each sub-band. The results show that the Hualien M_w 7.4 earthquake induced identifiable spectral energy enhancement in regional continuous gravity observations. The amplitude of energy enhancement and its spatial consistency vary significantly across different frequency bands: the energy enhancement in the low-frequency band is relatively large but exhibits strong inter-station discreteness, whereas the energy enhancement in the high-frequency band is relatively small but shows better consistency.

Key words: Hualien M_w 7.4 earthquake; Continuous gravity; Gravity signals; Spectrum analysis

Author Biography: Xiaotong Zhang (1990–), Female, Assistant Research Fellow, mainly engaged in research on processing of continuous gravity data. E-mail: 386741838@qq.com

DEVELOPMENT OF V_{S30} MODEL AND MAPPING BASED ON SITE MEASUREMENTS IN MAINLAND CHINA

Zhou Jian¹, Li Li¹, Xu Guangyin¹, Chen Kun¹, Xi Nan², Tian Xin¹, Li Xiaojun³

(1. Institute of Geophysics, China Earthquake Administration, Beijing 100081, China

2.China Earthquake Network Center, Beijing 100045, China

3.Key Laboratory of Urban Security and Disaster Engineering of China Ministry of Education,
Beijing University of Technology, Beijing 100124, China)

Abstract: V_{S30} , the time-averaged shear-wave velocity in the upper 30 m, is widely used to characterize seismic site conditions in ground-motion modeling, seismic hazard and risk assessment, and seismic zonation. Over the past several decades, extensive engineering construction and seismic microzonation projects in China have generated a large amount of site investigation data. However, much of this information has remained scattered in engineering reports and archives and has not been fully utilized for regional-scale site characterization.

In our work, more than 14,000 V_{S30} measurements from engineering boreholes and strong-motion stations across mainland China have been digitized and organized to support the development of measurement-based V_{S30} models and maps. In 2022, we developed the topographic Slope-based CoKriging (SCK) model, which integrates measured V_{S30} values with topographic slope through their spatial auto- and cross-correlations. Unlike conventional proxy models based solely on empirical regression, the SCK framework explicitly considers the spatial correlation of site conditions and preserves measured V_{S30} values as constraints.

The SCK model was subsequently refined by incorporating the surrounding topographic environment, improving the spatial distribution of selected neighboring measurements, and extending the effective modeling distance. Using 7,939 V_{S30} measurements, including data from strong-motion stations in data-sparse regions, we produced an updated V_{S30} map for mainland China at 30 arcsec resolution (~900 m). Comparison with the USGS global V_{S30} mosaic indicates generally consistent estimates in the eastern plains, while notable differences occur in mountainous and basin regions. The SCK map better reflects regional terrain and geological characteristics and avoids artificial boundaries associated with categorical proxy models.

Our ongoing developments further incorporate geological age and depositional environment as additional site-condition proxies. Particular attention is given to preferential sampling bias, because engineering measurements tend to overrepresent accessible flat terrain. A secondary-variable-based debiasing approach has therefore been developed to improve the representativeness of V_{S30} statistics. Together, these efforts establish an evolving, measurement-constrained framework for regional and national-scale site-condition modeling and provide a basis for improved seismic hazard assessment, ShakeMap applications, and seismic microzonation.

Key words: V_{S30} ; site condition; cokriging; topographic slope; site measurements; preferential sampling; mainland China

EXPLORING TOPOGRAPHIC SLOPE-BASED PROXIES FOR V_{S30} ESTIMATION IN VOLCANIC TERRAINS USING ARMENIAN V_{S30} MEASUREMENTS: A V_{S30} MAP FOR ARMENIA

Zhou Jian¹, Jon Karapetyan², Li Li¹, Wang Yongzhe¹, Wang Chao¹, Tian Xin¹, Sargis Hayroyan², Roza Karapetyan²

(1. Institute of Geophysics, China Earthquake Administration, Beijing 100081, China; 2. Nazarov Institute of Geophysics and Engineering Seismology, Ministry of Education, Science, Culture and Sport of the Republic of Armenia, Gyumri 3115, Armenia)

Abstract: In ground-motion prediction equations (GMPEs) and other earthquake engineering researches, V_{S30} (the averaged shear-wave velocity of soil to 30 m depth) is acted as the primary site condition parameter affecting ground motion amplification. For regional mapping of V_{S30} , topographic slope is widely employed as a proxy because it is readily available and straightforward to implement; for example, the USGS ShakeMap system is supported by a slope-based V_{S30} map, and many countries have adopted similar approaches in developing national V_{S30} products. However, slope- V_{S30} correlations derived largely from sedimentary terrains may not be transferable to volcanic regions, and volcanic-specific relationships remain insufficiently studied.

In this study, we use 250 in situ V_{S30} measurements from Armenia to investigate the slope- V_{S30} relationship in volcanic terrain. We find that, within volcanic regions, V_{S30} exhibits a negative correlation with topographic slope, opposite to the commonly observed pattern in non-volcanic regions, where steeper slopes are typically associated with stiffer sites. We further evaluate this behaviour using independent data from volcanic areas in Hainan, China, and observe a similar tendency, suggesting that the negative slope- V_{S30} relationship may reflect a broader characteristic of volcanic terrains rather than a phenomenon unique to Armenia. Using the empirically derived slope- V_{S30} spatial statistics, we develop slope-based cokriging models (SCK) for Armenia and map V_{S30} across Armenia by modelling volcanic and non-volcanic regions separately. The resulting map indicates generally high V_{S30} values, dominated by ~ 450 -900 m/s, consistent with the widespread distribution of volcanic rocks. In contrast, the USGS global mosaic V_{S30} product used in ShakeMap, without volcanic-specific treatment, shows substantial underestimation in Armenia, particularly in capital Yerevan.

This study provides a systematic assessment of volcanic-terrain slope- V_{S30} behaviour and delivers the first Armenia-wide V_{S30} map constrained by local site measurements. The map supports GMPE development, seismic-hazard assessment, and risk applications in Armenia. The prevalence of high V_{S30} values also suggests that existing site-classification schemes emphasizing low- V_{S30} thresholds may not suit to distinguishing site-condition variability in Armenia. More broadly, the pronounced contrast between volcanic and non-volcanic slope- V_{S30} relationships highlights the need to update global slope-based V_{S30} models in regions with extensive volcanic coverage. We expect this work to serve as a starting point for more sophisticated research of V_{S30} modelling for volcanic terrains.

Key words: V_{S30} ; Site Condition; Map; Topographic Slope; Volcanic Terrain; Armenia

EXPERIMENTAL EVALUATION OF METHODS FOR IMPROVING THE SEISMIC RESISTANCE OF BUILDING AND CIVIL ENGINEERING MODELS

Nataliya Surovtseva^{1,2}, Tanatkan Abakanov²

(1. National Scientific Center for Seismological Observations and Research, Almaty, Kazakhstan; 2. International Educational Corporation, Almaty, Kazakhstan)

Abstract: Experimental studies are among the most reliable methods for measuring the dynamic response of buildings and structures to seismic loading. The present study aimed to experimentally assess the effectiveness of various seismic strengthening techniques applied to small-scale models of a soil slope, an earth dam, and a single-story building. The experiments were carried out using a seismic shaking table developed by the authors at the International Educational Corporation. The shaking table tests demonstrated that reinforcing the soil slope with stabilizing piles connected by beams significantly improved its resistance to dynamic loading. The reinforced slope remained stable under excitation frequencies of up to 8 Hz, whereas the unreinforced model exhibited progressive deformation and slope failure at considerably lower loading levels. Experimental investigations of earth dam models confirmed the dominant influence of water saturation on seismic performance. Failure of the saturated dam model occurred at ground accelerations of 70–90 cm/s², whereas the dry model withstood accelerations of 430–480 cm/s² before failure. Reinforcement of the upstream slope using polymer-based strengthening elements substantially enhanced the seismic stability of the model and increased its capacity to withstand dynamic excitation. The shaking table tests of the single-story building model demonstrated the effectiveness of geogrid reinforcement of the foundation soil. Following reinforcement, foundation settlement decreased from 9 mm to 5 mm. Analysis of the recorded accelerograms revealed improved dynamic performance of the soil–structure system under simulated seismic loading. The experimental findings are consistent with previously published shaking table investigations on reinforced slopes and embankment dams, confirming the effectiveness of engineering reinforcement techniques for improving the seismic performance of soil foundations, slopes, and earth structure. The proposed experimental approach and obtained results can be applied to the design, rehabilitation, and seismic upgrading of buildings and geotechnical structures located in earthquake-prone regions of Kazakhstan.

ЭКСПЕРИМЕНТАЛЬНАЯ ОЦЕНКА МЕТОДОВ ПОВЫШЕНИЯ СЕЙСМОСТОЙКОСТИ МОДЕЛЕЙ ЗДАНИЙ И СООРУЖЕНИЙ

Н.В. Суровцева^{1,2}, Т.Д. Абаканов²

(1.Национальный научный центр сейсмологических наблюдений и исследований, г. Алматы, Казахстан; 2.Международная образовательная корпорация, г. Алматы, Казахстан)

Экспериментальные исследования являются одним из наиболее достоверных методов оценки динамической реакции зданий и сооружений на сейсмические воздействия. Целью настоящей работы являлась экспериментальная оценка эффективности различных способов повышения сейсмостойкости маломасштабных моделей грунтового откоса, земляной плотины и одноэтажного здания. Испытания проводились с использованием сейсмоплатформы, разработанной авторами в Международной образовательной корпорации [1]. Испытания на сейсмоплатформе показали, что армирование грунтового откоса стабилизирующими сваями, объединенными ростверчковыми балками, существенно повышает его устойчивость к динамическим воздействиям. Армированный откос сохранял устойчивость при частотах возбуждения до 8 Гц, тогда как неармированная модель испытывала прогрессирующие деформации и разрушалась при значительно меньших уровнях динамической нагрузки. Экспериментальные исследования моделей земляной плотины подтвердили определяющее влияние водонасыщения на сейсмическую устойчивость сооружения. Разрушение водонасыщенной модели происходило при ускорениях основания 70–90 см/с², тогда как сухая модель сохраняла устойчивость вплоть до ускорений 430–480 см/с². Усиление верхового откоса полимерными армирующими элементами существенно повысило сейсмическую устойчивость модели и ее способность воспринимать интенсивные динамические воздействия. Испытания модели одноэтажного здания на сейсмоплатформе подтвердили эффективность армирования грунтового основания георешеткой. После усиления осадка основания уменьшилась с 9 до 5 мм. Анализ зарегистрированных акселерограмм показал улучшение динамических характеристик системы «основание–сооружение» при моделировании сейсмических воздействий.

Полученные экспериментальные результаты согласуются с опубликованными исследованиями, выполненными на сейсмоплатформах для армированных откосов и земляных плотин, подтверждая эффективность инженерных методов усиления, направленных на повышение сейсмостойкости грунтовых оснований, откосов и земляных сооружений [2–4]. Предложенный экспериментальный подход и полученные результаты могут быть использованы при проектировании, реконструкции и сейсмическом усилении зданий, сооружений и геотехнических объектов, расположенных в сейсмоопасных районах Казахстана.

PRACTICAL EXPERIENCE IN SEISMIC RISK REDUCTION: THE CASE OF THE KAPCHAGAY HYDROPOWER PLANT IN KAZAKHSTAN

Nataliya Surovtseva^{1,2}, Tanatkan Abakanov², Gennadiy Nigmatov³, Oleg Beloslyudtsev¹,
Zauresh Sailaubayeva¹, Perizat Kilanbekova¹

(1. National Scientific Center for Seismological Observations and Research, Almaty, Kazakhstan; 2. International Educational Corporation, Almaty, Kazakhstan; 3. All-Russian Scientific Research Institute for Civil Defense and Emergencies, Moscow, Russian Federation)

Abstract: The Kapchagay Hydropower Plant (HPP), one of the largest hydraulic structures in Kazakhstan, is located in a seismically active region. This study was conducted after an abnormal drop in the water level in the Kapchagay Reservoir was discovered during its operation. A comprehensive investigation was conducted to identify the causes of water losses and assess the operational and seismic safety of the facility. The program included seismic hazard assessment, synthetic accelerogram generation, seismic risk modeling, vertical electrical sounding (VES), underwater inspections, and stability analyses of the riverbed and saddle dams. Based on geological, geophysical, and seismotectonic data, the characteristics of potentially hazardous seismogenic zones were refined, and design seismic loading scenarios were developed. The results showed that the Zailiysky seismogenic zone represents the most critical seismic source for the site, producing a peak ground acceleration of 205 cm/s², corresponding to an intensity of 8 points on the MSK-64 scale. Stability analyses confirmed that both dams satisfy the safety requirements for Class II hydraulic structures at the recommended normal retaining water level of 479 m. VES investigations identified seepage-related anomalies, which were subsequently confirmed through underwater inspections. Pressure grouting of the weakened zone eliminated abnormal water losses and improved the reliability of the hydraulic structures. The study demonstrates the effectiveness of integrating seismic hazard assessment, risk analysis, geophysical diagnostics, underwater inspections, and engineering remediation within a unified framework for hydraulic structure safety management. The scientific significance of this study lies in the development and validation of an integrated methodology for evaluating the seismic safety and technical condition of hydraulic structures located in seismically active regions. The novelty of the proposed approach is the combined application of seismic hazard assessment, synthetic ground-motion modeling, individual seismic risk analysis, geophysical investigations, and underwater inspection to solve a single engineering problem. The consistency of these independent methods enabled reliable identification and verification of a hidden seepage zone and supported the selection of effective remediation measures. The proposed methodology can be applied to improve the safety assessment and management of earth dams and other hydraulic structures in seismic regions.

Key words: Seismic Risk; Hydraulic Structure; Synthetic Accelerograms; GIS-based system "Extremum"; Vertical electrical Sounding; Injection Cementing

ПРАКТИЧЕСКИЙ ОПЫТ СНИЖЕНИЯ СЕЙСМИЧЕСКОГО РИСКА НА ПРИМЕРЕ КАПЧАГАЙСКОЙ ГЭС В КАЗАХСТАНЕ

Н.В. Суровцева^{1,2}, Т.Д. Абаканов², Г.М. Нигметов³, О.В. Белослюдцев¹,
З.А. Сайлаубаева¹, П.А. Киранбекова¹

¹ Национальный центр сейсмологических наблюдений и исследований, Алматы, Казахстан;

² Международная образовательная корпорация, Алматы, Казахстан.

³ Всероссийский научно-исследовательский институт по проблемам гражданской обороны и чрезвычайных ситуаций, Москва, Российская Федерация

Аннотация. Капчагайская гидроэлектростанция (ГЭС), являющаяся одним из крупнейших гидротехнических сооружений Казахстана, расположена в сейсмически активном регионе. Настоящее исследование было выполнено после выявления в процессе эксплуатации аномального снижения уровня воды в Капчагайском водохранилище. Для установления причин потерь воды и оценки эксплуатационной и сейсмической безопасности объекта была реализована комплексная программа исследований. Она включала оценку сейсмической опасности, построение синтетических акселерограмм, моделирование сейсмического риска, вертикальное электрическое зондирование (ВЭЗ), подводные обследования, а также расчеты устойчивости русловой и логовой плотин. На основе геологических, геофизических и сейсмотектонических данных были уточнены характеристики потенциально опасных сейсмогенных зон и разработаны расчетные сценарии сейсмического воздействия. Установлено, что наиболее опасным сейсмическим источником для рассматриваемого объекта является Заилийская сейсмогенерирующая зона, способная генерировать максимальное ускорение грунта 205 см/с^2 , что соответствует интенсивности сейсмического воздействия 8 баллов по шкале MSK-64. Расчеты устойчивости подтвердили, что обе плотины удовлетворяют требованиям безопасности, предъявляемым к гидротехническим сооружениям II класса, при рекомендуемом нормальном подпорном уровне 479 м. Исследования методом ВЭЗ позволили выявить аномальные зоны, связанные с фильтрацией воды, наличие которых впоследствии было подтверждено результатами подводного обследования. Инъекционное цементирование ослабленного участка обеспечило устранение аномальных потерь воды и повышение надежности гидротехнических сооружений. Научная значимость исследования заключается в разработке и апробации комплексной методики оценки сейсмической безопасности и технического состояния гидротехнических сооружений, расположенных в сейсмически активных районах. Новизна предложенного подхода состоит в совместном применении методов оценки сейсмической опасности, моделирования синтетических сейсмических воздействий, анализа индивидуального сейсмического риска, геофизических исследований и подводного обследования для решения единой инженерной задачи. Согласованность результатов, полученных независимыми методами, позволила достоверно выявить и подтвердить наличие скрытой зоны фильтрации, а также обосновать выбор эффективных восстановительных мероприятий. Предложенная методика может быть использована для совершенствования оценки безопасности и управления техническим состоянием земляных плотин и других гидротехнических сооружений, эксплуатируемых в сейсмических районах.

Ключевые слова: сейсмический риск, гидротехническое сооружение, синтетические акселерограммы, геоинформационная система «Экстремум», вертикальное электрическое зондирование, инъекционное цементирование.

Исследование сейсмического риска по результатам паспортизации жилого фонда города Алматы

V A LapinE S¹, Aldakhov², S K Sazanbayev¹, K A Turekulova¹, A F Ramazanov¹

Абстракт: Впервые в городе Алматы выполнена полная паспортизация многоквартирного жилого фонда, в рамках которой обследовано свыше 10 тыс. зданий. Определена структура жилого фонда с выделением групп зданий по конструктивным схемам, выполнена оценка их сейсмостойкости и эксплуатационной надежности.

По результатам паспортизации впервые получены количественные оценки вероятности отказа для различных конструктивных типов зданий и разработаны расчетные зависимости для определения сейсмического риска. При расчетах использованы данные карт общего сейсмического зонирования Республики Казахстан.

Проведена оценка сейсмической уязвимости зданий на основе их классификации в соответствии с Европейской макросейсмической шкалой EMS-98. Дополнительно выполнена оценка ожидаемой повреждаемости по сейсмической шкале MSK-64(K), применяемой в Республике Казахстан. Характеристики ущерба в рамках шкалы MSK-64(K) определены с использованием соотношений, предложенных профессором Хакимовым.

Выполнено сопоставление результатов, полученных по обоим методикам.

Определено количество многоэтажных жилых зданий различных конструктивных типов, расположенных в зонах тектонических разломов. На основе статистических данных о последствиях сильных землетрясений, произошедших в различных странах мира, выполнена оценка возможного числа погибших при расчетном землетрясении в городе Алматы.

Получена интегральная оценка надежности (вероятности безотказной работы) многоэтажного жилого фонда города Алматы. Показано, что снос несейсмостойких деревянных зданий позволяет повысить общую надежность многоэтажного жилого фонда почти на 15 %.

Установлено, что наибольшей сейсмической опасностью характеризуются здания с наружными несущими стенами и внутренним каркасом; здания с несущими стенами из кирпичной кладки и сборными железобетонными перекрытиями; двух- и более этажные здания с несущими стенами из кирпичной кладки и деревянными перекрытиями; одноэтажные здания с несущими стенами из кирпичной кладки и деревянными балочными перекрытиями при нормальном сцеплении кладки менее 120 кПа (1,2 кгс/см²), а также деревянные здания постройки 1950-х годов, возведенные без учета антисейсмических требований.

Результаты исследований, выполненных с использованием шкал сейсмической интенсивности EMS-98 и MSK-64(K), показали, что наименьшую степень повреждаемости имеют здания со стальным каркасом.

Полученные результаты количественной оценки сейсмического риска могут быть использованы при разработке схем рационального использования территорий, градостроительном планировании, экономической оценке городских земель, а также для информационного обеспечения работ, связанных с оценкой сейсмической опасности и снижением сейсмического риска в городской среде.

Ключевые слова: паспортизация зданий, сейсмический риск, надежность, вероятность безотказной работы, сейсмическая уязвимость, повреждаемость, повторяемость землетрясений, тектонические разломы.

SEISMIC RISK ASSESSMENT BASED ON THE BUILDING INVENTORY OF THE RESIDENTIAL HOUSING STOCK IN ALMATY

V A Lapin¹, Aldakhov², S K Sazanbayev¹, K A Turekulova¹, A F Ramazanov¹

Abstract: For the first time, a comprehensive building inventory of the multi-apartment residential housing stock in the city of Almaty has been carried out, covering more than 10,000 buildings. The structural composition of the residential building stock was determined by classifying buildings according to their structural systems, and their seismic resistance and structural reliability were evaluated. Based on the inventory results, quantitative estimates of the probability of failure were obtained for various structural building types for the first time, and analytical relationships were developed for quantitative seismic risk assessment. The calculations were performed using data from the General Seismic Zoning Maps of the Republic of Kazakhstan. The seismic vulnerability of buildings was assessed based on their classification according to the European Macroseismic Scale (EMS-98). In addition, the expected level of building damage was evaluated using the MSK-64(K) seismic intensity scale adopted in the Republic of Kazakhstan. Damage characteristics within the MSK-64(K) framework were determined using the empirical relationships proposed by Professor Khakimov. A comparative analysis of the results obtained using the two methodologies was performed. The number of multi-storey residential buildings of different structural types located within tectonic fault zones was determined. Based on statistical data from the consequences of major earthquakes in different countries, the potential number of fatalities resulting from a scenario earthquake in the city of Almaty was estimated. An integrated assessment of the reliability (probability of failure-free performance) of the multi-storey residential building stock in Almaty was obtained. The results demonstrate that demolition of seismically deficient wooden buildings would increase the overall reliability of the city's multi-storey residential building stock by nearly 15%. It was found that the highest seismic risk is associated with buildings having exterior load-bearing walls and an internal frame; buildings with masonry load-bearing walls and precast reinforced concrete floor systems; two-storey and taller buildings with masonry load-bearing walls and timber floor systems; single-storey buildings with masonry load-bearing walls and timber beam floors where the normal masonry bond strength is less than 120 kPa (1.2 kgf/cm²); and timber buildings constructed in the 1950s without seismic-resistant design provisions. The results obtained using the EMS-98 and MSK-64(K) seismic intensity scales indicate that steel-frame buildings exhibit the lowest level of expected seismic damage. The quantitative seismic risk assessment results can be used for land-use planning, urban development, economic evaluation of urban areas, and decision support for seismic hazard assessment and seismic risk mitigation in the urban environment.

Key words: building inventory, seismic risk, structural reliability, probability of failure-free performance, seismic vulnerability, building damage, earthquake recurrence, tectonic faults.

INFRASTRUCTURE, ADVANCED LABORATORIES, AND GEOSPATIAL CAPABILITIES OF İTÜ-MATAM (TÜRKİYE) FOR EARTHQUAKE HAZARD AND RISK ASSESSMENT

Yaltırak C^{1,2}, Zabcı C^{1,2}, Tarı U^{1,2}, Sunal G^{1,2}, Özcan O^{1,3}, Eriş K K^{2,4}, Uçarkuş G^{2,4},
Elitez İ^{1,5}, Akyüz H S^{1,2}, Yağcı H B^{1,6}, Sançar T⁷, Acar D^{4,1}, Alan H¹, Kıray Canik H
N¹, Geyik M¹, Gültekin D İ¹, Tülümen E B¹, Aksu A E⁸

(1. İstanbul Teknik Üniversitesi Türkiye İş Bankası Marmara Aktif Fay Tehlike ve Risk Uygulama ve Araştırma Merkezi (MATAM), 34467 Sarıyer, İstanbul, Türkiye, 2. İstanbul Teknik Üniversitesi, Maden Fakültesi, Jeoloji Mühendisliği Bölümü, 34467 Sarıyer, İstanbul, Türkiye, 3. İstanbul Teknik Üniversitesi, Avrasya Yer Bilimleri Enstitüsü, 34467 Sarıyer, İstanbul Türkiye, 4. İstanbul Teknik Üniversitesi, Doğu Akdeniz Oşinografi ve Limnoloji Uygulama ve Araştırma Merkezi (EMCOL), 34467 Sarıyer, İstanbul Türkiye, 5. İstanbul Teknik Üniversitesi, Maden Fakültesi, Jeofizik Mühendisliği Bölümü, 34467 Sarıyer, İstanbul, Türkiye, 6. İstanbul Teknik Üniversitesi, Elektronik ve Haberleşme Mühendisliği Bölümü, 34467 Sarıyer İstanbul, Türkiye, 7. Munzur Üniversitesi, Coğrafya Bölümü 62000 Aktuluk, Tunceli Türkiye, 8. Memorial University of New Foundland Dept Earth Sciences, NF Kanada)

Abstract: Established in 2024 through Istanbul Technical University and Türkiye İş Bankası collaboration, İTÜ-MATAM (İstanbul Technical University, T. İş Bankası Marmara Active Fault Hazard and Risk Application and Research Centre) serves as a premier research centre advancing earthquake hazard and risk assessment. To overcome the limitations of classical active fault mapping, MATAM integrates cutting-edge infrastructure spanning multidisciplinary domains. Its advanced capabilities include dedicated Mineral Preparation, OSL Dating, Stable Isotope, and ICP/MS laboratories, alongside a marine geology/geophysics facility established via EMCOL cooperation housing ITRAX and MSCL instruments. Furthermore, terrestrial mapping utilizes LiDAR-equipped JOUAV CW 15-II VTOL systems for sub-meter data, while high-performance computing centres drive seismic scenario modelling. Complemented by custom-designed, low-cost accelerometers forming an independent local network, MATAM establishes a rigorous empirical and computational framework for comprehensive earthquake research.

Key words: Active fault mapping; Research centre infrastructure; OSL dating; UAV-LiDAR; HPC; Seismic Hazard and Assessment

Author Biography: Zabcı C (1976–), Male, Associate Professor, mainly engaged in research on earthquake geology and neotectonics. E-mail: zabcı@itu.edu.tr

基于大数据下的人员安全避难情况推测研究 ——以 2024 年 1 月 23 日乌什 7.1 级地震为例

李 帅，李 波，柏 岩，古力孜帕·木拉提，侯欣宇

（新疆维吾尔自治区地震局，新疆 乌鲁木齐 830011）

摘要：为快速判定地震后的建筑抗震能力、科学划定安全与危险区域，引导群众合理避让、就近安全避难、最大限度减少人员伤亡。本研究通过建筑物的建筑年代、层数、层高、抗震设防等级、建筑物场地类别、活动断层的距离及道路交通条件等因素，构建多因子综合评定指标体系，采用定性定量相结合的方式对房屋抗震能力进行综合判定，将判定结果划分为抗震能力达标、疑似抗震能力不足和抗震能力严重不足 3 个等级，实现震区建筑抗震性能的空间分级。在此基础上，利用 GIS 空间叠加分析方法，将建筑抗震能力分级结果与地震烈度衰减规律、活动断层展布、道路通达性等空间要素进行叠加分析；同时结合离散元、有限元等数值模拟方法，对典型建筑结构在罕遇地震烈度与设防烈度作用下的破坏状态进行模拟评估，综合计算不同设防水准下的安全区域与危险区域，并据此划定就近避难路径、优化临时安置点布局，形成震区人员安全避难分级图。新疆地质构造复杂，地震多发、频发，科学合理开展震前房屋抗震能力评估与震后安全引导避难尤为重要。2024 年 1 月 23 日新疆乌什县发生 7.1 级地震，此次地震造成位于Ⅷ度（8 度）区内的亚曼苏乡和阿合奇县东侧的多数自建房屋发生严重破坏或毁坏。在收集了房屋数据的基础上按照上述方法进行了计算和分析。结果表明，所提方法能够较为合理地反映震区房屋抗震能力的空间差异，能够明确标识出需重点防范的危险建筑和相对安全的避难场地，为基层应急组织和群众自救互救提供直观依据，可有效引导群众避开危险区域、就近快速到达临时避难场所，减少盲目疏散造成的次生风险，为震后应急避险组织、避难场所规划与救援力量部署提供科学依据，对提升地震应急响应效率和减灾救灾能力具有重要参考价值。

关键词：房屋抗震能力；有限元分析；安全避难；乌什地震

作者简介：李帅（1982—），男，高级工程师，主要从事工程地质、地震地质灾害及地震应急工作的研究。E-mail: peter825550@163.com

RESEARCH ON INFERRING PERSONNEL SAFE EVACUATION BASED ON BIG DATA: A CASE STUDY OF WUSHI *M*7.1 EARTHQUAKE ON JANUARY 23, 2024

Li Shuai, Li Bo, Bai Yan, Gulizipa Mulati, Hou Xinyu

(Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, Xinjiang, China)

Abstract: To rapidly assess the seismic capacity of buildings after an earthquake, scientifically delineate safe and dangerous zones, guide residents to evacuate properly and take shelter nearby, and minimize casualties, this study comprehensively considered factors such as year of construction, number of stories, story height, seismic fortification level, site category, distance to active faults, and road traffic conditions to establish a multi-factor comprehensive evaluation index system. By combining qualitative and quantitative approaches, the seismic capacity of buildings was comprehensively assessed and classified into three levels—compliant with seismic fortification requirements, suspected insufficient seismic capacity, and severely insufficient seismic capacity—thereby achieving a spatial classification of the seismic performance of buildings in the affected area. On this basis, GIS spatial overlay analysis was used to overlay the classified seismic capacity of buildings with spatial elements such as seismic intensity attenuation, active fault distribution, and road accessibility. Meanwhile, combined with numerical simulation methods such as the discrete element method (DEM) and finite element method (FEM), the damage states of typical building structures under both rare earthquake intensity and fortification intensity were simulated and evaluated. The safe and dangerous zones under different fortification levels were then calculated, evacuation routes to nearby shelters were delineated, and the layout of temporary resettlement sites was optimized, resulting in a graded map for the safe evacuation of residents in the affected area.

Xinjiang has a complex geological structure and is prone to frequent earthquakes; it is therefore particularly important to scientifically assess the seismic capacity of buildings before an earthquake and to provide safe evacuation guidance afterward. On January 23, 2024, an *M*7.1 earthquake occurred in Wushi County, Xinjiang. In this earthquake, most self-built houses in Yamansu Township and the eastern part of Aheqi County, located in the intensity VIII (8-degree) zone, suffered severe damage or collapse. Based on the collected building data, calculations and analyses were carried out using the methods described above. The results indicate that the proposed method can reasonably reflect the spatial differences in the seismic capacity of buildings in the affected area and can clearly identify dangerous buildings requiring priority attention and relatively safe shelter sites, providing intuitive support for grassroots emergency organizations and residents' self-rescue. It can effectively guide residents to avoid dangerous zones and quickly reach nearby temporary shelters, reducing the secondary risks caused by blind evacuation, and providing a scientific basis for post-earthquake emergency evacuation organization, shelter planning, and rescue force deployment. This study is of important reference value for improving the efficiency of earthquake emergency response and disaster mitigation.

Key words: Building seismic capacity; Finite element analysis; Safe evacuation; Wushi earthquake

Author Biography: Li Shuai (1982-), male, senior engineer, primarily engaged in research on engineering geology, seismic geological hazards, and earthquake emergency response. E-mail: peter825550@163.com

新疆近年来的城市震害与抗震设防

温和平, 谭明, 李帅, 阿里木江·亚力昆, 赵江涛, 李波, 罗炬

(新疆维吾尔自治区地震局, 新疆 乌鲁木齐, 830011)

摘要: 1990 年以来新疆城市遭遇的震害最高烈度为Ⅷ度。本世纪以来的震害表明, 天山、昆仑山前逆冲推覆断褶区域的城镇, 遭遇超越设防地震动的可能性是存在的。在《中国地震动参数区划图》(GB 18306—2015) 中, 新疆基本地震动参数 $0.1g \sim 0.15g$ 区域内的人口占总人口的 49.6%, $0.2g$ 区域的人口占比 44.8%, $0.3g$ 及以上区域的人口占比为 3.6%。因此人口集中区遭受 $0.3g$ 及以上地震动的危险性相对较低。

由于地震动参数区划和抗震设防标准的变化, 目前 8 度设防的阿合奇县城有 81% 的建筑物为 7 度设防。2024 年乌什 7.1 级地震中, 阿合奇、乌什县城的调查烈度分别为Ⅷ度和Ⅶ度, 基岩仪器烈度分别为 7.4 度和 6.2 度; 加速度反应谱分析表明, 阿合奇镇遭遇了明显高于设防地震动的地震破坏, 设防建筑物以轻微至中等破坏为主, 经受住了超设防地震动的考验。乌什镇遭受的场地地震动至少与设防地震动相当, 设防建筑以轻微破坏为主, 个别中等破坏, 抗震性能表现良好。

2013 年乌鲁木齐 5.1 级、2015 年皮山 6.5 级地震属于城市直下型地震。5.1 级地震作用下, Ⅷ度 ($0.2g$) 设防的乌鲁木齐市城区震害综合判定为Ⅵ度, 自建房、老旧砖混房屋出现不同程度的破坏, 设防建筑主体结构完好; 皮山 6.5 级地震中, Ⅷ度 ($0.1g$) 设防的县城固玛镇地震烈度为Ⅷ度, 造成老旧砖混结构多层建筑较多破坏, 15% 达到中等以上破坏, 个别严重破坏; 框架结构个别构件破坏, 多为轻微破坏。

综上所述: 相对于当地建筑的设防标准, 乌鲁木齐市在多遇地震动作用下, 设防建筑结构完好; 乌什镇设防建筑在基本地震动下多为轻微破坏; 固玛镇、阿合奇镇遭受的地震烈度高于设防标准, 其设防建筑表现为“大震不倒”。因此可以说, 在地震动参数区划的指导下, 新疆 3 座城市的建筑抗震设防总体上都实现了“小震不坏、中震可修、大震不倒”的震害防御目标。

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作者简介: 温和平 (1970~), 男, 高级工程师, 硕士, 1997 年毕业于新疆工学院地质系矿产普查与勘探专业, 主要从事震害防御与地震应急工作。E-mail: 459972647@qq.com

URBAN SEISMIC DAMAGE AND SEISMIC FORTIFICATION IN XINJIANG IN RECENT YEARS

Wen Heping, Tan Ming, Li Shuai, Alimujiang Yalikun, Zhao Jiangtao, Li Bo, Luo Ju

(Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi, 830011, Xinjiang, China)

Abstract: Since 1990, the maximum seismic intensity encountered by cities in Xinjiang has been Intensity VIII. Seismic damage records in this century show that towns in the thrust-nappe fold regions in front of the Tianshan and Kunlun Mountains face the possibility of experiencing ground motion exceeding the seismic fortification level. According to the Seismic Ground Motion Parameter Zonation Map of China (GB 18306-2015), 49.6% of Xinjiang's total population resides in areas with basic seismic ground motion parameters of 0.1g to 0.15g, 44.8% in areas with 0.2g, and only 3.6% in areas with 0.3g and above. This indicates that the risk of population-concentrated areas being subjected to ground motion of 0.3g or higher is relatively low.

Due to revisions in seismic ground motion parameter zonation and seismic fortification standards, 81% of buildings in Akqi County, which is now designated for 8-degree fortification, were originally built to meet the 7-degree fortification standard. During the *M*7.1 Wushi earthquake in 2024, the surveyed seismic intensities in Akqi and Wushi counties reached Intensity VIII and Intensity VII respectively, with bedrock instrumental intensities of 7.4 and 6.2. Acceleration response spectrum analysis shows that Akqi Town experienced seismic damage significantly exceeding its design ground motion, yet the fortified buildings only sustained slight to moderate damage and withstood the over-design ground motion. The site ground motion in Wushi Town was at least equivalent to its fortification level, with fortified buildings showing mainly slight damage and a few moderate damages, demonstrating excellent seismic performance.

The 2013 Urumqi *M*5.1 earthquake and the 2015 Pishan *M*6.5 earthquake are typical urban direct-hit earthquakes. Under the *M*5.1 earthquake, the comprehensive seismic damage intensity of Urumqi urban area (fortified for VIII degree, 0.2g) was determined as Intensity VI. Self-built houses and old brick-concrete structures suffered varying degree of damage, while the main structures of fortified buildings remained intact. During the *M*6.5 Pishan earthquake, the seismic intensity in Guma Town (the county seat, fortified for VII degree, 0.1g) reached Intensity VIII, causing extensive damage to old multi-story brick-concrete buildings: 15% of them sustained moderate or above damage, with a few severely damaged. Only individual components of frame structures were damaged, mostly with slight damage.

In conclusion, relative to local building fortification standards: the fortified buildings in Urumqi remained structurally intact under frequent earthquake ground motion; those in Wushi Town mainly sustained slight damage under basic design ground motion; and in Guma Town and Akqi Town, where the encountered seismic intensity exceeded the fortification standard, the fortified buildings achieved the goal of "no collapse under major earthquakes". Therefore, guided by the seismic ground motion parameter zonation map, the seismic fortification of buildings in the three cities in Xinjiang has generally fulfilled the seismic damage prevention objectives of "no damage under minor earthquakes, repairable under moderate earthquakes, and no collapse under major earthquakes".

Author Biography: Wen Heping (1970), male, senior engineer, master's degree. He graduated from the Department of Geology, Xinjiang Institute of Technology in 1997, majoring in Mineral Prospecting and Exploration. He is mainly engaged in seismic damage prevention and earthquake emergency response work. E-mail: 459972647@qq.com.

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如何提升地震监测中心站科普宣传工作的能力

张振斌， 晁东瑜

（新疆维吾尔自治区地震局，新疆 乌鲁木齐 830011）

摘要：长期以来，台站的工作重点都以地震监测作为基础工作，形成了基本固定的工作模式，加上经费短缺、人员能力培养不足，科普宣传水平参差不齐，致使台站工作人员对科普宣传工作的重视程度远远不够，防震减灾科普宣传工作显得较为单薄。随着中心站的改革，职能变化，社会对地震服务工作要求不断提高，地震科普宣传逐渐成为中心站工作的一项重要任务，防震减灾科普宣传工作的开展提上工作日程。这还需要一个过程来充实、完善和加强台站的防震减灾科普宣传工作。

一、不断改善群众对地震科普知识不感兴趣，用不上的思想

中心站首先要逐步提升科普人员的专业素养，加强对地震科普知识的积累和思考，平时多查资料收集和整理，多收集各类地震科普中的人和事，总结出科普宣传中一些好的做法和相应的问题，如今在人工智能的普及发展下，每年防震减灾日后网络上都会出现大量科普作品，可以借鉴学习，提升思路，同时可以经常和当地社区群众代表交流讨论和调研，同时做好科普工作六进，针对不同群体不断地推出科普宣传的相关内容，确保科普宣传方式、内容精彩有效，科普宣传内容要与人民群众的需求和宣传效果息息相关，科普宣传后，让参与的群众感觉到了他们需要的东西，逐步建立起老百姓对科普宣传工作的认可。

二、强化基层科普员培养

新疆是边疆少数民族地区，乡镇大多在山区，防震减灾科普宣传工作存在很大的困难，尤其是处在地震带上的地区，需要基层干部和中心站职工付出更大的努力。地方地震科普宣传人员多为兼职，很多宣传照本宣科，千篇一律，缺乏深入思考，甚至自己都没搞懂，加之行业系统内部培训机会少，讲授效果不理想。为此，需要他们有更多的知识储备，同时还要结合农村少数民族人民群众的接受能力和需求来开展工作，对现有的三网一员人员开展定期培训，考虑待遇或政策上的适当支持。

三、与地方地震相关部门合作，发挥好双方优势

对中心站来说，充分利用好地方地震局在地方上的沟通协调作用，中心站找准自己的方向，将各方面的优势在科普宣传中充分体现，发挥最大作用，需要中心站的领导统筹谋划、精心安排，为区域地震安全，地方经济的发展保驾护航。

四、结合地方特色，加强旅游区流动人员的防震减灾科普宣传

要了解不同时段这些旅游人员特点及集中地段，并进行有针对性的科普宣传，如在旅游景点等人口密集区长期摆放应对地震的宣传册，大屏宣传视频等，也可以和各大旅游网站进行合作，进行地震科普知识的宣传，使旅客快速了解区域灾害特点，对地震的基本知识有所了解，懂得如何在地震时有效地避震、自救和互救。

REFLECTIONS ON THE DEVELOPMENT OF SCIENCE POPULARIZATION ACTIVITIES AT THE EARTHQUAKE MONITORING CENTER STATION

Zhang Zhenbin, Chao Dongyu

(Earthquake Agency of Xinjiang Uygur Autonomous Region, Urumqi 830011, Xinjiang, China)

Abstract: For a long time, the primary focus of these stations has been on seismic monitoring as their foundational activity, leading to the establishment of a largely fixed operational model. However, due to funding shortages, inadequate training of personnel, and varying levels of effectiveness in science popularization efforts, the staff have not given sufficient attention to science popularization activities; as a result, the science popularization work related to earthquake prevention and disaster reduction has remained relatively underdeveloped. Following the reform and functional restructuring of the Central Station, along with the growing public demand for earthquake-related services, earthquake science popularization has gradually become an important task for the Central Station, and the implementation of such science popularization initiatives has been placed on the official agenda. Nevertheless, this process requires time to enrich, refine, and strengthen the earthquake prevention and disaster reduction science popularization efforts conducted by these stations. To better understand the characteristics of tourists and their preferred travel destinations across different time periods, targeted public awareness campaigns should be launched—such as placing earthquake preparedness brochures or displaying large-screen educational videos in densely populated areas like tourist attractions. Additionally, partnerships can be established with major travel websites to promote earthquake science knowledge, enabling travelers to quickly grasp the regional disaster risks, acquire fundamental earthquake-related knowledge, and learn how to effectively take shelter, perform self-rescue, and provide mutual aid during an earthquake.