IASPEI Commission for Rapid Interdisciplinary Investigation of Significant Earthquakes

Newsletters

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Happy Chinese New Year of the Horse

Happy Year of the Horse! May your career gallop to new heights!

Wishing you a year full of vitality and the strength to overcome any challenge, may you seize every opportunity and charge forward to your goals!

In the previous issue of our newsletter, we mentioned that in this issue we would invite an expert to share his views on the January 26, 2001 Gujarat earthquake.

The following is content contributed by Prof. Prantik Mandal:

Intraplate Earthquakes in the Kachchh Rift: Twenty-Five Years of Progress Since the 2001 M_W7.7 Bhuj earthquake

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Introduction

The January 26, 2001 Bhuj earthquake (M_W 7.7) marked a turning point in our knowledge of earthquakes that happen within plates. Earlier, earthquakes in stable continental regions (SCRs) like Bhuj were thought to be strange since they were big and destructive and happened in places we thought were tectonically stable, distant from active plate boundaries. The Bhuj event called into question our basic ideas about where and why big earthquakes happen. Now, twenty-five years later, the scientific response to this disaster has been nothing short of amazing. The Kachchh Rift Zone has changed from a seismological mystery to one of the most well studied intraplate areas on Earth, significantly changing how we think about how earthquakes happen on continents.

The post-Bhuj research endeavour is different not only because of its size, but also because it brings together people from many different fields. Indian seismologists, especially those at CSIR-NGRI Hyderabad, have used modern geophysical tools like dense seismic networks, GPS geodesy, magnetotelluric surveys, and advanced computational modelling to put together a complete picture of how inherited rift structures, deep magmatic intrusions, crustal fluids, and far-field stresses work together to cause terrible intraplate earthquakes. This synthesis is a big step forward from simply describing things to using physics to comprehend them. It has big effects on how we assess seismic hazards in stable continental areas around the world.

Seismotectonic Framework: Reactivation of Ancient Structures

The main thing to learn from Kachchh is that intraplate earthquakes don't happen randomly in "stable" crust; instead, they are systematic reactivations of pre-existing zones of weakness. In this case, a Mesozoic failed rift occurred during the breakup of Gondwanaland some 180 million years ago[1][2]. The Kachchh Rift Zone has classic extensional architecture, with faults that run east-west (the Kachchh Mainland Fault, North Wagad Fault, Katrol Hill Fault, and Allah Bund Fault), half-grabens filled with kilometres of sediment, and basement uplifts that mark the shoulders of old rift-bounding faults[1][2].

The India-Eurasia collision is what keeps these faults seismically active today. It sends north-south compressive forces thousands of kilometres into the Indian plate's interior[3]. This tectonic inversion, where structures that were once extended are reactivated under pressure, happens a lot in intraplate seismicity. It may be seen in the New Madrid Seismic Zone, the Reelfoot Rift, and some portions of cratonic Australia[4]. The Kachchh example shows that ancient rift zones are still mechanically weak compared to nearby shield regions. This makes them great places for stress to build up and cause seismic failure, even after hundreds of millions of years of inactivity.

Since 2001, intensive seismic monitoring in Kachchh has precisely imaged the seismogenic structure through over 10,000 aftershocks of the M_W7.7 Bhuj mainshock—17 events M_W5–5.9, 250 M_W4–4.9, 4000 M_W3–3.9—relocated using double-difference methods ([5], Fig. 1). These delineate a south-dipping blind thrust along the previously undetected North Wagad Fault (NWF), active between 10–35 km depth without surface rupture—a hallmark of major stable continental region (SCR) earthquakes[6][7]. The most recent M_W5.3 event occurred 20 June 2020. Kachchh's exceptionally thick seismogenic layer (25–35 km) reflects the strength of crystalline continental crust[8], contrasting sharply with the thinner (<20 km) zones typical of plate boundaries. This thick, brittle lower crust, combined with inherited rift weaknesses and far-field compression, defines the intraplate earthquake paradox exemplified by Bhuj.

Focal mechanism solutions show a complicated combination of faulting types. Most of the time, reverse faulting is consistent with regional N-S compression, but there are also large strike-slip components that show local stress changes and fault segmentation[9]. Stress inversion from 466 well-constrained focal mechanisms records a 44-degree rotation of the highest compressive stress axis within the center aftershock zone[9]. This diverse stress field cannot be elucidated just by plate-scale forces; it indicates localised mechanical heterogeneities within the crust that influence stress distribution and rupture propagation.

The Role of Mafic Intrusions and Lithospheric Heterogeneity

The most important idea that has come out of Kachchh investigations is that deep crustal heterogeneity, especially mafic plutonic rocks, has a big effect on how earthquakes start and how long aftershocks last[5][10][11]. Three-dimensional seismic tomography has shown that there are two huge bodies of rock underneath the Wagad and Banni uplifts that are moving at speeds 10–14% faster than the surrounding crust. These bodies are between 5 and 35 km deep[5][6][7]. These anomalies are thought to be mafic to ultramafic intrusions that happened about 65 million years ago during the Jurassic rifting and the Deccan magmatism that followed.

Why do these plutons have anything to do with earthquakes? First, their higher density and hardness relative to felsic crustal rocks make them mechanical stress concentrators, which are areas where tectonic stress is increased, which causes faults to slip[5]. Aftershock clusters are seen along pluton edges, which suggests that rupture starts at rheological borders where powerful mafic bodies touch weaker, broken host rock[5][10][11]. Second, the plutons change the temperature of the crust around them, which changes the depth of the brittle-ductile transition and the thickness of the seismogenic layer[9][11]. Receiver function analysis substantiates considerable crustal thinning in Kachchh (37-45 km Moho depth) relative to the stable Indian Shield (40-50 km), with lithospheric thinning (64-106 km lithosphere-asthenosphere boundary) indicative of plume-related thermal erosion[12].

The tomographic images also show an equally crucial counterpart to the high-velocity plutons: low-velocity zones next to them with high Vp/Vs ratios (>1.85), which means that the crust is fluid-saturated and broken[5][13][14][15][16]. These regions with a lot of fluids are found at depths of 10 to 35 km, which is exactly where aftershocks happen. The strong, rigid mafic bodies and the weak, fluid-infiltrated fracture zones are next to each other in space, which makes a mechanical framework that is perfect for causing earthquakes. Stress builds up in the strong areas and is released through slip in the weak, fluid-lubricated fault zones.

Crustal Fluids: The Key Weakening Agent

If mafic intrusions set the stage for mechanical movement, crustal fluids are the main cause of fault slip. This revelation—that subsurface fluids influence earthquake initiation in intraplate environments—signifies a pivotal transformation in our comprehension of stable continental earthquakes. Several lines of evidence converge on the significance of fluids in Kachchh seismogenesis.

Temporal tomography offers the most unequivocal proof. Researchers kept an eye on seismic velocities for ten years after the 2001 earthquake. They found that the P-wave velocity dropped by 8–15% and the S-wave velocity dropped by 10–20% in shallow to mid-crustal fault zones. At the same time, crack density and fluid saturation rates rose dramatically, by up to four times[13][14][15][16]. In the years that followed, velocities slowly returned to normal as cracks filled and fluids moved, which is thought to be a sign of post-seismic fault zone healing[13][15]. This temporary change in velocity connects the flow of fluids to co-seismic fracture, and fluid pressure helps trigger aftershocks in the early post-mainshock period.

Magnetotelluric surveys support the seismic results by showing large conductivity anomalies that line up with significant faults[14][16]. These low-resistivity zones, which go from the surface to the middle of the crust, show that there are fluid channels that are related. The electrical conductivity structure indicates that the fluids present are not solely local pore waters, but also encompass deeper metamorphic fluids and CO_2-rich volatiles originating from mantle sources.

Petrological investigations of mantle xenoliths transported to the surface by Deccan volcanism show where these deep fluids come from. Xenolith mineralogy clearly reveals signs of carbonatite metasomatism, which is when CO_2-rich melts from the upper mantle change the minerals[17]. Carbonatite melts that are rich in volatiles can flow through the crust above them during magmatic events, leaving behind a reservoir of pressurised fluids that lasts for a long time. When tectonic stress gets too high, these fluids lessen the effective normal stress on faults by raising pore pressure. This lowers frictional strength and makes it easier for the fault to break.

Modelling the way aftershocks move about supports a fluid-diffusion mechanism. Aftershocks spread along the fault strike over years to decades, with migration rates that were in line with hydraulic diffusivity values of about 1–5 m^2/s[18]. This pore-pressure diffusion model suggests that redistributing fluids after the mainshock made nearby fault segments less stable over time, which caused delayed seismic activity far from the initial rupture zone. This kind of behaviour has been seen in other intraplate sequences, like the Guy-Greenbrier sequence in Arkansas. It shows how important fluid-fault interactions are in influencing how earthquake sequences change over time and space.

Assessing seismic hazards and ground motion characteristics

From an engineering and public safety point of view, the improvements in predicting ground motion in the Kachchh area are especially important. The Bhuj earthquake had peak ground accelerations (PGA) that were far higher than expected, and it inflicted terrible damage over 100 km from the epicentre. This was partly because of basin amplification effects in the thick sedimentary fill of the rift basin.

After the earthquake, strong-motion investigations found region-specific Ground Motion Prediction Equations (GMPEs) based on recordings from the mainshock in 2001 and more than 200 aftershocks[19]. These empirical attenuation relationships take into account the size, distance, and kind of site, which makes them able to capture the distinctive properties of Kachchh ground motions. More recently, machine learning methods like artificial neural networks and XGBoost algorithms have been used to improve and expand GMPEs. These methods have achieved prediction correlations of more than 0.90 and have greatly reduced uncertainty compared to traditional regression methods[19][20][21].

Three-dimensional ground motion modelling that includes realistic basin velocity structures created by genetic algorithm inversion of strong-motion waveforms accurately reproduces the patterns of ground shaking that have been seen[22]. These simulations show that sediments in the basin with low velocities ($V_s < 1.5$ km/s) increase ground motions by 2–5 times in the 0.1–1 Hz frequency region, which has a big effect on damage to structures. The wavefield is made even more complicated by basin-edge effects and the creation of surface waves. This causes longer shaking periods that make buildings more likely to fall down.

Coda-Q attenuation tests measure the seismic quality factor for the area, showing considerable attenuation ($Q_c = 100–300$ at 1 Hz) that is in line with a cracked, fluid-bearing crust[23]. These attenuation factors are necessary for forecasting ground motion attenuation with distance and for evaluating shaking strength in forthcoming earthquakes. The combination of site-specific GMPEs, 3D velocity models, and attenuation relationships makes a strong framework for seismic microzonation and earthquake-resistant design in Gujarat.

Future Directions and Global Implications

The Kachchh study program shows that there are a number of important things that need to be done to move intraplate seismology ahead.

First, we need to keep monitoring seismic activity closely. The current network of broadband and strong-motion stations should be enlarged and kept up to date so that we can see how faults are changing, how stress is moving, and any possible warning signs[26]. Long-term monitoring will let time-lapse tomography keep an eye on how fluids move and faults mend over decades.

Second, combining geochemical tracers with geophysical measurements helps directly test ideas about where fluids come from, how they move, and how they interact with fault rocks. Taking samples of groundwater chemistry, monitoring radon and CO_2 emissions, and looking at isotopic fingerprints can all help us understand how fluids behave on their own.

Third, realistic numerical models that combine fluid flow, stress transfer, and fault friction (using constitutive equations from the lab) may make it possible to predict earthquakes based on physics. Current models only look at fluid effects in a limited way. To really understand how fluids and faults interact, future research should look at multiphase flow, poroelasticity, and geochemical processes.

The Kachchh data support the idea that many damaging SCR earthquakes have the same causes: reactivated rift structures, deep magmatic intrusions, crustal fluids, and tectonic forces that are far away. Comparative studies involving the New Madrid Seismic Zone (USA), the East African Rift, and cratonic Australia demonstrate remarkably comparable geological frameworks, indicating that hazard assessment approaches devised for Kachchh may be applicable to other intraplate areas[20][21][24].

The stakes for society are huge. Stable continental areas are home to big cities and important infrastructure that are often not ready for earthquakes because they were built with the idea that the risk of earthquakes was low. The Bhuj disaster, which killed more than 20,000 people and cost the economy more than $5 billion, ended that complacency. The scientific legacy of the last 25 years is not just academic information; it is also knowledge that can be used: updated building codes, microzonation maps, public awareness campaigns, and emergency preparedness programs based on thorough geophysical research.

Conclusion

In the 25 years following the 2001 Bhuj earthquake, our understanding of intraplate seismogenesis has changed in amazing ways. What used to be a mystery in seismology—why big earthquakes hit "stable" cratons—has turned into a clear scientific story that brings together tectonics, petrology, geophysics, and fluid mechanics. The Kachchh Rift Zone shows how inherited rift architecture, mafic intrusions, deep crustal fluids, and compressional reactivation may all work together to cause terrible earthquakes in the middle of continents.

This comprehensive understanding has significant ramifications for seismic hazard evaluation, not only in India but also in stable continental areas globally. The methods that were first used in Kachchh, such as dense seismic networks, high-resolution tomography, temporal monitoring, fluid modelling, and machine learning-enhanced ground motion prediction, can be used to assess hazards in other intraplate situations. To turn scientific discoveries into better public safety and resilience, we will need to keep doing research across disciplines and work together with people from other countries.

The 2001 Bhuj earthquake left behind two things: a human tragedy that sparked action and a scientific breakthrough that has greatly improved our understanding of how the Earth functions. We promise to keep doing the research that could one day save lives in the next big intraplate earthquake in honour of those who died.

References

[1] Biswas, S.K. (1987). Regional framework, structure and evolution of the western marginal basins of India. *Tectonophysics*, 135, 302-327.

[2] Biswas, S.K. (2005). A Review of Structure and Tectonics of Kutch Basin, Western India, with special reference to Earthquakes. *Current Science*, 88(10), 15

[3] Bilham, R., Bendick, R., & Wallace, K. (2003). Flexure of the Indian plate and intraplate earthquakes. *Proceedings of the Indian Academy of Sciences*, 112(3), 315-329.

[4] Johnston, A. C. (1994). Seismotectonic interpretations and conclusions from the stable continental regions, In: the earthquakes of stable continental regions: Assessment of Large Earthquake Potential. *Electric Power and Research Institute*, Ch.3, 20 – 40.

[5] Mandal, P. (2020). Relocations and local earthquake tomography: Implications toward the mafic pluton induced crustal seismicity in Kachchh, Gujarat, India, for last 18 years. Journal of Asian Earth Sciences, 2020, 190, 104196, 1-9.

[6] Mandal, P. and Pujol, J. (2006). Seismic imaging of the Aftershock zone of the 2001 M_W7.7 Bhuj earthquake, India. *Geophysical Research Letters*, 33, L05309, 1-4.

[7] Mandal, P., Rastogi, B. K, Satyanarayana, H. V. S, Kousalya, M, Vijayraghavan, R, Satyamurthy, C, Raju, I. P, Sarma, A. N. S and Kumar, N. (2004) Characterization of the causative fault system for the 2001 Bhuj earthquake of M_W 7.7, Tectonophysics, 378, 105-121.

[8] Bodin, P., & Horton, S. (2004). Source parameters and tectonic implications of aftershocks of the M_W 7.6 Bhuj earthquake of January 26, 2001. *Bulletin of the Seismological Society of America*, 94(3), 818-827.

[9] Mandal, P., and Horton, S. (2007). Relocation of aftershocks, Focal Mechanisms and Stress Inversion: Implications toward the seismo-tectonics of the causative fault zone of M_W7.6 2001 Bhuj earthquake (India). *Tectonophysics*, 429, 61-78.

[10] Campbell, D. L. (1978). Investigation of the stress-concentration mechanism for intraplate earthquakes. *Geophysical Research Letters*, 5(7), 477-479.

[11] Mandal, P. and Pandey, O. P. (2010). Relocation of aftershocks of the 2001 Bhuj earthquake: A new insight into seismotectonics of the Kachchh seismic zone, Gujarat, India. *Journal of Geodynamics,* 49, 254-260.

[12] Mandal, P. (2012). Passive- Source Seismic Imaging of the Crust and Upper Mantle beneath the 2001 M_W 7.7 Bhuj Earthquake Region, Gujarat, India. *Bulletin of Seismological Society of America,* 102, 252-266.

[13] Mandal, P. (2024). Temporal fluctuations (2001–2013) in crack density, saturation rate, and seismic velocities and their implications for the occurrence of the 2001 M_W7.7 Bhuj earthquake sequence. Natural Hazards, 121, 759-780.

[14] Pavan Kumar, G., P. Mahesh, M. Nagar, E. Mahender, V. Kumar, K. Mohan, and M. Ravi Kumar (2017). Role of deep crustal fluids in the genesis of intraplate earthquakes in the Kachchh region, northwestern India, Geophys. Res. Lett., v. 44, pp. 4054–4063, doi:10.1002/2017GL072936.

[15] Mandal, P. (2016). Variations of seismic velocities in the Kachchh rift zone, Gujarat, India, during 2001–2013. Tectonophysics, 672/673, 68-86, DOI:10.1016/j.tecto.2016.01.040.

[16] Mandal, P. (2025). Evidence of deep crustal fluids facilitating intraplate earthquake generation beneath the seismically active Kachchh rift zone in Gujarat, India. Jou. Geol. Soc. Ind., 101 (6), 793–797, 2025.

[17] Sen, G., Bizimis, M., Das, R., Paul, D.K., Ray, A., Biswas, S. (2009). Deccan plume, lithospheric rifting, and volcanism in Kutch, India. Earth Planet. Sci. Lett., 277, 101–111.

[18] Mandal, P., Kumar, M., and Biswas, K. (2016). Evidence for a fluid flow triggered spatiotemporal migration of seismicity in the 2001 M_W7.7 Bhuj earthquake region, Gujarat, India, during 2001-2013. Jou. Ear. Syst. Sci., 2016, 125, 1285-1298.

[19] Mandal, P., Kumar, N., Satyamurthy, C. and Raju, I.P. (2009). Ground motion attenuation relation from strong-motion records of the 2001 M_W 7.7 Bhuj Earthquake Sequence (2001-2006), Gujarat, India.Pure and Applied Geophysics, 166, 451-469.

[20] Mandal Prantik and Mandal Priyank (2024). Peak Ground Acceleration Prediction using supervised Machine Learning algorithm for the seismically hazardous Kachchh rift zone, Gujarat, India. Natural Hazards, 120, 1821-1840.

[21] Priyank Mandal and Prantik Mandal (2026). A model for predicting pseudospectral acceleration and peak ground acceleration utilising supervised machine learning algorithms for seismically hazardous areas in India. Acta Geophysica, 74, 17.

[22] Mandal, P. and Kimiyuki Asano (2019). Three-dimensional ground motion modelling in the Kachchh rift zone, Gujarat, India. PEPI, 2019, 297, 106322, 1-15.

[23] Biswas, K., Kumar, M., and Mandal, P. (2016). Lapse time dependent Coda-Q (QC) in the Kachchh rift zone, Gujarat, India. Natural Hazards, 81, 1589-1610.

[24] Rastogi, B.K., Mandal, P., Biswas, S. (2014) Seismogenesis of earthquakes occurring in the ancient rift basin of Kachchh, Western India. In the book on “Intraplate Earthquakes” edited by P. Talwani, Cambridge University Press, pp.126-161. 10.1017/CBO9781139628921.007.

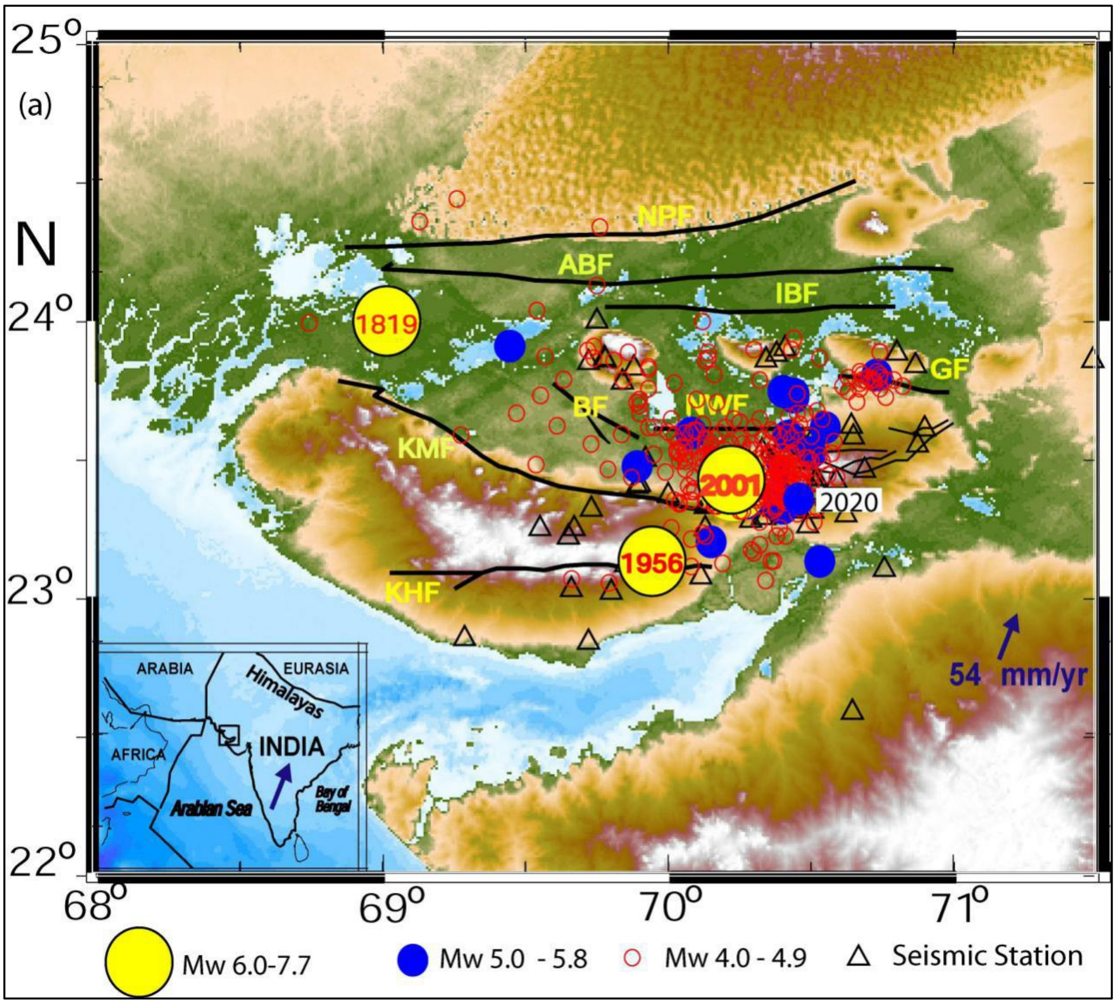

Figure 1. Kachchh (Gujarat) seismic station map showing relocated hypocenters from simultaneous inversion (small red circles), broadband stations (open black triangles), and major faults (solid black lines: IBF, NWF, GF, KMF, KHF). Large blue circles mark *M*5 epicenters; yellow circles show historic $M \geq 6$ events (1819 Kachchh, 2001 Bhuj, 1956 Anjar). Inset: regional study area (open square) with N-S compression (black arrow).

International Contest on Aftershock Forecasting is Coming Soon

Earthquakes are among the most destructive natural disasters. Accurately forecasting the frequency, spatial distribution, and maximum magnitude of aftershocks is essential for mitigating secondary disaster risks and optimizing the allocation of rescue resources. For a long time, aftershock forecasting has largely relied on traditional statistical models, which exhibit clear limitations in both prediction accuracy and applicability. In recent years, advances in big data and artificial intelligence have opened new avenues for overcoming these bottlenecks. To unite global research efforts, identify core scientific challenges in earthquake sequence forecasting, and promote interdisciplinary collaboration, we are pleased to announce the International Aftershock Forecasting Competition. The competition encourages participating teams to explore innovative pathways for aftershock prediction using cutting-edge technologies such as artificial intelligence and large-scale models. The goal is to enhance the accuracy and practicality of forecasting, thereby providing technical support and practical insights for evidence-based responses to earthquake disasters worldwide.

This competition will feature strong earthquake sequences of magnitude 6 and above from around the world, including seismic events from different tectonic settings such as intraplate environments and subduction zones. Individual participants or teams will be provided with seismic data following a major earthquake and are expected to forecast the time and magnitude of the largest aftershock within a specific time window in the affected area.

For more information about the competition, please see the poster below.

余震预测技术国际大赛

International Contest on
Aftershock Forecasting

比赛时间

2026年3月-11月

from March to
November 2026

报名链接(Access Link)：
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competition/entrance/532460

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Earthquake Science期刊
Earthquake Science (an international journal)

Significant Earthquakes: This Month in History — 1975 Haicheng Earthquake

51 years ago this month, on February 4, 1975, a magnitude 7.3 earthquake shook Haicheng, Liaoning Province, China.

Before the earthquake occurred, the Liaoning Earthquake Agency made an imminent forecast, prompting the Liaoning Provincial Government to order an evacuation four hours in advance.

The Haicheng earthquake caused more than 1,000 casualties, but if people had continued to stay at home, the number would exceed 100,000, as estimated.

In Haicheng area, 90% of the buildings were severely damaged, and many of them collapsed. Although it happened in the evening, the vast majority of people did not stay in the houses that would later collapse, thanks to the government's timely decision to evacuate.

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