

The June 2022 Afghanistan earthquake M W 6.2: Tectonic implications and Coulomb stress change

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Abstract

The June 21, 2022 strong earthquake Mw 6.2 occurred nearly 165 km southeast of Kabul city, Afghanistan, and caused more than 1000 casualties and huge property losses. An untimely occurrence of the shallow focus event (~ 10 km, USGS report) at mid-night when people were asleep and the poor constructed houses caused so many casualties. It is one of the most devastating earthquake in Afghanistan in the recent years. The GCMT solution shows a strike-slip faulting at a centroid depth ~ 15 km; the NNE-SSW nodal plane is comparable with the trend of Chaman-Gardez fault system, though the epicenter is ~ 50 km away from the surface fault traces. Afghanistan is under tectonic stresses from the Hindu-Kush collision zone to the north, Makran subduction zone to the south and from the transpressional zones to the east and west. Stress inversion study shows a NNW-SSE compressional stress and NNE-SSW extensional stress in the study area, the central intra-plate zone of Afghanistan. A seismic cross section of the main shock, aftershocks and the past events shows shallow near vertical source zones. The aftershock trend and the maximum PGA trend are parallel to the Chaman-Gardez fault system. Coulomb stress-change images after the main shock show that the aftershocks occurred in the increased stress zone of the rupture area.

Introduction

Tectonically Afghanistan falls in the active Alpine-Himalayan orogenic belt that resulted from collision of the Indian and Arabian plates with the Eurasian plate. The region is seismically much active, and produce moderate to large earthquakes with several catastrophic events ($M_w \geq 7.0$) in the past (Wheeler *et al.*, 2005; Ruleman *et al.*, 2007). On June 21, 2022 a strong earthquake Mw 6.2 occurred at a shallower depth (~ 15 km), ~ 165 km southeast of Kabul, and killed more than 1000 people with huge property losses. It is considered to be a devastating event with MM intensity VII⁺ (NCS, 2022). We made an attempt to understand seismotectonics of the main shock and aftershocks, regional tectonic stress regime and the Coulomb stress change in the hypocentral area of the main shock.

Tectonic Setting And Seismicity

2.1 Tectonic setting

The continental collage of Afghanistan is made up of different tectonic domains or blocks from continental masses, sutured together through subduction and collision tectonics. The plate tectonic evolution of Afghanistan in the Phanerozoic yielded three main plate-tectonic provinces: (1) North Afghan platform, (2) Accreted terranes composed of crustal fragments and volcanic arcs, and (3) Transpressional plate boundary between the Eurasian and Indian plates. Afghanistan is under the influence of oblique subduction between the Indian and Eurasian plates to the north and gentle shallow subduction of the Arabian plate at the Makran trench in the south (e.g. (Wheeler *et al.*, 2005). To the west the collision shear component between central Iran and Afghanistan is taken up by a series of N-S trending right-lateral strike-slip faults. To the east, the left-lateral Chaman transform fault system, on the other hand, makes the eastern boundary between the Indian plate and Eurasian plate (Fig. 1). The Chaman transform fault links the Makran convergent zone to the south and the Hindu-Kush -Pamir to the north (Lawrence *et al.*, 1981). The ~ 850 km long left-lateral Chaman transform fault system, inferred with a highest slip rate of 26 mm/y (Apel *et al.*, 2006), is exhibited by the

Chaman-Gardez (CH-GA) fault system (Fig. 1), and it affect the continental deep-subduction in Hindu-Kush (Mohadjer *et al.*, 2010). In central Afghanistan intra-plate zone, the right-lateral strike-slip Helmand (HM) - Herat (HR) - Qarghanaw (QA) faults are, however, less active. To the northeast, the western Himalayan syntaxial Hindu-Kush as well as Pamir zone is represented by the Main Frontal Thrust, Main Boundary Thrust, Main Mantle Thrust and Main Karokarum Thrust, and the zone is seismically intensively active (Fig. 1).

2.2 Seismicity

A recent (1976–2020) seismicity map using the events Mw 6.0 and above of the region is shown in Fig. 1. Relocated events documented in the EHB (ISC) catalog are used to prepare the map. The map shows no much seismic activity at the central part of Chaman fault, but three large earthquakes, the 1909 (Mw 7.0), 1935 Mw7.5 and the 2013 Mw 7.7, occurred in the south and several in the northern segment of this fault system (Fig. 1). Epicenter of the 2013 event (Mw 7.7) is, however, not shown in the Fig. 1 as it falls outside the considered map. The ~ 1100 km long right-lateral strike-slip *Herat (HR)* fault system shows distinct morphological features that traverse almost the entire length of northern Afghanistan also seems to be seismically less active. To the northeast, the *Hind Kush - Pamir* collision zone, however, shows intense seismic activity down to 300 km depth, a zone at the final stage of subduction of oceanic lithosphere along the India-Eurasia collision boundary (Ambraseys and Bilham, 2003). The seismicity beneath Hindu Kush mostly occurs at a depth range of 70–300 km, slightly deeper than the earthquakes in Pamir region to its north. Relocated seismicity in Hindu-Kush and Pamir regions revealed a steeply northward dipping structure beneath Hindu-Kush, and a southward dipping structure under Pamir (e.g. Hamburger *et al.*, 1992; Negredo *et al.*, 2007; Sippl *et al.*, 2013). It is, however, still under debate whether there is a single contorted slab or two subducting slabs under the Pamir and Hindu-Kush (e.g. Billington *et al.*, 1977; Vinnik *et al.*, 1977; Pegler and Das, 1998; Negredo *et al.*, 2007; Sippl *et al.*, 2013; Kufner *et al.*, 2016, 2017).

The June 21, 2022 Main Shock And Aftershocks

The USGS reported the June 21, 2022 main shock M 6.0 at a focal depth ~ 10 km. The GCMT solution of the main shock, however, estimated Mw 6.2 at a centroid depth (15 km). The epicenter of the main shock is located to the east of Chaman (CH)–Gardez (GA) fault system, about 165 km southeast of the Kabul city (Fig. 1). The main shock was followed by a sequence of aftershocks; hypocentral details are given in Table 1. The epicenters of the main shock and aftershocks along with the past seismicity (Mw ≥ 5.0) are separately shown in Fig. 2a. The available GCMT solutions of the past events (Mw ≥ 5.0) are also illustrated in Fig. 2a. Though the June 21, 2022 main shock and aftershock epicenters are more than 50 km away from the CH–GA fault system, the northeast trending nodal plane of the main shock solution is comparable with the fault system. The largest aftershock Mw 4.8 occurred on July 18, and it caused a few more casualties and damages. A NW-SE seismic section of the main shock and aftershocks, across the CH-GA fault system as well as the aftershock trend, is examined and shown in Fig. 2b. It may be mentioned here that the main shock was well recorded by the CSIR-NEIST broadband observatory at Tezpur, Assam in northeast India (Fig. 3), which motivated us to understand this event.

Table 1
The June 21 2022 main shock and aftershock sequence, Afghanistan

The June 21, 2022 main shock and aftershock sequence, Afghanistan										
Sl. No.	YYYYMMDD	HH:MM:SS.SS GMT	Lat (°N)	Long (°E)	Mag	Depth (KM)	Strike (°)	Dip (°)	Rake (°)	Source
Main-shock										
A	20220621	20:54:39.10	32.94	69.51	6.2 Mw	15	202	57	10	GCMT
		20:54:36.14	33.09	69.51	6.0 M	10	...	...	...	USGS
Aftershocks										
1	20220621	21:49:22.18	33.07	69.94	3.5 mb	...	...	...	...	ISC
2	20220621	21:50:22.87	32.95	69.55						
3	20220623	08:07:13.14	33.13	69.43	3.8 mb	...	...	...	...	ISC
4	20220623	12:07:37.62	33.08	69.75	3.6 mb	...	...	...	...	ISC
5	20220623	19:51:49.54	32.96	69.17	3.5 mb	...	...	...	...	ISC
6	20220624	01:43:28.94	33.01	69.53	4.3 mb	10	...	...	...	NEIC
7	20220627	23:48:56.38	33.05	69.38	3.7 mb	...	...	...	...	ISC
8	20220718	12:22:44.35	33.06	69.50	4.8mb	...	...	...	...	ISC
9	20220718	15:12:25.59	32.87	69.29	3.4mb	...	...	...	...	ISC
10	20220718	16:47:44.59	33.01	69.65	3.5mb	...	...	...	...	ISC
11	20220718	19:23:14.90	32.94	69.52	4.5mb	10	...	...		GFZ
12	20220719	01:09:58.66	33.04	69.66	3.9mb	...	...	...	...	ISC
13	20220724	21:41:08.86	33.16	69.40	3.4mb	...	...	...	...	ISC
14	20220727	01:47:08.54	33.02	69.57	3.7mb	...	...	...	...	ISC
15	20220802	13:42:30.23	33.09	69.86	3.8mb	...	...	...	...	ISC
16	20220822	13:53:50.40	33.05	69.61	4.5mb	...	...	...	...	ISC

According to the NCS report (2022), a maximum MM intensity VII⁺ was estimated. The USGS reported PGA contours are shown in the main shock epicenter area (Fig. 2a). The main shock and the largest aftershock caused some 1,150 casualties 6,000 injuries and over 360,000 affected. A total of 10,000 houses were partially or totally destroyed. In terms of casualties and damages, it is reported as a deadliest earthquake in

Afghanistan during the last two decades. The shallow focus night time event when people were asleep and poor construction of the houses caused such devastation. A similar observation was reported for an earthquake Mw 6.3 in May, 1993 in early hours in Kilari in the intra-plate region of central India (Kayal and Mukhopadhyay, 2002).

Coulomb Stress Change

Numerous studies are made for forecasting aftershocks triggered by main shock estimating Coulomb stress change analysis (e.g. Kilb, Gomberg, and Bodin 2002; King, Stein, and Lin 1994; Weatherley 2006). We examined the Coulomb stress change after the June 21, 2022 main shock at the rupture zone for a definite time window. The Coulomb 3.2 software (<https://earthquake.usgs.gov/static/lfs/software/coulomb34.zip>) is used. The Coulomb stress change is defined as (King *et al.*, 1994; Toda *et al.*, 1998), where $\Delta\sigma$ and $\Delta\tau$ are the shear and normal stresses over the target fault plane respectively. While μ is the apparent coefficient of friction (Harris, 1998), and given as $\mu = \frac{\Delta\tau}{\Delta\sigma}$, where, B is the Skempton's coefficient varying between 0 and 1 (Skempton, 1954; Brown and Korrington, 1975; Zhang *et al.*, 2009). We estimated the stress change assuming (Stein *et al.*, 1994) based on the elastic dislocation modelling of earthquakes on a rectangular fault (e.g. Gahalaut 2006; Okada 1992). We considered the NNE-SSW orientated plane as the fault plane for the receiver fault. We assumed Young modulus of dyne-cm^2 and Poisson's ratio of 0.25 for computation. The Coulomb stress change map at the hypocentral of the main shock is shown in Fig. 4.

Discussion And Conclusions

The study area in Afghanistan is intersected by several faults like, the Mokur (MO), Chaman (CH), Gardez (GA) etc (Fig. 1). The epicenter of the main shock is much away from the northern Hindu-Kush collision zone, southern Makran subduction zone or from the Iran transpressional zone (Fig. 1). This shallow focus main shock and its aftershocks may be considered as intra-plate earthquakes near the left-lateral CH-GA fault system. The tectonic stresses from surrounding tectonic domains are transmitted to the intra-plate area, and the accumulated stresses at the fault intersection zone triggered a hidden fault in the intra-plate zone. Globally it is observed that fault intersecting zones in intra-plate areas are the source zones for infrequent medium to strong shallow earthquakes (e.g. Gangopadhyay and Talwani 2003; Kayal and Mukhopadhyay 2002). The GCMT solution of the main shock shows a strike-slip solution (Fig. 2a). The NE-SW trending nodal plane of the solution is correlatable with the left-lateral CH-GA strike-slip fault system in the intra-plate zone. Some 16 aftershocks ($M_w \geq 3.4$) were reported (Table 1); the largest aftershock (m_b 4.8) occurred on July 18, some four weeks after the main shock. The largest aftershock is about 1.2 to 1.4 magnitude unit down with respect to the main shock magnitude, which is near to the global average 1.0-1.2. The focal depths of the aftershocks are, however, not well estimated by the global network (Table 1).

The NW-SE seismic cross section of the main shock, aftershocks and the past earthquakes indicates that the CH-GA fault system is much active that produced large earthquakes ($M_w \geq 7.0$) in the past, and the hypocentral distribution indicates near vertical fault system, down to 30 km depth. The June 2022 main shock, aftershocks and the past events reveal a hidden fault with a near vertical shallow structure (depth 10–40 km). All the reported aftershocks in this study, however, are of much lower magnitude ($M_w \leq 4.8$), the depths are not well estimated by the global network; thus the fault geometry is not well reflected in the seismic section. Depth

distribution of the past events shows another near vertical shallow source zone / structure in the lower crust (depth 20–40 km) further southeast, at the Indian-Eurasian transpression boundary (Fig. 2b). These faults or structures are possibly not surfaced; these are hidden and not mapped. We believe that the June 2022 main shock and aftershocks are triggered by a shallow hidden fault structure which falls in the CH-GA fault system in the eastern transpression zone. Since no detailed aftershock investigation using a close-spaced microearthquake network is carried out, details of the subsurface seismogenic structure in terms of fault geometry or velocity structures of the source zone are not revealed, as investigated for the recent strong/large earthquakes in the Indian intra-plate region (e.g. Kayal and Mukhopadhyay 2002; Singh et al. 2016)

Stress regime of the study region is examined by stress tensor inversion that shows dominant NNW-SSE compressive stress and ENE-WSW extensional stress (Fig. 1). The Coulomb stress changes after the main shock is illustrated in Fig. 4. It is observed that all the aftershocks including the largest aftershock occurred in the positive stress change area (red loop) in the rupture zone. Thus immediate imaging of the Coulomb stress changes help us to understand the expected zone of the aftershocks or the largest aftershock. Normally the partially damaged structures/ houses collapse due to shaking of a largest aftershock. This has also been reported after the main shock (USGS Report).

In conclusion, we may infer that the CH-GA left-lateral strike fault system is seismically active, and causes shallow focus medium to strong (M_w 5.0–6.0) earthquakes in surrounding areas in the eastern transpression zone. Historically, three large earthquakes ($M_w \geq 7.0$) and several strong earthquakes ($M_w > 6.0$) are reported at the southern segment of the CH fault system which experiences much stress due to the Makran subduction as well as due to the Indian-Eurasian transpression (Fig.1). The northern segment of the fault system experiences much more stress due to Hindu-Kush collision as well as due to Indian-Eurasian transpression, and produces many strong or large earthquakes (Fig. 1). Large ($M_w \geq 7.0$) or strong ($M_w \geq 6.0$) earthquakes are, however, not frequent in the central part of the CH fault system. The central part of the fault system, our study area, behaves more like an intra-plate zone and produces infrequent strong earthquakes. The stress tensor inversion estimates a NNW-SSE compressional stress and WNW-ESE extensional stress in this zone, which is conducive for strike-slip movement on the existing fault system. The June 21, 2022 shallow focus main shock occurred by left lateral strike-slip movement in this zone. Though the main shock magnitude was of the order of M_w 6.0–6.2 only (USGS and GCMT Reports, respectively) the huge casualties and devastation were caused due to night time occurrence of the event when people were asleep and also due to poor construction of the houses. The Coulomb stress changes due to the main shock clearly depict the zone of aftershock sequence. A more detailed aftershock investigation by a temporary network was needed to image the fault / source zone of the earthquake sequence. However, within the data limitation, the results shed some light on seismotectonics of the recent deadliest Afghanistan earthquake.

Declarations

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Date & Resources: Global CMT solutions used in this study can be obtained through <http://www.globalcmt.org/CMTsearch.html> (last accessed October, 2022). While earthquake catalogue data are taken from International Seismological Centre via <http://www.isc.ac.uk/iscbulletin/search/catalogue/> (last accessed October, 2022). The BB waveform used in this study are taken from the Multiparametric Geophysical Observatory (MPGO) situated at Tezpur, Assam, India. These data can be directly accessible by sending a request to the Director, CSIR-North East Institute of Science and Technology, Jorhat-6, Assam, India at director@neist.res.in.

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Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Santanu Baruah, Chandan Dey, Sowrav Saikia, Timangshu Chetia, N Molia, P Borthakur & Devajit Hazarika. Devajit Hazarika & Santanu Baruah have prepared the figures. J R Kayal & Santanu Baruah wrote the manuscript and all authors commented and checked the manuscript for any mistakes. All authors read and approved the final manuscript before submission.

Ethical Responsibilities of Authors

- The manuscript has not submitted to other journal for simultaneous consideration.
- The submitted work is original and not published elsewhere in any form or language (partially or in full).
- Results are presented clearly, honestly, and without fabrication, falsification or inappropriate data manipulation (including image based manipulation).
- No data, text, or theories by others are presented in this work.

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Figures

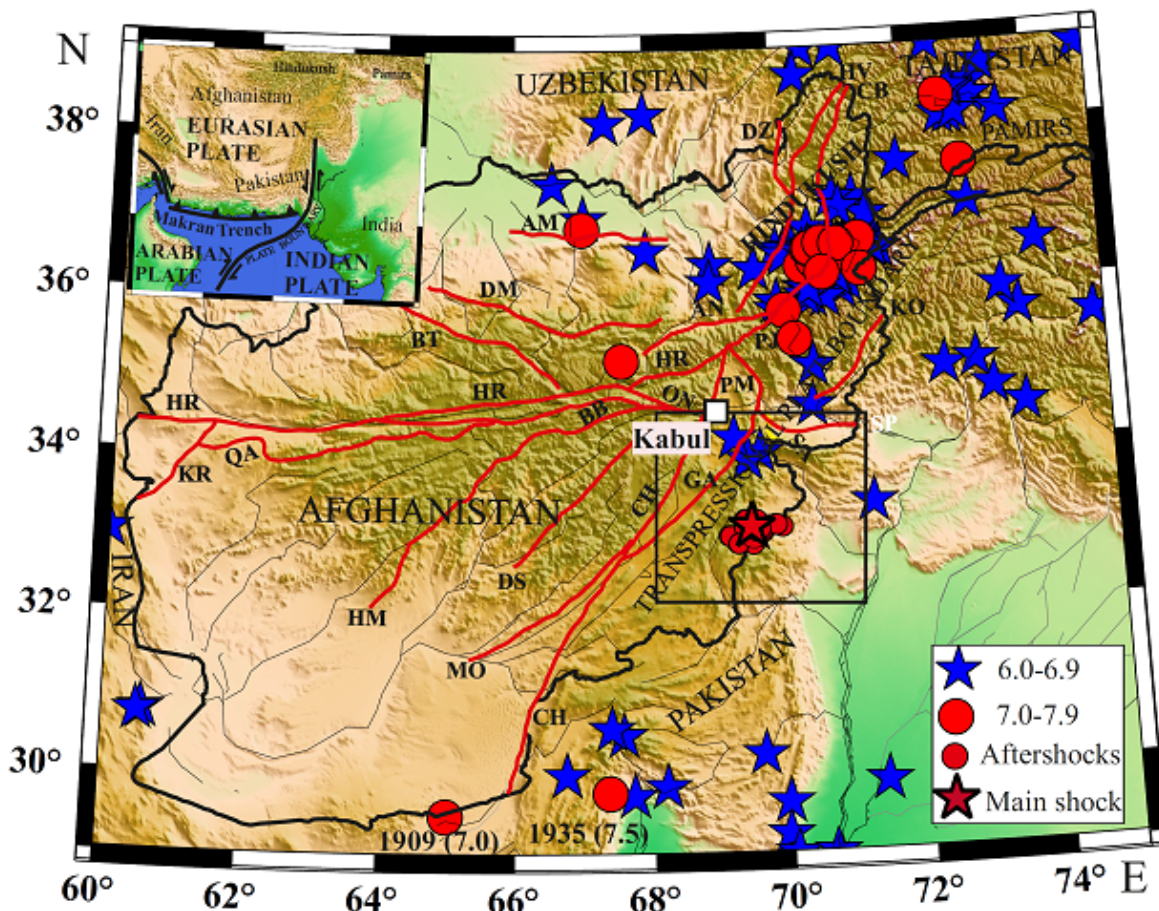


Figure 1

Map showing topography and epicenters of strong/ large earthquakes (M: 6.0-7.9) in Afghanistan. The June 21, 2022 main shock (Mw 6.2) and aftershocks are shown in the demarcated rectangle area. The major tectonic features (after Shareq and Chmyriov, 1977) are: AM: Alburz Marmul, AN: Andarab, BB: Bande Bayan, BT: Bande Turkestan, CH: Chaman, CB: Central Badakhshan, DS: Darafshan, DZ: Darvaz, DM: Dosi Mirzavalan, GA: Gardez, HR: Herat, HM: Helmand, HV: Henjvan, KR: Kaj Rod, KO: Konar, MO: Mokur, ON: Onay, PM: Paghman, PJ: Panjshir, QA: Qarghanaw, SA: Sarobi, SP: Spinghar. **Inset:** Regional tectonic map showing Makran subduction, eastern and western transpression and northern collision zones.

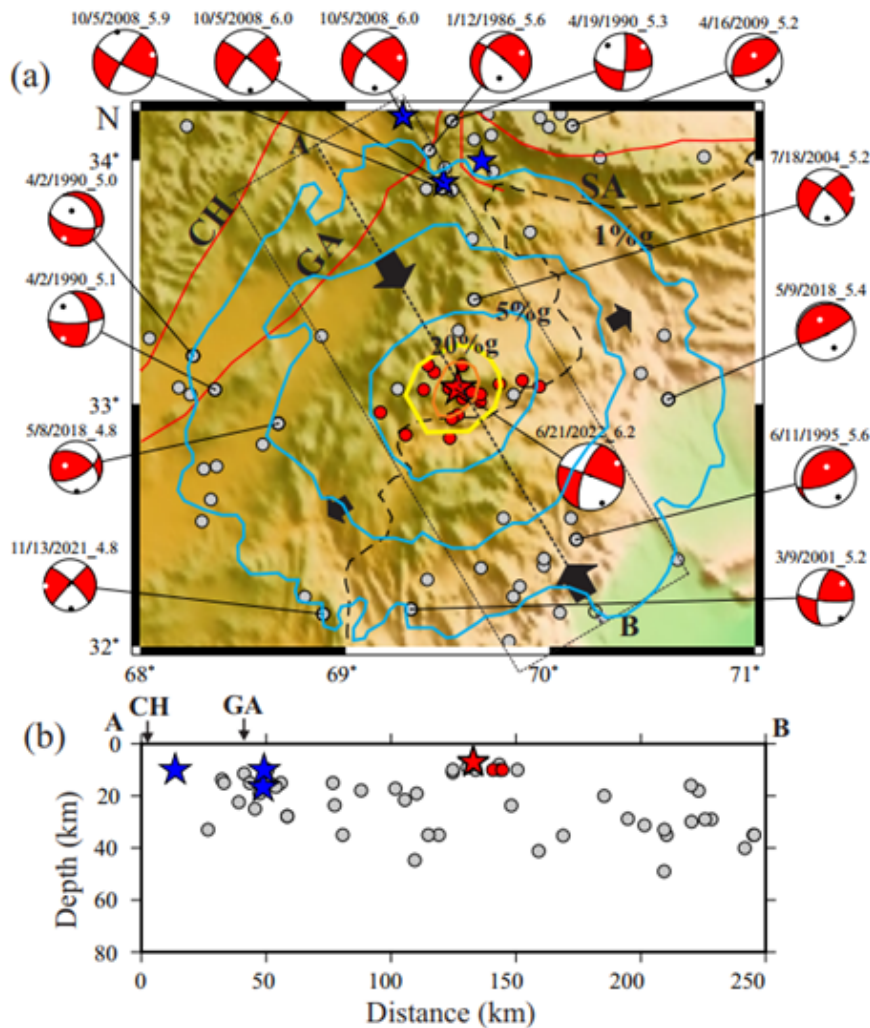


Figure 2

(a) Study area showing epicenters of the main shock, aftershock sequence (Table 1) in red, and the background seismicity (Mw > 5.0) in grey. The regional stress obtained by stress tensor inversion using the available fault plane solutions are shown by arrows; the NW-SE compression by thicker arrows, and the NE-SW extension by thinner arrows. (b) A seismic cross-section along A-B, in perpendicular direction of the tectonic as well as aftershock trend, showing depth distribution of the earthquakes within 0.50 on either side of the profile A-B. The PGA contours are shown as reported by the USGS ([https:// earthquake. usgs.gov/earthquakes/ eventpage/ us7000hj3u/map](https://earthquake.usgs.gov/earthquakes/eventpage/us7000hj3u/map)).

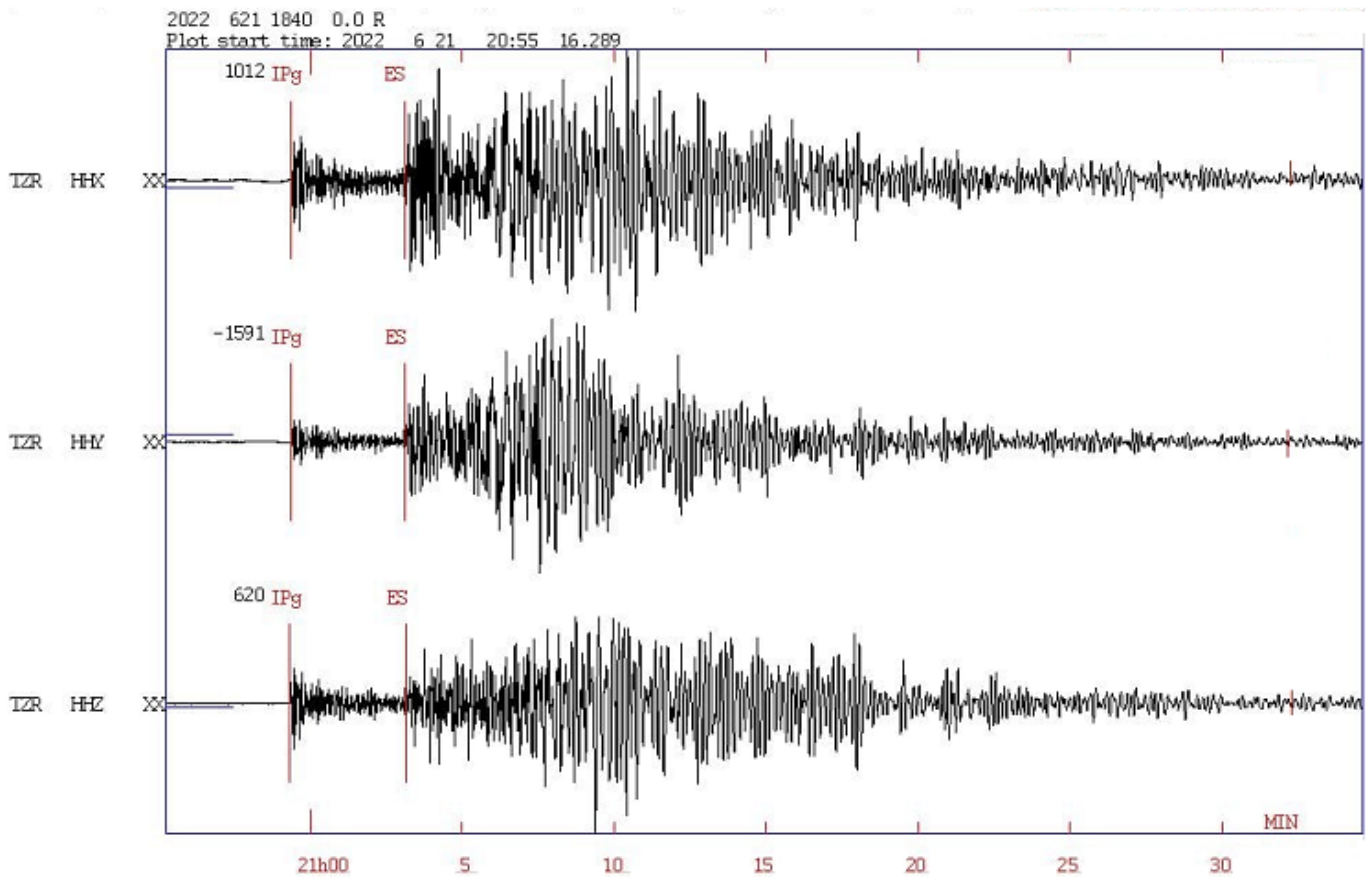


Figure 3

The seismograms of the June 21, 2022 Afghanistan earthquake (main shock) recorded by the BB seismic observatory at Tezpur, Assam, India more than 2000 km away from Kabul, Afghanistan.

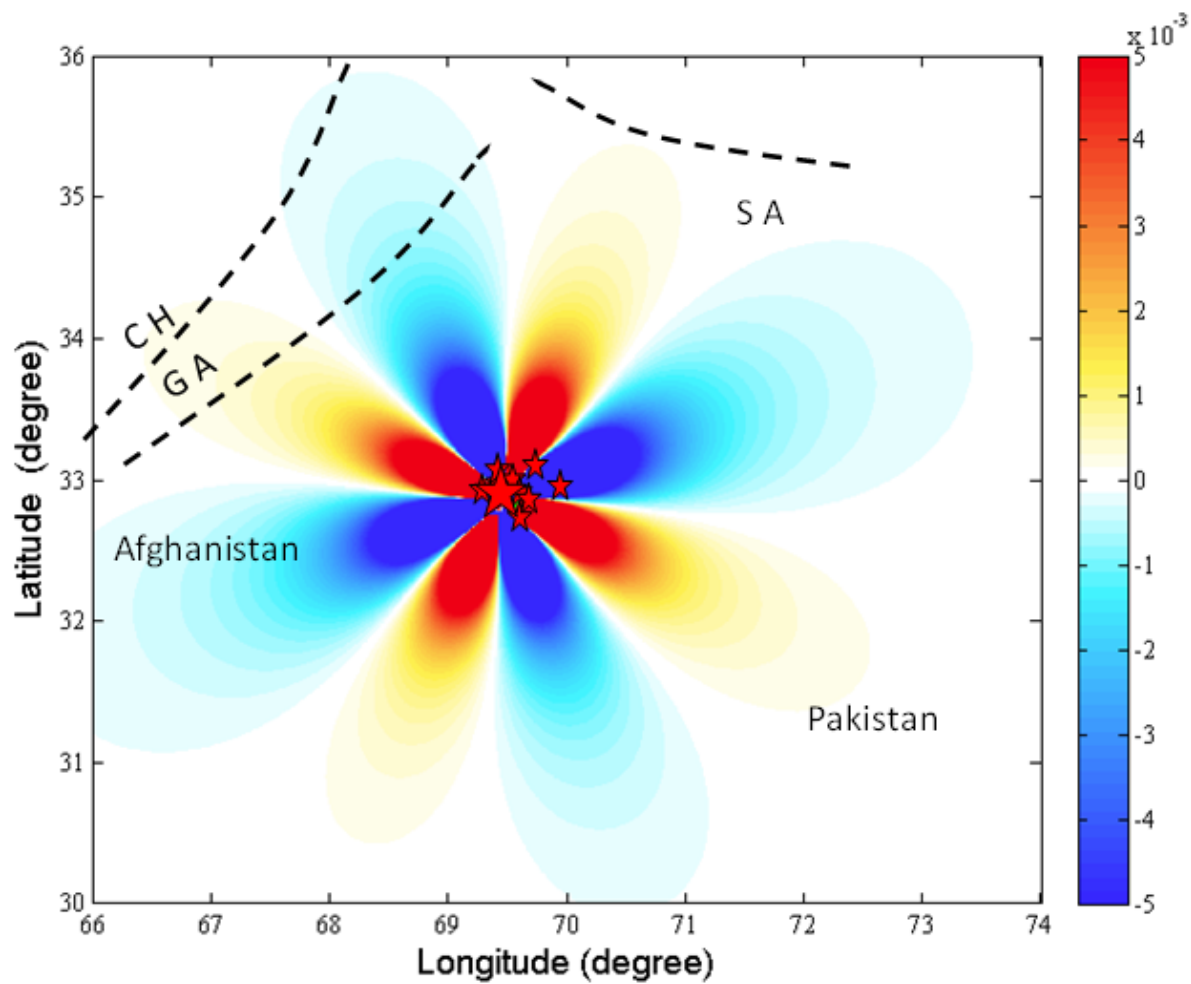


Figure 4

Change in Coulomb static stress ΔS_f on optimally oriented strike-slip plane due to slip on the rupture of the main shock. The hot color (red) indicates increase in stress and the light color (blue) decrease in stress. The red big star indicates the main shock and the smaller stars aftershock.