Project Name: Geodetic imaging of the interplay between creep, locking, earthquakes and land subsidence along the Chaman plate boundary.

Project Summary

The Chaman transform fault system of Pakistan and Afghanistan is one of the most prominent continental strike-slip plate boundary zones in the world. It stretches >1200 km from the Arabian Ocean in southern Pakistan to the Hindu Kush mountains in Afghanistan, forming the western boundary of the India plate with the Eurasian plate. The greater Chaman fault system has hosted a series of large and destructive earthquakes, including the 1892 M6.6 Chaman, the 1909 M7.1 Kachhi, the 1931 M7.3 Mach, the 1935 M7.7 Quetta, the 2013 M7.7 Balochistan, and the 2022 Khost (near the Afghanistan-Pakistan) earthquakes. Despite the history of large and destructive earthquakes, modern geodetic measurements across the Chaman transform boundary are limited, due to the harsh landscape and generally difficult access. To date, we do not know the individual slip rates and locking depths of faults within the Chaman fault system, nor do we know where interseismic strain is accommodated beyond the Chaman and Ghazaband faults.

In addition to the tectonic loading, hydrological processes also generate and impact deformation patterns throughout the Chaman fault system. In particular, the rapid exploitation of groundwater has caused widespread land subsidence across much of the Indus basin and northern Balochistan. The groundwater extraction and resulting subsidence not only cause damage to buildings and infrastructure and permanent compaction of fine sediment layers, resulting in a significant decline in the groundwater level and the storage potential of the aquifer in Quetta city. Measuring and modeling the rates and impacts of surface deformation in agricultural regions and densely populated cities in Pakistan are essential to reducing the damage of local buildings and infrastructure due to land subsidence associated with groundwater extraction and to help the local authorities better manage the groundwater usage.

The goals of this project are to quantify the spatial and temporal distribution of surface deformation along Chaman transform fault system in Pakistan and Afghanistan using satellite geodesy, including InSAR, GNSS, and creepmeter measurements; and explore the mechanical

interactions between fault creep, interseismic loading, seismicity, and ground deformation associated with groundwater extraction along the Chaman plate boundary.

The GNSS system that we use during the project surveys is called the Trimble Netrs GPS reference station which is one of the most advance and high accuracy GPS systems available. Its accuracy can reach up to sub-millimetres if installed as a continuous station. Trimble NetRS features extremely rugged construction, low power consumption and dual power ports with intelligent switching. Its advanced communications control makes it easy for you to operate the receiver and manage data from a convenient location—it's not necessary to have a local computer. Following problems such as power loss, the NetRS receiver can reload its last known configuration settings; this ability eliminates the need to visit remote locations to manually reset the receiver.

The project is undertaken collaboratively with colleagues at the Department of Earth & Planetary Science, Barkley University of California. From the Pakistan`s side the project is led by Mr. Najeebullah from the Department of Geology, University of Balochistan. In 2022 Najeebullah's research team in Pakistan measured two dozen new GPS points throughout eastern Baluchistan, and established several new continuous monitoring points that includes University of Balochistan main campus, Kharan campus, Baluchistan University of Engineering and Technology, Khuzdar and DC office Chaman to provide ground control of our collaborative space based InSAR studies.

Tools: GPS, InSAR and Creepmeter

Geographic Location: Chaman Plate Boundary, Pakistan

Group Members Involved: Najeebullah, Din Muhammad kakar (Department of Geology, University of Balochistan), Roger Bilham (University of Colorado Boulder), Roland Bürgmann, Kang Wang (Department of Earth & Planetary Science, Barkley University of California)

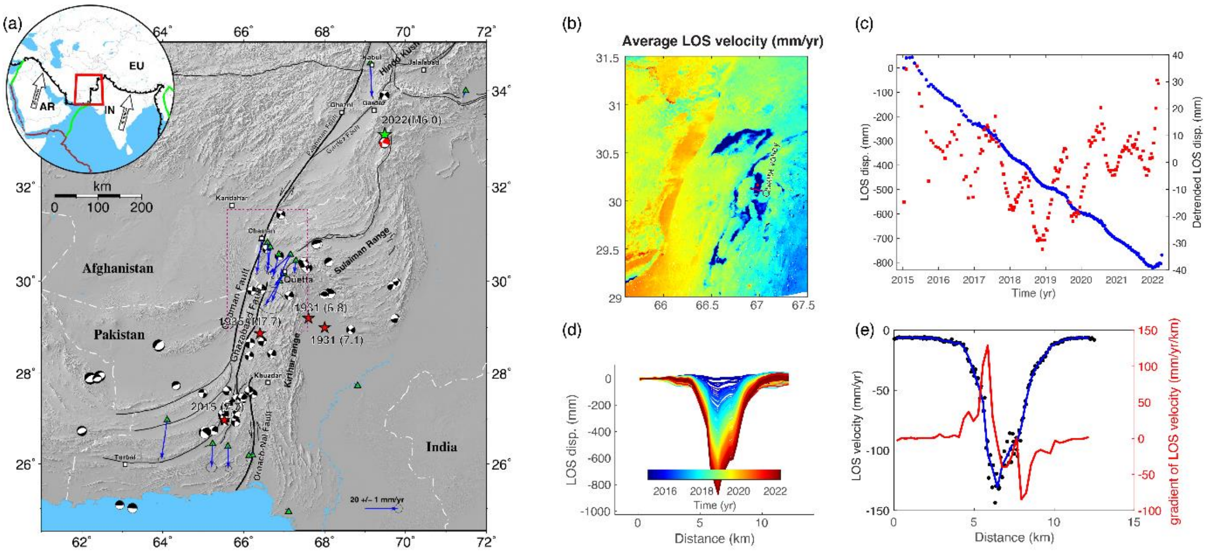

Figure 1 Tectonic setting of the Chaman plate boundary and Sentinel-1 InSAR observations covering the central portion of the Chaman fault. (a) Geologic setting of the Chaman transform fault system. Black lines represent Quaternary faults from Mohadjer et al. (2016). Focal mechanisms represent earthquakes >M5 from 1976-2019; red stars indicate historical earthquakes >M7 (Ambraseys and Bilham, 2003). Blue vectors represent GPS velocities relative to stable India (Szeliga et al. 2012). White, magenta, and green rectangles indicate the ground coverage of SAR images from the ALOS-2 (ascending) and Sentinel-1 (ascending and descending) instruments, respectively. White squares show the locations of cities with populations >100,000. (b) Average InSAR line-of-sight (LOS) velocity covering the central portion of the Chaman fault (purple dash box in panel a) derived from Sentinel-1 data of the ascendign track T42 from 2015 to 2022. Red color represents motion toward the satellite, and blue represents motion away from the satellite. Note the sharp gradient in LOS velocity across the trace of Chaman fault, indicative of fault creep at the surface. The InSAR data also reveal clear and widespread ground subsidence across many of the residential and agricultural areas near the Chaman fault system in southern Pakistan. Particularly, up to >15 cm/yr of ground subsidence is observed across the Quetta valley, where the capital and largest city of the Baluchistan province is located. From 2015 to 2022, the central portion of the Quetta valley has produced ~1 meter of ground deformation along the radar line-of-sight (panels b-e). We also notice that although the LOS deformation related to the groundwater extraction is mostly linear with time, removing a best-fit linear trend from the original time series reveals clear seasonal variations in the residual deformation time series across much of the Quetta valley (red dots in panel c), indicating that part of the aquifer compaction in the Quetta valley is still

elastic and recoverable, so timely recharge and proper management of groundwater usage may prevent further damage and permanent loss to the storage capacity of the aquifer.

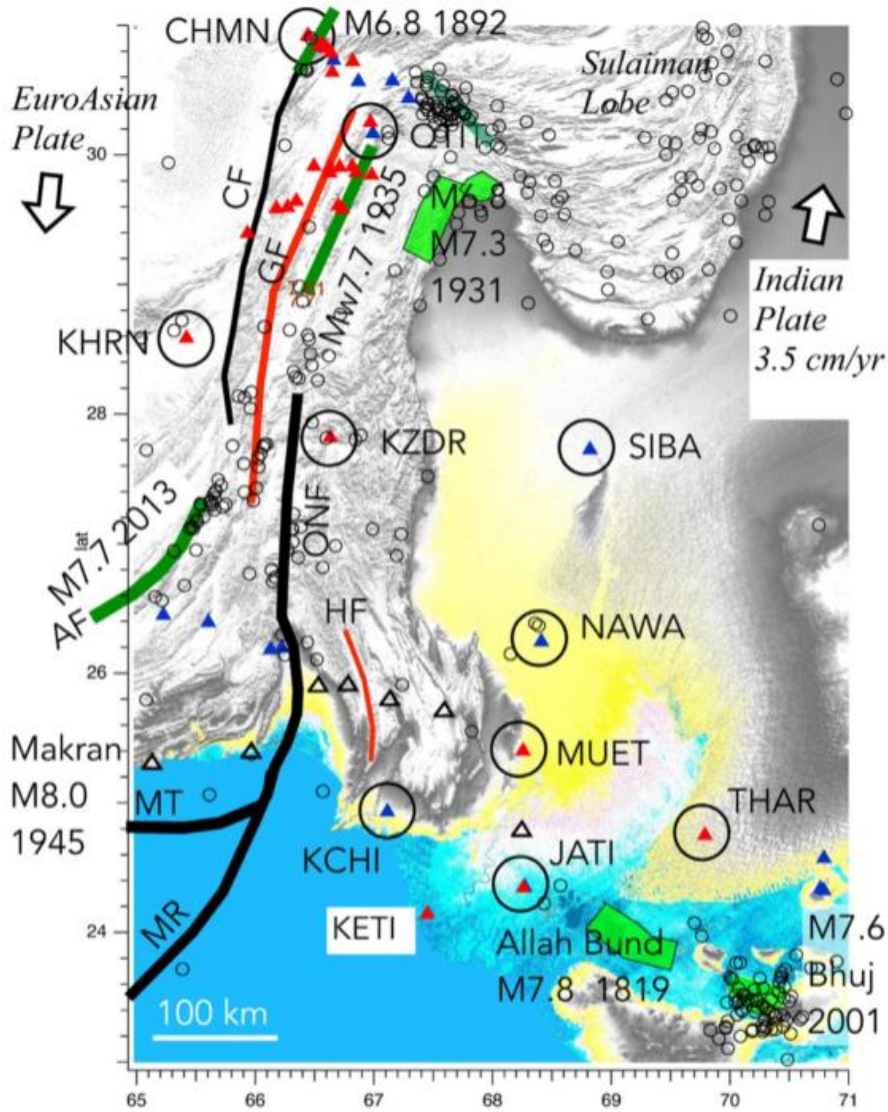

Figure 2 Baluchistan/Sindh study area of southern Pakistan showing major plate boundary faults black, and ruptures in the past century Mw>6.8 (green) with date. Red faults have not slipped historically. Earthquakes Mw>4.5 since 2000 shown as open circles, blue triangles pre-2022 GPS, 25 red triangles newly established GPS points 2022/3. Online cGPS points circled. Light blue to yellow shading highlights elevations <100 m. AF=Awaran Fault, CF=Chaman Fault,

GF=Ghazaband Fault, HF=Hab Fault, MT=Makran Thrust, ONR=Ornach Nal Fault, MR=Murray Ridge. KETI is a proposed site for a focussed delta subsidence study.

Continuous GPS stations

Latitude	Longitude	Elevation (meters)	Site Name
30.162949	66.98888	1673	QTIT
30.250952	66.97027	1611	DNKR
30.920362	66.44374	1227	CHMN
27.819381	66.631308	1412	KZDR
28.586585	65.41985	730	KHRN

Campaign GPS stations

Latitude	Longitude	Elevation (meters)	Site Name
30.841979	66.534689	1662	GNCP
30.843427	66.559485	2027	MJNR
30.846744	66.569276	2208	KJPT
30.821906	66.604715	1871	SBSL
30.785398	66.641219	1681	ZBLS
30.721824	66.820833	1480	LMRN
30.638	66.649681	1515	LJWR
29.912891	66.494755	1498	PNJP
29.898728	66.629705	1570	ABAD
29.860755	66.628399	1678	BGTB
29.905468	66.7121	1745	BBRI
29.908311	29.908311	1605	DRNG
29.909347	66.817543	1643	KOSH
29.864649	66.849269	1644	PRING
29.844741	66.980612	1784	DHOR

29.582051	66.733446	1776	KDKH
29.608533	66.699704	1783	KDHU
29.644392	66.346535	1583	KOTL
29.595603	66.274142	1484	GLNG
29.585583	66.17873	1318	KSHG

Field Photos