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RESEARCH ARTICLE

FOCAL MECHANISM SOLUTIONS AND SEISMIC IMPLICATIONS FOR THE EASTERN MAKRAN: A 30-YEAR PERSPECTIVE

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ABSTRACT

The Makran Subduction Zone, straddling the nothern Arabian Sea along the borders of Pakistan and Iran, represents one of the most seismically complex regions on Earth, where the Arabian, Eurasian, and Indian plates converge. This study delves into the seismic intricacies of Eastern Makran, an area delineated by a labyrinth of tectonic demarcations including the Zendan, Jiroft, and Ornach-Nal faults, to uncover the underpinnings of its seismicity through an analysis of focal mechanism solutions (FMS) for earthquakes occurring between 1990 and 2019. Utilizing the Kikuchi and Kanamori method for modeling teleseismic P-waves and their surface reflections, this research filters through the data, discarding those compromised by noise, to present a clear picture of seismic activity ranging in magnitude from 4.0 to 7.8 Mw. Contrary to the expected prevalence of major earthquakes, findings reveal a rarity of such events in Eastern Makran, suggesting a nuanced interaction between the Indian and Eurasian plates marked by anticlockwise rotation. This rotation potentially fosters the isolation of microplates, hinting at a dynamic interplay of tectonic forces. Our comprehensive 30-year perspective provides new insights into the focal depths and fault plane solutions, contributing to a better understanding of the seismic behavior and tectonic mechanisms governing the Eastern Makran Subduction Zone.

KEYWORDS

Subduction Zone, Earthquake focal depths, Focal mechanisms, Seismogenic thickness

1. INTRODUCTION

The Makran Subduction Zone (MSZ), delineating the convergent boundary where the Arabian, Eurasian, and Indian plates meet (Abbasi, 2020). It is renowned for its seismic complexity and significant geotectonic interest. This nexus of tectonic activity forms a pivotal triple junction, situated along the northern expanse of the Arabian Sea, extending from the eastern shores of Iran to the southern coastlines of Pakistan (see Figure 1).

The MSZ is distinguished by the Left-lateral Chaman and the Right-lateral Zendan strike-slip faults, with the Northward Jiroft Fault (comprising ophiolites) and the Oman trench to the south, framing this subduction zone in the offshore landscape (Siddiqui and Jadoon, 2012).

MSZ is said to be World's largest accretionary prism extending over 1000 kilometers, a testament to its complex subduction mechanics characterized by a significant influx of sediments, leading to a profound sedimentary cover measuring approximately 7.5 km resulting from the accumulation and deformation of marine flysch deposits (Kopp et al., 2000; Gutscher and Westbrook, 2009; Ellouz-Zimmermann et al., 2007a; Smith et al., 2012; Burg, 2011).

The Eastern part of MSZ is a region where Triple Junction is present, where the Arabian Plate is undergoing beneath Eurasian plate at speed of 40 mm/yr as an average of whole Makran in Pakistan and Iran (Ellouz-Zimmermann et al., 2007b; Abbasi, 2020; Romano and Matteucci, 2007; DeMets et al., 2010; Siddiqui and Jadoon, 2012; Smith et al., 2012; Burg, 2018a; Siddiqui and Jadoon, 2012; Smith et al., 2012). The interplay between the Eurasian and Indian plates features a counter-clockwise motion, accentuating the tectonic dynamism of the area (Reilinger et al., 2006) (see Figure 1).

Figure 1: Study Area, showing Tectonic Boundries.

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Eastern Makran is marked by prominent sinistral faults, with the Chaman fault, initially a transform fault, orchestrating lateral movement along the North-South axis (Khan et al., 1991).

In several zones of Makran, there are different tectonic features; through the difference in style and intensity of tectonism. The surface of the accretionary prism of Makran might be marked by steep, asymmetrical folds and imbricate thrust wedges. Folds mainly strike EW; almost parallel to the fold axes there are Reverse faults roughly dipping to NW, (Ahmed, 1969)). As we observed, offshore of Makran is situated in water depths of almost 750 to 3000 meters, the Makran coast, despite high sedimentation, lacks significant bathymetric trench features, indicative of the intense tectonic forces at play (White, 1979). It is typically a region bounded by Faults from almost all sides and and is a critical fragment of the Neo-Tethys realm (Siddiqui and Jadoon, 2012).

Based on tectonic and stratigraphy Makran can be split into four parts from north to south as stated below,

Northern Makran is demarcated by the Jaz Murian Depression and Mashkel Depression to the north, transitioning southward through a series of ophiolites and lithological imbrications initiating thrusting within the Bajgan-Durkan Complex, delineating North Makran's lower boundary (McCall and Kidd, 1982; McCall, 1985; Glennie et al., 1990; Burg et al., 2013; Burg, 2018b). Inner Makran has thrust sheets between Bashakerd Thrust at the upper boundary and Ghasr Ghand Thrust (GGT) at the lower boundary (McCall and Eftekhar-Nezad, 1993; Haghipour et al., 2012). Outer Makran has GGT at the upper margin and Chah Khan thrust CKT located at the lower boundary with deep-sea fans (Harms et al., 1982; Dolati, 2010). Finally, Coastal Makran CKT is marking the northern boundary and the South end has been marked coastal line and then Oman trench (Mohammadi et al., 2016) (see Figure 2).

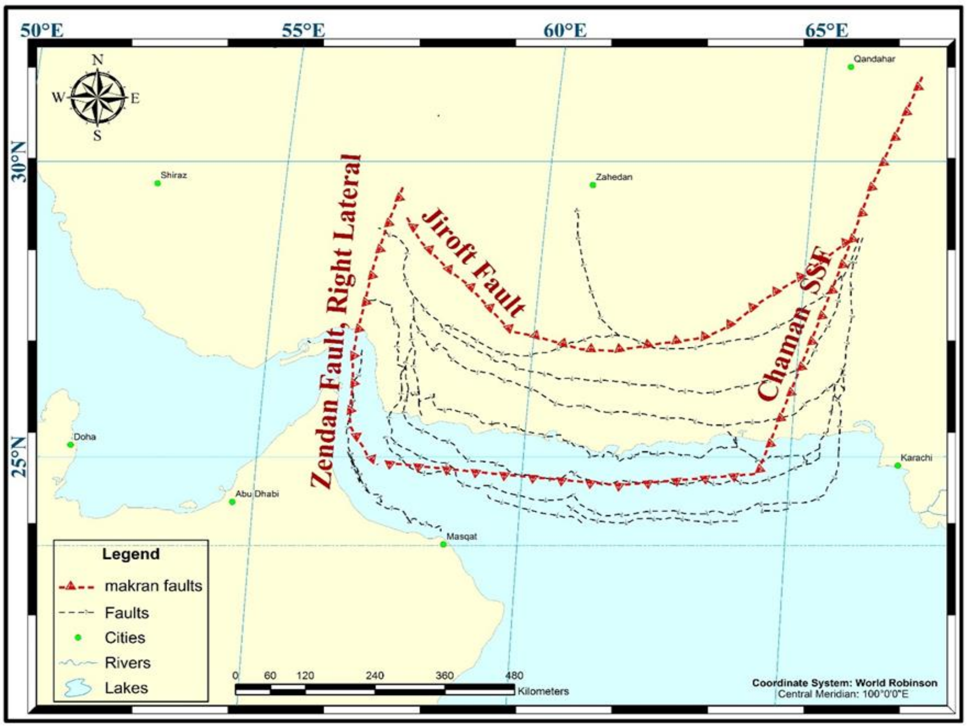

Figure 2: Showing documented faults as "Makran faults" while proposed faults for this area as "Faults" for this region.

The seismicity within MSZ is anomalous; despite being an active subduction zone, it exhibits relatively low seismic activity compared to global counterparts (Mokhtari et al., 2008).The dichotomy between Eastern and Western Makran is striking, with the former exhibiting notable seismicity, including the historic 1945 Mw 8.1 earthquake, which was situated nearly 30 km Northwards from Oman trench on Continental crust, whereas the latter remains ominously quiescent, fostering speculation of impending seismicity (Rajendran et al., 2013a; Jacob and Quittmeyer, 1979; Pacheco and Sykes, 1992; Musson, 2009; Rajendran et al., 2013b).

Seismicity in the Iranian segment of Makran appears diminished especially in the vicinity of the Zagros ranges in Western Makran, with earthquake events confined to the crust (<20 km depth) (Byrne et al., 1988; Masson et al., 2005; Paul et al., 2006; Maggi et al., 2000). Understanding seismic wave behavior through FMS unveils critical insights into source rupture, subduction zones, and fault dynamics (Banghar and Sykes, 1969; Shimizu et al., 2019).

Prior investigations into the seismicity of the Makran region have yielded significant insights, integrated FMS with geodetic and geomorphologic data to delineate the intricacies of the Makran Subduction Zone (MZS) using events from 1945 to 2013 with magnitudes above 4.0 (Penney et al., 2017). Furthermore, researcher conducted a comprehensive geophysical study on Western Makran, employing synthetic seismograms from the Iranian Seismological Center to create detailed tomographic maps, analyzing nearly 630 seismic events recorded from January 2006 until May 2019 (Shirzad et al., 2019). These foundational studies have established a precedent for our research, highlighting the variability in seismic activity across the Makran region, from the subdued seismicity in the Iranian segment to the pronounced historical events in Eastern Makran. Our study seeks to extend this knowledge base by elucidating the seismic mechanisms and tectonic dynamics specific to Eastern Makran, with an analysis that bridges the gap between past seismic observations and present-day understanding.

2. Material and Methods

This study utilizes the moment tensor inversion technique to analyze seismic events occurring from 1990 to 2019. The methodology is underpinned by seismic inversion, which involves transforming seismic observation data into a comprehensive mechanical source model of earthquakes. Moment tensor inversion is a critical technique in seismology that reveals the earthquake source mechanism, including the orientation and movement on the fault plane.

To ensure the accuracy of our inversion results, we have implemented stringent noise mitigation strategies. Specifically, we selected earthquake recordings with epicentral distances ranging from 30° to 90° to minimize the effect of shallow mantle triplications on the vertical component data. We applied a range of bandpass filters to isolate the relevant seismic frequencies, with corner frequencies tailored to the expected signal bandwidth of each individual event. This approach has been instrumental in enhancing the signal-to-noise ratio, ensuring the reliability of our seismic event characterizations. For a more detailed analysis of each seismic event, we utilized the Global Centroid Moment Tensor (GCMT) catalog, which provided additional attributes for each event (Ekström et al., 2012).

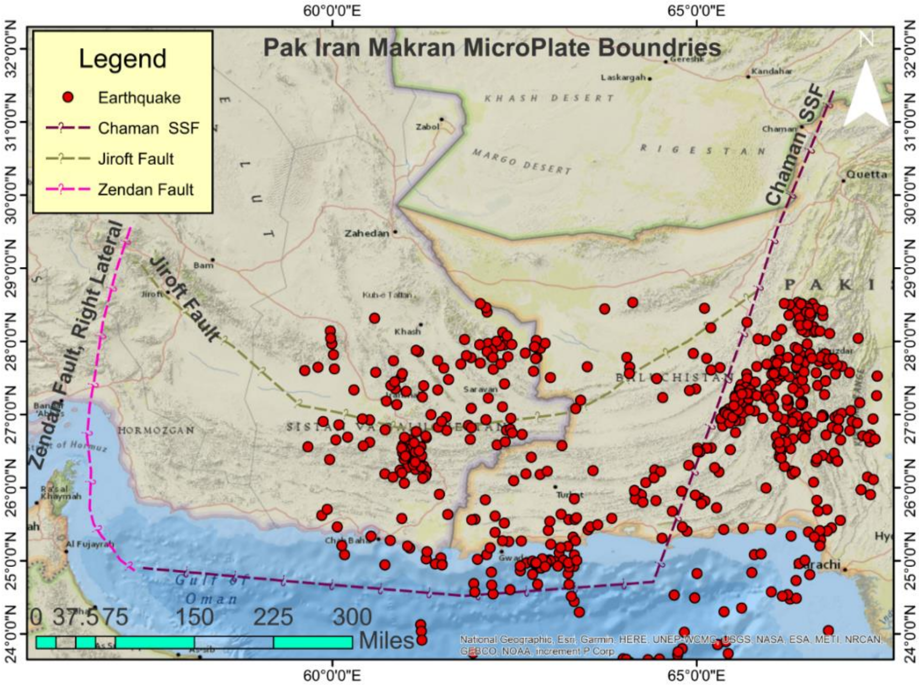

Figure 3: Boundaries selected on the base of major faults and structures along with Earthquake events (1990-2019) along Eastern Makran.

Table 1: Data of earthquake events used during this research.

S.No	Latitude	Longitude	Depth	Strike	Dip	Slip	Magnitude
1	65.25	26.75	19	210	63	15	5.8
2	65.81	27.44	43	209	63	2	5.8
3	62.94	25.08	29	309	8	133	5.3
4	62.88	24.25	29	298	10	126	5.6
5	65.97	27.47	33	102	60	156	5.9
6	61.43	25.68	33	8	54	142	5.7
7	62.38	27.88	56	82	36	-81	5.7
8	63.25	24.79	10	300	19	101	5.1
9	62.42	27.77	56.7	61	41	-92	5.5
10	60.91	27	61.3	97	45	-65	5.3
11	62	26.73	54	253	37	-89	5.9
12	61.23	26.07	43.8	107	67	-12	5.1
13	64.99	24.31	51.7	137	61	9	5.1
14	66.14	28.38	35	197	86	-2	5.1
15	64.36	23.22	13	215	50	-146	5.8
16	66.13	27.62	10	90	58	-176	5.6
17	61.24	23.88	15.3	94	58	36	5.1
18	65.85	27.06	30	216	61	-157	5.1
19	66.02	27.37	12	41	23	73	5.3
20	61.23	23.76	17.8	103	54	44	5.1
21	65.89	27.3	10	47	21	96	5.3
22	61.23	26.12	10	308	83	4	4.8
23	65.81	27.1	52	124	65	-27	5.4
24	65.88	27.51	26	100	46	174	5.2
25	64.21	25.81	18.7	125	72	-173	4.6
26	65.5	27.11	14.8	111	59	158	6.8
27	64.19	25.78	18	309	70	-162	4.7
28	65.04	26.7	15	223	39	4	7.7
29	65.53	26.96	24.3	107	68	175	5.5
30	62.21	27.89	80	80	35	-72	7
31	64.99	27.56	37	11	72	-163	5.7
32	66.31	28.1	35	208	83	-5	5
33	66.04	27.87	10	196	83	6	5
34	67.42	25.84	27	214	45	106	5
35	61.37	27.64	69	21	35	167	5.7
36	66.37	26.98	35	189	81	-6	5.1

The Seismic Analysis Code (SAC) was employed to preprocess the time series data, which involved phase picking, data inspection, and signal-to-noise ratio improvement (Goldstein and Snoke, 2005). The inversion process was conducted using the numerical method developed by Kikuchi and Kanamori which facilitates the modeling of complex teleseismic body waves through the correlation with synthetic waveforms (Kikuchi and Kanamori, 1982). Synthetic seismograms were generated using a layered velocity and density model based on CRUST1.0, which provides a global crustal model derived from seismic, geodetic, and geophysical information (Laske et al., 2013).

3. Discussion and Results

Our study reveals that, along with the Ornach-Nal Fault system, the Eastern side of the Makran region exhibits deep seismic events that penetrate beyond the typical crustal thickness. These events, generally located at depths exceeding 50 km, sometimes reach up to 80 km, suggesting complex fault dynamics at play beneath the Earth's surface (see Figure 4.

Our comprehensive investigation into the seismicity of the Eastern Makran region has produced a detailed catalog of seismic events. Through the application of moment tensor inversion techniques and seismic waveform analysis, we have mapped the intricate pattern of seismic activity that characterizes this complex subduction zone.

Contrary to the expected uniformity of seismic behavior, our findings indicate a heterogeneous distribution of seismicity, which challenges some traditional views on subduction dynamics. While shallow events are typically associated with higher risk due to their proximity to the surface, our results demonstrate that in the case of the Eastern Makran, seismic risk may not be as straightforward to assess. The variance in focal mechanisms across all depths suggests a more nuanced interaction between the subducting Arabian plate and the overlying Eurasian plate.

Additionally, our study contributes to the growing body of evidence that suggests a variable rate of subduction along the MSZ. This has significant implications for understanding the seismic hazard in the region. The presence of deep seismicity, with focal mechanisms indicative of different styles of faulting, underscores the complexity of the tectonic processes at play.

Comparison with existing seismological models shows that the Eastern Makran subduction zone exhibits unique characteristics that may not conform to global subduction norms. This finding emphasizes the need for region-specific seismic risk assessments and has potential implications for local building codes and disaster preparedness strategies.

The diversity of seismic mechanisms observed across various depths in the Eastern Makran region illustrates the complexity of the subduction zone's dynamics. It underscores the importance of continuous, in-depth seismological studies to accurately inform local seismic hazard models. Our study sets the stage for future research aimed at unraveling the intricate tectonic interactions within this region and for developing more refined seismic hazard models tailored to the unique characteristics of the MSZ.

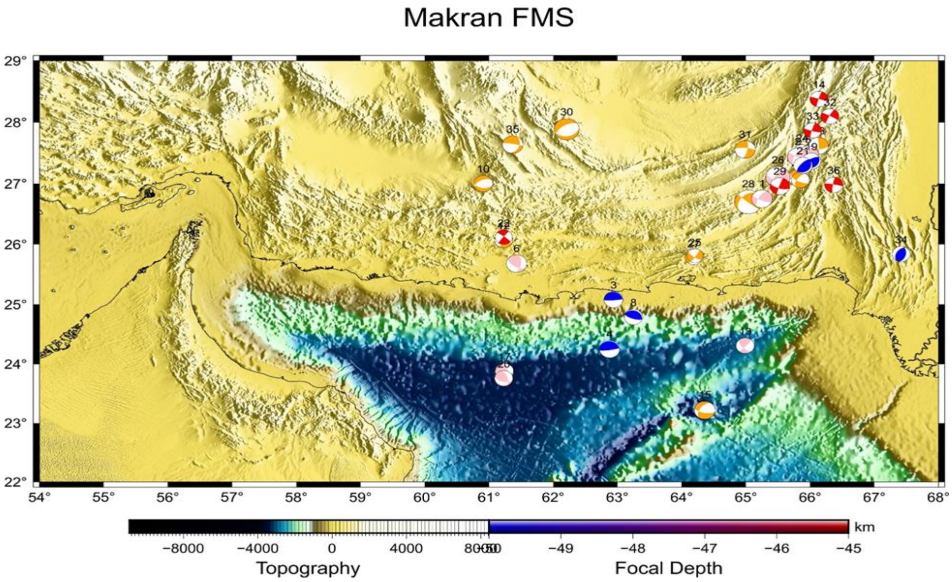

Figure 4: Focal Mechanism Solution of all the events recorded in the range from 1- 80.9 kms depth have been plotted here for correlation.

3.1 Cross Sections

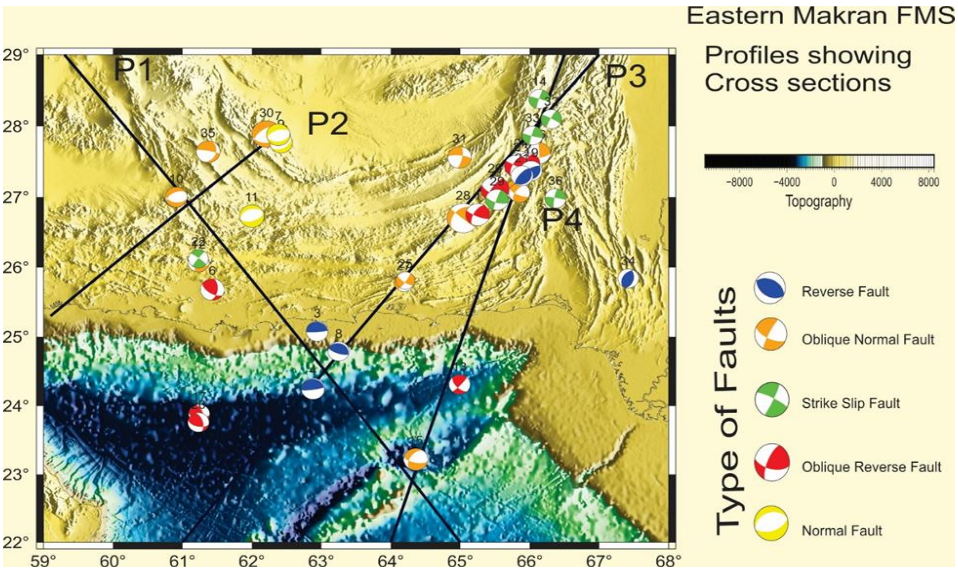

Figure 5: Profiles plotted for cross-sectional view below our desired area in Eastern Makran.

A comprehensive cross-sectional analysis has been conducted to elucidate the subsurface structural dynamics of the Eastern Makran region. Four cross-sectional profiles (P1, P2, P3, and P4) have been strategically delineated across the area to explore variations in faulting mechanisms and seismotectonic features, as illustrated in the regional map (see Figure 5). This distribution signals an active seismic zone that transcends the crust, penetrating the upper mantle.

The depicted profiles intersect key seismogenic zones, capturing a spectrum of faulting behaviors—reverse, oblique normal, strike-slip, oblique reverse, and normal faulting—identified by the FMS of seismic events. This array of mechanisms reflects the intricate deformation processes governing the subduction system. The color-coding corresponds to the type of faulting, facilitating a visual correlation between seismic activity and tectonic structures. The topographic gradient, represented by the background shading from deep oceanic blues to continental yellows, provides a contextual backdrop for the varying depth of seismic events.

Each profile is meticulously plotted to traverse distinct geological formations and fault lines, contributing to our objective of characterizing crustal thickness variations and the nature of subduction across Eastern Makran. The synthesis of this cross-sectional data portrays a vivid picture of the seismic landscape, allowing for an in-depth interpretation of the subsurface phenomena that define the tectonic vigor of the region.

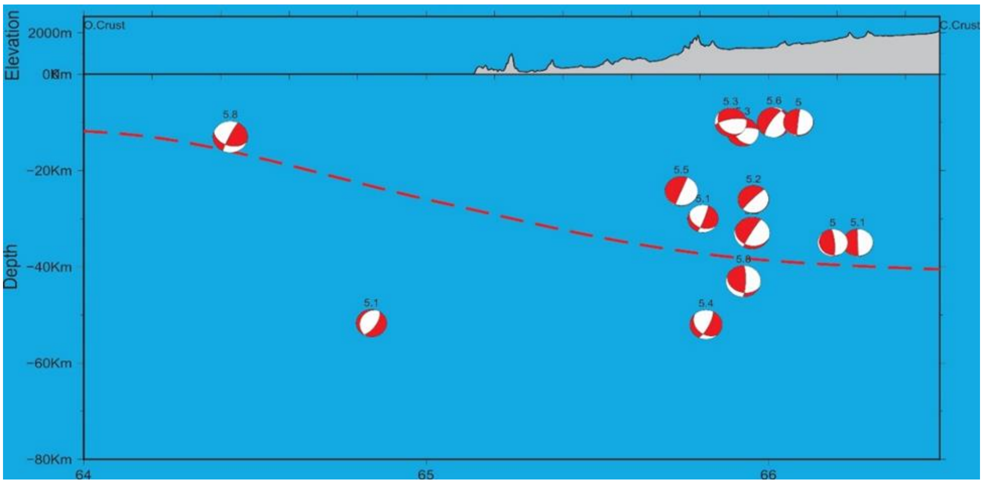

Figure 6: Showing Cross Sectional view of Profile 1, plotted from NW 59.2° Longitude and 29° Latitude, while ending on SE 66° Longitude and 20° Latitude.

Profile 1, (see Figure 6) indicates that seismic activity occurs at various depths, with a noticeable concentration of events between the surface and approximately 60 km depth. The distribution of earthquakes suggests a relatively active seismic zone extending well below the Earth's crust, into the upper mantle. The focal mechanisms, represented by beachballs, show a mix of reverse strike-slip and oblique events. This diversity in event types is indicative of complex stress regimes and suggests that a variety of tectonic processes are at work. The numbers next to the focal mechanism beachballs represent the seismic moment magnitude of each event. The presence of multiple events with magnitudes greater than 5.0 Mw signifies that the region has the potential for destructive earthquakes. The red dashed line, denoting the Moho boundary, delineates a steep subduction zone where the oceanic plate dives beneath the continental margin. The steepness of the Moho boundary across the profile reflects a rapid transition from thinner oceanic crust to thicker continental crust.

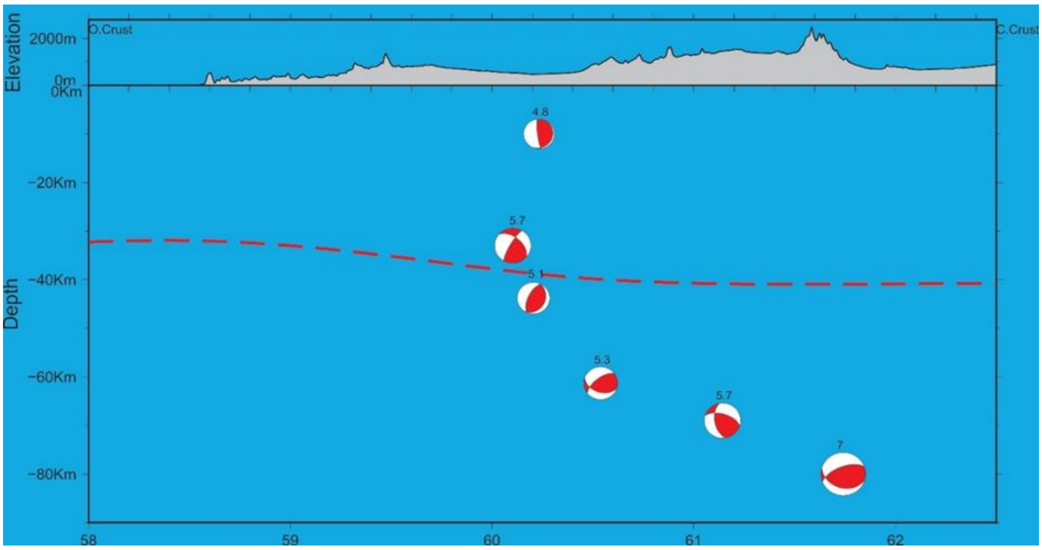

Figure 7: Showing Cross-Sectional view below Profile two, plotted from NE 62.5° Longitude and 28° Latitude while ending on SW 58° Longitude and 25.2° Latitude.

Profile 2 (see Figure 7) reinforces this narrative, with the detection of a substantial 7.0 Mw event at around 80 km depth near the Jiroft Fault. The gentle angle of subduction and the gradual morphological changes in the Moho support the hypothesis of reduced subduction activity in Makran's western segment, as previously suggested by (Paul et al., 2006)". Profile three, the range of seismic magnitudes for the events plotted on this profile varies from moderate (M 4.6 Mw) to significant (M 7.7 Mw), (see Figure 8). The presence of a M 7.7 Mw event is of particular note as it represents a potentially major earthquake capable of significant impact. Profile four, The distribution of events shows that seismicity occurs from shallow levels down to about 60 km depth. This pattern suggests that the subduction zone is active across a considerable vertical extent, influencing not just the crust but also the upper mantle. The seismic events represented by the beachballs show a range of magnitudes from 5.1 to 5.8 Mw. Collectively, these profiles unveil the Makran subduction zone as a region of significant seismic complexity and potential hazard. The steep subduction angle, as evidenced by the Moho boundary's delineation, portrays a dramatic interplay between the subducting Arabian plate and the Eurasian continental margin, hinting at the profound tectonic forces shaping this region's geodynamics (see Figure 9).

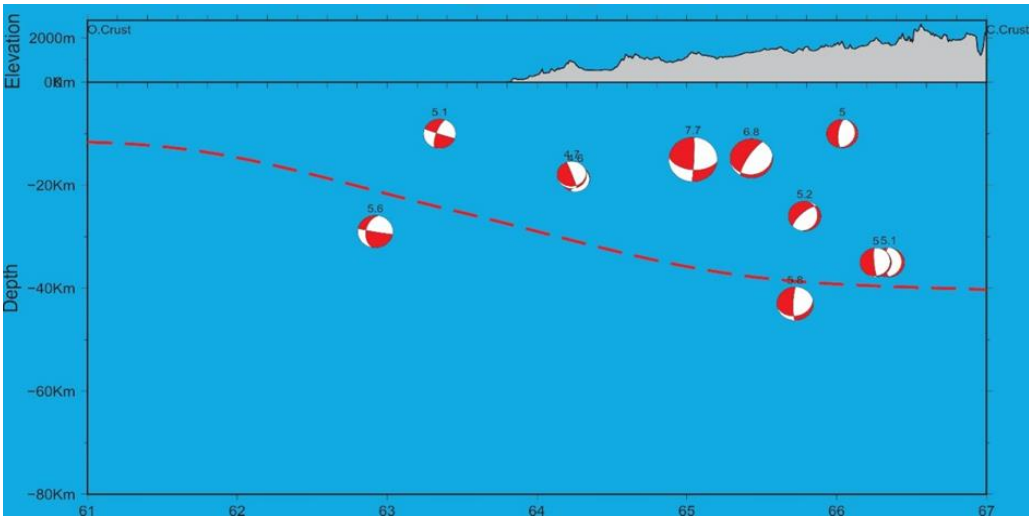

Figure 8: Showing Cross-Sectional view below Profile Three, plotted from NE 67° Longitude and 29° Latitude while ending on SW 61° Longitude and 22° Latitude.

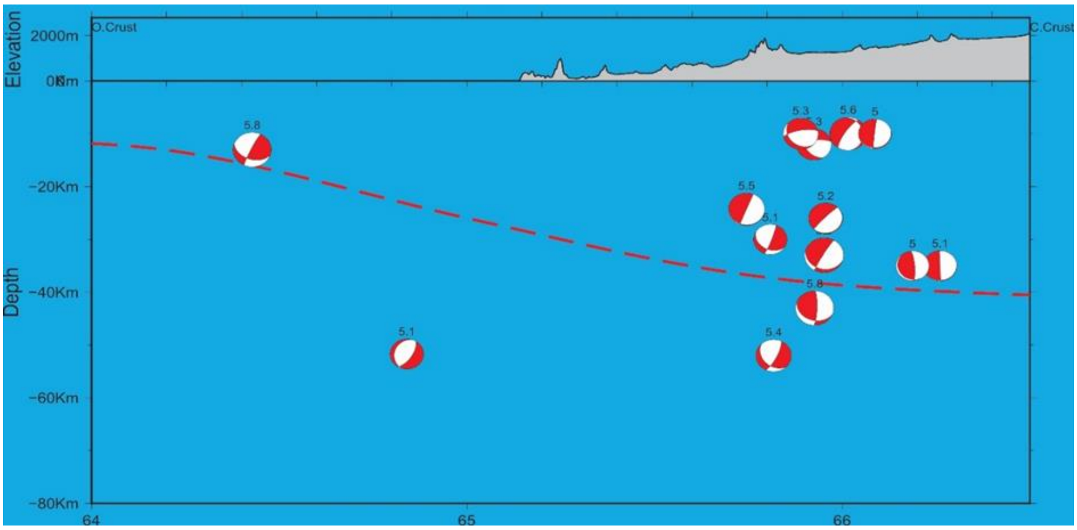

Figure 9: Showing Cross-Sectional view of Profile 4, plotted from NE 66.5° Longitude and 29° Latitude, while ending on SW 64° Longitude and 22° Latitude.

4. CONCLUSIONS

This study has delineated the seismicity and geotectonic features of the Eastern Makran subduction zone with significant implications for understanding regional tectonics and seismic risk. Our analysis has detected seismic events exceeding conventional crustal boundaries, calling for a re-evaluation of the tectonic isolation hypotheses of the Pakistan-Iran Makran microplate. These events, notably along the Jiroft and Ornach-Nal faults, suggest deeper and more intricate seismic activities than previously recognized.

In the western segment of the Makran subduction zone, a tectonic lock indicative of strain accumulation heralds the potential for substantial seismic events. This contrasts with the active tectonic dynamics observed in Eastern Makran, propelled by the Owen Fracture Zone and manifested through anticlockwise rotation. A noticeable westward attenuation of subduction activity raises crucial considerations for regional seismic hazard assessments, particularly in terms of earthquake preparedness and infrastructure resilience.

While our findings contribute insights into the region's seismic behavior, they also underscore the need for ongoing, detailed seismological surveillance. Future studies should aim to refine these observations, potentially revising the seismic hazard models for the Makran subduction zone. As we look to the future, comprehensive monitoring and targeted geophysical investigations will be pivotal in enhancing our understanding of this complex seismic landscape.

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