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Is Ziarat a Potential Site for Conventional or Unconventional Energy Resources?

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Abstract: A structural interpretation of the Ziarat block in the Balochistan region (a part of the Suleiman Fold and Thrust Belt) has been carried out using seismic and seismological data. Seismic data consists of nine 2.5D pre-stack migrated seismic lines, whereas the seismological data covers the Fault Plane Solution and source parameters. Structural interpretation describes two broad fault sets of fore and back thrusts in the study area that have resulted in the development of pop-up structures, accountable for the structural traps and seismicity pattern in terms of seismic hazard. Seismic interpretation includes time and depth contour maps of the Dungan Formation and Ranikot group, while seismological interpretation includes Fault Plane Solution, that is correlated with a geological and structural map of the area for the interpretation of the nature of the subsurface faults. Principal stresses are also estimated for the Ranikot group and Dungan Formation. In order to calculate anisotropic elastic properties, the parameters of the rock strength of the formations are first determined from seismic data, along with the dominant stresses (vertical, minimum horizontal, and maximum horizontal). The differential ratio of the maximum and minimum horizontal stresses is obtained to indicate optimal zones for hydraulic fracturing, and to assess the potential for geothermal energy reservoir prospect generation. The stress maps indicate high values towards the deeper part of the horizon, and low towards the shallower part, attributed to the lithological and structural variation in the area. Outcomes of structural interpretation indicate a good correlation of structure and tectonics from both seismological and seismic methods.

Key words: fault plane solution, reservoir monitoring, stress analysis, hydraulic fracturing, geothermal energy, structural interpretation

1 Introduction

Study of the seismic data in oil and gas exploration fields provides key physical parameters of subterranean rock formations (Raza et al. 1989; Khan and Raza 1986). Geophysical researchers investigate and develop seismic and structural imaging techniques and their application to a spatial resolution scale (Van der Pluijm and Marshak 1997). According to Miller (1996), it is a science which summarizes: a) geology at some depth from the seismic waves, b) shape and strength of the reflector and c) the time of arrival of reflection or refraction from Earth's surface.

Among the various available geophysical techniques, 2D and 3D seismic attributes are particularly useful for identifying faults/fractures and other stratigraphic features and zones amenable to fractures, that fall below seismic resolution (Rijks and Jaufred 1991). From the seismic data, one can obtain information about the characteristics and parameters of the subsurface strata i.e., Young's modulus, Poisson's ratio, and *in situ* stress directions and magnitudes.

Several researches have investigated the tectonically unstable Balochistan province and considered it to be a highly active seismic region (Ramanathan and Mukherji 1938; Schoeppel 1977; Ambrasseys and Bilham 2003; George 2006; Saeed et al. 2012). The study area is sandwiched between the north-south trending Kirthar-Brahui and Suleiman ranges and lies in the main convergent zone, prone to major seismic hazard. This

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study is focused on the interpretation of fault structures generated in the strata due to compressional forces. These fault structures can act as traps for hydrocarbons.

2 Geology of the Study Area

The study area has highly active regional tectonic settings and lies in a seismic zone IV (BCP 2007). The contact of various tectonic elements, i.e., the Chaman transform fault, the southward progressing Suleiman Lobe, and the resistant mass at the Sibbi trough, form a complex of structural styles and tectonics in the region (Naimatullah 1992; Seeber et al. 1981; Farah and Zaigham 1979). The study area is a part of the Suleiman Fold and Thrust Belt and consists of Jurassic to Pleistocene age sedimentary strata (Khan et al. 2010). The exposed rocks in the region (Fig. 1) are: the Cretaceous Parh group; the Upper Cretaceous Bibai Formation; the Paleocene Dungan limestone; the Ranikot group, including the lower Ranikot sandstone and the upper Ranikot limestone of Vredenburg (1906), Williams (1959) and Cheema et al. (1977); and the Ghazij Formation of Eocene age. Other formations, including the Nagri and Dhok Pathan formations, are also exposed in some places (Kazmi 1979). The Upper Cretaceous Bibai Formation is well-exposed near the Muslim Bagh Ophiolites, east of the Quetta Syntaxis (in the Kach-Ziarat

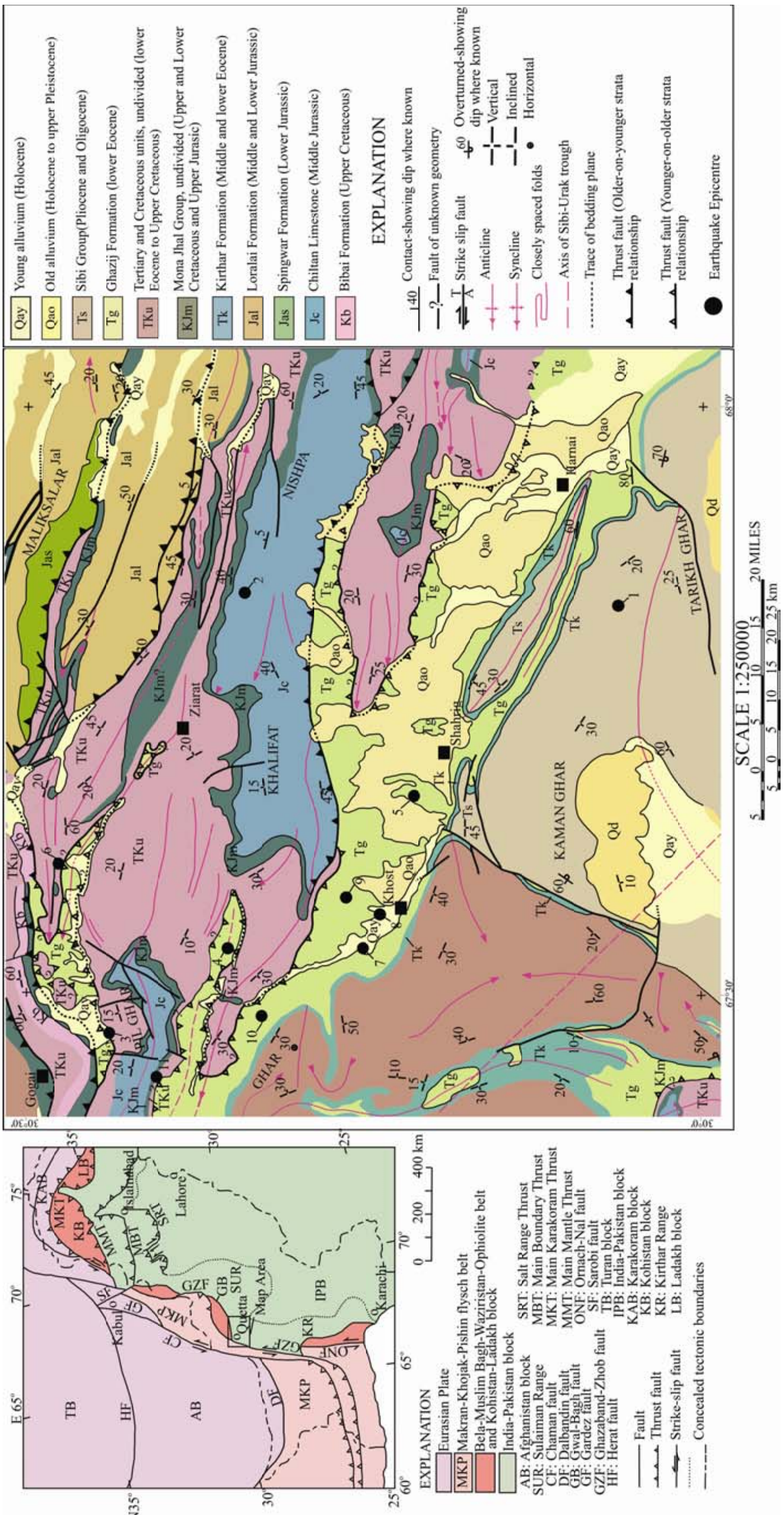

Fig. 1. Seismotectonic map of the study area.
Earthquake epicenter are shown by black dots, details of the earthquakes is given in Table 1.

and Spera Ragha-Chinjun valleys). The Bibai Formation is predominantly composed of volcaniclastic sediments (Otsuki et al. 1989; George 2006) and sporadic lava flows (within the Kach-Ziarat valley), as well as *in situ* basaltic volcanic rocks (within the Spera Ragha-Chinjun valley) (MonaLisa and Jan 2015).

3 Seismic Interpretation

Seismic interpretation entails the conversion of seismic data into useful geological information. The interpretation of seismic reflection data requires the fitting of all the geological and geophysical information into an integrated picture that is complete and reliable (Mitchum et al. 1977; Vail and Mitchum 1977; Hardage and Remington 1999; Khan et al. 2016).

Figs. 2 and 3 show the detailed well log analysis of both formations (Dungan and Ranikot), specifically their petrophysical properties with regard to their hydrocarbon prospects. Figs. 4–6 give a clear insight into the pop-up

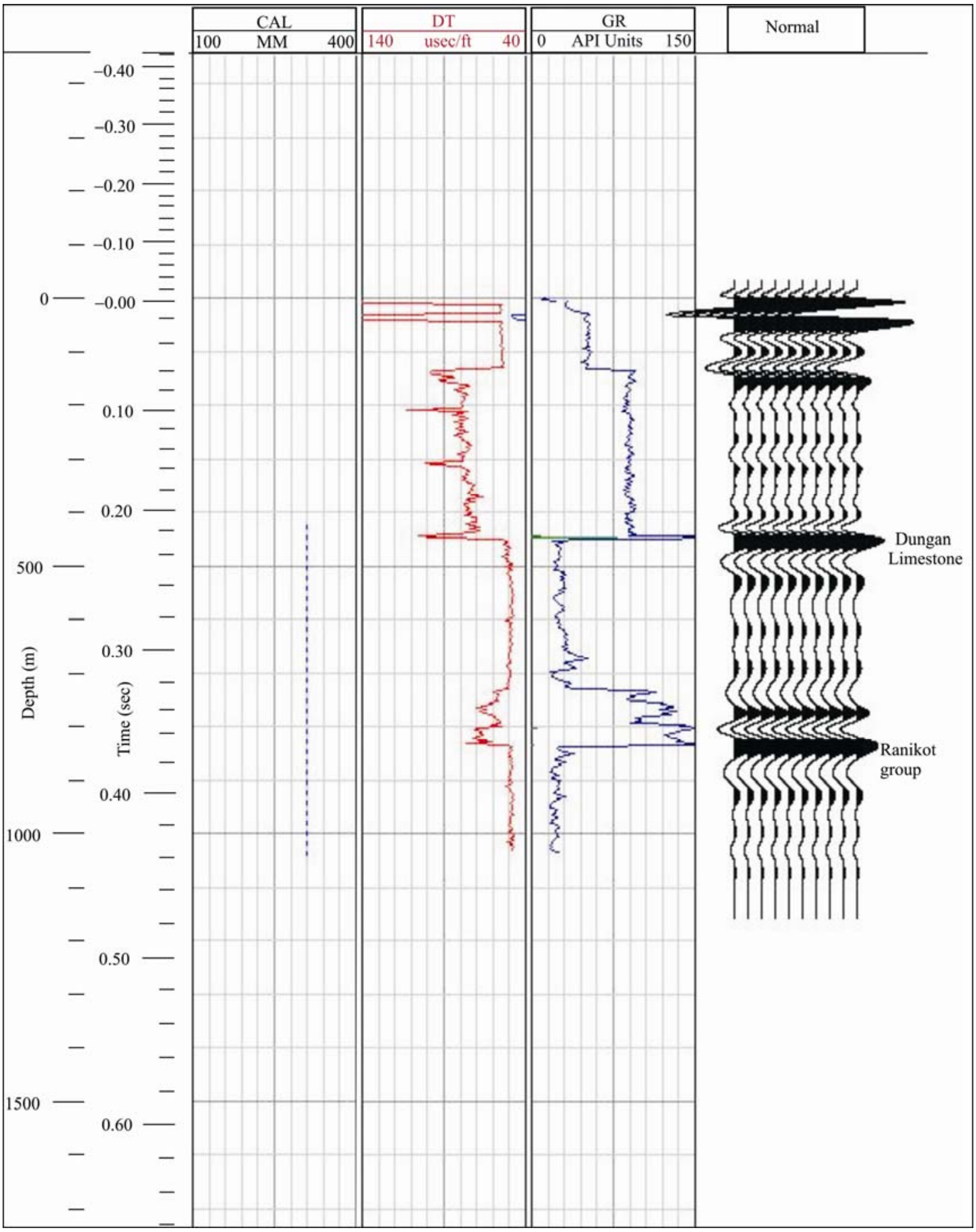

Fig. 2. Sonic and gamma ray logs readings, showing the boundaries of Dungan Formation and Ranikot Group.

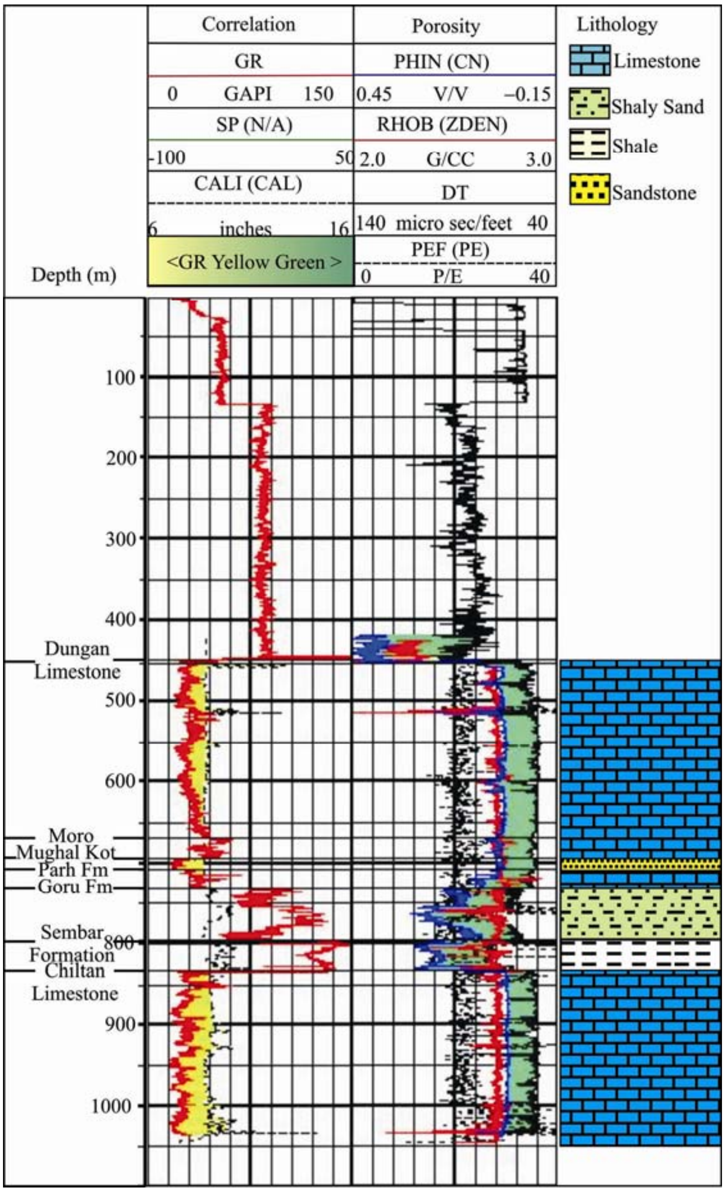

Fig. 3. Detailed well logs analysis showing the formation porosity with corresponding depth. Dungan Formation (limestone) and the lower part, Chiltan limestone show high porosity that could be the prospect zones for hydrocarbon.

structure and the horst, and reflect the compressional tectonics using seismic lines. Fig. 6 represents seven faults which are more faulted towards the east than the west. Fault lines are marked on the seismic time sections that indicate that the area is dominated by the tectonic forces, mostly directed towards the north and northeast, and are responsible for the development of faults and fractures.

Two horizons are picked and named as the Ranikot group and the Dungan Formation (Fig. 4). The area lies in a compressional regime, having a majority of reverse faults with some strike-slip component. In this area, three wells are drilled, i.e., the Ziarat-01 well is drilled on seismic line ZRT-04-02 (shot point (SP) 420); the Shahrig well is drilled on line BOL-98-12 (shot point 440) while the Khost-02 well is drilled on the intersection of lines ZRT-04-01 (shot point 630) and BOL-98-09 (shot point 130). Two-way travel-time (TWT) for the Dungan Formation ranges from 2000 milliseconds (ms) and for the Ranikot group 2200 ms in Fig. 4 at SP 110. From the structural perspective, the Dungan Formation is faulted at different levels, forming horst and graben structures in the north and south respectively, which demonstrates that the compressional forces are more active in the north.

The computer-based interpreted time section sections of the BOL (98-03, 98-11, 98-12, and 98-19) and ZRT (04-01, 04-02, 04-03, 04-04, 04-05 and 04-06) lines are given in Fig. 7. These seismic lines show that the horizons are uplifted more from the eastern or northeastern side.

4 Three Dimensional (3D) Structural Contour Map

Time values were picked from the time sections and plotted against every 10th shot point value. A time and depth structure map on top of the Dungan Formation and the Ranikot group is shown in Fig 8, where the time is in milliseconds (ms), the depth is in meters and the contour interval is 20 ms. The scale used for this map is 1:50,000. Depth values are calculated using the relationship $S = V_{ave}' \, t/2$; where V_{ave} is the average velocity of the horizons and 't' is the time (ms) of the horizons.

TWT and depth for the Dungan Formation increase towards the east and southeastern sides of the area, showing the dip direction of the horizon. There is a closure of contours in the map which represents a four-way dip closure structure. The values are decreasing inward and represent a likely structure for hydrocarbon accumulation. This horizon is faulted, and the major faults trend in a north-south direction. The color scheme also helps in determining the structural highs or lows. TWT and depth for the Ranikot group increase towards the east, showing the dip direction of the horizon. There is a closure of contours at SP 210-270 of the line BOL 98-12 and ZRT 04-04, which indicates a probable structure for hydrocarbon accumulation. This structure is termed as a pop-up structure which is faulted on both sides and the upthrown part serves as an accumulation place for hydrocarbons. The major fault trend direction is N-S. For greater convenience, a light blue color (zone A) shows the low time contour values and an orange color (zone B) shows

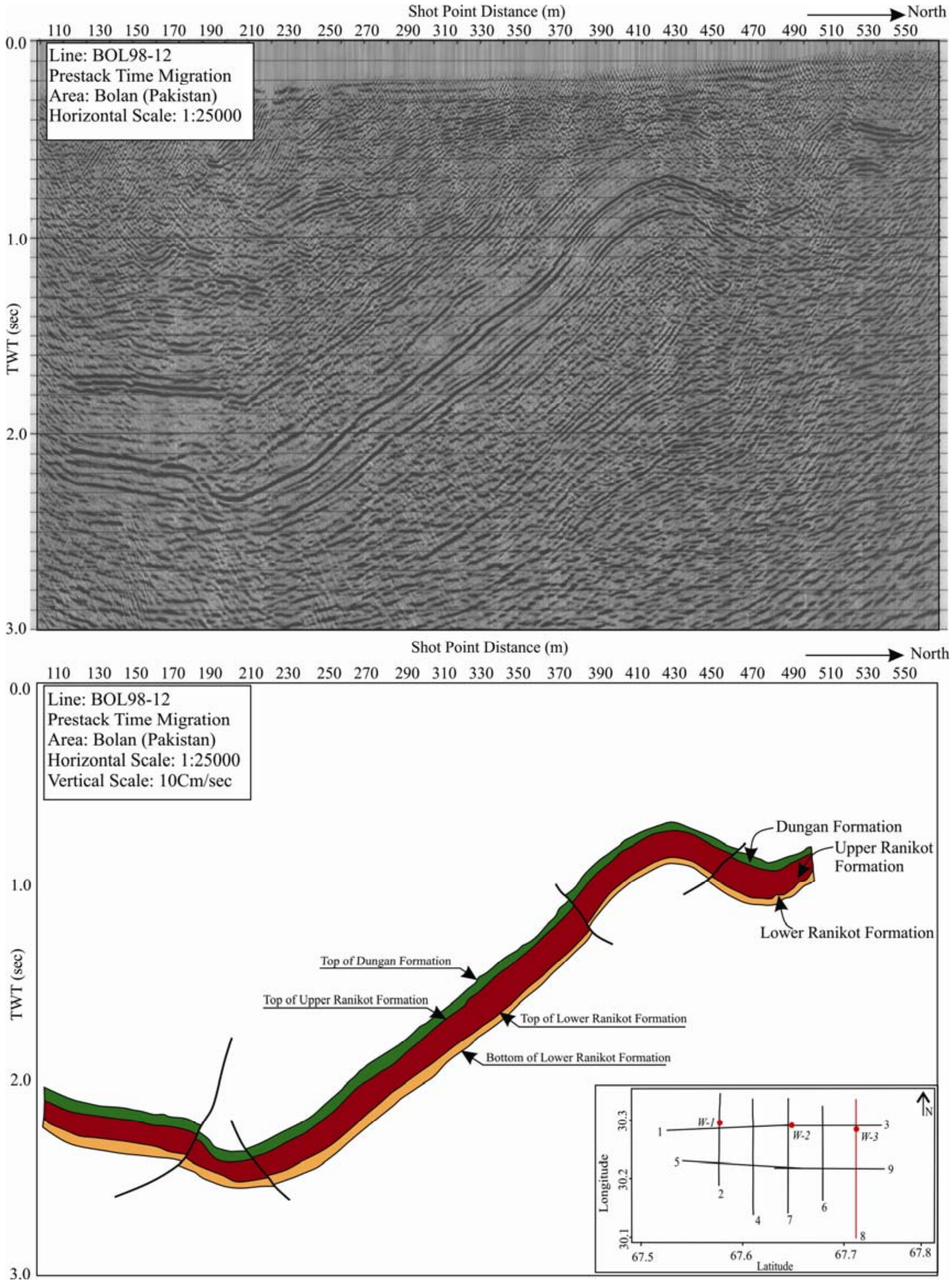

Fig. 4 Time structure map on top of the Dungan Formation.

the high time contour values. These formations (Ranikot and Dungan) are marked on the basis of well log data by generating a synthetic seismogram. On observing the reflection continuity, we can see that reflection thins out towards the west, and thickens towards the east (Figs. 4–6). The reason for this is the overburden pressure due to the greater depth at the western side, compared to the eastern side. Due to this variation in thickness, the Ranikot group is more faulted and damaged than the Dungan Formation.

5 Fault Plane Solutions (FPS)

Earthquakes provide the seismologist with an opportunity to view the force system that is responsible, at

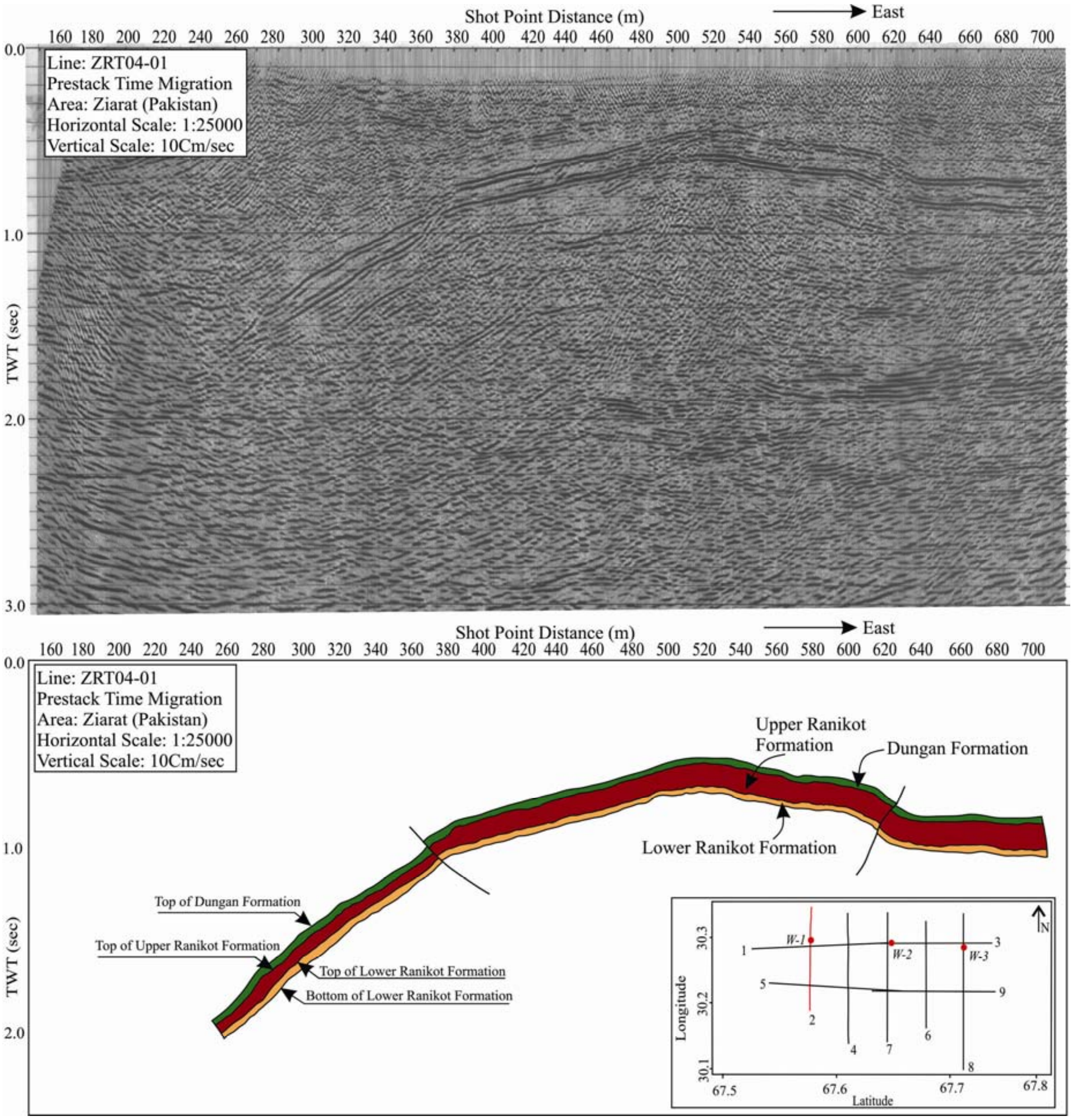

Fig.5. Figure shows Ziarat line with two thrust faults which together make a popup structure and the horst and reflect the compressional tectonics.

least in part, for the mountains and valleys of Earth's surface and the structural style of the area (Sherburne and Cramer 1984). The seismological study of the displacements and forces at the focus of an earthquake are commonly referred to as focal (or earthquake) mechanism studies (Khawaja and MonaLisa 2004; Nowroozi 1972; Sykes 1967; Stein and Wysession 2003). Different approaches are being adopted to understand the earthquake phenomenon (Bolt 1989; Isacks and Molnar 1971; Quittmeyer et al. 1984; 1979). One such approach is the Fault Plane Solution (FPS) that helps in the identification of seismic faults and their rupture processes (Menke and Jacob 1976). Furthermore, the Fault Plane Solution in combination with the tectonic history and structural features provide an improved understanding of the earthquake occurrence of an area.

In the present work, 11 FPS of earthquakes that occurred near the study area during the period from 1964 to 2008 (Table 1) have been carried out using P-wave polarity data. The standard lower half hemisphere projections on an equal area net have been used. Due to insufficient coverage of the area in terms of a reduced number of stations and the non-availability of relevant parameters such as polarity data and azimuthal angles, only the solutions for 2 events could be carried out.

In Fig. 9 the events have been numbered 1-11

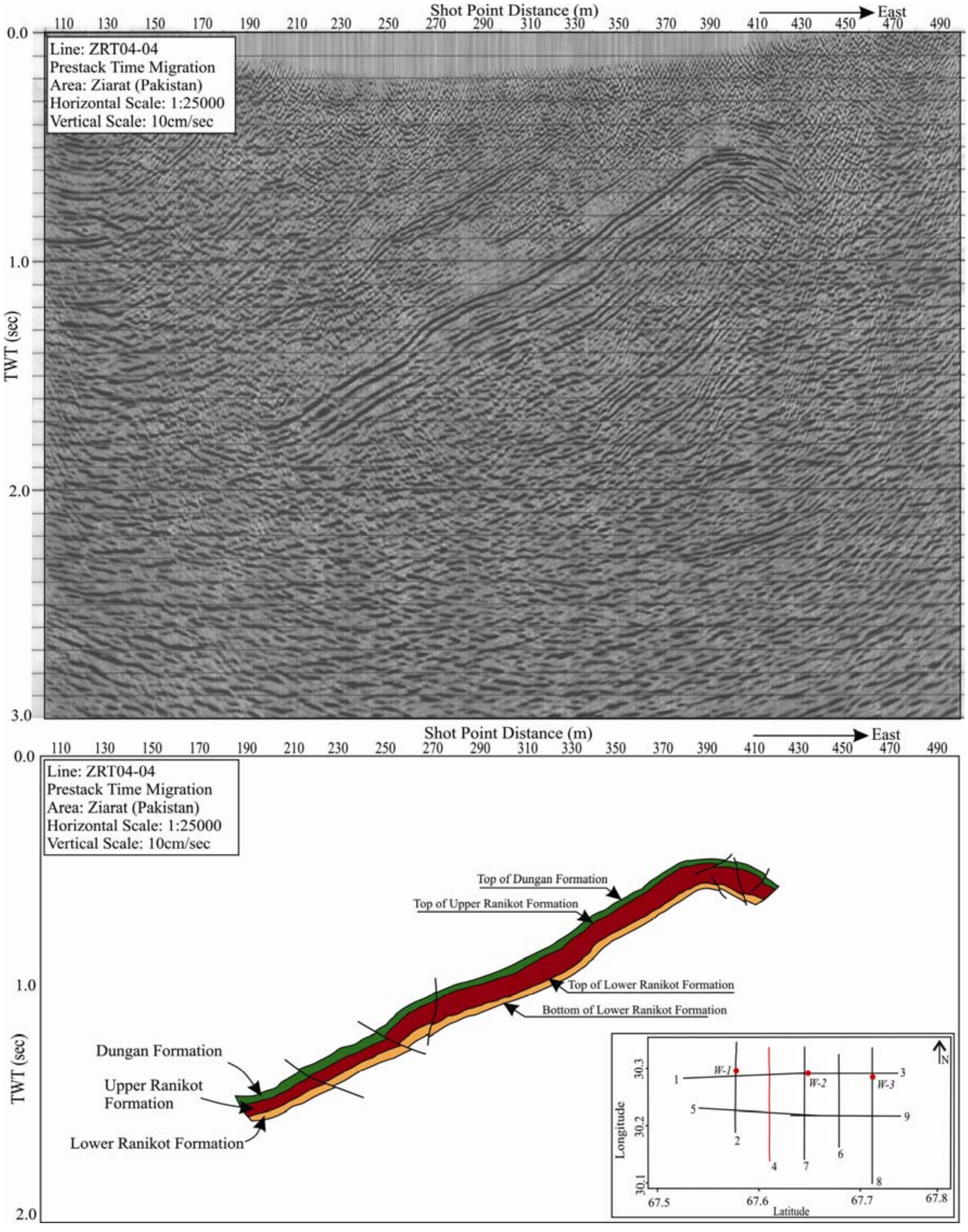

Fig. 6. Seismic line show seven faults, with more faulting towards east compared to west.
The strata are uplifted more from eastern or north-eastern side.

considering their date of occurrence, with number 1 being the oldest and number 11 the last event to have occurred within the studied time period.

6 Stress Analysis

Generally, the stress analysis includes determination of the principal stresses (vertical stress, the minimum horizontal stress, and the maximum horizontal stress) of a rock formation, for which conventional 3D seismic data (Gray et al. 2010a; 2012) and multi-component seismic data is utilized. Before proceeding to the next step, the necessary rock strength parameters i.e., Young's modulus (elastic deformation according to Hook's law); and

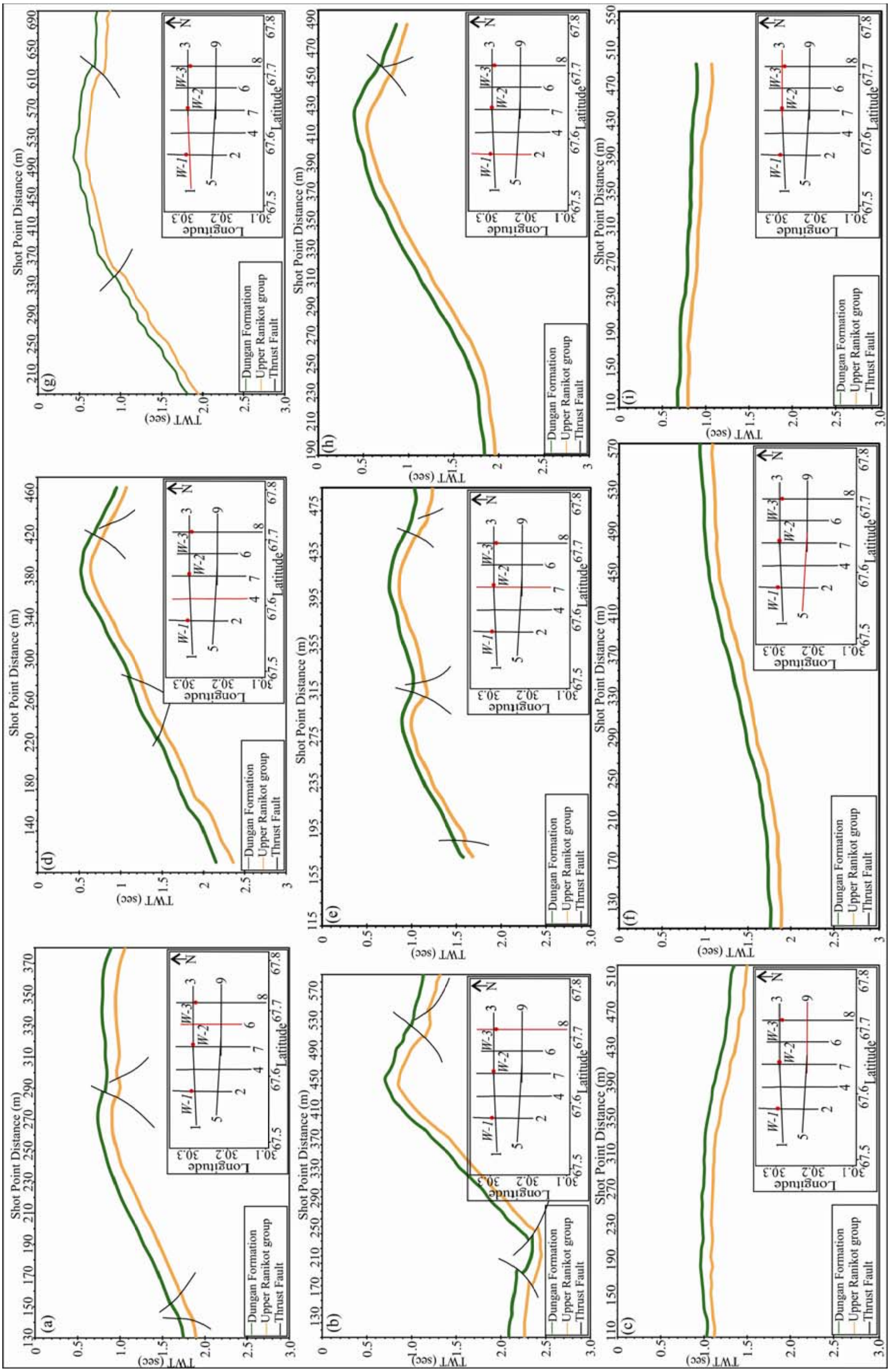

Fig. 7. Structure and tectonics of the seismic lines of the study area (inset is the base map of seismic lines).

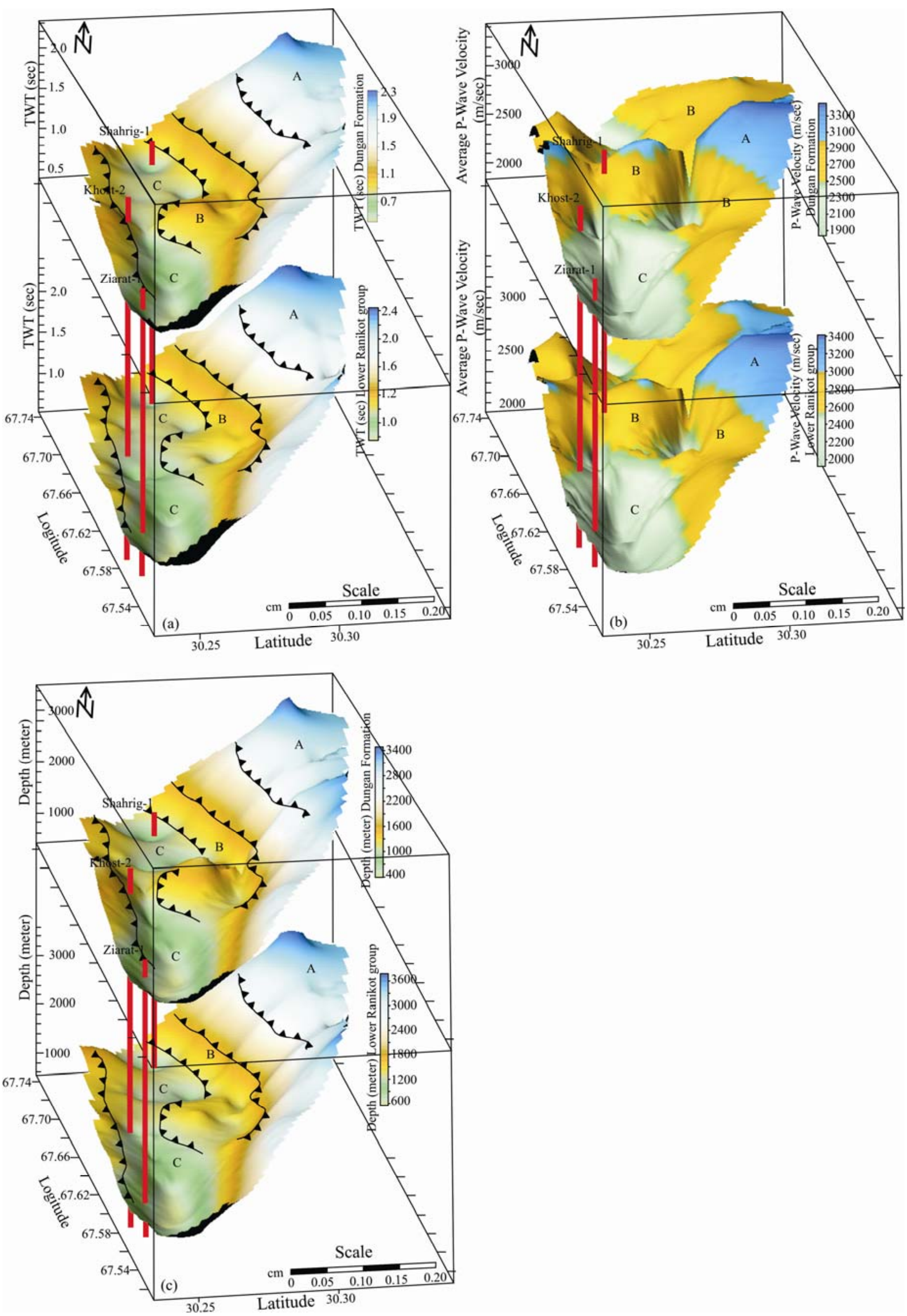

Fig. 8. 3D tectonic setting and model of the study block in time. (a) TWT (sec); (b) average velocity (m/s); and (c) depth (m).

Table 1 Detailed chart of seismological events in the study block with Focal Mechanism Solution (FMS)

FMS No.	Latitude	Longitude	Depth (km)	Strike	Dip	Rake	Author	
1	30.17	67.68	9	315	8	128	NEIC	
				96	84	85		
2	30.39	67.69	12	86	4	−66	HRVD	
				242	87	−91		
3	30.47	67.43	16.6	128	70	151	GCMT	
				229	63	22		
4	30.40	67.48	17.2	37	81	18	GCMT	
				304	73	171		
5	30.29	67.57	12	233	88	−22	GCMT	
				324	68	−178		
6	30.50	67.53	10	326	59	−173	NEIC	
				232	85	−30		
7	30.32	67.48	16.5	333	83	169	GCMT	
				64	79	7		
8	30.31	67.50	15.4	330	80	163	GCMT	
				63	73	11		
9	30.33	67.51	15.9	152	90	−165	GCMT	
				62	75	0		
10	30.38	67.44	10	158	72	−145	NEIC	
				57	58	−21		
11	30.44	67.40	10	330	86	173	NEIC	
				61	83	4		

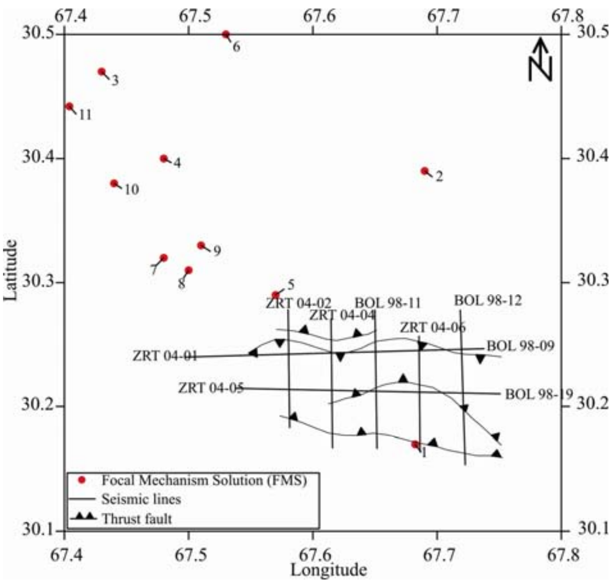

Fig. 9. Tectonic map with the GIS information with the projected seismic lined and the position of fault plane solution (FPS).

Poisson's ratio (relationship of longitudinal to lateral strains) need to be obtained from either seismic amplitude inversion of multicom-ponent (Gray et al. 2010c; Gray 2010b; Blanton and Olsen 1999; Schoenberg and Sayers 1995; Varela et al. 2009; Warpinski and Smith 1989), 3D seismic data or of conventional 3D seismic data.

In this regard, first vertical stress, σ_v or σ_z has been estimated by integrating a density log (r(h)) over depth (z) Eq (1), which has been obtained from seismic inversion.

$$\sigma_v(z) = \int_0^z g\,\rho(h)\,d(h), \tag{1}$$

where z: depth; g: gravity ≈9.8 m/s^2; $\rho(h)$: density at depth h and $\sigma_v(z)$: vertical stress at depth z. Eq (1) is simplified to equation (2) to calculate vertical stress from seismic data in the time domain (Gray 2011).

$$\sigma_v(z) \approx \sum_{h=0}^{z} g\,\rho(h)\Delta h \tag{2}$$

and the depth-step Δh is approximated by

$$\Delta h \approx \frac{V_p\,\Delta t}{2} \tag{3}$$

The minimum horizontal stress and maximum horizontal stress is determined by the Eq (4) and (5) respectively (Gray 2011):

$$\sigma_x = \sigma_z \frac{v(1+v)}{1+EZ_N - v^2} \quad (4)$$

$$\sigma_y = v\sigma_z \left(\frac{1+EZ_N + v}{1+EZ_N - v^2}\right). \quad (5)$$

Between the vertical stress σ_z, Young's modulus E, Poisson's ratio v, and the normal fracture compliance Z_N (calculated using Eq 6)

$$Z_N = \frac{\Delta N}{M(1-\Delta N)} \quad (6)$$

where ΔN is estimated by azimuthal simultaneous elastic inversion as below:

$$\Delta N = \frac{4\sigma_z}{3g_o(1-g_o)} \quad (7)$$

In above Eq (7) $g_o = \beta_o^2/\alpha_o^2$ and $M = \lambda+2m$ whereas; β_o: vertical shear-wave velocity of non-fractured material; α_o: Vertical compressional-wave velocity of non-fractured material; λ= Lambda parameter, where $\lambda=\rho\alpha^2-2\rho\beta^2$; m= rigidity of rock, or shear modulus, where $m = \rho\beta^2$; α = vertical compressional velocity; β = vertical shear-wave velocity.

7 Results and Discussion

7.1 Structural interpretation using FPS and seismic data

Fault Plane Solutions are useful for the interpretation of geological structures, either dip-slip or strike-slip faults (Bolt 1989; Sykes 1967; Stein and Wysession 2003; Isacks and Molnar 1971). There are 11 FPS obtained on the basis of seismicity parameters. FPS obtained for these events are of right lateral strike-slip with some thrust components. Structurally, these events are located near the Harnai and Tatra faults, the left-lateral Kingri, Chaudhwan and Domanda faults (Mekhtar–Kohlu Fault Zone) and the Kakar Khorasan, Zhob, Mekhtar, Kohlu, Tatra, Quetta and Khalifat thrust faults (Zhob Fault Zone) (MonaLisa and Jan 2015; Arthurton et al. 1979; Rowlands 1978; Khurshid 1991; Jadoon and Khan 1990; Humayon et al. 1991). The FPS are determined by the Harvard Centroid Moment Tensor Solution (Table 1), using the first motion data.

Structurally, the concentration of this seismic activity lies in the area surrounded by a number of thrusts/reverse faults as well as strike-slip faults (Ambraseys and Bilham 2003; Ramanathan and Mukherji 1938). Therefore, FPS (strike-slip with reverse components) employed in the present work are consistent with the structural setting of the area (Quittmeyer et al. 1984; 1979; Menke and Jacob 1976).

The Urghargai Fault extends from Sibi to Shahrig northwest of Ziarat (Rahman 1969; Lillie et al. 1989). Two strike-slips with reverse component FPS (1 and 5) are correlated with seismic data in Fig. 10 and extend to a maximum depth of 9–15 km. The strike of the fault planes, carried out in FPS 1 and FPS 5 results (table 1), are NNW-SSE (i.e., 96° and 84° NNE, depth 9 km) and NNW-SE (324° and 68° NNE, depth of 12 km) respectively.

7.2 3D stress diagrams

3D Stress diagrams indicating vertical, minimum horizontal and maximum horizontal stresses were generated for the Dungan Formation and the Ranikot Group (Fig. 11). Overall stress variations were consistent for both formations as both lie close to each other in depth. The high -stress values (vertical, maximum horizontal and minimum horizontal) were observed towards the western part of the study area, whereas the low-stress values were observed towards the eastern part of the study area. The higher values of stress are attributed to greater depth and increasing overburden pressure, furthermore, the lower stress values are indicative of shallower subsurface structures and less overburden pressure. The moderate and slightly abnormal stress values observed towards the center are indicative of fault activity in the study area. In addition to this, these stress behaviors give an insight into the nature of the faults present in the study area. Two behaviors of fault activity were observed i.e., thrust/ reverse and strike-slip.

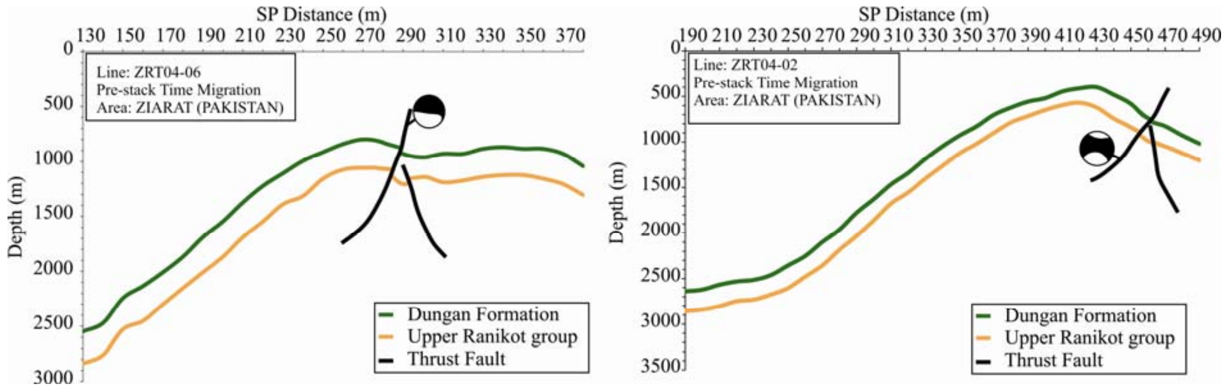

Fig. 10. 3D stress diagram for Dungan Formation and Ranikot Group.

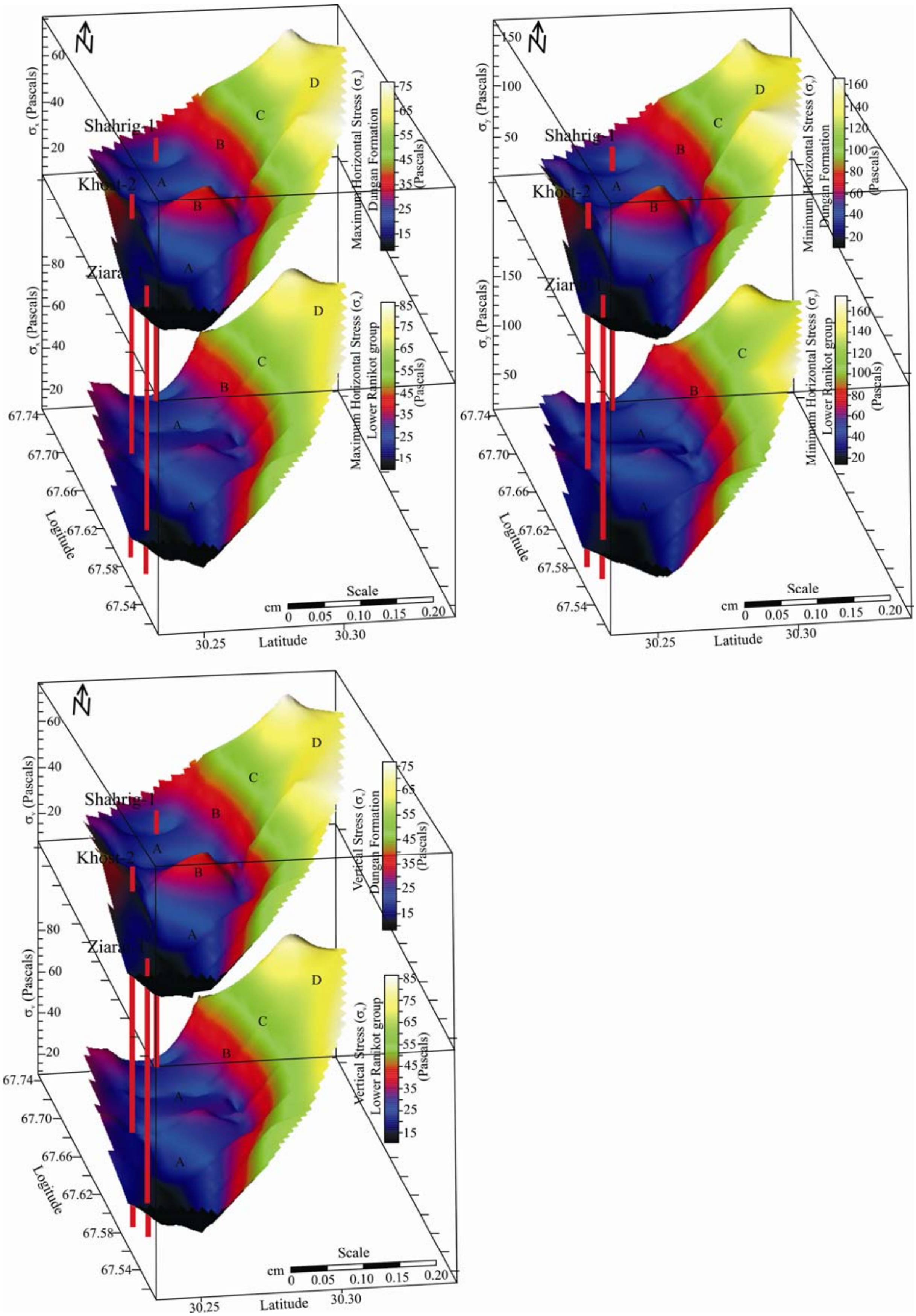

Fig. 11. Structural interpretation using seismic data and seismological data.

8 Conclusions

The integration of active (seismic) and passive (seismological) data in this study has proven worthwhile to investigate the complex structured lithology. This investigation has then been used by expert geoscientists to localize and identify the nature of faults that not only contribute to the activation and generation of seismicity but also can help in the exploration and production of subsurface natural resources. Fault Plane Solutions (FPS) indicated several faults that were responsible for the seismic activity. The identified faults include thrusts/reverse along with strike-slip in nature. We can conclude that some of them are oblique-slip. The structure was interpreted as a four-way dip closure with pop-up behavior towards the north side, and could be suitable for hydrocarbon accumulation. The stress diagram represented a normal stress nature, except for areas where there was fault activity. Additionally, FPS (reverse with strike-slip components) employed in the present work are consistent with the structural scenario of the area. Furthermore, the stress diagrams, in addition to delineating the structure, also confirmed the presence of thrust/reverse and strike-slip components in the study area, which is the result of multi-dimensional tectonic forces.

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References

Ambrasseys, N., and Bilham, R., 2003. Earthquakes and associated deformation in North Baluchistan 1892-2001. *Bull. Seismol. Soc. Am.*, 93(4): 1573–1605.

Arthurton, R.S., Alam, G.S., Ahmed, S.A., and Iqbal, S., 1979. Geological history of Alam Reg-Mashki Chah area, Chagai District, Balochistan. In: Farah, A., and DeJong, K.A. (eds.), *Geodynamics of Pakistan*: 325–331.

BCP., 2007. *Building Code of Pakistan Seismic Provision: In Ministry of Housing and Works*. Pakistan: Islamabad.

Blanton, T.L., and Olson, J.E., 1999. Stress magnitudes from logs: Effects of tectonic strains and temperature. *SPE Reservoir Evaluation & Engineering*, 2(01): 62–68.

Bolt, B.A., 1989. Earthquake Seismology. In: James, D.E., (ed.), *Encyclopedia of Solid Earth Geophysics*. Springer US publishers, Boston, MA, *Geophysics*: 300–308. doi:10.1007/0-387-30752-4_9.

Cheema, M.R., Raza, S.M., and Ahmad, H., 1977. Cenozoic. In: Shah, (ed.), *Geological survey of Pakistan Memoir*s. *Stratigraphy of Pakistan*, 12: 56–98.

Farah, A., and Zaigham, N.A., 1979. Gravity anomalies of the ophiolite complex of the Khanozai, Muslimbagh-Qila Saifullah area, Zhob District, Baluchistan. In: Farah, A., and Dejong, A.K., (eds.), *Geodynamics of Pakistan.* Geological Survey of Pakistan, Quetta., 251–262.

George, P.-C., 2006. The potential of tsunami generation along the Makran subduction zone in the northern Arabian Sea. Case study: the earthquake and tsunami of November 28, 1945. *Science of Tsunami Hazards*, 24(5): 358–359.

Gray, F.D., Schmidt, D., and Delbecq, F., 2010a. Optimize shale gas field development using stresses and rock strength derived from 3D seismic data. *Canadian Unconventional Resources and International Petroleum Conference, 19-21 October: Calgary, Alberta, Canada*. Society of Petroleum Engineers. doi:10.2118/137315-MS.

Gray, F.D., 2010b. Targeting horizontal stresses and optimal hydraulic fracture locations through seismic data. *6th Annual Canadian Institute Shale Gas Conference*. http://www.cggveritas.com/technicalDocuments/cggv_0000006453.pdf.

Gray, F.D., Anderson, P., Logel, J., Delbecq, F., and Schmidt, D., 2010c. Estimating in-situ, anisotropic, principal stresses from 3D seismic. *72nd EAGE Conference & Exhibition*, Extended Abstracts, J046.

Gray, F.D., 2011. Methods and systems for estimating stress using seismic data. United States Patent Application, 20110182144A1. http://www.google.com/patents/US20110182144.pdf?source=gbs_overview_r&cad=0.

Gray, F.D., Anderson, P., Logel, J., Delbecq, F., Schmidt, D., and Schmid, R., 2012. Estimation of stress and geomechanical properties using 3D seismic data. *First Break*, *30*. doi:10.3997/1365-2397.2011042.

Hardage, B.A., and Remington, R.L., 1999. 3-D seismic stratal surface concepts applied to the interpretation of a fluvial channel system deposited in a high-accommodation environment. *Geophysics*, 64(2): 609–620. http://dx.doi.org/10.1190/1.1444568.

Humayon, M., Lillie, R.J., and Lawrence, R.D., 1991. Structural interpretation of eastern Sulaiman fold belt and foredeep, Pakistan. *Tectonics*, 10: 299–324.

Isacks, B.L., and Molnar, P., 1971. Distribution of stresses in the descending lithosphere from a global survey of focal-mechanism solution of mantle earthquakes. *Reviews of Geophysics and Space Physics*, 9: 103–174.

Jadoon, I.A.K., and Khan, S.H., 1990. Pop-up structures in the central Sulaiman fold belt of Pakistan: EOS, Transaction, *American Geophysical Union*, 71:1592.

Kazmi, A.H., 1979. Active fault systems in Pakistan. In: Farah, A., and DeJong, K.A., (eds.), *Geodynamics of Pakistan.* Geological Survey of Pakistan, Quetta. 285–294.

Khan, M.A., and Raza, H.A., 1986. The role of geothermal gradients in hydrocarbon exploration in Pakistan. *J. Petroleum Geology*, 9:245–258.

Khan, M.A., Siddiqui, R.H., and Jan, M.Q., 2010. Temporal evolution of Cretaceous to Pleistocene magmatism in the Chagai Arc, Balochistan, Pakistan. In: Leech, M.L., and others, (eds.), *Proceedings for the 25th Himalaya-Karakoram-Tibet Workshop: U.S* (p. 2). Geological Survey, Open-File Report 2010-1099. [http://pubs.usgs.gov/of/2010/1099/khan/].

Khan, S., Latif, Z., Hanif, M., Jan, I.U., and Iqbal, S., 2016. Velocity and Structural Modeling of Mesozoic Chiltan Limestone and Goru Formation for Hydrocarbon Evaluation in the Bitrisim Area, Lower Indus Basin, Pakistan. *Acta Geologica Sinica* (English Edition), 90(1): 258–275. doi:10.1111/1755-6724.12656

Khawaja, A.A., and MonaLisa, 2004. Structural trends and focal mechanism studies in the Potwar area with special emphasis on hydrocarbon exploration. *Pakistan J. Hydrocarbon Res.*, 14:49–60.

Khurshid, A., 1991. *Crustal structure of the Sulaiman Range, Pakistan from gravity data*. Master's thesis, Department of Geosciences: Oregon State University, Corvallis, Oregon, 1–56.

Lillie, R.J., Lawrence, R.D., Humayon, M., and Jadoon, I.A.K., 1989. The Sulaiman thrust lobe of Pakistan: Early stage underthrusting of the Mesozoic rifted margin of the Indian subcontinent. *GSA Abstracts with Program*, 318.

Menke, W.H., and Jacob, K.H., 1976. Seismicity pattern in Pakistan and northwestern India associated with continental collision. *Bull. Seismol. Soc. Am.*, 66:1695–1711.

Miller, S., 1996. *Multicomponent seismic data interpretation*. Unpublished M.Sc. Thesis, University of Calgary: Calgary, Alberta.

Mitchum, R.M. Jr., Vail, P.R., and Thompson, S.I., 1977. Seismic Stratigraphy and Global Changes in Sea Level, Part 2, The Depositional Sequence as a Basic Unit for Stratigraphic Analysis. In: Payton, C.E., (ed.), *Seismic Stratigraphy: Applications to Hydrocarbon Exploration*. American Association of Petroleum Geologists Memoir. AAPG Bookstore or AAPG Archives. 26: 53.

MonaLisa, and Jan, M.Q., 2015. Awaran, Pakistan, earthquake of Mw 7.7 in Makran accretionary zone, 24 September 2013: Preliminary seismotectonic investigations, *Proceedings of the Pakistan Academy of Sciences*, 52(2): 159–168.

Naimatullah, M., Durrani, K.H., Qureshi, A.R., Khan, Z., Kakar, D.M., Jan, M.R., and Ghaffar, A., 1989. Emplacement of Bibai and Gogai Nappes, NE of Quetta. *Geological Bulletin University of Peshawar*, 22: 153–158.

Nowroozi, A.A., 1972. Plate Tectonics of the Middle East. *Bull. Seismol. Soc. Am.*, 62: 823–850.

Otsuki, K., Anwar, M., Mengal, J.M., Brohi, I.A., Hohino, K., Fatmi, A.N., and Okimura, Y., 1989. Muslimbagh area of Baluchistan. *Geological Bulletin University of Peshawar*, 22: 103–126.

Quittmeyer, R.C., Farah, A., and Jacob, K.H., 1979. The seismicity of Pakistan and its relation to surface faults. In: Farah, A., and DeJong, K.a., (eds.),. *Geodynamics of Pakistan*. Geological Survey of Pakistan, Quetta. 351–358.

Quittmeyer, R.C., Kaffa, A.A., and Armbruster, J.G., 1984. Focal mechanism and depths of earthquakes in Central Pakistan: A tectonic interpretation. *J. Geophysical Res.*, 89: 2459–2470.

Rahman, A., 1969. Crustal section across the Sibi-Syntaxial Bend, West Pakistan, Based on gravity measurements. *J. Geophysical Res.*, 74: 4367–4370.

Ramanathan, K., and Mukherji, S., 1938. A seismological study of the Baluchistan, Quetta, earthquake of May 31, 1935. *Records of the Geological Survey of India*, 73: 483–513.

Raza, H.A., Ahmed, R., Alam, S., and Ali, S.M., 1989. Petroleum Prospects: Sulaiman Sub-Basin, Pakistan. *Pakistan J. Hydrocarbon Res.*, 1(2): 21–56.

Rijks, E.J.H., and Jauffred, C.E.M., 1991. Attribute extraction: An important application in any detailed 3-D interpretation studies. *The Leading Edge*, 10: 11–19.

Rowlands, D., 1978. The structure and seismicity of a portion of southern Sulaiman Ranges, Pakistan. *Tectonophysics*, 51: 41–56.

Saeed, M., Rana, A.N., Mehtab-ur-Rahman, and Abbas, S.A., 2012. Lava effusion in Ziarat, Balochistan, Pakistan. *J. Himalayan Earth Science*, 45(2): 112.

Schoenberg, M., and Sayers, C.M., 1995. Seismic anisotropy of fractured rock. *Geophysics*, 60: 204–211.

Schoeppel, R.J., 1977. *Prospects of Geothermal power in Saindak area, Baluchistan province, Pakistan*. Final report for Oil and Gas Development Compan, 15.

Seeber, L., Armbruster, J.G., and Quittmeyer, R.C., 1981. Seismicity and continental subduction in the Himalayan Arc. In: Gupta, H.K., and Delany, F.M., (eds.), *Zagros, Hindukush, Himalaya: geodynamic evolution.* American Geophysical Union Geodynamic Series. 3: 215–242.

Sherburne, R.W., and Cramer, C., 1984. Focal mechanism studies: an explanation. *California Geology*, 37(3): 54–57.

Stein, S., and Wysession, M.E., 2003. *An Introduction to Seismology*. Earthquakes and Earth Structures: Malden: Blackwell, 1–498.

Sykes, L.R., 1967. Mechanism of earthquake and nature of faulting on the mid-oceanic ridges. *J. Geophysical Res.*, 72: 2131–2153.

Vail, P.R., and Mitchum, R.M. Jr., 1977. Seismic Stratigraphy and Global Changes of Sea Level, Part 1, Overview. In: Payton, C.E., (ed.), *Seismic Stratigraphy: Applications to Hydrocarbon Exploration*. American Association of Petroleum Geologists Memoir, AAPG Bookstore or AAPG Archives, 26: 51–52.

Van der Pluijm, B.A., Marshak, S., 1997. *Earth Structure: An Introduction to Structural Geology and Tectonics*. WCB/ McGraw-Hill. pp. 495.

Varela, I., Maultzsch, S., Chapman, M., and Li, X., 2009. Fracture density inversion from a physical geological model using azimuthal AVO with optimal basis functions. *79th SEG Annual Meeting, Expanded Abstracts*, 28: 2075–2079.

Vredenburg E.W., 1906. The classification of the Tertiary system in Sind with reference to the zone distribution of the Eocene Echinoidea described by Duncan and Sladen. *India Geological Survey Records*, 34(3): 172–198.

Warpinski, N.R., and Smith, M.B., 1989. Rock mechanics and fracture geometry in recent advances in hydraulic fracturing. In: Gidley, J.L., (ed.), Recent Advances in Hydraulic Fracturing. *Society of Petroleum Engineers, Monograph*, 12: 57–80.

Williams M.D., 1959. Stratigraphy of Lower Indus Basin, West Pakistan. *5th World Petroleum Congress, 30 May-5 June, New York, USA*, *1*, 277–394.

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