Thematic Mapping of Basement-Related Cross-Strike Structural Discontinuities and Their Relationship to Potential Oil-Bearing Structures

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ABSTRACT: A DIGITALLY ENHANCED Landsat 5 Thematic Mapper mosaic (TM) data, a hand-held color space photograph from one of the early NASA satellite missions (Gemini), and field data were used to delineate three major basement-controlled, cross-strike sturctural discontinuities (CSDs) with the Zagros Basin of southwestern Iran. Three major subparallel CSDs are, from north to south, Kazerun-Qatar (N05°W trend), Razak (N17°E trend), and Oman (N18°E). These subparallel CSDs subdivide the Zagros Basin into northern, central, and southern sub-basins.

Piercement salt domes of Precambrian salt are abundant within the southern Zagros sub-basin, are absent east of the Oman CSD, and are scarce in the area west of the Razak CSD. The salt dome distribution and the N17°E Razak trend suggest that these lineaments are surface manifestations of boundaries of basement crustal blocks which have been reactivated periodically since the Precambrian. Along the eastern boundary of the Razak CSD, near the juncture of the southern Zagros sub-basin and the western Makran Ranges, the trend of fold axes changes from east-west to northwest-southeast, further delineating this lineament.

The Razak and Oman CSD enclose a relatively nonproductive area, separating the southern Zagros sub-basin from more productive regions to the northwest and the nonproductive Makran Ranges to the southeast where chromite and iron deposits are common. These findings suggest that CSD may serve as an exploration guide for hydrocarbons and economic mineral deposits, and as a model for developing the tectonic framework of sedimentary basins. The results of this investigation also prove that lineament analysis is a potentially effective method for interpreting the basement-related CSD within a basin setting.

INTRODUCTION

The association of oil and gas deposits with regional basins and uplifts has long been recognized as an aid in the exploration for hydrocarbons (Thomas, 1974). The applicaiton of Landsat imagery in the exploration for hydrocarbon and mineral deposits has been extensively studied by Halbouty (1976). An excellent example of the application of multispectral data in search for hydrocarbon was published by Collins *et al*. (1974). Saunders *et al*. (1973) noted that linear features control the location of oil and gas fields in the San Juan basin. Wheeler (1980) has discussed the possible application of cross-strike structural discontinuities (CSDs) for exploration of natural gas in part of the central Appalachian Plateau province.

Lineament analysis from the southern Zagros sub-basin has been utilized as a reconnaissance tool for hydrocarbon prospecting and for identifying basement-related structures. The study area covers approximately 8,697 square kilometres of the southern and central Zagros sub-basin (Figure 1).

The objectives of this study were four fold: (1) to trace the major and minor linear features from Landsat imagery and to describe their orientation; (2) to compare these linear features with the reported geologic structures and previously mapped fracture zones; (3) to define the relationship of the linear features to basement structures, and correlate the trend of these linear features with subsurface data, e.g., isopach maps, geological cross sections, and seismotectonic information; and (4) to compare and interpret the distribution of oil and gas fields with the trend of the major linear features (CSDs).

The Razak CSD has been interpreted using a statistical method designed to reduce interpreter subjectivity. This CSD exists as a series of subparallel linear features, concentrated in a general orientation of north-south.

The Razak CSD was first identified from a hand-held color space photograph from one of the early NASA Satellite Missions (Gemini) as a zone of concentrated linear features (Iranpanah *et al*., 1979), and was later detected from Landsat 5 Thematic Mapper (TM) data (Iranpanah 1986). Hydrocarbon accumulations require certain lithologic characteristics; understanding the basement topography is very important in defining the zones of lithologic changes and the extent of basin (Halbouty, 1976). The north-south trend of the Razak CSD corresponds directly to basement structures interpreted from subsurface data. Examination of subsurface data and consideration of the geologic sections from this area suggests that the structural fabric within the covered basement rocks may have been the controlling factor in the development of the Razak CSD.

METHODS

Prior to 1982, geological mapping using satellite data was carried out primarily with multispectral scanner (MSS) imagery having a resolution cell (RC) of approximately 80 m by 80 m. MSS provide four wavelength channels of predetermined spectral bands. A new generation of satellite data (Thematic Mapper) with an RC of 30 m by 30 m was introduced for geological mapping in 1982. It provides seven channels of data, three in the visible, three in the reflected infrared, and one in the thermal infrared (RC = 120 m by 120 m) portions of the spectrum.

In this study, the lineament analysis was conducted using a digitally edge-enhanced Landsat 5 thematic Mapper mosaic of the southern Zagros Basin. Winter images were chosen for minimum cloud cover and lower sun angle in order to enhance topographic features. Additional imagery utilized included a color photograph from Gemini. Ancillary data include a regional geological map, subsurface data which consist of geological cross sections and isopach maps, and seismotectonic information. A controlled mosaic at a scale of 1:250,000 was made from the computer-enhanced TM data to cover the study area in the southern Zagros Basin.

Lineaments were compiled by tracing the observed linear features. An arbitrary 2-km lower limit of length was used in compilation. Through-going continuous linear features were inferred even though they were locally discontinuous. It is assumed that

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 55, No. 10, October 1989, pp. 1491-1496.

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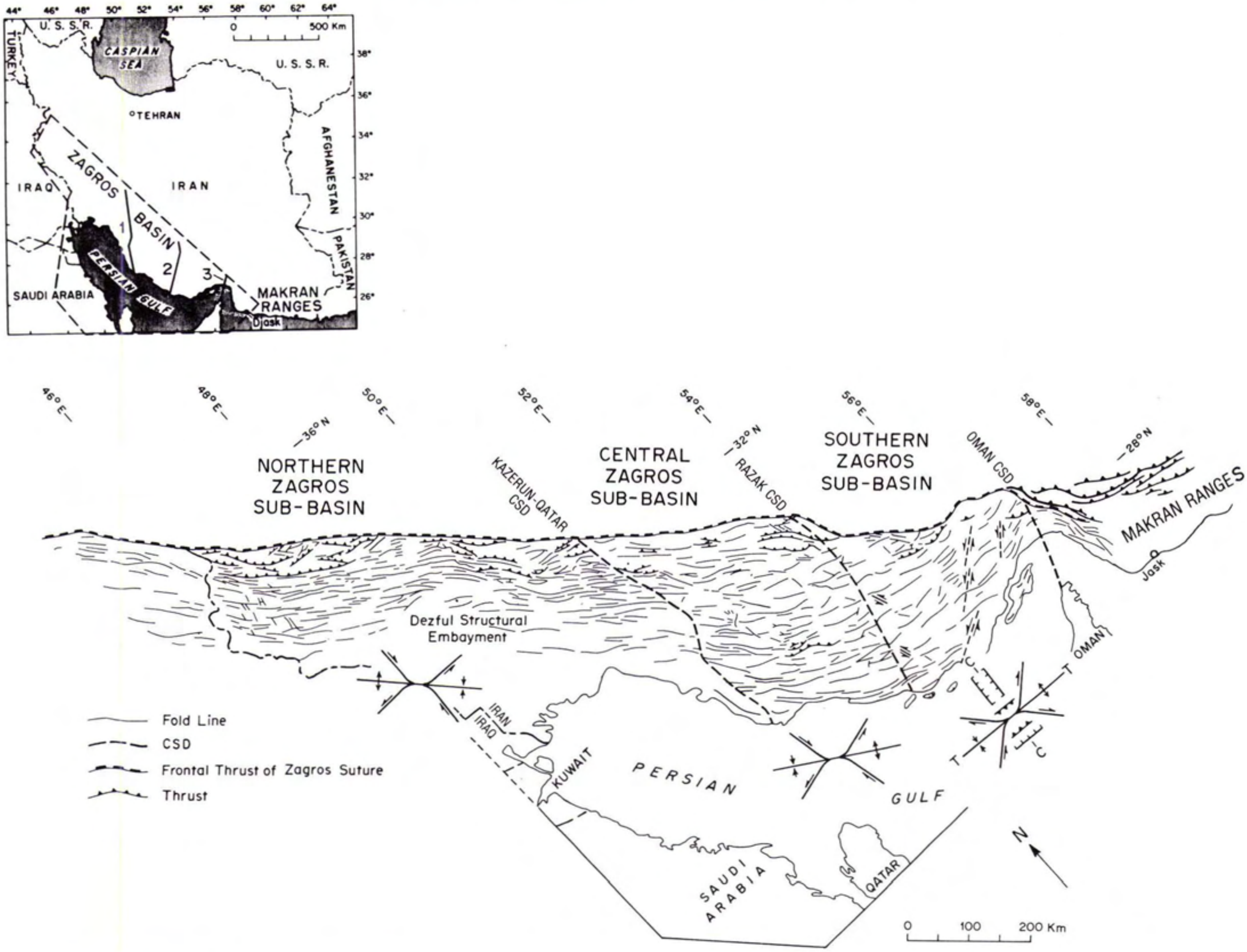


FIG. 1. Generalized tectonic map of the Zagros fold belt. The map shows the subparallel trend of the Kazerun-Qatar, Razak, and Oman CSDs, and the northern, central, and southern Zagros sub-basins. Note the change in the orientation of the principal compressional stress (C) on the deformation diagrams, which changes from north-south in the southern Zagros to northeast-southwest in the central and northern sub-basins. Inset top left: Showing the geographic setting of the Zagros Basin and the Makran Ranges. Heavy solid lines demonstrate the approximate locations of CSDs: 1 = Kazerun-Qatar; 2 = Razak; 3 = Oman.

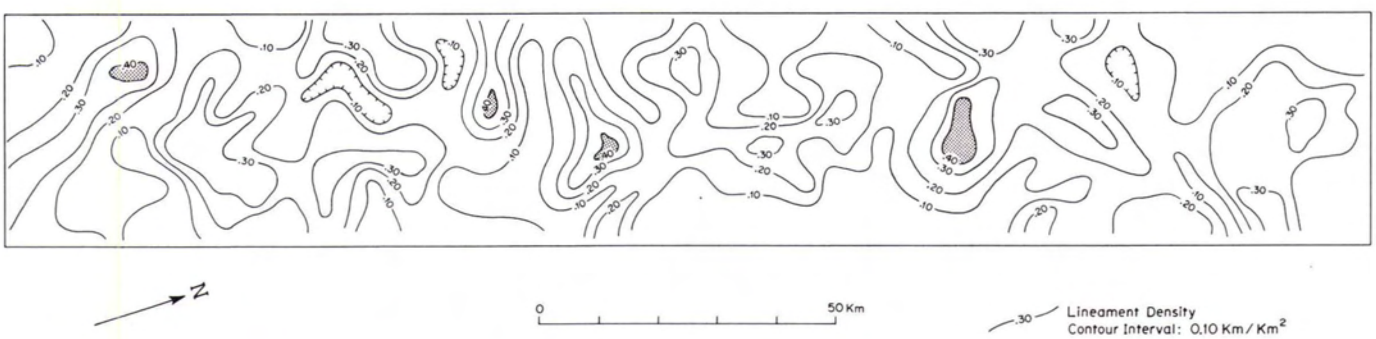


FIG. 2. Lineament density contour map along the Razak CSD between the central and the southern Zagros sub-basins.

such through-going lineaments represent deep, regional structural features such as deep basement faults, whereas the shorter lineaments manifest local and smaller fault lines.

GEOLOGIC SETTING

The Zagros fold-thrust belt is an active belt which resulted from the collision of the Arabian and the Cimmerian continents.

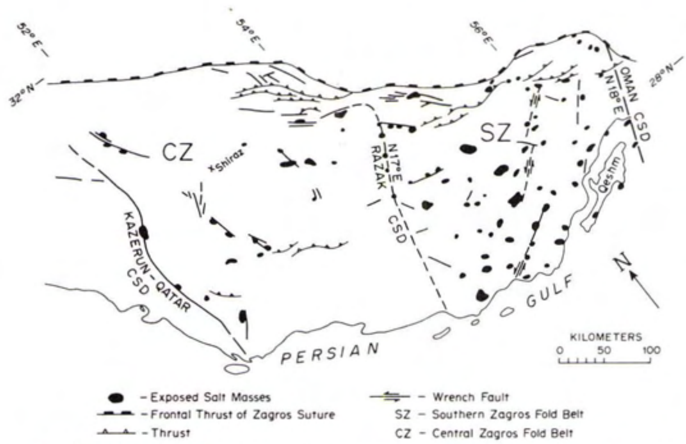


FIG. 3. Map showing the domain boundaries of the southern, central, and northern Zagros sub-basins, as interpreted from a Landsat 5 Thematic Mapper mosaic. Note the exposed Infra-Cambrian salt masses in the central Zagros sub-basin which generally occur along the fault lines (base map modified from Huber (1978)).

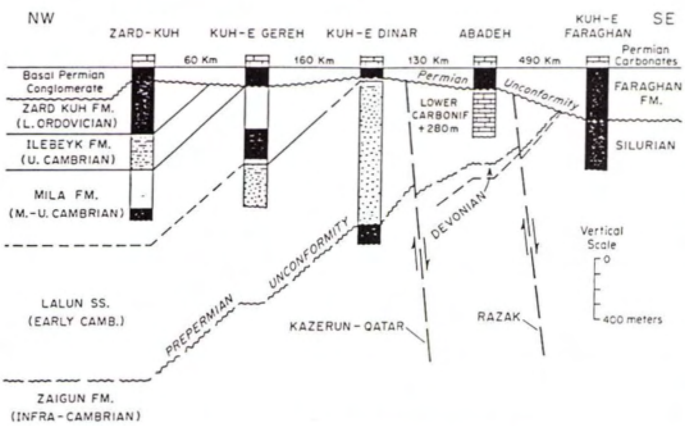


FIG. 4. Northwest-southeast stratigraphic correlation showing the Permian and Prepermian unconformities and the traces of the interpreted Razak CSD and the Kazerun-Qatar basement faults; horizontal distances not to scale (modified from Szabo and Kheradpir (1978)).

The Zagros Basin is located in the southwestern part of the Iranian Plateau, Between a foreland basin to the southwest and the main Zagros Thrust (a Neogene continent-continent suture zone) to the northeast. The sedimentary rock cover was thickened by layer parallel shortening (folding and faulting above 10-km deep salt layers), and apparently the basement also was thickened and several high-angle reverse faults extended to a depth of about 25 km. The crust was also thickened by aseismic creep or plastic deformation to Moho depths (Synder and Barzangi, 1986). Geologic evidence suggests that the basin has experienced at least two major collisional orogenies during the Cretaceous and late Miocene (Stocklin, 1974; Sengor and Kidd, 1979; Stoneley, 1981; Berberian and King, 1981).

Early events affecting the region of the Zagros date to the Precambrian. Following an ancient orogenic phase suggested by Brown and Coleman (1972), Al-Shanti and Mitchell (1976), Greenwood *et al.* (1980), and Frisch and Al-Shanti (1977), an episode of plate collision occurred about 600 to 550 Ma in Arabia. The Upper Precambrian - Cambrian Hormoz salt (Stocklin, 1968, 1974) was deposited in a basin(s), and exposed masses of the salt are now found in the present position of the southern Zagros sub-basin (Figure 3). Although the orogenic phases recognized within the Arabian Shield (Greenwood *et al.*, 1980) have not been reported directly from the basement of the Zagros Basin, it seems likely that underneath this basin there are similar structural features. The crystallization of the Precambrian basement in this area is assumed to have taken place prior to the deposition of the Upper Precambrian - Cambrian Hormoz salt (Stocklin, 1968; Kent, 1979) and terrigenous sediments in the Zagros Basin.

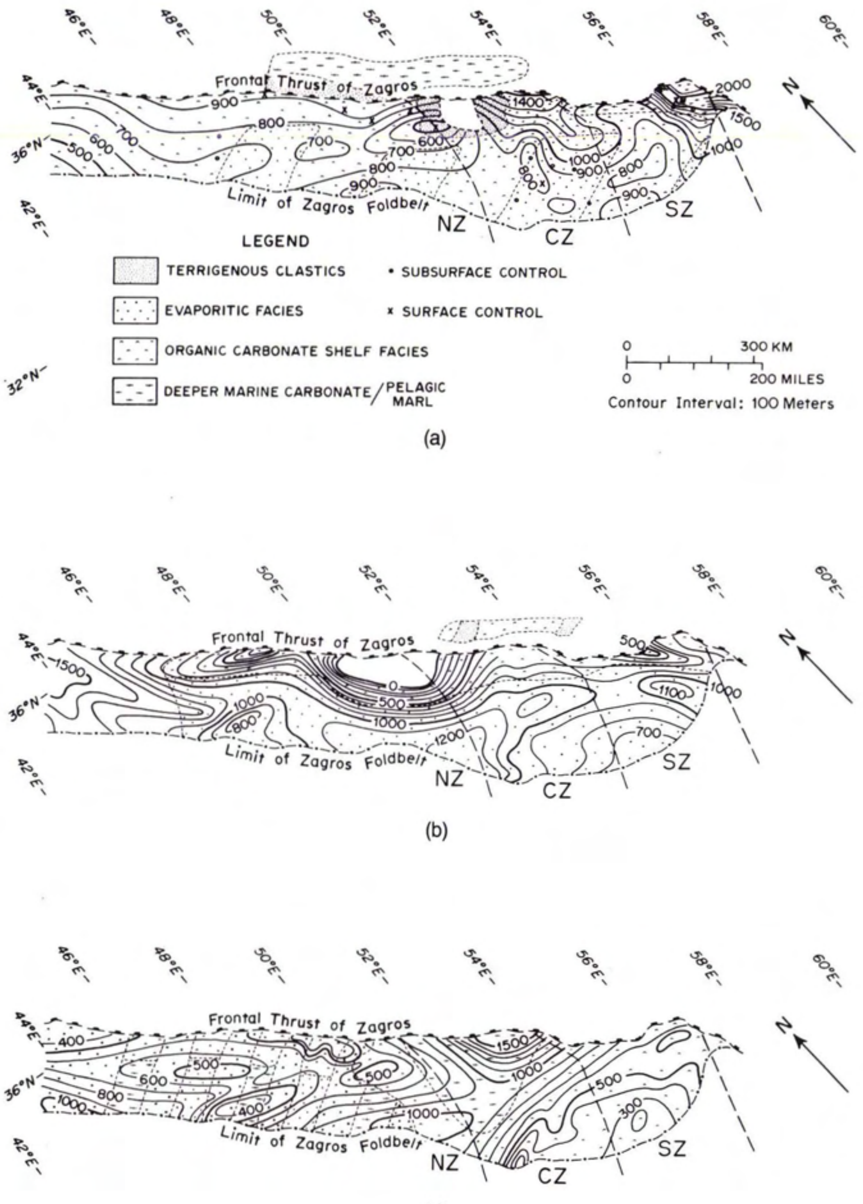
During late Precambrain, Paleozoic, and early Mesozoic time the sense of movement along the Najd fault in the northeastern part of Arabia changed from compressional to an extensional motion, introducing normal faults. Thrust faults developed later as compressional motion ensued from the late Cretaceous to the Recent (Berberian and King, 1981). The reactivation of the normal faults within the basement of the Zagros Basin has probably resulted in the development of cross-basinal subdivision lines (ramp structures) such as the Kazerun-Qatar and the Razak CSDs. These transverse ramps are facies dividers, partitioning the Zagros Basin into three sub-basins (Figures 1 and 4).

DISCUSSION

Recent studies (e.g., Sykes, 1978) have shown that the continental lithosphere in many regions is not rigid and continuous, as first envisioned in simple plate tectonic models. Block tectonic structures within the basement have been reported in the eastern United States, e.g., Pennsylvania (Canich and Gold, 1977), (Rodgers and Anderson, 1984), (Iranpanah and Hopkins, 1987) and New York (Diment *et al.*, 1980). Independent motion of these basement blocks is alleged to reactivate the boundary faults, and eventually create topographic ramps at the basement surface (Iranpanah, 1989). These large-scale topographic ramps control lateral facies distributions within the basin. Identification of these basement structures can help to define basin limits and basin subdivisions due to lateral facies changes and subsurface fracture zones that may aid in the search for hydrocarbons at depth. This method is particularly useful in the early stages of the search for hydrocarbons in relatively unexplored areas.

A 39-km wide and 223-km long strip of the southern Zagros Basin was chosen for mapping of the most prominent linear physiographic features observable on a Landsat 5 Thematic Mapper image. No major faults were observed in this area from available geological information. The area is characterized by a relatively dense array of linear features with a clear concentration in a N17°E orientation (Figure 2). Examination of isopach maps (Koop and Stoneley, 1982) from the area shows a distinct discontinuity in the lateral distribution of facies from late Permian to late Miocene. The trend of the Razak CSD has also been traced in the subsurface using the stratigraphic sections from Szabo and Kheradpir (1978). The Razak CSD has been interpreted as a high-angle normal fault dipping to the south (Figure 4). The Razak feature is subparallel to the Kazerun-Qatar transverse fault which has been mapped at the surface (Huber, 1978). Both the Razak CSD and the Kazerun-Qatar fault in the south and the central Zagros sub-basins appear to be related to structurally-controlled ramp structures of the basement, along which significant changes are observed in rock thickness and lithology.

The shortest linear feature recorded along the Razak CSD is approximately 2 km long, whereas the longest lineament is measured to be 20 km. Lineament density values (i.e., lineament length/area) were calculated over the entire area (8697 km^2), along the Razak CSD, and are shown in Figure 2. The lineament density values were obtained within a square block of 2.5 by 2.5 kilomeres of 6.25 km^2. This density was then contoured using the original lineament data sheets. The highest and lowest vlaues as calculated per 6.25 km^2 block were used as the highest and lowest contours, respectively. The



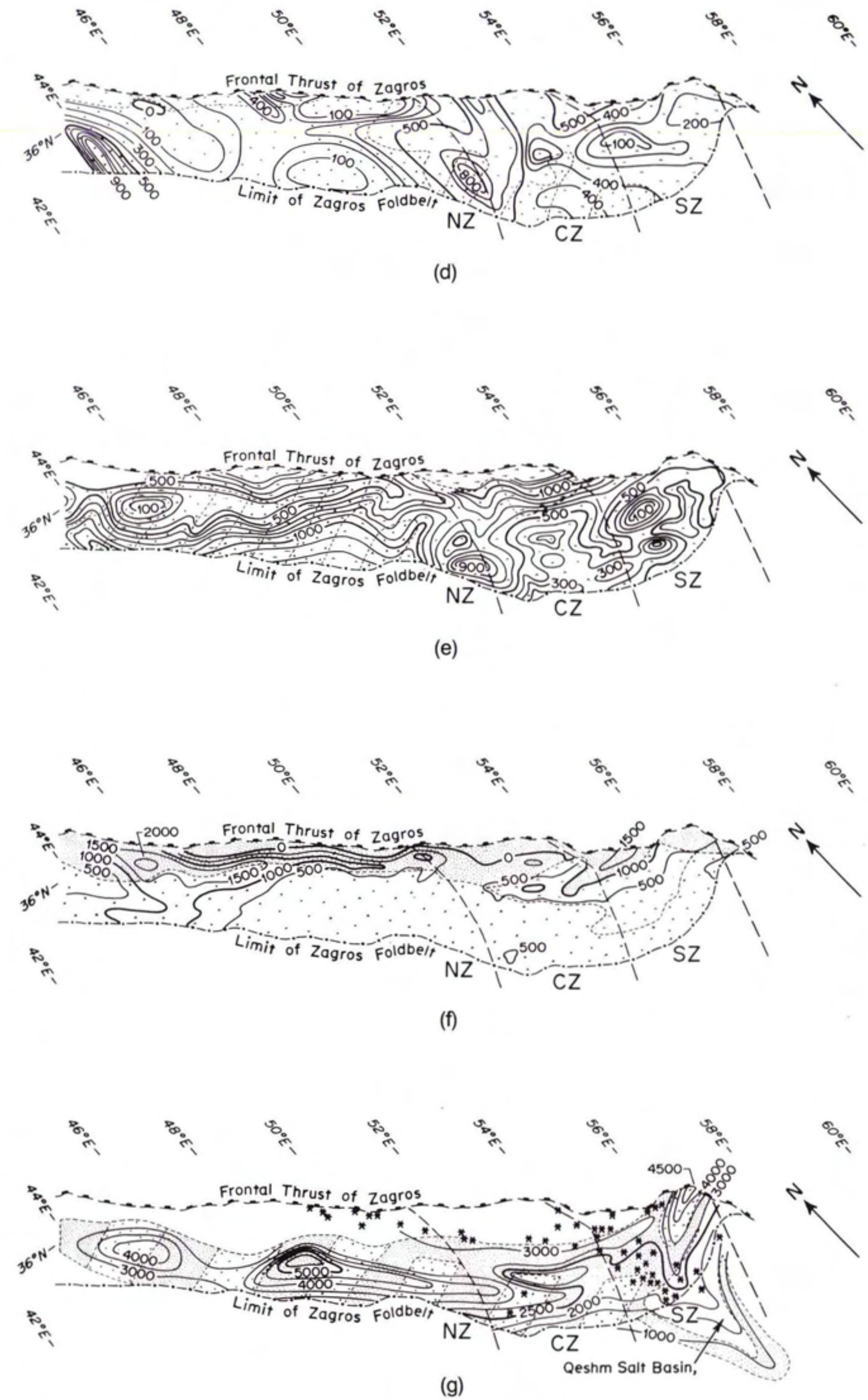


FIG. 5. Map showing the regional geographic and tectonic setting of the Razak and the Kazerun-Qatar CSDs in relation to the (a) Permian, (b) Triassic, (c) Lower and Middle Jurassic, (d) Upper Jurassic, (e) Lower Cretaceous, (f) Upper Cretaceous, and (g) Lower Miocene — Recent isopachs and facies distributions (modified from Koop and Stoneley (1982)).

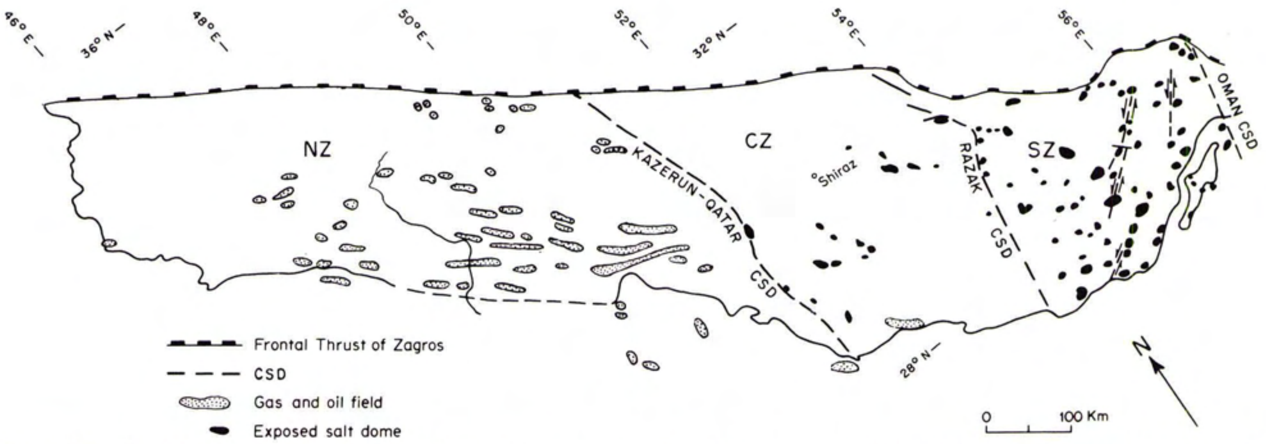


FIG. 6. Map showing the relation between the Kazerun-Qatar and the Razak CSDs to the areal distribution of the hydrocarbon reservoirs and the exposed Infra-Cambrian salt masses (the base map is generalized from Huber (1978)).

lineament density along the Razak CSD varies from 0.1 km/km^2 to 0.4 km/km^2. The overall average lineament density along the Razak CSD is approximately 0.17 km/km^2 (Figure 2).

Comparison of the lineament contour map with the coordinates and depth of earthquake epicenters in the period of 1900 to 1973 (Berberian, 1976) and other seismic studies (Ni and Barzangi, 1986), have shown local concentrations of epicenters in the adjacent sub-basins of the Razak and Kazerun-Qater CSDs. A number of epicenters are localized in the southern Zagros sub-basin between the Razak and the Oman CSD to the north and south, respectively. In principal, the sources are located within the crust, generally at depths of 5 to 100 km, less commonly up to 150 km, with measured intensities ranging from 3.5 to 7.00 (Berberian, 1976).

The Razak CSD is interpreted to represent a deep-seated basement fault which has been periodically reactivated with varying intensity throughout geologic time. It is still active according to present seismotectonic data (Berberian, 1976). Isopach maps (Koop and Stoneley, 1982) commonly show a parallel alignment of contours over or on-line with the Razak CSD, suggesting that these physiographic alignments owe their origin to a deeply buried (6 to 12 km) ramp within the crystalline basement. The pattern of Precambrian faults and deposition shows that the study area was affected by basement-controlled adjustments parallel to the Razak CSD. The exact timing of displacements along the ramp structure can not be resolved with the present data.

The Kazerun-Qatar, Razak, and Oman CSDs are shown in isopach and facies maps from Permian to Recent, to permit a comparison of these linear trends with major facies distributions and basinal configuration (Figure 5). During the Permian period, terrigenous sediments (T) were limited to the northern part of the central Zagros sub-basin, which was enclosed between the Kazerun-Qatar and the Razak CSD (Figure 5a). During the Triassic period, deeper marine carbonates and pelagic marls (DP) were deposited outside of the central Zagros sub-basin (Figure 5b). There is a close correlation between the trend of the Kazerun-Qatar and the Razak CSDs and the occurrence of Lower and Middle Jurassic deep marine carbonates and pelagic marls (DP) in the southern Zagros sub-basin (Figure 5c). The Upper Jurassic sediments do not show much variation in facies distribution in the central Zagros sub-basin (Figure 5d). When the Lower Cretaceous facies distribution and isopach map is superimposed over the CSDs, a locally closed basin in the central Zagros sub-basin, where deep marine carbonates and marls (DP) were deposited, is revealed (Figure 5e). During late Cretaceous time, the Razak CSD paritally delimited the southern margin of the central Zagros sub-basin (Figure 5f). The Infra-Cambrian Hormoz salt masses have penetrated the Tertiary sediments. They are abundantly exposed in the southern Zagros sub-basin, and are scarce or absent in most parts of the central and northern sub-basins, where they are most characteristically associated with local faults (Figures 3, 5g, and 6).

This comprehensive study, incorporating Landsat images, surface geology-geomorphology, and seismotectonic data (Kadinsky-Cade, and Barzangi, 1982), yields more detailed knowledge about the local configuration of the basement surface and sedimentary cover flooring the Zagros Basin. The data also explain the distribution of hydrocarbon occurrences within the stratigraphic framework of the defined sub-basins. There is a close correlation between the Razak CSD and the paleostructures and sedimentation patterns indicated by isopach maps and geological section data (Figures 4 and 5). The Razak CSD forms the southernmost boundary of established hydrocarbon production. Understanding the nature of the geographic extension of the Razak CSD and its relationship to reservoir distribution within the Zagros Basin may help to extend production and introduce new reserves. Similar examples of such structurally and geomorphologically controlled basins can be seen in southwestern Mississippi, southern Arkansas, within the Anadarko Basin in Oklahoma, and along the Gulf Coast in Louisiana. Knowledge of local basement influences should thus be considered as an important step in any reconnaissance study during hydrocarbon exploration. Recognition of such basement structures could also be useful in the analysis of regional seismicity and seismic risks in engineering projects, because deep basement faults are potentially active fault zones.

Additional field studies of the linear features collected from Thematic Mapper data, and comparison of the orientation of the surface lineament with results obtained from analysis of oriented cores, may also cast some light on the effect of deeply buried ramp structures on the tectonics, sedimentation, and pattern of the oil fields in the Zagros Basin.

SUMMARY AND CONCLUSIONS

This paper has attempted to study the cross-strike structural discontinuities within the Zagros Basin identified from a handheld space color photograph and a Landsat 5 Thematic Mapper mosaic. The investigation was intended to provide an analysis of the developmental history of the Zagros Basin. A combination of remote sensing techniques, surface and subsurface geologic information, and seismotectonic data were employed to develop a structural model, and to allow geomorphological subdivision of the Zagros Basin.

Three major subparallel CSDs – Kazerun-Qatar, Razak, and Oman – divide the northwest-southeast trending Zagros Basin into three sub-basins. These features trend approximately N05°W, N17°E, and N18°E, respectively, subdividing the Zagros Basin into the northern, central, and southern sub-basins.

Precambrian salt domes are abundant within the southern sub-basin, are absent east of the Oman line, are scarce in the central segment (except along local fault lines), and are absent or scarce on the surface in the northern sub-basin. The fold axes trend east-west in the southernmost part of the southern sub-basin, but their trend changes to northwest-southeast in the vicinity of the Razak CSD (Figure 1).

It is believed that the Razak CSD as well as the Kazerun-Qatar and the Oman lineaments are manifestations of deep-seated basement faults. Ongoing, intermittent tectonic movements along these buried faults have been impressed upon the overlying sediments by affecting sedimentation patterns, as well as by creating faults, megajoints, and other fracture patterns. These linear features would have an important bearing on the delineation of the distribution of hydrocarbon reserves and the subdivision of the Zagros Basin. The northern sub-basin is highly productive, whereas the central sub-basin is less productive, and the southern sub-basin, at least at the present stage of development, is non-productive (Figure 6).

This work has shown how basement structures can influence the tectono-sedimentary setting and, accordingly, the occurrence of hydrocarbons in a sedimentary basin. The study shows that CSD analysis is an attractive tool in the exploration for oil and gas fields in a sedimentary basin.

REFERENCES

Al Shanti, A.M.S., and A.H.S. Mitchell, 1976. Late Precambrian subduction and collision in the Al-Amar-Idsas region, Arabian Shield, Kingdom of Saudi Arabia, *Tectonophysics*, Vol. 30, pp. T41–T47.

Berberian, M., 1976. *Contribution to the Seismotectonics of Iran*, II, Rep. Geol. Surv., Iran, 39, 516 pp.

Berberian, M., and G.C.P. King, 1981. Towards a paleogeography and tectonic evolution of Iran, *Can. J. Earth Sci.*, 18(2).

Brown, G. F., and R. G. Coleman, 1972. The tectonic framework of the Arabian Peninsula, *Proceedings of the 24th International Geological Congress*, Montreal, section 3, pp. 300–305.

Canich, M. R., and D. P. Gold, 1977. *A Study of the Tyrone-Mt. Union Lineament by Remote Sensing Techniques and Field Methods*, ORSER Technical Report 12-77, Contract NAS 5-22822, 54 p., Office for Remote Sensing of Earth Resources, Pa. State Univ., University Park, Pa.

Collins, R. J., F. P. McCown, L. P. Stonis, G. Petzel, and J. R. Everett, 1974. An evaluation of the suitability of ERTS data for the purposes of petroleum exploration, *3d Earth Resources Technology Satellite-1 Symposium*, vol. 1, sec. A: U.S. Natl. Aeronaut. Space Admin. Spec. Pub. 351. 351, pp. 809–821.

Diment, W. H., O. H. Muller, and P. M. Lavin, 1980. Basement tectonics of New York and Pennsylvania as revealed by gravity and magnetic studies, *Proceedings, The Caledonides in the USA*, pp. 221–227, Virginia Polytechnic Institute and State University, Department of Geological Sciences, Blackburg, Va.

Frisch, W., and A. Al-Shanti, 1977. Ophiolite belts and the collision of island arcs in the Arabian Shield, *Tectonophysics*, Vol. 43:(4/3), pp. 293–306.

Greenwood, W. R., R. E. Anderson, and R. J. Roberts, 1980. *Precambrian Geologic History and Plate Tectonic Evolution of the Arabian Shield*, Bull. Saudi Arabian Directorate General of Mineral Resources, Vol. 24, 35 p.

Halbouty, Michel T., 1976. Application of Landsat imagery to petroleum and mineral exploration. *Amer. Assoc. Petrol. Geol. Bull.*, Vol. 60, No. 5, pp. 745–793.

Huber, H., 1978. Geological map of Iran, 1:1,000,000, with explanatory note, NIOC, Exploration and Production Affairs, Tehran.

Iranpanah, A., 1986. Paleobasin analysis and tectonic framework development of southern Zagros Basin, Interpreted from Landsat 4 Thematic Mapper. *Amer. Assoc. Petrol. Geol. Bull.*, Vol. 75/5, pp. 604.

———, 1989. Interpretation of fault-controlled ramp structures in sedimentary basins – an example from the Caspian Sea using Landsat TM data, Abstract: *Amer. Assoc. Petr. Geol. Bull.*, vol. 73/3, pp. 367.

Iranpanah, A., F. Barzgar, and B. Esfandiari, 1979. Structural lineament studies of the Iranian Plateau using Landsat imagery, *Geol. Soc. Amer., Abstracts with Programs*, Vol. 11, No. 5, pp. 232.

Iranpanah, A., and E. Hopkins, 1987. Tectonic analysis of lineaments delineated on Landsat imagery of the Allegheny Plateau in North-Central Pennsylvania and Western New York, *Geol. Soc. Amer., Abstracts with Programs*, Vol. 19, No. 1, pp. 21.

Kadinsky-Cade, K., and M. Barzangi, 1982. Seismotectonics of southern Iran: The Oman Line, *Tectonics*, Vol. 1, pp. 389–412.

Kent, P. E., 1979. The emergent Hormoz salt plugs of southern Iran, *Jour. Petrol. Geol.*, Vol. 2(2), pp. 117–144.

Koop, W., and R. Stoneley, 1982. Subsidence history of the Middle-East Zagros Basin, Permian to Recent, *Philos. Trans. R. Soc. London*, Ser. A., vol. 305, pp. 149–168.

Ni. J., and M. Barzangi, 1986. Seismotectonics of the Zagros continental collision zone and a comparison with the Himalayas, *J. Geophys. Res.*, Vol. 91, pp. 8205–8218.

Rodgers, M. R., and T. H. Anderson, 1984. Tyrone-Mt. Union cross-strike lineament, *Amer. Assoc. Petrol. Geol. Bull.*, Vol. 68, no. 1, pp.. 92–105.

Saunders, D. F., G. E. Thomas, F. E. Kinsman, and D. F. Beatty, 1973. *ERTS-1 Imagery Use in Reconnaissance Prospecting – Evaluation of the Commercial Utility of ERTS-1 Imagery in Structural Reconnaissance for Minerals and Petroleum*, Type III Final Report to NASA: U.S. Dept. Commerce, Natl. Tech. Inf. Service, E74-10345.

Sengor, A. M. C., and W. Kidd, 1979. Post-collisional tectonics of the Turkish-Iranian Plateau and a comparison with Tibet, *Tectonophysics*, Vol. 55, pp. 361–376.

Snyder, D. B., and M. Barzangi, 1986. Deep crustal structure and flexure of the Arabian Plate beneath the Zagros collisional mountain belt as inferred from gravity observations, *Tectonics*, Vol. 5, No. 3, pp. 361–373.

Stocklin, J., 1968. Structural history and tectonics of Iran – a review, *Amer. Assoc. Petrol. Geol. Bull.* Vol. 52, No. 7, pp. 1229–1258.

———, 1974. Possible ancient continental margins in Iran, *The Geology of Continental Margins* (C. A. Burk and C. L. Drake, eds.) Springer, New York, pp. 873–887.

Stoneley, R., 1981. The geology of the Kuh-e-Dalneshin area of southern Iran, and its bearing on the evolution of southern Tethys, *J. Geol. Soc. London*, Vol. 138, pp. 509–526.

Sykes, L. R., 1978. Intraplate seismicity, reactivation of pre-existing zones of weakness, alkaline magmatism, and other tectonism postdating continental fragmentation, *Rev. Geophys. Space Phys.*, Vol. 16, pp. 621–688.

Szabo, F., and A. Kheradpir, 1978. Permain and Triassic stratigraphy, Zagros Basin, southwest Iran, *J Geol.*, pp. 57–82.

Thomas, G. E., 1974. Lineament block tectonics: Williston Blood Creek Basin, *Ameri. Assoc. Petrol. Geol. Bull.*, Vol. 58, No. 7, pp. 1305–1322.

Wheeler, Russell L., 1980. Cross-strike structural discontinuities: Possible exploration tool for natural gas in Appalachian over-thrust belt. *Amer. Assoc. Petrol. Geol. Bull.*, Vol. 64, No. 12, pp. 2166–2178.

(Received 3 February 1989; revised and accepted 30 June 1989)