Multi-phase inversion tectonics related to the Hendijan–Nowrooz–Khafji Fault activity, Zagros Mountains, SW Iran

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A B S T R A C T
Distinctive characteristics of inverted structures make them important criteria for the identification of certain structural styles of folded belts. The interpretation of 3D seismic reflection and well data sheds new light on the structural evolution and age of inverted structures associated to the Hendijan–Nowrooz–Khafji Fault within the Persian Gulf Basin and northeastern margin of Afro-Arabian plate. Analysis of thickness variations of growth strata using “T-Z” plot (thickness versus throw plot) method revealed the kinematics of the fault. Obtained results show that the fault has experienced a multi-phase evolutionary history over six different extension and compression deformation events (i.e. positive and negative inversion) between 252.2 and 11.62 Ma. This cyclic activity of the growth fault was resulted from alteration of sedimentary processes during continuous fault slip. The structural development of the study area both during positive and negative inversion geometry styles was ultimately controlled by the relative motion between the Afro-Arabian and Central-Iranian plates.

1. Introduction

Inversion tectonics was introduced by several authors (e.g. Glennie and Boegner, 1981; Cooper and Williams, 1989) to describe changes of tectonic regime from extension to compression, and vice versa. After introducing different type of inverted structures (i.e. positive and negative types) by Williams et al. (1989), several examples of these structures were recognized and described worldwide (e.g. Biji, 2006 and references cited therein). Positive and negative inverted structures are created in response to change of tectonic regime following the contractional reactivation of inherited normal faults or extensional reactivation of inherited reverse faults, respectively (Fig. 1). Distinctive characteristics of inversion-related structural geometries consist of anomalous variations of fault-throw with depth, thicker strata on the hanging wall of thrusts faults and footwall shortcut thrusts (Cooper and Williams, 1989). The recognition of inverted structures is important in the oil industry because inversion can: a) modify the burial history of a sedimentary basin, b) uplift sediments above sea level generating secondary porosity, c) modify the attitude of the sedimentary package, allowing different directions of fluid migration with time, d) reactivate older faults, changing their sealing properties and e) form complex structures at depth and care needs to be taken to differentiate these from single event compressive thin-skinned thrust structures (Coward, 1994).

Constraining reactivation processes has practical implications for improving the evaluation of seismic hazards (Lisle and Srivastava, 2004) and assessing the impact of reactivation on fault seal quality and fluid migration (Holdsworth et al., 1997). The main goal of this study is to describe and quantify the style of inversion tectonics adjacent to the Hendijan–Nowrooz–Khafji Fault from the Persian Gulf Basin and northeastern margin of the Afro-Arabian plate (Fig. 2). Due to the occurrence of large oil and gas resources of Iran and Saudi Arabia (Fig. 3) in the vicinity of this fault, it has tremendous geological and industrial importance. The Hendijan high and the Burgan–Azadegan high with NE–SW and N–S trends are the most prominent structural features in the Persian Gulf Basin. The Hendijan and Burgan–Azadegan high are structural trends were named based on elongated topographical feature in north part of Persian Gulf (the geological map of National Iranian Oil Company in SW Iran at scale 1:10,000,000). The Hendijan high in SW Iran hosts several Iranian and Saudi Arabian oil fields (Abdollahie...
The Hendijan Fault is one of the Important Lineaments that have Arabian tectonic trend and refer to a syncline structure in Arabian plate (Bahrouri and Talbot, 2003). These structures extend to the N within the Zagros Mountains (Fig. 2). Hence, we discuss the kinematic evolution of the Hendijan Fault based on the qualitative interpretation of 3D seismic reflection and well data. In this paper, we present new tectono-sedimentary data based on the geological interpretation of seismic sections to support the occurrence of a multi-phase inversion tectonics related to the Hendijan—Nowrooz—Khafji Fault activity within the Zagros Mountains, SW Iran. Based on the interpretation of growth strata and seismic stratigraphy, this paper describes the geometry styles of inverted structures and reliably approximates the age of the beginning of the positive and negative inversions in the Persian Gulf Basin.

2. Geological and tectonic settings

The Zagros Mountains is one of the most active collisional orogens within the Alpine–Himalayan orogenic belt. Closure of the Neotethys Ocean which resulted from oblique convergence between the Afro-Arabian plate and Central Iranian plate during the Cenozoic led to formation of this belt (Mouthereau et al., 2012 and references cited therein). Both the Zagros Range and its foreland belong to the northeastern part of the Afro-Arabian Plate. The Persian Gulf Basin, a rich region of hydrocarbon resources, is a part of this lithospheric plate. This basin is surrounded by the Arabian Shield in the west, Taurus range in the north and the Zagros range in the east and northeast. The regional geology of the Persian Gulf Basin has been described and analyzed in detail because of the high hydrocarbon potential of this region (e.g., Stern, 1985; Beydoun, 1991; Edgell, 1996; Alsharhan and Nairn, 1997; Bahrouri and Talbot, 2003). The Persian Gulf Basin was the site of ancient passive margin sedimentation on the margin of Gondwana during most of the Phanerozoic, which faced toward the Neotethys in the Mesozoic and toward the Paleotethys Ocean in the Paleozoic (Alavi, 1994; Bahrouri and Talbot, 2003; Abdollahie Fard et al., 2006). Main faults and folds in the northeast margin of Afro-Arabian plate have different trends such as N–S, NNW–SSE or NNE–SSW (Abdollahie Fard et al., 2006). North–south-trending faults within the Arabian basement have been repeatedly reactivated during the Permo-Triassic opening of the Neo-Tethys and have exerted a strong control over the structure, thickness and facies of the cover rocks (Zeigler, 2001). In the foreland part of the Zagros, north–south trends are attributed to the reactivation of Pan-African basement faults (Edgell, 1991, 1996) during the Permo-Triassic (Alsharhan and Nairn, 1997) till Late Cretaceous (Abdollahie Fard et al., 2006 and references cited therein). The ductile deep seated Precambrian Hormuz salt series, basement rocks movement and the late Tertiary Zagros orogeny, are main factors that have influenced the formation of the structural anomalies in the Persian Gulf (Saadatinejad et al., 2012). The study area is located in the Persian Gulf Basin along the northeastern margin of the Afro-Arabian plate adjacent to the Hendijan—Nowrooz—Khafji Fault. The names, lithologies and ages of the stratigraphic formations and groups used here (Fig. 4) are based on the classical stratigraphic chart for this region established by James and Wynd (1965), correspond to those employed by the National Iranian Oil Company in their regular exploration tasks synthesized in unpublished and confidential annual reports. The ages of the various stratigraphic units were established by determining foraminifera biozones and employing fossils such as sponge spicules, algae, echinoids, rudists, radiolarians, ostracods, gastropods, foraminifers, bryozoans, corals, stromatoporoids, crinoids, tintinnids, Favreina, annelids and polyplacophorans collected in confidential exploration wells. The Hendijan—Nowrooz—Khafji Fault with few tens of kilometers is located in the southeastern-east part of Zagros range in Iran and the west of Persian Gulf (Fig. 1).

3. Methods

In active tectonic settings, growing structures often control the deposition process at different scales (Vergès et al., 2002). Growth fault activity led to change in the sediment thickness across the fault (i.e. synsedimentary fault). This event causes the differences in thickness of sediments both on the footwall and hanging wall during time of fault activity. Fault throws subsequent to the sedimentation of each horizon and the fault movement history can be determined using these thickness changes. Analysis of these thickness changes along a fault is now feasible using high quality...
3D seismic data (Childs et al., 2003). Displacement and the growth history of individual fault surfaces can be determined through this analysis. The analysis of syn-tectonic sedimentation is widely used to determine the kinematics of growth-faults (e.g. Castelltort et al., 2004a,b). In order to highlight the activation interval of Hendijan–Nowrooz–Khafji Fault, we used the ‘T-Z plot’ method introduced by Pochat et al. (2004). Using this method one can constrain the slip history of growth faults. The application of this method is based on the “fill-to-the-top” sedimentation assumption which is considered that sedimentation always fills-up fault-generated topography. In faulted settings, lithological variations due to fault activity can be predicted on seismic profile using this method. (Castelltort et al., 2004a,b and references cited therein). Among the n stratigraphic horizons across a growth fault, the younger horizon at i = 0 is considered as the first stratigraphic surface without fault generated topography while the older i = n is the youngest pre-faulting horizon (Fig. 5). The obtained data from analysis of thickness variations of growth strata may provide

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**Fig. 2.** Map of basement lineaments and oil- and gas fields in the Zagros Basin (compiled from Beydoun, 1991; Alsharhan and Nairn, 1997; Weijermars, 1998).
information about fault kinematics even in the absence of palaeo-
bathymetry and the age of each horizon.

Generally, throw variations represent a combination of
placement and topography across the growth fault (Fig. 6).
Therefore, the throw $t_i$ on the first increment of sedimentation
(interval $i; i-1$) after time $i$ (Fig. 6) is expressed as:

$$t_i = d_i + e_i$$

in which the vertical displacement on the fault between $i$ and $i-1$ is $d_i$, and the topography at time $i$ is $e_i$. It is assumed that fault
displacement variations can cause thickness variations in the
sedimentary layer in two sides of fault. Alteration in this type
of plot indicating positive, null and negative slopes reflects variations
of thickening of the sedimentary strata towards the hanging wall
(Baudon and Cartwright, 2008 and references cited therein).
Thickening of strata towards the hanging wall resulted from fault
activity, whereas during periods of fault quiescence (null slopes)
associated with non-thickened intervals. Negative slopes the T-Z
plots may indicate fault linkage or fault inversion (Castelltort et al.,
2004b and references cited therein). Assuming fill-to-the-top
model (Fig. 7), the T-Z plot is useful to constrain the displacement
history of growth faults (Pochat et al., 2004).

To construct a T-Z plot, the vertical throw $T_i$ related to each
horizon is plotted against the depth $Z_i$ in the hanging-wall
(Castelltort et al., 2004a). The first step for constructing this type
of plot consists of picking some markers on a seismic section that
are correlatable around a fault. Then, the thickness of intervals
between successive markers and the associated vertical throw
across the fault related to each horizon are measured and plotted.
Starting from the shallowest unfaul ted interval, the throw related
to each horizon (Y-axis) and their depth (X-axis) down the fault are
plotted against each other. In this case, evolution of fault growth
and associated sedimentological patterns can affect quantitatively
slope variations on a T–Z plot. Therefore, this type of analysis be-
comes a powerful tool to unravel main lithological alterations on
seismic sections in faulted domains. This research carried out based
on the mapping and interpretation of a net of high quality seismic
sections acquired in two orthogonal sets: one set strikes NNE–SSW
(referred to as N–S below) and the other strikes WNW–ESE
(referred to as W–E below). The Schlumberger Petrel software was
used for most of interpretation. Sixteen different horizons were
picked and interpreted in each seismic section. Sixteen different
horizons were picked and interpreted in each seismic section
(Fig. 8).

4. Results

4.1. Analysis of throw versus time

The long-term evolution of the fault displacement rate during
time was analyzed in order to determine the major factor which
controls short-term thickness variations in growth strata (i.e. fault
movement or sedimentation dynamics). This research focuses on
the study of variation of the vertical throw of each timeline during
time (Fig. 9). These particular stratigraphic surfaces can be
considered as representing a nearly instantaneous event at the
scale of a sedimentary basin or such km-scale structures (Mitchum
and Van Wagoner, 1991). These time lines are also not usually
related to erosive events which may preclude the mapping of the
true displacement of fault (Childs et al., 1993). Therefore, the
measured vertical throw related to time line associated the footwall
and the hanging wall is correlatable with the true fault
displacement.

Changing slope of the curve is interpreted as reflecting a change
of fault mechanism during the time (Pochat and Van Den Driessche, 2007 and references cited therein). Unthickened layers on both sides of the fault are shown by zero-slope interval, thus the fault has been inactive and a positive slope corresponds to a thinner layer and reverses dip slip mechanism of the fault and finally, negative slope shows thicker deposits in the footwall and a normal dip slip mechanism.

The analysis of our data reveals that the vertical throw of the fault encompasses a long-term, progressive diminution with time of the fault scarp from 607 m to 30 m, over 240 million years.
According to the Fig. 6, two major inclinations are distinguished (Fig. 9) as follows: The slope of the T-Z curve shows the same trend in three time intervals; Tatarian to Norian, Kimmeridgian to Portlandian and Aquitanian to Burdigalian. Throws in four steps are different from each other, Norian to Kimmeridgian, Portlandian to Aquitanian and Burdigalian to Serravallian that represents the changing of tectonic conditions or the stress regime which caused deposition of growth strata in the basin and reverse dip-slip movement. Based on the above mentioned results, the fault movement can be divided into 6 phases (Fig. 9 and Table 1).

4.2. Thickness versus throw analysis

The main feature can be seen on the T–Z plot is a long-term quasi linear decrease of the vertical throw from −358.1–479.72 m, over a sediment thickness of 2771 m on both sides of the Hendijan–Nowrooz–Khaflji Fault (Fig. 10). Based on the seismic interpretation, the width of the Hendijan–Nowrooz–Khaflji Fault is about 1 km including many sub-faults with normal and reverse dip-slip movements during the period of our data (more than 240 million years). These long-term relationship of thickness versus time is characteristic of syndepositional faults.

Based on the results, the fault activity can be divided into 6 phases (Fig. 10): a first phase from −11.62 to −15.97 Ma (4.35 Ma) with displacement rate of −2.60 m/Ma and in second phase from −15.97 to −20.44Ma (6.47Ma) with displacement rate of −5.88 m/Ma and in third longer phase from −20.44 to −145 Ma (122.56 Ma) with displacement rate of 2.73 m/Ma and in fourth phase from −145 to −152 Ma (7Ma) with displacement rate of −22.24 m/Ma and in fifth phase from −152 to −208.5Ma (56.5Ma) with displacement rate of 6.97 m/Ma and in latest phase from −208.5 to −252.17 Ma (43.67Ma) with displacement rate of −8.12 m/Ma. As show in Table 1, maximum of activity rate of Hendijan–Nowrooz–Khaflji Fault during −11.62 to −252.17 Ma has been on normal mechanism from −145 to −152 and minimum activity rate of Hendijan–Nowrooz–Khaflji Fault has experienced a reverse mechanism from −11.62 to −15.97. In addition, the longest active phase along the Hendijan–Nowrooz–Khaflji Fault was in the 3rd phase lasting 124.56 Ma and shortest phase was the 1st lasting only 4.35 Ma.

5. Discussion

5.1. Tectonic inversion adjacent to the Hendijan–Nowrooz–Khaflji Fault

Reactivation of faults activity during different deformation phases has been reported for several tectonic regimes worldwide...
The stresses acting along the plate margins can be transmitted far into the foreland resulting in the reactivation of pre-existing normal faults (Ziegler et al., 1995). Moreover, changes from early extension to later contraction in the foreland domains which previously affected by normal faulting have promoted positive tectonic inversion (Butler et al., 2006 and references cited therein). Resulting changes from early contraction to later extension have promoted negative tectonic inversion (Pasculli et al., 2008).

Sherkati and Letouzey (2004) presented evidence for the effects of reactivation of N–S basement faults (e.g. the Hendijan–Nowrooz–Khafji Fault) on basin architecture and on lateral changes of facies and formation thickness in the Izeh zone and Dezful embayment. The Hendijan–Nowrooz–Khafji Fault is collection of a number of vertical strike-slip faults with dip-slip components that were reactivated under regional tectonic conditions during different time periods. Observing seismic cross line of Hendijan–Nowrooz–Khafji Fault in Persian Gulf reveals changes in thickness of syn-tectonic deposition above fault zones and on both sides of the fault zone. Observation of stratal on-lap and/or off-lap pattern in seismic reflector in some strata with different ages in the study area reveal that this thickness change is not related to the
primary basin floor roughness. This represents a change in the dip-slip component of fault zone due to a changing tectonic regime in the study area as follows.

1- When we carefully scrutinized sedimentary layers deposited during the Scythian to Tatarian (Fig. 11a), Pliensbachian to Kimmeridgian (Fig. 11c) and Priabonian to Burdigalian (Fig. 11e); we found that the fault had a normal dip-slip component. The thickness of sediment in the west side of the fault is greater than that of east side. On-lap features in the strata explain that the sedimentary basin developed on the fault zone had subsidence both toward the east and west resulting in a normal fault component of dip-slip activity.

2- From Norian to Pliensbachian (Fig. 11b) and Kimmeridgian to Priabonian (Fig. 11d) and Burdigalian to Serravallian (Fig. 11f), the deposition level of the fault zone was significantly reduced compared to the east and west sides due to reverse dip-slip movement along the fault. Therefore, the fault zone was seated higher than its sides. This has resulted in a lower rate of sedimentation in the fault zone or the sediments have been exposed to erosion as a result of fault uplifting. This is visible on high-resolution seismic images and it can be seen in the large scale of growth strata on both sides of the fault zone. Due to the normal motion during Tatarian and reverse motion during Norian to Kimmeridgian, negative inversion structures formed on the fault zone during these times. During orogenic evolution of collided passive continental margins of the Afro-Arabian continent, basement faults are reactivated. The Zagros Mountains resulted from the ongoing collision of the Afro-Arabian plate with the Central Iranian continental blocks (e.g. Stocklin, 1968; Jackson and Mckenzie, 1984).

In order to determine the geometric and kinematic evolution of the Zagros basin and the trapping of hydrocarbons, it is necessary to distinguish its pre and post-collisional structures. The Arabian Shield displays two sets of Pan-African tectonic fabrics (Stern, 1985; Kusky and Matsah, 2003; Jackson et al., 2013) formed between 900 Ma and 600 Ma ago (Stacey et al., 1984); one set dips steeply with a N-S trend and the other has a NW-SE trend and shows left-lateral strike-slip displacement (Stern, 1985). The Phanerozoic cover of the Arabian Platform is affected by broad anticlines and narrower synclines (Beydoun, 1991) mostly trending N-S. A number of terms have been used for such structures (Bahroudi and Talbot, 2003), including lineaments and blind basement faults (Berberian, 1995). These structures are attributed to the reactivation of one of the two sets of Pan-African basement structures (Edgell, 1991). Most have been active since the Late Paleozoic (Alsharhan and Nairn, 1997; http://www.hindawi.com/68351920/Abdeen et al., 2008; Tairou et al., 2012). Old N-S basement faults have been repeatedly reactivated since the Permo-Triassic opening of Neo-Tethys which has exerted a strong control over the thickness and facies of Mesozoic sediment (Zeigler, 2001; Bahroudi and Talbot, 2003). The reactivation of N-S basement fault (e.g. Hendijan—Nowrooz—Khafji Fault) affected basin architecture and created lateral changes in the facies and thickness of formations in the Izeh zone and Dezful Embayment as observed on seismic sections (Tavakoli Shirazi, 2012; Sherkati and Letouzey, 2004; Abdollahie Fard et al., 2006; Soleimany and Sabat, 2010). According to Fig. 2, the T-Z plot in Tatarian to Norian has a positive slope that represents normal dip-slip along the fault at this time. This behavior of the fault is consistent with the regional tectonic regimes. The opening of the NW-SE trending Neo-Tethys Ocean in the Permo-Triass separated the Arabian plate to the southwest from the Iranian plate to the northeast and the sedimentary cover rocks which were later to become part of the Zagros deformation belt (Berberian and King, 1981; Sengor, 1990). Thus, when the Neo-Tethys Ocean has been opened, the fault acted with a normal dip-slip component.

In the Norian stage, slopes of graphs in the T-Z plot change to positive and thickness of sediment above the fault zone is less than its two sides which indicates a reverse component and uplift movement along the fault. In this time, the Hercynian Ocean was to the north of Iran and the northward subduction and closure of the this Ocean happened at about 220 Ma in the Triassic period (Berberian and King, 1981). We suggest that as a result of closing the Hercynian Ocean at this time suddenly the kinematics of the Hendijan—Nowrooz—Khafji Fault changed. Prior to the middle Triassic orogenic event (210 Ma), late Paleozoic ophiolite complexes were emplaced in the north, presumably at the time of the collision of the continental fragments with Asia (Shafai Moghadam et al., 2014; Shafai Moghadam and Stern, 2015). In the Kimmeridgian stage, the fault zone changed in its function, as a result, an extensional tectonic regime caused pelagic sedimentation of upper Triassic–Jurassic period along the active central Iranian and the passive Zagros continental margins, providing the first sedimentary evidence for the appearance of a true oceanic environment (Shafai Moghadam et al., 2015). Therefore, we notice an increase in the thickness of the sediments in the fault zone at this time which reflects tension function and normal dip-slip component of the fault zone at this time.

A compressional event occurred in Late Jurassic–Early Cretaceous (140 Ma). At the middle of the period when the High-Zagros Alpine Ocean supposed to have been closing (Alavi, 2007) as shown in T-Z plot from Portlandian to Albian curve, the slope is almost uniform and the fault zone had a reverse dip-slip component consistent with a contractional tectonic regime in the region during that time. In the Turonian, the thickness of sediments was sharply reduced along the fault zone (Fig. 8). During the latest Turonian (~90 Ma) stacked thrust sheets, composed of oceanic crust and upper mantle rocks (ophiolites), were obducted onto the northeastern Afro-Arabian passive continental margin (Alavi, 2004, 2007). Thus, the result of an extremely functional reverse dip-slip of the fault zone was result of Alpine Ocean (Neo-Tethys) ophiolite obduction during Turonian. The latest Turonian regional unconformity, which marks a drastic change from a continental shelf tecono-sedimentary setting to a relatively narrow and elongated proforeland basin, records the initiation of this “obduction” event (Alavi, 2004). So function of the erosion phase and ophiolite obduction cause a sudden change in the slope of T-Z plot in Turonian.

The Middle Alpine orogenic events ended at about 20 Ma (Berberian and King, 1981; Alavi, 2004, 2007). Thus the fault zone acted with a reverse dip-slip component from Turonian to Priabonian (Fig. 8). After the collision, a relative calm prevailed in the region as reflected by normal dip-slip displacements representing a period of tectonic relaxation after beginning of collision from the Aquitanian to Burdigalian. As a result with opening of the Red Sea and pushing the Arabian plate toward Asia, compressional regime again dominated in the region and the fault zone has reverse dip-slip in Serravallian (Fig. 8).

6. Conclusion

Kinematic Analysis of the Hendijan—Nowrooz—Khafji Fault based on T-Z plot method provided a long-term evolution characterized by altered rate of the fault continuous slip during 240.55 millions of years. Based on the detailed interpretation of a high quality 3D seismic reflection sections, the throw versus times measurements reveal six phases of the fault activity with different rate of throw in each phase. Two distinct mode of reactivation (i.e. positive and negative inversion) are recognized which give insights into the mechanism and kinematics of the fault reactivation. The structural style of the study area during inversion realm was ultimately controlled by the motion of the Afro-Arabian plate relative to the Arabian plate.
Fig. 11. High-resolution record of tectonic and sedimentary processes in growth strata based of Hendijan–Khafji fault activity. In (a), (c) and (e) we can see increase of strata thickness in fault zone related to one or both sites its and on lap toward those, in these stages fault had normal dip-slip component and in (b), (d) and (f) we see decrease of strata thickness in fault zone related to one or both sites its and on lap toward fault zone That because of reverse dip-slip component in these stages.
to the Iranian plate.

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