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Geophysics of the Arabian Gulf

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ABSTRACT

Among the marine basins around the Arabian Peninsula, the Arabian Gulf is geophysically the least studied. This paper describes the regional gravity field of the Gulf and reviews the limited seismic reflection data available in open files. The upper part of the sedimentary column has a simple structure and does not show any intense deformation. Continental convergence along the Zagros apparently has not yet affected these sediments. High resolution seismic records show the Holocene sediments forming a transparent unit lying over a highly eroded surface. The pre-Quaternary sediments exhibit a gentle dip and thickening northeastwards with at least two prominent unconformities of Late Cretaceous and Oligocene ages. Seismic data also suggest diapiric movement of salt beneath the sedimentary cover. The gravity field of the Arabian Gulf is dominated by the Zagros trend reflecting effects of the post-collision sedimentation and thickened mountain roots. Numerous north-trending, short-wavelength anomalies superimposed on the broader pattern represent the pre-collision structures of the Arabian plate. A relative positive anomaly in the central Gulf is correlatable with a basement high.

INTRODUCTION

Much of our knowledge about the crustal structure of the Arabian Gulf and southern Iran comes from the petroleum industry geological data reported in the literature (e.g. Falcon 1967; Mina *et al.* 1967; Kamen-Kaye 1970; Murris 1980; Koop & Stonely 1982). The available geophysical data in the region are very limited in comparison to that for other basins around the Arabian Peninsula. Nevertheless, they provide valuable information on the structural and tectonic framework of the region. Previous geophysical studies of the Arabian Gulf region were based largely on earthquake seismicity and gravity data and focused primarily on the continental collision tectonics along the Zagros (e.g. Nowroozi 1971; Bird 1978; Berberian 1981; Dehghani & Makris 1983; Jackson & McKenzie 1984; Snyder & Barazangi 1986; Ni & Barazangi 1986). The present study describes the upper crustal structure of the Gulf based on available marine geophysical data.

The convergence of the Arabian and Central Iranian plates has directly influenced the tectonics and sedimentation in the Gulf at least since the Early Miocene. The available seismic data show that the structure of the upper part of the sedimentary cover is uncomplicated and largely free from tectonic disturbances. Due to a lack of detailed seismic mapping, the crustal structure of the Arabian Gulf is poorly defined but it is believed to be underlain by normal continental crust of the Arabian plate. A new gravity map presented here shows the Gulf to be a laterally segmented basin.

GEOLOGIC AND TECTONIC BACKGROUND

The Arabian Gulf is an elongate basin located to the south of the Zagros Fold Belt between the Tigris-Euphrates Delta and the Strait of Hormuz (Fig. 1). It is a part of the Arabian plate. Its evoluation at least since the Late Tertiary has been directly influenced by the continental collision along the Zagros. The first continental collision of Arabia and Central Iran took place during the Late Cretaceous and by Early Miocene a Proto-Arabian Gulf had evolved from closure of the Neo-Tethys (Koop & Stonely 1982). The present-day Gulf is shallower than 100 m and the deepest part paralleling the Zagros Belt lies closer to the Iranian coast. A north-trending bathymetric high centered around 52°E longitude divides the Gulf into two major parts. The relief involved is rather small but this subdivision may be tectonically controlled. The basement of the Arabian shield under the Gulf dips towards the northeast and extends up to the Main Zagros Thrust (MZT). The sedimentary

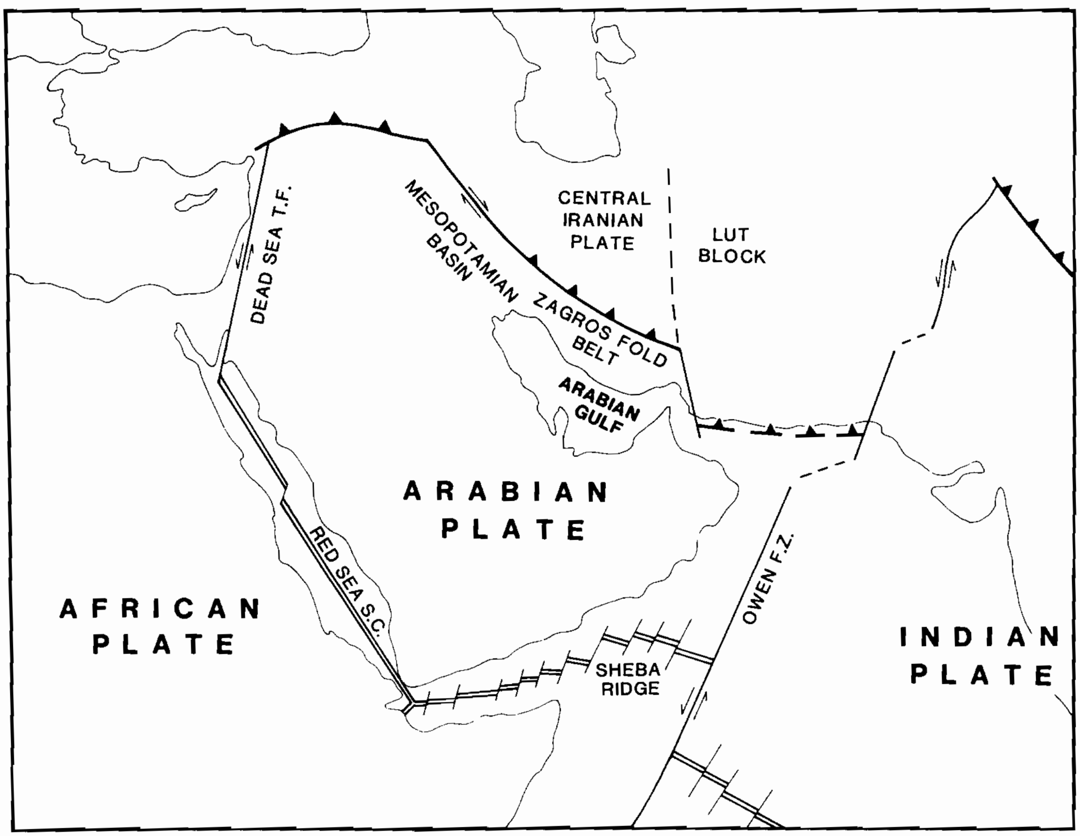

Fig. 1. Map showing generalized tectonics of the Arabian Gulf and Mesopotamian Basin region.

column above the basement is largely composed of shallow marine deposits including evaporites. The base of the succession is the Infracambrian Hormuz Salt which has been mobilized from time to time resulting in diapirism in the eastern Gulf (Ala 1974). The sediments thicken towards the Zagros mountains with an estimated total thickness of over 9 km close to the foothills (Kamen-Kaye 1970).

The relative motion between the Arabian and Central Iranian plates is continuing in a northeasterly direction as evidenced by present-day seismicity along the Zagros. Thrust-type earthquakes with steeply dipping fault planes occur along the MZT which marks the northern limit of the Arabian plate (Nowroozi 1971; Jackson & McKenzie 1984; Ni & Barazangi 1986). Continental convergence in the region has resulted in folding of sediments in southern Iran and Makran. The young folds are still continuing to develop to the north of the Gulf along the coast of Iran (Shearman 1976). Assuming symmetrical folding of a young fold, Vita-Finzi (1982) has estimated a rate of convergence of 2·9 cm/year near the Strait of Hormuz. Jackson & McKenzie (1984) calculate a similar rate from earthquake slip vectors for the eastern part of the MZT. They suggested, however, that a part of the convergence may be accommodated further to the north of the MZT. The coastal region on the Arabian side of the Gulf is tectonically stable with only gentle movements (Kassler 1973). In the interior of the Arabian Gulf, particularly in the eastern part, the dominant activity is diapiric movement of salt (Ala 1974).

SEISMIC DATA AND SEDIMENTARY STRUCTURES

A variety of seismic reflection data are available for the Gulf which include high resolution data with shallow penetration as well as the sparker and air-gun profiles with deeper penetration. These data are from the RV Meteor Cruise (Seibold & Vollbrecht 1969), Shell Oil Company sparker survey reported by Kassler (1973) and RV Atlantis II Cruise (Ross 1978; Ross *et al.* 1986). The seismic lines are regionally well distributed and exhibit variations in acoustic structure of the sediments. The following is a brief account of seismic information reported by the authors mentioned above.

Quaternary sedimentation:

During the Pleistocene world-wide lowered sea level the Arabian Gulf was completely drained and the area was eroded by the distributaries of the Tigris-Eupharates river system. Topographic relief of salt cored diapiric structures was accentuated as a result of this erosion. Beach dune ridges were also deposited during this period in several parts of the Gulf (Ross *et al.* 1986). The unconsolidated sediments began to deposit about 18,000 years B.P. with the postglacial rise in sea level (Kassler 1973).

On seismic records the Holocene submarine sediments are seen as a transparent unit overlying an irregular surface (Kassler 1973; Ross *et al.* 1986). These sediments are generally deposited in depressions in the pre-Holocene surface and are, on average, 10 m thick. Their thickness increases towards the north and in places they are eroded by bottom currents. The transparent nature of these sediments is due to the uniform carbonate mud lithology (Stoffers & Ross 1979). Closer to the Iranian coast the Holocene unit displays internal bedding which represents the clastic input from erosion in the Zagros Fold Belt.

Topographic highs are commonly observed in the southeastern part of the Gulf. The Holocene unit is not observed on top of these highs but is restricted to depressions around them. These highs are believed to be pre-Recent structures (Kassler 1973) possibly having diapiric salt cores.

A zone of northwest-trending ridges is observed near the Tigris-Eupharates Delta adjacent to the Iranian Coast. The ridges have a relief of 10 m and are spaced 4–5 km apart. These were described by Seibold & Vollbrecht (1969) as erosional/depositional morphology caused by tidal currents. Similar features are also recorded east of the Qatar Peninsula and in the Gulf of Salwa (Kassler 1973). Evans *et al.* (1969) suggested them to be beach dune ridges formed during the Pleistocene regression and now submerged due to the rise of sea level.

The sparker reflection profiles reported by Kassler (1973) show the structure of the topmost 20–40 m of the sedimentary section. These data show a northward thickening of the Pleistocene sediments. Kassler (1973) also suggests the existence of some tectonic hinge zones in the southern Gulf representing slight tilting of the Arabian plate as it converges towards Iran.

Pre-Quaternary sediments:

A deeper look into the older sediments is provided by the multi-channel seismic reflection data reported by Ross *et al.* (1986). These are the best available seismic lines with a penetration of up to 4 seconds of two-way travel time. These profiles span the entire length of the Arabian Gulf and cover half the area lying closer to Iran. Two prominent unconformities in the Late Cretaceous and Oligocene are observed throughout the Gulf. A conspicuous absence of faults is noted on the seismic sections. The presence of buried diapirs is recorded on several profiles. On one profile a reef-like structure is observed in the sedimentary column above the Oligocene unconformity. Several of the lines described by Ross *et al.* (1986) extend to within 10–15 km from the Iranian coast but none display any evidence of folding commonly observed on land.

REGIONAL GRAVITY FIELD

A free-air gravity anomaly (F.A.) map of the Arabian Gulf (Fig. 2) has been compiled from the RV Atlantis II cruise data (Ross 1978). The anomalies are based on the International Gravity Formula, 1967 (IGSN 1971) and referred to the International Gravity Standardization Net 1971 (Morelli *et al.* 1974). Gravity control is indicated by the ship's track shown in Fig. 2. The Arabian side of the Gulf lacks gravity coverage. Gravity contours in this part are controlled by sparse land measurements along the coast. Some land measurements along the Iranian coast have also been utilised in the preparation of the map.

The Zagros trend dominates the regional gravity field of the Arabian Gulf with contours trending in a NW–SE direction. Free-air anomalies show a northeast gradient with -10 to -30 mgal values along the Arabian coast decreasing to -70 to -90 mgal in the vicinity of the Iranian coast. Gravity anomalies decrease further

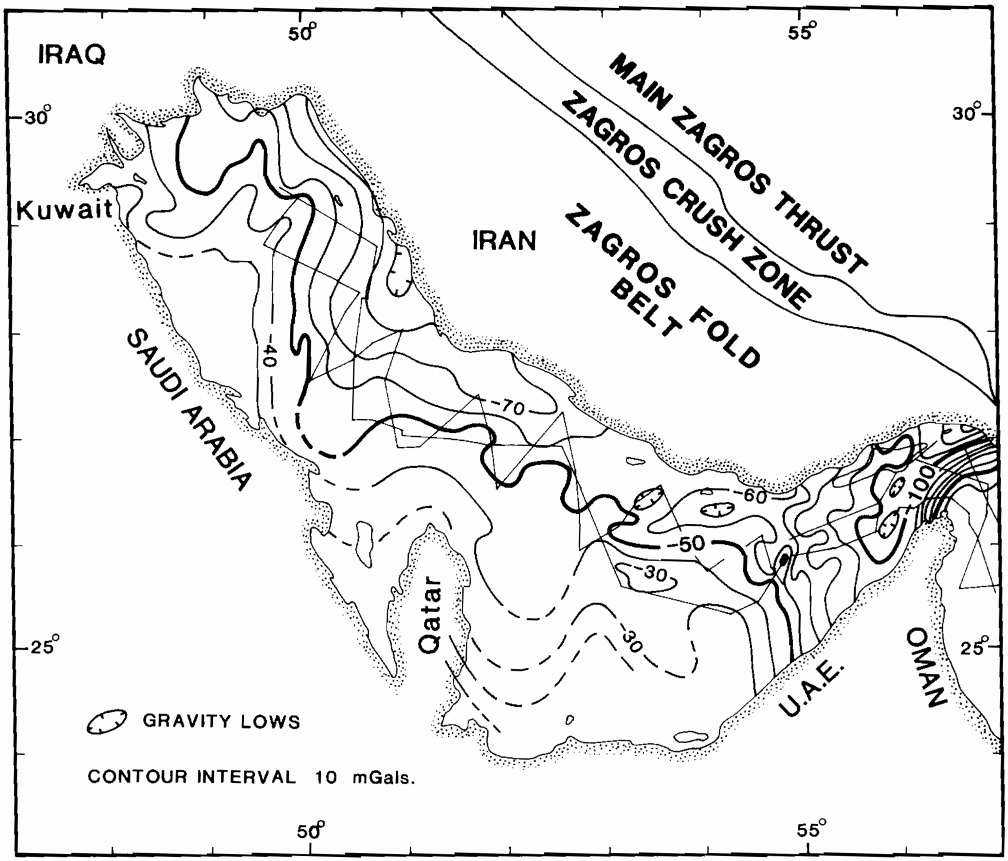

Fig. 2. Free-air anomaly map of the Arabian Gulf. Gravity control is shown by RV Atlantis II tracks. The contours show parallelism with the Zagros trend. Note the break in continuity of the gravity low near the Iranian coast.

inland and a Bouguer anomaly minimum of about −225 mgal is located to the north of the Main Zagros Thrust (Dehghani & Makris 1983; Snyder & Barazangi 1986). The northward decrease is consistent with the general deepening of the basement and thickening of the sediments towards Iran. A qualitative discussion of the anomaly pattern is presented here.

Two sources that contribute significantly to the general northwest-trending pattern are the negative gravity effects of the thick crustal root of the Zagros Mountains and a large thickness of the post-collisional sediments. The isostatic effect of the Zagros roots along the Iranian coast is of the order of −20 mgal and decreases further southwestwards (Dehghani & Makris 1983). Thus a significant part of the negative anomaly is caused by the low-density sediments. Linearity of the pattern can be attributed to the elongate nature of the Zagros Basin in which the post-collisional sediments are deposited. The axis of the basin is not located within the Arabian Gulf as the contours do not show any significant closure. There is a suggestion of a gravity low closure to be located landward of the Iranian coast. Maximum thickness of the sediments thus appears to lie northwards of the Gulf.

The gravity low along the Iranian coast exhibits a break in the vicinity of 53°E longitude. The bathymetric high mentioned earlier is located slightly to the west of this break. Close association of the gravity and morphological discontinuity suggests a major structural break in the central part of the Gulf, possibly with an active tectonic control. It is also interesting to note that the Qatar Arch-Kazerun Fault trend is located in the same general vicinity. The two gravity minima on either side of the break have different amplitude and wavelength characteristics. The western low has a larger extent with a minimum contour value of −90 mgal. On the other hand the eastern low has a much smaller extent with a minimum of −70 mgal except for the NE-trending negative anomaly in the vicinity of the Musandam Peninsula. The western low is a part of a large negative anomaly observed over the Mesopotamian Basin (Bowin *et al.* 1982). The Arabian Gulf between the Tigris-Euphrates Delta and the Qatar Arch trend thus seems to be a part of the greater Mesopotamian Basin.

The largest negative gravity anomaly in the Arabian Gulf with a closure of −110 mgal is observed near its eastern extremity, located to the west of the Musandam Peninsula. Clearly, this anomaly is not related to the Zagros collision and appears to be due to a thick accumulation of pre-collision sediments deposited in a NE-trending basin. This gravity minimum occurs in the region of maximum sedimentary thickness reported by Koop & Stonely (1982) for the eastern Gulf. A significant proportion of these sediments could be the low-density evaporites.

Superimposed on the Zagros trend are several smaller amplitude gravity highs and lows. Fig. 3 shows axes of these maxima and minima. Most axes have northerly orientation making high-degree angles to the Zagros trend. These anomalies are clearly due to the pre-collision structures of the Arabian platform. Some of the positive axes are obvious northward extensions of anticlinal structures mapped on land like the Qatar Arch (Mina *et al.* 1967). Similar subsurface extensions of the Indian Shield basement structures are noted in the Ganges Basin region located to the south of the Himalaya (Qureshy & Warsi 1980). Numerous gravity anomalies with small lateral extent are observed in the eastern Gulf. The pattern of salt distribution at shallow depths may be partially responsible for these short wavelength anomalies.

SUMMARY AND CONCLUSIONS

The available geophysical data for the Arabian Gulf provide valuable information on the geological and structural framework of the basin. The Gulf has an uncomplicated structure and is largely free from severe deformation associated with the continental collision along the Zagros. Although the igneous basement is not directly observed beneath the sediments except in the Strait of Hormuz area (White & Ross 1979), the Gulf is believed to be underlain by continental crust. Direct measurements are needed to map the nature of the Arabian Gulf basement but collision along the Zagros implies northward continuation of the Arabian Platform crust up to the MZT.

The topmost cover of unconsolidated Holocene sediments is on average 10 m thick and is mainly composed of carbonate mud and silt. The Holocene unit is deposited on a highly eroded and irregular Pleistocene surface. In some areas these sediments show erosion by bottom currents. The pre-Quaternary sediments show

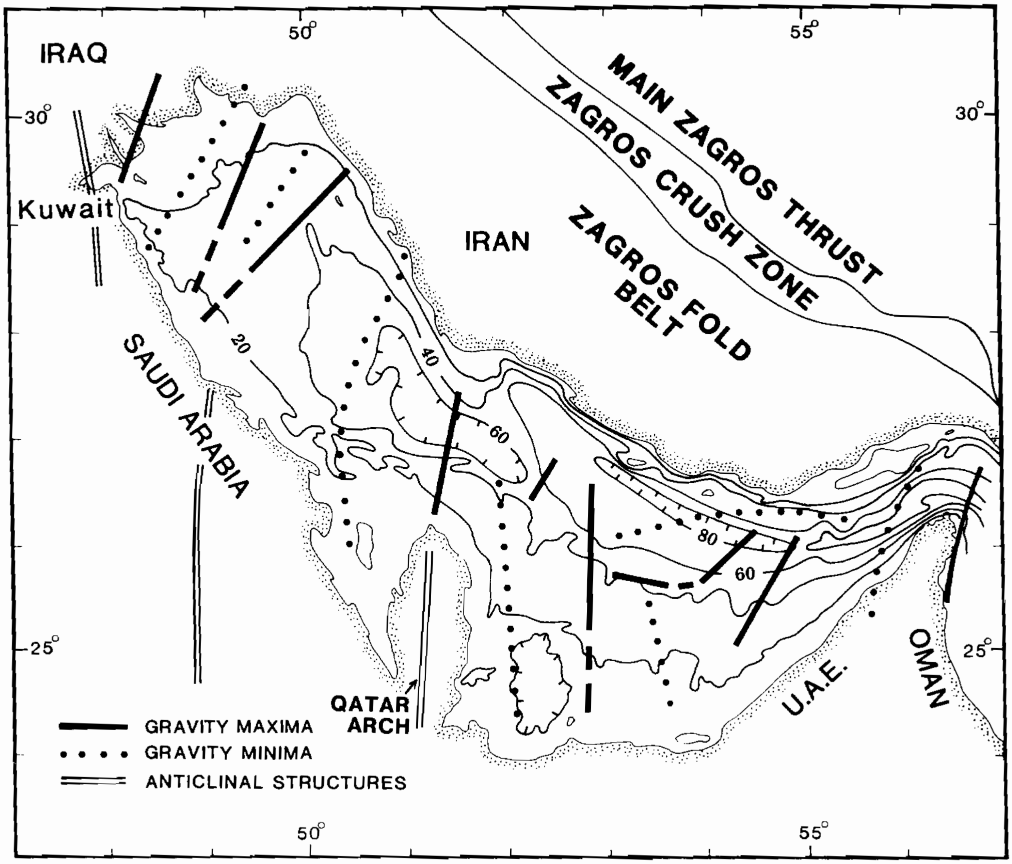

Fig. 3. Gravity axes map of short-wavelength anomalies in the Arabian Gulf. These north-trending anomalies represent pre-collision structure of the Arabian platform. Note the northward continuation of the Qatar Arch trend. Contours (in meters) show generalized bathymetry.

existence of at least two prominent unconformities in the Late Cretaceous and Oligocene (Ross *et al.* 1986). Folding of sediments associated with continental convergence is generally confined to the north of the Iranian coast. A lack of large-scale faulting on the seismic sections indicates a tectonically quiet environment in the Gulf. The only prominent activity observed in the area are the diapiric structures formed due to periodic mobilization of salt.

The regional gravity field of the Arabian Gulf is dominated by the effects of the post-collisional sedimentation and the Zagros roots. Gravity variations indicate a northward deepening of the igneous basement and thickening of the overlying sediments. The basement control inferred from the gravity data suggests segmentation of the basin within its present coastlines. A broad basement high in the central Gulf divides it in two separate basins. This high seems to have provided a fundamental tectonic control for sedimentation in the region including the post-collision deposits. Numerous north-trending short-wavelength gravity anomalies described earlier may also be related to basement features. These anomalies clearly demonstrate the continuation of the Arabian plate beneath the sediments. The Arabian Gulf is thus analogous to the Ganges Basin which is a fore deep laterally segmented by northward extensions of the Indian Shield elements.

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جيوفيزيائية الخليج العربي

وارث وارثي
قسم الجيولوجيا بجامعة الكويت ،
ص . ب . ٥٩٦٩ ،
الصفاة ١٣٠٦٠ ، الكويت

خلاصة

يفتقر الخليج العربي إلى الدراسات الجيوفيزيائية ، بالمقارنة مع الأحواض البحرية التي تحيط بشبه الجزيرة العربية . ويتناول هذا البحث مجال الجاذبية الأقليمي للخليج ، ويستعرض كذلك المعلومات المحدودة للانعكاس السيزمائي ، التي تحويها التقارير المتاحة . لقد وجد أن الأجزاء العليا للعمود الرسوبي بسيطة التركيب ولا تدل على حدوث حركات أرضية عنيفة . ويبدو أن التلاقي القاري على طول سلسلة جبال زاجروس لم يؤثر بعد على وضع تلك الرسوبيات . وتدل سجلات القياسات الزلزالية عالية التحليل على أن رواسب العصر الحديث تشكل وحدة منفذة تعلو سطحا شديد التعرية ، وأن رسوبيات ما قبل الحقب الرباعي تميل ميلا طفيفا وتزداد سماكتها في اتجاه الشمال الشرقي ، وتضم على الأقل سطحين متميزين من سطوح عدم التوافق يتبعان العصر الطباشيري المتأخر والأوليجوسين على التوالي .

وتشير المعلومات السيزمائية إلى وجود صواعد اختراقية ملحية تحت الغطاء الرسوبي . ويسود ميل سلسلة جبال زاجروس مجال الجاذبية الأقليمي في الخليج ، عاكسا بذلك أثر الإرساب وسماكة رواسي (جذور) الجبال بعد التصادم القاري . وهناك العديد من الشواذ قصيرة الموجة ذات اتجاه شمالي ، تسود النموذج العام ، وتمثل تراكيب الصفيحة العربية قبل حدوث التصادم . كما أن هناك شذوذا ايجابيا نسبيا في منتصف الخليج يرجع إلى ارتفاع صخور الأساس .