Engineering Geology, 22 (1986) 247—255
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

TECTONIC STRESS IN THE SOUTHWESTERN ARABIAN SHIELD

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(Received November 15, 1984; accepted after revision September 9, 1985)

ABSTRACT

Giraud, A., Thouvenot, F. and Huber, R., 1986. Tectonic stress in the southwestern Arabian shield. Eng. Geol., 22: 247—255.

Studies of dam sites in the southwestern region of Saudi Arabia gave the opportunity to undertake an in-depth study of the old basement of the Arabian shield.

By comparing the results obtained at all scales (seismicity, fracturing of the shield, data on overall tectonics and in-situ measurements) it has been possible to formulate an explanation concerning the anisotropy observed during the geotechnical surveys of the studied sites.

In our view, this anisotropy is to be considered in relation to a substantial stress condition in the Arabian plate, at least towards its southwestern limits. The observed compression would appear to occur in a NE—SW to E—W direction.

INTRODUCTION

Conventionally (Richardson et al., 1979), there are several ways to approach the question of the orientation and extent of the stress field induced within a lithospheric plate by forces acting at its limits, i.e. at the level of the ridges, the subduction zones and the zones of continental convergence.

(a) The focal mechanism of intraplate earthquakes can indicate, if the earthquake studied has a sufficient magnitude (higher than 5), the direction of the regional stress.

(b) The geological study and more precisely the analysis of fractures at all scales provides numerous indications of the principal stress orientations.

(c) The use of in-situ measurements to evaluate the regional stress field (Zoback and Zoback, 1980) is more problematical. Indeed, stresses related to the local topography can completely dissimulate the regional stress. Thus very special care is required in interpreting in-situ measurements. Therefore, it is only by comparing, for a given location, the different types of information provided by the three approaches described above that it can be envisaged to acquire knowledge of the regional stress field.

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SEISMICITY OF THE SOUTHWESTERN PART OF THE ARABIAN SHIELD

Whereas the seismicity of the Red Sea, the Gulf of Aden and the Afar depression have been studied since the beginning of the century (Fairhead and Girdler, 1970), it is only in 1977 that the U.S.G.S. and the Ministry of Petroleum and Mineral Resources of Saudi Arabia started to concern themselves with the study of the microseismicity on the western coast of the Arabian Shield in Saudi Arabia.

Macroseismicity

The seismicity of the southwestern part of the Arabian Peninsula, as can be studied using the U.S.G.S. data bank (covering the period 1911—1983) presents several characteristic features. The most notable features are the axial zones of the Red Sea and the Gulf of Aden, which appear clearly on the seismicity map (Fig.1). The following features can also be observed: (a) the almost complete absence of seismicity in the axial zone of the Red Sea to the north of the 21st parallel; (b) the irregularity of seismicity in the Gulf of Aden, where earthquakes of magnitudes greater than 4 are grouped together in tight clusters.

A significant asymmetry appears on either side of the Red Sea. From 17° to 18°N and as far as Afar it is possible to identify on the western side the North Danakil plate, which provides an explanation for the seismicity observed in Ethiopia. The existence of this plate was suggested for purely kinematic reasons as early as 1972 (Francheteau and Le Pichon, 1972). By contrast, on the Arabian side, the map suggests almost complete aseismicity of the peninsula, except at its southwestern extremity.

The North Yemen earthquake (13 December, 1982, magnitude Ms = 6) and its aftershocks (notably that of 29 December 1982 of magnitude Ms = 5) have recently drawn attention to the danger of considering a seismicity map as definitive, especially when the period of observation does not exceed a century. Ambraseys and Melville (1983), compiling the archive data going back to the 8th century, show that historical seismicity is far from negligible in this part of Yemen.

To date, it may thus be said that from the purely macroseismic standpoint, the part of the Arabian shelf studied here is aseismic except at its southwestern extremity.

A wedge effect related to the geometry of the plates is not to be excluded in explaining this anomaly, the regional stresses probably varying suddenly under the combined effect of the opening of the Red Sea and of the Gulf of Aden.

Microseismicity

In relation with industrial development on the western coast of Saudi Arabia, several studies of microseismicity have been carried out (Merghelani

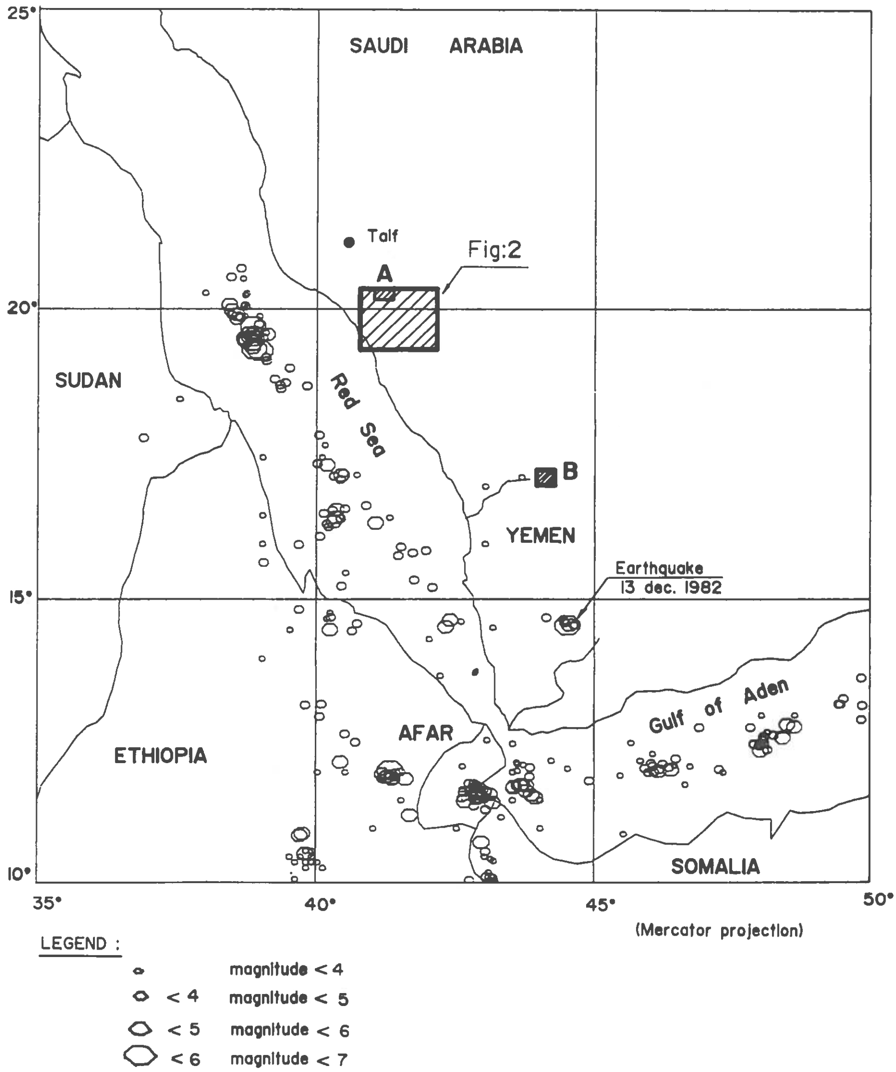

Fig.1. Seismicity map of the southwestern part of the Arabian shield (1911—1983) (data from USGS world seismicity data bank). A = sites studied in the Taïf region; B = Mudhiq dam site.

and Gallanthine, 1980; Merghelani, 1981). The results of these surveys indicate a strong microseismic activity which is unrelated to the axial zone of the Red Sea and is interpreted by these authors as the expression of the penetration of transform faults within the Arabian shield, as suggested by the essentially NE—SW alignments of epicentres.

These results are debatable, however, because of the poor accuracy with which the events have been determined, almost all of them being outside the observation network. Consequently, it was impossible to define the focal mechanisms of these microearthquakes.

Although the procedure followed by Ambraseys and Melville (1983) is even more open to doubt, it must be noted that these authors also suggest evidence of a NE—SW alignment of a certain number of supposed epicentres of historical earthquakes.

Conclusions regarding seismicity

The following conclusions may be drawn from this study of seismicity: (a) the Arabian plate is relatively inactive in seismic terms except at its southwestern extremity; (b) in Yemen there is substantial macroseismicity and historical seismicity; (c) the microseismicity observed in Saudi Arabia appears to be related to the transform faults of the Red Sea.

All these observations lead to the conclusion that there is a significant state of stress in the Arabian plate, at least approaching its southwestern extremity.

TECTONICS OF THE ARABIAN SHIELD

The old basement of the Arabian shield which crops out in the southwest of Saudi Arabia is constituted by Precambrian metasedimentary and metavolcanic series that are intersected at numerous points by intrusive plutonic rock formations.

The fracture system of this shield is the heritage of older orogenic phases, among which the following are generally distinguished.

(a) The Hijjaz orogenesis (between 650 and 610 million years), which gave the metamorphic units a N—S foliation and a series of faults also largely oriented N—S.

(b) The Najd orogenesis (between 590 and 540 million years), which results from an E—W compression (Moore, 1979) and gives rise to a major system of left-lateral tear faults (the Najd fault system) oriented N 130° to N 140°.

(c) Also associated with this Najd episode are dextral tear faults oriented N 50° to N 65° and fractures oriented roughly E—W, often injected by dykes, which must be interpreted as fractures of tension (T) parallel to the direction of compression.

RESULTS OF THE IN-SITU MEASUREMENTS MADE AT THE DAM SITES

Sites studied in the Taif region (Fig.1.A)

There are two dam sites founded on plutonic diorite, intrusive in the metamorphic series, about 100 km south of the town of Taif. On these two sites on the wadi Aridah and the wadi Buwwah, a geophysical seismic survey was undertaken on cross-sections and on lines parallel to the dam axis (Antoine and Giraud, 1982).

The seismic velocities measured (Vp of the order of 5000 m/s on average) are systematically greater in a direction approximately NE—SW, normal to

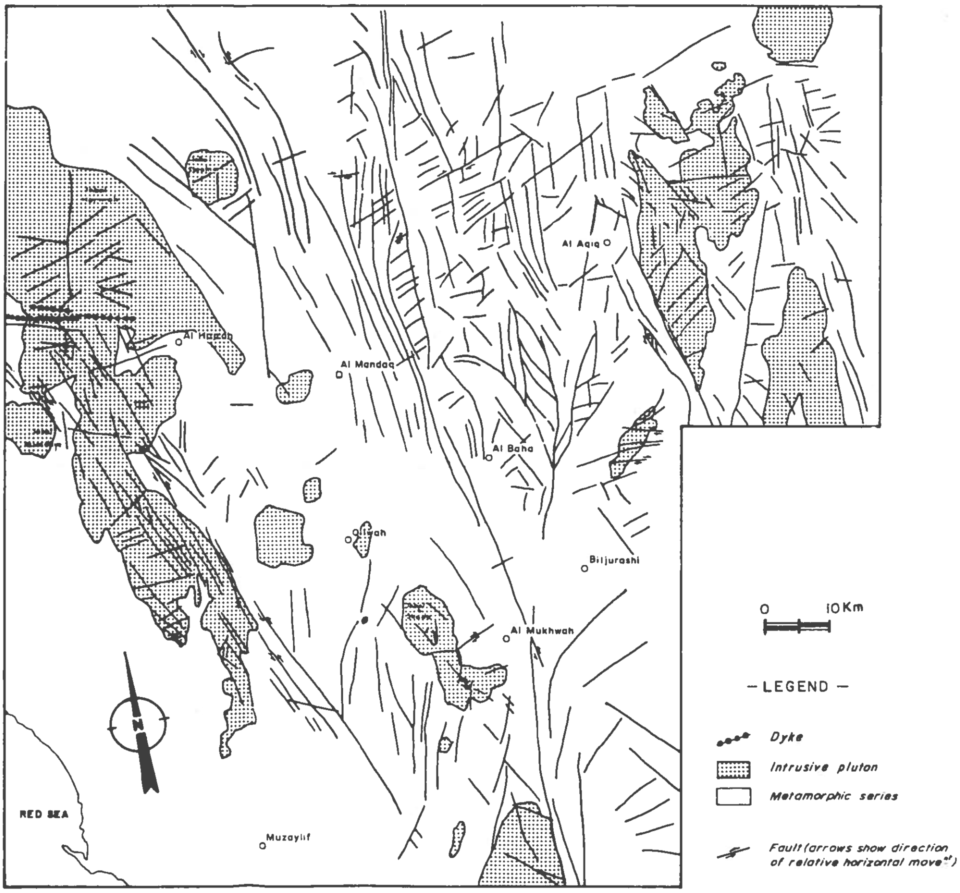

Fig.2. Regional tectonical sketch (map drawn from LANDSAT photo satellite).

the greatest density of fractures observed at the site and well individualised on the scale of the Arabian shield (Fig.2).

This difference of velocity (of the order of 1000 m/s) measured according to the direction of the two sections, seems to provide evidence of a certain wedge effect occurring at present in these plutonic formations, in a broadly NE—SW direction.

Mudhiq dam site (Fig.1.B)

At this site, near the southern tip of Saudi Arabia (Giraud and Barbier, 1982), the dam is founded on metamorphic rock (rhyolitic tuff) that is heavily fractured, with a maximum frequency of discontinuities in the direction NNW—SSE.

(a) *Results of the geophysical seismic survey.* The values measured during the geophysical survey (longitudinal wave velocity Vp) are very disparate, and no evidence was found of anisotropy of velocity depending on the orientation of the profiles, transverse or longitudinal to the valley.

In fact we expected to measure lower velocities along profiles running perpendicular to the direction of fracturing (NNW—SSE). This was not the case and the measurements can be interpreted as representing a pronounced compaction of the rock in a broadly E—W direction.

(b) *Results of the dilatometric tests.* Although on the sample scale the elastic properties of the rock are isotropic, the elastic characteristics of the formation, measured in three vertical exploratory boreholes (dilatometric tests) between 6 and 54 m depth, are generally greater in a broadly E—W direction.

(c) *Remarks on the water tests and grout curtain.* The results of the water tests carried out in the exploratory boreholes and of the injections for the grout curtain show unexpectedly low absorption rates in this context of extensive fracturing.

This whole series of tests leads to the same conclusion: at the level of the Mudhiq dam site and below a certain depth (that is excepting the loosened surface layer from 0 to 15 m), the discontinuities of the rock mass are tightly closed under the broadly E—W confining effect.

DATA ON PLATE TECTONICS

In a certain number of lithospheric plates (North America, Eurasia), the information is sufficiently dense for a certain variation of the stress field to be mapped. In the plate studied more particularly here (the Arabian plate), direct measurements of stress are few and far between.

Focal mechanism of the North Yemen earthquake

One of the few intraplate earthquakes to have occurred is the North Yemen event (13 December 1982, magnitude Ms = 6). It must be noted however that it occurred 200 km from the Red Sea rift. Under these conditions, is it suitable to call it an "intraplate" earthquake?

Although it was recorded by the seismological detection network throughout the world, the focal mechanism is far from explicit.

For the U.S.G.S. Earthquake Data Report, this is a normal fault formation, with a fault plane oriented N 160°, dipping 75° to the NE, caused by pressure oriented N 250° and dipping at 60°. This mechanism is in agreement with the NNW—SSE oriented extension fissures observed in the field in the epicentral area over distances of about 15 km.

On the other hand, taking the original data supplied by the seismological observations, this could also be a strike-slip mechanism, with a near-horizontal pressure axis oriented N 33°. This strike-slip mechanism would also have a slight normal fault component.

Faced with such widely varying interpretations, it does not seem sensible to give much weight to this mechanism. It is simply worth remarking here that in both cases the pressure axis is oriented roughly NE—SW.

Data supplied by model calculations

In the absence of reliable data on the regional stress field concerning the Arabian plate, one approach is to calculate this field reasoning in terms of models of lithospheric plates treated as finite elements. Here too the problem is not simple, since the multiplicity of models gives a multiplicity of solutions.

The multiplicity of models is here understood to mean the choice of forces to apply to the plates: horizontal thrust at the ridges, traction at the subduction trenches and compression in the zones of continental collision. The models become even more complicated if the relative viscosity between the lithosphere and the mantle is taken into account.

Of all the calculated models, it may be observed in the case of the more complex models that the stress field calculated at the centre of the Arabian plate gives an axis of pressure that remains oriented in the azimuthal sector NNE—SSW.

If at the same time account is taken of the experimental data available for the surrounding plates (Eurasia, Africa, India), the most coherent model is the E 31 model developed by Richardson et al. (1979), which gives the orientation of the pressure axis as N 45°.

It must be noted that this orientation is valid at the centre of the Arabian plate. Since the present study field is at a relatively short distance from the Red Sea ridge (250—300 km), a reorientation of the stresses close to the rift is not to be excluded.

Kinematic data

Although it is impossible to establish a rigid link between the orientation of a lithospheric plate velocity and the orientation of stresses, the error committed in approaching the problem in this way is probably only of the same order of magnitude as when using the other methods.

Using the pole of instantaneous rotation determined most recently for the Arabian/Danakil couple (Le Pichon and Francheteau, 1978), the calculation gives, for a point situated on the borders of the Arabian plate (latitude 20°N, longitude 40°E), a drift velocity oriented NE (heading N 50°).

It should be noted that this direction corresponds to the mean direction of the transform faults in the south of the Red Sea (Stuart, 1979). Thus, here too it is the same NE sector which still appears to be predominant.

Finally, an interesting means of comparison is provided by the map in Fig.3 (Le Pichon and Francheteau, 1977), which shows the total movements since the Lower Miocene between the different plates involved. On this map, the magnitude of the vectors of total motion was calculated according to the poles of finite rotation between the different plates (Arabia, Nubia, Somalia and Danakil). Although this map is even more delicate to interpret from the point of view of regional stresses than a map giving the instantaneous movements, the change it shows in the orientation of vectors north and south of

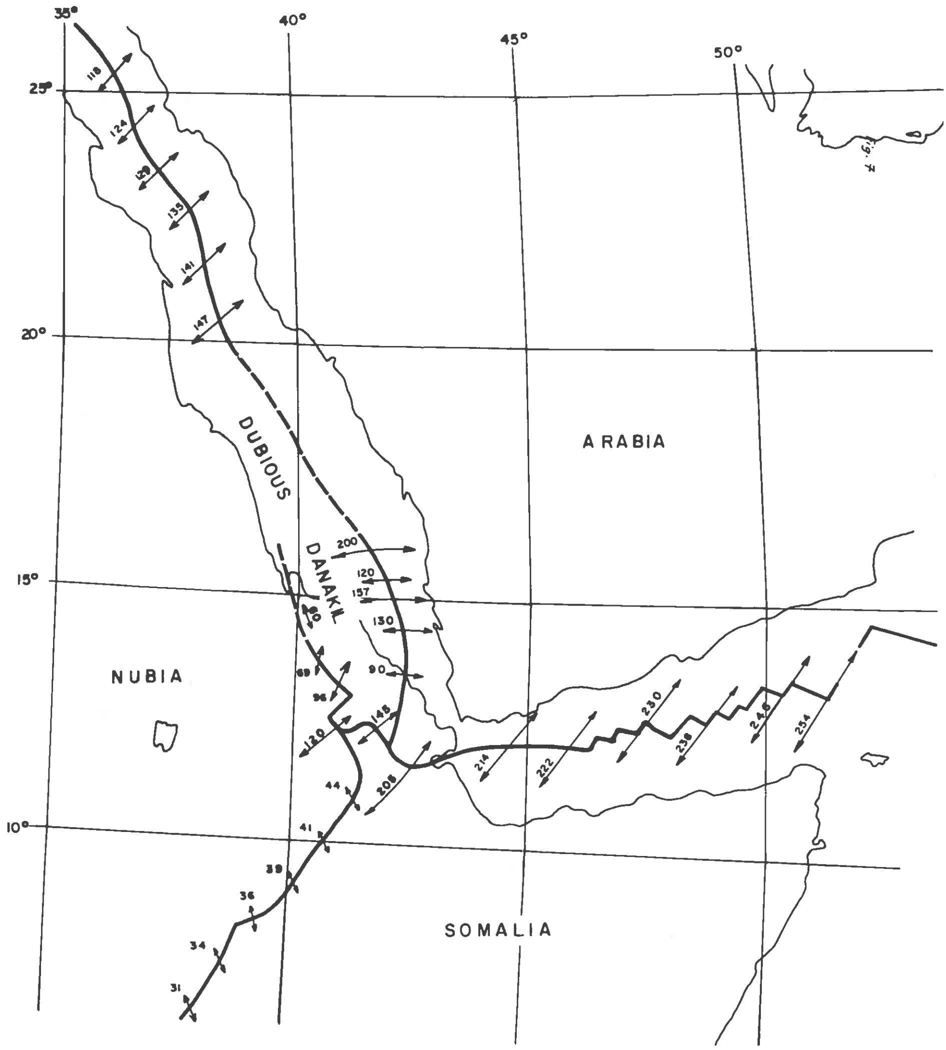

Fig.3. Map of the vectors of total movement since the lower miocene for the finite rotations of the various plates present in the region: Arabia, Somalia, Nubia and supposed Danakil (after Le Pichon and Francheteau, 1977). The vectors have the same scale as the map with their movement expressed in kilometres (azimuthal projection).

the Red Sea is particularly striking. This phenomenon could of course be explained by the splitting of the African plate into the Nubia and Danakil plates, but this change in orientation is more particularly coherent with the observed confining effect, which tends to be NE—SW oriented in the Taif region and E—W oriented at the Mudhiq dam site near the Yemen border.

CONCLUSIONS

The studies of seismicity carried out on the Arabian plate lead to the conclusion that there is a substantial state of stress at the level of this plate, at least close to its SW limits and more especially close to the Red Sea rift.

All the results provided by the geological studies, the in-situ measurements and the data on plate tectonics are in concordance, and offer an explanation for the anisotropy observed at places on the studied sites, which are all relatively close to the Red Sea rift (250—300 km).

This example shows that in any geotechnical study it is interesting to place the studied sites in their regional geological and geodynamic context. Indeed, the straightforward juxtaposition of survey results that are by their nature discontinuous, without any consideration of general trends, does not allow a rational understanding of certain cases of mechanical or hydraulic anisotropy in rock masses.

ACKNOWLEDGEMENTS

For assistance in preparation of this article, thanks are due to SOGREAH, GTM and the Ministry of Agriculture and Water of the Kingdom of Saudi Arabia.

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