Fault patterns of northwestern Hegaz, Saudi Arabia

Fault Patterns of Northwestern Hegaz, Saudi Arabia

By **Raoul C. Mitchell**, Baghdad and Luxembourg

With 3 figures

INTRODUCTION

That part of NW Hegaz bordering the Gulf of Aqaba is virtually terra incognita as regards geological information. (Fig. 1) Few scientific travellers and even fewer scientific writings and trustworthy maps make reference to this little-known region. The arduous and dangerous travels of the Czeck Orientalist ALOIS MUSIL (1926–28), accompanied by the later famed Austrian geologist, Prof. Dr. LEOPOLD KOBER, resulted in a most detailed, interesting and accurate topographic presentation of the region, his topographic map being by far the most detailed which the writer has seen.

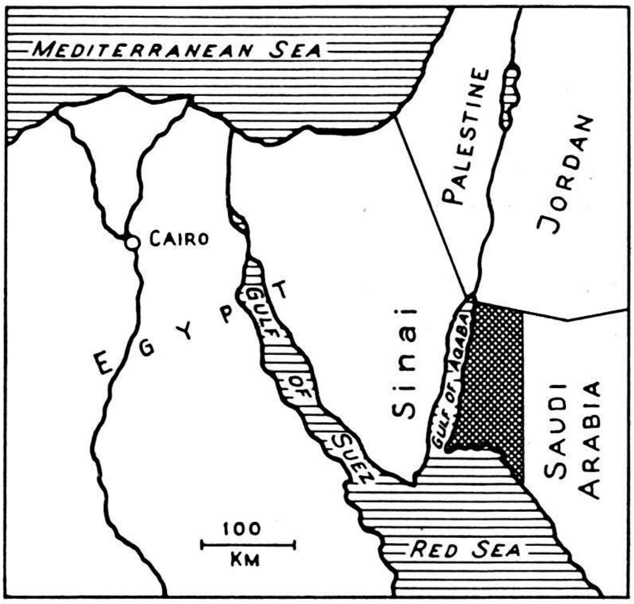

Fig. 1. Location Map showing Northwestern Hegaz, 1:10000000.

Brief reconnaissance observations, combined with studies of available topographic maps (mostly on a scale of 1:250,000 or smaller), oblique and vertical aerial photographs (scale 1:40,000) covering part of the area, have enabled the writer to gather some information relative to the geology of this part of Saudi Arabia.

Herein a brief discussion will be given treating only of the fault patterns, perhaps the most outstanding geological feature.

TOPOGRAPHY

From the Gulf of Aqaba the land rises very abruptly to heights over 1500 m within 10 km of the coast. A range of mountains ('Coastal Range') paralleling the Gulf reaches a maximum elevation of 1900 m in Djebel Shausha, east of which the Djebel Mazhafa trends NE–SW. East of the latter there is an impressive precipitous descent down into the valley of the Wadi El-Afal (fig. 3), which runs N–S for a distance of some 120 km. Almost the entire length of this valley lies below 450 m, with very steep slopes rising on either side to elevations of 700–900 m and more. East of the El-Afal, again the land rises steeply to a series of ranges running in a general N–S direction. The highest and most prominent range within these 'Interior Ranges' is the Djebel Loz (fig. 3), 2580 m. SE of Khureiba a series of parallel mountains, collectively named here the Djebel el Shifa, approach close to the shoreline, due to the pronounced easterly 'offsetting' of the coast.

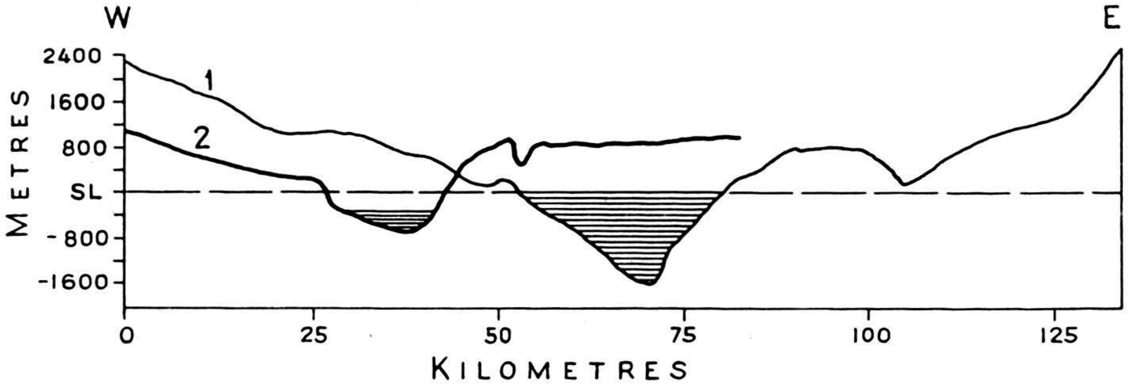

Fig. 2. Profils 1:1250000: (1) across G. of Aqaba in Lat. 28° 30′ N, and (2) across the Dead Sea in Lat. 31° 30′ N. (Vert. Exaggeration=8)

From the summits of the 'Interior Ranges' the land slopes gently eastwards down to elevations of about 700 m in the large interior basin of Al Hisma, through which the old Damascus-Medina railway once went, via Tebuk.

The Gulf of Aqaba, deep and treacherous, is bordered by forbidding, rugged, steep and inhospitable highlands. The average height of these highlands bordering the Gulf is about 850 m. Maximum depths in the Gulf exceed 1800 m and throughout the 100 m isobath follows close to the shoreline. The bottom of the Gulf depression thus lies some 2650 m below the level of the enclosing highlands, compared to a similar measurement of about 1500 m in the latitude of the deepest part of the Dead Sea (fig. 2). Between Ras el Qaaba and Khureiba the plain is broad, low and swampy, showing evidences of recent submergence.

The present-day landforms are directly related to tectonic processes, such that everywhere tectonic relief (COTTON, 1953) predominates. Earth movements have left their imprint upon the landscape to a most marked degree. In time, denudational agencies will modify this relief and create in turn a structural relief, where geomorphic adjustment is made to the structure. Crustal adjustments by means of faulting have caused the strong slopes, abruptness and 'freshness' of the landscape, indicating the importance of recency in tectonic movements.

STRATIGRAPHY

Sketchy and brief though it is, the only notable geological information available regarding this ancient land of Madian is that given by KOBER, (1911, 1919) gathered during a few days in the summer of 1910.

Precambrian outcrops throughout most of the region. It is likely that a twofold lithological division can be adopted, such as is found in southern Jordan and further south in Arabia (MITCHELL, 1955). Here, however, two discordances can clearly be noted within the Complex, with a strong possibility of a third one near the top of the exposed Precambrian. A lower unit, essentially metamorphic, comprising both low- and high-grade metamorphic suites, as well as acidic lava flows and basic dyke swarms, is succeeded by a mélange of erosion products of the older series, along with basic intrusives, acidic and basic dykes, sills, flows. Lineation and foliation is characteristic of the older series, both showing a tendency to orientate in a NE–SW direction. Fracture cleavage is very common, flow cleavage much less so.

A conservative estimate of the thickness of the exposed Precambrian would be about 4000–5000 m, compared to about 3000 m in southern Jordan (QUENNELL, 1951) and 13,000 m in West-Central Arabia (KARPOFF, 1955).

East of the Precambrian occur predominantly terrigenous deposits of the Nubian facies. (Desert facies of KOBER) Lithological similarities to rocks seen in southern Jordan suggest a Cambrian age. Specimens of *Ptychoparia* in blackish dolomitic limestones outcropping on the eastern slopes of Djebel Loz very possibly correlate these rocks with the Burj Limestone Group of QUENNELL (op. cit.), and can be accepted as indicative of the Cambrian, either Lower or Middle. The eastward dipping beds are presumed to include later Palaeozoic(?) and Mesozoic Nubian rocks.

The SW corner of the region is characterized by gravels, grits, conglomerates, sandstones, coral débris, etc. which have all the appearances of being relatively young deposits. Limestones are here prevalent, mostly seemingly of coral type. These sediments are considered to be Pliocene-Quaternary in age, though there is a possibility of Miocene on account of the innumerable species of *Ostrea latmarginata* VREDENBURG. East of the 'Interior Mountains' large areas are covered by dunes and Recent sands.

FAULTING

The resulting strains developing from deforming forces have been dominantly of rupture type. Even the folds and monoclinal flexures of the Complex all show strong evidences of the rôle of shearing. Deformations have caused failure by fracturing – faulting and jointing – rather than by plastic moulding.

Faults are the commonest rupture forms, the most impressive and exert the major influence in tectonic and structural control. Adopting a geometric classification based on direction of movement along the fault – vertical or horizontal – the faults can be classed as gravity-normal and strike-slip – wrench; reverse and thrust faults appear to be relatively scarce (fig. 3).

(1) Gravity-Normal Faults. The effect of gravity is obvious in those cases in which the hanging wall has moved downward in relation to the footwall, so

Fig. 3. Fault Patterns of Northwestern Hegaz, 1:1500000.

that the hade is towards the real downthrown side. Several of the larger faults, however, indicate a hade towards the apparent downthrown side, and thus, strictly speaking, are normal faults. The importance of the distinction lies in the fact that with the former type, lack of support under the downthrown block as well as room for horizontal extension is obligatory, whereas in the latter type, one of the blocks may have moved upward, thus obviating vertical and horizontal extension within the crust.

Gravity-normal faults have a disposition to occur in pairs, the intervening block forming a horst or graben. The largest graben is that represented by the Gulf of Aqaba, bounded on either side by long, impressive fault scarps and fault-line scarps. This graben feature is of course merely a small part of the immense Afro-Arabian-Levantine rift valley. Continued study in the Levantine section has shown conclusively that this great fault-trough is not bounded by two hugh, unbroken, parallel faults, as per textbooks, but rather the limiting faults are discontinuous, frequently curved and off-set in an echelon pattern, and that monoclinal flexures form the rims in places. Further, the throw varies considerably within the Levantine area, being about 500 m in the Djebel Ansarieh region of Syria (VAUMAS, 1950) whereas in the Wadi Araba north of Aqaba the throw more nearly approximates 1800 m.

The boundary fault on the Sinai side – as well as other Sinai faults shown – have been adopted from the morphologic map prepared by AWAD (1952). Here in Sinai, as throughout the Levant, the western edge of the rift valley forms a more continuous feature, the break in slope being throughout a faulted one.

On the Arabian side, it is clear that the subsidence block was not downthrown as one sheer drop, but rather gradually, resulting in a step-series of parallel faults, the individual 'steps' being 50–200 m different in elevation and varying up to 400 m in breadth. (Because of this small lateral space between the stepfaults, they are not shown on the map.) These fault-controlled terraces vary in dimension and profusion, such that the descent down from the 'Coastal Range' to the littoral region may, on the one hand, occur as one stupendous drop, or then as a series of descending 'steps'. The eastward tilting of many of the 'steps' suggests curvature of the individual step-fault surfaces. The littoral zone – named the Tihama further south along the Red Sea Arabian coast – varies in width as a consequence of the degree of development of these step-faults, in places non-existent and extending up to 10 km wide. Much further south, at Jidda, GUILCHER (1954) mentions a thickness of at least 210 m for the loose gravels, silts, coral débris formation of this coastal area. In the Gulf section of the rift valley, basaltic flows are not present, though to the south and farther inland, the great Harrat flows form high, fantastically sculptured mountains. This vulcanism, like that of the Hauran flows of southern Syria, is of Pleistocene age. (KOBER refers to vulcanism also within historic times.)

No direct evidences were obtained as to the age of the rift faulting. TROMP (1949, 1950), discussing more specifically the Gulf of Suez section of the Red Sea graben, believes that the faulting began in basal Middle Eocene times, the movements continuing as late as Pleistocene. The writer would merely amend this statement by saying that fault movements have continued into the Present.

The next most important graben structure forms the valley of the Wadi El-Afal, parallel throughout to the rift valley. The narrow, flat valley floor is enclosed between straight, steep slopes – fault-scarps – in some cases rising a sheer 600 m.

Strictly speaking, it is not certain whether the bounding faults are of gravity or normal type, but on mechanical principles, one would suspect them to be normal. The upper El Afal (called the Al-Abaz) has its source at an altitude of about 1200 m, on the S flank of a horst. For some 10 km the wadi lies in a narrow graben; the valley then meets a NW-SE striking gravity-strike-slip (rotational) fault, with downthrow to the SSW and lateral movement to the SE(?). Over this tilted fault-block, in which the throw decreases to the SE, the wadi-bed descends 500 m in a distance of 10 km, then re-enters the graben, and in the next 100 odd km gradually drops down to sea-level.

North of Bed, the valley broadens on the west side, due to two strike-slip faults of dextral movement.

Immediately N of Bed, the graben valley loses its distinctive features, and for the next 30 km or so southwards the western side of the valley is formed by a sharp monoclinal flexure, eroded into a fault-line scarp, whereas the eastern side broadens into a wide plain, flanked on the E by a fault. This fault strikes SE from Bed, and W of this village, it trends SW. W and S of this fault the rocks consist of young sedimentaries, whereas E and N thereof the Basement Complex outcrops. The physical characteristics of the sedimentaries have allowed them to be more easily eroded and also flexuring is more prevalent. A prominent range of hard limestone hills parallels the west bank of the El-Afal S of Bed, which have been eroded into a fault-line scarp, thus preserving a partial graben aspect. The plain east of the wadi is extremely flat and littered with sub-angular cobbles, gravels, etc. of cherts, limestones, siliceous nodules.

Some 25 km from its mouth, the El-Afal carves its way as an antecedent gorge through a prominent E-W trending horst, here called the Ndejira horst. The wadi-bed lies some 100 m below the surrounding levels, and in places is constricted to a width of no more than 20 m. South of the coast, submarine contours indicate that the graben follows a SW course between the islands of Senafir and Suswe.

One may speculate whether this fault separating Complex rocks from young sedimentaries might not be the actual continuation of the rift fault, as KOBERS's map (1919) seems to suggest. (Several other small-scale geological maps have copied KOBER in this respect.)

It is undeniable that the stratigraphy, lithology and physiographic expression is markedly different on either side of thes SW-SE fault, the impression being that this SW region is a depressed fault-block. In the Wadi Msejr, eroded within a small graben in the Ndejira block, loose, angular débris of typical Complex rocks are profuse in the middle section of the wadi. As the wadi has its source and continues throughout a region of exposed young sedimentary rocks, one concludes that these Complex rocks must have been derived from within this area. Presumably the horst has raised the Complex surface to within vertical range of river erosion, and hence the Complex must lie at very shallow depth beneath the sedimentary covering. It appears that this SW–SE fault is of older origin – the palaeo-rift fault – and that S of Maqna the coastal fault is a later feature – the neo-rift fault.

The horst-block of the Djebels Shausha and Mazhafa forms the highest elevations within the 'Coastal Range'. The eastern side of the horst forms a prominent high wall, but to the west, the descent is more gradual through a series of step-faults. The horst as a whole is broken-up into many smaller blocks which have undergone unequal degrees of tilting in more than one direction. The boundary faults of the horst show a wide variation in degree of vertical movement, the general tendency being an increase in throw as one approaches the northern and southern extremities. The variously disposed smaller fault-blocks within the horst give every indication of having been subjected to intense stresses, evidenced by the abundance of dykes, joints, tear faults, small reverse and/or thrust faults, etc. In fact, this horst-block, on the basis of the extensive fracturing, appears to have undergone more intense deformation than any other locality within the region discussed. (The scale of the accompanying map prohibits showing all the many fractures.) The extremities of the boundary faults tend to split into smaller faults, all curving outwards. These 'feather' faults are of gravity type, with the exception of one small thrust fault, thrust movement to the E.

Djebel Loz is a horst tilted towards the E. On the eastern slopes of the range, the Nubian Palaeozoic facies rests unconformably upon the eroded and planed Precambrian surface. The dip of these terrestrial deposits averages 10° to the ENE. In the upper reaches of the eastward-draining wadis, the steep valley walls, traced longitudinally, show the Precambrian peneplaned surface, underneath the Nubian sediments, tilted eastwards at angles as high as 30°. We conclude therefore that the horst-block was tilted in late Precambrian or early Cambrian times. (There are evidences elsewhere in the Middle East that in the Lipalian interval pronounced tilting was a characteristic tectonic occurrence.)

A large NE–SW striking fault of undetermined type (transverse fault?) separates the Djebel Loz structure from a horst to the SE, which latter includes the high northern ranges of the Djebel el Shifa. As distinct from the Loz structure, the Shifa horst is far less clearly defined structurally and also shows almost no tilting.

Parallel to the western horst-block fault are many small antithetic faults dipping eastwards. The rectangular-shaped blocks within these antithetic faults show slight tilting to the west.

These two horst-blocks of Djebels Loz and el Shifa show a rebroussement, a trending SW towards the palaeo-rift fault then a doubling back towards the SE. Within this inflection area, the fracture pattern is extremely complicated, whilst to the E the fault pattern shows a radial development, with a few peripheral-type faults. Due E of where these horsts show inflection, a broad E–W basin leads downward to the vast el Mehteteb depression. This E–W basin is partly bounded by faults, partly by sharp monoclinal flexures. The development of ring-dykes and the scattered black, conical appearance of hills and mountains E of the above region indicates igneous activity, whilst the structural patterns suggest some type of collapse phenomenon. Whether the fractures are associated with calderas or crypto-volcanic structures is not certain, but most certainly this whole area warrants careful field study in order to elucidate its structural complexity.

The Ndejira horst-block meets the coast at right-angles, but eastward dovetails towards the palaeo-rift fault. As remarked above it is presumed that the Precambrian rocks lie at shallow depth beneath the exposed young sedimentaries. The presence of the Complex so near the surface results from uplift associated with the horst plus the more extensive denudation of the softer cover rocks. Many small yet prominent cuestas, scarps, buttes, composed of more resistant crystalline limestones, have been eroded out of these younger rocks. The horst as a whole has undergone remarkably little fracturing, but on the other hand shows strong tilting towards the SE. Styolitic growths are well developed in some of the limestones, the seams being stained red with iron oxide. Whatever the origin of styolites, it is accepted that they have been formed in such a position that the bisectrices of the angular zig-zags are always vertical, and variation from the vertical indicates tectonic movement. Limestones in which the styolites occur at present dip about 30° E, the dip of the styolite seams being about 20° E. Analysis of the bisectrices and seam-dips leads to the conclusion that the limestones were dipping at an angle of about 10° E when the stylolites were formed. This amount of eastward tilting, viz. 20°, can not generally be applied to the whole horst structure, however. Such tilting has occurred since Quaternary times, raising the sedimentaries higher in the western sector, where stripping of the cover has been more drastic.

The southern coastal region S of the Ndejira horst is undergoing subsidence. The actual coastal strip is marshy, extremely flat, composed of much coral débris washed up and deposited by the inundating sea. The off-shore islands – Tiran, Senafir, etc – are characterized by precipitous southern slopes, gentle northern ones, raised coral reefs and beaches, suggest that these islands lie on the southern edge of horst tilted to the NE, the NE edge subsiding in the coastal region. On Tiran, limestones containing abundant *Melania*, *Limnaea*, etc. occur at elevations up to 500 m, are absent throughout the S coastal plain, but reappear E of Maqna at elevations of about 350 m.

Indubitably the Ndejira horst-block faulting is young, representing perhaps the youngest major faulting in the region.

Most of the smaller graben and horsts, as well as the single gravity and normal faults, have a diagonal pattern, a NE–SW strike being more in evidence. Especially in the N, many small such faults are of pivotal type, whereas in the S, hinge faults are more common. Variation in amount of vertical displacement along the strike of the faults may be gradual, but the frequent abrupt change in degree of throw necessitates postulating cross-faults with consequent development of fault-blocks.

As would be expected, the great majority of the gravity-normal faults have a steep dip. However, instances occur – best example noted is the gravity fault paralleling the palaeo-rift fault SE of Bed for a distance of some 25 km – in which the dip decreases southwards to values as low as 45°. The explanation of such presupposes rotational stresses and curving of the shear surfaces towards loci of less resistance.

(2) Strike-slip and Wrench Faults. Here the dominant feature is the relative or true movement of the fault-blocks in a horizontal direction. Where the fault surface is vertical or nearly so, we have a wrench fault; otherwise the fault

is described as strike-slip. (Tear faults are either strike-slip or wrench faults of relatively small dimensions, showing a tendency to occur transverse to the general structure.) The literature makes no distinction in differentiating between actual and apparent horizontal movement for such faults, such as is made for gravity and normal faults. Borrowing from MOODY and HILL (1956), however, we may adopt the terms lateral strike-slip and lateral wrench to indicate true horizontal movement, and strike-slip and wrench to signify apparent horizontal movement. The prefixed adjectives sinistral and dextral apply to either true or apparent movements of the block(s). In looking across the strike of the fault, if the distant block has actually moved to the left, the near block being stationary, the fault is sinistral lateral strike-slip or wrench: if the apparent movement is to the left, the fault is sinistral strike-slip or wrench. Similar displacement, true or apparent, to the right defines the dextral character.

Faults in which horizontal movement, actual or relative, is the the significant feature, are far less comprehensible, involve more complicated mechanics, show a more intricate fault pattern than is the case with gravity-normal faults. In the absence of detailed field investigations, it is not possible to catalogue precisely all horizontal-type movement faults in the region in question.

The most prominent sinistral wrench faults are those striking NW–SE and cause the off-setting of the major rift. Only apparent horizontal displacement is discernible, to the extent of some 20 km.

Along these faults there has also been some vertical movement, the SW block being lowered with respect to the NE block, and, in fact, basculatory movement is apparent. The recency – or then renewed activity – of these faults is seen in the off-setting of Recent littoral terraces, screes, coarse 'delta' débris. The major rift fault and these wrench faults intimately outline the present configuration of the coast, i. e. the coastal zone is of tectonic origin. Here, however, the effects of marine attack have become manifest in a remarkably short space of time. The coasts of the Gulf of Aqaba are described as one of the most windswept in the world (Meteorolog. Off., 1951), gales usually blowing from E of N or N, whereas prevalent winds blow from the S and SW. Gale-force winds arising with fierce suddenness whip the narrow, deep waters of the Gulf into storm-tossed waves, and as deep waters extend near-shore, the powerful waves hurl themselves with damaging results against the land.

There is a temptation to regard the NE–SW trending section of the palaeo-rift as a strike-slip or wrench fault. It is well known that quite a few major faults once considered to be of gravity-normal type, have, upon more careful study, proven to be wrench faults, e.g. the Great Glen fault of Scotland (KENNEDY, 1946). The confusion is readily understood when it is realized that some degree of vertical displacement always seems to be present along wrench faults, and if the latest movement along a wrench fault was vertical, mistaken identification is easily possible, the more so as it is often extremely difficult to distinguish the relative rôles of vertical and horizontal displacements associated with wrench faulting. The juxtaposition of Complex rocks N of this fault with young sedimentaries to the S requires vertical movement. Paralleling this fault, several tear faults occur in the Precambrian rocks, which certainly testify to lateral movements within the

Complex. No doubt vertical and horizontal displacements have taken place, the former estimated to be about 400 m, the latter some 25 km.

As far as can be determined, wrench faults more commonly have a NW–SE strike with sinistral lateral displacement. Strike-slip faults, on the other hand, show wide variations in strike directions, with dextral lateral movements most prevalent. Horizontal shifts along these types of faults do not seem to exceed some 25 km.

(3) Compressional Faults. Compressional fractures of reverse and thrust fault types seem to be very scarce. As strike-slip, wrench, reverse and thrust faults are all due to lateral compression, gradation of one into the other is to be expected. Such indeed is obvious in the region discussed, for faults resulting from horizontal shortening due to compression usually are intimately associated with wrench and strike-slip faults. Thrust faults are of small magnitude, and nowhere does the fracture system suggest strong tangential pressures.

AGES OF FAULTS, DYKES

The age relations of compressional-type faults to tensional faults has not been clearly deciphered. Both mechanical principles and geological inferences present arguments on the one hand for considering the major rifting as older, on the other hand for considering the prevalent fracturing as older. The general consensus of opinion, however, considers the major rift faulting of the Levantine-Afro-Arabian region to have begun in Tertiary times. The dating of subsequent movements along a fault is a simpler matter than dating the inception of faulting. For the area here discussed, it cannot specifically be stated whether the original faulting is old, with rejuvenation of fault movements, or whether the faulting is young. That later rupturing would occur in response to stress increments is to be expected, and evidences certainly point to fault movements in Recent and historical times. The fact that the Precambrian rocks are more strongly faulted and shattered than the Cambrian Nubian rocks, and these latter in turn more faulted than the young sedimentaries refers rather to the physical characteristics of the rocks involved than intensity of rupture or age of rupturing.

A dextral wrench fault off-sets the western southern side of the Ndejira horst, and would therefore be considered younger than the horst faulting. However piedmont scarp faults S of the horst-block, strike uninterruptedly across the wrench fault but are abruptly terminated against the horst-block, suggesting that they are pre-horst fault and post-wrench fault in age. Be that as it may, it is concluded that this horst-block region represents the locus of major young rupturing, though minor faults here and there are younger still and even active at present.

The neo-rift faulting probably began in late Pliocene, continued into the Quaternary, perhaps even Recent, but is believed to have been quiescent during historical times.

That taphrogenesis was operative in Precambrian times is manifested by the many dykes which intersect the Complex. As in Jordan, the dykes comprise both acidic and basic rocks, and, in fact, the close petrological affinities of the dykes of both regions imply a common source. These dykes of southern Jordan which cut the crystallines and granites of the Complex are of Precambrian age, and a similar age may safely be assigned to these dykes of the Hegaz. (Basaltic dykes on the eastern side of Djebel el Shifa may be of Recent date, genetically related to the great basalt outpourings of the Harrat ar Rha, SE of the above range of mountains.) The length (up to 15 km) and breadth (up to 200 m) of some dykes bear witness to extensive fissuring of the Complex. The pattern of the dykes is subparallel to the palaeo-rift fault and approximately at right angles thereto. Unmistakable displacements seen in many dykes and the low dips of some dykes may be associated with disturbances in the Lipalian interval. The more leucocratic acidic dykes appear to be far more irregular, both in trend and thickness, than the basic ones, and give the impression of being under more strict tectonic control.

INTERPRETIVE NOTES

In Upper Algonkian times, orogenesis folded, warped and fractured the crystallines and igneous mélange of Complex rocks. Early Infra-Cambrian times witnessed disturbance leading essentially to tilting of folded, warped and fractured masses – the dying-away phase. During the remainder of the period, extensive and profound denudation wore down these ancient mountains into a flattened peneplain. By comparison with the Precambrian Saramuj series of Jordan, we may accept the contentions of QUENNELL (op. cit.) and PICARD (1941) that this Precambrian fold movement was directed towards the NE. Likewise in southern Jordan we have evidence of sinistral wrench faulting in the Saramuj which does not affect the overlying Quweira series. From this we may assume that at least some of the tensional and compressive stresses were initiated in the Precambrian, and it is in in order to conclude that differential fault-block movements took place then also.

According to PICARD (1937), the long interval from Cambrian to late Mesozoic-early Tertiary was characterized by epeirogenic vertical movements, foldings being conspicuously absent throughout this Arabian peninsula region.

The uparching of the Afro-Arabian massif is postulated as being initiated in early Tertiary times (Palaeocene?). The vertical and compressive forces maintaining the uplift would have three important results: (i) re-activation along old fractures, (ii) development of new fractures as a means of strain relief, (iii) the jostling and nudging, hence unequal tilting, of fault-blocks. (In Jordan, however, it is almost certain that some of the Complex blocks were tilted during the early Infra-Cambrian.) Increments of stress, though relieved locally and sporadically in time, must build-up to a critical point. The physical behaviour of the rocks was such that rupture followed elastic deformation. (Because of the lack of any relation between brittleness and strength, because strength has no relation to the boundaries of bending and rupture, and because of the imperativeness of precise knowledge of stress-strain environments and conditions which is utterly unobtainable in structural geological studies, the terms brittleness and strength are better ignored.)

Given a consistency in physical rock characteristics, the dimensions of a fault bear a direct relation to the intensity of the stresses operative. Of course, small fractures may develope simultaneously with larger ones, having a 'sympathetic' relationship, in which case the larger ruptures are the real clues to intensity of the stresses.

In the uparching of a large mass of the crust, tangential and vertical stresses are active, and as a consequence tension developes in the outer part of the bending arch – witness compression causing anticlinal folds and tensional fractures developed towards the circumferential part of the fold. The crestal part of the arch is under greatest tension, where there is a maximum degree of curvature, the tensional fractures converging downwards. In this part of the arch optimum conditions prevail for subsidence of the 'keystone' of the arch, viz., graben formation. (The essential mechanical principles apply equally well to micro- and macrostructures, and it is from study of the former that we can reason to the latter.) The recognized inability of rocks in general to withstand great tensile stresses favours rupturing rather than bending; gravity faulting results in graben formation – the palaeo-rift fault.

Rupture of the Afro-Arabian shield imparted to the Arabian part a regional tilt to the ENE. The author (MITCHELL in press) has treated of isostatic changes affecting the Arabian shield or sialic 'raft', but we may merely note here that the western fractured edge of the shield displays a lack of isostatic compensation, whereas the eastern part, geographically represented by Mesopotemia, Persian Gulf and the Alpides, is over-compensated. Hence there must be a tendency to restore isostatic equilibrium by depression of the western edge of the socle. The rôle of deep tectonics (CIZANCOURT, 1948) within the Arabian shield is an unknown factor at the present, but that profound crustal adjustments are operative seems mandatory. The neo-rift fault may represent a partial expression of attempts to restore isostatic equilibrium.

As previously mentioned, the Ndejira horst is likely the youngest, or one of the youngest major structures occurring on land. The disposition of submarine contours, the alinement of the off-shore islands with their raised beaches, etc. and the subsiding southern coastal area are taken as outlining another horst-block, uprighted along its southern margin and depressed along its northern margin. The relatively shallow 'saddle' of the Straits of Tiran lend some substantiation to this concept. The occurrence of tsunami-type waves (in the sense of their violence, suddenness and independence of meteorological conditions) in the waters of this general area are probably instigated by submarine fault adjustments leading to downward displacements of the sea-bed. Might not a new rift fault be developing here, S of the off-shore islands, the tilted horst of the island-edge representing the raised lip of the rift?

It is true that fault movements will prefer to utilize fractures already in existence, but we would also note that gravity faults (the rift faults) demand necessary space for horizontal adjustment. (At the surface the Gulf of Aqaba averages about 20 km in breadth; the surface width across the N end of the Red Sea W of this postulated fault is about 100 km.) In this connexion we might note that the wrench faults affecting the neo-rift fault on either side of the Gulf have broadened the graben, representing perhaps a final effort to acquire necessary space for horizontal distension. The writer cannot subscribe to the contention of QUENNELL (op. cit.) that the graben has been formed by drift: throughout, any extension in width has been accomplished by horizontal mevements along fault surfaces.

CONCLUSION

Discussions of fracture patterns invariably involve analyses of stresses and strains, their magnitude, directions, point of application, etc., the use of stress-strain ellipsoids, and so forth. The very nature of the structural problem renders it impossible to carry out a rigorous analysis along these lines, for the unknowns are too numerous, the integrals remain unsolved because the differentials escape us. Even the terminology used is frequently ambiguous, sometimes contradictory. Stress is used in different senses by various writers; stress and force are often considered erroneously as synonymous terms; the all-too-common habit of treating stress in terms of vector analysis; the continually changing angular relations between stress and strain axes in rotational development; the universal fact that rocks display fracturing only after the strain exceeds the elastic limit, whereas the requirement of the strain ellipsoid demands strain within the elastic limit; conflicts between stress, strain and shear theories of rock failure – all these render extremely tenuous any theoretical attempt to analyse fracturing of the crust. No less inadequate are the frequent presentation of theories which the authors imply can be made to solve all our structural and tectonic problems, but which in actuality represent only deus ex machina.

The writer intentionally abstains from presenting any fanciful theory to account for the fracturing of this part of the Hegaz. With next to no geological literature to draw upon, inability to discuss the topic with others, (for how many 'others' have visited this region?) and because of the author's own hurried observations, it would be rash indeed to allow imaginative constructions substitute for sober observations.

REFERENCES

AWAD, H. (1952): *Présentation d'une carte morphologique du Sinai au 1/500000.* Bull. Inst. Fouad Ier. du Désert, *2*, No. 1, pp. 132–138.

CIZANCOURT, H. (1948): *La tectonique profonde de la Syrie et du Liban.* Notes et Mém. Dél. gén. franc., Levant, *4*, pp. 157–190.

COTTON, C.A. (1953): *Tectonic Relief.* Geogr. Jour., *99*, Pt. 2, pp. 213–219.

GUILCHER, A. (1954): *Structure et relief de l'Arabie, du Sinai et de la Mer Rouge.* L'Inform. Géogr., 18e ann., No. 2, pp. 55–63.

KARPOFF, R. (1955): *Observations préliminaires sur le socle ancien de l'Arabie.* C. R. somm., Soc. Géol. France, pp. 105–106.

KENNEDY, W. Q. (1946): *The Great Glen Fault.* Quart. J. Geol. Soc., *102*, pp. 41–76.

KOBER, L. (1911): *Vorbericht über die Forschungsreise in den nörderlichen Hegaz.* Kais. Ak. Wiss. Wien. Anz. math.-nat. Kl., 18. Mai. pp. 285–288.

– (1919): *Geologische Forschungen in Vorderasien.* II. Teil: *Das Nördliche Hegaz.* Denkschr. Akad. Wiss. Wien, math.-nat. Kl., *96*, pp. 779–820.

Meteorological Office (1951): *Weather in the Indian Ocean to lat. 30 deg. S and long. 95 deg. E, including the Red Sea and Persian Gulf. 2.* Local Inform., Pt. 1, The Red Sea. No. 451 b (1), 109 pp.

MITCHELL, R. C. (1955): *Note sur le Précambrien de Transjordanie.* C. R. comm., Soc. Géol. France, pp. 262–263.

– (In press): *Notes on the Geology of Western Irak and Northern Saudi Arabia.*

MOODY, J. D., & HILL, M. J. (1956): *Wrench-Fault Tectonics.* Bull. geol. Soc. Amer., *67*, pp. 1207–1246.

Musil, A. (1926–28): *Topographical Itineraries of Exploration in Arabia and Mesopotamia, 1908–1915.* In: *Oriental Explorations and Studies, 1, Northern Hegaz.* Amer. geogr. Soc., Spec. Publ. No. 6, 374 pp.

Picard, L. (1937): *On the Structure of the Arabian Peninsula.* Geol. Dept., Hebrew Univ., Jerusalem, Ser. 1, Bull. 3. pp. 1–11.

– (1941): *The Pre-Cambrian of the North Arabian-Nubian Massif.* Ibid, *3,* Nos. 3–4.

Quennell, A.M. (1951): *Geology and Mineral Resources of (Former) Transjordan.* Colon. Geol. Min. Resources, *2,* No. 2, pp. 85–115.

Tromp, S.W. (1949): *Blockfolding Phenomena in the Middle East.* Geol. en Mijn., *11,* No. 9, pp. 273–278.

– (1950): *The Age and Origin of the Red Sea Graben.* Geol. Mag., *87,* No. 6, pp. 385–392.

Vaumas, E. de (1950): *La Structure du Proche-Orient.* Bull. Soc. roy. de Géogr. d'Egypte, *23,* pp. 265–320.